International Committee for Future Accelerators
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Beam Dynamics Newsletter

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Editor in Chief:
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Contents

1 Foreword

1.1 From the Chair

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The International Committee for Future Accelerators (ICFA) met on August 19, 2009 in Hamburg, Germany. Sachio Komamiya chaired the meeting on behalf of ICFA Chair, Atsuto Suzuki. Reports from ILCSC and FALC were presented. A close collaboration between ILC and CLIC has been established. Seven accelerator working groups have been formed. In addition, a working group on common issues (planning, siting, etc) and another working group on detectors will be organized. The ILC accelerator and detectors are on track for a proposal to be submitted to governments in 2012. The FALC is considering enlargement of its membership and possible extension of its purpose beyond large colliders to other subjects such as astrophysics. FALC also discussed expansion of CERN scientifically and geographically. ICFA decided to form a new subgroup on Particle Physics Data Preservation. Cristinel Diaconu will be chair of this subgroup for the first year. ICFA also decided to disband the IHEPCCC panel.

Wolfgang Sandner, Vice Chair of the International Committee on Ultra Intense Lasers (ICUIL) and Director of the Max Born Institute in Berlin, attended the ICFA meeting and gave a presentation on the mission and objectives of ICUIL. He presented a proposal to form a *Joint Task Force* of ICUIL and the ICFA Panels on Beam Dynamics and Advanced Accelerators. The mission would be "*to promote and encourage international collaboration between the accelerator and laser communities on future applications of laser acceleration*." ICFA enthusiastically endorsed formation of this Joint Task Force. Three people will serve as the coordinators: Sandner, Uesaka (Chair of the ICFA Advanced Accelerators Panel) and I. The first step is to organize a workshop for strategic planning, which is tentatively scheduled for April 8-10, 2010 at GSI. This is an important development in the communities that the two international committees represent. A "*marriage*" between the accelerator world and laser world opens a new door that may lead to profound progress on a number of research frontiers. At this moment, the applications under consideration include laser-electron acceleration for future TeV colliders and laser-proton/ion acceleration for future radiotherapy machines.

ICFA approved two advanced beam dynamics workshops (ABDW): the 48th, *Future Light Sources 2010 (FLS-2010)*, which will take place from March 1-5, 2010 at SLAC, USA; and the 49th, *Ecloud 2010,* to be held from October 8-12, 2010 at Cornell University, USA.

The Fourth International Accelerator School for Linear Colliders will be held from September 7-18, 2009 at Hotel Jixian in Huairou near Beijing, China. The school received 244 applications from 41 countries. Through a rigorous selection process, the curriculum committee admitted 71 students from 21 countries: 20 from North and South America; 21 from Europe; and 30 from Asia. All students will receive financial aid for attending the school. A report can be found in Section 3.2 of this newsletter.

The Advanced Beam Dynamics panel held its biennial meeting on May 6, 2009 at the Fairmont Hotel in Vancouver during PAC09. The meeting minutes are published in Section 5.1. An important part of the meeting was to select the newsletter editors for the next two years. They are: J. Urakawa (No. 50, December 2009), S. Chattopadhyay (No. 51, April 2010), W. Fischer (No. 52, August 2010), R. Baartman (No. 53, December 2010), J. Gao (No. 54, April 2011) and M. Palmer (No. 55, August 2011).

The editor of this issue is Prof. Jiuqing Wang, a panel member and Deputy Director of IHEP, China. Jiuqing chose Accelerator Driven Sub-Critical Assemblies (ADS) as the theme of this newsletter. This is a topic that could have a deep impact on the future of our society. As we all know, developing clean energy and protecting the environment are two top priorities in countries around the world. ADS is an accelerator-based technology that may provide a viable solution to these major problems. Jiuqing collected 6 excellent articles in the newsletter theme section. They give a comprehensive review of this important accelerator field, including valuable lessons learned from the past. On behalf of the panel, I thank Juqing for editing a newsletter of great value.

1.2 From the Editor

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At the time I was invited to edit this issue, I had just become involved in discussions initiated by the CAS (The Chinese Academy of Sciences) on long term and sustainable nuclear energy development. After correspondence with Weiren Chou, I chose as the theme for this newsletter "ADS and its challenge for accelerator science and technology." The current interest in ADS (Accelerator Driven System) is driven by the urgent and strong demand to develop new sources of clean energy. ADS is rapidly becoming an important accelerator application. My goal was to collect articles on the general principles of ADS, the status of projects and R&D activities, and articles that highlight the main Beam Dynamics challenges for ADS accelerators. Thanks to the enthusiastic support of the authors, I received 6 excellent papers. They are arranged as follows:

First, Richard L. Sheffield and Eric J. Pitcher give a comprehensive review on the development of the application of accelerators in nuclear waste management, with the concept and technology of SMART described in detail. Following are three papers about ADS research in Europe: Jean-Luc Biarrotte and Alex C. Mueller on the European ADS project and its challenges; the physics and technology challenges on the MW Superconducting Linac for ADS by Carlo Pagani; and J. Grillenberger and M. Seidel on research using cyclotron based high intensity proton accelerators at PSI (Paul-Scherrer-Institute). There is a paper by H. Xia and Z. Zhao on R&D progress on key technologies in China. Finally, this section of the newsletter concludes with the paper by Yoshiharu Mori about a successful ADS experiment at KURRI in Japan.

Just before I completed the editing, I received a letter forwarded by Weiren from the U.S. Department of Energy about a symposium on *Accelerators for America's Future.*

This issue also contains a section on the International Linear Collider (ILC), including an article from Ewan Paterson on beam dynamics and related studies that may lead to possible changes to the ILC baseline design. There is a report on the fourth International Accelerator School for Linear Colliders, which took place at Hotel Jixian, Huairou near Beijing, China from September 7–18, 2009.

In section 5 are two workshop announcements: 1) the ICFA mini-workshop on novel concepts for linear accelerators and colliders, 2) the workshop on future directions for accelerator R&D at Fermilab.

In section 6, we have abstracts of five doctoral theses, one from Cornell University, USA, and four from the University of Hamburg, Germany.

I appreciate very much the high quality of the papers from all the contributors. Finally, I would also thank Ms. Ning Zhao, secretary of the accelerator division of IHEP, for her efficient professional editing of the whole issue.

2 Letters to the Editor

2.1 U.S. DOE Symposium: Accelerators for America's Future

The Office of High Energy Physics in the DOE Office of Science will hold an accelerator symposium, ***Accelerators for America's Future***, October 26, 2009 in Washington DC at the Washington Marriott Wardman Park Hotel.

Purpose

The symposium will examine the challenges for developing and deploying accelerators to meet the nation's needs in discovery science, medicine, energy and the environment, national security, and industry.

Goals

- To identify current and future needs of stakeholders
- To seek out crosscutting challenges – technical, technical, cost, policy – whose solutions may have transformative impacts on opportunities for the future
- To identify the areas of accelerator R&D that hold greatest promise
- To provide guidance to bridge the gap between basic accelerator research and technology deployment

Poster Session and Reception

The symposium will include a poster session and reception on the evening of October 26. Symposium participants are invited to submit posters and white papers.

On October 27-28, following the symposium, working groups of invited experts in each area will meet to discuss and draft a report to the Office of Science and the Office of High Energy Physics. Symposium posters and white papers will serve as inputs to the working groups. The reception will bring together symposium participants and working group members for dialogue and discussion.

Space is limited. For symposium information and registration:

www.acceleratorsamerica.org

3 International Linear Collider

3.1 Some Beam Dynamics and Related Studies of Possible Changes to the ILC Baseline Design

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3.1.1 Introduction

Since the completion of the ILC Reference Design Report (RDR) in 2007, global R&D has continued on all ILC systems in a coordinated program titled Technical Design Phase 1. This program, which is planned and coordinated by the Program Managers and the Technical Area Group Leaders, will transition to a Phase 2 in 2010 which has the goal of producing a more complete Technical Design Report in 2012. In this transition there will be a re-baseline process which will update and or modify the RDR baseline design taking into account progress with systems design and progress with various technologies coming from the continuing R&D programs. [1]

The RDR design was considered by some to be a conservative one and many of the topics being studied for inclusion in a new baseline are directed towards more optimum cost versus risk designs. Some of these are engineering systems design modifications, both technical and civil, while others are accelerator parameters, technical system designs and beam dynamics optimizations. A few of the latter are described here.

3.1.2 ILC Systems Updates

3.1.2.1 Damping Rings

There have been significant changes to the design of the ILC Damping Rings since the RDR where the lattice had six-fold symmetry and had beam parameters satisfying the overall requirements but was known to be non optimum in accommodating RF, wiggler and injection/extraction systems. Many design options continued to be studied and by 2008 they converged on a two-fold race track layout which still maintained a 6.4 km circumference with two ~ 1 km straight sections. [2, 3] These long straight sections allow practical design layouts for RF systems, wigglers, circumference chicanes and injection/extraction systems. This lattice design, arcs and straights, is very flexible allowing a range of parameter choices. For example, while maintaining all the required beam parameters, one can have a smaller momentum compaction factor giving a shorter bunch length (6 versus 9 mm) with the same installed RF power. This has significant benefits downstream in the bunch compression system (see below).

In ongoing design studies of smaller half sized rings (3.2 km circumference), it looks like this lattice can adjust to smaller arc lengths while leaving the straight sections with all the component layouts and constraints, as in the larger ring. A half size ring with half the number of bunches, has similar beam dynamics properties regarding electron cloud effects, ion instabilities, etc., and would use the same mitigation techniques which are selected from the ongoing R&D programs around the world. In this and in other areas of beam dynamics in storage ring design, the ILC Damping Rings and Super B-Factories have much in common.

3.1.2.2 RTML and Pulse Compressors

The Ring To Main Linac (RTML) lines are required to transport the relatively low energy, (5 GeV), low emittance beams from the DR's to the beginning of the linacs, a distance of more than 10 km, with minimal degradation of the beam properties. This has been extensively studied; however some assumptions are no longer valid and require further study. In the RDR the RTML beam line was in the beam tunnel along with main linac while equipment that could produce significant pulsed or static stray magnetic fields were in a parallel "support" tunnel. Under study today is the elimination of this support tunnel so that all or nearly all equipment shares a single tunnel as in shorter accelerators such as the XFEL. This requires a re-evaluation of the possible effects of these fields and their impact on beam properties, measurement and correction systems and mitigation of any deleterious effects.

The pulse compressors take the beam from the RTML and compress the bunch length, after acceleration to full energy, to that required at the Interaction Point (IR).

In the RDR this compression ratio was 45/30:1. (9 mm to 200/300 μm) and two stages of compression were required in order to minimize changes in other beam parameters using practical tolerances. This was a large (1 km) and complex (expensive) RF and Optics system.

With the shorter input bunch length from the damping ring and if one eases the bunch length requirement to 300 μm, the compression ratio becomes 20:1 and a single stage, much less complex, compression system becomes possible. This is under active development to become part of the new baseline design. [4]

3.1.2.3 Range of Design Parameters

In the RDR there was not a single set of Beam and IR parameters but rather a range which gave the same luminosity at 500 GeV cms, with various tradeoffs between IR optics functions and beam emittance or number of bunches in the train. The ILC systems were then designed to accommodate the total range of parameters. The table below is from the RDR and the parameter range is displayed as four possible self consistent parameter sets.

When one examines these sets from the point of view of simplification or less costly engineering solutions, the Low P, or lower beam power option looks interesting. The beam power is reduced by halving the number of bunches in the train while maintaining the single bunch charge. This would enable the use of a damping ring of half the circumference (3.2 km) with little or no change of the beam dynamics in the rings. (The bunch pattern in the rings with ion clearing gaps may need re-optimisation.). The RF power required (number of RF stations or Klystrons) is reduced in both the rings and the main linacs and the beam power to be handled by the sources and dumps is also reduced. These allow very significant changes in the overall engineering design and costs.

However to maintain the luminosity, the beta-Y and the corresponding bunch length at the IP must be reduced. Although these changes in IR optics functions are already required in other parts of the parameter range, the reduction in bunch length gives problems for a single stage bunch compressor (see above) and the beamstrahlung and related detector backgrounds might be of concern. It was to reduce and control beamstrahlung that Balakin proposed the use of a Travelling Focus. [5]

TABLE 2.1-2
Beam and IP Parameters for 500 GeV cms.

Parameter	Symbol/Units	Nominal	Low N	Large Y	Low P
Repetition rate	f_{rep} (Hz)	5	5	5	5
Number of particles per bunch	N (10^{10})	2	1	2	2
Number of bunches per pulse	n_b	2625	5120	2625	1320
Bunch interval in the Main Linac	t_b (ns)	369.2	189.2	369.2	480.0
in units of RF buckets		480	246	480	624
Average beam current in pulse	I_{ave} (mA)	9.0	9.0	9.0	6.8
Normalized emittance at IP	$\gamma\epsilon_x^*$ (mm·mrad)	10	10	10	10
Normalized emittance at IP	$\gamma\epsilon_y^*$ (mm·mrad)	0.04	0.03	0.08	0.036
Beta function at IP	β_x^* (mm)	20	11	11	11
Beta function at IP	β_y^* (mm)	0.4	0.2	0.6	0.2
R.m.s. beam size at IP	σ_x^* (nm)	639	474	474	474
R.m.s. beam size at IP	σ_y^* (nm)	5.7	3.5	9.9	3.8
R.m.s. bunch length	σ_z (μm)	300	200	500	200
Disruption parameter	D_x	0.17	0.11	0.52	0.21
Disruption parameter	D_y	19.4	14.6	24.9	26.1
Beamstrahlung parameter	Υ_{ave}	0.048	0.050	0.038	0.097
Energy loss by beamstrahlung	δ_{BS}	0.024	0.017	0.027	0.055
Number of beamstrahlung photons	n_γ	1.32	0.91	1.77	1.72
Luminosity enhancement factor	H_D	1.71	1.48	2.18	1.64
Geometric luminosity	$\mathcal{L}_{geo}$ 10^{34}/cm^2/s	1.20	1.35	0.94	1.21
Luminosity	$\mathcal{L}$ 10^{34}/cm^2/s	2	2	2	2

Figure 1: Beam and IP Parameters for 500 GeV cms.

A Travelling Focus has been applied to the RDR Low P parameters set to produce a New Low P set which has a bunch length of 300 μm while maintaining comparable luminosity and beamstrahlung to other parts of the parameter range. [6] This again allows single stage bunch compression along with reduced RF and smaller DR's. Variations around this set will be explored further to understand possible parameter ranges. It is noted that the Travelling Focus technique is also now being considered for application in Super B Factories.

3.1.2.4 Beam Delivery System

There continues to be many developments of the Beam Delivery System which stretches from the end of the linac through the Interaction Region (IR). [6] Crab cavities are incorporated because of the 11 mrad crossing angle and the Travelling Focus requires transverse deflecting cavities, (~ 20% of the strength of the crab cavities) and sextupoles. In addition, more compact lattice alternatives for energies up to 1 TeV cms, are being studied and much work is directed to optimizing the optics and engineering of the final focus and the machine detector interface. Here the optics and design of the final doublets have to be compatible with different detector designs which are in a push-pull arrangement.

When one includes the need for collimation systems and special instrumentation such as polarimeters, one has many interacting requirements for the overall beam delivery optics design. Such a complete design solution will be available later this year.

3.1.3 Summary

The ILC design continues to evolve with strong coupling between beam dynamics and engineering design. As with all accelerators this will continue until a site is selected and actual construction begins. I have not covered the major R&D and Test Facility efforts (global Superconducting RF developments, ATF2 at KEK, CESR-TA at Cornell) or the design of conventional facilities.. All are very important components of the ILC design and progress on these and of the topics mentioned here will be reported on at the following meeting.

2009 Linear Collider Workshop of the Americas (ALCPG09)
The University of New Mexico, Albuquerque, New Mexico, USA
29 September - 3 October 2009

This will lead to working decisions, by the end of 2009, on changes to the baseline design which will be used for the Phase 2 of the Technical Design.

The work reported on in this brief article represents what is being done by the many members of the ILC GDE Global Collaboration. This should be recognized and the author takes sole responsibility for errors and omissions.

3.1.4 References

1. N. Walker, M. Ross, Akira Yamamoto,“Progress Toward the International Linear Collider”, Proceedings of PAC 09, Vancouver, 5/09. to be published.
2. S. Guiducci,“ Damping Rings” , AAP Review Tsukuba, 20 April 09. http://ilcagenda.linearcollider.org/getFile.py/access?contribId=13&sessionId=1&resId=2&materialId=slides&confId=3154
3. A. Wolski et al., https://wiki.lepp.cornell.edu/ilc/bin/viewfile/Public/DampingRings/TeleConference?filename=2009-06-22-Wolski.pdf
4. N. Solyak, “RTML Progress” , AAP Review Tsukuba, April 09. http://ilcagenda.linearcollider.org/getFile.py/access?contribId=14&sessionId=1&resId=3&materialId=slides&confId=3154
5. V. Balakin, “ Third International Workshop on Linear Colliders LC91”, BINP , January 1992.
6. A. Seryi, “BDS & MDI TILC09”, Tsukuba, April 09. http://ilcagenda.linearcollider.org/getFile.py/access?contribId=15&sessionId=1&resId=1&materialId=slides&confId=3154

3.2 Fourth International Accelerator School for Linear Colliders

Barry Barish, Director, ILC GDE,
Enzo Iarocci, Chair, ILCSC,
Shin-ichi Kurokawa, KEK
Weiren Chou, Chair, ICFA BD Panel
http://www.linearcollider.org/school/2009/

The Fourth International Accelerator School for Linear Colliders will take place at Hotel Jixian, Huairou near Beijing, China from September 7–18, 2009. The announcement and curriculum can be found in the last issue (No. 48) of this newsletter (see page 17 at http://www-bd.fnal.gov/icfabd/Newsletter48.pdf).

The school received 244 applications from 41 countries. The overall popularity and success of the school clearly indicates that it is filling an important need for the high-energy physics community. Like last year, there are about as twice many applicants from the host region, Asia, as from Europe or the Americas. This year, there were more from China (37 vs. 5 last year), because the school is to be held in China, and we had a significant increase from Switzerland (14 vs. 3 last year), mostly from CERN (13). There are fewer applications, but still a substantial number from India (39 vs. 81 last year) and we also received applicants from developing countries such as Cuba, Kenya, Azerbaijan and Kyrgyzstan.

Each applicant was required to submit a CV and a letter of recommendation from his or her supervisor. The Curriculum Committee, which is responsible for student selection, met in June in the three regions and admitted 71 students from 21 countries: 20 from North and South America, 21 from Europe, 30 from Asia. The geographic distribution of applicants and students is shown in the figures. This is a talented and highly motivated group of young people and represents the future of our field. We believe that in one or two decades, some among them will play leadership roles and make important contributions to the accelerator field.

Financial support for all the students to attend the school has been confirmed. This year’s sponsors include: CAS, NSFC, CCAST, IHEP, KEK, KNU, CERN, DESY, IN2P3, INFN, Oxford Univ., U.S. DOE, U.S. NSF, Fermilab and ILC GDE.

The focus of the school will be on Terascale linear colliders including the ILC, the Compact Linear Collider (CLIC) and the muon collider. For this year's school, we are evolving our curriculum to provide a more in-depth experience that could be of value to students who participated in our earlier schools. As a result, we have accepted eight students who have taken part in previous years. The curriculum will contain an overview of the different future Terascale lepton collider options and a lecture on linac basics, followed by a choice of two in-depth tracks: one on damping rings, linacs and the beam delivery system; and one on superconducting and room temperature radio frequency (RF) technology, low-level RF and high-power RF.

The lecturers are listed in the table. These are well-known experts in their respective fields. The students will receive good training and a great education from these instructors.

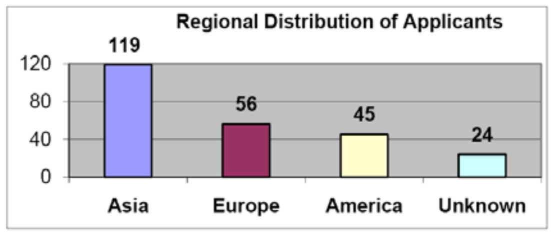
Lecturers of the 2009 LC Accelerator School

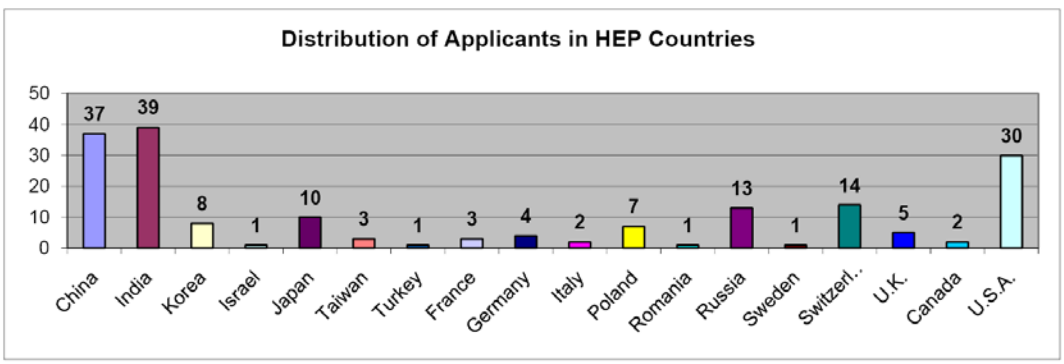
Lecture	*Topic*	*Lecturer*
I1	Introduction	Barry Barish (Caltech)
I2	ILC	Barry Barish (Caltech)
I3	CLIC	Frank Tecker (CERN)
I4	Muon collider	Bob Palmer (BNL)
A1	Linacs	Daniel Schulte (CERN)
A2	Sources	Masao Kuriki (Hiroshima Univ.)
A3	Beam delivery & beam-beam	Olivier Napoly (Saclay)
A4	Damping rings	Andy Wolski (Liverpool Univ.)
B1	Room temperature RF	Sami Tantawi (SLAC)
B2	Superconducting RF	Kenji Saito (KEK)
B3	LLRF & high power RF	Stefan Simrock (DESY)

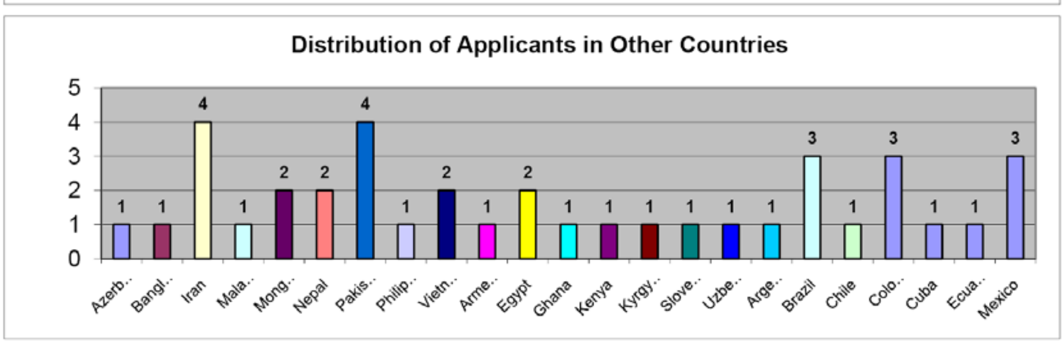
2009 LC Accelerator School – Applicants Distribution

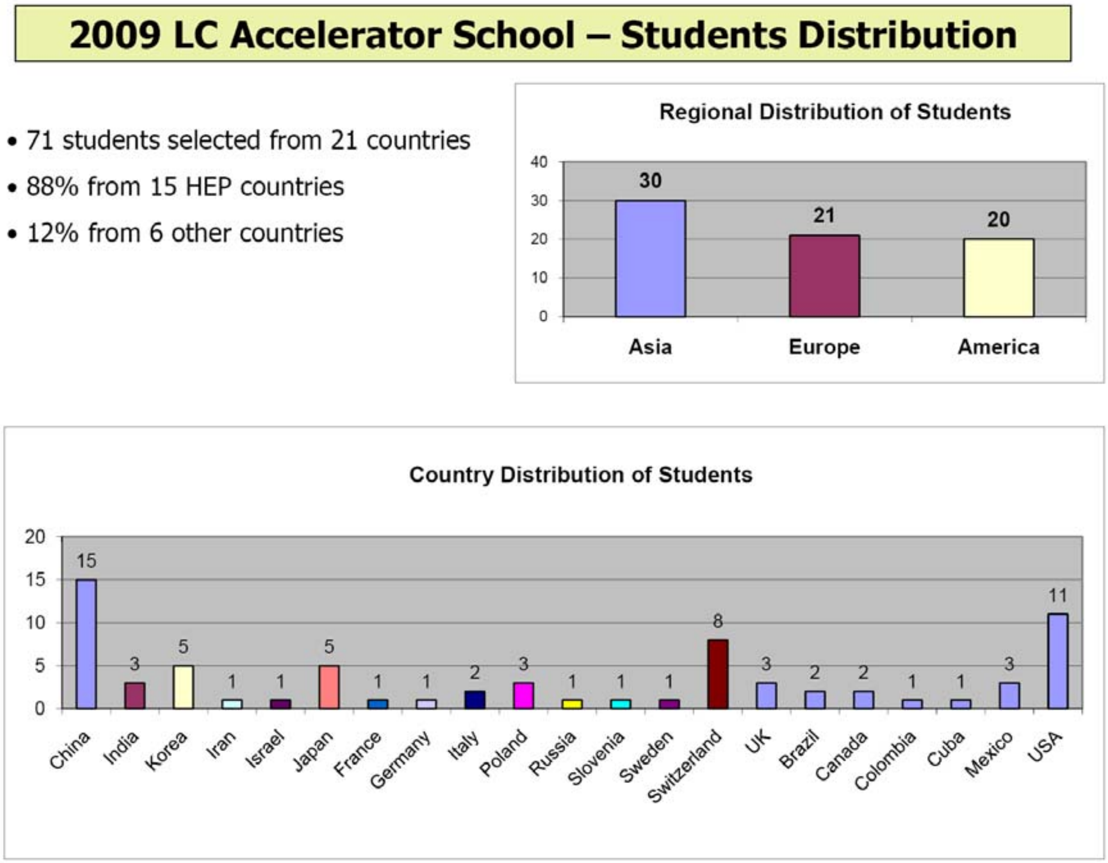
244 applicants from 41 countries

- 74% from 18 HEP countries
- 16% from 23 other countries
- 10% unknown









4 Theme Section: ADS and Its Challenge to Accelerators

4.1 Application of Accelerators in Nuclear Waste Management

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4.1.1 Introduction

A key roadblock to development of additional nuclear power capacity is the concern over management of nuclear waste. Nuclear waste is predominantly comprised of "spent" fuel discharged from operating nuclear reactors. The 104 operating US light water reactors (LWRs), that currently produce about 20% of the US electricity or more than 70% of the U.S. emission-free electricity, and, given the life extension of present plants, will create about 120,000 tons of such spent fuel over the course of their lifetimes. Worldwide, more than 250,000 tons of spent fuel from reactors currently operating will require disposal. The toxicity of the spent fuel, mainly due to ionizing radiation, will affect future generations for long into the future. The large quantity and its long-lived toxicity present significant challenges in waste management.

Nearly all issues related to risks to future generations arising from long-term disposal of such spent nuclear fuel is primarily attributable to the transuranic elements and long-lived fission products, approximately 2% of its content, as shown in Figure 1. The transuranic elements of concern are plutonium, neptunium, americium, and curium, which are produced by neutron captures in uranium fuel. Long-lived (>100,000-year half-life) isotopes of iodine and technetium are created by nuclear fission of uranium. If we can reduce or otherwise securely handle this 2% of the spent fuel, the toxic nature of the remaining spent fuel after a few centuries of cooling is below that of the natural uranium ore that was originally mined for nuclear fuel.

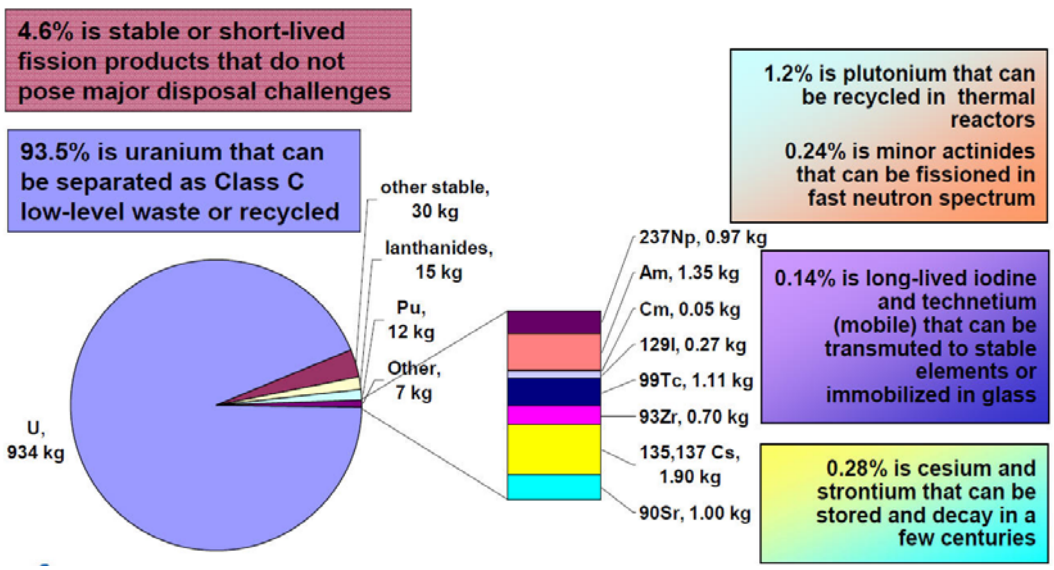


Figure 1: The isotopic fractions per metric ton for high-burn of initial fuel, 50 GW/Mt, PWR fuel at 25-year cooling. Nuclear waste is 92% U238 and has the same health concerns as with any heavy metal.

The U.S. employs "once-through" nuclear fuel cycle. Concerns about an ever expanding "Plutonium Economy" and the associated proliferation concerns in other countries led the U.S. to the "once-through" fuel cycle. Also, the low price for uranium ore over the last several decades has made "once-through" cycle economical. However, the long term nuclear waste disposal still needs to be addressed. Under any scenario, at some point in time either short-term or long-term geologic repository(ies), Figure 2, must be made available to receive the reactor waste. In the U.S., spent nuclear fuel is presently stored in buildings on reactor sites, with the expectation that it will be sent to the proposed Yucca Mountain repository once the repository receives regulatory approval to accept high-level waste. Recently a change in government opinion has led to a determination that the financial or political cost of Yucca Mountain may not be acceptable, which has revived the question of what is the best course of action for spent nuclear fuel.

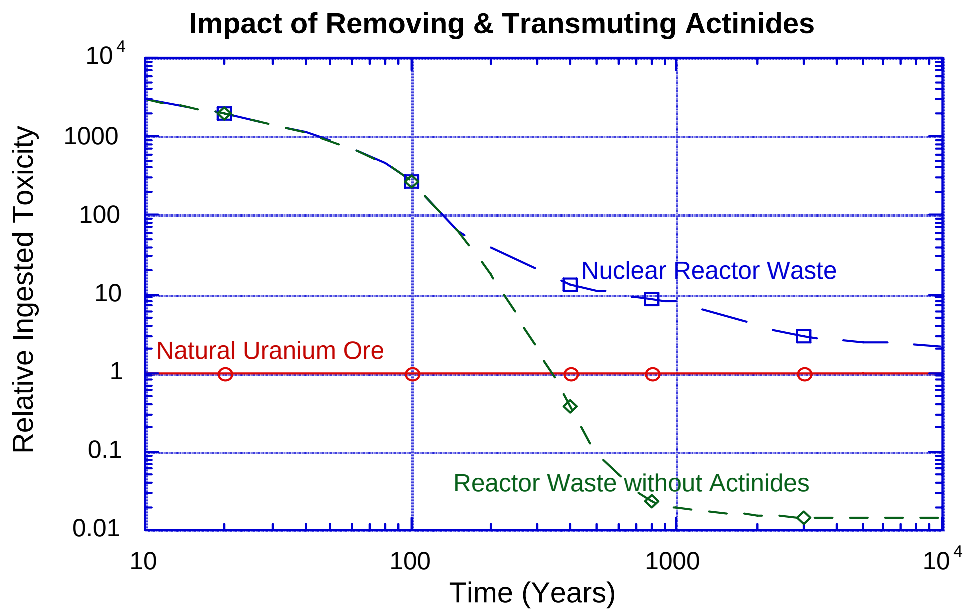


Figure 2: Unprocessed spent fuel containing materials that need isolation from environment for greater than 10,000 years requires a geologic repository. This type of repository uses geologic characteristics to isolate wastes after containers and barriers fail. For geologic repositories, the ground water transport is a key issue and climate change and population shifts add uncertainty to the long term isolation design basis. However, if the plutonium and minor actinides are removed, the requirements change in that the toxicity falls below natural uranium ore within a few centuries. Current man-made containers are capable of providing more than 300 years of isolation.

Nuclear fuel seems ideally suited for recycling. Only a small fraction of the available energy in the fuel is extracted on a single pass and the majority of the "problem wastes" could be burned in fast-neutron spectrum reactors. Most of the remaining wastes have half-lives of a few hundred years and can be safely stored in man-made containment structures (casks or glass). The very small amount of remaining long-lived waste could be safely stored in a small geologic repository. The problem for the next 100 years is that a sufficient number of fast reactors will not be built by industry to burn their own waste and the LWR waste from existing and new reactors. So an interim solution is required to transition to a fast reactor economy, as shown in Figure 3.

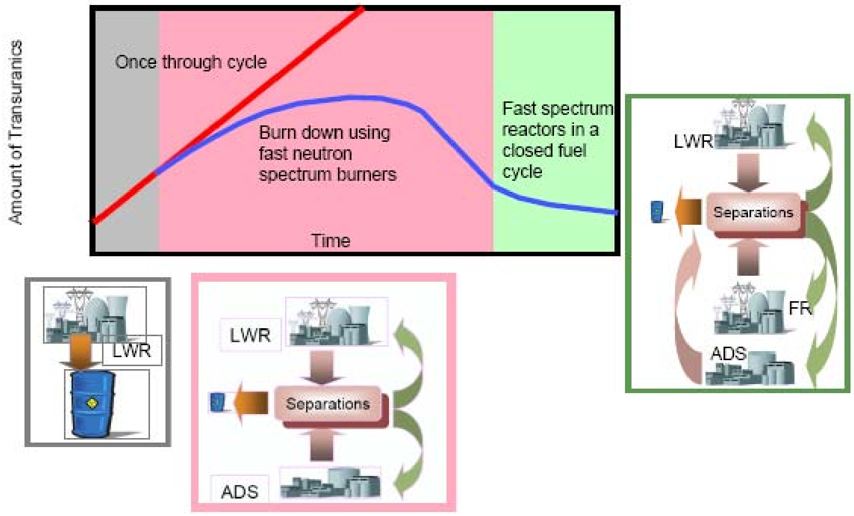


Figure 3: In the long term, a transition is needed to implement a fully closed nuclear cycle. Light water reactor – LWR, Accelerator driven system – ADS, Fast reactor – FR.

