# THE DUAL USE OF BEAM LOSS MONITORS AT FAIR-SIS100: GENERAL DIAGNOSTICS AND QUENCH PREVENTION OF SUPERCONDUCTING MAGNETS

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*Abstract*

In view of the planned coverage of the FAIR SIS100 synchrotron with beam loss monitors, FLUKA studies were performed aiming at two goals: (i) evaluation of the sensitivity of the LHC-IC type detectors to the potential beam losses at SIS100; (ii) estimation of the BLM quench prevention threshold via the correlation between the energy deposition inside the superconducting coils and the BLM active volume. A full spectrum of ion species and energies to be accelerated with SIS100 was considered in the simulations. The results of the studies presented in this paper support the use of BLMs both for diagnostics and for quench prevention via an interlock generation, as used at the LHC.

## INTRODUCTION

To achieve the goal of providing a world-wide unique operation with high-intensity intermediate charge-state heavy ions ($5\times10^{11}$ $U^{28+}$ per pulse), the FAIR synchrotron SIS100 is designed as a superconducting machine with short cycling times and a ramping rate of 4 T/s up to 1.9 T [1]. Due to the intermediate charge states, ionization processes driven by collisions with the rest gas are the main mechanism for beam losses at SIS100. Although the machine is optimized for fast extraction, slow extraction will also be used which presents another important and inevitable source for losses due to the interaction of the beam with the wires of the electrostatic septum. The details of the mechanisms for beam losses at SIS100 and their locations are summarized in [2].

In order to detect beam losses and to verify whether or not the losses are acceptable, a complete coverage of the SIS100 with sensitive beam loss monitors of adequate time resolution is essential. The planning foresees an installation of about 180 LHC-IC type BLMs along the whole SIS100 circumference. Given the lower sensitivity threshold of these BLMs of about 10 pA, FLUKA simulations were performed to calculate the response of the detectors to the expected losses as to the lowest level detectable [3]. Since the BLM system can be used not only for diagnostics, but could also play an essential role in the machine protection system, the FLUKA simulations were extended to estimate the BLM quench prevention thresholds for use in an interlock system preventing the superconducting magnets from quenches, as used at the LHC [4]. The results of the FLUKA studies are reported here, addressing the two issues separately.

## FLUKA RESULTS

In order to obtain a realistic radiation field from the beam losses and to evaluate the sensitivity of the LHC-IC type monitors with a high reliability, a precise modelling of the geometry of the SIS100 quadrupole modules (representative for SC magnets), the SIS100 extraction straight section and the superconducting coils including the cable details is required.

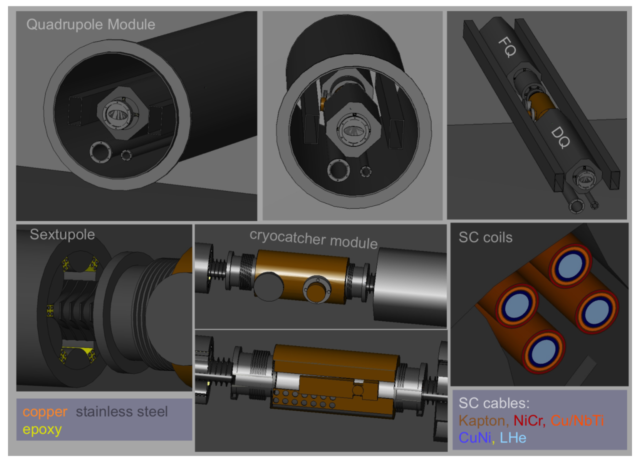


Figure 1: FLUKA geometry of a SIS100 quadrupole module with defocussing quadrupole (DQ), cryocatcher module, sextupole (or steerer) and focussing quadrupole (FQ).

Figure 1 shows the geometry of a SIS100 quadrupole module as modelled for the FLUKA simulations.

