Internal Note: A Study of ESS HEBT Collimator Options

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With a nominal beam power of 5 MW, the demands for low relative beam losses in the European Spallation Source (ESS) accelerator are unprecedented. In the High Energy Beam Transport (HEBT), where the beam first reaches full power, this is especially relevant. The acceptance of the HEBT should thus encompass beams of non-nominal parameters and ideally be tolerant to partial hardware failure for at least a full pulse of 2.86 ms. In this paper, the need for HEBT collimators is assessed by discussing beam simulations and typical hardware failure modes. Only collimation of the primary proton beam is treated here, *i.e.* not *e.g.* the neutrons backstreaming from the target.

I. INTRODUCTION

Collimator systems can be deployed in accelerators to offer protection against primary beam losses. With the ESS being a single-pass machine, any collimator can only mitigate downstream loss effects. The beam losses can be divided into two classes that need to be treated differently: operational beam losses and accidental beam losses, cf. Tab. I. It is often difficult to design a collimator that fully covers both scenarios, and the purpose of a collimator system thus needs to be very specific and used to drive the requirements.

As will be discussed, the decision to change from a HEBT beam expander system based on non-linear magnets to a raster-based system is believed to have lead to a significant change in the collimator requirements and subsequently the need to revise the HEBT collimator baseline, cf. Appendix A. The revising process was initiated by hosting a recent workshop on the topic of "Beam Losses and Collimators in Transfer Lines" [1]. With experts from CERN, SNS, J-PARC, and PSI present, the following recommendations were put forward

- Experience from similar operating facilities should be studied with the SNS being the lead candidate.
- Beam physics studies should be performed to fully determine the need for collimation. Assess beam problems that collimators could help mitigate, both covering every-day operation & infrequent catastrophic events.
- If possible, consider a more global collimation strategy, *i.e.* the performance of combining collimation systems at low and high energy.

An ESS working group was established late August 2014, including experts from the Accelerator Division, Beam Instrumentation, Target Division, Machine Protection System, and HEBT groups.

This note aims at addressing the first two points above. To evaluate the performance of a combination of the medium and high energy collimator systems, *e.g.* determining how well the HEBT losses can be controlled by introducing collimation in the Medium Energy Beam Transport (MEBT), is however beyond the scope of this note. Likewise, a full, revised risk and hazard treatment will not be given here and requires, preferably external, experts of such analyses. Such a study is however planned for the future.

II. SIMILAR FACILITIES

Although ESS will be unprecedented in terms of beam power, operational experience from similar high-power facilities can still be invaluable when setting needs and component requirements. It should be noted that ESS will be unique in its power class by being a long-pulse machine, *i.e.* not having a rapid cycling synchrotron or accumulator ring and the associated operational complexity and loss patterns. Additionally, the ESS will accelerate only protons from ion source to target, thus excluding loss mechanisms such as intra-beam stripping of negative ions [2]. The Oak Ridge SNS is by far the most comparable and recent operational machine. The SNS features several collimator systems of which those upstream of the ring are most relevant to the ESS [3]:

SNS MEBT Scrapers: very efficient and have reduced the necessity of the SNS HEBT collimators. Beyond 1–2%, further MEBT collimation has diminishing benefits in terms of improving the downstream losses. The effectiveness of the MEBT scrapers varies with the ion source and the machine lattice. The system has been retrofitted to the MEBT.

SNS HEBT Scrapers + Collimators: transverse (occasionally used) and momentum (rarely used) collimators. Presently used to scrape only a small amount of beam tails and to make small improvements on the beam loss rates.

	Operational beam losses	Accidental beam losses
Origin	Halo growth (mistuning & resonances)	Hardware failure affecting the beam parameters
Conditions	Continuous, low power losses	Full power beam on downstream component(s)
Unmitigated impact	Activation, material degradation	Semi-instantaneous component damage
Upper limit	1 W/m	Component damage
Collimator type	Movable scrapers / jaws	Fixed-aperture masks to intercept stray beam
Design challenges	Simulate loss patterns	Failure coverage
Alternative	Increase normalized aperture	Rely on fast loss monitors and beam interlocks

Table I. Typical beam loss modes.