An interim solution is to dispose spent fuel using a combination of approaches depending on the lifetime of the radioactive isotope. Long-lived fissile isotopes like Pu239 and U235 can be stored with U238 and Np237 for fabrication into nuclear fuel at a future date. The short-lived fission products can be stored in man-made containers until they safely decay to low radiotoxicity levels. The long-lived fission products can be vitrified and buried. A number of projects have looked at transmuters with only minor actinide loading. [1] We have put forward a proposal called Subcritical Minor Actinide Reduction through Transmutation (SMART). The goals of SMART are: 1) to significantly reduce the impacts due to the intermediate-lived actinide, americium, on the packing density and long-term radiotoxicity in the repository design, 2) preserve the energy-rich component of spent fuel for future use, and 3) reduce proliferation risk. Storage is limited by the heat from radioactive decay in the short-term (<500 year). Long term storage is limited by container failure and the potential spread of radiotoxic isotopes. Isotopic contributions to the decay heat are shown in Figure 4. The contributions to the radiotoxicity are shown in Figure 5.

Americium can be most efficiently eliminated through nuclear transmutation using fast neutrons. One fast-neutron production method is by a high-energy proton beam generating spallation neutrons. These spallation neutrons can drive a subcritical core to transmute the long-lived Am isotopes to shorter-lived fission products, and these products are disposed in short-term repositories. The Am feedstock is assumed to be from spent fuel that has set for 50 years after removal from the reactor. At 50 years, 97% of the Pu241 has decayed to Am241. The remaining un-decayed 3% of Pu241 can be sent for long-term storage with the other Pu isotopes without significantly impacting the overall properties (internal heating, neutron source, etc.) of the stored material.

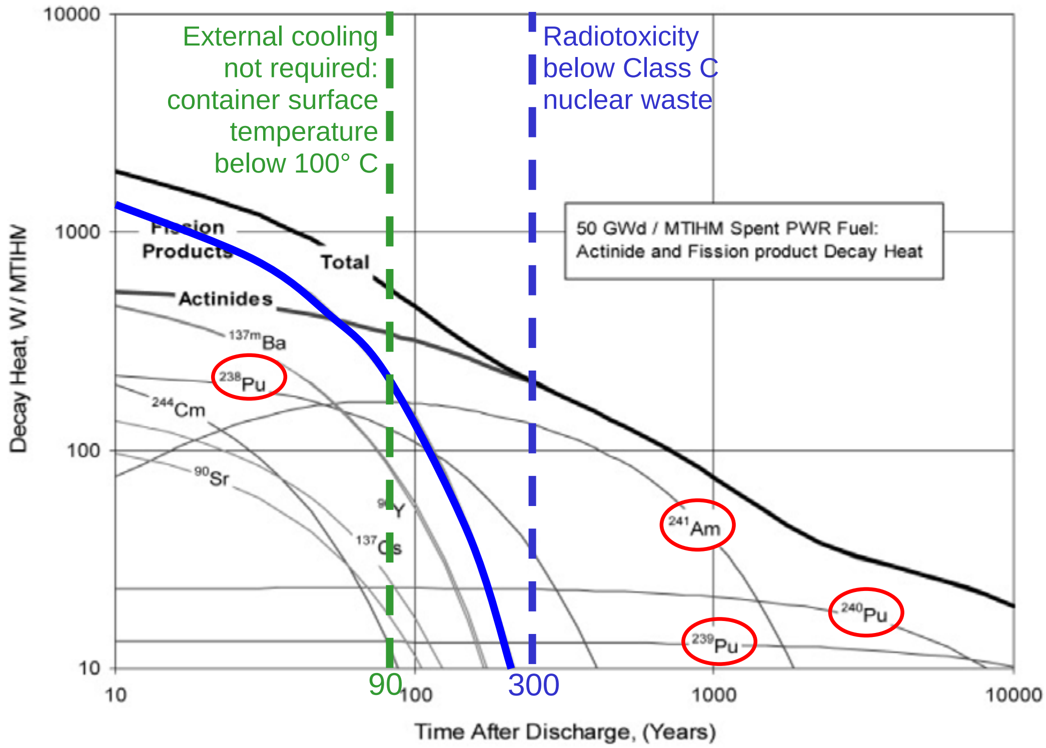


Figure 4: Dominant decay heat contributors in spent PWR fuel irradiated to 50 GWd/MTHM. [2] Goal is to eliminate components of the nuclear waste stream that account for the majority of the heat load and toxicity over the 300 to 10,000 year time frame. The isotopes circled in red are the major contributors to the decay heat in this time frame. If these isotopes are removed then: the solid blue line shows the decay heat of the remaining waste; the green dashed line shows the time at which the surface temperature of the waste container is below the boiling point of water; and the blue dashed line gives the time at which the waste radiotoxicity is below Class C nuclear waste.

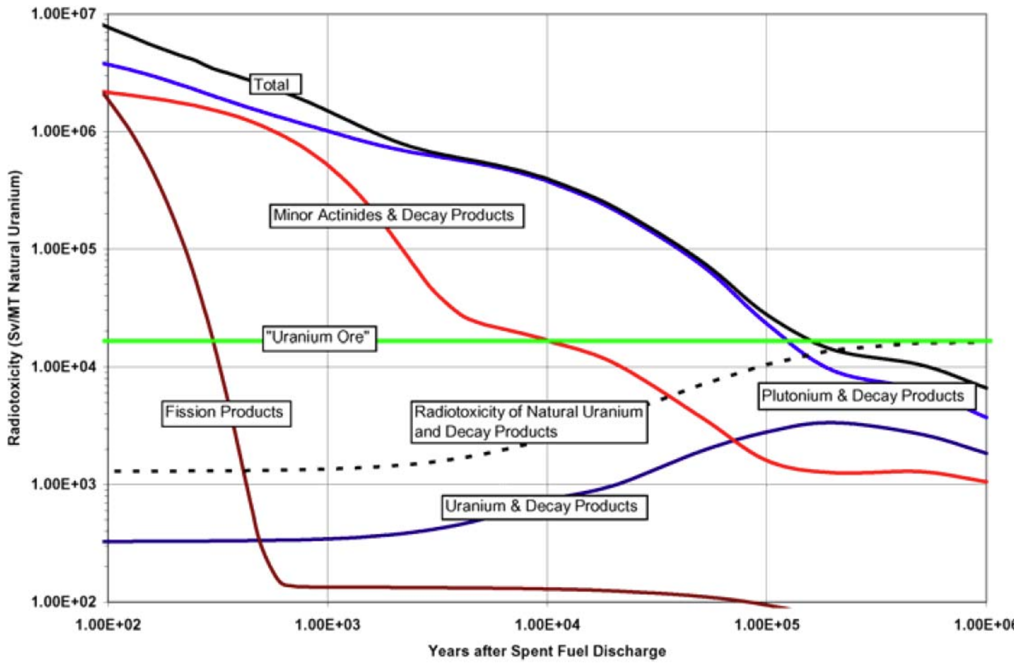


Figure 5: A radiotoxicity level equivalent to "Uranium Ore" is reached by spent nuclear fuel only after periods of more than 100,000 years. [3] The specific radiotoxic inventory of spent LWR fuel greater than 300 years is dominated by the transuranic elements, and in particular Am241, Pu240, and Pu239. The fission products decay is dominated by Sr90 and Cs137.

4.1.2 Accelerator Based Transmutation

Fast-neutron based transmutation has three major technology elements: separations, fuels and waste forms, and a fast neutron source coupled with a transmuter. A well designed accelerator-driven transmuter would operate in a sub-critical mode, and with limited excess reactivity such that the transmuter cannot reach criticality under any design basis accident. [4] For this type of transmuter, the fission rate is directly proportional to the source neutron production rate. The flexibility enabled by subcritical operation has several advantages:

- Can drive systems with low fissile content (Th or M.A.) or high burden of non-fissile materials
- Unlike critical reactors, can safely operate with fuel having a relatively low delayed neutron fraction.
- Can compensate for large uncertainties in initial reactivity or burnup reactivity swings by varying the source rate, which for an accelerator driven system is proportional to the beam current.

4.1.2.1 Accelerator Technology

The power of the accelerator is determined by the design of the subcritical multiplier. For example, for a subcritical blanket fission power of 3 GW and with the multiplier k_{eff} in a range of 0.95 to 0.98, the proton beam power ranges from 55 MW to 21 MW and a beam current swing of 37 mA to 14 mA, assuming a beam energy of 1.5

GeV. Either starting out with a lower k_{eff} or going to deeper burn, again resulting in a lower k_{eff}, would require an increase in the accelerator current. Given fixed beam energy, the accelerator capital cost is determined in large part by the average current. Designing an accelerator for a large current swing requires a very high beam current that is used for only part of the transmutation cycle. For example, a k_{eff} range of 0.90 to 0.98 for the same transmuter thermal power of 3 GW and beam energy of 1.5 GeV requires a beam power swing of 116 MW to 21 MW and a current swing of 78 mA to 14 mA.

This application is best served by a continuous wave machine, either linac or cyclotron. Cyclotrons could potentially deliver up to 10 MW of beam power (10 mA at 1000 MeV). Linacs are limited to about 100 mA per front end system, with funneling used to double this amount. Either type could serve to drive a subcritical transmuter.

Since this transmuter system will be a production system, a factor of 1.5 to 2 overhead margin is typically built into the performance specification to assure high operational reliability and long life. So the maximum operational currents are 5 to 8 mA for cyclotrons and 50 to 75 mA for linacs. In this article we are looking at accelerator systems that could drive plants of several GW thermal power and have currents up to 40 mA, and so the accelerator technology covered in this article will be limited to linac systems.

Economy of scale generally favors going to the highest average power from a single accelerator. Note that the beam may impinge on a single target in a core, be split into separate targets in a single core, or be directed to multiple cores. Of course, with the consideration of multiple targets, multiple accelerators may provide system redundancy and improved reliability, but at added cost. Beam parameters consistent with the above operating numbers were demonstrated to be feasible under the Accelerator Production of Tritium (APT) [5,6] program (Figures 6 and 7).

The axial profile of the deposited power density in a spallation target is determined by the proton beam energy. A uniform profile reduces excessive local heating. Figure 9(a) shows the profiles of the deposited power density in tungsten for different proton beam energies. The power density profile is characterized by a smooth curve ending with the Bragg peak where the proton stops in the tungsten. At low proton beam energies, the peak power density is defined by the maximum of the Bragg peak. At high beam energies, multiple scattering and nuclear processes lead to power peaking within a few centimeters of the front face of the tungsten target. Also, neutron production goes as beam energy less a 240-MeV offset, which favors higher beam energy. A beam energy of 1500 MeV distributes the neutron source over an appropriate length (about 90 cm) along the direction of proton beam propagation, and yields high neutron production per unit beam power.

The beam current of the linac is determined by the required neutron yield. The number of spallation neutrons produced per proton is shown in Figure 9(b) as a function of proton beam energy. Beyond 500 MeV, neutron yield per proton increases linearly with proton beam energy. This linear dependence, extrapolated towards low proton beam energy, has a 240-MeV offset because of nuclear reaction thresholds of neutron production. Simulations show that spallation from heavy sub-actinide metals (Ta, W, Hg, Pb, Bi) all produce about the same number of neutrons. Neutron production from uranium is about 60% greater than heavy metals due to a ~1-barn fission cross-section above 1 MeV. Using only the neutron yields in Figure 9(b) and a k_{eff} of 0.95, a transmuter fission power of 3 GW can be produced using a beam current 37 mA. Note that target losses are not a factor only for a lead-bismuth eutectic (LBE) target, and the number of neutrons available for transmutation cannot be directly calculated from the graph for other target materials.

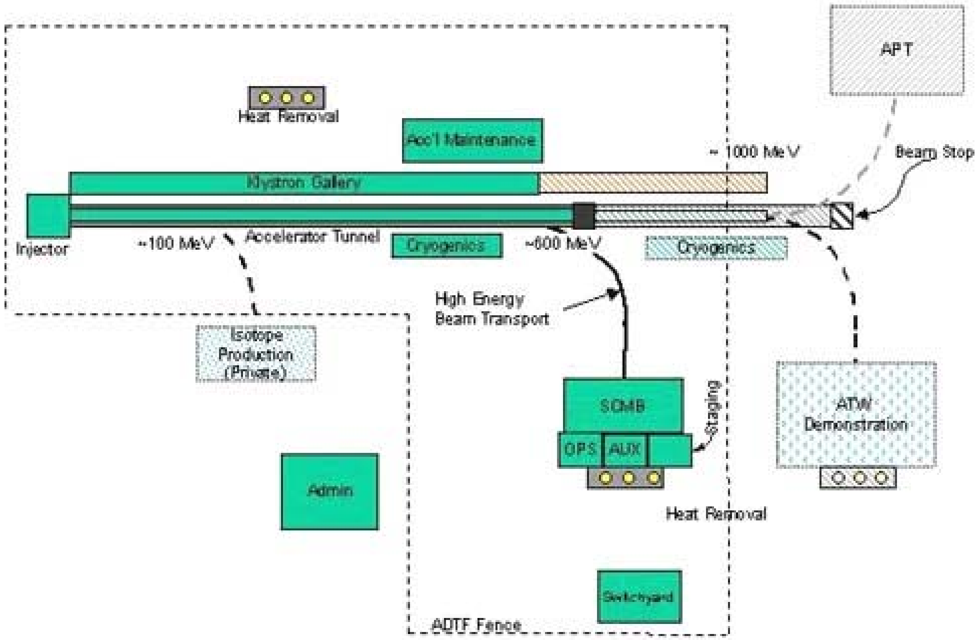


Figure 6: A schematic layout of the Accelerator Production of Tritium Facility with an Accelerator Transmutation of Waste (ATW) target station added.

Other linac requirements follow from other sub-system requirements, but more thorough studies are required to determine the full sets of requirements. For example, beam interrupts longer than 300 ms might negatively impact the subcritical multiplier. The engineering challenges need to be fully scoped out for the safe, controlled coupling of an accelerator to a subcritical reactor through a spallation target. System control and safe operation will demand the understanding and resolution of the potentially complex behavior of this coupled accelerator/target/reactor system.

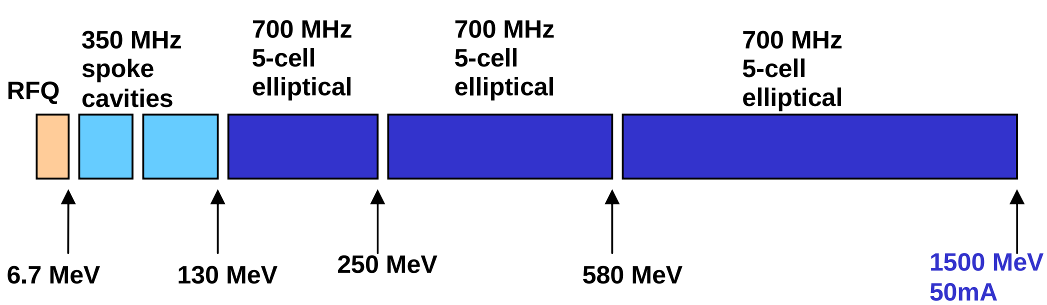


Figure 7: The accelerator preliminary design is based on the technologies developed for the APT program. The superconducting linac reduces cost and improves performance and reliability (i.e. beam continuity).

A SCRF linac has been chosen for the linac because, compared to linacs using traditional room-temperature (RT) copper technology, SCRF linacs are more power efficient and expected to have higher reliability. A comparison of SCRF and RT technologies has been reviewed at Los Alamos by a panel of accelerator experts [7]. The SCRF linac will employ independently controlled RF modules with redundancy, allowing the less than 300 ms adjustment of RF phases and amplitudes of RF modules to compensate for faults of individual cavities, klystrons, or focusing magnets. The SCRF cavities will have larger bore radius that relaxes alignment and steering tolerances, as well as reducing beam loss. Thermal transient has been a major cause of out-of-lock trips in RT linacs. Operating at a stable cryogenic temperature, SCRF linacs are expected to have significantly reduced number of such trips.

Table 1 shows the ADTF linac architecture. Except for the room-temperature RFQ, the linac is made up of superconducting sections of spoke cavities and elliptical cavities designed to match the proton energy (also referred to by β, the proton velocity divided by the speed of light) at the section location. Except for the spoke cavities operating with a high power proton beam, the baseline linac technology has all been demonstrated. The injector and the RFQ have been fabricated and tested in the Los Alamos Low-Energy Demonstration Accelerator (LEDA) [66]. The elliptical cavities, both the medium-energy cavities [8,9] and the power couplers [10,11], have shown excellent performance in R&D for the APT project.

Table 1: Linac architecture of ADTF linac

RFQ	*Spoke*	*Spoke*	*Spoke*	*Elliptical*	*Elliptical*
350 MHz	350 MHz	350 MHz	350 MHz	700 MHz	700 MHz
	2-gap	3-gap	3-gap	5-cell	5-cell
	β_g=0.175	β_g=0.20	β_g=0.34	β_g=0.50	β_g=0.64
6.4 MeV	14 MeV	40 MeV	104 MeV	211 MeV	600 MeV

Spoke cavities are low-energy SCRF structures developed originally at Argonne National Laboratory and have been adopted as the baseline for the RIA (rare-isotope accelerator) linac. [12] Development of spoke cavities in Los Alamos [13] was started in spring of 2001. Excellent results were obtained for single cell spoke cavities [14]. Figure 8 shows an engineering model of a multi-cell spoke cavity. A SCRF linac has higher availability and reliability because of the short cavities and RF-system design allows for quick recovery from a RF-system failure, which is a major cause of linac unreliability. The RF system for the superconducting linac is designed to operate with failed cavities. The RF windows and all transmission-line components can be isolated if a failure is anticipated by observing an increased arc rate or increase in temperature of the RF window. If such incident occurs, the associated cavities will be detuned. Cavities adjacent to the failed cavity will be adjusted in phase and amplitude to make up for detuned cavities. This strategy will minimize the interruption of the beam by RF-system failures to less than 300 milliseconds as required. While the linac operation continues, the failed RF station will be repaired, tested, and made ready for return to service. This strategy has been successfully demonstrated on the Spallation Neutron Source linac at Oak Ridge National Laboratory [15].

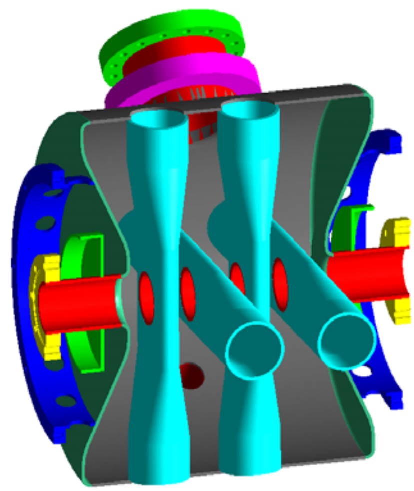
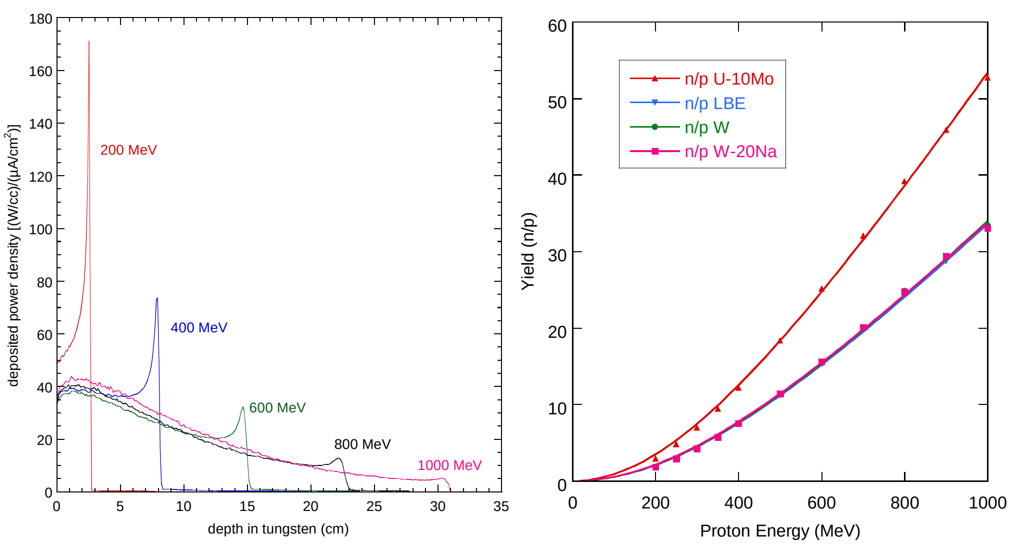


Figure 8: Engineering model of a β=0.125, 5-gap spoke cavity at 350 MHz



9(a) 9(b)

Figure 9: Profiles of deposited power density as a function of depth in a tungsten spallation target for proton beam of various energies is shown on the left 9(a). Number of spallation neutrons per proton as a function of proton beam energy is shown on the right 9(b).

4.1.2.2 Subcritical Core Design.

The subcritical blanket that surrounds the spallation target has many characteristics similar to that of a fission nuclear reactor. For the transmutation application, a fast neutron spectrum offers a higher fission-to-capture ratio in actinides that have fission thresholds near 1 MeV (so-called threshold fissioners, also known as fertile isotopes) than a does a thermal neutron spectrum. A higher fission-to-capture ratio offers better neutron economy because fewer neutron reactions must occur to induce actinide fission.

To simplify core cooling, the design should have a nearly constant fission power density as a function of core radius. This is a challenge in subcritical core design because the neutron flux naturally peaks near the external neutron source, i.e., the spallation target. Proposed solutions for addressing this issue include multiple spallation targets driving a single core [16] and adjusting the fuel composition in different radial regions of the core. [17].

Another goal in optimizing subcritical core performance is minimization of the reactivity swing during burnup. For the scheme proposed here, the equilibrium cycle feed stock is Am from reprocessed 50-year-old spent fuel. Neutronics calculations performed using the Monteburns code [18] show this feed stock has acceptable reactivity swing (from 0.97 to 0.945) over an 18-month operating cycle for an 840-MW system [19].

Transmuters must be designed to operate in a harsh radiation environment. The lifetime of structural components in the core, as well as the fuel cladding, is limited by radiation damage. In fast reactors, the demonstrated limit for ferritic-martensitic steels is nearly 200 displacements per atom (a unit of measure for radiation damage), corresponding to a fast neutron fluence (E > 0.1 MeV) of 4×10^{23} n/cm^2. For transmutation fuel subjected to this same fluence, the fraction of actinide material destroyed by fission is about 35%. Barring the development of new alloys with greater radiation tolerance, this is the maximum per-pass destruction rate for clad fuel in a fast spectrum system. After destruction by fission of up to one-third of the actinide material in a blanket fuel assembly, the assembly is removed, stored while it cools for a period of years, and is then chemically reprocessed in a manner similar to that for spent LWR fuel.

The proposed European Facility for Industrial Transmutation (EFIT) is one example of a typical demonstration-scale transmutation facility [44]. The 400-MW blanket will be driven by an 800-MeV, 20-mA proton beam incident on an LBE target. The core vessel, shown in Figure 10, shares many features seen in a fast reactor vessel, but also the additional structure associated with transporting a high-power proton beam to a centrally located spallation target. Provisions must be made to allow replacement of the target, or target container for liquid metal targets, on a regular basis, preferably on the same frequency as fuel replacement. Most designs strive to replace fuel every 12 to 18 months. For comparison, another core vessel for transmutation designed for the Intensity Proton Accelerator Project at JAERI/Tokai is shown in Figure 11.

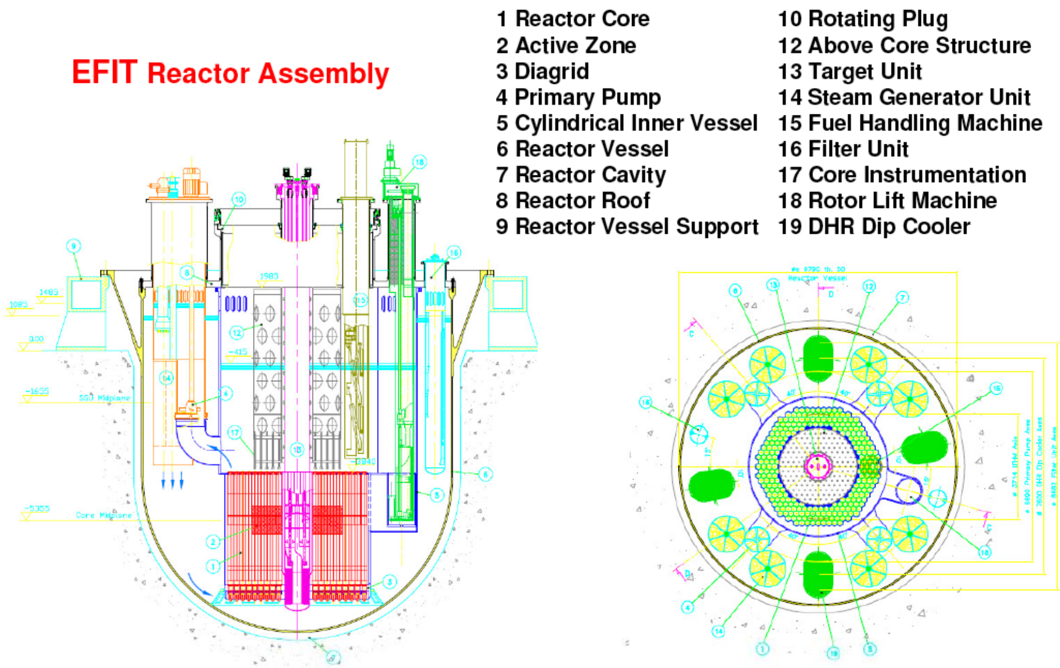


Figure 10: The EFIT core vessel and internals [20].

On the way to an EFIT-class facility, component testing will need to be done in a prototypic radiation environment. Several facilities have been proposed for irradiation testing, including the Materials Test Station (MTS) at LANL [21], the Transmutation Experiments Facility at the Japan Proton Accelerator Complex [22], and the MYHRRA facility at SCK·CEN [39]. When completed, the Materials Test Station will provide a fast neutron spectrum (see Figure 12) appropriate for irradiating transmutation fuels, cladding, and material specimens for core internals. It will use 1 MW of proton beam power delivered by the LANSCE accelerator to produce 10^{17} neutrons per second through spallation reactions in tungsten. While the principal mission is testing fuels and materials for fast reactor application, this facility will be well suited for testing components for ADS applications as well.

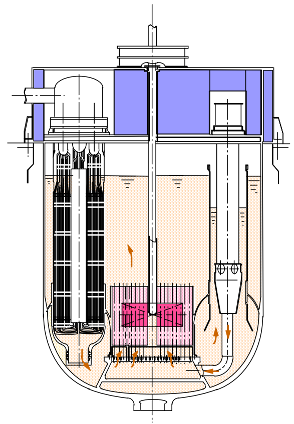


Figure 11: High Intensity Proton Accelerator Project in JAERI/Tokai. [23] The target parameters are: proton beam is 1.5 GeV at 22 – 30 MW; spallation target is Pb-Bi that also serves as the coolant; minimum keff is 0.95 maximum keff is 0.97; thermal output is 800 MWth; core height is 1 m; core diameter is 2.44 m; MA initial inventory is 2.5 MT; fuel composition is 40% Pu + 60% MA mono-nitride; transmutation rate is 10% MA /Year (10 units of LWR); burn-up reactivity swing is +1.8% Δk/k.

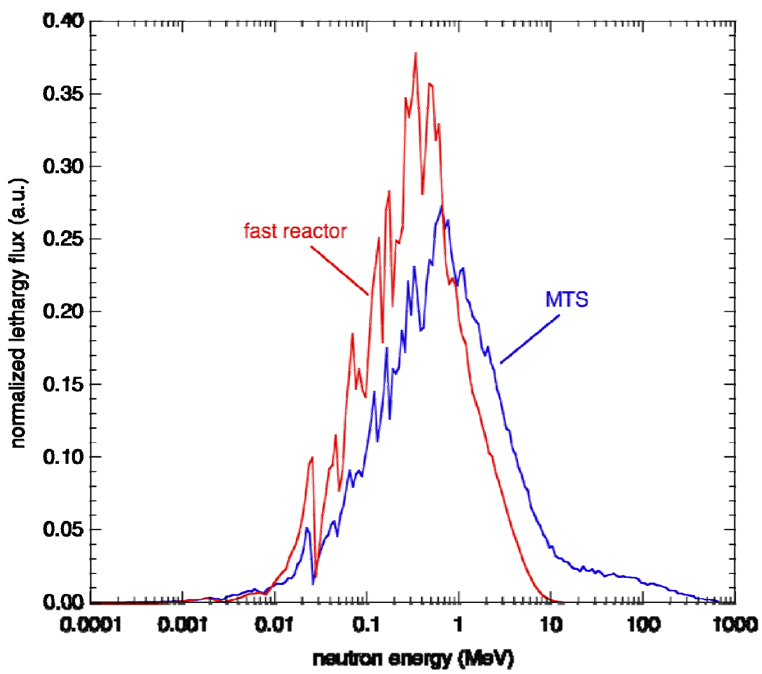


Figure 12: The MTS is well suited to investigate the performance of fuel and cladding for an accelerator driven transmuter. The MTS neutron spectra is similar to fast reactors, with the addition of high energy "tail" (6% of neutrons greater than 10 MeV).

4.1.2.3 Process Chemistry

Perhaps the most significant cost component in any closed fuel cycle is associated with the chemical reprocessing. It is an area where research and development has the potential to make significant impact on the economic competitiveness of a closed cycle as compared to an open, once-through cycle.

Currently PUREX is the only industrially operating reprocessing flowsheet(s), which generates separate streams of Pu, U, and fission products along with the minor actinides. While there have been some flow sheet options tested it would be fair to say that a significant amount of R&D is required to realize the Am and Cm separation from the lanthanides. SESAME [24] is one process being studied for Am/Cm separation. Although electrochemical processing options exist, it has yet to be demonstrated that they can provide a clean Am/Cm product (from other actinide and lanthanide elements) [25]. Work has only just started on tailoring a process for separation and fuel fabrication that optimally matches an Am burner fuel cycle. Example flowsheets are shown in Figure 13.

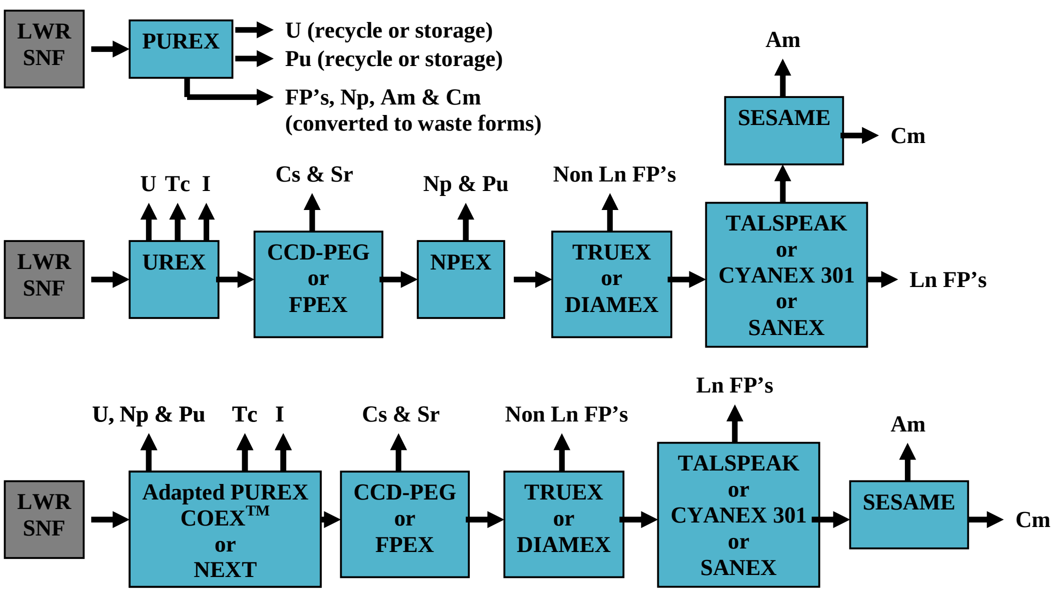


Figure 13: Examples of aqueous/solvent extraction-based flowsheet options are shown.

4.1.2.4 Previous Concerns Regarding Accelerator Driven Systems

Past issues with accelerator-based-transmuter technology and budget limitations effectively eliminated accelerator-based transmuters as a component of U.S. fuel cycle research. The major points that have been raised in the past are:

- The 1996 National Research Council Study (NRCS) [26] that was very negative on transmuter systems of any type and
  - Presumed that ADS should eliminate the need for a geologic repository.
  - Concluded that an accelerator based system is too expensive
  - Had concerns about faults/trips by reactor designers and the effect of beam transients on materials and fuels.

- The electrical power produced was too intermittent to be delivered to the electrical grid.
- Periodic accelerator maintenance leads to long down-times.

The points raised above are addressed in the rest of this section, but in summary many of the 1996 NRCS conclusions were predicated on faulty assumptions, for example:

- The study specified that a burner needs to eliminate the need for a HLW repository – an extremely difficult, if not impossible, requirement. A transmuter does not preclude the need for a HLW repository, but it does greatly reduce the quantity of HLW per MWe.
- The study assumed aqueous processing of very young (hence hot) spent fuel; this is an unnecessary requirement.
- The aqueous and molten-salt processing separations technologies required for an Accelerator Transmuter of Waste (ATW) were immature.
- The study assumed a single blanket power of 8 GWth. No study since has assumed blankets that would handle this power level.
- Superconducting accelerator was not widely used at the time of the study. Superconducting technology has a much lower capital and operating cost than the assumed room-temperature accelerator in the study. The study assumed a 1992 room-temperature accelerator design of 250 mA beam of protons at 1.6 GeV, an accelerator real-estate gradient of 1 MV/m, and a D_2O moderated target generating 2×10^{15} n/cm^2-sec. Modern superconducting transmuter accelerator designs are 20 times the accelerator real-estate gradient and, with superconducting structures, much more electrically efficient, yielding significant capital and operating cost savings.
- Of the three options considered, the study concluded that the once-through cycle option was significantly less expensive and risky than either an Advanced Liquid Metal Reactor/Integral Fast Reactor or an ATW.
- The intermittent operation of accelerators was a large issue in previous studies based on the fault/trips experienced with existing research accelerators. Given the high accelerator trip rate and the GW of electrical power the transmuter could generate, the swings in grid power produced from an accelerator-based transmuter was deemed too great to be connected to the electrical grid.