### *General Diagnostics: Response of LHC-IC type BLMs to the Beam Losses*

The simulations are based on uranium beam energies of $E_k$=2.7 GeV/u (extraction) and 0.2 GeV/u (injection) at a maximum intensity of $5\times10^{11}$ ions/cycle(3.2 s). Based on beam optic studies combined with a realistic beam tracking with FLUKA, about 10% of the beam will interact with the wires of the electrostatic septum, while most of the particles lost will be intercepted within the two warm radiation-hard quadrupoles which also play the role of the absorber for the beam halo collimation. While the analysis of the tracking of the interacting particles through the two warm quadrupoles, including the optimization of the position for the planned collimator in between the quadrupoles, is still in progress, for the time being the following assumption is made. The lost ions are assumed to interact with the surface of the stainless steel beam pipe at the centers of the two quadrupoles, with equal probabilities. In order to study the response of the BLMs to a radiation field, eight positions were defined around the entire extraction straight section. The response of the LHC-IC type BLMs in terms of currents was extracted in two different ways. In the first method, the




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fluence spectra of all particles within the active volume of the BLMs are extracted, followed by a folding of the spectra with a detector-specific response function expressed in fC×cm$^2$/primary. The folded spectra are then integrated over energy and multiplied with the beam loss intensity to obtain the current to be measured by a BLM. In the second method, the energy deposited in the active volume of the BLMs is directly evaluated and then converted to charge via the average energy required to produce an electron-ion pair (34.8±0.2 eV for nitrogen). Although the two methods give the same results at normal pressure [5], the folding method has several advantages (e.g. much less CPU time required). The results of the response of the LHC-IC type BLMs expressed in pA to the 10% beam-loss particles intercepted within the two warm quadrupoles are shown in Figure 2 for two different energies.

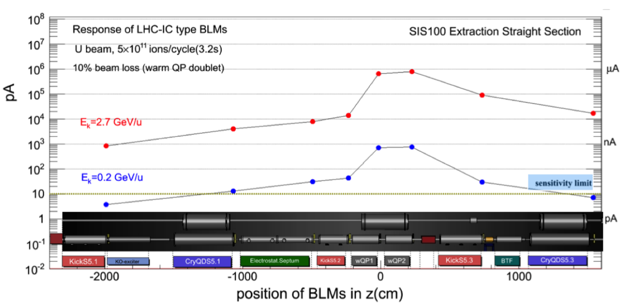


Figure 2: Response of the LHC-IC type BLMs in pA to 10% beam losses within the warm quadrupoles

The eight points associated with each of the curves indicate the BLM response at the selected locations along the extraction section. The following conclusions can be drawn. Instantaneous radiation caused by 0.1% beam losses at injection- and 0.0001% at extraction energy will be detectable by these monitors if placed close to the source, providing a sensitivity to beam loss rates of $>1.5\times10^8$ and $>1.5\times10^5$ ions/s, respectively. Losses of only 0.1% (a beam loss rate of $>1.5\times10^8$) at the extraction energy would be detectable by a BLM independent of its position along the entire long extraction straight section. Although the simulations should be redone once more details on the exact beam loss probability distribution become available, the main conclusion on the high sensitivity of the BLM monitors to beam losses along the extraction straight section will remain unchanged.

### *Quench Prevention of the SIS100 Superconducting (SC) Magnets by a BLM System*

Machine protection is always of central concern for accelerators, using a variety of systems for the detection of uncontrolled beam losses. The LHC-IC type BLMs, originally designed for the use at the LHC [3], are proven to play an important role in protection against uncontrolled beam losses. They are so far the only active system for protection of SC magnets in case of fast losses with time scales between 100 $\mu$s and 10 ms. While the total energy and therefore the overall damage potential is very much larger at the LHC, certain accidental scenarios can be equally severe at SIS100, due to the $Z^2$ dependence of the initial energy deposition of heavy-ion beams. Quenching would cause a downtime of more than one hour, while real damage of a single magnet would cause much longer downtimes at very high costs. All this suggests that the protection of the SIS100 machine should also be strict.

