

SIMULATIONS AND DETECTOR TECHNOLOGIES FOR THE BEAM LOSS MONITORING SYSTEM AT THE ESS LINAC

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Abstract

The European Spallation Source (ESS), which is currently under construction, will be a neutron source based on 5 MW, 2 GeV superconducting proton linac. Among other beam instrumentation systems, this high intensity linac requires a Beam Loss Monitoring (BLM) system. An important function of the BLM system is to protect the linac from beam-induced damage by detecting unacceptably high beam loss and promptly inhibiting beam production. In addition to protection functionality, the system is expected to provide the means to monitor the beam losses during all modes of operation with the aim to avoid excessive machine activation. This paper focuses on the plans and recent results of the beam loss studies based on Monte Carlo (MC) simulations in order to refine the ESS BLM detector requirements by providing the estimations on expected particle fluxes and their spectra at detector locations. Furthermore, the planned detector technologies for the ESS BLM system will be presented.

INTRODUCTION

The ESS is a material science facility, which is currently being built in Lund, Sweden and will provide neutron beams for neutron-based researches [1]. The neutron production will be based on bombardment of a tungsten target with a proton beam of 5 MW average power. A linear accelerator (linac) [2] will be used to accelerate protons up to 2 GeV and transport them towards the target through a sequence of a normal conducting (NC) and superconducting (SC) structures (Fig. 1). The ESS linac will create a pulsed beam with an average pulse current of 62.5 mA, pulse duration of 2.86 ms and repetition rate of 14 Hz. The beam will be bunched at 352.21 MHz frequency in the first and 704.42 MHz in the ending part of the linac.

It is essential to have a linac equipped with a certain

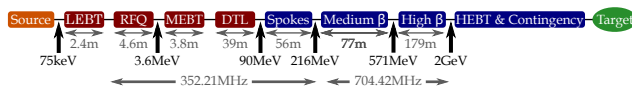


Figure 1: The ESS linac layout. Red color represents the NC and blue the SC parts of the linac.

set of beam instrumentation. An example of such an instrument is a BLM system, which is designed to detect high beam losses potentially harmful for the linac components and inhibit beam production the appropriate time scale if needed. Additionally the system provides information about the particle rates during all linac modes of operation in order to keep the machine activation low enough for hands-on

maintenance. Furthermore this information can serve as an input for tuning the linac ???

ESS BLM DETECTOR TECHNOLOGIES

The ESS BLM system is planned to employ 3 types of detectors.

In the SC parts of the ESS linac parallel plate gas ionisation chambers (ICs) developed for the LCH BLM system [3] will be used (Ionisation Chamber based BLM – ICBLM), which were chosen due to their fast response. The chambers were order in summer 2014 and currently being produced. However background due the RF cavities must be taken into account when using ICs in a linac. This background is mainly due to the electron field emission from cavity walls resulting in bremsstrahlung photons created on the cavity or beam pipe materials [4]. The background levels are difficult to predict numerically as they depend on the quality of the cavities, beam loading, operation conditions and time. It is planned to assess this experientially at the ESS RF test stand in Uppsala with the spoke and potentially at the CEA Saclay with the elliptical cavities. Nevertheless simplified energy spectra estimations show that photons with energies up to tens of MeV can be expected [5]. On the other hand the characteristic cut-off value for the photons is found to ~ 2 MeV for the LHC ICs [3]. Therefore background sampling and subtraction in the signal processing is planned to be employed for the ICBLM system.

In addition to the ICs as the primary BLM detectors in the ESS SC linac, a second type of a detector is planned to be used the SC parts. Currently designing a Cherenkov radiation sensitive detector is under consideration which offers minimal sensitivity to the RF cavity background.

BLM detectors are planned also in the MEBT and DTL sections of the NC part of the ESS linac. Here the particle fields outside the tanks and beam pipe are expected to be dominated by the neutrons and photons. Thus a neutron sensitive detector must be considered as a BLM in these parts. Special micromegas detectors will be used, designed to be sensitive to fast neutrons with minimal sensitivity to photons in order to suppress the RF cavity background, where the γ and thermal neutron rejection is based on the signal discrimination. The detector design is currently on-going by the micromegas team from the CEA Saclay as part of the French In-Kind contribution to the ESS project.

Current proposal for the ESS neutron sensitive BLM (nBLM) is an assembly of two modules [6]:

- The first module aimed to monitor low fluxes of fast neutrons of few $\text{n}\cdot\text{cm}^{-2}\text{s}^{-1}$ (slow losses) consists of a polyethylene bulk as a moderator (to thermalise the incoming fast neutrons) surrounding a B_4C layer or

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layers (to capture the thermalised neutrons through $n+^{10}\text{B} \rightarrow ^7\text{Li}+\alpha$) with micromegas (to detect the charged products). The module is coated with $\sim\text{mm}$ thin Cd layer to eliminate background thermal neutrons.