Newer studies have been done to estimate the additional cost to electrical rates using an accelerator based transmuter. A study by JAEA [15] has estimated that an Accelerator Driven System (ADS) will result in a 2-3% increase in electricity cost. The cost included operating cost, partitioning, dedicated fuel fabrication facilities, reprocessing, and decommissioning (electricity is ~ 17¢/kWhr in Japan). A study from Sweden [27] gives another scenario that shows the cost of electricity for ADS + recycling is 30% more expensive than once through. The results they presented are not directly applicable to the fuel cycle presented in this paper, but provide a basis for doing more refined calculations on cost. However, even though the advanced fuel cycles studies show a higher cost of electricity, they are still low enough to be competitive in a future market with the anticipated higher electricity prices using other technologies.

The expected cost of an accelerator based transmuter system compared to a reactor is expected to be ~30%, as given above. As will be seen later, we estimate that just 2 to 3 transmuters can support the entire existing fleet of US LWRs. So if the incremental cost to the present electrical rate is based on the adding of two to three more plants (that don't produce any power), the incremental cost to the electrical rate of the 104 LWRs should be just a 2 to 5 percent not including reprocessing costs. Not including reprocessing costs is fair if the U.S. decides that the new fuel cycle going forward will be a closed cycle and reprocessing will be an inherent feature; the additional cost for reprocessing for the accelerator transmuter system would be incremental. Since operation of the transmuter is expected to generate an excess of 7 GWth/year, converting that power into a useable energy source is highly advantageous to help recover the facility capital and operating costs.

- Electrical generation can be used to cover the transmuter facility's own operating needs but some storage capacity is needed to be able to run through the intermittent accelerator beam trips.
  - Improvements in power storage devices allow for significant power storage to cover fault interruptions (Superconducting coils: 100MW for 100sec, flywheels ~ MWs, Vanadium Redux Battery ~ MWs, steam storage) A strong push will be made on high capacity storage technologies for due to the expected increase in wind and solar power, and these technologies will have the potential for far greater grid interruptions than for an accelerator based system.
- Consideration should still be given to converting the generated energy to another form useful for national consumption.
  - One option is to sell the excess power to the grid
    - » Based on recent experience with superconducting accelerator technology, the design of highly fault-tolerant accelerators is a reasonable expectation. [28]
    - » Storing power with the use of the above mentioned power storage devices could provide the electricity to run through faults if they can store enough electricity to enable providing steady power to the grid through the longest of expected interruptions. The practicality of running through the range of possible interruptions requires a more detailed design effort.
  - Another option is to convert the power into another energy form.
    - » Charles Forsberg has proposed that biomass can be converted to greenhouse-gas-neutral liquid fuels. [29] The conversion of biomass-to-liquid fuels is energy intensive but the transmuter can produce the significant amount of heat, electricity, and hydrogen required for the processing of biomass-to-liquid fuels. The overall process has a comparable efficiency to electrical production, but the end result can be carried away in tankers. If the accelerator operation is deemed too unreliable for the electrical grid, then converting biomass into fuel for a net-zero carbon-footprint would seem to be not only a good option, but the preferred option.
- Other than intermittent operation affecting the quality of the power produced by the transmuter, transients will affect the lifetime of components in the transmuter assembly.
  - Effect of transients on materials and fuels was evaluated at LANL for the proposed Material Test Station [30]

    - » The studies show no significant deleterious effects for core clad or structural materials for the expected accelerator interruptions.
    - » Similar studies also show no concern for fuels.
  - – Effect of transients on reactor structures was evaluated at JAEA. [15]
    - » This study showed that the number of allowable trips were determined by the following major components:
      - beam window: 105 trips per 2 yrs of <1 sec
      - reactor vessel: 104 trips per 40 yrs of 1 sec to 5 min
      - system availability: 1 trips per week of > 5 min (if used for electrical power generation)

4.1.2.5 International Efforts in Accelerator Driven Transmutation

Table 2 shows some of the efforts that either have been or are being pursued around the world. As a representative effort, we will briefly cover the MYRRHA collaboration (see Figure 14).

Table 2: Parameters of the different ADS projects from updated Table 1 of Gulevich[31].

Project	***Accelerator power (MW)***	***keff***	***Blanket power (MW)***	***Spectrum Flux (n/cm2/s)***	***Target***	***Fuel***	***Ref.***
OMEGA	58 (1.5 GeV, 39 mA)	0.9	820	Fast 4 x10^{15}	W	Np/5Pu/30Zr	[32]
JAERI-ADS (Japan 2004)	27 (1.5 GeV, 18 mA)	0.97	800	Fast	Pb-Bi	MA/Pu/ZrN	[33]
HYPER (Korea)	15 (1 GeV, 10-16 mA)	0.98	1000	Fast	Pb-Bi	MA/Pu	[34]
XADS Design A (Italy)	3.6 (600 MeV, 3-6 mA)	0.95-0.97	80	Fast 10^{15}	Pb-Bi	U/Pu/MOX	[35]
Design B (France)	3.6 (600 MeV, 3-6 mA)	0.95-0.97	80	Fast 10^{15}	Steel	U/Pu/MOX	[9]
Design C (Belgium)	1.75 (350 MeV, 5 mA)	0.95	50	Fast 3x10^{15}	Pb-Bi windowless	U/Pu/MOX	[36]
INR (Russia)	0.15 (500 MeV, 0.15-0.3 mA)	0.95-0.97	5	Fast	W	MA/MOX	[37]
NWB (Russia)	3 (380 MeV, 10 mA)	0.95-0.98	100	Fast 10^{14} -10^{15}	Pb-Bi	UO2/UN U/MA/Zr	[38]
CSMSR (Russia)	10 (1 GeV, 10 mA)	0.95	800 cascade scheme	Intermediate 5x10^{14}	Pb-Bi	Np/Pu/MA molten salt	[39]

Since 1998, SCK•CEN, Mol, Belgium, in partnership with many European research laboratories is designing a multipurpose Accelerator Driven System for R&D applications called MYRRHA. In parallel, an associated R&D support program is being conducted. MYRRHA aims to serve as a basis for the European experimental ADS providing protons and neutrons for various R&D applications. It consists of a LINAC proton accelerator delivering a 600 MeV, 4 mA proton beam to a windowless liquid Pb-Bi spallation target that, in turn, couples to a Pb-Bi cooled, sub-critical fast core of 80 MW thermal power.

Figure 14: The MYRRHA project [40] is based on the coupling of a proton accelerator with a liquid Pb-Bi windowless spallation target, surrounded by a Pb-Bi cooled sub-critical neutron. The project is planned to replace the BR2 reactor, as shown in the upper picture. The lower graphic shows the collaboration partners in Eurotrans.

4.1.2.6 SMART: Subcritical Minor Actinide Reduction through Transmutation

SMART was developed at Los Alamos National Laboratory to support the existing U.S. LWR economy, preserve the energy rich component of nuclear waste as a future energy resource, and provide a long-term strategy enabling the continuation and growth of nuclear power in the U.S.

The basic concept of SMART was discussed in the Introduction of this paper. SMART is to extract and store the Pu, U, and Np together in interim storage facilities for future fabrication into fuel, vitrify and store the short-lived in interim storage facilities, vitrify and store the long-lived fission products in small geologic repositories along with small amounts of other residual high-level waste, and burn the Am in an accelerator driven transmuter.

The reason for burning only the Am is economic and technical. From an economic stand-point, no incentive exists for the large scale deployment of accelerator-based facilities by private industry, and so any facility whose primary function is to deal with burning nuclear waste will probably be government owned and operated by a government contractor. This implies a scenario that uses the minimal number of facilities to support the waste mission. The number of facilities depends in large part on what mixture of actinides the facility is to burn. A reactor of fixed size is ultimately limited by the thermal heat generated from burning its nuclear fuel. A 3 GW thermal (GWth) reactor burns about 1.1 metric tons (MT) of fuel each year. A sub-critical transmuter also burns fuel, but the composition of the fuel is not limited by the same safety considerations as a critical reactor. Since every nucleus burned generates a roughly comparable amount of heat, in a core composed Pu, Np, Cm, and Am, the Am is just 11% of the total actinide loading, or, in other words, for every nucleus of Pu, Np, or Cm burnt is one less nucleus of Am burnt. The equilibrium feed for an Am burner is 100% Am. Therefore, SMART, Figure 15, is focussed on transmuting the one element that has the greatest impact on nuclear waste management.

The major technical reasons, the high radiotoxicity and long half-life, for concentrating on Am was given in the Introduction, but other related aspects give concern for storing Am as a future fuel component follow:

- Am and its daughter nuclides are difficult to handle because of their high decay heat and radioactivity.
- The vapor pressure of americium limits fuel pellet fabrication temperatures.
- In fast reactor accident scenarios the americium could boil out of the fuel and thus present a more difficult safety case.

Separating out and storing the Np, U and Pu for future use has several advantages.

- Neptunium has similar chemical properties to uranium and plutonium and shows good compatibility not only in nitride fuel but also in oxide fuel.
- Processing criticality issues are mitigated since the Pu is not separated out.
- U/Pu/Np ratios are 98.7:1.2:0.1 making this a very unattractive material for diversion since the fertile elements are heavily diluted.
- Pu240 (0.3% of U, Np, Pu at 50 years) has an easily detectable neutron signature adding in diversion detection. [41]
- The U.S., a weapons state, has the necessary extant infrastructure for long term safe storage of nuclear fuel.

Addressing the Cm disposition is still an on-going concern. Some considerations for Cm are:

- The major Cm isotope, Cm244, has a half-life of 18 years, and will be nearly gone in 180 years.
- Cm can either be put with the Pu, U, and Np or segregated for the 180 years.
- Removing the Cm early in reprocessing significantly reduces the radioactivity in the reprocessing stream, and reduces the shielding requirements for the later reprocessing streams and so reduces costs.
- Even though the Cm is only 18% of the mass of the actinide fuel if mixed with the Am, Cm doubles the radioactivity.
- Storing the Cm with the Pu, U, and Np increases the radioactivity of the mixture and might provide some degree of proliferation resistance.
-

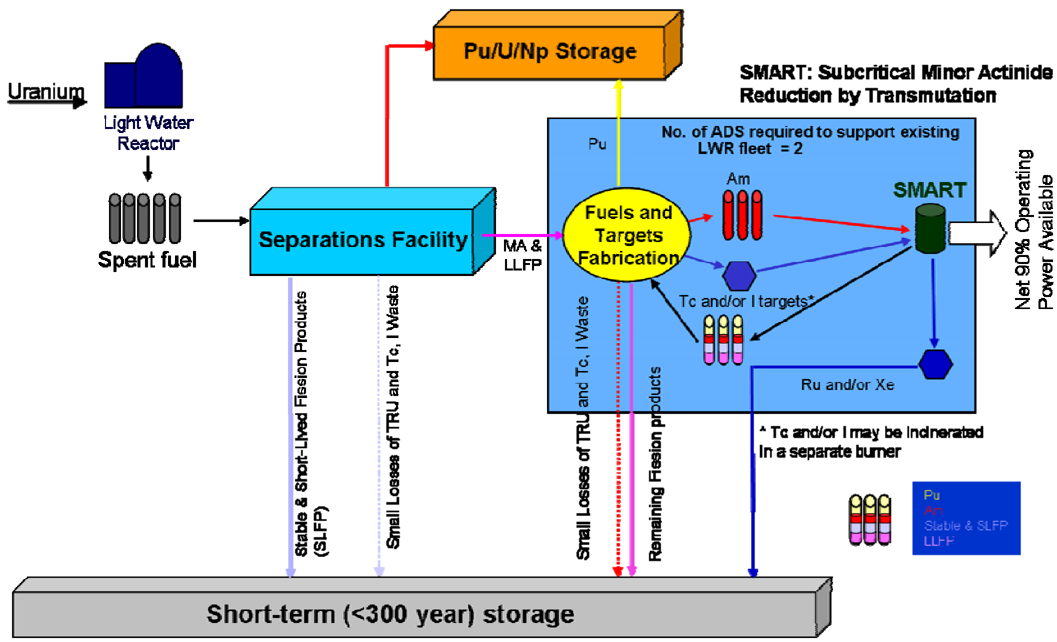


Figure 15: The SMART concept is shown above. Spent LWR fuel is sent to a reprocessing center where the short-lived fission products are vitrified and sent to short-term (300 year) storage. The Pu, U, and Np are sent to another storage facility for later fabrication into fuel. After transmuter start-up with an initial feed of Am and Pu, the only feedstock is Am. In equilibrium, an excess of Pu is generated from the Am transmutation chain. This Pu supplies the required fertile fuel component for maintaining k_{eff} and the excess goes back into the separations facility and ends up in the Pu, U, Np storage. [42]

Flow sheets for this transmuter can be based on advances to PUREX reprocessing, which can be further split depending on whether or not Cm is a fuel constituent.

The initial separation of an Am/Cm product stream from reprocessing does not appear to be the major technical challenge from a chemistry/materials view point. [43] However, the following could be problem areas:

- Target manufacture if Cm is a component of that fuel target.
- Dissolution of that target after irradiation for recycle of actinides.
- A recycle option needs to be considered that doesn't involve aqueous separations, for instance, a molten salt recycle.

A fuel form optimized for the proposed Am transmuter needs to be developed. Although some effort has been undertaken for heavily Am-loaded fuels, [44] each different type of transmuter requires its own fuel form depending on the isotopic composition of its radionuclides and the reprocessing flow sheets.

More effort is needed to fully develop the SMART concept, specifically:

- Design an optimized sub-critical reactor core and associated refueling methodology
- Develop a tailored flow-sheet for Am, U, Pu, and Np separation
- Determine the optimal fuel form for an Am burner
- Develop fair cost comparison to other fuel cycles

4.1.2.7 Summary

A significant impact on nuclear waste treatment can be made by conversion of the 0.24% non-fissile fraction of the commercial spent fuel that requires long-term isolation into materials that are primarily stable or short-lived. The use of an accelerator adds flexibility in burning these "difficult" fuels and is the missing link in integrated waste transmutation systems. Most likely the LWR waste will be the government's problem – this is consistent with an accelerator collocated with a government reprocessing facility with the following objectives:

- Reducing isolation requirements to fit the lifetime of man-made containers and barriers.
- Reducing incentives and consequences of intrusions into repositories.
- Improving prospects for waste storage and nuclear technologies.
- Improving fuel utilization.
- Reducing proliferation risk.

The major challenges in accelerator driven transmuters are related to fuel forms and separations; the accelerator is based on demonstrated technologies.

Production of electricity or converting the energy to other forms is optional but would pay for the facility and associated operational costs. Since only two to three transmuters are required for the present LWR fleet then the incremental electrical cost should be a few percent, neglecting the other components needed to close the nuclear fuel cycle (e.g., reprocessing and hot fuel fabrication). If reprocessing is funded separately as part of a new nuclear fuel cycle, then the facility will more than pay for itself. Over the next three decades a reasonable expectation is that:

- Accelerator faults can be reduced to an acceptable level through technology improvements
- High-capacity energy storage systems will see significant improvements driven by alternative energy sources, such as solar and wind.

We have proposed SMART as an approach to address the above considerations.

4.1.3 References

1. C. Artiolia, X. Chen, F. Gabrielli, G. Glinatsis, P. Liu, W. Maschek, C. Petrovich, A. Rineiski, M. Sarotto, M. Schikorr, "Minor actinide transmutation in ADS: the EFIT core design", International Conference on the Physics of Reactors "Nuclear Power: A Sustainable Resource", Casino-Kursaal Conference Center, Interlaken, Switzerland, September 14-19, 2008; Toshinobu Sasa, Kenji Nishihara, Takanori

Sugawara,Yoshihiro Okamoto, Hiroyuki Oigawa, "Actinide reformer concept", Progress in Nuclear Energy 50, pp 353-358 (2008); A. Zrodnikov, A. Gulevich, V. Chekounov, A. Dedoul, N. Novikova, I. Tormyshev, Y. Orlov, D. Pankratov, A. Roussanov, E. Smetanin, And V. Troyanov, "Nuclear Waste Burner For Minor Actinides Elimination," Progress in Nuclear Energy; Vol. 47, No. 1-4, pp. 339-346 (2005).

2. Roald Wigeland, Figure 1 from Nuclear Technology, Vol. 154, p95, April (2006)
3. NEA Report 6090, "Physics and Safety of Transmutation Systems – A Status Report," ISBN 92-64-01082-3 (2006).
4. Gérald Rimpault, "Safety coefficients and sub-criticality levels EFIT and XT-ADS," EUROTRANS DM1 Safety Meeting, FZK , RFA, 27-28 November (2008).
5. Lisowski, P.W., "Accelerator Production of Tritium Program," Proceedings of the 1997 17th Particle Accelerator Conference, PAC-97 ; May 12-May 16, Vancouver, BC, Canada, vol:3 pg:3780 -3784 (1998).
6. Schneider, J.D.,Sheffield, R. ,Smith Jr., H. Vernon, "Low-energy demonstration accelerator (LEDA) test results and plans," Proceedings of the IEEE Particle Accelerator Conference, Jun 18-22 2001, Chicago, IL, United States, Vol.5, p.3296-3298 (2001).
7. "Accelerator-Driven Test facility Linac Review, April 10-12, 2001," Los Alamos National Laboratory report LA-UR-01-2834, May (2001).
8. T. Tajima, et al., "Test Results of □=0.64, 700 MHz, 5-cell elliptical Cavities," PH002, SRF2001, The 10th Workshop on RF Superconductivity, September 6-11 (2001).
9. "Executive Summary; Development and performance of Medium-beta Superconducting cavities", Los Alamos National Laboratory report LA-CP-01-0202, April (2001).
10. E. N. Schmierer, et al, "Results of the APT RF Power Coupler Development for Superconducting Linacs, this Workshop.
11. "Executive Summary; Development and Performance of Superconducting-Cavity Power Couplers," Los Alamos National Laboratory report LA-CP-01-461, August (2001).
12. Shepard, KW, Kelly, MP, Fuerst, J, Kedzie, M , Conway, ZA, et. al. "Development of spoke cavities for RIA," Physica C-Superconductivity And Its Applications, Vol.441, iss.1-2, p.205-208 (2006).
13. F. L. Krawczyk, "Design of a □=0.175 2-Gap spoke Resonator," T. Tajima, "Status of the LANL Activities in the Filed of RF Superconductivity," Paper FA002, SRF2001, The 10th Workshop on RF Superconductivity, September 6-11 (2001).
14. T.Tajima, "Status of the LANL Activities in the Field of RF Superconductivity," Paper TL020, SRF2001, The 10th Workshop on RF Superconductivity, September 6-11, (2001).
15. J. Galambos, S. Henderson, A. Shishlo, Y. Zhang, "Operational Experience of a Superconducting Cavity Fault Recovery System at the Spallation Neutron Source," Proceedings of the Workshop on Utilisation and Reliability of High Power Proton Accelerators (HPPA5), 6-9 May 2007, Mol, Belgium, p. 161 (2008).
16. P. McIntyre, et al., "Accelerator-Driven thorium cycle Power Reactor: Design and Performance Calculations," unpublished article.
17. Research Project Office, "Compendium of Initial System Point Designs for Accelerator Transmutation of Radioactive Waste," Los Alamos National Laboratory report LA-UR-01-1817, February 2001.
18. D.I. Poston and H.R. Trellue, User`s Manual, Version 1.00 for Monteburns, version 3.01, Report no. LA-UR--98-2718, 1998.
19. H.R. Trellue, private communication, August 4, 2009.
20. L. Mansani, "XT-ADS & EFIT: Two Machines not so Different for the Same Goal," presentation at the International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, Vienna, Austria, 4-8 May 2009.

21. E. Pitcher, "The materials test station: a fast-spectrum irradiation facility," Journal of Nuclear Materials 377 (2008) 17-20.
22. http://j-parc.jp/Transmutation/en/ads.html.
23. Hiroyuki Oigawa, "Activities on ADS at JAEA," OECD/NEA 9th Information Exchange Meeting on Partitioning & Transmutation, September 26-28, (2006).
24. C. Madic, C. Hill, "A 'golden key' in the set of chemical separations," CLEFS, CEA, iss:46 pg:24 -7 (2002).
25. Iain May, private communication.
26. "Nuclear Wastes: Technologies for Separations and Transmutation," National Academy Press Washington, D.C. (1996).
27. D. Westlén, "A Cost Benefit Analysis of an Accelerator Driven Transmutation System," M.Sc. Thesis, KTH Royal Institute of Technology, Stockholm (2001).
28. Campisi, I. E., Casagrande, F., Crofford, M., Howell, M., Kang, Y., Kim, S. H., Kursun, Z., Ladd, P., Stout, D., Strong, W, "Operation Of The Superconducting Linac At The Spallation Neutron Source," AIP conference proceedings [0094-243X] vol:985 iss:1 pg:1586 -1593 (2008).
29. C. W. Forsberg, "Meeting U.S. liquid transport fuel needs with a nuclear hydrogen biomass system," Volume 34, Issue 9, May, Pages 4227-4236 (2009).
30. E. Pitcher, et al., "Progress on the Materials Test Station," PHYSOR08 (Proc. of the Int. Conf. on the Physics of Reactors, Interlaken, Switzerland, 2008), log 574.
31. A. Gulevich, A. Kalugin, L. Ponomarev, V. Seliverstov, N. Seregin, "Comparative study of ADS for minor actinides transmutation," Progress in Nuclear Energy 50, pp 359-362 (2008).
32. Y. Kurata, T. Takizuka, T. Osugi and H. Takano, "The accelerator driven system strategy in Japan," Journal of Nuclear Materials,Volume 301, Issue 1, Pages 1-7, February (2002).
33. Ikegami, T., Inoue, T., Minato, K., "Resent research and development activities on partitioning and transmutation of radioactive nuclides in Japan." In: Eighth Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation, Las Vegas, Nevada, USA, 9-11 Nov. (2004); Shigeru Saito, Kazufumi Tsujimoto, Kenji Kikuchi, Yuji Kurata, Toshinobu Sasa, Makoto Umeno, Kenji Nishihara, Motoharu Mizumoto, Nobuo Ouchi, Hayanori Takei and Hiroyuki Oigawa "Design optimization of ADS plant proposed by JAERI," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 562, Issue 2, 23 June 2006, Pages 646-649 (2006).
34. Jae-Hyung Yoo, P&T Studies in Korea. In: Eighth Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation, Las Vegas, Nevada, USA, 9-11 Nov. (2004); Won S. Park, Tae Y. Song, Byoung O. Lee and Chang K. Park , "A preliminary design study for the HYPER system," Nuclear Engineering and Design, Volume 219, Issue 3, Pages 207-223 February (2003).
35. Abderrahim, H.A., Cinotti, L., Giraud, B., et al., The experimental accelerator driven system (XADS) designs in the EURATOM 5th framework programme. Journal of Nuclear Materials 335, 148 (2004).
36. Abderrahim, H.A., Haeck,W., Malambu, E., Sobolev, V., , MA and LLFP transmutation performance assessment in the MYRRHA experimental ADS. In: Eighth Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation, Las Vegas, Nevada, USA, 9-11 Nov (2004).
37. Markov, S., et al., The basic features of multipurpose target-blanket complex of Moscow Meson Factory. In: Proceedings of the 16th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-XVI), Duesseldorf-Neuss, Germany, vol. III, p. 1097, 11-15 May (2003).
    http://iac.isu.edu/docs/workshops/beller/ADSS2005/Ponomarev ID ADSS 05 Russia.pdf (2005)

38. Pavlopoulos, P., Rubbia, C., Zrodnikov, A., Nuclear Waste Burner (NWB) - an ADS Industrial Prototype for Minor Actinides Elimination. IPPE, Obninsk (2003). http://iac.isu.edu/docs/workshops/beller/ADSS2005/Ponomarev ID ADSS 05 Russia.pdf (2005)
39. Degtyarev, A.M., Kalugin, A.K., Kolyaskin, O.E., et al., Cascade subcritical molten-salt reactor for burning of the transplutonium elements. Atomnaya Energiya 101 (2), 116 (2006). Degtyarev, A.M., Kalugin, A.K., Ponomarev, L.I., Cascade Subcritical Molten Salt Reactor (CSMSR): main features and restrictions. Progress in Nuclear Energy 47 (1-4), 99 (2005). http://iac.isu.edu/docs/workshops/beller/ADSS2005/Ponomarev ID ADSS 05 Russia.pdf (2005)
40. Hamid AÏT ABDERRAHIM and Pierre D'HONDT, "MYRRHA: A European Experimental ADS for R&D Applications", Journal of Nuclear Science and Technology, Vol. 44, No. 3 Special Issue on GLOBAL p.491-498 (2007).http://www.sckcen.be/myrrha/MYRRHA/myrrha.php (2009)
41. S.T. Belayev et al., " The Use of Helicopter-Borne Neutron Detectors to Detect Nuclear Warheads in the USSR-US Black Sea Experiment", Science and Global Security 1, no. 3-4 (1990).
42. Based on simulations by Holly Trellue (LANL).
43. Private communication with Iain May (LANL).
44. W. Maschek, X. Chen, F. Delage b, A. Fernandez-Carretero, D. Haas, C. Matzerath Boccaccini, A. Rineiski, P. Smith, V. Sobolev, R. Thetford, J. Wallenius, "Accelerator driven systems for transmutation: Fuel development, design and safety", Progress in Nuclear Energy 50, pp 333-340 (2008).

4.2 European ADS and Its Challenge to Accelerators

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4.2.1 Introduction

The basic purpose of Accelerator Driven Systems (ADS) is to reduce – by orders of magnitude – the nuclear wastes' radio-toxicity, volume and heat load before their underground storage in deep geological depositories [1]. This issue is particularly significant in the European Union, where about 2500 tons of used fuel are produced every year, containing 25 tons of plutonium, 3.5 tons of minor actinides (Np, Am, Cm) and 3 tons of long-lived fission products.

"Partitioning & Transmutation" (P&T) has been pointed out in numerous studies as the strategy that can relax the constraints on the geological disposals, and reduce its monitoring period to manageable time scales. Within the P&T process, the different elements of the spent fuel are chemically separated, isolated and recombined to obtain new assemblies to be used and burnt either in (certain types) of critical Generation-IV reactors or into dedicated, sub-critical ADS "transmuter" facilities, therefore also limiting nuclear proliferation risks.

An ADS transmuter system is composed of two main parts: an "intrinsically safe" sub-critical reactor ($k_{eff} < 1$), in which the chain reaction can not be self-sustained, and an intense spallation source that provides the missing neutrons needed to keep the reaction going on. Such a neutron source, composed by a target subjected to a high energy proton flux, also produces the suited broad energy spectrum required to "burn" the minor actinides components, that are otherwise accumulated in conventional thermal spectrum critical reactors.

4.2.2 The European ADS Demonstrator Project

The EUROpean research programme for the TRANSmutation of high-level nuclear waste in accelerator driven systems (EUROTRANS) is funded by the European Commission within the 6^{th} Framework Programme, and involves more than 40 partners (research agencies, universities and nuclear industries). It is a 5-year programme (2005-2010), extending previous R&D (e.g. the PDS-XADS project), and which activities are split into five main domains, respectively devoted to:

- DM1: the advanced design of a transmuter demonstrator including all its sub-components, together with a generic conceptual design of an industrial transmutation facility (see Table 1);
- DM2: experiments dealing with the coupling of an accelerator, a spallation target and a sub-critical core, like the zero-power GUINEVERE experiment [2];
- DM3: studies on advanced fuels for transmuters;
- DM4: research on suited structural materials and heavy liquid metal technology;
- DM5: collection of nuclear data for transmutation.

Table 1: European Transmuter Main Specifications.

Transmuter demo (XT-ADS / MYRRHA project)	***Industrial transmuter (EFIT)***
50 – 100 MWth power	Several 100 MWth power
k_{eff} value ~ 0.95	k_{eff} value ~ 0.97
Highly-enriched MOX fuel	Minor Actinide fuel
Pb-Bi Eutectic coolant & target	Pb coolant & target

The main objective of the EUROTRANS programme is actually to pave the road towards the construction of an eXperimental facility (MYRRHA) willing to demonstrate the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS concept).

SCK.CEN (Mol, Belgium) has initiated the MYRRHA project in 1998 [3]. Its purpose is to design and later to build a flexible irradiation facility as suitable replacement for the existing Material Testing Reactor BR2 that is operating since 1962. The new facility would serve both as a test-bed for transmutation and as a fast-spectrum facility for material and fuel developments. It would operate first as a sub-critical (accelerator driven) system and later as a critical reactor. The Central Design Team (CDT) project, supported by the European FP7, is presently being settled to further develop the engineering design of such a facility, which should be fully operational in 2020.

4.2.3 The Reference ADS Accelerator

The European ADS concepts requires a high-power proton accelerator operating in CW mode, ranging from 2.4 MW (XT-ADS operation) up to 16 MW for the industrial EFIT. The main beam specifications are shown in Table 2. At first glance, the extremely high reliability requirement (beam trip number) can immediately be identified as the main technological challenge to achieve.

Table 2: Proton Beam General Specifications.

	Transmuter demo (XT-ADS / MYRRHA project)	***Industrial transmuter (EFIT)***
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	~ 800 MeV
Allowed beam trips (>1 sec) nb	< 5 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ± 1% - Current: ± 2% - Position & Size: ± 10%	
Beam time structure	CW (w/ low-frequency 200µs zero-current beam holes for sub-criticality monitoring)	

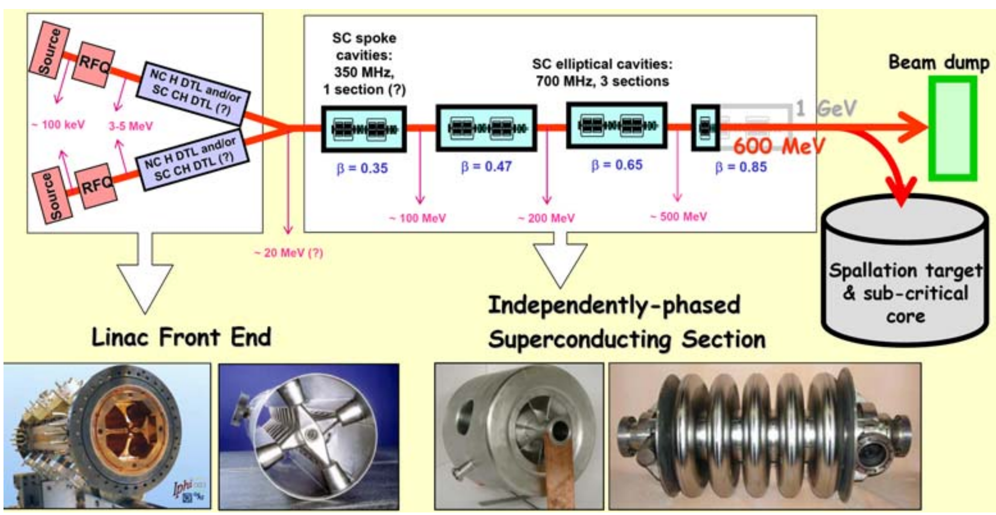

Figure 1: European ADS accelerator conceptual scheme.

The conceptual design of the accelerator has been developed during the PDS-XADS project [4]. It is a superconducting linac-based solution (see Figure 1), leading to a very modular and upgradeable machine (same concept for demonstrator and industrial scale), an excellent potential for reliability (see dedicated section here after), and a high RF-to-beam efficiency thanks to superconductivity (optimized operation cost). A more advanced reference design is presently under final definition – to be frozen by mid 2010 – in the MYRRHA context. The main characteristics, still subjected to slight changes, are detailed below. The investment cost for such a machine has been assessed around 200 M€ (manpower included, buildings and general utilities excluded).

4.2.3.1 The Linac Front-End

The linac injector is composed of a 50 kV ECR proton source, a short magnetic Low Energy Beam Transport line and a 3 MeV 4-vane copper RFQ operating at 352 MHz. This RFQ, designed to handle up to 30 mA CW beams with close to 100% transmission for all currents, is about 4.5 metres long, and operates with moderated Kilpatrick factors (~1.7).

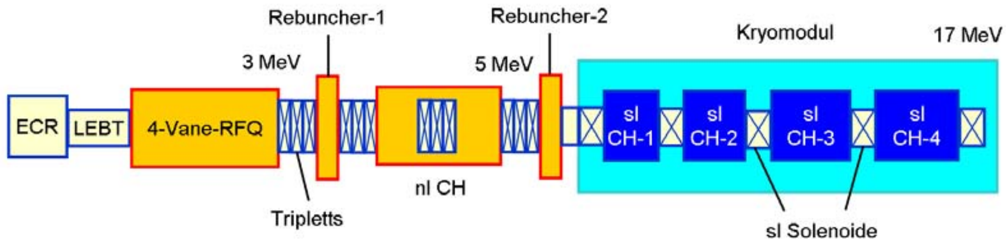

Figure 2: The reference linac front-end.

This "classical" injection section is then followed by a more "exotic" but promising energy booster [5], that is a combination of normal conducting and superconducting CH (Crossbar H-mode) DTL structures as shown in Figure 2, bringing the beam up to 17 MeV. Focusing is ensured by quadrupole triplets and superconducting solenoids inside the cryomodule containing the 4 superconducting CH cavities, and a couple of re-bunchers is used to perform the longitudinal beam adaptation. The design of the DTL structures is based on the KONUS beam dynamics concept [6], which allows to exhibit excellent accelerating efficiency at these low energies with a net energy gain of 14 MeV in 7.5 metres, while having very low power consumption in CW operation. Multiparticle beam-dynamics simulations of the whole front-end show very good beam behaviour, with moderate emittance increase (~10%), and low sensitivity to errors.

In this front-end line, the beam beta-profile is frozen by design, so that any accelerating section failure will inevitably lead to a beam interruption. For this reason and in order to enhance the machine reliability, it is proposed to duplicate the injector (at least the ion source, at most the whole 17 MeV front-end) to provide a hot stand-by injection line able to relieve the main one in case of failure.

