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ESSνSB Linac Design and Beam Dynamics

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The ESS neutrino superbeam project is being studied as an upgrade to the European Spallation Source. This would entail the addition of an H^- source to the existing beamline to send H^- pulses in between proton pulses, effectively doubling the beam power from five to ten megawatts. An obstacle to smooth operation is the intra-beam stripping of H^- within bunches; preliminary beam transport simulations are performed to quantify the magnitude of such losses. Recent design work is also reviewed, including the added cavities for increasing beam energy from 2 to 2.5 GeV and favored bunch-pulsing schemes.

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1. Introduction

The ESS Neutrino Superbeam (ESSνSB) experiment is in the feasibility-study phase with target dates for groundbreaking and data taking of 2027 and 2035, respectively. This project requires interleaving the 5 MW proton beam of the European Spallation Source (ESS) with an additional 5 MW H^- ion beam, then diverting the H^- beam at the end of the ESS linac through a transfer line and injected by charge exchange injection into an accumulator ring where pulses are stacked in order to achieve short proton pulses ($\sim$1 μs) of high intensity. Phase space painting of the injected beam is used in order to reduce space charge effects and to mitigate high stripper foil temperatures.[1]

The accumulated pulses are then extracted through a switchyard to a target of packed, helium-cooled titanium spheres to produce a shower of pions which are focused by four magnetic horns; this is followed by a beam dump and an onsite near neutrino detector. The ideal candidate location for the far detector is then at a distance of around 500 km, allowing for high-sensitivity study of the PMNS phase δ_{CP} mixing angle at the second oscillation peak.[2]

The integration of an additional 5 MW H^- beam to the existing ESS linac design presents a few serious technical challenges. This includes increasing the average beam energy to 2.5 GeV for a reduction in beam current; which in turn relaxes the practical requirements in reaching the cumulative 10 MW of delivered beam power. The fall and rise times of the accumulator ring's extraction kicker magnets also require a pulsing scheme with pulses and subpulses having 100 μs and 100 ns gaps, respectively.[3] This pulse structure will be created with the choppers in the LEBT and MEBT.

The primary concerns specific to the H^- beam are: losses due to higher order modes in the elliptical cavities induced by this sub-pulse chopping scheme; and stripping losses of the outer electron in H^-, which has a low binding energy of $\sim$0.75 eV. For the former: a recent work [3] simulated same and higher-order mode effects, with results showing no beam degradation to be expected due to the requisite chopping. In light of this, the present paper is mainly concentrated on stripping-related losses in the linac.

2. H^- Stripping

For a successfully accelerated H^- bunch, stripping is induced intentionally upon arrival to the accumulator ring (that is, the outset of charge-exchange injection). Otherwise, stripping leads to the production of electrons and neutral H^0 in unwanted sectors, which are inevitably ejected from the reference trajectory to impact the beam pipe or component walls. Although the relative particle loss due to H^- stripping is expected to be highest at low energies, the power loss scales with energy and at beam energies greater than 100 MeV activation of machine components can potentially become untenable. At low energies, activation is not significant, although residual-gas stripping can cause a significant fraction of the beam to be lost – we address this latter concern in the following subsection.

2.1 Residual Gas Stripping

This phenomenon occurs when H^- ions collide with neutral gas particles in the beam pipe. As

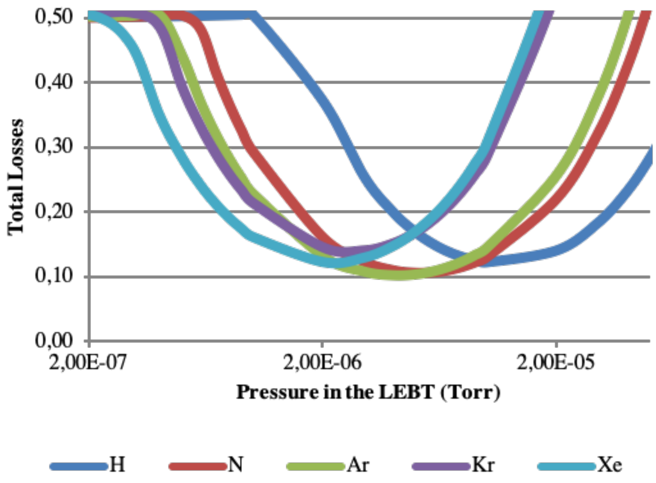

Figure 1: Balancing losses due to space charge (low pressure) versus those from residual-gas H^- stripping (right). Figure reproduced with permission, from [4].

