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STATUS OF ESS LINAC UPGRADE STUDIES FOR ESSnuSB*

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Abstract

The European Spallation Source (ESS), currently under construction in Lund, Sweden, is the world's most powerful neutron spallation source, with an average power of 5 MW at 2.0 GeV. In the ESS neutrino Super Beam Project (ESSnuSB) it is proposed to utilise this powerful accelerator as a proton driver for a neutrino beam that will be sent to a large underground Cherenkov detector in Garpenberg, mid-Sweden. In this paper we discuss the required modifications of the ESS linac to reach an additional 5 MW beam power for neutrino production in parallel to the spallation neutron production.

INTRODUCTION

In the ESS baseline design, the linac will accelerate protons to the energy of 2 GeV in 2.86 ms long 62.5 mA pulses at 14 Hz repetition rate, for spallation neutron production [1, 2]. The relatively low duty cycle of 4% of the ESS linac allows for accelerating additional pulses of H^- ions, interleaved with the proton pulses. By adding a second H^- beam, interleaved with the proton beam, the duty cycle will be increased to 8% and the average power to 10 MW. The objective of the ESS neutrino Super Beam (ESSnuSB) project is to make high precision measurements of possible CP-violation. The large underground Cherenkov detector will be placed near the 2nd oscillation maximum, in Garpenberg mid Sweden, thereby increasing the sensitivity [3]. The pion focusing horns at the neutrino target provide focusing during only 1.5 µs, requiring the proton pulses to be of the order of microseconds. These short pulses can be achieved by injecting the H^- beam into an accumulator ring by charge exchange injection before they are sent to the neutrino target. The spallation neutron users could also benefit from short pulses giving synergy effects of the upgrade of the linac and the accumulator ring [4]. The layout of the beam line for neutrino production including accumulator ring, production target and near detector are shown in Fig. 1.

As the average power of the linac will be doubled from 5 MW to 10 MW, a corresponding increase of the output power from the RF sources and of the capacity of the different cooling systems will be required. The baseline upgrade plan of the linac is to increase the energy of 2.5 GeV, Fig. 2, which allows a lower average beam current of ~50 mA, instead of 62.5 mA. This lower current will limit the demands for the RF power upgrade in each module to an additional 80% increase instead of 100%. Furthermore, stripping losses of H^- ions due to intra-beam scattering will be reduced, which has been identified as major loss mechanism at SNS [5].

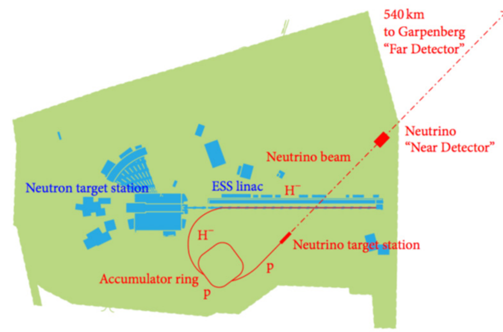

Figure 1: Layout of the ESS neutrino Super Beam facility added to the ESS neutron spallation facility.

The accelerator layout is shown schematically in Fig. 2, including an upgrade section in the high-energy end to 2.5 GeV. The beam parameters are summarised in Table 1.

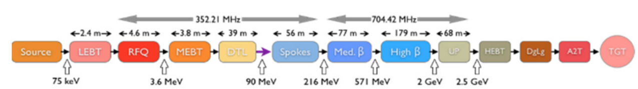

Figure 2: The layout of the upgraded linac.

Table 1: Beam Parameters

Parameter	ESS	Upgrade
Ion	p	p + H^-
Average beam power	5 MW	10 MW
Kinetic energy	2 GeV	2.5 GeV
Macro pulse current	62.5 mA	~50 mA
Pulse repetition rate	14 Hz	28 Hz
Beam Duty cycle	4%	8%
Linac length	352.5 m	352.5 + ca 70 m

Linac Front-End and Ion Source

The acceleration of H^- ions requires the linac front-end section to be modified and a new ion source to be added, see Fig. 3. One option (left) is to merge the beams in the LEBT and use the same RFQ, the other option (right) is to use two separate front-end sections and merge the beam in

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the MEBT. The option with separate LEBT and RFQ sections for protons and H⁻ ions is more straightforward to realize, since the beam transport of the protons and H⁻ beams are independent. The option with shared RFQ and MEBT will be less expensive and require less space, and studies are ongoing to conclude if such a design is feasible. One challenge of the LEBT is that beam is highly space charge dominated so that the emittance tends to blow up quickly. Space charge compensation thus is important including the composition and pressure of the background gas in the LEBT [6]. The MEBT needs to be redesigned so that it works for both species including the fast chopping requirements creating extraction gaps in the beam, see below.

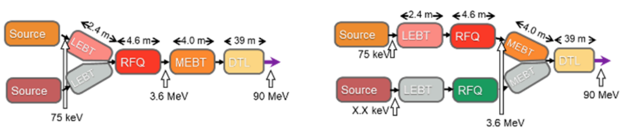

Figure 3: Layout of the front end of the accelerator showing different options for adding the H⁻ source.

