CONCEPTUAL DESIGN OF A NEW 800 MeV H^- LINAC FOR ISIS MEGAWATT DEVELOPMENTS

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Abstract

Several schemes have been proposed to upgrade the ISIS Spallation Neutron Source at Rutherford Appleton Laboratory (RAL). One scenario is to develop a new 800 MeV, H^- linac and a ~3 GeV synchrotron, opening the possibility of achieving several MW of beam power. In this paper the design of the 800 MeV linac is outlined. It consists of a 3 MeV Front End similar to the one now under construction at RAL (the Front End Test Stand - FETS). Above 3 MeV, a 324 MHz DTL will be used to accelerate the beam up to ~75 MeV. At this stage a novel collimation system will be added to remove the halo and the far off-momentum particles. To achieve the final energy, a 648 MHz superconducting linac will be employed using three families of elliptical cavities with transition energies at ~196 MeV and ~412 MeV. Alternative designs are also being investigated.

INTRODUCTION

The ISIS Spallation Neutron Source consists of an 800 MeV proton RCS and a 70 MeV H^- injector. It is currently capable of delivering proton beam powers of up to 0.2 MW to its two target stations. With calls from the user community for an increase in neutron yield and machine reliability, a number of possible upgrade schemes have been analysed. One option is to add a new ~3 GeV, 30-50 Hz RCS to the existing facility, increasing the power to ~1 MW. By replacing the old ISIS machine and injecting directly from a new 0.5 MW, 800 MeV linac, beam powers of up to 5 MW are achievable [1].

LINAC DESIGN OVERVIEW

The design of the new linac follows the same overall guiding principles as several recent major proton/H^- linac projects (ESS, J-PARC, Linac4/SPL, SNS). It consists of a 3 MeV front end copying the FETS project currently under construction at RAL [2]. After 3 MeV, a DTL will accelerate the beam up to 74.8 MeV at which stage an intermediate energy beam transport line (IEBT) with an innovative collimation system will be used to remove the halo and the far off-momentum beam. Although this adds ~7.5 m to the overall linac length, hence increasing its cost, it is imperative to control the beam loss of quality ahead of the superconducting stages. The superconducting linac (SCL) uses 648 MHz cavities to accelerate the beam to 800 MeV with three families of elliptical cavities and transition energies at ~196 and ~412 MeV. A beam line of ~87 m with achromatic bending sections is used to transport the beam between the linac and the ring [3]. The main linac parameters are presented in Table 1 and a schematic overall layout in Figure 1.

Table 1: General Linac Parameters

Ion Species	H^-
Output Energy	800 MeV
Accelerating Structures	DTL/SC Elliptical Cavities
Frequency	324/648 MHz
Beam Current	43 mA
Repetition Rate	30 Hz (Upgradeable to 50)
Pulse Length	0.75 ms
Duty Cycle	2.25 %
Average Beam Power	0.5 MW
Total Linac Length	243 m

The Front End

The linac front end will consist of an H^- ion source, a Low Energy Beam Transport Line (LEBT), an RFQ and a Medium Energy Beam Transport Line (MEBT) with a beam chopper.

The FETS Penning type surface plasma H^- ion source will be adopted for the new linac. This source is already operating at parameters exceeding those required for the new linac having been improved over many years in ISIS and FETS. A beam of 65 keV, 2 ms at 50 Hz with beam currents exceeding 60 mA is routinely extracted [4].

A three solenoid magnetic LEBT will transport and match the beam from the ion source to the RFQ. A 4 m long, 4-vane RFQ operating at 324 MHz will accelerate the beam up to 3 MeV making use of the available 2.5 MW Toshiba klystron used at J-PARC. An RMS emittance in the region of 0.27 π mm mrad transversally and 0.39 π mm mrad longitudinally is expected at the output of the RFQ.

The RFQ is followed by the MEBT line. It is nearly 5 m long and consists of 11 quadrupoles, 4 re-bunching cavities, a beam chopping system with dedicated beam dumps, collimators for removing beam halo and a comprehensive set of diagnostics. The quadrupole gradients and the voltages in the cavities are variable and will depend on the RFQ output beam. The last 4 quadrupoles and two bunchers form the section matching into the DTL [5].

The fast-slow chopping system developed for FETS will also be employed here [6]. The MEBT optics have been optimised to accommodate two choppers: a fast transition time, short duration deflector (the fast chopper) and a slower transition time, longer duration deflector (the slow chopper). The fast chopper removes three adjacent bunches at the beginning and at the end of the chopping interval creating two gaps in the bunch train. These gaps will then be used by the second chopper field as a transition interval, thus preventing bunches being partially