4.2.3.2 The Independently-Phased SC Linac

From 17 MeV, a fully modular superconducting linac then accelerates the proton beam up to the final energy (600 MeV), through ~230 metres including MEBT. It is composed (see Table 3) of an array of independently-powered spoke and elliptical cavities with high energy acceptance and moderate energy gain per cavity – low number of cells and conservative accelerating gradients (around 50 mT and 25 MV/m peak fields nominal operation point) – in order to increase as much as possible the tuning flexibility and provide sufficient margins to allow the implementation of fault-recovery scenarios.

The linac design is based on the use of regular focusing lattices, with not-too-long cryostats – easy maintenance and fast replacement – and room-temperature quadrupole doublets. The beam tuning has been performed with great care, e.g. keeping a constant longitudinal acceptance, and limiting phase advances below 90° per lattice, while tuning them as continuous as possible, especially at the frequency jump [7]. This "conservative" optical design leads to very safe beam behaviours, with low sensitivity to mismatched conditions or current fluctuations, and producing very low emittance growths (below 5%).

Table 3: Independently-Phased Superconducting Linac Overview (still prone to changes)

SC cavity type	***# Cavities # Cryomodules***	***Energy range***	***Section length***
352 MHz 2-gap β0.35 Spoke	60 cavities 20 cryomodules	17 – 90 MeV	~ 50 m
704 MHz 5-cell β0.50 Elliptical	30 cavities 15 cryomodules	90 – 190 MeV	~ 60 m
704 MHz 5-cell β0.65 Elliptical	42 cavities 14 cryomodules	190 – 450 MeV	~ 80 m
704 MHz 6-cell β0.85 Elliptical	16 cavities 4 cryomodules	450 – 600 MeV	~ 35 m

4.2.3.3 The Final Beam Transport Line

The objective of the final transport line is to safely inject the proton beam with the specified footprint –donut-shaped – onto the spallation target located inside the reactor (~30 metres deep). The line is composed of two non-dispersive 2×45° achromats, so that the beam spot position and size at the target is independent from energy jitter and spread. In the dispersive region of the last achromat, position and size monitors will be able to provide information on proton energy variations, and to trigger a feedback system. Natural defocusing is used in the last straight line to get the desired beam spot size, and the footprint is then obtained by raster scanning (see Figure 3), using a redundant set of fast steering magnets operated at frequencies of 50 to a few hundreds Hz, and acting in the two transverse directions.

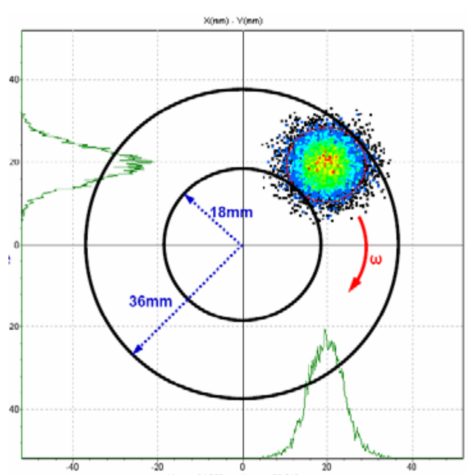

Figure 3: Beam footprint on target.

4.2.4 The Reliability Issue

The ADS accelerator is expected – especially in the industrial scenario – to have a very limited number of unforeseen beam interruptions per year. This requirement is motivated by the fact that frequently-repeated long enough beam interruptions induce high thermal stresses and fatigue on the reactor structures, the target or the fuel elements, with possible significant damages especially on the fuel claddings; moreover these beam interruptions decrease the plant availability, implying plant shut-downs of tens of hours in most of the cases. The present rough requirement in the XT-ADS/MYRRHA case is therefore that beam trips in excess of one second duration should not occur more frequently than five times per 3-month operation period.

4.2.4.1 Reliability-Oriented Design

To reach such an extremely ambitious goal, it is clear that reliability-oriented design practices needed to be followed from the early design stage. In particular:

- “strong design” is needed: every linac main component has to be de-rated with respect to its technological limitation (“over-design”);
- a high degree of redundancy needs to be planned in critical areas; this is especially true for the identified “poor-reliability” components like the linac injector area, which is duplicated, or the RF power systems, where solid-state amplifiers should be used as much as possible;
- the accelerator should be able, to the maximum extent, to pursue operation despite some major faults in basic components (“fault-tolerance” capability); it has been shown in [8] that a solution based on a modular independently-phased SC linac is indeed capable to easily adapt its nominal tuning in the case of a loss of any RF cavity or power loop unit (see here after), and even of a quadrupole doublet, while keeping beam dynamics and beam properties on target into specifications.

4.2.4.2 Tolerance to RF Faults in the Superconducting Linac

Because we deal with a non-relativistic proton beam, any RF cavity fault implying beam energy loss will also lead to a phase slip along the linac. It will increase with distance, and thus push the beam out of the stability region: the beam will be completely lost.

To recover such RF faults conditions, the philosophy is to re-adjust the accelerating fields and phases of some non-faulty RF cavities to recover the nominal beam characteristics at the end of the linac, and in particular its transmission, phase and energy. A simple way to perform it is to react on the accelerating cavities neighbouring the failing one. This so-called “local compensation method” (see Figure 4) has the advantage of involving a small number of elements, and therefore of being able to compensate multiple RF faults in different sections of the machine at the same time.

Beam dynamics simulations show that nominal beam parameters at the target can always be restored using such a retuning method, given the condition that a 20 to 30% rise in accelerating field and RF power can be sustained in the few (4 to 8) retuned elements [8]. This method is of course rather demanding in terms of linac length and installed RF power budget, but is on the other hand totally in-line with the ADS over-design criterion, and in any case required to try to reach the required reliability level.

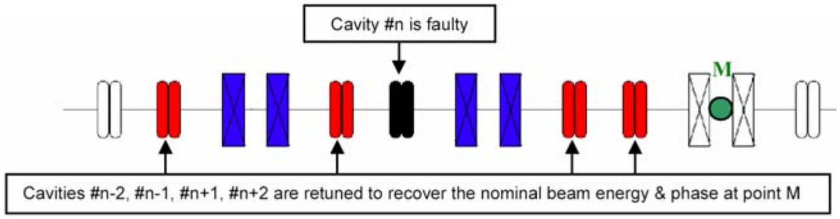

Figure 4: The local compensation method.

Transient beam dynamics have been performed to better analyse what happens to the beam during such retuning procedures, keeping in mind that they have to be performed in less than 1 second ideally. A new simulation tool has been developed, based on the TraceWin code [9], allowing analysing the effect of time-dependent perturbations on the beam through RF control loop modelling. From this work [10], a reference "fast failure recovery scenario" has been defined, that consists in stopping the beam for 1 sec maximum while achieving the retuning. The following sequence (~100ms duration) is proposed:

- the RF fault is detected (or anticipated) via suited dedicated diagnostics and interlocks, and a fast beam shut-down is triggered;
- the new correcting field and phase set-points (previously stored in the low level RF cards' memory during the commissioning phase) are updated;
- the failed cavity is quickly detuned (using piezo-actuators) to avoid the beam loading effect, and the associated failed RF loop is cut off;
- once steady-state is reached, beam re-injection is triggered.

A conceptual design of a suitable Low Level RF (LLRF) system has been performed [11], based on the use of an integrated digital board containing a FPGA chip able to process the feedback control algorithms, several ADCs and DACs to convert the received and produced signals, a RAM memory used to store set-points or save operating parameters, a serial bus to communicate with the general control/command system, and a fast serial bus to communicate with boards of adjacent cavities.

4.2.4.3 Tolerance to RF Faults in the Superconducting Linac

Two independent integrated reliability analyses have been performed so far to try to estimate the number of malfunctions of the XT-ADS accelerator that could cause beam/plant shutdowns per 3-month operation cycle, and to analyze the influence of MTBFs (Mean Time Between Failures), MTTRs (Mean Time to Repair), and of the whole system architecture on the results.

These studies have been respectively performed by means of a reliability block diagram analysis using the Relex© software [12] and by home-made Monte-Carlo simulations [13] with slight differences in the hypotheses. In both cases, the results show that such linacs have a high potential for reliability improvement if the system is properly designed with this particular objective: from about 100 unexpected beam shut-downs per 3-month operation period for a "classical "all-in-series" SC linac, this figure falls around 5 beam interruptions – which is actually the XT-ADS goal – in the case where a second redundant injector stage with fast switching capabilities is used, and when fault-tolerance is included in the independently-phased linac via fast fault-recovery scenarios. Nevertheless, the obtained absolute figures remain highly questionable, because of the somewhat crude modelling used for such a complex system, and because of the lack of a well-established component reliability figures database.

Having a look at present high-power hadron facilities – like the SNS, not specifically designed for reaching a high reliability – it appears that the experienced number of beam trips longer than 1 second is much higher, by at least one order of magnitude [14], showing that there is still a long way to go on this topic. But on the other hand, facilities like ESRF, which is very much concerned by the reliability issue, prove that overall MTBF of several days can already be obtained routinely [15], leading to an equivalent of about 20 beam interruptions per 3-month operation.

As a conclusion, it seems at least not completely unrealistic to approach and ultimately reach the ADS accelerator reliability goal. It will imply, as underlined before, to include in the linac design de-rating, redundancy and fault-tolerance, and to have a few years of commissioning and training to identify and fix the weak elements. Approaching the goal “from the other side”, i.e. relaxed specifications on beam trip numbers and their durations by appropriate design measures in the target/reactor system, would also help.

4.2.5 Related R&D Activities

4.2.5.1 Source and RFQ Long-Run Beam Tests

In the past years, the CEA Saclay SILHI source has been successfully used for several week-long reliability tests at currents of 30 mA, showing no beam stops and occasional sparks in the extraction region, causing no beam interruptions [16]. In the EUROTRANS context, these tests are planned to be extended using the 3 MeV IPHI RFQ [17], still presently under final construction (see Figure 5), for a 2-month long-run reliability beam test.

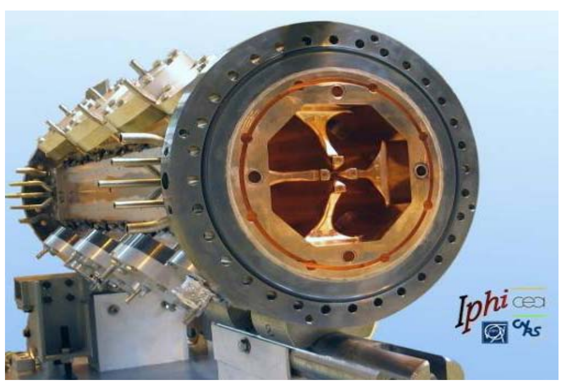

Figure 5: First section of the IPHI RFQ.

4.2.5.2 Development of Superconducting CH-Cavities

A 19-gap superconducting 352 MHz low energy CH prototype has been successfully built and tested at IAP Frankfurt in vertical cryostat. Excellent effective gradients of 7 MV/m [18] have been reached so far, as shown in Figure 6, and the cavity is now ready to be tested in a horizontal one with its associated slow and fast tuners. In parallel, a new optimized prototype cavity, more suited to the XT-ADS linac layout, has been designed and will shortly enter in its construction phase. In the long run, this cavity will be able to be tested with beam.

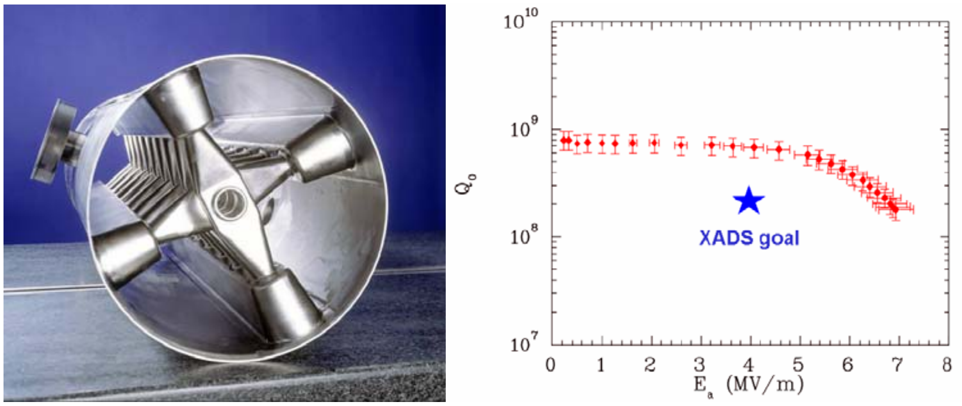

Figure 6: The 19-gap superconducting CH prototype (left) and its 4K test results (right).

4.2.5.3 Development of Superconducting Spoke Cavities

IPN Orsay is presently testing at 4K and 2K a β 0.15 spoke cavity [19] in an "accelerator-like" horizontal cryostat configuration; i.e. fully equipped with its tuning system, magnetic shield, RF power coupler, and fed by a 10 kW 350 MHz solid-state amplifier and its associated digital LLRF loop. RF couplers (see Figure 7) have been successfully conditioned up to 10 kW in TW mode, with only a few easily processed multipacting barriers above 7.5 kW [20]. During previous low-power cold tests, the tuning system, newly equipped with two piezo-actuators, has been validated together with the digital low level RF control system, reaching a field and phase stability respectively better than 1% and 0.5° at 2 σ. In the fault-recovery scenario context, preliminary experiments have also been performed to test the fast cavity detuning procedure, with very good results (~1 kHz detuning in less than 5ms).

Figure 7: RF conditioning of the Spoke power couplers.

4.2.5.4 700 MHz Cryomodule Prototyping

A prototypical 700 MHz cryomodule [21], funded by the EUROTRANS project, is presently being built and will be installed end 2009 in a former cyclotron pit at IPN Orsay. A 5-cell β 0.5 elliptical superconducting, equipped with its blade tuner system, will be fed by a 80 kW Thales Electron Devices® IOT by means of a 150 kW power coupler and its associated door-knob transition (see Figure 8). The main goal of the experiment is to evaluate the efficiency, but above all the reliability, of such an accelerating device. In particular, the capability of the piezo-based tuning system coupled with the digital LLRF I/Q feedback loop will be evaluated, while microphonics influence on the cavity resonance frequency will be estimated. Experimental results will be compared to MATLAB Simulink® simulations of the cavity's behaviour. In the long run, the experiment will also be able to provide a testing bench for specific sequences of the XT-ADS fast fault-recovery reference scenario.

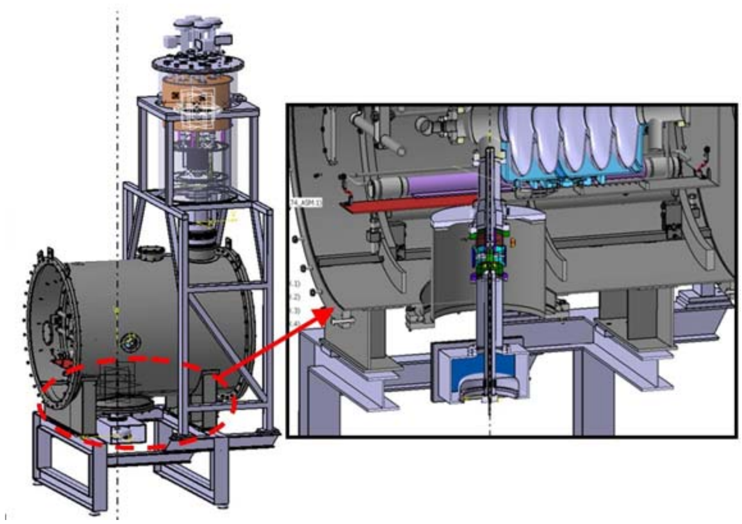

Figure 8: 3D view of the prototypical EUROTRANS cryomodule.

4.2.6 Conclusion

A reliability-oriented superconducting linac has been identified as the reference solution for the European ADS demonstrator project MYRRHA. An advanced design of the machine is proposed, and will be frozen by 2010. R&D activities will be pursued after the EUROTRANS contract, especially on the very challenging reliability issue, before a possible construction start by 2012-2015.

4.2.7 References

1. S. Saritepe, G. Goderre, and S. Peggs, "Observations of the Beam-Beam Interaction in Hadron Colliders", in "Frontiers of Particle Beams: Intensity Limitations", Springer-Verlag, Lecture Notes in Physics (1991).
2. A. Billebaud et al, "The GUINEVERE project for ADS physics", inc. GLOBAL 2009, Paris, France.
3. H. A. Abderrahim et al, "MYRRHA: A multipurpose accelerator driven system…",

Nucl. Instr. and Meth. in Phys. Res. A 463 (2001), pp. 487-494.
4. J-L. Biarrotte, A.C. Mueller et al, “A reference accelerator scheme for ADS applications”, Nucl. Instr. and Meth. in Phys. Res. A 562 (2006), pp. 565-661.
5. C. Zhang et al, “Conceptual studies for the…”, Proc. PAC2007, Albuquerque, USA.
6. U. Ratzinger and R. Tiede, “Status of the HIIF RF linac study based on H-mode cavities”, Nucl. Instr and Meth. in Phys. Res. A 415 (1998), pp. 229-235.
7. R. Duperrier et al, “Impact of a RF frequency change…”, Proc. LINAC 2006, Knoxville, USA.
8. J-L. Biarrotte & al., “Beam dynamics studies for the fault…”, Proc. HPPA 2004, Daejeon, Korea.
9. http://irfu.cea.fr/Sacm/logiciels/index.php
10. J-L. Biarrotte, D. Uriot, “Dynamic compensation of an rf cavity failure in a superconducting linac”, Phys. Rev. ST – Accel. & Beams, Vol. 11, 072803 (2008).
11. O. Piquet et al., “VHDL analysis and synthesis”, Eurotrans DEL n°1.66 (CEA), 2008.
12. L. Burgazzi, P. Pierini, “Reliability studies of a high-power proton accelerator…”, Reliability engineering & systems safety, Vol. 92, n°4 (2007), pp. 449-463.
13. R. Brucker et al, “Integrated reliability analysis of the …”, Eurotrans DEL n°1.69 (Empres. Agrup.), 2009.
14. J. Galambos et al., “Commissioning strategies…”, Proc. ICFA HB 2008, Nashville, USA.
15. L. Hardy et al., “Operation and recent developments at the ESRF”, Proc. EPAC 2008, Genoa, Italy.
16. R. Gobin et al, “Saclay High Intensity Light Ion Source status”, Proc. EPAC 2001, Paris, France.
17. P-Y. Beauvais, “Recent evolutions in the design of the…”, Proc. EPAC 2004, Lucerne, Switzerland.
18. H. Podlech et al, “Recent developments on SC CH-structures…”, Proc. LINAC 2008, Victoria, Canada.
19. G. Olry et al, “Spoke cavity developments for the EURISOL…”, Proc. LINAC 2006, Knoxville, USA.
20. E. Rampnoux et al, “RF power coupler development for…”, Proc. PAC 2009, Vancouver, Canada.
21. S. Barbanotti et al., “Design of the prototypical cryomodule…”, Proc. EPAC 2008, Genoa, Italy.

4.3 MW Superconducting Linac for ADS: Status and Challenges on Physics and Technology

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4.3.1 Introduction

In spite of the construction of about 400 nuclear power plants, > 350 of them still in operation, the disposal of radioactive waste represents a problem that is not yet properly solved, especially in terms of social acceptability and long term environmental impact. A planet in equilibrium with 7 or more billions of human beings, hopefully all living a human life, will possibly require a large number of high power plants to be integrated in a network of localized electric power sources from wind, water and sun.

Fission nuclear power respects in principle most of the requirements should a new generation being developed, now generically called “Generation IV”, with fuel regeneration, breading, and ultimate waste with a long term acceptable radioactivity, i.e. which remains in equilibrium with the planet life. The Roadmap for Generation IV is presented in Figure 1, from ref. [1]. The fact that the actual nuclear power plants are far from this objective can be easily understood considering the huge amount of dollars already spent by the US for the Yucca Mountain geological repository and the recent declaration of the Energy Secretary Steven Chu who told a Senate hearing the Yucca Mountain site is no longer viewed as an option for storing reactor waste.

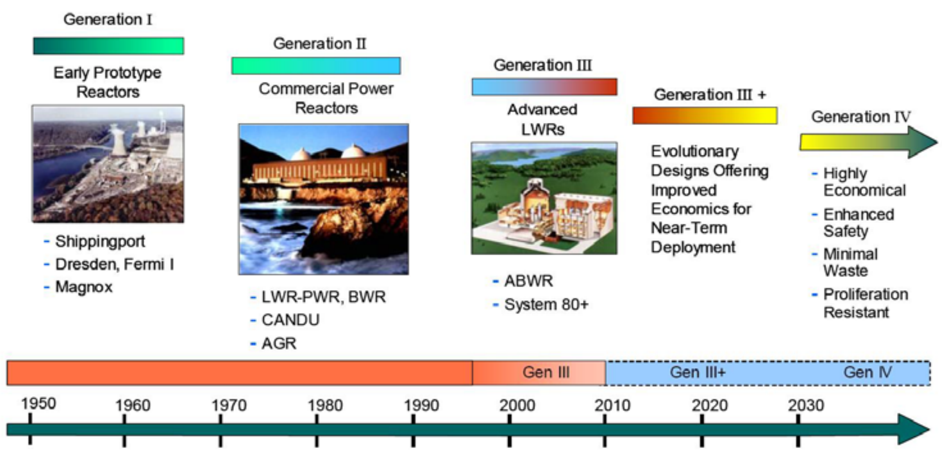

Figure 1: A Technology Roadmap for Generation IV Nuclear Energy Systems [1].

The radiotoxicity of the spent fuel decreases to the level of the starting raw uranium ore used to produce the fuel elements only after a period greater than a million years. In order not to release these toxic elements in the biosphere it is thus necessary to dispose of the waste in deep and stable geological repositories, ensuring proper containment and surveillance for this extremely long period. The Partioning and Transmutation (P&T) goal is, via chemical separation and irradiation in a fast and intense neutron flux, to reduce this time to 700-1000 years (See Figure 2).

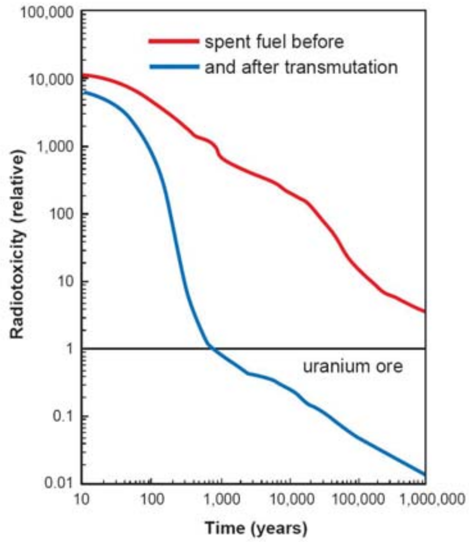

Figure 2: Ingestion radiotoxicity of spent nuclear fuel,before and after partitioning and transmutation, compared to the uranium ore level [2].

In mid ninetieth Carlo Rubbia promoted the idea of using a high intensity proton accelerator to drive a subcritical nuclear reactor specifically designed to transmute the high toxicity waste produced by conventional plants [2]. This concept that uses spallation neutrons to compensate for sub-criticality had a large consensus worldwide encouraging a few R&D programs in Europe, US and Asia. In year 2000, OECD/NEA created a specific “Working Party on Partitioning and Transmutation”, WPPT, to monitor the activities while helping, through workshops and committees, the creation of basic guidelines. The schematic concept is that, by using partitioning and transmutation technologies, the most hazardous elements could be separated (partitioning) from the nuclear wastes and, then, converted to shorter-lived elements (transmutation). Generally speaking, transuranic elements, Actinides, would be transmuted by nuclear fission, and dangerous Fission Products (Lanthanides) by neutron capture and beta decay.

Accelerator Driven Systems (ADS) were generally believed to be particularly suited for assessing the transmutation of nuclear waste and have become a major R&D topic in Europe, TRASCO in Italy and IPHI-ASH in France. Since 2001 the European Commission, EC, is funding the ADS activities through EURATOM specific programs included in the FP5 and FP6. A continuation of the ADS activity in the EC-FP7 is expected to start in 2010. The availability of consistent EC funds extended the number of the European institutions engaged in this field. In the same time ADS R&D was pursued in US (ATW), Japan (J-Park) and Korea (KOMAC).

In 2004 the mission of the OECD/NEA WPPT was considered concluded and a new more general Working Party was constituted, named “Working Party on Fuel Cycle, WPFC. Having been a member of both Parties I draw the following conclusions:

- In order to cure the toxicity of nuclear waste, partitioning is the most difficult and challenging problem. In many cases a very high purity is required to ensure positive effect of transmutation.
- New fuel elements mast be conceived and designed to allocate both fissile materials and waste to be transmuted.

- High energy neutrons from spallation should add a nicely positive effect to the transmutation conceivable in fast reactors. Nevertheless experiments are needed and much more nuclear data have to be collected to validate the scheme.
- Breading is another key component of the scenario based on fission nuclear power. The partial contradiction between the extraction of fission elements and the non-proliferation concept is still a problem to be solved . As an example Plutonium is considered either an Actinide to be transmuted or a fuel to be extracted, depending to the Agency you pose the question.
- In this complex long term R&D scenario that is the path to the so called "Generation IV" the ADS is still supposed to play an important role, but one has to be aware that it cannot be considered by itself the solution of the problem.

In the following I will draw what I consider the major achievements of more than 10 years of R&D for the ADS, mainly in Europe, focusing the attention on the high power proton accelerator that is required to produce, trough spallation on a heavy target, the high energy neutron flux that sustains the nuclear reaction in a subcritical reactor while improving its transmutation capability.

4.3.2 Proton Accelerators and Sub-Critical Reactors

The ADS concept requires a high energy neutron flux generated at the core center of a sub-critical fission reactor. The reactor criticality parameter, k_{eff}, which is usually maintained equal to 1 to sustain a constant power reaction, is set to a value ranging from 0.95 to 0.98. The difference is supplied by the spallation neutrons. It is worthwhile to note that as low is the value of k_{eff} as large is the number of spallation neutrons required to sustain the reaction. Conversely as much k_{eff} approach 1, as less will be the positive effect on transmutation induced by the high energy neutrons from spallation.

From a proton beam energy from 1 to 2 GeV, and a spallation target made by Pb-Bi or pure Pb, it turns out that the flux of spallation neutron is proportional to the beam power. Lower beam energies have a lower conversion efficiency.

What is peculiar for an ADS proton accelerator is a multi-MW proton beam power combined with a level of reliability and availability that has never been reached up to now. Apart from this, the machine looks quite simple, because the final user is just asking for a CW proton beam power, uniformly distributed on a large target ($\sim 10^2$ cm^2).

It is worthwhile to mention that a nuclear reactor is a very delicate and demanding item. In particular it's intrinsic time constants have to be strictly respected. To simplify the picture we can say that any beam trip shorter than 1 ms does not significantly perturb the nuclear reaction and the reactor core thermal equilibrium. Conversely, any beam trip longer than 1 second can cause significant problems in term of both, thermal stresses and fuel poisoning, the last being the opposite of what is the objective for a transmutation plant. In practice, after 1 second of beam off, the reactor will automatically start the shut down procedure in order to limit the fuel poisoning effect to a well known level. A part from the fuel poisoning that while reduced is always present, this turn off – turn on procedure needs at least one full day.

The required beam power depends on the reactor power and on the assumed value for the criticality parameter k_{eff}. From the user side proton energy is not an issue, the choice being left to the accelerator designer, because what counts is the spallation neutron flux. Schematically we can say that a final large transmutation plants, which includes a sub-critical reactor of the GWe size, will require an accelerator delivering a proton beam power of several tenth of MW at an energy ≥ 1 GeV. Final choice of the beam power being determined by the choice of the reactor k_{eff} for efficient transmutation. Meanwhile, resources are concentrated on the design of demonstration plants to experimentally verify the effectiveness of the ADS scheme. In this scenario the first step of a demonstration sub-critical reactor has the moderate size of a few tenth of MWe, up to 100 MWe, and the required neutron flux is at least one order of magnitude lower, even if a large variation of k_{eff} is envisaged for a wide scanning of the optimal transmutation parameters. Figure 3, taken from a NEA/OECD Public Report [3], shows the relation between the beam parameters (beam current I_b and beam energy E_b) and the electric power level of the ADS for a fixed k_{eff} of 0.97. It presents the parameter space of the envisaged scenario for a demonstration plant with a reactor power limited to 100 MWe and a proton beam power limited to 5 MW.

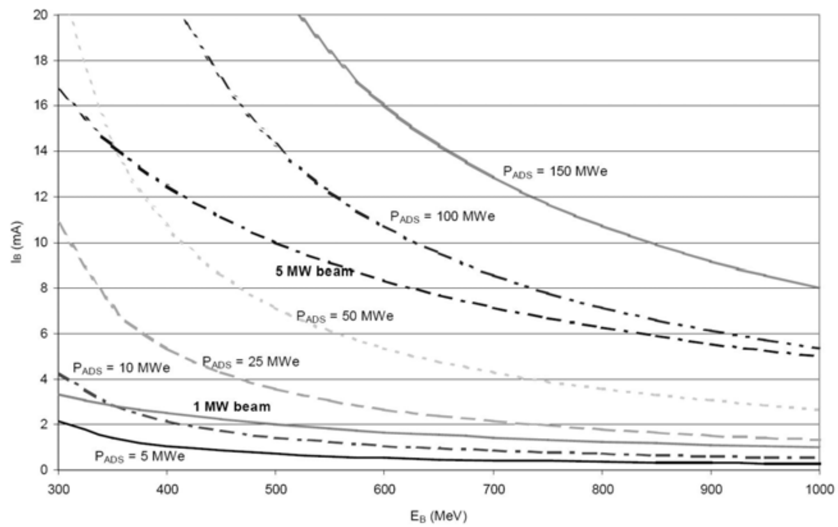

Figure 3: Proton beam parameters for a demonstration ADS, according to the agreed limitations fixed for the beam power, 5 MW, and the reactor power, 100 MWe [3].

In the following I will sketch the ADS program ongoing in Europe, focusing the attention of the accelerator. In my opinion it is a good example of the path to be followed in the direction of a future transmutation plant. In Europe the ADS work started in mid ninetieth with national programs in Italy (TRASCO) and France (IPHI-ASH) to merge in a common European Program supported by the European Commission. EC, including several national institutions and universities.

4.3.3 The EUROTRANS Program in Europe

The European Research Program for the Transmutation of High Level Nuclear Waste in an Accelerator Driven System is a research program funded by the European Commission in the 6th Framework Program, involving 31 partners between research agencies and nuclear industries and with the contribution of 16 universities. EUROTRANS is a 5 year program extending previous activities (PDS-XADS, Preliminary Design Study for an experimental Accelerator Driven System) and paving the road towards the construction of an experimental facility demonstrating the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS) in the next EC framework programs [4].

The main objective of EUROTRANS is to work towards a European Transmutation Demonstration (ETD) in a step-wise manner:

- to provide an advanced design of all components of an XT-ADS system at significant power levels of the subcritical assembly (50 to 100 MWth), driven by conventional MOX fuel, in order to allow its realization in a short-term (~10 years),
- to provide a generic conceptual design of modular European Facility for Industrial Transmutation (EFIT), with power levels exceeding several 100 MWth and operated with new fuel loaded with reprocessed waste. The EFIT is the long-term objective of the program.

Within the EUROTRANS program the activities are carried in five main technical areas (called Domains):

- The first domain is dedicated to the design of the ADS systems (XT-ADS and EFIT), and subcomponents. The accelerator activities are carried in one workpackage of this domain.
- The second domain is devoted to experimental activities on the coupling of an accelerator, a neutron spallation target and a subcritical blanket. Experiments have been proposed using research reactors at low power levels driven by photofission generated neutrons by small electron accelerators.
- The remaining domains are concerned with the study of advanced fuels for transmuters, the investigation of structural materials for ADS systems and heavy liquid metal technologies (in particular the spallation target design), and nuclear data for transmutation.

EUROTRANS aims at proceeding towards the demonstration of the industrial transmutation through the ADS route, primarily with the design of the XT-ADS and EFIT systems. The first is intended to be as much as possible a test bench of the main components and of the operation scheme of the EFIT, but at the lower working temperatures allowed by the use of Lead-Bismuth Eutectic (LBE) as core coolant and spallation target material. The EFIT design will be detailed to a level which will allow a parametric cost estimate of the ADS-based transmutation process. The reactor coolant and the spallation target material will be pure lead. Both designs (XT-ADS and EFIT) share the same fundamental system characteristics in order to allow for scalability considerations.

The EFIT is intended as a full-scale transmutation demonstrator system, loaded with transmutation dedicated fuel. The machine becomes operational many years after the XT-ADS (around 2040) and takes into account all the experience gained from the already running R&D programs on fuel and materials. On the other hand, the XT-ADS is meant to be built and tested in a near future. The machine should be completely operational around 2017 – 2018 and fulfill three objectives:

- demonstrate the ADS concept (coupling of accelerator, spallation target and sub-critical core) and its operability,
- demonstrate the transmutation,
- provide an irradiation facility for the testing of different EFIT components (samples, fuel pin, fuel assembly).

Even though the EFIT and XT-ADS have different objectives, they share as many designs characteristics as possible. As EFIT is an industrial-scale transmutation facility, the characteristics were meant to maximize the efficiency of transmutation, the easiness of operation and maintenance, and the high level of availability in order to achieve an economical transmutation. For XT-ADS on the other hand, the characteristics have been defined to deploy a flexible testing facility. Despite those sometimes contradictory definitions, many characteristics remain identical in the EFIT and XT-ADS machines:

- A superconducting linac solution has been chosen for both systems. The main reasons for that choice are the perspectives of improvement of beam reliability at such levels of proton energy [5,6].
- The cores of both systems are significantly different, but some characteristics are still identical.
- The vessel designs, which integrate the primary cooling system, share many design features.

Besides these identical features, divergence has occurred in the choices of components or parameters of the two machines. The main differences in the two concepts are resumed in Table 1.

Table 1: Main differences in the two European Transmutation concepts.

