BEAM LOSS MONITORING AT THE EUROPEAN SPALLATION SOURCE

L. Tchelidze, H. Hassanzadegan, M. Jarosz, A. Jansson, ESS, Lund, Sweden

Abstract

At the European Spallation Source proton linear accelerator will generate 5 MW protons to be delivered to a target. This high power accelerator will require significant amount of beam instrumentation, among which the beam loss monitoring system is one of the most important for operation. An LHC type ionization chamber is planned to be used with ~54 μC/Gy sensitivity. At most 1.5 mGy/sec radiation levels are expected close to the beam pipe during normal operation, resulting in up to 80 nA current signal in detectors. Loss monitor electronics is designed to be able to measure currents as little as 1% of the expected current up to as much as 1% of the total beam loss, thus ~800 pA – few mA. In order to study beam loss pattern along the accelerator a coherent model of the whole machine is created for the purposes of Monte Carlo particle transport simulations. Data obtained using the model will be stored in a database together with the initial beam loss conditions. The contents of the database will then be processed using custom neural network algorithms to optimize number and position of the loss monitors and to provide reference on the beam loss localization during operation of the machine.

INTRODUCTION

The European Spallation Source is a planned spallation neutron facility in Lund, Sweden. The facility will produce neutrons for science experiments via hitting a target with an average 5 MW proton beam. Based on the current design, the proton beam will be generated and transported to a target by a linear accelerator (linac), accelerating protons to a maximum 2.0 GeV energy. The linac will create pulsed beam with 14 Hz and pulse duration of 2.86 msec. These are the top-level parameters that should stay the same despite the redesign process of the current linac layout.

The beam loss monitoring (BLM) system is one of the most important beam diagnostics systems during commissioning and running of the facility. It is a tool to measure and monitor both controlled and unexpected beam losses. Ionization chambers will be used as a primary beam loss detector at the ESS, and N_2 filled parallel plate ionization chamber, similar to those used at the large hadron collider (LHC) is planned for this purpose [1].

PREDICTED POWER DENSITY LEVELS

The ESS linac consists of an ion source, low energy beam transport, medium energy beam transport, drift-tube linac – all at room temperature, spoke accelerating section, medium-beta and high-beta sections – all superconducting, followed by a high energy beam transport and accelerator-to-target sections where the beam is finally delivered to the target. Quadrupole magnets in between the cold sections/cryomodules of the accelerator will also be kept at room temperature.

A MARS model of spoke and medium/high beta accelerating sections of the accelerator was composed. A quadrupole doublet was inserted in the middle of every adjacent cryomodule. MARS [2, 3, 4] Monte Carlo particle transport code was used to simulate beam losses and generate power density maps. MARS is a Monte Carlo program for inclusive and exclusive simulation of three-dimensional hadronic and electromagnetic cascades, muon, heavy-ion and low-energy neutron transport in accelerator, detector, spacecraft and shielding components in the energy range from a fraction of an electronvolt up to 100 TeV. The MARS15 code includes links to the MCNP4C code for neutron and photon production and transport below 20 MeV, to the ANSYS code for thermal and stress analyses and to the STRUCT code for multi-turn particle tracking in large synchrotrons and collider rings.

Power density was calculated for normal operations, when a maximum allowed beam loss equals to 1 W/m. A shallow loss angle, 3 mrad was chosen in the simulations. Power density, in Gy/sec is shown in Fig. 1 and 2 for beam energy 200 MeV and 2 GeV respectively.

