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Section A

Beam loss monitor for superconducting accelerators

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A special beam loss monitor (BLM) for SC accelerators–colliders as an integral part of SC magnet (quadrupole or/and corrector) design is proposed. The main BLM parameters calculated under the real UNK and SSC conditions are presented in comparison with the traditional BLM, which is planned to be used at SSC now.

1. Introduction

All the superhigh energy accelerators–colliders of the generation to come (HERA, UNK, RHIC, SSC, LHC) have a huge amount of energy accumulated in the beam (400 MJ for SSC) and they are based on the use of superconducting (SC) magnets. A functional regime of these facilities is very sensitive to the beam loss and can be aborted wreckly at quite insignificant levels of pulse beam loss. This fact explains the special requirements to the beam loss monitoring system (BLMS) that must guarantee a possibility for the unique accelerator complex effective operation. In addition, this system has also to be used for solving the traditional tasks for all accelerators:

- study and optimization of the functional regimes;
- control of the radiation influence on the equipment;
- control of the radiation safety.

Beam loss can be classified as inevitable and accidental. There are various reasons for beam loss:

- particle scattering on the residual gas;
- scraping of beam edges;
- injection errors;
- various nonstabilities of beam parameters;
- regime deviations from the operating points of elements;
- interaction of colliding beams (for colliders);
- operation of beam extraction system.

The inevitable beam loss can be minimized. Special protection systems are being developed to reduce its harmful influence. To reduce the influence of the accidental loss a sensitive and reliable BLMS must be designed and installed in the machine. The key element of the BLMS is a set of beam loss monitors (BLMs). In this report a special type of BLM for SC accelerators is proposed.

2. Beam loss monitoring

Beam loss exceeding a certain level in SC magnets leads to the emergency situation, i.e. to the coil transition from the superconducting to the resistive state – to the so-called quench that results in the loss of the beam control. The quench is a fast consequence of radiation-induced coil warmups that cannot be compensated (at the given current level) by relatively slow process of the heat-exchange with the cryoagent. One distinguishes slow (100 ms) and fast beam loss. Their tolerable levels are not identical and are given in table 1 [1]. One can see from the table that the tolerable beam loss levels are negligible as compared to the number of circulating protons (10^{14} in SSC [2]), which results in high requirements to the BLM sensitivity.

BLMSs of the operating accelerators are designed following the traditional method. Primary beam loss is obtained from the measurements of the secondary radiation field induced in the accelerator components. The external detectors, radiation monitors, usually called BLMs are used for the relevant measurements. They are disposed outside the beam pipe at the places of the most probable beam loss. A few hundreds of BLMs are mounted at big accelerators. As a result, there is a very big amount of data during each accelerator cycle. Till recently BLMS information was qualitative rather than quantitative due to the complicated nature of the registered signals and low accuracy of the beam loss measurements. Thus, BLMSs are usually

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Table 1
Tolerable energy depositions and relevant beam loss levels in the SSC dipole coil

Energy [TeV]	Fast loss [mJ/g]	Fast loss [ppp]	Slow loss [mW/g]	Slow loss [p/s]
2	5 -10	3.1×10^8	20	6.3×10^8
20	0.3- 1	2.3×10^6	4-8	1.9×10^7

considered as auxiliary beam diagnostic systems. But in the case of SC machines more stringent requirements are imposed on the BLMS. The characteristics of BLMS depend mainly on the choice correctness of the BLMs type, their design and arrangement on the ring.

It was mentioned above that the BLM detects the products of the primary beam particle interaction with the matter. The lost hadrons interact along their path with the beam pipe wall, which is a thick (greater than nuclear length) target for them. The main part of the nuclear and electromagnetic cascade energy propagates forward in a very small solid angle. Fig. 1 presents the angular distributions of the integral yield of the cumulative cascade hadrons from a thick Fe target for various incident proton energies (data were obtained using the MARS10 [3] computer code). One can notice that the relative part of the particles, produced near the axis, increases sufficiently with the energy growth.

Until recently the recognized optimal type of the BLM was a gas-filled ion chamber (IC) [4,5]. This BLM type is relatively inexpensive, fast, simple in exploitation, has a wide dynamic range, very high radiation resistance, long time stability of characteristics and a weak sensitivity to magnetic field. A set of such detectors does not require relative calibrations. Gas-filled BLM, similar to the monitor used at FNAL, is proposed to be used at SSC [2]. It is a cylindrical IC that has the following parameters: diameter – 40 mm, length – 100 mm, volume – about 110 cm^3, electrodes spacing – 16 mm. It is filled with gaseous argon under the pressure of 725 mm Hg and sealed. The sensitivity of such a monitor is 0.07 μC/rad. It is proposed to dispose the BLMs at each quadrupole point and after each 30 m, symmetrically between upper and lower SSC rings, i.e. 0.4 m from the beam axes. Thus, it is proposed to use one BLMS for two accelerators.