	XT-ADS	***EFIT***
Objective	Irradiation facility and EFIT test bench	Industrial waste burner prototype
Power range	50-100 MWth	>> 100 MWth
Subcriticality factor k_{eff}	~ 0.95	~ 0.97
Beam characteristics	5 mA@350 MeV or 2.5 mA@600 MeV	20 mA@800 MeV
Fuel	Conventional MOX	Minor Actinides loaded
Coolant	Lead-Bismuth Eutectic	Lead (gas as backup)

4.3.3.1 The Reference Accelerator

The ETD requires a high power proton accelerator operating in CW mode, ranging from 1.5 MW (for XTADS operation) to 16 MW (for the EFIT). Additional requirements at the neutron spallation target are a 2% beam power stability and 10 % beam size stability, in order to provide a sufficiently stable neutron flux [5,6].

The reference design for the accelerator has been developed during the PDS-XADS program and is shown in Figure 4. For the injector, an ECR source with a normal conducting RFQ is used, followed by an energy booster section which uses either a normal conducting IHDTL or superconducting CH-DTL structures up to a transition energy still under optimization, around 20 MeV. This first part of the linac is duplicated in order to provide good reliability perspectives [7]. Then a fully modular superconducting linac (based on different RF structure) accelerates the beam up to the final energy.

The design of such a linac configuration has been motivated by the specific reliability requirements imposed to the ADS accelerator, which are summarized in the following.

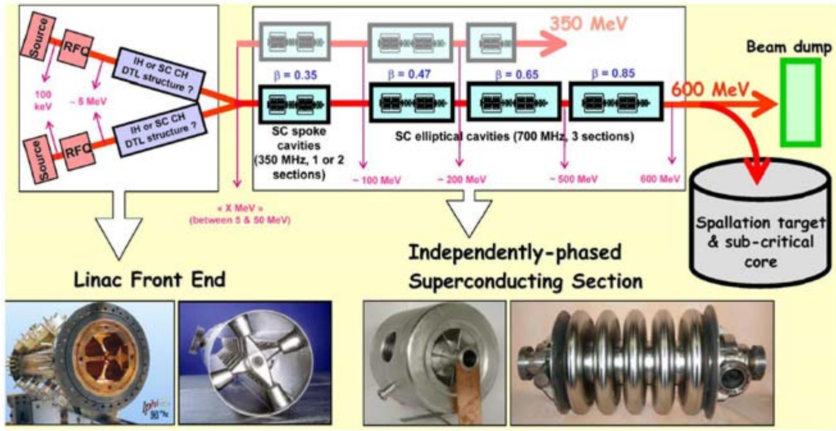

Figure 4: The reference accelerator scheme for the ETD/XT-ADS.

4.3.3.2 Issues and Challenges for an ADS Driver

The ADS accelerator is expected - especially in the long term EFIT scenario - to have a very limited number of unexpected beam interruptions per year which cause the absence of the beam on the spallation target for times longer than a second. As already mentioned, this requirement is motivated by the fact that frequently repeated beam interruptions can significantly damage the reactor structures, the target or the fuel elements, and also decrease the plant availability.

Therefore, it has been estimated that beam trips in excess of one second duration should not occur more frequently than five times per year (EFIT). To provide such an ambitious goal, which exceed the reliability experience of typical accelerator based user facilities by orders of magnitude, it is clear that reliability-oriented design practices need to be followed from the early stage of component design. In particular, "strong design" practices (based on component derating with respect to limiting performances) are needed, a rather high degree of redundancy needs to be planned and fault tolerance capabilities has to be introduced [7].

The chosen strategy to implement reliability relies on over-design, redundancy and fault-tolerance. Redundancy at the low energy stage has been obtained by duplicating the source, RFQ and booster stage, while a superconducting linac, with its modular and repetitive design, consisting in accelerating sections grouped in "cryomodules", naturally meets this reliability strategy.

A second requirement on the operation of the CW ADS linac comes from the requirement to perform on-line reactivity measurements of the subcritical assembly. For this reason, the accelerator, while the RF operates in CW, needs to provide zero current beam "holes" with durations up to 200 μs and sharp rise and fall times of few μs, at a very low duty cycle, with a repetition rate ranging from 10^{-3} Hz to 1 Hz.

The accelerator workpackage of EUROTRANS is dedicated to the design, operation and experimental characterization of the reliability characteristics of each of the major linac component in the various energy sections.

4.3.3.3 Design for Reliability

As previously mentioned, the fundamental reliability guidelines have been extensively used in the linac design, in terms of:

- component derating,
- inclusion of redundancies,
- capabilities of fault tolerance operation..

During the PDS-XADS program a preliminary bottom-up reliability analysis (Failure Mode and Effects Analysis, FMEA) has been performed [7] in order to identify the critical areas in the design in terms of impact on the overall reliability. This activity suggested to provide a second, redundant, proton injector stage (composed of the source, RFQ and low energy booster), with fast switching capabilities.

After the injector stage, the superconducting linac has a high degree of modularity, since the whole beamline is an array of nearly identical "periods". All components are operating well below any technological limitation in terms of potential performances, and therefore a high degree of fault tolerance with respect to cavity and magnets can be expected in the superconducting linac, where neighbouring components have the potential to provide the functions of a failing component without affecting the accelerator availability. Clearly this approach implies a reliable and sophisticated machine control system, and in particular a digital RF control system to handle the RF set points to perform fast beam recovery in the case of cavity failures. Deliverables on these topics are due in the framework of the EUROTRANS program.

4.3.3.4 The High Energy Superconducting Linac

While proton source and normal conduction RFQ are components that have demonstrated to be reliable enough and able to deliver a CW proton current exceeding 100 mA [8], the linac section between 5÷6 MeV, RFQ output, and 100 MeV (β~0.5), elliptical SC cavity input, can in principle be normal or superconducting. The experience that will be collected from the ongoing large projects, as RIA and IFMIF, will determine the final choice for the future full scale transmutation plant. In the actual R&D phase the European strategy is privileging SC options to support the development of advanced solutions that should demonstrate their superiority. It is worthwhile to mention that, in case of the choice of a normal conducting solution for the linac up to 100 MeV, the reliability and availability issues, mentioned above, will possibly require a duplication of the linac up to that energy. In the following I want just to outline the status of the development of the most critical SC linac section using multi-cell elliptical cavities, i.e. the linac section that is supposed to accelerate the beam from ~ 100 MeV to ~ 200 MeV. On the basis of the work done in the framework of the TRASCO Project, two identical 5-cell elliptical cavities, operating at 700 MHz (704.4 MHz is the exact value used in Europe to be compatible with the 352.2 MHz frequency of LEP), are chosen instead of the currently more popular solution based on multi-spoke SC cavities.

Figure 5 (right) shows one of the two β=0.47 cavities built on the basis of the well established TESLA Technology[9] and designed according to the cavity design criteria[10] we developed for TRASCO[11] and successfully applied for SNS[12]. In Figure 5 (left) the vertical test results of both cavities are presented, treatments and tests having been performed in two different labs, namely TJNAF and CEA-Saclay.

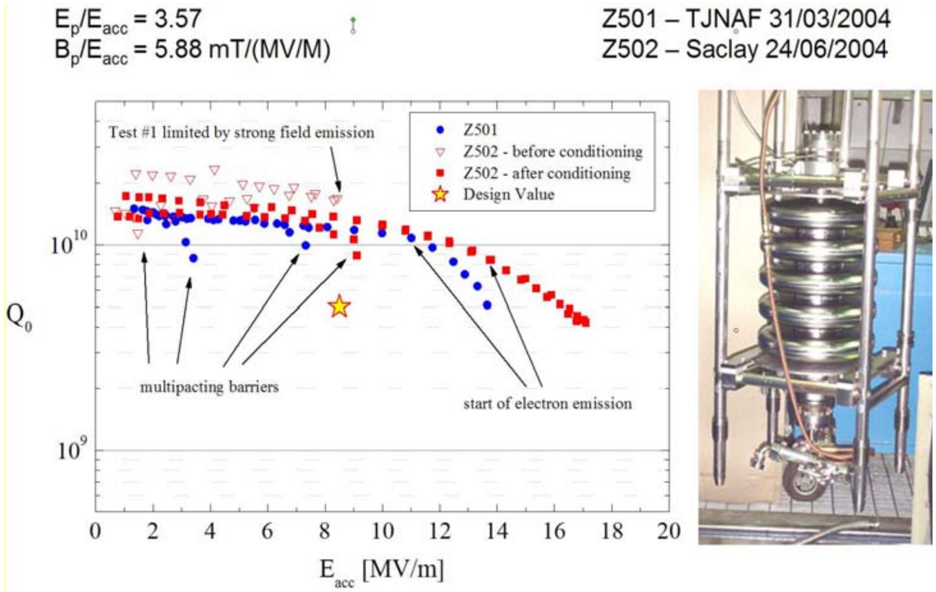

Figure 5: Vertical test results of the two, β=0.47, 5-cell, 700 MHZ, SC cavities developed in the context of TRASCO. One of the two cavities, equipped with helium tank, internal magnetic shield and ancillaries, will be horizontally tested in the framework of EUROTRANS.

Figure 6 shows on the left one of the two cavities, tuned at the nominal frequency and equipped with helium tank, internal magnetic shield and piezo-assisted Blade Tuner. The 3D model of the prototype cryomodule, in advanced fabrication stage, is presented on the right side of Figure 6. The complete prototype cryomodule will be tested next year at CNRS/IPN Orsay with a coupler developed by CEA-Saclay.

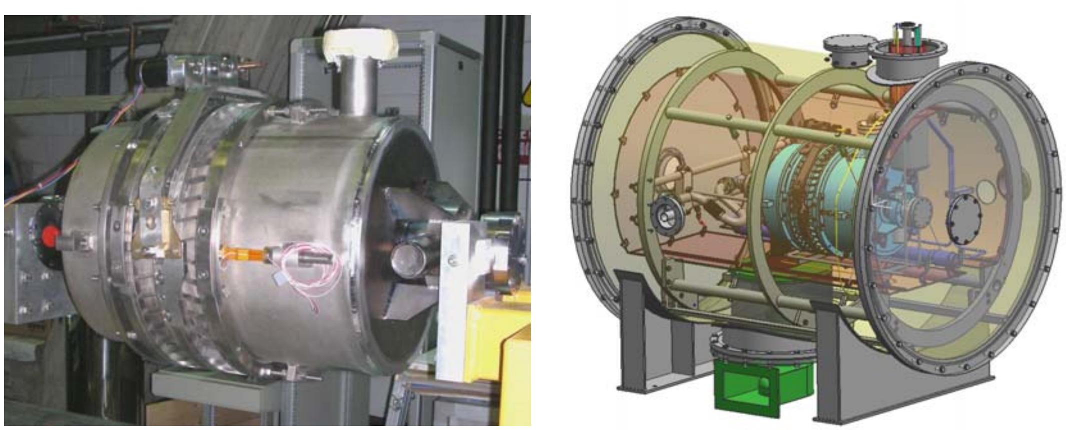

Figure 6: Fully equipped β=0.47, 5-cell, 700 MHZ, SC cavity and 3D model of the cryomodule to be tested next year at CNRS Orsay with a coupler developed by CEA-Saclay.

In my opinion, for the ADS application that is looking for a GeV proton energy, the advantage of elliptical cavities in this energy region, with respect to multi-spoke, is mainly the fact that the technology is exactly the same required for the higher energy parts of the linac. Moreover the TESLA/ILC cavity technology is fully developed, successfully applied for SNS, utilized in the European XFEL, and, last but not least, the piezo-assisted tuning system, “Blade-Tuner”, developed by the INFN for Lorentz force detuning in TESLA/ILC, looks fully adequate also for the eventual cure of microphonics[13]. HOM couplers in each cavity are, always in may opinion, non necessary in the ADS application and, after the experience of SNS, to be avoided.

4.3.3.5 Beam Dynamic Issues

Mainly because of the final user requirements and CW operation, it turns out that the beam dynamic issues are not highly demanding [5,6]. Once the beam is properly formed in the low energy part, criteria have been established to guarantee beam losses substantially lower than the value if 1 W/m that is considered acceptable to avoid a machine activation that would require remote handling. This encouraging situation allow a machine design that accepts the concept of fault tolerance, avoiding beam interruption in case of components failures[7]. Extensive analysis has been performed to validate the concept of maintaining the beam on during the machine retuning time that follows a major component fault, at least in the superconducting part of the linac.

4.3.3.6 Proton Linac to Sub-critical Reactor Interface

While for a moderate scale demonstrator, with a proton beam power of the order of a few MW, one could imagine a physical separation between the beam and the target performed with a window, for the high energy required by a transmutation plant the more exotic window-less solution looks more promising. Extensive studies have been carried out to validate this solution in the case of the Pb-Bi target that is planned for the European program. Differential vacuum issues have been studied and target design is well advanced, as intrinsic part of the sub-critical reactor core.

It is worthwhile to mention that one very critical problem was that of the volatile Polonium production by transmutation of the Bismuth in the target. A specific experiment with Pb-Te at different temperatures, validated with Pb-Bi on a fission reactor, measured the specific vapor pressures and sets the basis for the development of a code able to predict vapor dynamics[14]. The accelerator to reactor interface is a crucial issue for the ADS also because the licensing procedures are very different for accelerators and reactors. One very important issue will be to fix a net separation between the two environments, in spite of the fact that the beam is moving through. According to the discussions we had so far with the licensing agencies, a double thin window scheme, with automatically exchangeable foils, should be sufficient for the Polonium issue, given its very low evaporation rate.

4.3.4 Conclusions

The path to clean affordable energy is long and difficult. I believe that the new generation nuclear fission power outlined as Generation IV will play the central role for the required large power units to be associated with smaller and distributed units based on wind, water and sun. I also believe that the Accelerator Driven Systems will be an important part of the complex Generation IV scenario and that our accelerator community, originated with basic science motivations, has all the expertise required for this more socially understandable task. From the accelerator side, the major difference of the ADS application is the impressive requirement on reliability and availability, compensated by a less stringent budget restriction. Actual R&D phase looks very tight.

4.3.5 Acknowledgments

The principal institutions in the accelerator workpackage of EUROTRANS are CNRS, CEA (F), IBA (B); IAP-Frankfurt University (D) and INFN (I). Additional contribution, especially in issues with the coupling to the subcritical assembly, is provided from AREVA NP (D), ITN (P) and UPM (S). The program has the financial support of the European Commission through the contract FI6W-CT-2004-516520.

4.3.6 References

1. "A Technology Roadmap for Generation IV Nuclear Energy Systems", Issued by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, 03-GA50034, December 2002. http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf
2. "The European Roadmap for Developing ADS for Nuclear Waste Incineration", European Technical Working Group, ISBN 88-8286-008-6, ENEA 2001.
3. "Accelerator Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles: A Comparative Study", NEA/OECD Report, 2002/3109, chapter 4. http://www.nea.fr/html/ndd/reports/2002/3109/nea3109ch4.pdf
4. P. Pierini, "European Studies for Nuclear Waste Transmutation" in CP773 High Intensity and High Brightness Hadron Beams, I. Hoffmann, J.M. Lagniel e R.W. Hasse eds., 2005 American Institute for Physics, 0-7354-0258-2/05.
5. A.C. Mueller, "The PDS-XADS reference accelerator", International Workshop on P&T and ADS Development, Oct 2003, SCK•CEN, Belgium.
6. J-L. Biarrotte et al., "A reference accelerator scheme for ADS applications", International Conference on Accelerator Applications, August 2005, Venice, Italy.
7. P. Pierini, "ADS Reliability Activities in Europe", 4th OECD NEA International Workshop on Utilization and Reliability of HPPA, May 2004, Daejon, S. Korea.
8. J. D Schneider et al., "LEDA: a High Power Test Bed of Innovation and Opportunity", XX International Linac Conference, Monterey, CA, August 1998.
9. B. Aune, et al., Superconducting TESLA Cavities, Phys. Rev. STAB 3, 092001, (2000), pp.25.
10. C. Pagani et al. "Design Criteria for Elliptical Cavities", 10th Workshop on RF Superconductivity, Tsukuba, Japan, September 2001, KEK Proceedings 2003-2.
11. C. Pagani, "The TRASCO Project", *Twentieth ICFA Advance Beam Dynamics Workshop*, Batavia, IL, USA, April 2002, ICFA- HB2002, **AIP 642**.
12. J. Stovall et al., "Superconducting Linac for SNS", European Particle Accelerator Conference 2000, Vienna, Austria, June 2000.
13. A. Bosotti et al., "Full Characterization of the Piezo Blade Tuner for Superconducting RF Cavities", European Particle Accelerator Conference 2008, Genova, Italy, June 2008.
14. P. Michelato, E. Cavaliere, C. Pagani, E. Bari, A. Bonucci, "Vacuum Interface Analysis of a Windowless Spallation Target for Accelerator Driven Systems", Nuclear Science and Engineering 157, 95-109 (2007).

4.4 Cyclotron Based High Intensity Proton Accelerators

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4.4.1 Introduction

The demand for green energy, avoidance, transmutation, or incineration of nuclear waste has led to an increasing interest in accelerator driven systems (ADS) which would act as power amplifiers and transmuters. Thorium, Uranium-238, and existing nuclear waste are suggested as fuel, and, are said to abound for the next 10 000 years. Such a facility would require a 10 MW – 100 MW proton accelerator with a beam energy of 1 GeV as a driver. Both the reactor target and the accelerator definitely need R&D for a reliable and safe production of energy. The Paul-Scherrer-Institut operates a 590 MeV proton accelerator that drives the neutron Spallation source SINQ and two carbon targets for meson production. An average beam power of 1.3 MW delivered in continuous wave operation renders the PSI proton facility the most powerful proton accelerator at present. With special focus on ADS requirements, this article describes the performance of the PSI facility by means of statistics on operational performance, beam trips and losses, the overall reliability as well as important aspects of maintenance. The experience gained with the operation of this facility demonstrates that the cyclotron based accelerator concept represents a feasible alternative to linac based systems for ADS applications, where a high power CW beam is required as well. Above all, we will come forward with a concept for a 10 MW proton driver based on the design of the PSI Ring Cyclotron. We want to point out that a design study for a cyclotron based ADS driver was already published by Stammbach et al. in 1996 as an extrapolation from the PSI isochronous Ring accelerator [1].

4.4.2 The PSI High Intensity Proton Accelerator Facility

4.4.2.1 The Accelerators

The PSI High Intensity Proton accelerator facility consists of a Cockroft-Walton pre-accelerator and a chain of two sector cyclotrons. A continuous proton beam of approximately 10 mA is extracted from a multi-cusp ion source with 60 kV and is successively pre-accelerated to 870 keV. The beam is then bunched to a 50.63 MHz continuous-wave (CW) structure using a buncher cavity superimposed by a 3^{rd} harmonic to linearize the bunching voltage and to achieve a shorter longitudinal bunch length [2]. The 2.2 mA of protons left after bunching and collimation are further accelerated to 72 MeV in the Injector Cyclotron and then transferred to the Ring Cyclotron. The final beam energy extracted from the Ring Cyclotron is 590 MeV at a beam current recently raised from 2.0 mA to 2.2 mA for standard operation in 2009. Consequently, the beam power amounts to 1.3 MW which is at present the highest average beam power generated by any proton accelerator. The PSI cyclotrons are realized as isochronous sector cyclotrons. These cyclotrons do not use the classical “Dee’s” for acceleration, but closed box-resonators that accelerate the beam using a

TM11 mode at 50 MHz. An important advantage of this concept is that the magnet and the RF-system are decoupled. Throughout the acceleration process the revolution time of the particles has to be kept constant, although their velocity is changed significantly. In consequence, the orbit radii vary strongly, for example from 2.1 m to 4.5 m in the PSI Ring Cyclotron. Vacuum chamber and dipole magnets have to accommodate this large lateral variation of the beam position. This fact is often considered as an important disadvantage of the cyclotron concept in comparison to a synchrotron. For high power beam acceleration it actually presents also an advantage because it allows the individual turns to be separated and results in the ability to continuously extract the accelerated beam from the cyclotron. For the purpose of extraction the electrode of an electrostatic deflector is placed in-between the orbits of the last two turns. Scattering of protons from beam tails in this electrode presents the most severe loss mechanism in a high power cyclotron.

4.4.2.2 Targets and Experimental Facilities

At PSI the 590 MeV beam is used to produce pions and muons by interaction with two graphite targets that are realized as rotating wheels for optimized heat dissipation. After the second target, with a thickness of 40 mm, a fraction of 30% of beam current is lost because of nuclear reactions, Coulomb scattering, and subsequent collimation. The remaining beam is transferred to the neutron Spallation source SINQ in order to produce neutrons in a target that contains lead filled Zircaloy tubes. The research based on the PSI 590 MeV proton driver covers a broad range of applications involving neutron scattering experiments, muon spin resonance spectroscopy and several particle physics experiments. Fig. 1 shows an overview of the accelerator facility including the secondary beamlines.

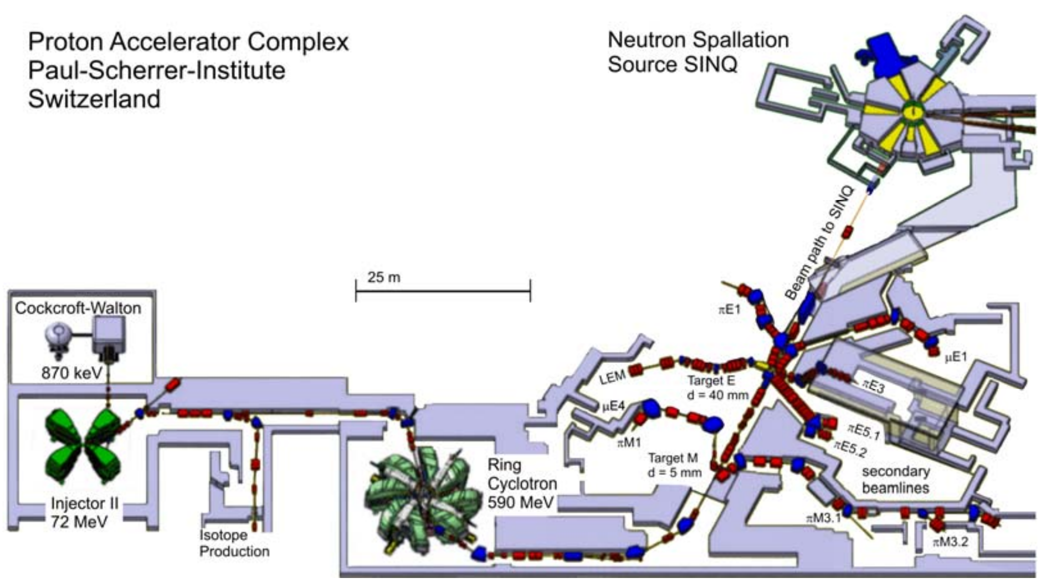

Figure 1: View of the PSI high intensity proton facility including the experimental facilities, i.e. the secondary beamlines for meson production and the neutron Spallation source SINQ.

For the purposes of neutron production a high beam power is particularly important in order to maximize the neutron flux. Under the constraint of constant beam power the rate of spallation neutrons is not a strong function of beam energy above 600 MeV.

Since altering the beam energy is not possible within the present geometry, the obvious upgrade path for the facility is a stepwise increase of the beam power by means of raising the beam current. In the context of potential ADS applications the efficiency for the conversion of grid power to beam power is of interest. The total power consumed in the PSI facility is 10 MW when the full beam power of 1.3 MW is produced. From that the overall efficiency of the PSI facility is approximately 13%. At zero beam current but with magnets and RF systems in operation there are still 8 MW drawn from the grid. Many magnets and other auxiliary systems contributing to the power balance are not needed for the basic accelerator operation, but for secondary experimental facilities only. Thus, the total power consumption of the PSI facility is not representative for a cyclotron based AD system.

In Fig. 2 the PSI-wide power consumption is plotted as a function of beam current. The slope of the curve represents the differential power consumption per mA of beam current, and was determined to be 0.8 MW/mA. On the other hand the kinetic energy of the protons is 590 MeV which determines the power the beam carries per mA and hence amounts to 0.6 MW/mA. This approach allows determining the differential grid-to-beam efficiency around the working point of 2 mA. The ratio of the two numbers yields the differential conversion efficiency of wall plug power to beam power which amounts to 73%.

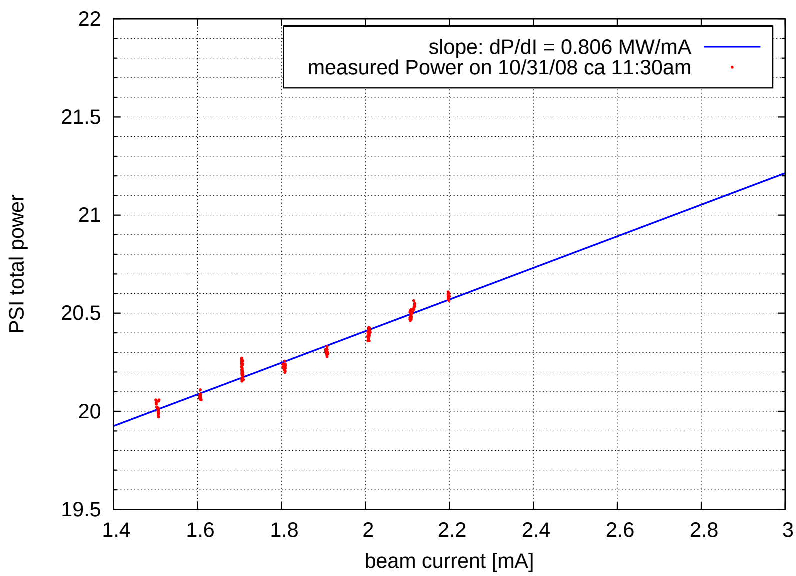

Figure 2: PSI-wide power consumption as a function of the proton beam current. The proton facility consumes roughly 10 MW, the remaining power is used by other accelerators and the PSI infrastructure.

4.4.2.3 Performance and Limitations of the PSI-Proton Accelerator

The maximum beam power in the PSI facility is in fact not limited by the power transfer from the grid, or the performance of the RF system. In practice the limitation is given by the beam losses that cause activation and, as a consequence, the radiation dose the technical personnel are exposed to during maintenance work on accelerator components. Intensity upgrades were realized only if the relative beam losses could be lowered in proportion, thus keeping the absolute losses constant. Over the long term history of the accelerator the typical collective radiation dose received by the personnel during maintenance and modification of the accelerator was continuously decreased. This was mainly achieved by optimized handling procedures of activated components and the introduction of specifically customized mobile shielding devices for critical components, e.g. electrostatic elements and targets. With respect to activation the critical components in a high power cyclotron are the extraction elements and the magnets in the subsequent beamline. The electrostatic deflector channel of the PSI Ring Cyclotron deflects the beam within the last turn by 8 mrad, which then allows extracting the protons from the cyclotron using a magnetic septum. The inner electrode of the electrostatic element consists of 50 µm thick tungsten foils, which are placed between the last and the second last turn. Protons in the beam tails may hit the tungsten foils and as a result of scattering and energy loss these particles are separated from the beam core and hit components in the extraction beamline. The activation levels in this region amount to several mSv/h with a local peak value of 9 mSv/h. Under optimized conditions the losses in the extraction beamline are at the level of $2 \cdot 10^{-4}$ relative to the total beam current. In order to keep those losses at a minimum the generation of beam tails originating from space charge effects is minimized by maximizing the turn separation between the outer turns. Joho has argued convincingly that the extraction losses are a strong function of the number of turns in the cyclotron, and in fact they scale with the third power of the number of turns [3]. Under the constraint to keep the absolute losses constant, the beam current was raised in inverse proportion to the third power of the number of turns in the Ring Cyclotron, as shown in Fig. 3b.

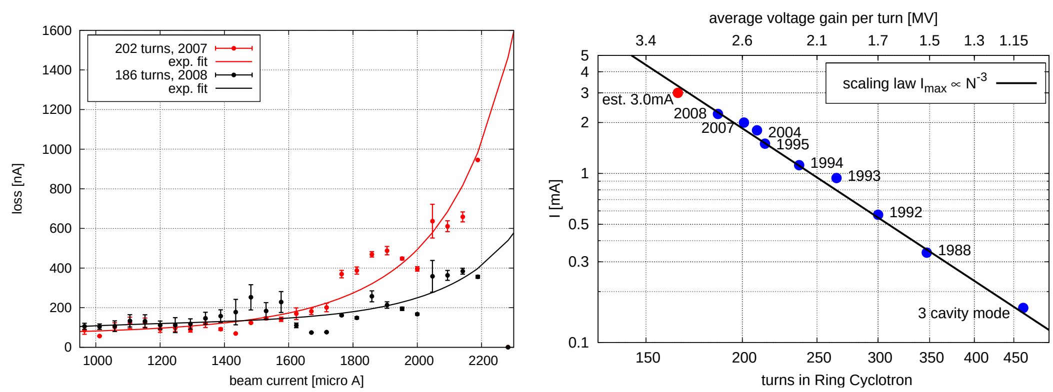

Figure 3: a) Scaling of the beam losses as a function of current. b) Maximum beam current extracted from the PSI-Ring Cyclotron as a function of the number of turns. The linear fit within the double logarithmic diagram nicely confirms the scaling law $I_{max} \sim n^{-3}$ [3]

Evidently, the number of turns can be decreased by raising the gap voltage of the accelerating structures, i.e. the RF-cavities. Hence, the most important upgrade of the PSI-proton accelerator in order to reach higher beam currents is the installation of more powerful resonators. During the shutdowns between 2004 and 2008 the 4 original aluminium resonators were successively replaced by 4 new structures made of copper. The copper surface allows for higher gap voltages (currently 830 kV) and thus a faster acceleration in the Ring Cyclotron which in turn reduces the number of turns from 202 to only 186 at present. This has led to a significant reduction in the extraction losses by a factor of approximately 2. Fig. 3a shows the observed dependence of the extraction losses on the beam current. The losses are measured with ionization chambers that are calibrated by purposely arranging a complete loss of a very small beam current. The data is taken from normal operation periods during which the accelerator was operated at 2 mA for most of the time. Consequently, the accelerator was optimized to this current and the data points are sampled in a non-uniform way. Nevertheless, the non-linear increase of the losses, caused by space charge effects, is visible in Fig. 3a.

4.4.2.4 Operation Statistics and Reliability

The deployment of a particle accelerator for transmutation purposes requires extremely reliable operation of the facility. Frequently repeated beam trips can cause fatigue of the cladding for fuel elements because of the thermal cycles and, therefore, decrease the availability of an ADS power plant. In this context we present a statistical analysis of the recently achieved accelerator trip rate of the PSI facility, specifically the distributions of recovery times and uninterrupted run periods. In addition we will present data on the subsystems that caused longer interruptions.

The operation of the PSI proton accelerator is characterized by sudden interruptions, with durations ranging from 30 seconds to failures which require repair before restart. Most of the short term interruptions in the PSI-facility are caused by high voltage breakdowns of the electrostatic elements which deflect the injected and extracted beam. Other triggers of the interlock system are intermittent spikes in the loss rates or trips of the RF system. In most cases the system that triggered the interruption is automatically reset and the beam current is ramped up again within 30 seconds. Therefore, the minimum time required for recovery is determined by the ramping procedure even though triggers may only last for a few milliseconds. In order to quantify the trip statistics we have analyzed the run periods in 2007 and 2008 [4, 5].

Table 1: Reasons for interruptions with durations longer than 5 minutes in the years 2007 and 2008. The percentage values are relative to the total downtime [4, 5].

Year	Vacuum	Controls	Magnets	RF systems	Site power/cooling
2007	9	8	6	13	22
2008	19	11	1	6	4

[Continued…]

Year	Electrostatic elements	Targets and SINQ	Ion source	Magnet cooling	Power supplies	Misc.
2007	4	13	12	8	0	5
2008	27	2	7	5	4	14

In 2008 the reduction of the number of turns from 202 to 186 turns in the Ring Cyclotron resulted in a significant improvement of the operation. Actually, two new records were achieved in 2008: After receiving legal permission to exceed 2 mA for 18 hours every other week, a stable operation at 2.2 mA was achieved after just 5 hours of tuning from 202 to 186 turns in the Ring Cyclotron. Reducing the current back to the working point of 2.0 mA but keeping the number of turns at 186 lead to the longest period without any interruption, i.e. 21 hours. Therefore, we will consider here the period after the upgrades finished up to 2008, which includes 165 days of operation with a total of 3,478 trips.

In 2007 the considered time amounts to 254 days with 15,593 trips [4, 5]. Histograms with the probability distribution of run durations and trip durations were computed. However, it is circuitous to derive practical information from such histograms since the number of events in a bin depends on the bin width itself. A more conclusive way to evaluate the data is to integrate the histograms with the duration of a run, respectively, the interruption period as variables of integration. The resulting number *N* yields the number of events with duration longer than the value *t* read from the abscissa (Fig. 4).

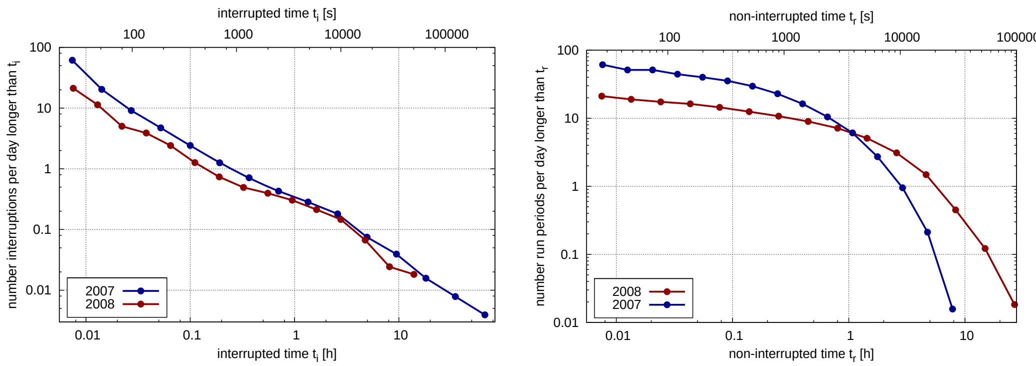

Figure 4: a) The number of interruptions per day lasting longer than *t* scale inversely in contrast to b) the number of run periods longer than *t* [4].