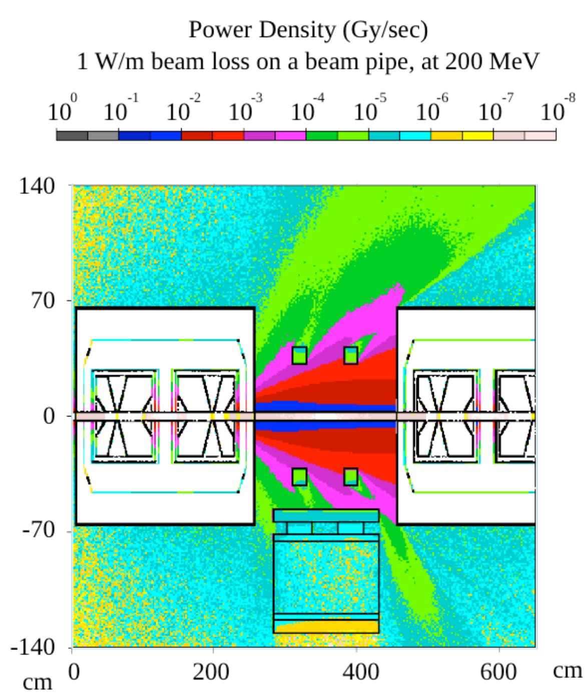

Figure 1: Power density, in Gy/sec, for 1 W/m distributed beam loss on a beam pipe, at 200 MeV.

ISBN 978-3-95450-127-4

In the Figures, two sections of two cryomodules and a quadrupole magnet doublet in between them is displayed. In Fig. 1, cryomodules with spoke accelerating cavities are shown from a side, while in Fig. 2 part of cryomodules with simplified elliptical cavities are seen. Beam is lost on a beam pipe uniformly with a same shallow angle.

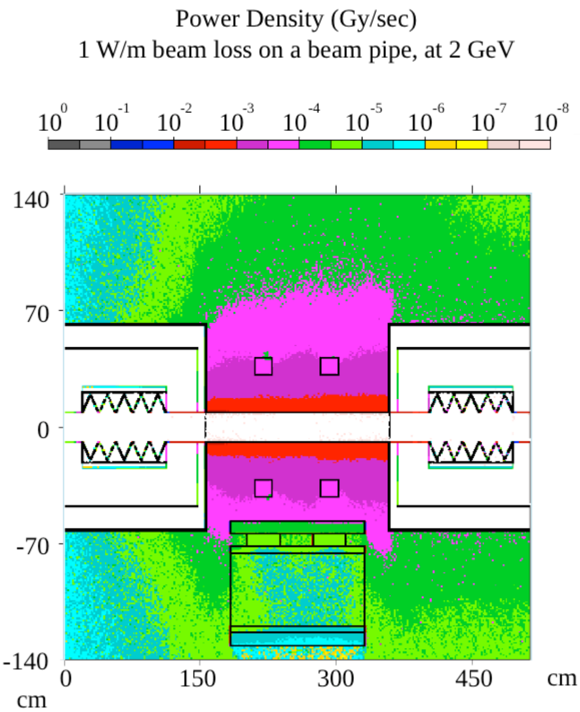

Figure 2: Power density, in Gy/sec, for 1 W/m distributed beam loss on a beam pipe, at 2 GeV.

EXPECTED CURRENTS

Beam loss monitoring system is required to be able to measure at least 1 % of the maximum allowed beam losses during normal operations up to 1 % of the total beam loss. Ionization chamber, similar to those used at LHC, is planned as a main beam loss monitor at ESS. This detector has ~ 54 µC/Gy of se1nsitivity [1]. Based on the expected power density levels at ~ 20-25 cm from the beam pipe, as seen in Fig. 1 and 2, we require the loss monitors to be able to measure a current in the range of ~800 pA – few mA.

TIME RESPONSE

One of the main purposes of the BLM system is to protect accelerator from damage in case of accident/high/full beam loss. The ESS machine protection system will be linked to the BLM system and receive beam abort signals if necessary. The system will be designed to be fast enough to prevent accelerator damage. To understand better how quickly one would have to react, a time period in which a full beam would start melting stainless steel or copper accelerator components was calculated. Calculations were done for proton beam energy range of 5 MeV – 80 MeV only and for few different beam sizes. Figure 4 summarizes the outcome and shows that the response time strongly depends on a beam size and gets relatively relaxed at energies above ~10-20 MeV. Note that the response time in Fig. 3 is a detector reaction time (time in which a detector gives measurable current signal) plus time for electronics to issue a beam abort signal.

