UPGRADE STRATEGIES FOR HIGH POWER PROTON LINACS

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Abstract

High power proton linacs are used as drivers for spallation neutron sources, and are proposed as drivers for subcritical accelerator driven thorium reactors. A linac optimized for a specific average pulse current can be difficult, or inefficient, to operate at higher currents, for example due to mis-matching between the RF coupler and the beam loaded cavity, and due to Higher Order Mode effects. Hardware is in general designed to meet specific engineering values, such as pulse length and repetition rate, that can be costly and difficult to change, for example due to preexisting space constraints. We review the different upgrade strategies that are available to proton driver designers, both for linacs under design, such as the European Spallation Source (ESS) in Lund, and also for existing linacs, such as the Spallation Neutron Source (SNS) in Oak Ridge. Potential ESS upgrades towards a beam power higher than 5 MW preserve the original time structure, while the SNS upgrade is directed towards the addition of a second target station.

INTRODUCTION

Spallation is a nuclear process in which neutrons of different energies are emitted in several stages following the bombardment of heavy nuclei with energetic particles. The spallation process is the most practical and feasible way of producing neutrons for a reasonable effort (or cost) of the neutron source cooling system. Spallation sources come in at least three types: short pulse sources (a few μs), long pulse sources (a few ms) and continuous sources. The European Spallation Source (ESS) will be a long pulse source and the first spallation source with a time average neutron flux as high as that of the most intense research reactors.

The highest power spallation source currently in operation – the Spallation Neutron Source (SNS) in Oak Ridge – combines a full energy SC linear accelerator with an accumulator ring to provide very high intensity short pulses of neutrons to the instruments. The ESS will provide even higher intensities, but is developing instruments able to use longer linac pulses directly for spallation, avoiding the need for a costly and performance-limiting accumulator ring [1].

The obvious advantage of a linac is that beam passes only once through the accelerating structures, enabling it to accelerate a high current beam with a minimum of constraints. The current limit is mainly set by space charge effects at low energy, as well as the power that can be delivered to the beam in each accelerating cavity at medium and high energies, and by beam losses.

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GENERAL CONSIDERATIONS FOR UPGRADES

All upgrades beyond the original design goals will require a redesign of the target for cooling, shielding, or/and the possible addition of a new target station. The macroscopic time structure of the proton beam at a pulsed spallation source is intimately linked to instrument design and location.

The spallation cross section for protons on heavy nuclei increases as a function of proton energy up to several tens of GeV [2]. Nonetheless it is generally agreed that a kinetic proton energy between 1-3 GeV is optimal for practical target and moderator designs, and in order to keep the shielding requirements reasonable. An upgrade based on an energy upgrade must consider this limitation and also take into account the change of target conditions at higher energies e.g. the peak of neutron production for the proton beam will move by a few cm for an energy increase from 2.5 to 3 GeV. This will influence the efficiency of the neutron moderators and possibly increase the number of protons scattered around and through the target. However, a pure energy upgrade using additional accelerating structures will have little infleunce on beam dynamics and will not require any major modification of the existing lattice.

Increasing the current of the proton beam will require more RF power to the beam, and will require a redesign of the front end, including the ion source, and of the RF sources for all accelerating structures. Since space charge increases, and the matching between RF sources and the accelerating structures will change, it is also likely to require a change of the accelerating structures, and of both the primary RF couplers and possible HOM couplers. For extreme cases it might be necessary to have two front-ends from which the beam eventually is funneled toegther at a higher energy when space charge is less of an issue. It will also have an overall impact on beam dynamics.

Increasing the repetition rate or the pulse length will require will require new RF sources but will have little or no impact on beam dynamics and SCRF. However, it will require new instruments or a redesign and possible relocation of existing instruments. A possible away around this is to add a second target station to which e.g. the additional pulses are extracted or part of the pulse is deviated.

FIRST IDEAS FOR ESS UPGRADE STRATEGIES

The ESS accelerator high level requirements are to provide a 2.86 ms, 2.5 GeV proton pulse, with a repetiton rate of 14 Hz, and 5 MW of average beam power on target. The general lay-out of the linac can been seen in Fig. 1.