At the very left end of each graph the total number of interruptions a) respectively runs b) per day can be extracted. Consequently, the total number of interrupts and runs are equal. However, the shapes of the distributions which are a function of duration differ. The probability of an interruption roughly scales inversely with its duration. This can be explained by the fact that the probability of a successful restart (provided that failures are instantly recognized and repair work is immediately initiated) increases linearly with the time of recovery. The duration of the run periods is determined by the first failure of one of the many accelerator components. The times between failures of single components are often exponentially distributed and a summation of many of such contributions is observed. The overall availability of the PSI accelerator is defined as the ratio of delivered and scheduled run time. Over the past two years the average availability was 90% which presents a relatively good performance in comparison with other high power accelerators. In the second half of 2008, after the intensity upgrade, a final value of 94% was achieved at the end of the operating year. The total trip rate is now roughly 20/d versus 60/d in 2007. The classification of failures that cause interruptions longer than 5 minutes is shown in Tab. 1 for the years 2007 and 2008. Some prominent downtimes are caused by subsystems that require, as matter of principle, long repair or recovery times, such as site cooling or vacuum failure. In the summers of 2007 and 2008 the operation of the facility was restricted by limited cooling power due to extraordinary warm environmental temperatures. In summary, the performance of the facility is still more than 3 orders of magnitude away from the trip rate of about 0.01/d which is presently postulated for ADS applications. In the next section we will describe the upgrade path of the PSI-facility and will also address conceivable improvements to increase the reliability of the accelerator.

4.4.2.5 Upgrade to 1.8 MW

The PSI follows an upgrade path to further increase the beam power to an ultimate level of 1.8 MW at a beam current of 3 mA. Since the Ring Cyclotron has now been equipped with more powerful resonators (see Fig. 5 left image) the Injector Cyclotron will be upgraded with two additional accelerating resonators [6]. One of these (Fig. 5, right image) has just arrived at PSI (June 2009). Those resonators will replace the two existing 150 MHz 3^{rd} harmonic flattops. Because a short bunch length was achieved using a recently added 3^{rd} harmonic buncher, which is installed right after the 50 MHz buncher in the 870 keV injection beam line, the flattop resonators are redundant. Due to strong space charge effects the bunches will stay compact in circular shape [2]. This fact and further reduction of the turn number will enable us, also for this cyclotron, to reduce the losses and to produce a qualitatively better beam. Other measures include the installation of a 10^{th} harmonic buncher between the Injector and the Ring Cyclotron, which will improve the quality of the beam injected into the Ring Cyclotron by means of reducing energy spread and the bunch length.

Figure 5: On the left, one of the 4 new copper resonators before installation into the Ring Cyclotron. Hydraulic tuning devices on the top and bottom of the cavity provide active compensation for deformation due to air pressure with a precision of ~10 μm. The resonators operate at a frequency of 50.63 MHz and are capable of providing a maximum gap voltage of 1.2 MV. The right image shows one of the two new resonators designed for the Injector Cyclotron [6]. These additional accelerating structures will lead to a reduction of the number of turns also in the Injector and to a better beam quality.

The quality of the proton beam is also influenced by the ion source. Presently, a multi-cusp ion source is used to generate the proton beam. To generate the plasma such an ion source uses electrically heated filaments which have to be exchanged roughly every other week. This causes a downtime of about two hours per exchange. Therefore, a new compact microwave source was developed and tested with promising results. Microwave power is fed through a ceramic window into the plasma chamber whilst a magnetic field generated by an arrangement of permanent magnets confines the plasma. First measurements have shown that the new ECR-source exhibits a smaller beam emittance and thus a better beam quality. Furthermore, the source has already been operated for a period of 6 weeks without any interruption. Such excellent performance will ultimately support a better availability of the proton facility.

The electrostatic injection and extraction channels in the Ring Cyclotron cause the most short beam trips at present. Therefore, these deflectors are continuously improved with respect to breakdown characteristics. At present, a trip rate of about 15/d can typically be achieved under optimal conditions, i.e., a machine tuned to minimal losses. Two major factors are observed to affect the reliability of the electrostatic elements in the Ring machine. Firstly, beam losses cause evaporation or sputtering of material in the cyclotron which can then be deposited on the insulators sustaining the cathode. On the one hand the insulating property of the ceramics will be lost, on the other hand charge can accumulate on islands of deposited material which will cause an ever-growing rate of discharges and thus eventual damage. The second factor is RF-power decoupled from the resonators which can be in the range of several hundred Watts. The electrostatic element could then act as pick-up for the RF-power which would lead to localized heating and discharging. At PSI both aspects were approached by attaching RF-shielding to the septum.

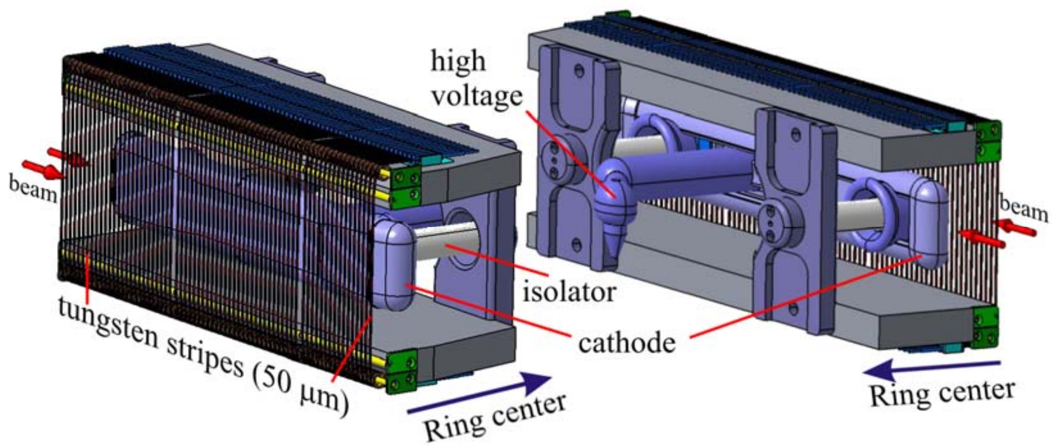

Figure 6: On the left, front view of the electrostatic injection channel looking towards the tungsten stripes and the cathode. The right image shows the rear view looking towards the high-voltage connector. The red arrows denote the injected beam and the first turn in the cyclotron, respectively.

Since then, the trip rate has decreased by far and the extraction and injection element could be operated for more than 15 months without any maintenance. In Fig. 7 a schematic view of the electrostatic injection channel is shown. The cathode consists of platinized aluminum and is supported with a ceramic insulator. The outer electrode consists of a series of 50 μm thick tungsten foils which are 3 mm apart and 3 mm wide. These stripes separate the injected beam and the first turn in the cyclotron.

4.4.3 Proposal for a 10 MW Cyclotron

Within the last sections we discussed the performance of the PSI high power proton accelerator with special emphasis on a possible application of such a cyclotron based facility for AD systems. With 1.3 MW power at a beam energy of 590 MeV the facility has reached a performance less than one order of magnitude below the useful range for AD systems. However, the observed reliability and trip frequency are still 3 orders of magnitude worse than the values desirable for an accelerator driven system. These issues can be resolved by several measures like implementing redundancy of components.

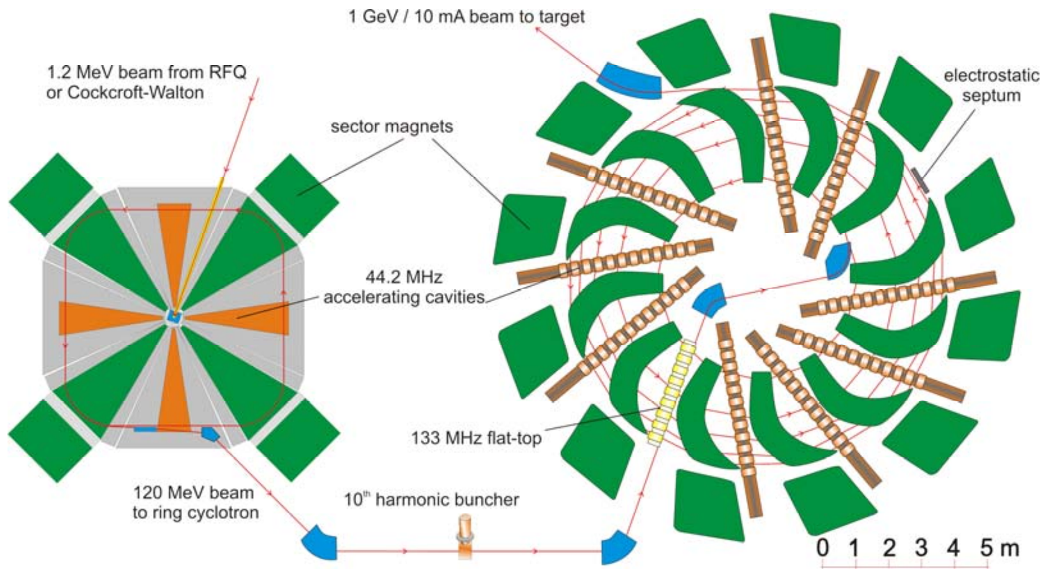

Figure 7: Schematic view of a proton driver based on two isochronous sector cyclotrons. An RFQ would act as a pre-accelerator. A similar proposal for the Ring Cyclotron on the right hand side of the figure was already given by Stammbach et al. [1]

For the postulated high beam power of 10 MW the relative beam losses have to be reduced further. This can be achieved by an even faster acceleration in the main cyclotron in combination with a larger extraction radius.

In the following we will describe the concept of a 10 MW proton driver based on the design of the PSI-Ring Cyclotron. In reference [1] a proposal has already been worked out for a 1 GeV/10 MW cyclotron which is in principle an up-scaled version of the presently operating PSI machine. The proposed cyclotron employs 12 sector magnets with 8 embedded accelerating resonators to be operated at peak gap voltages of 1 MV. The projected number of turns would then be around 140, which is even less than the 186 turns for the 590 MeV PSI-Ring Cyclotron. Consequently, the condition of fast acceleration to deal with longitudinal space charge forces would be fulfilled by the increased number of sector magnets and, thus, the space available for more accelerating structures. Because of relativistic effects the energy of 1 GeV seems to be the ultimate limit for an isochronous cyclotron. On the other hand, there is no fundamental limit for the beam power, although at some point technical challenges will arise from limitations in the power couplers of the accelerating resonators. The limited maximum energy would not pose a problem to an AD system based on a cyclotron because the neutron production rate in a spallation source is not a strong function of energy but scales almost linearly with beam power. In Fig. 6 the concept for a 10 MW/1GeV cyclotron is shown with only slight modifications compared to the original proposal by Stammbach et al. There, the authors embedded two flat-top resonators into the cyclotron to compensate longitudinal space-charge forces. In our proposal we suggest to use a 10^{th} harmonic buncher in the transfer line between the Injector Cyclotron and the booster cyclotron to be able to replace one flat-top cavity with another accelerating resonator. Either an even faster acceleration or a certain redundancy for the RF-system can be obtained. In the case of nine accelerating cavities the average energy gain per revolution would be around 7 MeV.

Table 2: Parameters for the proposed 1 GeV / 10MW proton driver in comparison to the existing PSI 590 MeV / 1.3 MW Ring Cyclotron.

Parameter	***1 GeV Ring***	***PSI Ring***	***120 MeV Injector***	***PSI Injector***
Energy	**1000 MeV**	**590 MeV**	**120 MeV**	**72 MeV**
Maximum current	**10 mA**	**2.2 mA**	**10 mA**	**2.7 mA**
Magnets	12	8	4	48
Maximum magnetic field	2.1 T	1.1 T	1.3 T	1.2 T
Cavities	8 (9)	4	4	2
Peak voltage	1 MV	0.8 MV	0.6 MV	0.3 MV
Frequency	44.2 MHz	50.6 MHz	44.2 MHz	50.6 MHz
Flat tops (3rd harmonic)	2(1)	1	--	2
Peak voltage	650 kV	460 kV	--	40 kV
Harmonic number	6	6	10	10
Injection energy	120 MeV	72 MeV	1.2 MeV	0.87 MeV
Injection radius	2.8 m	2.1 m	0.6 m	0.4 m
Extraction radius	5.7 m	4.5 m	4.0 m	3.5 m
Number of turns	140	186	68	86
Energy gain at extraction	6.3 MeV	2.4 MeV	2.3 MeV	1.4 MeV
Beam power	**10 MW**	1.3 MW	1.2 MW	0.2 MW

The higher energy gain would lead to a larger turn separation at extraction in an isochronous field of the 1 GeV cyclotron. Furthermore, the beam width scales with $(\beta\gamma)^{-1}$ and should therefore be smaller in the 1 GeV cyclotron by a factor of about 0.8. As mentioned by Stammbach et al. the beam should be accelerated into the fringing field to further widen the turn separation. The extraction itself would be accomplished by an electrostatic deflector following the design of the existing septum in the PSI cyclotron. The second most important aspect concerns drastic improvements to the reliability and the reduction of the trip rate. Large turn separation at the electrostatic elements will improve their trip rate. Since short beam interruptions below 1 s can be ignored from the point of view of thermal cycling of the target, another possible measure is to recharge the electrostatic elements very quickly after a trip. At PSI it has already been demonstrated that the Ring Cyclotron can be operated with only three accelerating resonators instead of 4 by redistributing the RF-power. Therefore, fault tolerance against RF trips can possibly be achieved by installing a larger number of resonators and an automated redistribution of the RF power, thereby guaranteeing a constant integral gap voltage even when a single resonator fails.

Because of geometrical and technical restrictions the energy gain factor in a sector cyclotron is limited. For the 10 MW facility as shown in Fig. 6 we propose a three stage design, where an injector cyclotron produces a 120 MeV beam for injection into the main cyclotron. In this injector cyclotron four resonators operated at 44.2 MHz and a peak voltage of approximately 600 kV would be sufficient to push the maximum beam current up to 10 mA. Pre-acceleration of the protons would be accomplished by a radio-frequency quadrupole rather than a Cockcroft-Walton as currently used at PSI. These RFQ’s have proved to be reliable in other contexts and have the advantage of focusing and bunching the beam at the same time. On the other hand high-voltage issues like breakdowns would be eliminated increasing the reliability of the facility. Instead of a multi-cusp-ion source we would rather use an ECR-type source as mentioned in the section on the PSI-upgrade path to 1.8 MW.

We have already discussed the power conversion efficiency of the PSI facility which amounts to approximately 13%, whereas ancillary systems not needed for an AD system are also taken into account. Since wall losses scale quadratically with the gap voltage it is more efficient to distribute the total circumference voltage over many resonators. The employment of many resonators is also advantageous in view of redundancy of RF-systems and increased reliability of the accelerator. Assuming about 5 MW power for the magnets and auxiliary systems, the power efficiency of the 1 GeV / 10 MW cyclotron would thus be dominated by the RF-system. The use of copper not only leads to better breakdown characteristics, but also reduces wall losses. If the AC to RF conversion is optimized to 75%, the overall efficiency would be around 40%.

4.4.4 Summary

The objective of this study was to present the performance of the PSI-proton accelerator facility with special emphasis on the feasibility of a cyclotron based AD system. With 1.3 MW power at a beam energy of 590 MeV the PSI-facility has reached a respectable performance which can still be improved to reach our ultimate goal of 1.8 MW. This is already within the useful range for experimental AD systems, but the observed reliability and the trip frequency are still 3 orders of magnitude worse than desired. Implementing measures like redundancy of vital systems or, in the best case, multiple redundant accelerators, the availability could strongly be improved. Nevertheless, one may doubt whether the desirable trip rate of 0.01/d can ever be reached with any type of accelerator. To gradually approach the aspects of accelerator reliability with the requirements of an AD system it will be helpful to re-evaluate limitations carefully and possibly implement more tolerant target systems. As a next step in cyclotron development the design of a facility that provides a 1 GeV/10 MW beam with improved reliability seems feasible. Therefore, we have seized the study of such a cyclotron and discussed the concept of a proton driver based on an isochronous sector cyclotron. The most critical aspects therein were the feasibility of accelerating structures capable of imposing 1.2 MW to the beam at a gap voltage of 1 MV and the extraction of 1 GeV protons at a high intensity level of 10 mA. Due to the excellent experience we have with the new Cu-resonators and the resulting very low beam losses observed at the extraction from the PSI-cyclotron we believe that a cyclotron is a possible candidate for an accelerator driven system. Furthermore, the cyclotron concept has advantages with respect to the relative compactness of the accelerator, which also results in an effective shielding layout with a square like footprint of the facility. Megawatt scale power levels can be transferred from grid to the beam using a small number of amplifier chains and resonators. Critical aspects in comparison to a LINAC solution are given by the necessity to place extraction electrodes close to the beam, and by the relatively complicated tuning procedure to achieve isochronicity and optimum loss levels. Finally the high predicted efficiency of around 40% and possibly lower start-up costs of such a facility which could outperform other types of accelerators.

4.4.5 References

1. Th. Stammbach, S. Adam, H.R. Fitze, W. Joho, M. Msrki, M. Olivo, L. Rezzonico, P. Sigg, U. Schryber, “the feasibility of high power cyclotrons”, Nuclear Instruments and Methods in Physics Research B 113 (1996) 1-7.
2. J. Grillenberger, M. Humbel, J. Y. Raguin, P. A. Schmelzbach, Commissioning and Tuning of the new Buncher System in the 870 keV Injection Beamline, 18th Int. Conf. on Cyclotrons and their Application, Catania (2007) 464.
3. W. Joho, Proc. 9th Int. Conf. on Cyclotrons and their Application, Caen (1981).
4. M. Seidel, A.C. Mezger, Performance of the PSI High Power Proton Accelerator, International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, Vienna (2009).
5. A.C. Mezger, private communication on failure statistics (2009).
6. L. Stingelin, M. Bopp, H. Fitze, Development of the New 50 MHz Resonators for the PSI Injector II Cyclotron, Cyclotrons and Their Applications, Catania (2007) 467.

4.5 The Progress of Researches on ADS in China

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Abstract

The conceptual study of the accelerator driven system (ADS) which lasted for about five years ended in 1999 in China. As one project of the National Basic Research Program of China (973 Program) in energy domain, which is sponsored by the China Ministry of Science and Technology (MOST), a five-year-program of fundamental research of ADS physics and related technology was launched in 2000 and passed national review at the end of 2005. From 2007, another five-year 973 Program, Key Technology Research of Accelerator Driven Sub-critical System for Nuclear waste Transmutation, started. The research activities will focus on HPPA physics and technology, reactor physics of external source driven sub-critical assembly, nuclear data base and material study. For HPPA, a high current injector consisting of an ECR ion source, LEBT and an RFQ accelerating structure of 3.5 MeV has been built and will be improved. In reactor physics study, a series of neutron multiplication experimental study has been carried out and still being done. The VENUS facility has been constructed as the basic experimental platform for neutronics study in ADS blanket. It’s a zero power sub-critical neutron multiplying assembly driven by external neutron produced by a pulsed neutron generator. The theoretical, experimental and simulation study on nuclear data, material properties and nuclear fuel circulation related to ADS is carrying on to provide the database for ADS system analysis.

4.5.1 Introduction

China, as a developing country with a great population and relatively less energy resources, actively emphasizes the development of nuclear energy. To develop nuclear power in such a large scale, two problems must be solved. First, as technically and economically exploitable natural uranium resources are limited domestically or overseas, uranium utilization rate has to be greatly raised. Second, long-lived radioactive nuclear wastes have to be safely disposed to reduce the impact on the environment and to eliminate public fear of nuclear power.

Right now only a small amount of spent fuels from NPPs has been accumulated in China. But the situation will be very serious in the future according to the prediction of nuclear energy development in China. The annual generated waste is estimated to be 7 500 $m^3$and 10 000 m^3 respectively for the year 2010 and 2020.

Considering MA and LLFP transmutation with more efficiency and non-criticality risk for new nuclear application the accelerator-driven sub-critical system (ADS) have been started to develop as a national research projects in China.

The conceptual study of the accelerator driven system (ADS) which lasted for about five years ended in 1999 in China. As one project of the National Basic Research Program of China (973 Program) in energy domain, which is sponsored by the China Ministry of Science and Technology (MOST), a five-year-program of fundamental research of ADS physics and related technology was launched in 2000 and passed national review at the end of 2005[1,2,3]. From 2007, another five-year 973 Program, Key Technology Research of Accelerator Driven Sub-critical System for Nuclear waste Transmutation, started. China Institute of Atomic Energy (CIAE), Institute of High Energy Physics (IHEP), School of Nuclear Science and Engineering in Shanghai Jiao Tong University, Institute of Heavy Ion Physics in Peking University (PKU-IHIP) and other institutions jointly carried out the research. The research activities will focus on HPPA physics and technology, reactor physics of external source driven sub-critical assembly, nuclear data base and material study. For HPPA, a high current injector consisting of an ECR ion source, LEBT and an RFQ accelerating structure of 3.5 MeV has been built and will be improved. In reactor physics study, a series of neutron multiplication experimental study has been carried out and still being done. The VENUS facility has been constructed as the basic experimental platform for neutronics study in ADS blanket. It’s a zero power sub-critical neutron multiplying assembly driven by external neutron produced by a pulsed neutron generator. The theoretical, experimental and simulation study on nuclear data, material properties and nuclear fuel circulation related to ADS is carrying on to provide the database for ADS system analysis.

In the last few years the scientific and technical exchange and cooperation with foreign research institutions in different aspects are of great help to the related work.

Some important results were summarized as follows.

4.5.2 Venus I Experiment—The Measurement on Sub-Critical Assembly Driven by Pulsed External Source

A composed structure of zero-power sub-critical assembly combined with a pulsed neutron source, Venus I program is currently being carried on. The pulse-neutron was provided by a Cockroft-Walton machine, routinely operated since 2001. 14 MeV and 2.5 MeV neutron was derived by d-T and d-D reaction. The neutron yield in DC mode can reach 10^{12}n/s, while in micropulse mode 10^9n/s ~ 10^{10}n/s for d-T reaction.

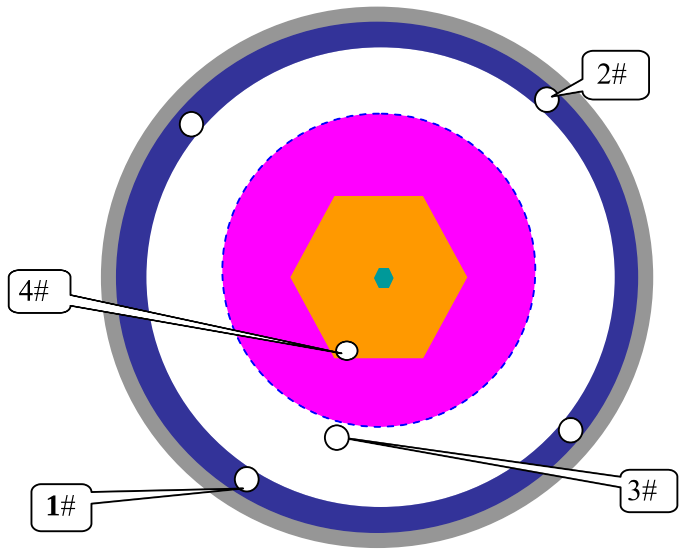

Figure 1: The subcritical reactor core arrangement of the Venus I program.

As shown in Fig.1, there are source and buffer in the center of the composed core, a driven zone consisting of natural Uranium pin is very dense lattice with aluminum in between, an active zone with 20% and mainly 3% enriched ^{235}U fuel pin is polyethylene lattice and the polyethylene reflector. Different neutron spectra in different zone are expected. The buffer will shift the sharp 14 MeV and 2.5 MeV neutron to the fast neutron spectra to mock-up the evaporation bump in the spallation neutron spectrum and fission spectrum as possible as. In the driven zone not much neutron multiplication is expected, while the hard neutron spectra with an average energy about 700 keV is expected. In the active zone, thermal neutron is expected. The assembly will be operated in deep sub-criticality $k_{eff} \approx 0.90–0.95$ range.

On July 18, 2005, the first fuel element was loaded into Venus-1 sub-critical assembly and the following preliminary experiments were subsequently conducted: determination of fuel loading, measurement of relative importance of external source at different positions, measurement of radial and axial thermal neutron flux distributions in the fast zone, and measurement of thermal neutron count changing with the fuel loading in the fast zone.

During the experiment, detectors were placed at the outer of polyethylene reflector and in the outer layers of the fast zone respectively. The detectors are one ^3He counter with dimensions of $\Phi 10 \times 150$mm as 1# detector, two BF_3 counter of $\Phi 65 \times 780$mm as 2# and 3# detectors and two gamma-compensated ionization chambers ($\Phi 50 \times 560$mm).The ^3He and BF_3 proportional counters were used for inverse multiplication measurement (critical approach). Gamma-compensated ionization chambers used for power monitoring. An additional detector 4 # was put in the vertex of the hexagonal fast zone (in the tenth layer) for observing neutron count trend.

The results of the preliminary experiments show that the design objectives and requirements for China's ADS sub-critical assembly Venus-1 have been fulfilled [4]:

- The effective neutron multiplication factor k_{eff} of the coupled core with a fast zone and a thermal zone is variable within a range of 0.90-0.98, hence the assembly is suitable for the study on neutron behavior of sub-critical reactor driven by an external neutron source.

- The average neutron energy is higher than 600KeV at a distance 4~36cm from the centre of the core, with the highest neutron energy at a position near the neutron source zone. The design requirement of neutron energy is satisfied. The fast zone can be used for transmutation research.
- There is a suitable space for transmuting MA in the fast neutron zone and sufficient fission for energy generation in the thermal neutron zone. There is also a epithermal neutron zone between the fast neutron zone and the thermal neutron zone and can be used for LLFP transmutation.
- The neutron importance of an external source is largest in the core center, indicating that the target for producing spallation neutrons should be placed in the core center region.
- The relative distribution of thermal neutron flux in 1-8 layers of the fast zone is very low. Whether it means a higher fast neutron flux in this region suitable for transmuting MA needs to be verified in the future. The relative distribution of thermal neutron flux in 8–10 layers is high due to the effect of thermal neutrons in the thermal zone, suitable for transmuting LLFR. Thermal neutron flux at the 10th layer (–42.5cm) is high due to the effect of the end reflector in the thermal zone. The asymmetry of axis distribution of thermal neutron flux is attributed to the end reflector mounted only at one side.
- The neutron counts of detectors at different positions vary in different ways with the loading of natural uranium fuels into the fast zone. The neutron count of detector 4# first increases to a peak value during the loading of the 1st- 6th layer of natural uranium fuel, then decreases when loading the 7-10th layer of the fuel rods. It may be explained by the effect of neutron energy of the external neutron source, as the spectrum of Am-Be steady neutron source has four peak energy, i.e. 3.5MeV, 5.0MeV, 8.0MeV and 10.0MeV, all greater than fission threshold of natural uranium (1.1MeV) and inevitably causing fast fission of U-238. While the effect of fast fission caused by Am-Be source can reach the 1st-6th layer, it becomes small in the 7th-10th layer. It has been confirmed that the effective range of fast fission caused by external source will extend with the increase of external neutron source energy. This has been done using D-T reaction source whose neutron energy is 14MeV.

Recently some experiments are performed on Venus-1 using the Cf-252 and Am-Be source as external neutron source. The relative counting rate curve vs adding layer of fuel rods are shown in fig 2.

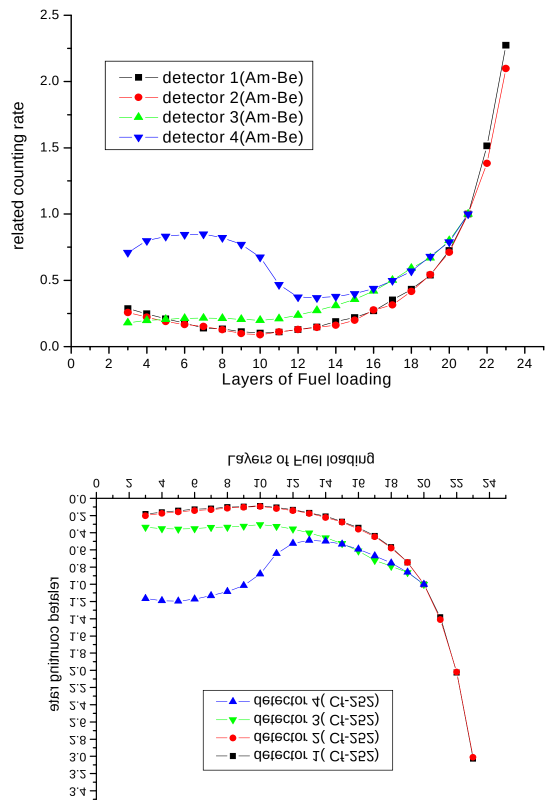

Figure 2: The relative counting rate curve vs adding layer of fuel rods with Am-Be and Cf-252 source.

4.5.3 Neutronics & Thermal-Hydraulics Technology Research of ADS –Venus 2

A conceptual design of ADS verification facility-Venus Ⅱ has been performed. The main parameters are listed in table 1.

Table 1: The Main Parameters of Venus Ⅱ.

Fuel	***Spent fuel of CARR, U3Si2-Al, 149.3kg***
Keff	0.982
Spallation Target	Solid W
Energy of Proton Beam	100MeV
Yield of spallation neutron	0.3 n/p
Beam Intensity	0.3 mA
Beam Power	30 kW
Thermal Power of the Core	200kW

A primary design of a LBE loop for thermo-hydraulic study and material study has been performed. The main parameters are listed in Table 2.

Table 2: Primary Parameters of LBE loop.

Highest Temperature	550 □
Maximum Flux	6 m^3/h（velocity 3 m/s）
Pressure	0.3 MPa
Oxygen Control	Ar＋5%H2/H2O
LBE capacity	100～150 l
Height of Loop	5 m
Experimental Segment	2
Height of Segment	1.5～2 m
Velocity of Flux	1 m/s
Temperature Difference	100 □

4.5.4 Intense Proton Ion Source

An electron cyclotron resonance (ECR) ion source[5] is selected for the source of our verification facility system. The microwave power generated by a 2.45 GHz-1 kW magnetron is coupled into the copper chamber (54 mm ×72 mm in cross section and 36 mm long) through a three stub tuning unit and ridged wave guide. Inside the chamber, a ϕ54 mm in diameter quartz tube which is tightly fixed by a BN disk and plasma electrode is placed to confine the plasma. A BN plate is placed between the ridged waveguide and plasma chamber to separate the plasma and vacuum. Three holes are made on the waveguide to evacuate the wave guide after the microwave window; with this configuration the gas in the waveguide can be evacuated quickly to avoid interfering with the discharge. The microwave window for vacuum sealing is placed behind a bent section in order to avoid any damage due to the back streaming electrons. The microwave system including its power supply is placed on the 75 kV high voltage platform.

A 90 mA hydrogen beam can be routinely extracted from a ϕ6.5 aperture of the source. The emittance of the extracted beam is measured by multi-slits and single thread emittance-measuring unit. The measured emittance of the total beam at 90 mA, 60 kV, 50 cm downstream of the ion source is 0.129π mm·mrad. At a specific extraction distance, an adequate extraction voltage always can be found for various beam currents to obtain minimum emittance. The proton ratio is measured by analyzing a portion of the beam with a mini-deflection magnet. The result shows that proton fraction is more than 80% which satisfies the requirement of the system. The proton fraction slightly varies with the changes of microwave power but no significant effect is found.

4.5.5 RFQ Accelerator Study

The structure of RFQ is a four-vane type and designed to accelerate 50 mA peak current of proton beam with input energy of 80 kV. In the preliminary research phase, the 352.2 MHz RF system will be operated in pulse mode. CERN kindly provided IHEP with some RF equipment. Because the given RF system was used for CW operation at CERN before, to apply them to our pulse mode operation, some modifications and improvements are necessary. We have made some indispensable assemblies, and also did some tests and commissioning of every sub-system. For example, we have finished the 100 kV power supply test and long pulse floating desk hard tube modulator test.

Furthermore, the initial high power condition of the klystron is carried out, and output power can reach up to 800 kW.

The fabrication of the RFQ copper model was done by a company in Shanghai, China. At first, some tests for development the mechanical technology had to be done, for example, the brazing technology for assembling four vanes together with required mechanical tolerance, the characteristics of melting filler, the structure surface and the vacuum leak; the drilling of the coolant hole through the 1.2 m RFQ cavity with 12 mm in diameter; the precision machining of the vane electrodes on the numerical controlled mill. The fabrication of the RFQ was finished last year.

After setup of the ion source, the LEBT and RFQ, we started RFQ beam commissioning on 7 July, 2006. We immediately got a beam of 20 mA from RFQ with a transmission rate of about 60%. After a few days, a 41 mA beam comes from the RFQ and the transmission rate reaches 92%. The duty factor is 15% at the beginning of 2009.

4.5.6 ADS Related Nuclear Data

The new nuclear reaction theoretical models code MEND, which can give all kinds of reaction cross sections and energy spectra for six outgoing light particles (neutron, proton, alpha, deuteron, triton, and helium), gamma and recoil nuclei in the energy range up to 250 MeV, is being developed. The incident particle can be neutron, proton, alpha, deuteron, triton and helium. A program[6] for automatically searching optimal optical potential parameters in E <300 MeV energy region has been developed. By this code the best optical potential parameters can be searched automatically to fit with relevant experimental data of total cross sections, nonelastic scattering cross sections, elastic scattering cross sections and elastic scattering angular distributions. The nuclear data evaluation method has been developed for ADS. According to the experimental data of neutron-induced reactions, and theoretical model calculation codes UNF[7], ECIS and DWUCK, all cross sections of neutron induced reaction, angular distributions, double differential cross sections for neutron, proton, deuteron, triton, helium and alpha emission, γ-ray production cross sections and γ-ray production energy spectrum are calculated and evaluated at incident neutron energies from 10^{-5} eV to 20 MeV. Since the recoil effect is taken into account, the energy for whole reaction processes is balance. Nuclei have been evaluated as follow: $^{28,29,30}Si$, $^{50,52,53,54,nat}Cr$, $^{54,56,57,58,nat}Fe$, $^{90,91,92,94,96,nat}Zr$, ^{93}Nb, $^{112,114,115,116,117,118,119,120,122,124,nat}Sn$, $^{180,182,183,184,186,nat}W$[8], $^{204,206,207,208,nat}Pb$[9], ^{209}Bi, ^{232}Th, $^{233,234,235,238}U$[10] etc. By using advanced nuclear models that account for details of nuclear structure and the quantum nature of the nuclear scattering. The nuclear data are calculated and evaluated for both incident neutrons and incident protons at incident neutron energy from 20 to 250 MeV as follow: ^{27}Al, ^{30}Si, $^{50,52,53,54}Cr$, $^{54,56,57,58}Fe$, $^{90,91,92,94,96}Zr$, $^{180,182,183,184,186}W$, ^{181}Ta, $^{204,206,207,208}Pb$, and at incident proton energy from threshold energy to 250 MeV as follow : $^{54,56,57,58}Fe$[11], $^{180,182,183,184,186}W$, $^{204,206,207,208}Pb$, ^{209}Bi.