BLM LAYOUT OPTIMIZATION

Creating a complete and coherent model of the whole accelerator is crucial for many aspects of the design phase of the machine and also for later when the facility is operational. Monte Carlo particle transport simulations performed with this kind of model brings answers to the questions raised by the machine and radiation protection issues and complement beam physics particle tracking works. At ESS, MARS based model of the accelerator is being put together based on a computer-aided design (CAD) drawings provided by the design group.

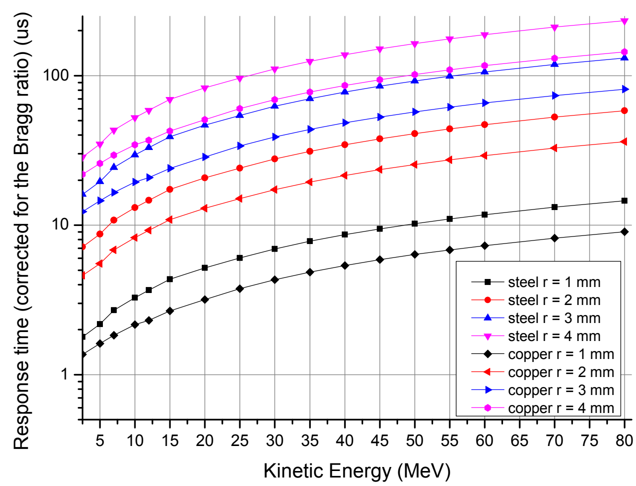

Figure 3: Desired time response (in µsec) for ionization chambers at different beam energies in the range of 5 MeV – 80 MeV.

Although the machine model is used for simulations of various kinds, beam instrumentation focuses on using it to predict consequences of beam losses in order to optimize the number and positioning of the beam loss monitors. As a result of first assessments it was requested that a beam loss monitor is placed in front and back of each quadrupole magnet. However, a more sophisticated optimization studies are planned, namely using of neural network for the necessary data processing. Successful usage of similar techniques (i.e. genetic algorithms) in problems of accelerator physics is shown in [5].

The results of the loss simulations, representing a detector response, are stored in a database together with the initial conditions (location of the detectors, type and place of the loss etc.).

ISBN 978-3-95450-127-4

Table 1: ESS BLM Requirements in Comparison with the SNS, DESY-XFEL and LHC Systems

	Detector Type	Beam abort time (µs)	Elect. B.W. (kHz)	Elect. dyn. range (dB)	Min. inp. cur. (pA)	Max. inp. cur. (µA)	Elect. Platform	Digitizer	Detector cable length (m)
Required at ESS	IC	10	350	128	800	2000	MTCA.4	16 bit, >100 MSa/s	60
SNS	IC	10	35 & 1	126	324	644	VME	16 bit, 100 kSa/s	23-91
DESY-XFEL	Scint. + PMT	4					MTCA.4	14 bit, 1 MSa/s	50-100
LHC	IC	89		136	50	200	VME	12 bit, 40 MSa/s	400

A large set of these input-output data is used to train the neural network, while other sets are used to test the system's efficiency in detecting the loss. This allows not only picking optimal locations for loss monitors, but also makes it possible to establish rules for loss detection during actual operation.

BLM ELECTRONICS

BLM Electronics of Other Labs

Table 1 makes a quick comparison between some of the ESS BLM requirements and the BLM specifications of spallation neutron source (SNS) [6], DESY-XFEL [7] and LHC [8].

It can be understood that none of these systems is fully compatible with the ESS requirements. The beam abort time of the SNS and LHC BLM system does not meet the ESS machine protection requirements. Also, the electronics platform of these two systems does not comply with the platform so far planned for ESS. The DESY-XFEL system meets these two requirements, but its front-end electronics is designed for a different type of detector, which cannot be used at ESS due to dynamic range considerations. Moreover, the timing requirements of the DESY-XFEL system are different from those at ESS.

