A HIGH ENERGY COLLIMATION SYSTEM FOR THE EUROPEAN SPALLATION SOURCE

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Abstract

At the European Spallation Source (ESS), a $\simeq$ 160 m long high energy beam transport (HEBT) system will guide the high-power (5 MW) proton beam from a 2.5 GeV superconducting linac (SCL) to a spallation target station. The HEBT could include a single-pass collimation system to protect all downstream accelerator components, including the vital target. The system would be built to withstand both continuous low-power losses (*i.e.* introduce halo reduction) and infrequent short-term, high-power beam exposure, essentially a fault scenario. Although a collimation system could reduce the uncontrolled beam losses and thus activation levels elsewhere, it takes up precious longitudinal space intended for future beam power upgrades and sets demands for the beam optics, as will be discussed. Possible materials and specifications will also be described.

INTRODUCTION

Modern high-power machines are often limited by the level of uncontrolled beam losses. At the ESS [1], with its unprecedented average power of 5 MW (125 MW during the 2.86 ms pulse), control of losses will be imperative.

A transverse collimation system (CS) is traditionally used to intercept some of the beam halo without affecting the main beam, *i.e.* introduce controlled beam scraping at well-defined locations to diminish uncontrolled beam losses that could cause activation and machine damage further downstream. To ensure hands on maintenance, the average uncontrolled losses should be restricted below the often acclaimed 1 W/m at energies $\gtrsim 1$ GeV, corresponding to 200 ppb/m at 2.5 GeV ($0.4\ \mathrm{nA/m}$ at the nominal average current of $2\ \mathrm{mA}$). Obtaining even smaller numbers is strongly favoured, and a continuous loss improvement will be advantageous, as experience at the SNS has shown. It should be noted that although the halo typically constitutes a very small fraction of the core, the halo beam power in a high power accelerator can still be quite considerable, *i.e.* potentially many kW's.

Collimation is foreseen in the medium energy beam transport (MEBT) [2], where collimation can be introduced without imposing unfeasible levels of deposited power. In the SCL, the apertures of cavities and quadrupoles are kept sufficiently large to maintain acceptable loss rates. Despite the MEBT collimation, various mechanisms will replenish the beam halo (mainly beam-lattice mismatch and space charge resonances for the ESS), possibly calling for collimation further downstream. Here, the HEBT will be the first and only chance to collimate the beam between the MEBT and the spallation target.

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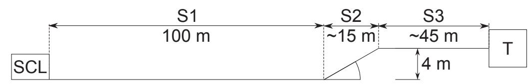

Figure 1: A sketch of the HEBT taking the beam from the underground SCL to the target station (T) at surface level.

In Fig. 1, a sketch of the HEBT layout is shown. S1 facilitates room for a possible SCL upgrade (installation of extra cryomodules with accelerating cavities), S2 is a semi-vertical achromatic elevation, while S3 contains a non-linear beam expander system to set the beam footprint and flatten the transverse profiles on the target surface [3].

FIXED COLLIMATOR

The non-linear magnetic system in S3 is particularly sensitive to beam halo due to over-focusing of these far-reaching particles, thus appearing downstream at large transverse distances [3]. To protect the proton beam window (PBW) and main target from the over-focused halo particles, a fixed collimator is planned immediately upstream of the PBW. We envisage a semi-rectangular collimator with negatively sloped inner surfaces setting a minimum aperture corresponding to the beam footprint on target, $16 \times 6\ \mathrm{cm}^2$ ($\mathrm{H} \times \mathrm{V}$). Judging from nominal beam expander optics resulting in different levels of beam flatness, this collimator could be subjected to 5–25 kW of average beam power. Clearly, the impact of non-nominal beams and fault scenarios need to be addressed before setting this collimator's maximum power acceptance. However, contrary to other facilities at similar power levels, the ESS will not feature a ring (RCS or accumulator), *i.e.* no transient steering elements (ramping magnets or ring kickers, *etc.*) are involved, reducing the risk of ultra-fast beam loss considerably. Having avoided kicker failures *etc.*, it is difficult to pinpoint locations in the HEBT being particularly susceptible to loss of a full pulse. This lessens the need for collimators being able to handle a full power pulse of nominal duration. Also, the ESS machine protection system is being designed to have a total response time of a few μs, beyond which the beam can be stopped at low energies. This feature greatly reduces the energy deposited during a fault scenario, even at the nominal current and maximum energy, $125\ \mathrm{MW} = 0.125\ \mathrm{kJ/\mu s}$. For reference, the peak beam power extracted from the SNS accumulator ring is

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more than two orders of magnitude larger, despite ESS's larger average beam power; a fact which relaxes handling of fault scenarios and *e.g.* choice of collimator materials.