- The second module appropriate for high fast neutron fluxes (accidental, fast losses) coming from the front. Here a few mm thick polyethylene serves for the convert the neutrons to recoil protons through the neutron elastic scattering on H atoms. An Al foil or deposition of $\sim 50\text{ mm}$ is placed on the polyethylene layer and followed by a micromegas. (???)

ESS BLM SIMULATIONS

MC simulations for tracking of the lost protons are needed in order to address several points crucial for the design of a BLM system, namely: system response time limit, detector locations and dynamic range of the system. In addition to this they represent the tool for determination of the initial machine protection threshold settings for the startup period and later adjustments to those. Furthermore the MC simulations serve to estimate the anticipated response of the system during fault studies aimed either to verify the BLM system response or to provide information to the accelerator physics fault studies. The focus of this chapter are the above mentioned first three points, while the last two are not discussed here.

Most of the results presented here are focused on the nBLMs as the anticipated neutron and photons spectra at detector locations are required for the in-kind partner to start the finalise the design. Furthermore all previous efforts were focused solely on the ICBLM in the SC parts, thus some preliminary results valid for these parts of the ESS linac already exist.

The Geant4 (version 10.00.03, QGSP_BIC_HP physics list) simulation framework [7] developed by the ESS neutron detector group has been used to perform the ESS BLM simulations. No tracking cuts have been employed, while production cuts were set to $10\text{ }\mu\text{m}$ for e^+ , e^- and photons.

Geant4 based ESS linac geometry (Fig. 2) has been made with certain element models (quadrupole magnets, spoke cavities and elliptical cavities and cryomodels) adapted and

changed where needed from the existing ESS linac ROOT [9] based model made for the shielding calculations [10] with the MARS [11] MC simulation code. Magnetic field maps [12] outside the beam pipe for the quadrupole magnets in the SC linac is included in the simulation due to important impact on the simulation results for the detectors place close to the these magnets. Aperture along the linac follows the values in the 2015 baseline beam physics lattice of the ESS linac (2015.v1 ???). Tunnel walls are included in the simulations due to their importance for the low energy parts of the neutron spectra. Current simplifications in the geometry include:

- Simplified quadrupole magnet geometry in the yoke and coil length. Also the total physical magnet length has recently been changed in the last parts of the ESS linac.
- Simplified model of the DTL gaps, where 1-2 cylindrical shapes on each side of the gap are used. The value of (gap length)/(cell length) is the same for all cells on one tank and taken as an average value in the.
- Model for cavities in HB sections is calculated by scaling part of the MB cavity profile.
- The following elements are currently not included: post-couplers in the DTL, beam instrumentation devices, correctors, supports, MEBT chopper and copper dump, spoke cavity insertions.

Certain set of inputs are needed in order to perform the BLM simulations. Ideally one would have a list of accidental beam loss scenarios with the loss maps in connection to the elements that must be protected together with the damage levels. In addition to this the anticipated loss maps during the normal operation are needed as the lowest detectable BLM signal levels are expected during these periods. However due to a large number of possible accidental scenarios in a linac, some form of simplifications and assumptions is needed, which is considered in the following subsection in connection to discussion of the worst case accidental beam loss scenario.

Response time

The response time requested by the ESS machine protection group is $\sim 5\text{ }\mu\text{s}$ in the NC (MEBT and DTL) and $\sim 10\text{ }\mu\text{s}$ in the SC parts of the linac [13]. The numbers are based on a past simplified melting time calculations, where a beam of protons with a uniform profile hits a block of material under perpendicular incident angle [14]. No cooling is considered in these calculations. The numbers have recently been re-checked with the update beam parameters and a Gaussian beam profile. These results support the $10\text{ }\mu\text{s}$ requirement in the SC parts of the linac. However the calculated melting time values of $3\text{--}4\text{ }\mu\text{s}$ imply even stronger demands on the response time in the NC parts (Fig. 3). The latter has additionally been confirmed with a MC simulation.