The possibility of quench prevention of the SIS100 SC magnets by the planned BLM system has been studied with FLUKA simulations, using the quadrupole modules. As a representative example the losses due to charge exchange of $U^{28+}$ beams were examined. Quench prevention is based on an accurate determination of the BLM 'quench prevention thresholds'. In order to determine the thresholds, FLUKA studies were performed to evaluate the correlation between the energy deposition inside the superconducting coils and the signal in the BLMs outside the cryostat. Given this objective, the exact geometry of the superconducting cables and thermal insulation had to be modelled. In order to satisfy the requirements for the SIS100 magnets, the improved Nuclotron-type cables will be used [6]. Their geometry, element composition and density of different layers of the hollow superconducting wires with the exact dimensions [6] have been modelled in FLUKA. The beam loss locations and the beam loss rates have been calculated with the accelerator tracking code 'StralSim' [7] and then used as an input for particle-shower simulations with FLUKA. The ionization beam losses, selected here as an example, can be controlled to a large extend by the installation of a system of beam collimators (cryo-catchers) to scrape off the $U^{29+}$ ions produced by charge exchange. The SIS100 lattice has been optimized to reach a maximum catching efficiency. The $U^{29+}$ ions hitting the cryo-catcher, called 'source I', produce a shower of particles carrying a fraction of the initial energy. The spatial distribution of the energy deposition as illustrated in Figure 3 is then calculated with FLUKA.

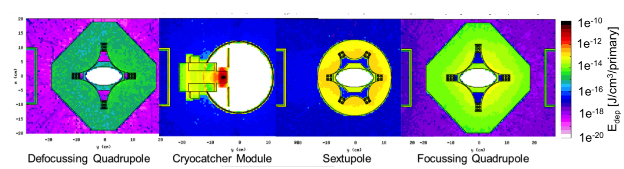


Figure 3: Energy deposition in the region of the SC coils due to charge exchange $U^{28+}\rightarrow U^{29+}$

The ion catcher system only works efficiently for the losses due to charge exchange $U^{28+}\rightarrow U^{29+}$. While the beam loss rate is not the same for all quadrupole modules, the impact points of the lost ions are always the same. However, there is also a small probability for beam losses due to double charge exchange $U^{28+}\rightarrow U^{30+}$ (called 'source II'). The geometric loss pattern of $U^{30+}$ ions calculated with 'StralSim' is also taken into account in the FLUKA simulations.

To extract the energy deposition within the different layers of the SC cables, very fine grids were used, in particular for the radial and azimuthal direction. The longitudinal profile

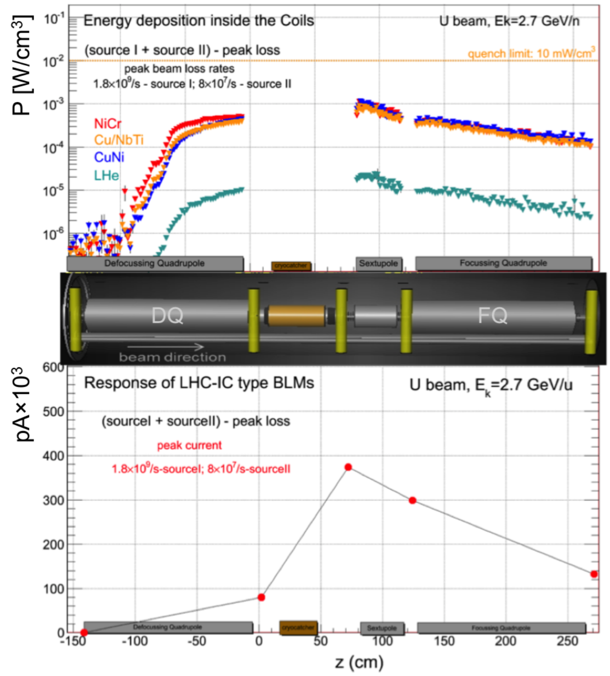


Figure 4: Correlation between the maximum power deposition in the SC coils and the BLM signals outside the cryostat due to ionization losses of the $U^{28+}$ beams.