Energy Upgrade

The current design for the ESS linac is gradient-limited rather than power-limited, which implies that the beam energy cannot be increased without adding cryomodules. It is, however, close to also being power limited, with power couplers for the elliptical cavities being specified for 900 kW. This is near the approximately 850 kW of power transmitted to the beam in the high-beta section of the current linac design based on the hybrid cryomodules [3]. The RF sources are foreseen to match this power requirement and will be able to deliver 900 kW with a modest margin in the high-beta section [4]. In the spokes and low-beta section, the linac is more strongly limited by the gradient, and power to the beam per cavity is lower.

It follows that a significantly upgraded beam power, to 10 or 15 MW, which needs a combination of higher current and energy, will require both additional accelerating cavities that increase the energy to, say, 3.5 GeV, and an increased beam current, implying more powerful RF sources as well as power couplers either with higher power rating or where two couplers per cavity are used.

With the present layout of the linac and the 100 m space available in the HEBT for upgrades, it would be straightforward to start by increasing the energy to 3.5 GeV by adding 8 cryomodules of the kind already used at the end of the linac. Such an addition would fill up the 100 m of length available in the HEBT and give 7 MW of beam power. Therefore, the remaining part of the HEBT with the bends up to the target level should be designed for 3.5 GeV from the start to prepare for this upgrade scenario.

Instead of going to 3.5 GeV as a first step, one could envisage to increase the beam current to, say 75 mA. With the power couplers still limited to 900 kW, this would require 5 additional cryomodules, since the high-beta section would be limited by the couplers and the accelerating gradient there would have to be reduced. In the other sections, the power per cavity would have to increase to keep a velocity gain compatible with the cavity geometric betas. Thus new RF sources would be needed for these sections, which makes this option less attractive for a small power upgrade. Note that it may be possible to efficiently adjust the power sources, which would then have to be manufactured for these upgrade conditions. Increasing the current to 75 mA or higher also requires an ion source that is more powerful than the one immediately foreseen for ESS, although the RFQ will be designed for 100 mA. The DTL may need to be designed with stronger quadrupoles for 75 or 100 mA compared to 50 mA.

Combining increased energy and increased current to reach, for instance, 10 MW with 3.5 GeV and 75 mA or 14 MW with 3.5 GeV and 100 mA is not possible by just putting new cryomodules after the existing ones with their 900 kW couplers. The power in the the low-beta section would reach 1.1 MW per cavity with 100 mA, which more or less is within the error margin from 900 kW, and it can be reduced by adding an extra low-beta cryomodule in the 50 mA baseline if absolutely necessary. In the high-beta section, two couplers per cavity or a single one rated at close to 2 MW must be used. Although both alternatives require some extra R&D, they could probably be included from the start without increasing the total cost of the cryomodules with any large fraction.

The major cost for any power upgrade would clearly be the RF sources. If they are initially dimensioned for the baseline 5 MW linac – and anything else would come with a significantly increased initial cost – a substantial upgrade would require more or less all sources to be replaced. As a possible alternative, the old ones could be reused by having two klystrons per cavity in part of the linac, but this has the disadvantage of taking more space in the klystron gallery, which will be big even with a single klystron per cavity (and 1.6 m average spacing between cavities).

A further issue to consider is if the linac layout, with geometrical betas, number of cryomodules per section, etc., should be designed for 50 mA, as it is at present, or if it should rather be designed for a higher current already from the start. In the latter case, fewer cryomodules (may be only one for 7 MW) and power sources will be needed for the upgraded linac, saving costs, but there may be disadvantages initially in having, e.g., geometrical betas further from their optimum values because of increased power in the passband modes. The same holds for coupling of power to the beam which will become less optimal unless the couplers can be made adjustable.

SCRF

An upgrade scenario involving an increase of the beam current from the nominal 50 mA to 75 mA, while maintaining the kinetic energy of the protons at 2.5 GeV, would have several implications for the SCRF linac.

Power Couplers Power couplers are typically matched to a certain beam current so that the power reflected from the cavity is minimised by the term related to the beam loading. An increase in beam current in the cavity by 50% will increase the loading, resulting in an increase in the reflected power. An initial estimate suggests that this increase will be ∼4% of the power arriving at the coupler.