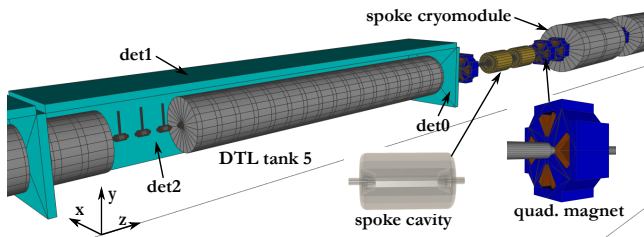


Figure 2: Geant4 based geometry of the ESS linac used in the BLM simulations, focused on the last tank of the DTL section. Phantom detector modules surrounding the tank are marked as det0, det1 and det2. Parts of the volumes are opened for a better view.

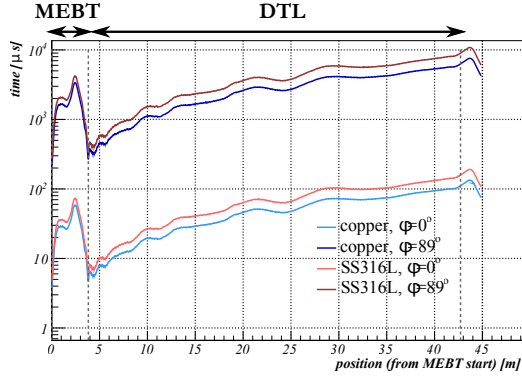


Figure 3: Time to melt a block of copper (red) or stainless steel (blue) under constant irradiation with a proton beam under perpendicular incidence ($\phi=0^\circ$) or a very shallow angle.

Worst case scenario Melting time depends on the beam incidence angle, thus the validity of the assumption of the perpendicular incidence as the worst case scenario can be argued. This poses a question on what is the worst case accidental loss, which translates to the need to understand what is the least shallow incidence angle of the most focused beam that can be expected to hit the aperture. This is expected to occur for a particular case of incorrect settings for a set of corrector magnets. Time consuming beam dynamics simulations are required in order to assess this. Therefore the following strategy to find the worst case angle has been suggested [15] and adopted here:

- Find such a deflection from the expected initial condition (x, x', y or y') at the beginning of a linac section, which still allows for the beam to enter the section. Increasing the difference would end with beam hitting the walls of the section.
- The highest deflection found along the section is taken as the worst case angle.

Assessment of this type has been performed for the the DTL and HEBT sections (Table 1 ??) [15].

ESS Linac section	Peak x' or y' [mrad]
DTL tank 1	50
DTL tank 2-3	15
DTL tank 4-5	10

Table 1: Worst case beam incidence angle. See text for explanation.

Implications on the response time Depending on the gap distance, an incidence close to perpendicular is potentially possible in the first DTL tank due to the almost flat surfaces between the gaps (Fig. 4). With the simplified DTL geometry used in the BLM simulations this

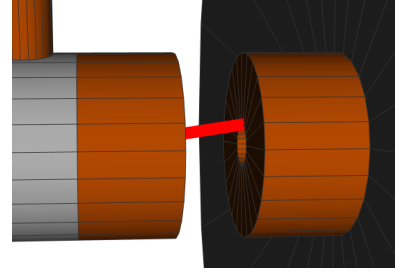


Figure 4: Example of beam hitting a tube in the DTL tank 1 (incidence angle set to 150 mrad).

is geometrically possible only for incidence angles above ~ 150 mrad. This is planned to be verified in a more realistic DTL geometry. Nevertheless 150 mrad is still close to the perpendicular incidence. ?????

In order to determined the time response limit in the SC parts, it is foreseen to check the beam pipe melting time with a focused beam under worst case angle discussed above. However a degradation of the cavities is observed at the SNS after loosing $<15 \mu s$ pulse of 26 mA beam about 10 times per day [16], which justifies the $10 \mu s$ time response requirement.

Detector locations

The most suitable set of detector locations and their count insures that the system is not blind to any accidental losses. In the absence of the list of accidental losses, the following strategy is assumed in order to select detector locations:

- A set of localised loss scenarios is considered, each with selected beam energy, incidence angle and loss location along the linac section under investigation.
- The incidence angle is varied from ~ 1 mrad up to the worst case angle as discussed in the previous subsection, while the lost proton energy ????
- By using phantom detectors (with vacuum as the volume material) surrounding the section a simulation for each of the loss scenarios is ran to produce hit maps of incoming neutrons (in case of nBLM) or all particles (in case of ICBLM).
- Hit map mean and RMS values along the section length and extracted for each of the loss scenarios and compared with the origin of the loss. Th best detector locations can be extracted by comparing the results from all simulation runs.

Similar strategy based on optimisation methods combined with genetic algorithms for selecting the detector locations have been tried in the past, though only for the case of the ICBLMs. It is planned to finalise this work in the near future with above mentioned strategy, as the past work has not been not completed with the final results. However as previously mention, the current efforts are focused on the nBLMs due to the In-kind partner's need for certain inputs to proceed

with the detector design.