SNS Ring Collimators: operated as single-stage collimators (scrapers almost never used, but left fully retracted).

SNS RTBT Collimators: fixed (passive) apertures for target protection. Cover partial failure of ring kicker system. So far there has never been a major incident for the system to mitigate.

The system nomenclature of SNS is used above. The SNS and other high power facilities (LANSCE, PSI, TRIUMF) have resorted to empirical low-loss tuning of beam transport lines. Apart from a larger beam size (to reduce the H^- intra-beam stripping rate), the SNS "Production" mode contains optics that may be severely mismatched for the beam core but provides an efficient halo transport and possibly lower halo production. This is the case for *e.g.* the SNS HEBT. To gain phase coverage, the location of collimator units are dependent on the beam optics, *i.e.* the transverse phase advance between collimator units. Resorting to empirical low-loss tune may thus reduce the phase coverage.

A novel comparison of the H^- and proton beam losses has been performed at the SNS [2] using similar beam current, size and dynamic characteristics. A specific proton beam mode is used only for machine studies and due to technical limitations, the proton beam could only be maintained with a lower duty cycle (50 μs × 1 Hz instead of the typical 850 μs × 60 Hz). Apart from determining intra-beam stripping to be the dominant mechanism for H^- beam losses, the SNS proton experiment also found the proton beam losses in the SuperConducting Linac (SCL) to be about an order of magnitude lower than the loss-minimized "Production" H^- optics [2]:

> The reduced beam loss for protons implies that a proton SCL should be able to provide several times higher power with the same low activation and "hands on" maintainability as the existing SNS linac.

It should be noted that although the ESS beam power will be 5.0 MW, compared to SNS presently at 1.4 MW, the average beam current, by which the proton beam losses should scale, will only be a factor $\lesssim 1.8$ larger, due to a factor 2 in beam energy. Even when taking the extra energy lost per particle into account, the ratio is only a factor $\lesssim 3.6$ larger.

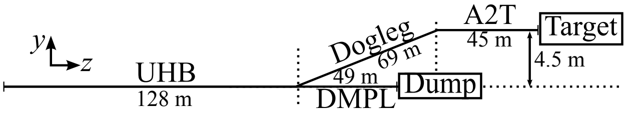

Figure 1. A sketch of the HEBT layout.

Combining all points above, it would appear that the need for full energy halo collimators in a single-pass (no ring) proton machine like the ESS is questionable. Although the ESS average beam power and current is larger, this is compensated by *e.g.* maintaining a larger normalized aperture (ratio of inner aperture radius and beam RMS size). In the ESS HEBT, the normalized aperture is typically $\gtrsim 30$. For reference, the normalized aperture in the SNS cold linac is $\simeq 10$ [2] and in the SNS HEBT it is 15–24 [4], hence the uncontrolled beam losses along the ESS HEBT would still in general be expected to be at least as low as in the SNS HEBT.

III. BEAM PHYSICS STUDIES

The primary line of the ESS HEBT transports the beam from the accelerator to the target, while leaving room for accelerator upgrades, overcoming an 4.5 m elevation, and setting the transverse profiles on the target. These requirements are met through three separate sections: the HEBT Upgrade High-Beta (UHB), dogleg, and Accelerator to Target (A2T). A sketch of the mechanical layout can be seen in Fig. 1. The lattice and beam optics of the HEBT can be seen in Fig. 2. In line of sight with the UHB and SCL, the tuning dump line (DMPL) is located below the dogleg and will accept only a low-power beam, $\simeq 5$ kW. The DMPL is thus not relevant for the present study.