One possible technique for reducing the impact of this is to design the coupler to be matched to an intermediate beam current. This trades off a marginal increase in the reflected power in the case of the nominal beam current for a reduction in the impact of the upgrade.

An initial configuration with two couplers per accelerating structure will require that both couplers are used from the beginning. If not, the second coupler would absorb a lot of power (if it is resistively terminated), or will shift the cavity modes significantly (if it is reactively terminated)

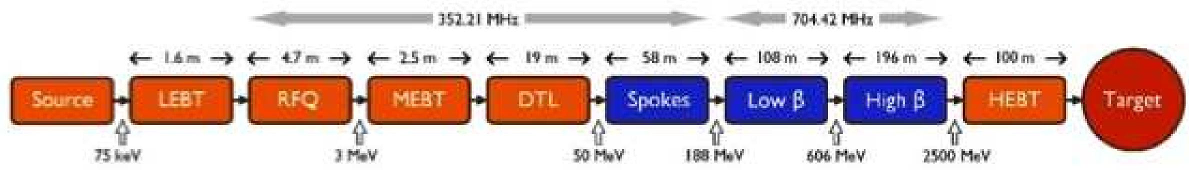

Figure 1: A block diagram of the ESS linac design. The Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) are normal conducting while the spoke resonator and low beta and high beta elliptical cavities are superconducting. Space has been reserved in the tunnel for a future upgrade

and most like cause large standing waves inside the idle coupler. It appears easier to over-design a single coupler for high power from the start (e.g. 1.8 MW for the ESS high beta elliptical section).

Higher Order Modes (HOMs) While the question of the installation of HOM couplers on the ESS cavities has not yet been resolved, an increase in beam current will cause a quadratic increase in the HOM power, and so will strongly increase the risk of these parasitic fields having negative effects on the operation of the machine.

Therefore, such an upgrade path would considerably strengthen the arguments for installation of HOM couplers as a part of the baseline.

RF Sources

The baseline of ESS with 5 MW beam power will require an unprecendented amount of RF equipment to be installed with only an avarage of 1.6 m between the accelerating structures. A possible way forward would be to initially supply more than one accelerating structure from each RF source at twice the nominal power, and leave space for additional sources to be installed later. Alternatively enough space must be left for a second RF gallery and associated wave guides. Two RF sources powering two different couplers on the same cavity would require that the RF sources are identical or that one RF source is split perfectly otherwise significant power bleeds from one system to the other.

UPGRADE STRATEGIES FOR SNS

The original Spallation Neutron Source construction included provisions for power upgrades. Power upgrade scenarios aim for a doubling of the operational beam power to at least 2 MW and a goal of 3 MW [5]. The beam power upgrade is accomplished by increasing the beam energy and the beam current. No change in the beam repetition rate nor the beam duty factor is envisioned. The beam energy can be increased to 1.3 GeV (from a design level of 1.0 GeV) with the addition of 9 extra cryomodules in the end of the linac tunnel. The original construction provided space for the additional cryomodules at the end of the linac tunnel, and almost all the transport line and storage ring magnets and power supplies are already 1.3 GeV capable. The increase in beam current will require an improved ion source and upgraded high-voltage convertor modulators. The rest of the RF system (klystrons, couplers, windows, etc.) is capable of handling the higher RF loads associated with the increased beam loading. The ion source improvements will require R & D for high current, high reliability H- sources, and adoption of a magnetic LEBT is being considered to facilitate use of a dual, hot-spare source. The present plan for the power upgrade activity is to combine this activity with a second target hall addition, which is expected to begin design in two to three years. The second target station will adopt a long pulse neutron source ($\sim$1 ms), as compared to the present short pulse target ($\sim$1 μs). Of the 60 Hz stream of proton pulses the accelerator produces, the long pulse target will accept 20 Hz and the short pulse target will accept 40 Hz. Adopting a long pulse second target station will obviate the necessity of using the accumulator ring for these pulses, and schemes are being considered to avoid the ring entirely for the 1/3 of the pulses going to the long pulse target. The cooling and shielding for the first target station are designed to accept 2 MW.

DISCUSSION

It is possible to envisage higher power operation of both the SNS and ESS. Further detailed studies will set the path and limit for possible upgrades. However, it is clear that major savings and flexibility can be gained from wise base line choices for ESS.

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