As an example some preliminary hit maps are presented in Fig. 5 for two detector volumes placed around the DTL tank 1. Here a focused beam was generated at 3 different locations along the tank. The beam angle of 50 mrad with respect to the z-axis was selected while the nominal value at the loss location was taken for the proton energy. The mean values along the z-axis agree to ~ 0.02 - 0.8 m with the loss location for both detectors, while the RMS values of ~ 1.4 - 1.5 m is observed. The same observations hold if a detector volume is placed below the tank, though this detector yields the lowest hit rate as expected. This suggest a possible solution with 2-3 (potentially granulated) 1-2 m long detectors along the tank. ????

Dynamic range

The dynamic range of the BLM system can be determined once the detector location are know by studying two extreme cases:

- **Highest expected hit rate.** This case marks the worst case accidental loss. By assuming the worst case angles discussed in subsection focused on the response time, the simulated particle hit rate (or energy deposition or current) to the estimated upper limit of the system's dynamic range.
- **Lowest expected hit rate.** Typically the lower limit of a BLM system dynamic range is to a fraction of a 1 W/m loss uniformly distributed along the linac, which is arguably coming from the activation limit for the hands-on maintenance. However, the system should be integrating the received dose and signal problems if the value reaches the allowed limit. Therefore it is important to asses what are the expected signals during the normal operation of the linac, when the lowest rates are expected. The lower limit of the dynamic range can than be set to a fraction of this signal. (???)

Expected loss map during normal operation. A Tracewin based beam dynamics error study has been performed on the 2015 baseline beam physics lattice of the ESS linac [17]. Here the error were applied to 10000 machines, each with 600000 macro-particles. The error tolerance was set to 100 % of the nominal values, except for the dynamic error (RF jitter), where it was increased to 200 %. The results of these study (Fig. 6) are used as the input to the BLM MC simulation of lost protons for the case of the ESS linac normal operation losses.

Normal operation versus 1W/m loss. In order to assess the difference in the normal operation and 1W/m loss BLM MC simulations of lost protons have been performed for both cases:

- Normal operation loss. Lost protons in the BLM MC simulation were sampled from the lost particle distributions obtained from the above mentioned error study.

This approach offers not limitation on the statistic of the BLM simulation and need for assumptions on the lost particle distributions. Correlation was observed between the azimuth angles for the lost proton position and momentum direction, which was taken into account in the simulation as well.

- 1 W/m loss. Uniform distribution of lost protons was assumed along the linac. Proton polar angle from the beam axis was fixed to 1 mrad while the azimuth angle was samples uniformly around the aperture. Proton energy was set to the nominal value at the lost proton location.

The simulated neutron spectra in units of neutrons/s hitting a detector volume for the the case of the normal operation loss and 1W/m loss expected in the ESS NC linac are shown on Fig. 7. For the case of the uniform loss an increase in incoming neutrons with the tank number can be observed which can be attributed to the increase of the neutron cross-section with increasing proton energy. On the other hand the normal operation loss results exhibit the lowest neutron fluxes in the last two tanks. The latter can be explained with emittance decrease with increasing beam energy. By comparing the results for the loss cases, it can be seen that all 1 W/m spectra lie above the corresponding ones for the case of normal operation loss, where the difference increases with the tank number from 0 to 1.5 order of magnitude. The exception is the det0 in the DTL tank1, where the 1 W/m curve lies slightly below corresponding for the normal operation.

ESS BLM dynamic range. Following the discussion above, once the nBLM detector locations are fixed, the lower limit of the dynamic range for the case nBLMs will ??? be set to 10 % of the neutron flux expected during the normal operation. The upper limit on the other hand can be estimated by assuming a focused beam under worst case incidence angle.

For the case of the ICBLMs preliminary values have been set in the past [18], by required the BLM to able to measure 1 % of the 1 W/m loss during normal operation and up to 1 % of the total beam loss. This gave an estimation on the IC output current to range from ~ 800 mA to few mA. It is planned to re-asses these value in the near future once the ICBLM detector locations are set as well. ???

SUMMARY

The ESS BLM system is planned to be based on 3 types of detectors. ICs will be used as the primary detector in SC parts of the linac (ICBLM). It is foreseen to explore an option to use a Cherenkov radiation sensitive detectors as complementary BLMs to the ICBLM in the SC parts. The advantage of these detectors lies in the low sensitivity to the RF cavity background. On the other hand, novel??? neutron sensitive micromegas detectors will be used as BLMs in the NC parts of the linac.