In an attempt to revise the collimator needs and requirements, the latest HEBT optics is studied in two complementary ways:

Operational beam losses: A semi-continuous loss background that occurs during beam operation. The losses may lead to long-term component failure (through material deterioration) and excessive activation of machine components. The losses can possibly be minimized by retuning the accelerator.

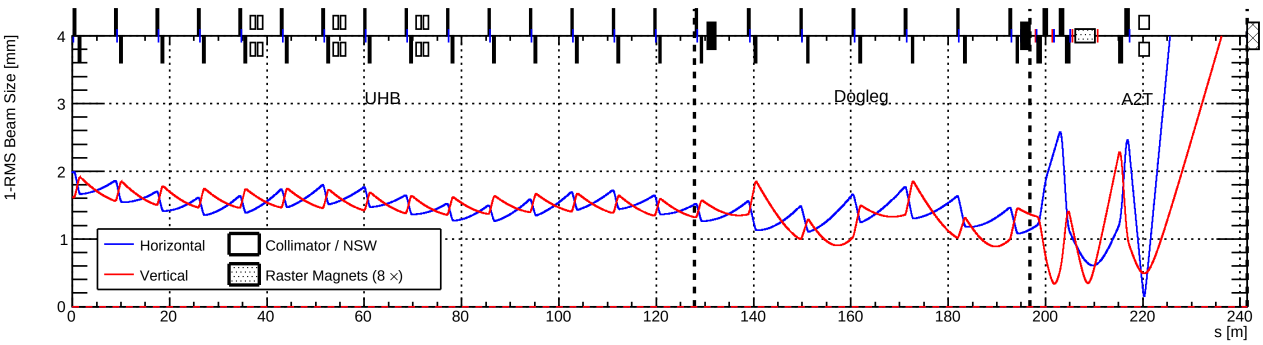

Figure 2. The HEBT optics leading the beam to the target.

Sources of operational losses are un-captured beam, loss of parasitic beam halo (generated by beam-gas collisions, space charge resonances, *etc.*). This can partly be simulated by nominal beam simulations and error studies.

Accidental beam losses: An accelerator component failure causes a significant and sudden change in the beam parameters, *e.g.* the beam could be severely deflected or mis-focused. This can potentially point a considerable part of the beam at downstream components, possibly leading to material damage. Such failures can be simulated by strong mistuning of critical elements or displacement of beam centroid parameters.

The first range of problems can possibly be mitigated by a transverse collimator system. In the latter case, fixed-aperture masks could offer passive local protection at specific downstream elements, leaving more time until accelerator component damage and for the Machine Protection System (MPS) to react and abort beam operation.

A. Operational Beam Losses

A detailed error study was recently performed [5] using beam optics that are very similar to the latest version (ESS Raster v.28). As described there, a wide range of dynamic and static errors were defined with realistic magnitudes and used as input for an error study using multiparticles, thus allowing to track indications of beam losses. Specifically, the envelope optics were used to apply dynamic and static errors and correct the latter using a range of virtual diagnostics. For each of 1000 simulated HEBTs, the achieved optics was then the basis of a multi-particle simulation with 10^6 macroparticles. The applied input beam distribution would consist of two overlapping Gaussians: a primary (99%) Gaussian distribution and a secondary (1%), with 5× emittance, representing beam halo. The simulated HEBTs have been combined and are represented in Fig. 3 by contour lines that transversely enclose the average beam power levels. The contours are to a large extent comparable to the 10 RMS nominal (no errors applied) beam size envelope (blue line). Due to the uncorrected input beam mismatch, some beta-beating is visible in the first 200 m. This is also believed to be the cause of an observed increase in transverse emittance, typically 10%, max. 20%, within the first 50 m of the HEBT. This could be reduced by applying the corrective matching in the beginning of the HEBT.