of the maximum energy deposition localized inside the two innermost coils in the middle plane will be used in the following part. In order to study the longitudinal dependence of the LHC-IC type BLM response to the ionization losses, 5×2 positions for BLMs were defined along a SIS100 quadrupole module, outside the cryostat. In order to determine their sensitivity to ionization losses and to investigate the quenching probabilities, the input of the beam loss rates for the two sources, which have to be superimposed since they happen simultaneously, is required. The final results on the correlation between the power deposition in the coils in W/cm$^3$ and the BLM signals in pA for the sum of the two sources and for the quadrupole modules which will receive the highest beam loss rates are shown in Figure 4. The steady state quench limit of 10 mW/cm$^3$ for Cu/NbTi coils based on [8, 9] is indicated in the upper panel of Figure 4. As visible there, the maximum expected power deposition within the SC coils of a SIS100 quadrupole module due to ionization losses is one order of magnitude below the quenching limit, while all currents are measurable by the LHC-IC type BLMs.

The final step is to determine the BLM quench-prevention threshold which is defined as the signal measured by the beam loss monitors corresponding to the energy deposition in the SC coils equal to the quench limit of the SC cables. The threshold can be calculated with the following equation:

$$Q^{th}[nA] = \frac{Pdep^{quench}[\frac{W}{cm^3}]}{Edep^{cable}[\frac{J}{cm^3 \cdot primary}]} \times Q_{BLM}[\frac{nC}{primary}]$$

As visible from this equation the threshold is independent of the beam loss rate. The absolute values of the BLM signals and the energy deposition in the cables are directly proportional to the beam loss rate which, however cancels in the ratio. With other words, since the beam loss positions of charge exchange ions are the same for all quadrupole modules, the calculated BLM thresholds will also be identical for each of 80 SIS100 quadrupole modules. However, for the same type of beam loss mechanism (the same loss location and duration), the BLM threshold depends on beam energy. The SIS100 will accelerate high intensity ion beams of all type of species, from proton to uranium up to a magnetic rigidity of 100 Tm. Therefore, different ion species and the energy dependence of the BLM quench prevention thresholds have also been studied, containing partially stripped ions $U^{28+}$, $Ta^{24+}$, $Xe^{22+}$, $Kr^{17+}$ and full-energy ions $Ar^{18+}$ and $Xe^{54+}$. Although the beam loss mechanism due to charge exchange considered here is irrelevant for the latter two, they are used to demonstrate the large range of different energies and ions. For each of the ion beams, the same analysis as for $U^{28+}$ was performed. Finally, the BLM quench prevention thresholds have also been determined for a SIS100 proton beam at $E_k$=29 GeV, considering the same loss location (for the sake of the same argument as before). The results of the BLM quench prevention threshold, expressed in units Gy/s, for these widely varying conditions are shown in Figure 5.

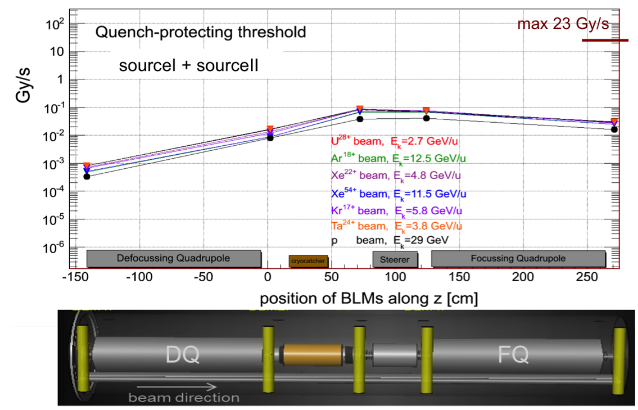


Figure 5: BLM quench prevention threshold along a quadrupole module for proton and different ion beams.

## CONCLUSIONS

The possibility of quench prevention of the SIS100 superconducting magnets by the planned BLM system has been studied with FLUKA simulations. The losses due to charge exchange of $U^{28+}$ beams were taken as a representative example. It is shown that the sensitivity range of LHC-IC type BLMs is compatible with the required quench-prevention thresholds and in general with the beam loss rates expected during the SIS100 operation. An interesting finding of this study was that, for the same beam loss location, the quench-prevention thresholds were almost identical for all ion species/energies including protons. A systematic investigation of all possible uncontrolled beam losses at SIS100 is still required for integration of the BLMs into the beam interlock system.




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