the ESS beam pipe is under ultra-high vacuum throughout the majority of the linac, gas stripping is only a concern in the LEBT, where inert gas is injected as a space-charge compensation measure. Since the beam in the LEBT is highly space-charge dominated, it is important to maximize space-charge compensation to avoid emittance blow up. Tests at the Spallation Neutron Source (SNS) indicate that for an H^- source of comparable performance to that needed for ESSνSB, space-charge compensation and H^- stripping have a trade-off point, with best-possible losses through the LEBT of roughly 10% (see Fig. 1).

Moreover, the configuration of the added H^- ion source in relation to the present proton ion source and the beamline within the tunnel is non-trivial. Although an arrangement with both sources at 30° relative to the downstream beamline will present a greater challenge in terms of installation and commissioning, the alternative with an unmoved proton source and the H^- source at 60° is more challenging from a beam physics perspective. Preliminary simulations indicate that balancing source current, space charge compensation, and gas stripping is highly restrictive in terms of RFQ transmission for the 60° option; however, it will remain under study in case of unavoidable civil engineering or logistics constraints.

2.2 Blackbody Radiation

Stripping can also occur when the typically innocuous blackbody radiation from room-temperature parts of the beam pipe and other machine components is witnessed from the H^- beam frame. Since the linac is superconducting at higher energies, this variety of stripping is not a major concern (except, for example, in the room-temperature segments between cryomodules). The transfer line connecting the linac to the accumulator ring will not necessarily be superconducting, and we expect a small but non-negligible loss rate (∼0.01 W/m) therein.

2.3 Lorentz Stripping

In a similar manner to blackbody stripping, the Lorentz forces of external magnetic fields have a $\beta\gamma$ dependence when shifting to the beam frame that can lead to stripping in bending and focusing magnets. In other words, the $|\vec{B}|$ field from a multipole magnet in the bunch frame is transformed to $|\vec{E}| = \beta\gamma c|\vec{B}|$. Such magnets have fields which increase linearly (dipole), quadratically (quadrupole), etc., with respect to a particle's displacement from the transverse origin. This results in stronger stripping forces for beams of larger transverse sizes and higher quadrupole gradients. [5]

For the nominal ESSνSB design, Lorentz stripping is predicted to be negligible, with a tolerance for transverse misalignment through the quadrupoles in the high-energy sector of approximately 15 mm before any substantial effect should be observed. This margin may be useful in alleviating intra-beam stripping. We will discuss this notion in the conclusion.

2.4 Intra-Beam Stripping

Within a bunch, the collisions of H^- ions with their neighbors can be a prevalent stripping loss mechanism, although it was largely overlooked until recently.[6] Indeed, this mechanism is expected to be the predominant cause of losses for H^- in the upgraded ESS linac,[7] where the target maximum beam-power loss rate is $\lesssim$0.5 W/m. For bunched beams, the fractional loss rate for this effect can be modeled in the lab frame as

$$\frac{1}{N}\frac{dN}{ds} = \frac{N\sigma_{H^-}\sqrt{\gamma^2\theta_x^2+\gamma^2\theta_y^2+\theta_s^2}}{8\pi^2\gamma^2\sigma_x\sigma_y\sigma_s}F\left(\gamma\theta_x,\gamma\theta_y,\theta_s\right)$$

where N is the particle count within a bunch, ds is along the beam axis, and the shape function $F\left(\gamma\theta_x,\gamma\theta_y,\theta_s\right)$ can also be defined in terms of transverse velocities. The spatial and angular rms values used here are defined in terms of the Twiss parameters as

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}} \qquad \theta_{x,y} = \sqrt{\frac{\varepsilon_{x,y}}{\beta_{x,y}}}$$