A comparison of the simulated beam boundaries and the vacuum aperture shows ample room on a relative scale. In general the HEBT simulations do not indicate beam losses until near the target, following the beam size magnification. Low intensity losses (on average 11 W, max. 100 W) are observed at the target monolith lip ($s \simeq 236$ m) with typically 0.6 kW, max. 1.4 kW, hitting the inner walls of the monolith beam duct leading to the target. The loss magnitudes are not considered critical taking into account the proximity of the target, and it should be noted that this can be reduced by adjusting the beamlet dimensions. It is very comforting to see that the simulations indicate that the beam waist at the Neutron Shield Wall (NSW) aperture ($s \simeq 220$ m) can be preserved despite applying the errors.

Complementary to the procedure mentioned above, *i.e.* conducting HEBT simulations that include a synthetic halo component in the input beam, accelerator end-to-end simulations are continuously being performed at the ESS. Typically, the beam is initiated at the beginning of the RFQ as a 5-sigma Gaussian and tracked through the linac and HEBT towards the target. Preliminary results reveal low-energy protons (300–600 MeV) that despite falling outside the RF bucket manage to coast with the primary beam at nominal energy. The first dipole of the HEBT dogleg will effectively filter out these protons of lower rigidity by introducing an excessive deflection, ultimately leading to losses in the dogleg. The low-energy particles appear to originate from tails of the RFQ output and most likely also from the 352–704 MHz frequency jump. The simulations tend to predict very small quantities of the order 5×10^{-7} or 0.5 W (time-averaged and normalized to 5 MW). It should be noted, however, that the quantities come with a large uncertainty, as only 5 out of 10^7 initial particles are observed through this loss

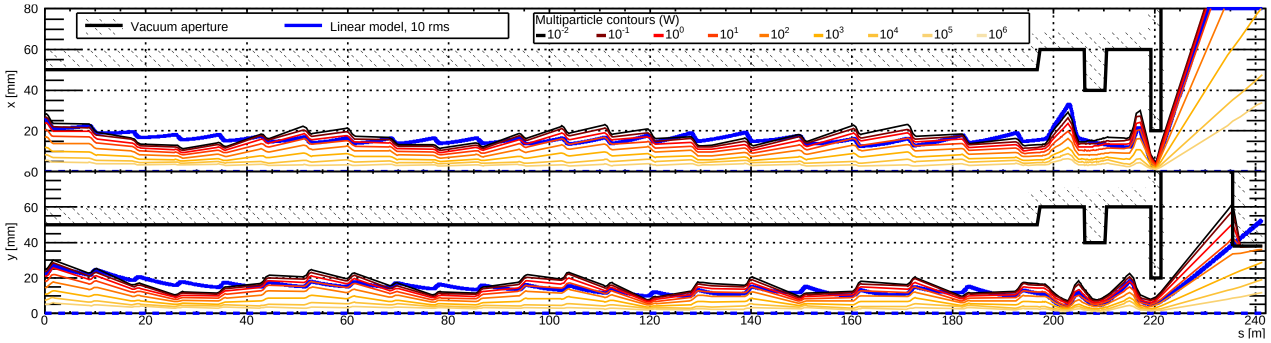

Figure 3. Multiparticle simulations including dynamic and corrected static errors. The vacuum aperture radius is indicated by black lines.

channel. Whether the MEBT scrapers can preventively intercept particles of this type is currently being studied [6].

A Movable Collimator System (MCS) has been suggested in the HEBT, cf. Sec. A 1. This would rely on specific transverse phase advances between similar collimator stations to provide Normalized Phase Space coverage. Although the observed low-energy particles undergo large orbit excursions, their phase advance will not follow that of the beam at the nominal energy, and may thus not necessarily be intercepted by a MCS early in the HEBT.