4.5.7 ADS Related Target Physics

The calculations for the standard thick target were made using different codes. The simulation of the thick Pb target with a length of 60 cm, diameter of 20 cm bombarded with 800, 1000, 1500, and 2000 MeV energetic proton beam was carried out. The yields and spectra of emitted neutron were studied. The spallation target was simulated by

SNSP, SHIELD, DCM\CEM (Dubna Cascade Model \Cascade Evaporation Mode), and LAHET codes[12,13]. The neutron yields calculated by SHIELD and DCM\CEM were in agreement within ±10%.

4.5.8 Material Development for ADS Beam Window

Three heats of 9Cr2WVTa steel have been smelted. The mechanical properties of the smelted 9Cr2WVTa steel have been investigated. It indicates that the C and Mn content as well as the heat treatment technologies affect the mechanical properties, therefore, the optimum element content and heat treatment technologies will be the key issues for the improvement of the 9Cr2WVTa steel. This research is being performed at moment. In order to get the martensitic structure and increasing its mechanical properties, the quenching treatment was performed. It can be seen that the black dots in the matrix increases when an increase in tempering temperature occurs, this may result from the increase of carbides with an increase of the temperature. There are little carbides in the matrix without tempering. The measurement results of the micro-hardness indicate that the hardness decreases with an increase of the tempering temperature, it may results from the dissolution of the martensitic under the increasing of the temperature.

Under the help of SCK and Brasimone, a few pieces of 9Cr2WVTa, 316LN and 12CrWTi have been tested in liquid Pb-Bi or liquid lead.

4.5.9 ADS Related Material Compatibility Study

The compatibility study is focused on the compatibility tests for the tungsten with water and sodium [14]. The compatibility tests for the forging tungsten with coolants have been performed in sodium at 500, 600 and 700 ℃, and in water at 100 ℃. The results show that a compact W_xO_y film was formed at the surface of the tungsten, its thickness is about 1–2 μm. There are also corrosion product Na_2WO_4 on the surface of the specimens, the amount of Na_2WO_4 dependents on the temperature and the oxygen content in the sodium. After test for more than 400 h, the matrix of tungsten has not been attacked further by sodium and oxygen resulting from the protection of the W_xO_y film, the thickness of W_xO_y film and the weight loss become a constant. For the corrosion of the tungsten in water, a W_xO_y film at the specimen surface was formed at the beginning of the test, its thickness is about 0.8 μm. This film is porous and loose, and they peeled off after test for more than 100 h. The new oxide film was not formed again because of the lack of the oxygen, the weight loss of the specimens is near a constant.

4.5.10 ADS Related Material Radiation Effects Study

The spallation neutron source system is one of the three key parts of ADS, which provides source neutrons of about 10^{18} n/s for the burning of fuels. It is composed of the target and beam window. Stainless steels and tungsten are important candidate materials of the beam window and spallation neutron source target. They are irradiated by high-energy and intense protons and neutrons during operation. The accumulated dose could reach a couple of hundred dpa per year, and radiation damage is very severe in them.

The radiation damage study of the spallation target and beam window materials is of great importance for the understanding of the lifetimes and safe operation of the ADS. Dependence of radiation damage in the modified 316L stainless steel has been investigated on irradiation temperature from room temperature to 802 ^{o}C at 21 and 33 dpa and on irradiation dose up to 100 dpa at room temperature by the heavy ion irradiation simulation and positron annihilation lifetime techniques[15]. A radiation swelling peak was observed at about 580 ^{o}C where the vacancy cluster contains 14 and 19 vacancies and has an average diameter of 0.68 nm and 0.82 nm, respectively for the 21 and 33 dpa irradiations. It can be seen that before the peak temperature, the variation of positron lifetime τ_2 with irradiation dose increases with the increase of irradiation temperature. The higher the irradiation temperature, the larger the increase of lifetime τ_2 with irradiation dose. This indicates that the radiation damage depends on irradiation temperature more sensitively than on irradiation dose.

Before this experiment, radiation damage and its detailed thermal annealing behavior in α-Al_2O_3 irradiated at the equivalent dose, respectively, by 5.28×10^{16} cm^{-2} 85 MeV ^{19}F ions and by 3×10^{20} cm^{-2} $E_n \geq 1$ MeV neutrons have been investigated by the positron annihilation lifetime technique[16]. The experimental results show that all the positron annihilation parameters of lifetime and intensity in the heavy ion irradiated α-Al_2O_3 are in good agreement with the ones in the neutron irradiated α-Al_2O_3, and verify that heavy ion irradiation can well simulate neutron (proton) irradiation.

4.5.11 Conclusion

For long term and sustainable nuclear energy development, the ADS is an option in fuel circulation and energy generation. The ADS development has been started with a rather moderate project in China and it is still in the early stage. The goal for our ADS research is to establish the scientific and technological foundation for the future development of the ADS research step by step.

4.5.12 Acknowledgements

The ADS research is supported by the China Ministry of Science and Technology (MOST) (Grant No. TG1999022600 and 2007CB209900).

4.5.13 Reference

1. Xia Haihong, et al, “The Summary of Researches on ADS in China”, Frontiers of Energy and Power Engineering in China - Selected Publications from Chinese Universities, Vol 1, No. 2, 2007.
2. Xia Haihong, “The Summary of Researches on ADS in China”, Proceeding of the 39th IAEA TWG-FR Annual Meeting, Beijing, 2006.
3. Zhao Zhixiang, et al, “The Progress of Researches on ADS in China”, Engineering Sciences, Vol 5, No. 4, 2007.
4. SHI Yongqian, et al, “China ADS Sub-critical Experimental Assembly – Venus-1 and Preliminary Experiment”, Frontiers of Energy and Power Engineering in China - Selected Publications from Chinese Universities, Vol 1, No. 2, 2007.
5. Cui Baoqun, et al, “A high intensity microwave ion source for high current RFQ”, REVIEW OF SCIENTIFIC INSTRUMENTS , 2004, 75.

6. Shen Qingbiao, "APMN—A program for automatically searching optimal optical potential parameters in E<300 MeV Energy region", Nucl Sci Eng, 2002, 141: 78.
7. Zhang Jingshang, "UNF code for fast neutron reaction data calculations", Nucl Sci Eng, 2002, 142: 207.
8. Yinlu Han, et al , "Calculation and Analysis of n + 180,182,183,184,186,natW Reactions in the En ≤250 MeV Energy Range", Nucl Sci Eng, 2007, 157, 78.
9. Han Yinlu, "Double differential cross sections of light—charged particle emission for n + 208Pb reaction", Annals of Nuclear Energy, 2008, 35, 187–195.
10. Han Yinlu, "Theoretical Calculations of n + 232,234,236,238,240U Reaction Cross Sections", Nucl. Sci. Eng., 2008, 158, 78.
11. Yinlu Han, et al, "Calculation and evaluation of cross—sections for p+54,56,57,58,natFe reactions up to 250 MeV", Nucl. Instr. & Meth., B, 2007, 265, 461—473.
12. S. Fan, J. Rong, Z. Zhao, "The Fragment Distribution of Nb, Au, and Pb from Proton-Induced Reactions with Energies Ranging from 100 MeV to 3 GeV", Nuclear Science and Engineering, 2003, 144.
13. S. Fan, Z.Zhao, "Study properties of the neutron production target induced from 150 MeV incident proton energy for the China ADS", Nuclear Science and Engineering, 2001, 139.
14. Yong-li Xu, Bin Long, Yuan-chao Xu, Hua-qing Li, "Investigation of the Compatibility Between Tungsten and High Temperature Sodium", Journal of Nuclear Materials, 2005, 343.
15. Shengyun Zhu, Yongnan Zheng, et al, "Temperature and dose dependence of radiation damage in modified stainless steel", Journal of Nuclear materials, 2005, 343
16. S.Zhu, Y. Xu, et al, "Experimental Verification of Heavy Ion Irradiation Simulation", Mordern Physics Letters B, 2004, 18.

4.6 Project on Accelerator-Driven Subcritical System (ADSR) Using FFAG Accelerator and Kyoto University Critical Assembly (KUCA)

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Abstract

The Research Reactor Institute of Kyoto University started the KART (Kumatori Accelerator-driven Reactor Test facility) project in fiscal year 2002 under the Contract with the Ministry of Education, Culture, Sports, Science and Technology of Japan and in March of 2009, the first experiment of ADSR with KUCA has been successfully carried out. The purpose of this research project is to demonstrate the basic feasibility of accelerator-driven system (ADS), studying the effect of incident neutron energy on the effective multiplication factor in a subcritical nuclear fuel system. For this purpose, a variable-energy FFAG (Fixed Field Alternating Gradient) accelerator complex was developed and constructed, and coupled with the Kyoto University Critical Assembly (KUCA).

4.6.1 Introduction

In FY2002, Kyoto University Research Reactor Institute (KURRI) started a new five year research project "Research and Development for an Accelerator-Driven Subcritical System Using an FFAG Accelerator" as part of the R&D Project on Innovative Nuclear Energy Systems which the Ministry of Education, Culture, Sports, Science and Technology (MEXT) started from FY2002 to give financial supports for the promotion of such R&D's. In this project, an FFAG (Fixed Field Alternating Gradient) proton accelerator complex would be constructed with the Kyoto University Critical Assembly (KUCA) to form an accelerator-driven subcritical reactor (ADSR) and to investigate basic characteristics of ADSR. [1]

On March 4th, 2009, the world's first injection of spallation neutrons generated by the high-energy proton beams into a reactor core was successfully accomplished. By combining the Fixed Field Alternating Gradient (FFAG) accelerator (Fig. 1) with the A-core (Fig. 2) of the Kyoto University Critical Assembly (KUCA), a series of Accelerator-Driven System (ADS) experiments was carried out under the condition that the spallation neutrons were supplied to a subcritical core through the injection of 100 MeV protons onto a tungsten target, whose size was 80 mm diameter and 10 mm thickness. In these experiments, the proton beams from the FFAG accelerator were 30 Hz repetition rate and 10 pA current. A level of the neutron intensity generated at the tungsten target was around 1×10^6 s^{-1}. The objective of these experiments was to conduct a feasibility study on ADS to develop an innovative nuclear reactor for a high performance transmutation system with the capability of power generation or for a new neutron source for the scientific research.

Figure 1: FFAG proton accelerator complex for ADSR experiment at KURRI.

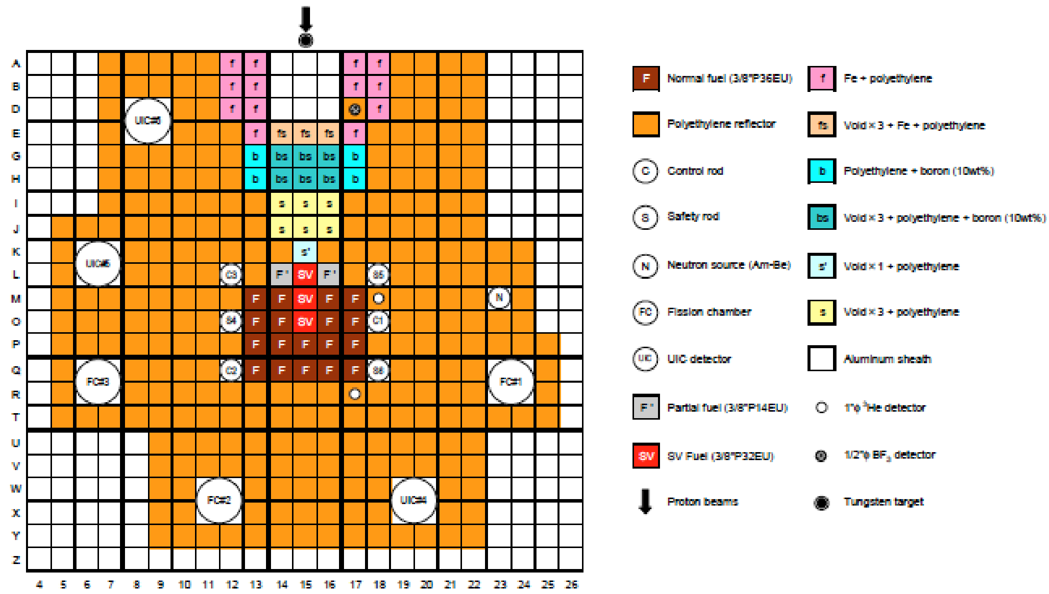

Figure 2: Top view of the configuration of A-core of KUCA in the ADSR experiments with 100 MeV protons

4.6.2 FFAG Accelerator

The accelerator complex is composed of three FFAG rings; injector, booster, and main ring. [2] The specifications of the each FFAG are summarized in Table 1. As a first stage, the accelerator complex has been planned to output 100 MeV / 0.1 nA proton beams.

The proton beams of 120 keV are accelerated in the injector FFAG betatron, called IONBETA. The IONBETA is composed of eight spiral sector magnets, two acceleration gaps, and electric septa for injection and extraction, respectively. The field distribution in the radial direction can be controlled by trim-coils, and which makes variable energy acceleration possible. Maximum beam energy is 2.5 MeV in design. We have accomplished the acceleration of proton beams up to 1.5 MeV in the IONBETA. The average output current is about 10 nA. Betatron tunes are also variable by the trim-coils. We are experimentally investigating fast integer-resonance crossing with the IONBETA. The first experiment showed that the integer resonance was successfully crossed when the crossing speed was high enough.

The booster FFAG adopts multi-turn beam injection using horizontal space, by a couple of bump magnets, an electrostatic septum (ES) and a pulse-magnetic septum (MS). Captured beam current is about 1~3 nA with 59 Hz repetition rate. Fast longitudinal matching with bunch rotation method was tried. In a rapid-cycling accelerator, adiabatic capture cannot be used, because it essentially requires long capture time compared to the period of the synchrotron oscillation. In the booster FFAG, the accelerating time is about 7 ms, while the synchrotron period is 0.1 msec. In the bunch rotation method, the accelerating bucket was rapidly produced after 1/4 synchrotron oscillation in a waiting bucket. The bunch length and the momentum spread after the rotation was controlled by the capture rf voltage. Saw-tooth rf was employed in order to minimize the filamentation. One advantage of this method is that the longitudinal beam loss is suppressed. In addition, the longitudinal emittance is kept small and momentum spread of an extracted beam is improved. With the bunch rotation, the quadrupolar synchrotron oscillation could be minimized and the extracted beam intensity increased at least three times. Final beam energy was estimated to be 11.6 MeV by the revolution frequency and the circumference. Horizontal and vertical betatron tunes were measured in the booster FFAG. Horizontal coherent betatron oscillations were excited by rf-modulation, and vertical ones were excited by a beam perturbing electrodes. The measured tunes agreed the designed ones. A rapid beam loss was observed when the current of defocusing magnets was increased. It is assumed that the beam loss was caused by the coupling resonance $\nu_x + 3\nu_y = 6$.

Proton beam of 11.6 MeV was injected in the main ring. The magnetic material in the straight section gathers the fringing field nearby, and thus distorts the closed orbit. The main source of the closed orbit distortion (COD) is the rf cavity, which is covered by a magnetic shield to protect the core from the fringing field. In order to correct the COD, a couple of correction magnet is put on both sides of the accelerating gap. The injected beam is kicked into the closed orbit by an electrostatic septum (ES) and a magnetic kicker (KCRI). The circulating beam was picked up by an electrostatic bunch monitor (BMON) in the main ring. The beam loss right after injection is assumed to be caused by horizontal aperture, which is limited by the ES. One method to increase the intensity is the beam injection without ES. In such case an additional kicker is necessary. The betatron-phase advance between the kickers is 550 deg, so that the kickers work on phase. This means that the strength of them is complementary. The beam was accelerated with the rf gap-voltage of 2.5 kV and the synchronous phase of 30 degree. A rapid beam-loss was observed at 4 ms at 20~25 MeV. The beamloss is related to $\nu_x - 2\nu_y = 1$. The beam-loss will be cured by putting locally additional yokes at the orbit. Accelerated beams after the beam-loss were observed by a radial probe with high-sensitivity fluorescent screen at its head. Beam energy can be estimated by the revolution frequency or the orbit radius, using scaling rule with k = 7.5. The injected beam energy was 11.6 MeV, capture frequency 1591.84 kHz, and measured beam position was 4430 mm at injection energy. The maximum orbit radius was measured by the fluorescent monitor, with changing rf frequency.

The beam was successfully accelerated up to 100MeV, which was the energy expected for the first ADSR experiment, and extracted and transported to the KUCA core. The beam current at the target placed in the KUCA core was about 10pA.

Table 1: Specifications of FFAG accelerator complex for ADSR

	Injector	Booster	Main Ring
Focusing	Spiral, 8 cells	Radial, 8 cells	Radial, 12 cells
Acceleration	Induction	RF	RF
Field index, k	2.5	4.5	7.5
Energy (Max)	0.1-2.5 MeV	2.5-20 MeV	20-150 MeV
Pext/Pinj	5.00(Max)	2.84	2.83
Ave. orbit radius	0.60-0.99 m	1.42-1.71 m	4.54-5.12 m

4.6.3 First ADSR Experiment

The A-core employed in the ADS experiments was essentially a thermal neutron system composed of a highly enriched uranium fuel and the polyethylene moderator/reflector. [3] In the fuel region, a unit cell is composed of a 93% enriched uranium fuel plate 1/16” thick and polyethylene plates 1/4” and 1/8” thick. In these ADS experiments, three types of fuel rods designated as the normal, partial and special fuel were employed. From the reason of the safety regulation for KUCA, the tungsten target was located not at the center of the core but outside the critical assembly, and an outside-location was similar to the previous experiments [4,5,6] using 14 MeV neutrons. As in the previous ADS experiments with 14 MeV neutrons, the introduction of a neutron guide and a beam duct is requisite to lead the high-energy neutrons generated from the tungsten target to the center of the core as much as possible. The detailed composition of the normal, partial and special fuel rods, the polyethylene rod, and the neutron guide and the beam duct was described in Refs. 4-6.

To obtain the information on the detector position dependence of the prompt neutron decay measurement, the neutron detectors were set at three positions shown in Fig. 2: near the tungsten target (Position of (17, D)) experimentally confirmed by observing the time evolution of neutron density in ADS: an exponential decay behavior and a slowly decreasing one, respectively. These behaviors clearly indicated the fact that the neutron multiplication was caused by an external-source: the sustainable nuclear chain reactions were induced in the subcritical core by the spallation neutrons through the interaction of the tungsten target and the proton beams from the FFAG accelerator. In these kinetic experiments, the subcriticality was deduced from the prompt neutron decay constant by the extrapolated area ratio method. The difference of measured results of 0.74% Δk/k and 0.61% Δk/k at the positions of (17, R) and (18, M) in Fig. 2, respectively, from the experimental evaluation of 0.77% Δk/k, which was deduced from the combination of both the control rod worth by the rod drop method and its calibration curve by the positive period method, was within about 20%. Note that the subcritical state was attained by a full insertion of C1, C2 and C3 control rods into the core.

Thermal neutron flux distribution was estimated through the horizontal measurement of $^{115}In(n, \gamma)^{116m}In$ reaction rate distribution by the foil activation method using an indium (In) wire of 1.0 mm diameter. The wire was set in an aluminum guide tube, from the tungsten target to the center of the fuel region (from the position of (13, 14 – A) to that of (13, 14 – P); Fig. 2), at the middle height of the fuel assembly. The experimental and numerical results of the reaction rates were normalized using an In foil (20×20×2 mm^3) emitted by $^{115}In(n, n')^{115m}In$ at the target. In this static experiment, the subcritical state (0.77% Δk/k) was also attained by the full insertion of C1, C2 and C3 rods. The numerical calculation was executed by the Monte Carlo multi-particle transport code MCNPX [7] on a nuclear data library ENDF/B-VII. [8] The generation of the spallation neutrons was included in the MCNPX calculation bombarding the tungsten target with 100 MeV proton beams. Since the reactivity effect of the In wire is considered to be not negligible, the In wire was taken into account in the simulated calculation: the reaction rates were deduced from tallies taken in the In wire setting region. The result of the source calculation was obtained after 2,000 active cycles of 100,000 histories, which led the statistical error in the reaction rates of less than 10%. The measured and the calculated reaction rate distributions were compared to validate the calculation method. The calculated reaction rate distribution (Fig. 3) agreed approximately with the experimental results within the statistical errors in the experiments, although these experimental errors were rather larger than those of the calculations. These larger errors in the experiments were attributed to the current status of the proton beams, including the weak beam intensity and the poor beam shaping at the target.

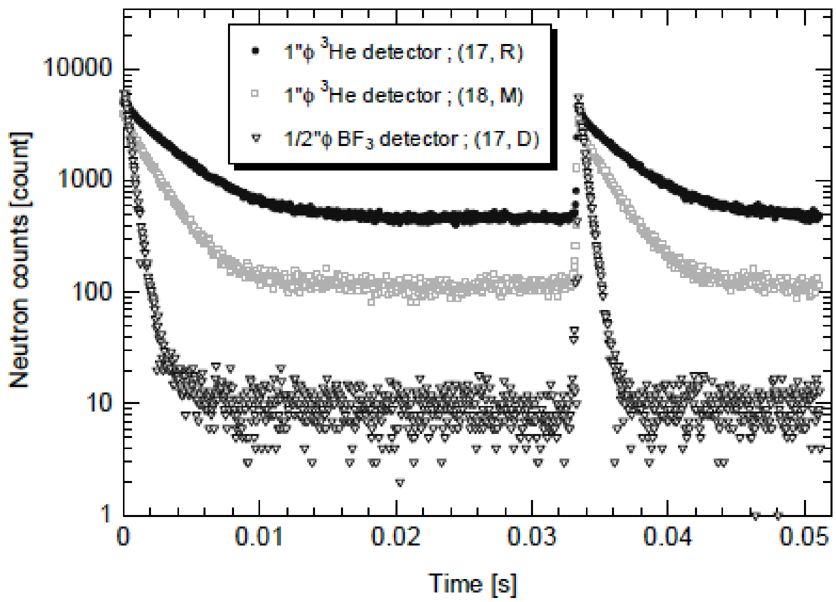

Figure 3: Measured prompt and delayed neutron behaviors obtained from BF_3 and ^{3}He detectors in the A-core in Fig. 2.

4.6.4 Conclusions

The world first injection of spallation neutron generated by the high-energy proton beams from FFAG proton accelerator into a reactor core was successfully accomplished. Various data concerning reactor physics, although in the preliminary stage, have been obtained from this experiment. For the FFAG accelerator, a beam upgrading is still under way to realize the stable beam characteristics, including the beam intensity and the beam shaping. Since the final objective is to carry out the ADS experiments with 150 MeV protons generated from the FFAG accelerator, the present results could be expected to be useful for the further researches and development of ADS at KUCA in the fields of both the reactor physics experiments and the nuclear design calculations

4.6.5 References

1. K.Mishima et al, "Research Project on Accelerator-driven Subcritical System Using FFAG Accelerator and Kyoto University Critical Assembly", J. Nucl. Scie. Technol., **44**, 499(2007).
2. Y. Mori, “Development of FFAG accelerators and their applications for intense secondary particle production”, Nucl. Instrum. Methods, **562** , 591, (2006).

3. C.H.Pyon et al., “First Injection of Spallation Neutrons Generated by High-Energy Protons into the Kyoto University Critical Assembly” J. Nucl. Scie. Technol. rapid communication, (2009). (in print)
4. C. H. Pyeon, H. Shiga, T. Misawa et al.Äi0, “Reaction rate analyses for an accelerator-driven system with 14 MeV neutrons in the Kyoto University Critical Assembly,” J. Nucl. Sci. Technol., (2009). (in print)
5. C. H. Pyeon, M. Hervault, T. Misawa et al., “Static and kinetic experiments on accelerator-driven system with 14 MeV neutrons in Kyoto University Critical Assembly,” J. Nucl. Sci. Technol., **45**, 1171 (2008).
6. C. H. Pyeon, Y. Hirano, T. Misawa et al., “Preliminary experiments on accelerator-driven subcritical reactor with pulsed neutron generator in Kyoto University Critical Assembly,” J. Nucl. Sci. Technol., **44**, 1368 (2007).
7. MCNPX User’s Manual, Version 2.4.0., LA-CP-02-408, Los Alamos National Laboratory (2002).
8. M. B. Chadwick, P. Oblozinsky, M. Herman et al., “ENDF/B-VII.0 next generation evaluated nuclear data library for nuclear science and technology,” Nucl. Data Sheets, **107**, 2931 (2006).

5 Workshop and Conference Reports

5.1 ICFA Beam Dynamics Panel Meeting Minutes

Weiren Chou, Fermilab, and Rohan Dowd, Australian Synchrotron
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There was an ICFA Beam Dynamics Panel meeting on May 6, 2009 from 18:00 to 20:30 in the Waddington Room, Fairmont Hotel in Vancouver, Canada during PAC09. Thirty-one people attended, including 16 panel members or their representatives, 11 from another ICFA panel, the Advanced and Novel Accelerators Panel, and 4 guests. They are listed in Appendix 1. The meeting agenda is in Appendix 2.

The meeting was chaired jointly by Weiren Chou, head of the Beam Dynamics Panel, and Matsuru Uesaka, head of the Advanced and Novel Accelerators Panel. It took the form of a working dinner, kindly sponsored by the Fermi Research Alliance LLC. It was the first joint meeting between the two ICFA panels and proved to be stimulating, productive and mutually beneficial.

After introductions, each of the three new panel members made a few remarks: Rick Baartman from TRIUMF, Wolfram Fischer from BNL and Mark Palmer from Cornell University.

Marica Biagini, new leader of the circular e+e- collider working group, gave a presentation. She had just finished editing No. 48 of the ICFA Beam Dynamics Newsletter, published in April 2009. This issue was dedicated to e+e- colliders – past, present and future. She received 27 articles and the issue is nearly 300 pages long, indicating the strong worldwide interest in this topic. She planned to update the working group website, which has not been done since 2006.

There was a discussion about the *World Accelerator Catalog Project*, which began several years ago but experienced difficulties in being completed. The goal was to have a web-based accelerator catalog, open to the public and maintained by designated contact persons in each accelerator laboratory. The panel chair received a list of designated contact persons from most laboratories. However, the difficulty came from the lack of technical support from database experts. The attempt was made to seek such support from laboratories but there is no agreement at this time.

Weiren Chou gave a report on panel activities over the past two years. The Panel organized a number of workshops and published six newsletters. It helped the ILC GDE organize the Linear Collider Schools and helped SCOPE promote Open Access publication of HEP journals. A complete archive of the newsletters is available online. A suggestion was made to add the theme section title under the links in the archive.

Matsuru Uesaka gave a report on behalf of the Advanced and Novel Accelerators Panel. There was a Compton Sources Workshop in 2008 in Italy. There will be a Laser and Plasma Accelerator Workshop in 2009 in Greece and a joint workshop with the Beam Dynamics Panel on high brightness electron beams in 2009 in Hawaii. The Advanced and Novel Accelerators Panel will publish its own newsletter. The first issue will be on ERL and edited by R. Hajima.

Yoshiharu Mori gave a report on a successful ADS experiment at KURRI. A proton beam line connecting an FFAG accelerator and a nuclear reactor was built and the neutrons generated by protons hitting a tungsten target in front of the reactor were observed and studied. This was a low power experiment (~1 W) but provides valuable information for future larger ADS experiments.

Chuang Zhang gave a report on the planning of the *2009 International Accelerator School for Linear Colliders*. It will take place from September 7-18, 2009 at the Jixian Hotel at Huairou near Beijing, China. The IHEP will host this school. The program includes the ILC, CLIC and the muon collider. There will be 70 students from all over the world. The school received sponsorship from a number of funding agencies and institutions, including several from China: CAS, CCAST and NSFC.

The meeting received two "full" new workshop proposals – *FLS2010* in March 2010 at SLAC, and *Ecloud 2010* in October at Cornell, both of which require ICFA endorsement – and several preliminary mini-workshop proposals: one on beam-beam interactions and another on compact secondary particle sources. These mini-workshops only require panel endorsement but their dates and places are yet to be determined.

The meeting decided the newsletter editors for the next two years. They are:

- No. 50 December 2009 – J. Urakawa (KEK)
- No. 51 April 2010 – S. Chattopadhyay (Cockcroft)
- No. 52 August 2010 - W. Fisher (BNL)
- No. 53 December 2010 - R. Baartman (TRIUMF)
- No. 54 April 2011 – J. Gao (IHEP)
- No. 55 August 2011 - M. Palmer (Cornell)

There was discussion about a page limit for the newsletter because of concerns about printing and mailing costs when the newsletter becomes too long. It was agreed that as long as the quality is maintained, there should not be any page limit. It will be the editor's decision how long a newsletter should be.

The next panel meeting will be during IPAC 2011 in Spain.

Appendix 1: List of Participants

ICFA Beam Dynamics Panel members

Rick Baartman (TRIUMF)
Marica Biagini (LNF-INFN)
Susan Smith (ASTeC, representing Swapan Chattopadhyay)
Weiren Chou (Fermilab)
Wolfram Fischer (BNL)
Miguel Furman (LBNL)
Jie Gao (IHEP)
Oliver Boine-Frankenheim (GSI, representing Ingo Hofmann)
Tor Raubenheimer (SLAC, representing Kwang-Je Kim)
In Soo Ko (POSTECH)
Yoshiharu Mori (KURRI)
Mark Palmer (Cornell Univ.)
Chris Prior (RAL)
Junji Urakawa (KEK)
Chuang Zhang (IHEP, representing Jiuqing Wang)
Rainer Wanzenberg (DESY)

ICFA Advanced and Novel Accelerators Panel members

Ilan Ben-zvi (BNL)
Ryoichi Hajima (JAEA)
Dino Jaroszynski (Strathclyde Univ.)
Wim Leemans (LBNL)
Patric Muggli (USC)
Akira Noda (Kyoto Univ.)
James Rosenzweig (UCLA)
Siegfried Schreiber (DESY)
Mitsuru Uesaka (Tokyo Univ.)
Bas van der Geer (Einphoven, representing Tom Luiten)
Wenhui Wang (Tsinghua Univ., representing Chuanxiang Tang)

Guests

Alex Chao (SLAC)
Rohan Dowd (Australian Synchrotron, Newsletter Regular Correspondent)
Liu Lin (LNLS Brazil, Newsletter Regular Correspondent)
Yuhong Zhang (Jlab, Newsletter Archivist)

Appendix 2: Meeting Agenda

1.	Round table introduction	All
2.	From new panel members	R. Baartman W. Fischer M. Palmer
3.	From the leader of the e+e- collider working group	M. Biagini
4.	FLS 2010	T. Raubenheimer
5.	Report from the Beam Dynamics Panel	W. Chou
6.	Newsletter and newsletter editors	All
7.	Report from the Adv. and Novel Accel. Panel	M. Uesaka
8.	First “accel. + reactor” experiment for ADS	Y. Mori
9.	2009 Int. Accel. School for Linear Colliders	C. Zhang
10.	New workshop and mini-workshop proposals	All

11. Any other business

5.2 ICFA Mini-Workshop on Novel Concepts for Linear Accelerators and Colliders

Tor Raubenheimer, SLAC
Mail to: tor@slac.stanford.edu

Electron-positron linear accelerators are used in many accelerator facilities as radiation sources, injectors, or colliders. Over the last few decades the advanced accelerator R&D programs have developed many novel approaches. These include new methods of acceleration such as beam-driven microwave high gradient acceleration and laser and beam-driven dielectric and plasma acceleration. Other potentially evolutionary techniques include high brightness particle sources, novel phase space damping and exchange techniques and new focusing concepts.

These novel developments have many possible applications in high energy physics as well as other fields that rely on accelerator science and technology. A TeV-scale linear collider has long been recommended as the next major facility for High Energy Physics and the current plan is to use conventional superconducting technology. If these novel concepts can be successfully applied to a linear collider, they could provide greater performance and/or energy reach as well as cost savings. Given the enormous progress in advanced accelerator R&D, it is now possible to sketch self-consistent designs based on these concepts which can be used to guide R&D towards a future multi-TeV linear collider.

This workshop focused on understanding the implications of the different concepts and technologies with a goal of developing self-consistent accelerator parameters and specifying the R&D programs needed for further progress.

There were six Working Groups:

1. Microwave structure-based linacs (Toshiyasu Higo, Sami Tantawi, Walter Wuensch)
2. Dielectric structure-based linacs (Eric Colby, James Rosenzweig)
3. Plasma-based linacs (Mark Hogan, Carl Schroeder)
4. Injector and beam manipulation concepts (John Power, John Sheppard)
5. Collimation & Focusing concepts (Tomas Rogelio, Andrei Seryi)
6. Cost Optimization and future R&D priorities (Jean-Pierre Delahaye, Tor Raubenheimer)

The goals for the first three groups were to: (1) develop self-consistent sets of parameters aimed at a desired energy and luminosity, (2) list critical R&D for the acceleration technology and associated beam generation and focusing systems, (3) consider the fundamental limits of the technology and describe how these will be approached, and (4) consider how new concepts for beam generation, manipulation and focusing could have major impact on the designs.

The goals of the last three working groups were to: (1) understand the current options and the potential of the novel concepts, (2) identify the main R&D issues in achieving the desired parameters corresponding to the different acceleration concepts, and (3) suggest possible future R&D paths.

A number of important results were discussed or originated at the workshop including a better understanding of the different regimes for gradient and breakdown limitations, different configurations for drive beam-based plasma or dielectric accelerators, and new concepts for dielectric, plasma, and microwave linacs that may have a wide range of applications. Also, a low charge per bunch parameter set was considered for the various acceleration schemes to see it would provide any obvious cost savings.

To encourage communication between the working groups, the workshop was organized so that everybody was expected to contribute to at least two groups and only three working groups were meeting at any one time. We hope that the discussions that were started between groups continue into larger collaborative efforts. The workshop agenda and talks are posted at: http://www-conf.slac.stanford.edu/RobertSiemann/.

5.3 Workshop on Future Directions for Accelerator R&D at Fermilab

V. Shiltsev, M. Church, P. Spentzouris and W. Chou, Fermilab
http://apc.fnal.gov/ARDWS/index.html

Accelerator R&D has played a crucial role in enabling scientific discovery in the past century and will continue to play this role in the years to come. In the U.S., the Office of High Energy Physics (OHEP) of DOE's Office of Science is developing a plan for national accelerator R&D stewardship. Fermilab's accelerator research, design, and development is focused on several important proton technologies: superconducting radio frequency (RF), superconducting magnets, beam cooling, and high-intensity proton beams. In addition, the laboratory pursues comprehensive integrated theoretical concepts and simulations of complete future facilities on both the energy and intensity frontiers. At present, Fermilab:

- (i) supplies integrated design concept and technology development for a multi-MW proton source (Project X) to support international programs in long-baseline neutrino and rare-processes experiments;
- (ii) plays a leading role in the development of ionization cooling technologies required for muon-storage-ring based facilities at the energy (multi-TeV Muon Collider) and intensity (Neutrino Factory) frontiers, including integrated design concepts for these facilities; and
- (iii) carries out a program of accelerator R&D (ARD) in the field of high quality beam sources, and novel beam manipulation techniques.