Where, also, the stripping cross-section is

$$\sigma_{H^-} \approx \frac{240a_0^2\alpha_f^2}{(\alpha_f+\beta)^2}\frac{(\beta-\beta_m)^6}{(\beta-\beta_m)^6+\beta_m^6}\ln\left(1.97\frac{\alpha_f+\beta}{\alpha_f}\right) \lesssim 4\cdot10^{-15}\ \mathrm{cm}^{-2} \tag{2.1}$$

Here, β is the transverse particle velocity relative to the reference particle, and $\beta_m = 7.5\cdot10^{-5}$ is the low-velocity cutoff where ion repulsion precludes stripping. In practice, the maximum of $4\cdot10^{-15}cm^{-2}$ should be used to find an upper limit of stripping. Otherwise, the substitution

$$\beta \to 0.72\beta_m + 2\beta\sqrt{\gamma^2\theta_x^2+\gamma^2\theta_y^2+\theta_s^2} \tag{2.2}$$

is necessary.

Figure 2 shows our loss predictions using these equations. Here we performed a post-processing on distributions taken from a TraceWin simulation of the upgraded ESS linac (from the nominal 2.0 GeV to 2.5 GeV). Although the loss rates from stripping are fractional and are not expected to affect the beam dynamics, the activation due to stripping of H^- and the resulting loss of H^0 can be considerable, especially at high energies.

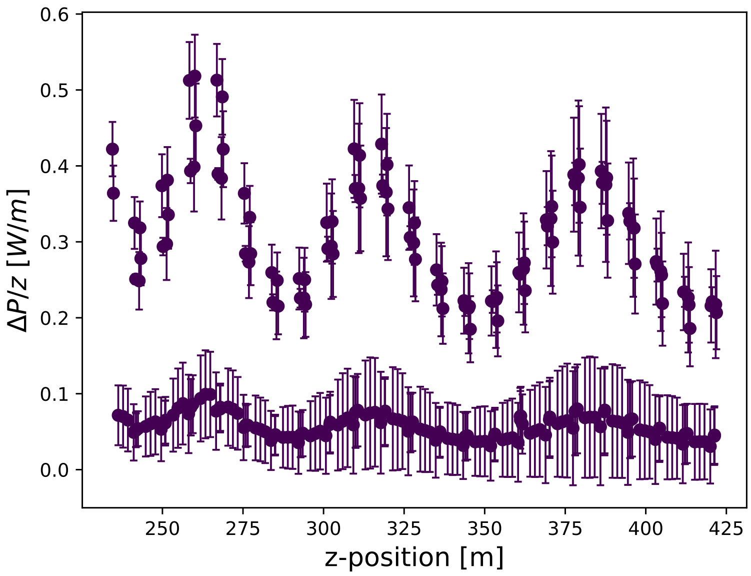

Figure 2: Power loss in the high-beta sector due to intra-beam stripping. This calculation includes the upgraded region of the linac which boosts the beam from 2 to 2.5 GeV.

The beam-power loss rate is shown through the high-beta sector – the quadrupoles there pose the greatest risk for reaching the imposed loss limit of 0.5 W/m. We should also note that a smoothing algorithm is necessary to estimate losses per meter: for individual test points, losses were not found to exceed 0.15 W/m.

3. Conclusion

The prevalent stripping mechanism of intra-beam collision is expected to induce losses within the prescribed limit of 0.5 W/m for the ESS linac with nominal design parameters. In general, since prohibitive losses are not expected due to H^- stripping or mode-resonance effects, beam dynamics concerns in the linac are not likely to hinder the feasibility of ESSνSB.

For further loss reduction, we note that such stripping has been alleviated at SNS by relaxing the focusing through quadrupoles in the high-beta sectors.[7] If the same treatment were used to reduce the ESSνSB H^- loss limit to 0.1 W/m, then Lorentz stripping may become non-negligible (for spot sizes exceeding approximately 10 mm) and balancing the two effects will be necessary.

Ongoing studies concern optimizing the beamline parameters for the interleaved proton and H^- species, retooling existing equipment for the task, and analyzing the cost impact of different sub-pulsing schemes in terms of cooling and facility power requirements.

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