B. Accidental Beam Losses

Uncontrolled accidental beam losses could potentially occur within very short timescales (microseconds) when an accelerator component starts to deviate considerably from nominal settings during operations. This would typically originate from a component failure but could also be caused by operator or control system errors setting a wrong component parameter setpoint. The MPS should abort the beam when such component faults or deviating beam parameters are detected, thus reducing the impact of the event. For reference, each SNS pulse corresponds to 133 μs of the nominal ESS beam pulse. The MPS and Beam Interlock System (BIS) should be supported by a highly efficient suite of fast detectors and beam abort system. In order to detect such failures and reduce the severity of the failure's consequence, the corresponding accelerator components are planned to be connected to the Beam Interlock System (BIS) being a vital part of the ESS Machine Protection Strategy. It is for example foreseen to connect the magnet power supplies to the BIS using hardwired connections and if such power supply fails, it will be notified on BIS level within a very short time (microseconds). The BIS would then trigger a beam stop signal and inhibit further beam operation by switching ON the HV of the LEBT and MEBT chopper, deflecting beam to the LEBT and MEBT chopper absorber within a less than a microsecond. The BIS will also remove RF from the magnetron of the proton source to stop beam operation which takes around 100 ms. Another layer of protection is being provided by the beam loss monitoring (BLM) system which can detect critical beam losses within a few (1–5) microseconds by online comparison of the measured signal with pre-defined thresholds. The BLMs are as well directly connected to the BIS to inhibit beam operation upon detection of a non-nominal condition leading possibly to damage of the accelerator. The goal at ESS is to be able to detect critical beam losses and having stopped completely beam operation within a total time of 10–20 ms. It is beyond the scope of this note to discuss the machine protection strategies at ESS, or the BIS functionality, but a highly dependable BLM system will be crucial to effectively detect sudden changes in terms of beam losses.

It is clear that the timescale of the initiating component failure is highly relevant in order to determine the impact and methods required to mitigate the event. Some systems (*e.g.* magnets) have an inherent minimum failure time constant τ_f that follows from physical laws (inductance). The most dangerous elements are thus typically the ones that are built to be dynamic during nominal operation. The failures are here divided into two categories:

Fast: time constants of the order of the beam pulse or faster, $\tau_\mathrm{f} \lesssim 2.86$ ms. The beam parameters can thus change considerably during a beam pulse. Examples are failures of RF structures (arcing) in the linac and low-inductance magnets.

Moderate: although having $\tau_\mathrm{f} \gtrsim 2.86$ ms, the impact could potentially build up over the course of a few pulses or even just the 68.6 ms between two beam pulses. With $\tau_\mathrm{f} = 1$ s, a parameter can change 7% during the latter time. An example is *e.g.* a high-inductance magnet.

As mentioned, fixed-aperture beam absorbers (or collimators) can set a minimum aperture, thus providing passive protection and extending the necessary time to respond to a failure. With a single pass machine, it is evident that global protection using collimators cannot feasibly be introduced. With only local protection possible, one has to instead focus on critical elements and try to predict the most likely failure modes. In the following a non-exhaustive set of collimator use cases will thus be discussed. Unless the components are inherently coupled (*e.g.* several magnets sharing the same power supply), coincident failures will not be discussed.

Major parts of the HEBT consists of smooth, periodic beam optics, consistent with the linac optics. In such regions, one cannot easily identify components that would require local collimator protection in particular. A few critical regions have been identified in the HEBT, and will be discussed in the following.

1. *First dogleg dipole*

In case of an RF failure, which belongs to the fast failure category, the beam may efficiently reach the dogleg with a beam energy deficit. Although being mis-focused, the most dramatic effect will occur at the first dipole of this full-wave linear achromat and in the dispersive sections found downstream of this. The vertical aperture of the first dipole chamber limits the energy acceptance to the extent that particles with $(E - E_0)/E_0 \lesssim -0.6$ ($E \lesssim 800$ MeV at $E_0 = 2000$ MeV) will be lost already at the dipole vacuum chamber. This energy range includes the previously mentioned low-energy, longitudinally uncaptured particles. Other low-energy particles (within the dipole's energy acceptance) may still be lost along the dogleg, where the vertical dispersion is largest, ±0.9 m. One may consider placing masks near the maxima of the dispersion function.