Possibilities for ARD along point (iii) above, and aligned with Fermilab's underlying capabilities, were presented and discussed at the *Workshop on the Future Directions of Accelerator R&D at Fermilab*. The charge to the Workshop participants included:

1. Solicit and evaluate ideas that could be incorporated into a possible accelerator R&D program based on the ILC Test Accelerator in the New Muon Lab (NML) at Fermilab., The NML is currently under construction. The Workshop will also solicit ideas for improving and refining the current NML design to further enhance its R&D potential.

2. Solicit and evaluate advanced accelerator R&D proposals specific to enhancing the potential of ongoing and planned Fermilab R&D efforts, including Project X, the ILC, and the Muon Collider. Special emphasis should be placed on efforts that are synergistic between these programs and/or utilize currently existing or planned facilities.
3. Solicit and evaluate ideas for future accelerator applications of great potential but not yet part of the current Fermilab planned program such as medical accelerators and accelerator driven systems (ADS), including those based on the currently envisioned Project X facility.

More than 30 presentations were given over the 2.5 days of the Workshop, which was attended by 50 people from the U.S. and other countries. The workshop agenda, the list of participants, and the names of the Organizing Committee can be found at: http://apc.fnal.gov/ARDWS/index.html

5.3.1 Accelerator R&D Opportunities at the SRF Test Accelerator at the New Muon Lab (NML)

The first use of the NML facility will be to test, both with and without beam, superconducting RF cryomodules for potential use in both Project X and the ILC. A 40 MeV injector will provide an electron beam to a string of up to six 8-cell cryomodules. This injector will be capable of producing ILC-like bunch intensity (>3 nC/bunch), bunch length (<300 ps), bunch train length (3000 bunches at 3 MHz), and repetition rate (5 Hz). The cryomodule string will produce beam energy up to ~1500 MeV with beam power up to 80 KW. Initial beam operation is scheduled to begin in 2012. This facility is being built with added floor space and infrastructure to accommodate additional test beam lines at both 40 MeV and 1500 MeV to support an ARD program. In particular there will be adequate floor space in the high-energy test area to accommodate a ~10 m diameter test storage ring.

Sixteen different speakers gave presentations in three broad categories: status of other ARD facilities, overview of specific ARD research fields, and specific proposals and suggestions for experiments at NML.

More than 20 proposals and suggestions for experiments were made at this Workshop. We list and elaborate on a subset of these below. The Workshop organizers have selected these based partly on the maturity of the proposal, partly on their viability at NML, and partly on our own current interests. This list is only intended to be a sampling of the possibilities and should not be deemed part of a "selection process."

Proposal	***Motivation/Application***	***Description***
Optical stochastic cooling proof-of-principle (Valishev, FNAL)	Possible use in a muon storage ring; possible use in a heavy ion storage ring	Concept: Use a wiggler as pickup and kicker for stochastic cooling at high frequency. Requirements: ~750 MeV storage ring; λ=40 cm permanent magnet wiggler; Ti:Sa optical amplifier @ ~1 μm.
Test of integrable beam optics (Danilov, ORNL)	Possible application to Project X and future proton storage rings	Concept: Storage ring with highly nonlinear but stable betatron motion using nonlinear lenses. Requirements: >300 MeV storage ring; flexible optics; 12.5 MHz RF.

Effect of power deposition in plasma on acceleration and focusing (Muggli, USC)	Future linear collider	Concept: Measure energy change and focusing of successive bunches in a plasma. Requirements: 3.2 nC/bunch; 1.5 GeV; short bunches; 3 MHz bunch train; 20 μm spot size; 15 cm $10^{16}/cm^3$ plasma; laser for interferometry.
Study ion motion in plasma (Gholizadeh, USC)	Future linear collider	Concept: Study ion motion in plasmas due to beam passage using Frequency Domain Holography. Requirements: >2 nC/bunch; 1.5 GeV; 3 MHz bunch train; short bunches; ~20 μm spot size; 1 cm $10^{17}/cm^3$ H plasma; 500 nm laser for holography.
Test of an Image Charge Undulator (Piot, NIU)	Compact x-ray source	Concept: Study radiation from 2 parallel gratings. Requirements: High peak current; short bunches; flat beam; emittance exchange for bunch train generation.
Test wakefield acceleration in a dielectric slab structure (Piot, NIU)	Test high gradient acceleration concept; extension of AWA work	Concept: Study slab dielectric wakefields with bunch trains. Requirements: High peak current; short bunches; ~20 μm spot size; flat beam (possibly); emittance exchange for bunch train generation.
Microbunching investigations (Lumpkin, ANL)	Improve understanding of the fundamental phenomenon of microbunching; understand instrumentation effects	Concept: Compare microbunching between chicane and dogleg configuration; investigate microbunching phenomenon in regime of high charge and $60<\gamma<100$. Requirements: High peak current; short bunches; chicane and dogleg beamline configuration.
Parametric Ionization Cooling lattice (Jansson, FNAL)	μ collider	Concept: Build an electron model of a lattice suitable for μ cooling; investigate optics. Requirements: Adequate space in a high energy beamline.
Test of 6-D μ cooling (Kaplan IIT)	μ collider	Concept: One of a number of cooling concepts can be investigated in a small μ storage ring. Requirements: ~300 MeV storage ring; e → μ production target.
Continuing emittance exchange experiment (Sun, FNAL)	Development of beam manipulation procedures for broad application	Concept: Transform longitudinal to transverse emittance in a dogleg configuration and a transverse mode cavity. Requirements: Low energy test beamline with dogleg and 3.9 GHz deflecting mode cavity.
Microbunch generation from slits (Sun, FNAL)	Generation of closely spaced bunch trains for broad application	Concept: Use emittance exchange with a slit mask to generate closely spaced bunch trains. Requirements: Low energy beamline with emittance exchange setup.
Electroproduction of μ's at 1.5 GeV (Striganov, FNAL)	Improved measurement of cross section; useful for a broad range of applications	Concept: This region of μ production has not been adequately measured; incorporate results into the MARS model Requirements: μ production target; 1.5 GeV beam.
Development of a compact μ source (Striganov, FNAL)	Cargo inspection for homeland security; medical imaging	Concept: Produce a 10 MeV μ beam from 300 MeV e^- on 0.1 rad length tungsten target. Requirements: 1.5 GeV beam, μ production target; sweeping magnets; dump.
FBT and EEX tests in support of MaRIE (Carlsten, LANL)	Proof of principle experiments for beam manipulations for proposed XFEL	Concept: Test performance of various FBT and EEX lattices at ~1 GeV. Requirements: Adequate space in high-energy beamline.

NML has the potential to be the largest general user facility for Accelerator R&D in the U.S. It has the potential for both directed ARD (aimed at specific applications) and generic ARD (furthering accelerator science for potential future uses). Judging from the attendance at this Workshop, there is extensive interest from the accelerator community in performing experiments at NML. There is also broad interest from FNAL scientists in participating in these experiments. The high beam charge, short bunch length, and high repetition rate make this a unique facility. A dedicated department, with a broad range of talent, will be required to commission and operate this facility. Extensive laser expertise will be needed.

5.3.2 High Intensity Beams R&D, Collimation, and RF

In the next decade, the HEP community will explore the energy frontier by operating the Large Hadron Collider (LHC) and designing LHC accelerator complex upgrades, and by developing novel concepts and technologies necessary for the design of the next lepton collider. Members of this community will also explore the intensity frontier by designing and possibly operating high intensity proton sources for neutrino physics and precision measurements in the framework of rare process searches, and designing high intensity muon sources, neutrino factories for neutrino physics. In both cases there is a need for theoretical R&D work including simulations and concept development. This is required for understanding the limiting factors in the design of high-intensity beam accelerators, both circular and linear, and for developing and implementing mitigation techniques. Some of the most important physics processes affecting high-intensity accelerators include space-charge, electron-cloud, and impedance effects. Beam loss minimization either by possible mitigation of such effects or by collimation are essential for successful high-intensity accelerator applications.

5.3.2.1 Space-Charge Effects

The role of space charge in the context of particle loss and resonances has received adequate attention in recent years due to the increased interest in designing and operating high-intensity linear and circular accelerators. It is now accepted that space charge is not only the source of incoherent single-particle tune shifts moving particles into machine resonances, but that it can also itself drive resonant mechanisms. These resonances may be further enhanced by the free energy from beam anisotropy, and cause dilution of the phase space density and eventually cause beam loss.

Fermilab has several machines in its accelerator chain that could be used for interesting measurements. Over the past few years the focus on the Booster has been maximizing luminosity for Run II. Nevertheless, this has already provided interesting data. The Booster could become an important laboratory for studying various effects such as synchro-betatron resonance, emittance growth and halo creation, scaling laws, and possibly mitigation prescriptions such as utilization of chromaticity and higher order multipoles. In the latter case it will be interesting to study the interplay between coherent (fast losses) and incoherent effects (slow loss, halo creation). Mitigation techniques will help incoherent effects but will worsen coherent effects. It will be important to schedule dedicated study time and include beam diagnostic improvements, especially turn-by-turn information on beam shape parameters.

In addition, the Main Injector could be used for studies when the beam currents required by Project X become available. Also, a low energy electron ring at NML could provide relevant information for lifetime and space-charge measurements, as long as the energy is low enough to avoid domination by synchrotron radiation. Finally, all these studies benefit from numerical simulations. Fermilab already has a lot of experience with the development and application of simulations capable of 3D modeling of space charge and other collective effects. Continuing to develop codes that can effectively take advantage of massive computing resources and employ many physics models in the same simulation will be beneficial.

5.3.2.2 Space-Charge Compensation

Over the past decade, the electron lens, a new type of accelerator component, has been actively developed at Fermilab. It employs the strong space charge forces of a beam of low energy electrons (~10 keV), which acts on high-energy (anti) protons. The magnetic field that focuses and steers the low-energy electron has little effect on the high energy anti protons. The technology necessary for electron lens applications is proven and available at Fermilab. It uses high field (>3T) superconducting solenoids with a very uniform B-field and correctors in all transverse phase-space planes. There is the capability to generate magnetized electron beams with a variety of current distribution profiles by utilizing thermionic cathodes. It requires novel beam diagnostics, such as beam profile and beam position monitors. Currently the electron lens is being studied at the Fermilab Tevatron for its effectiveness in beam-beam compensation. Potentially it could be used for this purpose in the LHC.

It was suggested that an electron lens application could be used for space-charge compensation, but the current thinking is that a variation of the same concept, the electron column, would be more effective. In this particular application, instead of uniformly distributing a low density of electrons around the ring, a high-concentration of electrons will be used over a small fraction of the ring circumference. It is believed that this design would provide better stability of the transverse motion of the system, allow for good dynamic matching of the transverse beam charge distribution, and possibly allow for longitudinal compensation (for not-flat proton bunches).

R&D on development of electron columns is just beginning. Fermilab is well positioned to support this R&D by providing support and beam time to achieve the following goals:

a) understand and characterize electron dynamics in e-columns (at a test facility and in the Tevatron), especially tune shift and coherent instability;
b) simulate improvement of slow extraction from the Debuncher ring with e-lenses/columns under the beam conditions of the mu2e experiment;
c) develop “stand-alone” superconducting solenoid technology for use in non-superconducting accelerators (cryocoolers);
d) build an electron column or electron lens prototype for the FNAL Main Injector and perform studies with the highest available bunch intensity.

5.3.2.3 Electron Cloud

The accumulation of electrons inside an accelerator beam pipe when sufficiently strong to affect the beam dynamics in the machine is called the “electron cloud” effect. This can cause beam loss, emittance growth and increase in the vacuum pressure. It is an important effect in high-intensity accelerators, relevant to both the design of intensity and energy frontier machines. It is essential that we have a good understanding (both experimental and with simulations) of the cloud buildup and its effects on beam dynamics.

At Fermilab we have an active program on electron cloud effect studies, focused on measurement and simulations of Main Injector configurations. This is relevant to the proposed Project X upgrades that call for the machine running at 3E11 protons per bunch and 540 bunches, compared to the current operation at 1E11 per bunch and a smaller number of bunches. The simulation studies and the measurements focus on characterizing and understanding the generation of the cloud, and how it is affected by the presence of external magnetic fields and the machine fill pattern. There are a few beam dynamics studies, employing a simplified lattice description and only modeling a single bunch. On the experimental front, both retarding field analyzer (RFA) detectors and the microwave propagation technique have been used to quantify electron cloud generation in the Main Injector, with poor agreement between the two techniques so far.

The electron cloud program at Fermilab is synergistic to the necessary studies required by LARP for the proposed upgrade of the LHC proton driver, the PS2, and synergistic to the CESR-TA experimental program. Regarding the future of this program at Fermilab, recommendations include:

- coherent tune shift measurement in the Main Injector, using a witness bunch technique. Such a measurement performed at CESR-TA showed good agreement with simulation, at least for the transverse phase-space coordinates, where details of the e-cloud field were taken into account.
- continue the development and deployment of instrumentation, both RFA and microwave, and test experimentally different mitigation techniques (beam pipe coating, bunch spacing, etc).
- continue both experiment and simulation development in order to understand discrepancies between the RFA and microwave methods.

5.3.2.4 Collimation

Beam collimation is mandatory at any high-power accelerator and hadron collider. Only with a very efficient beam collimation system can we reduce uncontrolled beam losses to an acceptable level, thus protecting machine components, detectors and personnel against excessive irradiation, maintaining operational reliability over the life of the complex, providing acceptable hands-on maintenance conditions, and reducing the impact of radiation on the environment, both in normal operation and in accident conditions. Fermilab has a well-established program on the design of collimators and the development of new collimator technology, and is responsible for the design of collimation systems both for Fermilab accelerators and other laboratories. In addition, an experiment on bent crystal collimation is being conducted at the Tevatron (T-980).

In order to be able to handle the increased collimation requirements for the LHC and for future intensity and energy frontier accelerators we need to continue developing new techniques, beyond the multi-stage collimators that are the state-of-the-art today. There are already plans and ongoing R&D for the replacement of the LHC system that call for the replacement of the existing carbon composite collimators with metallic ones. There are other ideas for collimator technology evolution, such as rotating collimators, bent-crystal collimators for high-energy machines (utilizing channeling), and new multi-strip crystals utilizing volume reflection (VR). VR radiation is very similar for both e+ and e-, and has large angular acceptance, thus it makes this option a good candidate for a linear collider collimation system. In addition, active elements for tail elimination, such as octupole doublets for nonlinear tail folding, and hollow electron lens collimators are being considered for various applications.

The development of hollow electron lens systems is well suited for Fermilab because it builds on the expertise of the electron lens development for beam-beam compensation. This particular system provides a good candidate option for LHC collimation evolution:

a) an indestructible non-invasive electron beam at a smaller radius can push halo out and can be used to eliminate loss spikes due to beam shaking and increase the impact parameter of primaries;
b) halo particles as close as three sigma could be effectively removed. No material used in conventional multi-stage collimators can survive to better than 5 sigma proximity to the beam;
c) the diffusion rate of halo particles would increase, which in turn would increase the impact parameter in the primary collimators, thus increasing efficiency;
d) the increase in the impact parameter would allow for the primaries (and secondaries) to be placed at a greater number of sigmas away, decreasing the impedance contribution, an important consideration for the LHC;
e) in addition, since there is no matter-particle interaction, such an e-scraper can be just as effective with ions.

The R&D recommendations in this area of research include:

a) study the hollow e-lens and build a prototype. This includes the development of a 10-15 mm hollow beam electron gun (suitable for the Tevatron e-lens), testing it and measuring its profile, installing it in the TEL2 and operating it (during beam studies) in the DC regime. Also included is the design of the TEL2 modification with hollow cathode/collector and straight configuration for a possible test at the end of Run II and building an electron scraper for the LHC and possibly installing it there.
b) design and perform NML experiments on beam folding technique with an octupole doublet;
c) continue the T-980 crystal collimation experiment at the Tevatron through the end (or even somewhat beyond) of collider Run II. A new advanced goniometer, 3 new crystals and enhanced beam diagnostics will be installed in Summer 2009. Pursue the study of the volume reflection technique. This involves designing and performing an experiment at NML on volume reflection radiation. This is an interesting possibility for e+e- beam collimation. The potential of this technique will be studied in T-980 using the Tevatron beam;
d) a materials beam test facility, possibly using antiprotons, will be very beneficial for Project X, the neutrino factory, the muon collider and the beam requirements for ADSMW.

5.3.2.5 RF

The need for an RF unit test facility at Fermilab was discussed in depth at the Workshop. Potential tests and R&D directions at such a facility would include:

a) study of individual tuning and power distribution to utilize the maximum gradient per cavity;

b) study and optimization of HOM absorption efficiency, design and prototype absorbers for what is not absorbed, perform direct measurements in NML;
c) build and test a prototype for a cavity BPM;
d) conduct BPM measurements and compare them with EM simulations;
e) perform EM simulations of coupler and wakes;
f) design and study coupler kick reduction schemes and eventually test at NML;
g) perform low level rf studies, e.g. jitter stabilization

5.3.3 Accelerator Driven Sub-Critical Assemblies (ADS) and Medical Accelerators

5.3.3.1 ADS

Clean energy and clean environment are the two top priorities in almost all developed and developing countries including the U.S., Europe, Japan, China, India, and Korea. A sub-critical thorium reactor connected to a high power proton accelerator as an alternative energy source has received the attention of many government policy makers. Such a system has a number of important advantages:

a) In the thorium fuel cycle, there are no fuel or waste products that can be used as bomb material;
b) A sub-critical reactor is inherently incapable of causing a meltdown, i.e. it contains passive safety features;
c) Thorium does not require enrichment, which guarantees there is no proliferation risk;
d) Waste consists mostly of U^{233}, which can be recycled as fuel;
e) Waste material is radiotoxic for tens of years, as opposed to the thousands of years with today's radioactive waste;
f) Thorium exists in great abundance.

While a), c), d), and f) are advantages of thorium itself, b) and e) are possible only when an accelerator is used as the driver.

The Indian government has announced the construction of a thorium reactor. The Chinese government plans to establish a new research institute dedicated to an ADS study and considers spending as much as 2-3 billion yuans (Chinese currency, equivalent to $300-450M) for this study from 2011 through 2015. The Japanese government issued a national license to Kyoto University to conduct an ADS experiment using the KUCA reactor and an FFAG accelerator. Europe has begun the EUROTRANS project for waste transmutation, funded by the European Union's Seventh Framework Program (FP7). In the U.S. Senate, Harry Reid and Orrin Hatch introduced a bill titled "*Thorium Energy Independence and Security Act of 2009*," which proposes investing $500M to a thorium study from FY2010 through 2014.

There are four basic requirements for an accelerator to be used as an ADS driver:

1) High beam power on the order of 10 MW. For demonstration purposes, however, the requirement can be greatly relaxed. For example, for a 10 MW demonstration reactor, a 100 kW proton accelerator would suffice.
2) Medium energy: In an ADS, the accelerator acts as a spallation neutron source. A proton hits a target generating tens of neutrons, which are absorbed by Th^{232}

and transforms it to U^{233}, which is fissile. The goal is to generate the maximum number of neutrons for a given proton beam power. The yield (number of neutrons per proton) peaks at about 1 GeV (though, the peak is broad) – the energy level is attainable by either a linac or a cyclotron.

3) Remote handling: This is a difficult issue since even a small loss in a MW accelerator leads to a high radiation dose to the machine components. For instance, if a magnet fails, one must use remote handling procedures to carry out the replacement, including the water and electric connections and the RF joints. Fortunately, some laboratories such as PSI, which operates the world's most powerful cyclotron at 1.3 MW, has accrued years of experience in remote handling.
4) Extremely high reliability is the most difficult and most challenging problem in designing, constructing and operating an accelerator for ADS. The requirement was set by reactor designers, i.e., beam trips longer than 1 second cannot be allowed. This requirement is based on the effect of transients on materials (target and windows), the effect of transients on fuels, the quality of electrical power delivered to the grid, and necessary periodic maintenance. The performance of existing accelerators has a long way to go to reach this goal. For instance, the typical duration of short trips in the PSI cyclotron is about 30 seconds.

Although ADS is not yet part of the current Fermilab planned program, it is a future accelerator application of great potential. At the Workshop, we discussed forming a joint task force with Argonne Laboratory and the University of Chicago (UC). The charge to this task force would be to work out a near-term and long-term R&D program for ADS. Note, that FNAL is organizing its own Workshop on Applications of High Intensity Proton Accelerators (FNAL, October 19-21, 2009), co-chaired by S. Mishra (FNAL) and R. Gerig (ANL), see details at http://conferences.fnal.gov/App-Proton-Accelerator/.

5.3.3.2 Medical Accelerators

The discussion on medical accelerators was focused on charged particle therapy. A good reference is Volume 2 of the journal *Reviews of Accelerator Science and Technology* (RAST), which is devoted to the topic of medical applications of accelerators and is scheduled for publication in late 2009. There was also a recent hadron therapy workshop at Erice (Sicily), Italy. (http://erice2009.na.infn.it/)

The main challenge to accelerator builders is how to make hadron therapy accelerators smaller, lighter, cheaper and more flexible so that every hospital could afford one, just like x-ray machines. Recent R&D is making progress in reducing the physical size of such installations. At this moment, medical accelerators are not yet part of the current Fermilab planned program. At the Workshop, it was proposed to form an exploratory team consisting of accelerator physicists and engineers from the Accelerator Physics Center and the Accelerator and Technical Divisions with a charge to develop an R&D program for compact proton accelerators in the range of 200-300 MeV for cancer therapy. The technology should not be limited to conventional RF acceleration and magnet bending but should also explore the possibility of using an intense laser beam for proton acceleration, a new technique that has been making extraordinary progress in recent years.

5.3.4 Conclusion

In conclusion the May Workshop at Lake Geneva considered many important aspects of the future accelerator R&D program at Fermilab and provided a coherent outline of the possibilities to guide further discussion and definition of the paths to follow.

6 RECENT DOCTORAL THESES

6.1 Energy Recovery Linear Accelerator Lattice Design & Coherent Synchrotron Radiation

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Abstract:
Energy Recovery Linear Accelerators (ERLs) are potential drivers for ovel fourth-generation synchrotron light sources. An ERL combines the high quality beams of a linear accelerator with the high currents possible in a storage ring. The excessive power needs of a lone linac are avoided by circulating accelerated particles back through the linac to recover their energy. This dissertation is focused on the lattice design of a high energy ERL synchrotron light source at Cornell University. In order to illustrate general ERL requirements, a simplerdesign is also presented. The mathematics needed to describe such a machine are particular to accelerator physics, and so a separate chapter is devoted to developing all of the relevant concepts. The short bunch lengths and high bunch charges possible in an ERL can give rise to Coherent Synchrotron Radiation (CSR) which can potentially limit the operation of the accelerator. CSR is a collective phenomenon where the energy radiated at wavelengths longer than the bunch length is enhanced by the number of charges in the bunch. The final chapter develops an exact model for CSR from an infinitely thin bunch. It reveals many interesting effects, including CSR at low energies, through multiple bends in a lattice, and in bunch compression. The model is also used to obtain the limits of validity of previously known approximations. Finally, CSR is examined for the ERL designs presented.

6.2 Theses from DESY

6.2.1 Machine Protection for FLASH and the European XFEL

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Graduation Date: May 29, 2009
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Abstract:

The Free-Electron Laser in Hamburg (FLASH) and the future European X-Ray Free-Electron Laser (XFEL) are sources of brilliant extreme-ultraviolet and X-ray radiation pulses. Both facilities are based on superconducting linear accelerators (linacs) that can produce and transport electron beams of high average power. With up to 90 kW or up to 600 kW of power, respectively, these beams hold a serious potential to damage accelerator components. This thesis discusses several passive and active machine protection measures needed to ensure safe operation.

At FLASH, dark current from the rf gun electron source has activated several accelerator components to unacceptable radiation levels. Its transport through the linac is investigated with detailed tracking simulations using a parallelized and enhanced version of the tracking code Astra; possible remedies are evaluated.

Beam losses can lead to the demagnetization of permanent magnet insertion devices. A number of beam loss scenarios typical for FLASH are investigated with shower simulations. A shielding setup is designed and its efficiency is evaluated. For the design parameters of FLASH, it is concluded that the average relative beam loss in the undulators must be controlled to a level of about 10^{-8}.

FLASH is equipped with an active machine protection system (MPS) comprising more than 80 photomultiplier-based beam loss monitors and several subsystems. The maximum response time to beam losses is less than 4 μs. Setup procedures and calibration algorithms for MPS subsystems and components are introduced and operational problems are addressed.

Finally, an architecture for a fully programmable machine protection system for the XFEL is presented. Several options for the topology of this system are reviewed, with the result that an availability goal of at least 0.999 for the MPS is achievable with moderate hardware requirements.

6.2.2 Spurious Dispersion Effects at Flash

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Graduation Date: July 16, 2009
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Abstract:
The performance of the Free-Electron Laser (FEL) process imposes stringent demands on the transverse trajectory and size of the electron beam. Since transverse dispersion changes off-energy particle trajectories and increases the effective beam size, dispersion must be controlled. This thesis treats the concept of dispersion in linacs, and analyses the impact of dispersion on the electron beam and on the FEL process. It presents generation mechanisms for spurious dispersion, quantifying its importance for FLASH (Free-electron Laser in Hamburg) and the XFEL (European X-ray Free-Electron Laser). A method for measuring and correcting dispersion and its implementation in FLASH is described. Experiments of dispersion effects on the transverse beam quality and on the FEL performance are presented.

6.2.3 Investigations on the Electron Bunch Distribution in the Longitudinal Phase Space at a Laser Driven RF Electron Source for the European X-FEL

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Graduation Date: May 27, 2009
Supervisor: Prof. Jörg Roßbach

Abstract:
The Photoinjector Test facility at DESY, Zeuthen site, (PITZ) is aiming for the optimization of electron guns for SASE-FELs. For this it is necessary to investigate the characteristics of the six dimensional phase space of the bunch produced by a photoinjector. This thesis is focused on the analysis of the longitudinal properties of the electron bunch distribution, this means the temporal current distribution and the momentum distribution as well as the correlation of both properties. The complete distribution of the electron bunch in longitudinal phase space of a photoinjector was measured directly for the first time at a beam momentum of about 5 MeV/c, using an existing apparatus. This system had been designed for an accelerating gradient of 40 MV/m. Its subcomponents were analysed to understand sources of uncertainties of the measurement system. The usage of higher accelerating gradients in the gun (60 MV/m, resulting in a beam momentum of about 6.8 MeV/c) demands major modifications of the existing measurement system for the longitudinal phase space distribution. An upgrade of the facility by an additional accelerating cavity required the design of further longitudinal diagnostics systems for the analysis at higher momenta

(up to 40 MeV/c). Measurements of the longitudinal beam properties to determine the influence of different operation parameters, like RF launch phase, charge, accelerating field gradient and laser distribution were performed and compared to simulations.

6.2.4 Optical Synchronization of a Free--Electron Laser with Femtosecond Precision

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Graduation Date: March 27, 2009
Supervisor: Prof. Dr. Joerg Rossbach and PD Dr. Bernhard Schmidt

Abstract:

High-gain free-electron lasers (FELs) are capable of generating sub-10 fs long light pulses. In order to take full advantage of these extremely short light pulses in time-resolved experiments, a synchronization with a so far unprecedented timing accuracy is required.

Within this thesis, an optical synchronization system providing sub-10 fs stability has been developed and was implemented at the ultra-violet and soft X-ray free-electron laser FLASH at DESY, Hamburg. The system uses a mode-locked laser as a timing reference. The laser pulses are distributed via length stabilized optical fiber-links to the remote locations. A key feature of the system is a bunch arrival-time monitor detecting the electron bunch arrival-time with an unrivaled resolution of 6 fs.

A feedback system based on the arrival-time monitor was established, improving the arrival-time fluctuations from 200 fs in the unstabilized case to 25 fs with active feedback. In order to achieve the high peak current of several thousand Amperes required for the FEL process, the electron bunches are longitudinally compressed in two magnetic chicanes. A second feedback system was developed stabilizing the bunch compression process based on measurements of diffraction radiation. The combination of both feedback systems improves the stability of the FEL radiation significantly.

7 Forthcoming Beam Dynamics Events

7.1 Workshop on Applications of High Intensity Proton Accelerators

Dates: October 19-21, 2009

Place: Fermi National Accelerator Laboratory, Batavia

Conference Website:
http://conferences.fnal.gov/App-Proton-Accelerator/index.html

Registration opens on July 28th 2009

Recent advances in superconducting rf technology have made possible the construction of high-intensity proton accelerators (10 Milliamp current or higher) at energies exceeding 1GeV. Fermilab is developing a design of a High Intensity Proton Linac (Project-X) to support future High Energy Physics Programs. The workshop proposes to bring together researchers working in areas as diverse as

* Production of high intensity proton beam for Muon Factory and Neutrino Factory
* Accelerator based solutions to Nuclear Energy and Transmutation of waste including Accelerator Driven Subcritical Systems
* Material Irradiation and development studies

Fermilab's future accelerator R&D program is focused on SRF Linac for Project-X, ILC, and any future machine. The present design of the Project-X linac is to provide 2 MWatt of pulsed beam power at 8 GeV. The workshop will cover topics related to challenges in the design of high-power CW and pulsed linear accelerators, targetry as well as design of systems to collect pions to achieve muon beams leading to a neutrino factory. The workshop is timed to enable the design of Project-X and other projects (SPL,...) to give due consideration to these future upgrade possibilities.

The proposed workshop is to focus ONLY on SRF Linac approaches and how it can be used (or have enough design hooks) for future accelerator applications. We want to discuss this in the light of our present program.

We encourage you to register as soon as the registration starts <http://conferences.fnal.gov/App-Proton-Accelerator/default.html> and make your travel plans early as the number of rooms we have reserved in the local hotel is limited.

(Pending DOE Approval)

8 Announcements of the Beam Dynamics Panel

8.1 ICFA Beam Dynamics Newsletter

8.1.1 Aim of the Newsletter

The ICFA Beam Dynamics Newsletter is intended as a channel for describing unsolved problems and highlighting important ongoing works, and not as a substitute for journal articles and conference proceedings that usually describe completed work. It is published by the ICFA Beam Dynamics Panel, one of whose missions is to encourage international collaboration in beam dynamics.

Normally it is published every April, August and December. The deadlines are 15 March, 15 July and 15 November, respectively.

Categories of Articles

The categories of articles in the newsletter are the following:

1. Announcements from the panel.
2. Reports of beam dynamics activity of a group.
3. Reports on workshops, meetings and other events related to beam dynamics.
4. Announcements of future beam dynamics-related international workshops and meetings.
5. Those who want to use newsletter to announce their workshops are welcome to do so. Articles should typically fit within half a page and include descriptions of the subject, date, place, Web site and other contact information.
6. Review of beam dynamics problems: This is a place to bring attention to unsolved problems and should not be used to report completed work. Clear and short highlights on the problem are encouraged.
7. Letters to the editor: a forum open to everyone. Anybody can express his/her opinion on the beam dynamics and related activities, by sending it to one of the editors. The editors reserve the right to reject contributions they judge to be inappropriate, although they have rarely had cause to do so.

The editors may request an article following a recommendation by panel members. However anyone who wishes to submit an article is strongly encouraged to contact any Beam Dynamics Panel member before starting to write.

8.1.2 How to Prepare a Manuscript

Before starting to write, authors should download the template in Microsoft Word format from the Beam Dynamics Panel web site:

http://www-bd.fnal.gov/icfabd/news.html

It will be much easier to guarantee acceptance of the article if the template is used and the instructions included in it are respected. The template and instructions are expected to evolve with time so please make sure always to use the latest versions.

The final Microsoft Word file should be sent to one of the editors, preferably the issue editor, by email.

The editors regret that LaTeX files can no longer be accepted: a majority of contributors now prefer Word and we simply do not have the resources to make the conversions that would be needed. Contributions received in LaTeX will now be returned to the authors for re-formatting.

In cases where an article is composed entirely of straightforward prose (no equations, figures, tables, special symbols, etc.) contributions received in the form of plain text files may be accepted at the discretion of the issue editor.

Each article should include the title, authors' names, affiliations and e-mail addresses.

8.1.3 Distribution

A complete archive of issues of this newsletter from 1995 to the latest issue is available at

http://icfa-usa.jlab.org/archive/newsletter.shtml.

This is now intended as the primary method of distribution of the newsletter.

Readers are encouraged to sign-up for electronic mailing list to ensure that they will hear immediately when a new issue is published.

The Panel's Web site provides access to the Newsletters, information about future and past workshops, and other information useful to accelerator physicists. There are links to pages of information of local interest for each of the three ICFA areas.

Printed copies of the ICFA Beam Dynamics Newsletters are also distributed (generally some time after the Web edition appears) through the following distributors:

Weiren Chou	chou@fnal.gov	North and South Americas
Rainer Wanzenberg	rainer.wanzenberg@desy.de	Europe++ and Africa
Susumu Kamada	susumu.kamada@kek.jp	Asia** and Pacific

++ Including former Soviet Union.

** For Mainland China, Jiu-Qing Wang (wangjq@mail.ihep.ac.cn) takes care of the distribution with Ms. Su Ping, Secretariat of PASC, P.O. Box 918, Beijing 100039, China.

To keep costs down (remember that the Panel has no budget of its own) readers are encouraged to use the Web as much as possible. In particular, if you receive a paper copy that you no longer require, please inform the appropriate distributor.

8.1.4 Regular Correspondents

The Beam Dynamics Newsletter particularly encourages contributions from smaller institutions and countries where the accelerator physics community is small. Since it is impossible for the editors and panel members to survey all beam dynamics activity worldwide, we have some Regular Correspondents. They are expected to find interesting activities and appropriate persons to report them and/or report them by themselves. We hope that we will have a "compact and complete" list covering all over the world eventually. The present Regular Correspondents are as follows:

Liu Lin	Liu@ns.lnls.br	LNLS, Brazil
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We are calling for more volunteers as Regular Correspondents.

8.2 ICFA Beam Dynamics Panel Members

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