MOVABLE COLLIMATORS

In addition to the fixed collimator, the HEBT could possibly also feature a set of movable collimators to be placed in a dispersion-free region for betatron collimation. Such collimators could reduce the losses in the HEBT and also lessen the power load on the fixed collimator. To properly cut a transverse phase space in a single-pass machine, a one-dimensional CS (2 jaws) needs to be accompanied by a similar system placed further downstream, optimally with a phase advance $\mu_{1,1} = \pi/2$ in between. In order to collimate the 4D transverse phase space, at least $2 \times 2 \times 2$ collimator jaws are thus necessary for single-stage collimation. If the more efficient two-stage collimation scheme (scraper + absorbers) is considered, the number of movable CSs grows rapidly, 12 CS units each of two jaws for two-stage 4D collimation. Due to the increased complexity, multi-stage collimation will not be considered unless single-stage collimation is found inadequate.

Momentum collimation will also not be considered as it seems unnecessary and also difficult with the beam of small longitudinal emittance. In the HEBT achromatic elevation, the dispersion and root mean square (RMS) momentum spread is small, $D_y \lesssim 2$ m and $\delta p/p_0 \simeq 10^{-3}$, compared to $\epsilon_{x,y} \simeq 0.3\,\pi$ mm mrad (normalized, RMS).

In the following, we shall focus on these movable betatron CSs.

Location

In the first section of the HEBT, S1, a continuation of the SCL focusing structure is chosen for now. Generally, lattice changes increase the risk of beam-lattice mismatch, potentially driving halo production. The end of the SCL features a doublet focusing channel with a low transverse phase advance ($\simeq \pi/6$ per period) to avoid space-charge resonances. On the contrary, a relatively large phase advance ($\mu_{1,1} \simeq \pi/2$) should be achieved between two primary CSs in each transverse dimension, necessitating $\simeq 3$ periods in between. It should be noted that exploiting the full length of S1 for power upgrades and maintaining the collimation system are thus incompatible. A large vertical phase advance of 2π is intrinsically available in the achromat of S2. Due to space constraints, however, a vertical CS is not possible in this region. Placing the CSs in S3 is also excluded; partly due to space constraints, but also due to the section's considerable prompt dose rate levels, which could be harmful to motors *etc.* on the CSs.

Until a future ESS upgrade is definite, the optimal place for the CSs seems to be S1. Although the upgrade and the CS are mutually exclusive, the CS could be found unnecessary by the time of upgrade.

In the following, we will refer to the usual normalized transverse phase space (X, P) in which the particle motion is a harmonic function of the transverse phase advance (μ_x)

$$X(\mu_x) = \sqrt{\epsilon_x}\cos(\mu_x + \phi) = x/\sqrt{\beta_x} \quad (1a)$$

$$P(\mu_x) = (\beta_x x' + \alpha_x x)/\sqrt{\beta_x}\,, \quad (1b)$$

where (x, x') represent the non-normalized phase space with its Twiss parameters (α_x, β_x) and emittance (ϵ_x). The latter is only a particle invariant when neglecting space-charge and other non-linear forces.

Choice of Material

To make a first evaluation of possible collimator materials for the ESS HEBT collimators, a 100 cm long collimator jaw is considered. The three materials carbon (graphite), stainless steel (SS316), and tungsten are commonly used for jaws, but have very different attributes. For example, their nuclear interaction lengths (λ_a) are 38.8 cm, 16.8 cm (Fe), and 9.95 cm, respectively. In units of λ_a, the jaw's mechanical length thus corresponds to 2.58, 5.96, and 10.1, respectively. Due to carbon's long λ_a, this material is not suitable for an absorbing collimator, unless a very long collimator is feasible. Whereas confinement of the nuclear and electromagnetic showers, (*i.e.* cleaning efficiency), generally favours a large material nuclear charge, graphite (and especially carbon fibre-reinforced carbon) possesses extraordinary thermo-mechanical properties, particularly being very robust towards large instantaneous energy depositions.

In the following, tungsten is assumed, although other material attributes, yet to be studied (instantaneous temperature rise, activation, *etc.*), could rule out this material. Future analysis might also explore new, 'crossbred' collimator materials [5].

STUDIES WITH BEAM DYNAMICS

For these initial collimator studies including beam dynamics, a test beam is generated from the Twiss parameters of a matched FODO cell with a period length of $\lambda_{\mathrm{FODO}} = 10$ m and transverse phase advance of $\mu_{x,y} = \pi/2$ per period, cf. Fig. 2. The simplified optics allow for initial studies of a single-stage collimation system within only a few periods.