The single power converter that feeds the two dipoles may also fail, leading to a similar outcome. The solid-yoke dipoles have, however, a moderate $\tau_f \simeq 1$ s which reduces the severity of the otherwise equivalent failure.

2. *Raster System*

The HEBT Beam Expander System (BES) is based on a set of 8 fast ($\simeq 40$ kHz), dithering Raster Scanning Magnets (RSMs), each with a dipole action amplitude of ± 5 mT.m. The RSMs are individually powered to reduce the frequency of common mode failures leading to a full failure of the combined system, *i.e.* leaving the beamlet unrastered. Since the static beamlet could lead to burn-in at the target and Proton Beam Window (PBW), this is regarded as the most critical failure of the raster system. Bear in mind that collimator(s) downstream of the RSMs will not be able to mitigate such an event, as the beam will only be even more centred. This type of failure will have to be detected and mitigated through the ESS MPS and the RSMs will have to be connected to the BIS as well as their power supplies. How to interlock the raster magnet system and how to connect which signals to the BIS is currently under investigation.

Additionally, one or several of the magnets in the raster system may introduce an excessive deflection of the beam. This may happen due to an amplitude set-point error or a failure in the reference clock [7]. A fixed-aperture mask between the final magnets and the target station may protect the latter. In order to understand whether this is needed, a risk analysis is being planned (taking place within the next few month). Conclusions should be made based on the results provided by this risk analysis. Being in the vicinity of the target station, there is however an incentive to not collimate close to the target, as it may generate a neutron background at the experiments.

It should be noted that due to its dithering nature, the performance of the raster system will have to be highly dependent and the system must be designed to a very high level of reliability. All single point of failures must be mitigated.

3. *Final A2T Doublet*

The final quadrupole doublet is located almost 25 m from the target surface. Being the strongest quadrupoles of the ESS, a failure will have a considerable impact on the beam if unmitigated. Under normal circumstances, their purpose is to magnify the action of the raster system, set a beam waist at the NSW and the nominal beamlet size at the target. Besides leading to the wrong beam sizes at critical locations, the beam centroids will in case of failure of the magnet system unintentionally oscillate at the raster frequencies at the NSW and the raster amplitudes at the target will deviate from nominal values.

The magnets are proposed to be manufactured with a solid iron yoke, leading to a moderate $\tau_f \simeq 1$ s and thus making the magnetic field somewhat resistant to *e.g.* a magnet power supply failure and increasing the required response time.

In addition to the beam delivery instrumentation, it is planned to have beam instrumentation embedded in the NSW that can detect the described beam deviations on the intra-pulse scale [9].

IV. DISCUSSION

Following the advice of a panel of collimator experts at a recent workshop, the justification for collimators in the HEBT has been discussed by studying experience from the most similar facility and by studying the HEBT beam optics with errors and the failures of critical accelerator components.

Looking at the Oak Ridge SNS, it is evident that their HEBT collimator systems are far from essential for operation. These systems' efficiency of reducing losses are by far surpassed by the MEBT scraper system which has partially been retrofitted to that section. Comparing the

SNS and ESS accelerators, the latter offers several technical simplifications that should compensate for the otherwise intimidatingly larger beam intensity of the ESS. Not only have accelerator design lessons been learned from experiences at the SNS, but the ESS will not suffer from H^- loss mechanisms, nor need to provide a beam quality suitable for multi-turns in a ring.

Trying to simulate the expected operational beam losses can be very challenging, as the 1 W/m is equivalent to an unprecedentedly low relative loss level of 200 ppb/m. Even when running very time-consuming high-statistics simulations including errors, only very weak beam loss patterns are found (with poor statistics). Although possibly being able to reduce unforeseen beam losses that will be present in the real machine, thus reducing the risk of the overall design and providing a gain in protection, a collimator system comes at a cost through design, production, tunnel modifications, shielding, maintenance and decommissioning. The last points can be non-negligible, if the system is to routinely intercept a large beam power.