A new ion source needs to be added for the production of the high intensity H⁻ beam. In the baseline pulsing scheme, see below, the requirement of the H⁻ ion source is 80 mA at 3 ms pulse length and 14 Hz (4% duty cycle). As candidate ion sources the penning surface source type, used at ISIS, and the RF volume source type, used at SNS and J-PARC, are being studied [7, 8]. Both types are employing caesium in order to enhance the ionisation rate. The performance of these sources could fulfil the requirements of the ESSnuSB H⁻ ion source with a development program in the timespan of the project.

H⁻ PULSING STRUCTURE

Different pulsing schemes of the H⁻ beam are being considered, see Fig. 4. The limitations of the accumulator ring, space charge and beam instabilities, do not allow for the full 2.86 ms beam pulses to be injected in one filling and the beam has to be split up in several sub-pulses or batches. The batch length is limited by the storage time in the accumulator ring, about 1000 turns, corresponding to 1.3 ms, before instabilities are likely to develop [9].

A pulsing scheme with an overall 28 Hz macro-pulse structure is selected as the baseline design, option A in Fig. 4. Other pulsing schemes are also considered, options B and C, where the H⁻ beam is pulsed at 70 Hz. These however result in a higher total load of the RF system, since the filling time of the superconducting cavities is in the order of 0.3 ms. Option B, with a pulse length of up to 1.3 ms, has the advantage that it allows for an evenlower beam current of about 30 mA, relaxing the demands on the ion source requirements and reducing intra beam stripping losses. The impact on the RF modulator systems of the different pulsing options are discussed further below.

The total number of particles delivered to the accumulator ring will be $8.9 \cdot 10^{14}$ per pulse cycle (macro-pulse), divided into four batches of $2.2 \cdot 10^{14}$. Each batch is stacked in the accumulator ring, compressing the pulses to 1.2 µs, which are subsequently extracted to the target. By splitting the macro pulse into four batches, the power on each target is limited to 1.25 MW, and the space charge tune shift in the accumulator ring is limited to an acceptable level [9, 10].

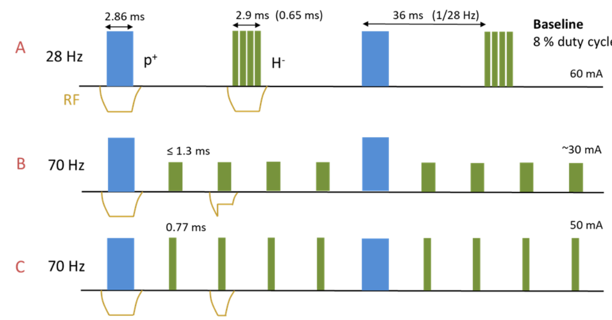

Figure 4: Different options for the H⁻ beam pulsing.

The extraction of the beam from the accumulator ring to the neutrino target requires extraction gaps in the accumulated beam in the order of 100 ns, corresponding to the rise time of the extraction kickers, not to cause beam loss and unnecessary activation, see Fig. 5. The different batches also need to be separated by at least 100 µs, in order for the accumulator ring to be ready for the next injection (extraction kicker fall time). The extraction and injection gaps will be created in the linac, by chopping of the beam in the Medium Energy Beam Transport (MEBT) section. Each batch will thus be chopped up into about 490 pulses.

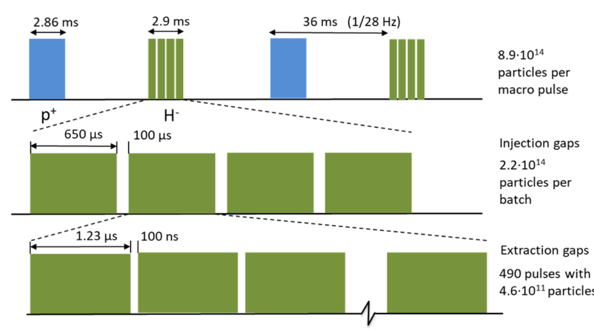

Figure 5: Bunch structure and chopping of the beam.

IMPACT OF THE CHOPPING SCHEME

The creation of the acceleration gaps in the linac could potentially drive higher order modes (HOMs) in the acceleration cavities, which can cause extra heating of the cavity walls, extra cryogenic heat load, and beam instabilities [11]. In the normal operating mode with protons the beam accelerated in the ESS linac has a beam power spectrum determined solely by the bunch-to-bunch spacing of 352.21 MHz. By introducing extraction gaps in the linac, additional resonances are created as side bands to the harmonics at multiples of the bunch spacing. The frequency of these side bands is 752 kHz, corresponding to the spacing between the pulses of 1.33 µs, see Fig. 5.

The relative beam power spectrum (BPS) as a function of frequency around the 352.21 MHz line is shown in Fig. 6. From the BPS it is clear that the HOM excitation

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will be at least two orders of magnitude weaker on the nearby secondary beam harmonics compared to the primary line. These modes are therefore not considered to be an issue. However, the modes in the accelerating passbands lie much closer and could cause degradation.