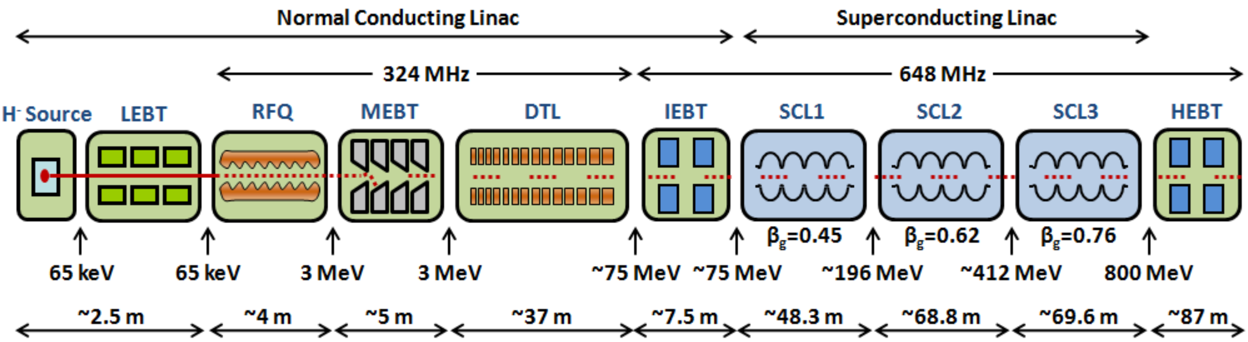

Figure 1: Schematic layout of the new 800 MeV ISIS Linac

deflected by the slow chopper. Rise/fall times of ~2 ns are achievable allowing bunch by bunch chopping of the 324 MHz beam. Voltages of ~±1.2 kV and 0.45 m long deflectors are required for 100% chopping efficiency.

The Drift Tube Linac

The DTL section is ~37 m long and accelerates the beam to 74.8 MeV in four tanks. Each tank is fed by a single 2.5 MW peak power Toshiba klystron with output energies of 19.4, 37.7, 56.4 and 74.8 MeV. The combined structure and beam power for each tank has been kept below 1.7 MW allowing a 30% margin for extra losses and control power. The number of cells in each tank is 62, 39, 35 and 31 respectively. The average axial electric field is ramped from 2.9 to 3.1 MV/m in the first tank and then kept constant. Post couplers are envisaged in the four tanks for field stabilisation.

From a beam dynamics point of view, equipartitioning between the transverse and the longitudinal energies is obtained in the first tank after the MEBT matching section and is maintained up to 800 MeV by varying the quadrupole settings while keeping the transverse and longitudinal phase advances per period below 90 degrees. A FODO focusing lattice is used throughout the linac.

A large longitudinal acceptance is needed at the beginning of the DTL and as a result the synchronous phase angle (φ_s) is set to -42 degrees in the first few cells. As the beam becomes more bunched, the phase is slowly increased to -35 degrees. In the other tanks the values are -32 degrees in tank 2, - 35 to -32.5 degrees in tank 3 and -33 to -31 degrees in tank 4.

Drift spaces between tanks lead to matching errors and it is imperative that these are corrected to avoid emittance growth, halo development and beam loss further downstream. Longitudinally, this is achieved by offsetting the synchronous phase in selected cells at the end of tanks 1, 2 and 3. Transversally, inter-tank matching is done with six end quadrupoles. Apart from these matching elements, the DTL assumes permanent magnet quadrupoles.

The Intermediate Energy Beam Transport Line

A novel addition to the linac design is the inclusion of a collimation section (IEBT) at the end of the DTL. It consists of three doublet focusing cells and a 648 MHz re-bunching cavity in the first and the third cell. Three dipole magnets are placed in the central cell providing an adjustable orbit bump. The IEBT is intended to limit the losses further downstream intercepting halo and far off-momentum particles with stripping foils and loss collectors located at specific locations between dipoles. Additionally, it facilitates the matching over a double frequency jump and accelerating structure change, providing ample space for diagnostic systems. Beam dynamics simulations indicate that the benefits of adding the IEBT in terms of beam quality outweigh the inherent overall cost increase.

The Superconducting Section

After the IEBT, superconducting cavities are used to accelerate the beam to the final energy. The transition energy between the DTL and the SCL is dictated by the lowest practical value of the geometric beta (β_g) for the elliptical cavities. The resonant frequency is doubled to 648 MHz in the SCL, mainly for cryogenic and manufacturing cost reasons. The development of a new high power klystron will be required for this frequency.

Acceleration is achieved in three stages with three cavity families (β_g=0.45, 0.62, 0.76). The overall design aim has been to minimize the number of cavities and cryostats without compromising practical and beam dynamics design aspects. A list of parameters of the SCL can be seen in Table 2.