As input beam for the MARS15 [4] Monte Carlo simulations, particles in the 4D transverse normalized phase space are sampled from distribution functions. The vertical normalized phase space is modelled by a 2D Gaussian distribution. For the RMS of the core distributions, we assume $0.32\ (0.31)\ \pi$ mm mrad for the normalized ϵ_x (ϵ_y), respectively, which is close to the expected normalized RMS transverse emittances at the exit of the ESS SCL. In the horizontal normalized phase space—the dimension in which collimation is studied—only an exponential halo distribution band is generated in the region $3.3 \leq n_1 \leq 10$, where n_1 is the particle radius in the normalized phase space in units of RMS. Since space charge forces are not included

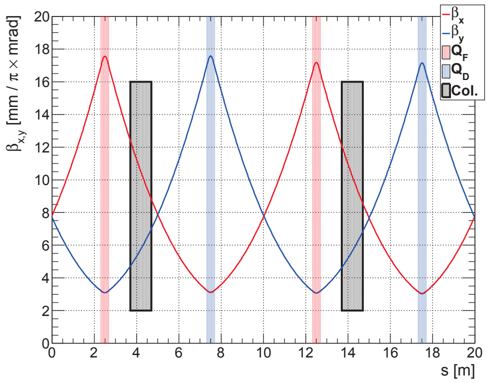

Figure 2: Two periods of the studied FODO channel with transverse β functions, quadrupole magnets, and possible location of collimators.

in the tracking, removing the core distribution does not influence the results.

The rectangular tungsten collimators are 1 m long. Each jaw surface begins and ends with 20 cm long tapering sections with tapering angles of 50 mrad, leaving 60 cm of flat surface. As a limiting case, we shall consider collimation to the level of $n_1 \geq 3.4$ beyond which a fractional halo of $f_{\text{halo}} = 3.09 \times 10^{-3}$ is assumed to be, corresponding to 15.4 kW of beam power in the band being probed by collimators. Placing the collimator front edges at $z_f = 350$ cm and $z_f + \lambda_{\text{FODO}}$ calls for a minimum half-gap of $a_x = 3.60$ mm to reach the desired degree of collimation. The simulations are run in two steps. First by setting the collimators to black absorbers while registering the primary particles touching them. The registered protons are then used as input for a consecutive run using realistic collimator materials. Out of the 20k primaries, 16k primaries touching the collimators are used in the second run, corresponding to $P_{\text{col}} = 16/20 \times f_{\text{halo}} \times 5\ \text{MW} = 12.4\ \text{kW}$.

In Fig. 3, the relative distribution of deposited energy (as found with MARS15) is shown. Besides the energy deposit in the two horizontal CSs, energy deposit in a Ø100 mm (ID) thick cylindrical shell (representing the beam pipe and tunnel) is also monitored. Adding the tapering sections to the front ($1\times$tapering) or also to the back ($2\times$tapering) of the collimator reduces the loss to the tunnel, which is on the scale of 1% of P_{col}. A few particles ($\simeq 10^{-3}$) undergo scattering with limited energy loss, thus leading to augmented radii in the normalized phase space. These grazing particles will be transported through the HEBT until possibly being intercepted by a limiting downstream aperture.

Introducing single-stage collimation in the S1 thus comes at a cost, as it inevitably introduces secondary losses downstream, possibly violating the principle of 1 W/m. Justification and further design of the systems will greatly benefit from input on typical collimator operational experience at existing high-power facilities and studies of fault scenarios. In case of a SCL beam with a large closed orbit deviation, for instance, collimators in the S1 could possibly

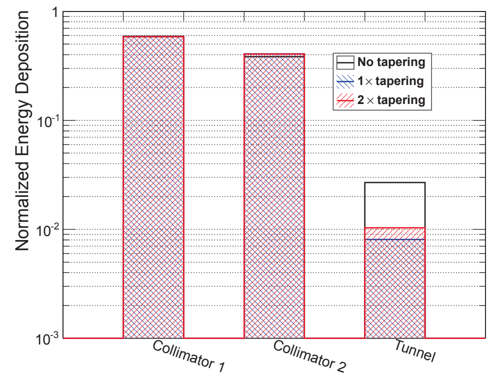

Figure 3: The relative distribution of energy deposition in the test beamline.

mitigate resulting losses further downstream.

SUMMARY

Despite following a low-loss design philosophy, the ESS SCL will produce a beam accompanied by a considerable halo in terms of power. To investigate the possibility of movable collimators in the ESS HEBT, a single-stage collimator system has been considered including test beam dynamics and Monte Carlo showers. Such a system will take up precious space in the HEBT and appears to be incompatible with a future power upgrade. Hence, the justification and design of high-energy movable collimators should be strongly driven by their usage and ability to mitigate typical fault scenarios in high-power facilities.

The design of the collimators will include implementing realistic S1 optics, studying deposited power densities (incl. instantaneous temperature rise), material activation and shielding, especially respecting the 1 W/m. Since the ESS HEBT only allows diminishing relative losses, adjustable β collimation could call for two-stage collimation at the expense of space and complexity.

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