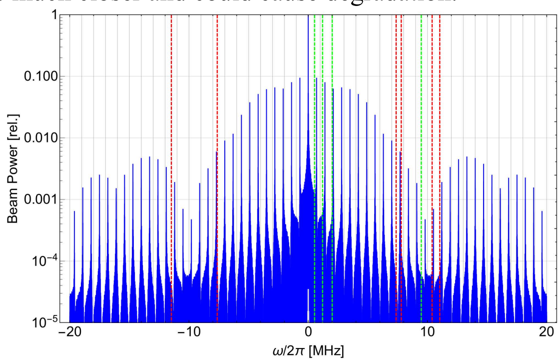

Figure 6: The beam power spectrum for the proposed chopping scheme as a function of frequency separation from a bunch harmonic. HOM modes are shown in red and the modes in the accelerating passbands in green.

In order to determine if there is any effect simulations have been carried out in the code HOMDynamics [12]. In total 200 simulations have been performed at each data point with a spread in the mode frequencies given by $\sigma = 1.09 \times 10^{-3}|f - f_0|$, where f is the mode frequency and f_0 is the frequency of the accelerating mode [13].

The results are shown in Fig. 7 where little difference between the case with and without the chopping can be observed. It is therefore expected that introducing the required chopped substructure into a H^- beam will not cause additional degradation.

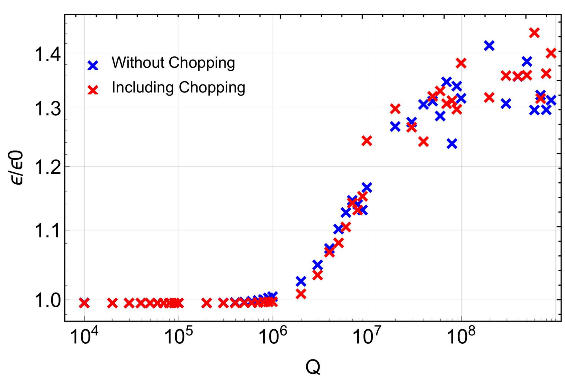

Figure 7: Change in the beam emittance as a function of the external quality factor, Q, of the cavities at the SOMs, with and without beam chopping.

RF MODULATOR UPGRADE

The options for H^- beam pulsing shown in Fig. 4 present different challenges in perspective of a future RF modulator upgrade. The RF modulators designed for the current ESS linac are based on the stacked multi-level (SML) topology and are each rated for peak power 11.5 MW and average power 660 kVA [14]. This modulator topology permits control of output pulse amplitude as well as variable pulse length on a pulse-to-pulse basis, allowing output of any one of the proposed pulsing schemes considered in Fig. 4. Hence, one possibility would be to upgrade the present SML modulators to handle the increased average power. This upgrade would mainly concern the input capacitor chargers and related components, not warranting upgrade of the high voltage system.

On the other hand, given that proposed pulsing schemes B and C feature pulses of lower pulse amplitude and shorter pulse length, respectively, another alternative is to add separate modulators based on conventional pulse transformer technology. Benefits of this alternative include the opportunity of tailoring the new modulators to the new pulsing scheme conditions as well as improved pulse-to-pulse ripple control. This alternative, however, would require an additional 41 modulators, each including a capacitor charger as well as a number of auxiliary compensating systems.

The two above alternatives have been studied in detail comparing cost (investment cost as well as the cost of increased power consumption), efficiency (average delivered beam power vs. average modulator input power from electrical grid), increased system footprint and height, pulse rise time, pulse flat-top performance and pulse-to-pulse ripple control. The derived models allow direct comparison of the two alternatives in context of the different pulsing schemes.

It has been concluded that 1) both of the above proposed alternatives are technically feasible, with the exception of utilizing a pulse transformer based modulator for the proposed scenario A; 2) upgrading the SML modulators would be considerably more cost-effective and require significantly less additional space (footprint); 3) scenario A is preferable from a modulator perspective, minimizing energy loss and providing a better pulse to pulse flat-top ripple control; 4) flat-top ripple and pulse-to-pulse ripple control have been demonstrated not to be show-stoppers for a potential SML modulator upgrade; 5) pulse transformer based modulators may straightforwardly be designed to minimize pulse rise time, representing potential improvements to system efficiency for scenarios B and C.

CONCLUSIONS

For the ESSnuSB project, the ESS linac needs to be upgraded to deliver an H^- beam of 5 MW in addition to the 5 MW beam for neutron spallation. The upgrade of the RF modulator systems has been studied, concluding that the present SML modulators can be used in the foreseen pulsing options, by upgrading the capacitor chargers. The possible side effects of the proposed chopping scheme, creating extraction gaps for the accumulator ring in the linac, has been studied by doing simulations of the beam degradation. The conclusion is that the suggested chopping scheme does not create additional degradation of the beam.

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