Table 2: Superconducting Linac Parameters

	SCL1	SCL2	SCL3
Energy (MeV)	~75-196	~196-412	~412-800
Cavity β_g	0.45	0.62	0.76
Cavity Length ($\beta_g\lambda$)	2	2.5	3
Cells per Cavity	4	5	6
$\varphi_{s\ (deg)}$	-22	-22	-21
E_{acc} (MV/m)	15.1-19.1	14.1-16.9	16.8-18.7
No. of Cavities	32	32	33
Cavities per Period	2	2	3
Focusing Period ($\beta_g\lambda$)	14.5	15	18
Period Length (m)	3.02	4.30	6.33
No. of Cryostats	16	16	11
Total Length (m)	48.3	68.8	69.6

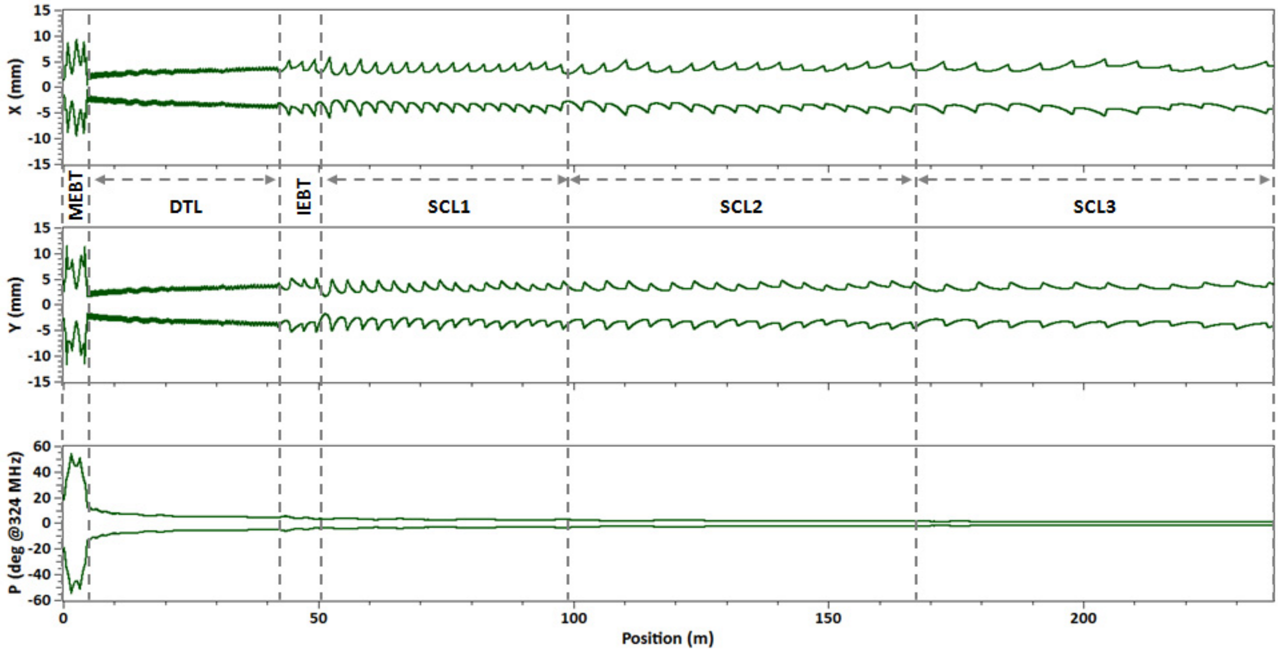

Figure 2: Beam envelopes along the linac (MEBT to SCL3).

The synchronous phase in SCL1 and SCL2 (Fig. 1) is set to -22 degrees and to -21 degrees in SCL3. Each cavity family is designed for the same energy gain and beam power per cavity. As a result, the accelerating fields have to vary from cavity to cavity due to phase slips when $\beta \neq \beta_g$. Assuming the use of 1.4 MW peak power klystrons and including safety margins, 4 klystrons are needed for SCL1, 8 for SCL2 and 16 for SCL3.

Transversally, the focusing is done with a doublet quadrupole arrangement located in the room temperature sections at the end of each cell. The six parameter matching between each SCL stage is found by varying six quadrupole gradients and the cavity phases at each transition region. An illustration of the beam envelope evolution along the linac can be seen in Figure 2.

After the SCL, an ~87 m long beam line will transport the beam to the ring. It consists of 10 cells with FODO doublet focusing as in the SCL. Two six-cell re-bunching cavities are placed in cell six to adjust the momentum spread and ramp the beam energy. Bending is introduced in the final achromatic section, which starts with a dipole in cell 7 and ends at the H^- stripping foil in the centre of the ring's injection dipole in cell 10.

Alternative Designs

As part of the design efforts, two alternative linacs are also being studied. The first option replaces the SCL1 section with a normal conducting 648 MHz coupled cavity linac (CCL). SCL2 and SCL3 are then used up to 800 MeV. The beam dynamics is similar; however, more power is needed and the overall linac length is ~42 m longer, making this a less cost effective solution.

The second option uses superconducting cavities after the DTL, but at different RF frequencies: 324 MHz up to ~228 MeV and 972 MHz for the rest of the linac. While this has the advantage of klystron availability, we have found that the triple frequency jump leads to unacceptable levels of halo and emittance growth [7].

CONCLUSIONS

A conceptual design is presented for a new 800 MeV H^- linac. It consists of a 3 MeV Front End, a DTL up to ~75 MeV followed by a superconducting section to the final energy. While the linac still presents opportunities for improvement, beam dynamics simulations indicate a robust and versatile design providing a baseline for further developments. Collaborations are ongoing with several similar projects in Europe and worldwide.

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