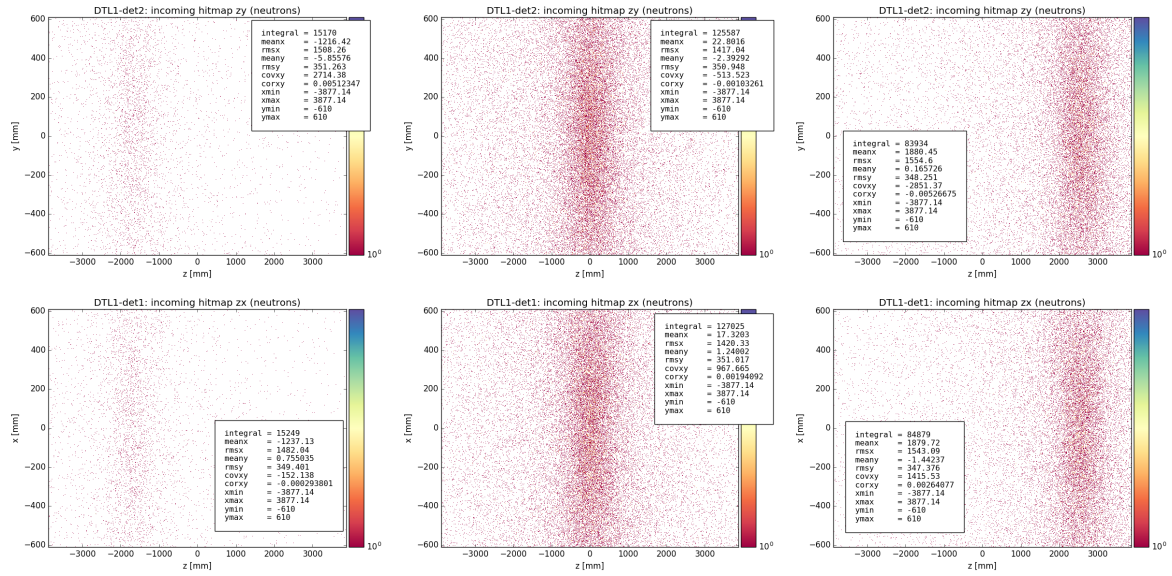


Figure 5: Simulated neutron hit maps for 3 different loss locations along the DTL tank1 scored in detector volumes det2 (top) and det1 (bottom). See Fig. 2 for the detector locations.

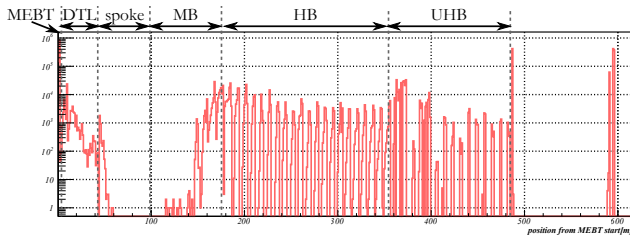


Figure 6: Distribution of the lost protons along the ESS linac resulting from the ESS linac error study, which served as an input loss map for the BLM simulation of the linac normal operation.

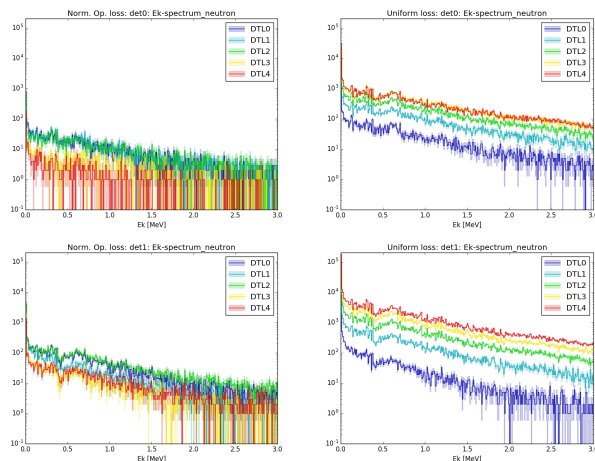


Figure 7: Simulated neutron spectra hitting the detector volume det0 (top) and det1 (bottom) for the case of normal operation (left) and 1W/m (right) loss. See Fig. 2 for the detector locations.

MC simulations of lost protons are a necessary tool when building a BLM system. In the past all effort connected to those was focused on the SC parts. Currently the focus has turned to the NC parts due to the in-kind partner's need for the inputs in order to design the nBLM detectors.

Strategies to determine the requirements ??? (response time, dynamic range and detector location) of the ESS BLM system were discussed. Selected preliminary results for the NC linac parts were presented, together with past results solely focused on the SC parts.

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