V. CONCLUSION

It is difficult to justify the Movable Collimator System of the ESS HEBT. We would thus propose to remove this system from the ESS baseline design. To minimize the risk of this proposal, we would strongly suggest to carry the design process as far as reasonably possible and in general try not to explicitly rule out such a system. It should be noted that if such a collimator system is ever retrofitted to the existing tunnel, the collimator units would have to be self-shielding to a level equivalent to 1 W/m (assuming that the entire tunnel is built for this level of beam losses). This will set a limit to the maximum beam power that the system can intercept. It is however worth emphasizing that introducing *e.g.* a total of a mere $\simeq 100$ W of controlled losses and thus reducing the HEBT uncontrolled losses similarly, leads to a major reduction in component activation when comparing to the minute 1 W/m.

Similarly we would propose to exclude the fixed collimator near the target monolith from the ESS baseline design. The original purpose of this collimator was related to strong non-linear magnets that have not been a part of the HEBT Beam Expander System for more than a year.

With a single-pass machine, only local protection can be introduced using fixed-aperture masks. Looking at a few other critical locations, it has been difficult to find regions or incidents that require protection by collimators in particular. It is clear, however, that in many cases the machine is believed to be able to be protected by other means, provided by the different machine protection strategies.

There is a general consensus that beam tails should be intercepted already at low energies, if possible. The ESS MEBT scraper system can feasibly collimate a considerable fraction of the beam while still only having to deal with modest heat loads and activation. At full energy, the collimation units would be considerable in transverse size to provide sufficient shielding, while only collimating a smaller fraction of the beam. To collimate at low energies relies on a degree of preservation of the emittance of beam halo particles at low and high energy. A study of the MEBT scraper system's efficacy to reduce losses far downstream, *i.e.* beyond the linac, is currently being performed [6].

Appendix A: The Baseline HEBT Collimators

The MEBT of the ESS will contain a scraper system, which has proved very useful at the Oak Ridge SNS, cf. Sec. II. Following a compact linac, the HEBT of the ESS offers the first chance for collimation after the MEBT.

The nominal HEBT optics is described in [8] and there shown to efficiently transport the intense proton beam from the linac to the spallation target. In general, the beam size remains small until the BES magnifies the beam to $\simeq 1$ cm^2 RMS size on the latter. The baseline collimator system was conceived while the BES was based on strong non-linear magnets. The main caveat of this system was the sensitivity towards the halo extent, leading to over-focusing of outlier halo particles which would typically be lost before reaching the target. The baseline HEBT collimator layout was thus designed with a focus on halo control. The old ESS HEBT would feature a movable collimator system for halo reduction and a fixed-aperture collimator which would partially mask the proton beam window and the target area.

1. Movable Collimator System

The MCS is a single-stage transverse collimation system consisting of $N_1 = 3$ primary collimator stations, each featuring four adjustable and complementary jaws (*i.e.* up, down, left, right). Due to the mechanical difficulty of having the four jaws in a single collimation unit, each of the N_1 collimator stations will consist of two adjacent units, each featuring 2 jaws arranged in an L-shape. This is similar to other collimator designs [10, 11]. Single-stage refers to employing only primary collimators (possibly in combination with passive absorbers) and not having *e.g.* movable secondary collimators. The latter option would require 2 secondary jaws for each primary jaw, meaning a large number of movable jaws.

High-power facilities based on H^--acceleration can more feasibly introduce two-stage collimation through primary scraper foils that change the charge of the halo through stripping, followed by downstream quadrupoles that defocus the stripped ions into secondary collimators.