Beam Loss Detection Methods

The above-mentioned systems each use a different method in their analogue front-end for the detection of beam losses. In the case of SNS, a fast analogue link for acting on the machine interlock system is provided, comprising a leaky integrator with a response time of 10 µs approximately. The output is fed into one input of a comparator while the other input is provided by a digital to analog converter; therefore it is user adjustable. If a large and sudden beam loss occurs, a pulse is generated at the comparator output for a fast shut-off of the beam. The integrator then discharges, thus re-arming itself for next loss measurement. In addition to the fast link, the current from the detector is split into two signal paths with bandwidths of 35 kHz and 1 kHz where the signals are filtered and amplified before being fed into their corresponding analog to digital converter (ADC) channels. The signals are then digitized and processed to calculate beam losses with some different integration times.

The BLM electronics of DESY-XFEL is based on a resettable integrator, which can measure beam losses due to individual bunches with a repetition rate of 1 MHz. The integrator voltage is sampled at the end of each acquisition period, thus giving the integrated beam loss corresponding to each bunch. The sampled value is then fed into a field programmable gate array (FPGA), where beam losses with three integration times are calculated and compared to thresholds. The FPGA determines the number of times that the ADC readout is above a user-defined threshold during the integration period. If the count value is above a limit, it initiates a beam abort request. After each acquisition, the integrator is reset using an external pulse from the timing system.

The BLM system of LHC uses a current to frequency converter (CFC) to measure the BLM signal and convert it to digital. The CFC is based on an integrator, which is automatically reset when its voltage reaches a fixed threshold. The CFC generates a stream of pulses whose frequency is proportional to the detector current. In order to increase the dynamic range, an ADC measures the integrated voltage as well. The count rate of the CFC then gives a rough estimate of the loss as an integer number,

ISBN 978-3-95450-127-4

while the ADC value gives the fractional part of the loss. These two values, when merged together, can give the exact beam loss with a dynamic range larger than 140 dB. The digitized data is then encoded and sent over a long fiber optic link to an FPGA-based system where integrated losses are calculated and compared to thresholds.

Discussion of the Loss Detection and Suggestion for ESS

A quick look at these three systems shows that they all use an analogue integrator consisting of a low-leakage capacitor which charges up with the detector current, thus measuring losses. The difference, however, lies in the way the capacitor is discharged so that the integrator is re-armed for next acquisition. The leaky integrator is a simple design, which uses a resistor across the capacitor for the capacitor discharge. The time constant of the RC circuit should be carefully chosen so that the integrator can measure fast losses, but does not discharge during a loss measurement. Meeting these two requirements simultaneously can be difficult due to the random nature of the beam loss and that can result in some unreliability in the measurement. For that reason, the leaky integrator is not considered for ESS. The other two solutions are currently being investigated in more details.

Another option, which is currently under study, is an in-house development of the BLM electronics. In that case, the front-end electronics can be in the form of a rear transition module (RTM) measuring signals from several BLMs. The RTM can be compatible with the micro telecommunications computing architecture (MTCA.4) standard so that it can be connected to a commercial digitizer card where the signals are converted to digital and FPGA processed for loss calculation and threshold comparison.

REFERENCES

[1] M. Stockner, B. Dehning, C. Fabjan, E.B. Holzer, D. Kramer, "Classification of the LHC BLM Ionization Chamber", Proceedings of DIPAC 2007

[2] N.V. Mokhov, "The Mars Code System User's Guide", Fermilab-FN-628 (1995)

[3] N.V. Mokhov, S.I. Striganov, AIP Conf. Proc. 896, pp. 50-60 (2007)

[4] http://www-ap.fnal.gov/MARS/

[5] A. Hofler, et al. "Innovative Applications of Genetic Algorithms to Problems in Accelerator Physics", Physical Review Special Topics, Accelerators and Beams 16, 010101, 2013-09-11

[6] D. Gassner, R. Witkover, "SNS Beam Loss Monitor Electronics Final Design Review", a power point presentation, 23 July 2002

[7] L. Fröhlich, "Machine Protection for FLASH and the European XFEL", Dissertation zur erlangung des Doktorgrades des Department Physik der Universität Hamburg, Hamburg (2009)

[8] C. Zamantzas, "The Real-Time Data Analysis and Decision System for Particle Flux Detection in the LHC Accelerator at CERN", Ph.D. thesis, (2006)

ISBN 978-3-95450-127-4