The 3 collimator stations are located with a zero-current transverse phase advance of 60° between adjacent stations, thus enabling a ⬡-coverage in each of the transverse Normalized Phase Spaces (NPSs). By inducing controlled losses at the collimators, the main purpose of the MCS is to limit the uncontrolled beam losses < 1 W/m, thus complying with the generally agreed upon activation limit that allows hands-on maintenance of accelerator components. For the total of $N_1 \times 4 = 12$ jaws, each estimated to intercept up to 1 kW, the system is classified to the order of 10^{-3} of the full beam power. It should be noted that this, seemingly small, controlled loss rate would not be tolerated as an uncontrolled loss rate, even if distributed evenly along the full length scale of the ESS facility.

The tunnel cross section offers limited room for shielding, while still allowing personnel and equipment to pass the collimator stations. This may set a limit to the loss rates that can be introduced with the MCS. These are topics for an undergoing study of the mechanical design of the MCS. The tunnel would probably also require extra shielding and foundation reinforcements at the MCS stations. If the tunnel is not prepared for these requirements, a retrofitted installation of the MCS may be quite cumbersome and costly. More details about the mechanical design of the MCS can be found elsewhere [12].

2. Fixed Collimator

The final quadrupole magnets of the BES magnify the beam size and thus also amplify the beam quality. When using non-linear magnets with strengths sufficient to modify the beam core, the halo is readily distorted by the non-linear magnets and lost downstream of the final magnification. Whereas the MCS was conceived to limit the halo before reaching the BES, a fixed aperture collimator would mitigate the effects of overfocused halo downstream of the BES. A Cu-based collimator with fixed aperture would be introduced upstream of the PBW, just outside the target monolith, to intercept these tails before reaching sensitive components. Variations of the non-linear expander optics led to a specification of typically a few kW and up to 25 kW of intercepted beam at nominal beam power.

Appendix B: Acronyms

A2T	Accelerator to Target
BES	Beam Expander System
BIS	Beam Interlock System
BLM	Beam Loss Monitor
ESS	European Spallation Source
HEBT	High Energy Beam Transport
MCS	Movable Collimator System
MEBT	Medium Energy Beam Transport
MPS	Machine Protection System
NPS	Normalized Phase Space
NSW	Neutron Shield Wall
PBW	Proton Beam Window
RSM	Raster Scanning Magnet
SCL	SuperConducting Linac
UHB	Upgrade High-Beta

[1] "Beam Losses and Collimators in Transfer Lines", ESS Workshop, 13–14 May (2014), `https://indico.esss.lu.se/indico/conferenceDisplay.py?confId=165`

[2] A. Shishlo *et al.*, IPAC'12, TUOBA03 (2012).

[3] M. Plum, "Beam losses and collimation at the Oak Ridge Spallation Neutron Source", ESS Workshop presentation, May 13 (2014).

[4] M. Plum, private communications, 28 June (2011).

[5] H.D. Thomsen *et al.*, IPAC'14, WEPRO074 (2014).

[6] R. Miyamoto, private communications, 20 October (2014).

[7] H.D. Thomsen *et al.*, IPAC'14, WEPRO072 (2014).

[8] H.D. Thomsen *et al.*, IPAC'14, WEPRO073 (2014).

[9] T. Shea *et al.*, "Machine Protection Strategy for the ESS Target Station", 5th High Power Targetry Workshop (2014).

[10] V. Sidorov *et al*, "Mechanical Design of MI8 Collimators", Fermilab-Beams-Doc-2287, 2006, `http://beamdocs.fnal.gov/AD/DocDB/0022/002287/001/Beams-doc-2287.pdf`

[11] M.J. Shirakata *et al*, "Beam Collimator System in the J-PARC 3-50BT Line", EPAC'06, Edinburgh, Scotland, 2006, TUPCH060, `http://accelconf.web.cern.ch/accelconf/e06/PAPERS/TUPCH060.PDF`

[12] K. Szymczyk, P. Warzybok *et al.*, "Intermediate Collimator Report", internal report (2014).