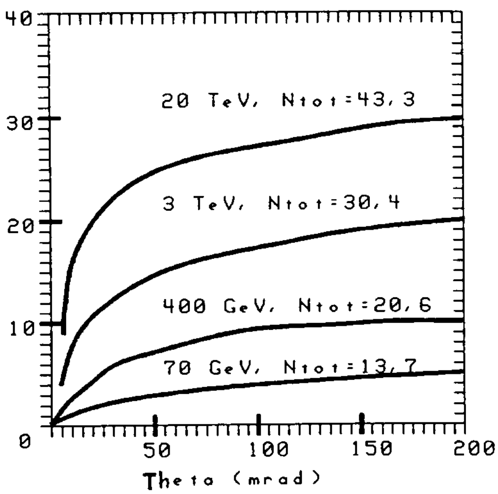

Fig. 1. The angular distributions of the integral yields of the cumulative cascade hadrons from a thick Fe target for various incident proton energies.

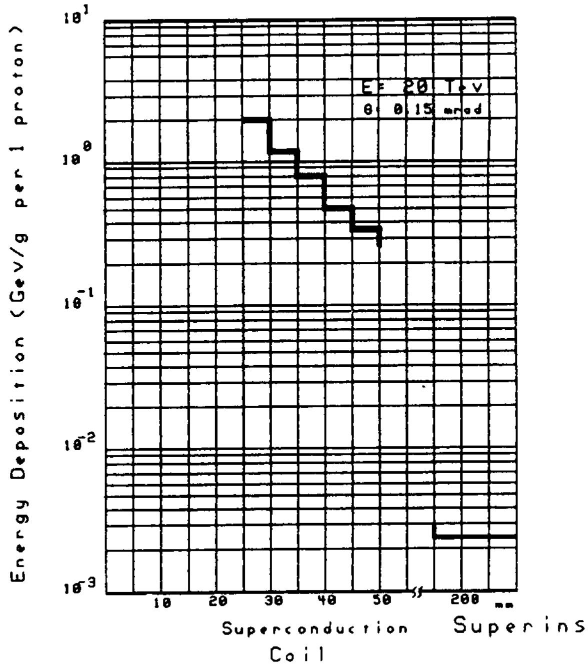

Fig. 2. Transverse distribution of the maximal energy deposition in the SSC dipole normalized to one incident proton from the 20 TeV Gaussian beam, $\sigma = 0.12$ mm, hitting the inner beam pipe wall at $\theta = 0.15$ mrad in the median plane.

We think that the BLMS project offered in ref. [2] is not adequate for the SSC complex as an advanced machine for the following reasons:

1. The use of the common BLM does not seem to be an optimal solution because the alarm beam loss level in one ring will cause the beam abort from both accelerators simultaneously. It is not gainful economically.

2. Fig. 2 presents the transverse distribution of the maximal energy deposition in the SSC dipole caused by the beam loss [1]. One can see a very strong radial dependence. At the periphery, where the BLM is planned to be placed, the value of the energy deposition is more than three orders of magnitude less than that near the coil. Thus, if one places the BLM at a distance of 400 mm from the beam center, he will

measure the "tails" of the distribution with very large relative errors.

3. If the averaged energy deposition in the shower maximum (normalized to one lost proton) is equal to 0.2 GeV/g [1] and the alarm beam loss level is equal to 1/40 of the quench threshold (2×10^6 ppp), then the relevant alarm signal of FNALs type BLM will be approximately 5 pC, which is not enough for the normal operation of the available electronics. But it is the alarm beam loss level and BLMS must be able to operate with the signals of two to three orders of magnitude lesser than this, which is hardly possible.

On the basis of the conclusions mentioned above we propose a new type of BLM meeting the SC accelerators requirements.

3. BLM for SC accelerators

As the energy deposition maximum occurs in the SC coil which is the weakest part of the magnet, we propose to measure here the energy loss of the produced particles. The main problem to be solved in such a common approach is to choose correctly the sensitive medium of the BLM. In this case one should take into account the design features and operation conditions of the cold-iron SC magnets. This magnet design is recognized as the best now. The use of liquid helium as the sensitive medium of the BLM seems to us the most preferable and natural decision. As the ion chamber is recognized to be the optimal BLM type, we have tried to design the BLM as a liquid helium-filled ion chamber. We called it HELION(L) – briefly (L). The main properties of liquid helium needed for such application are given in table 2 [6,9].

The possible layout of the UNK SC quadrupole, completed with the HELION(L) as an inseparable part of its design is shown in fig. 3. The volume of liquid helium is increased by less than 1%. The expected HELION(L) sensitivity (for the same volume with the FNAL type BLM) would be approximately about 3.5

Table 2
Some properties of liquid helium

Density at 4.2 K, 1 atm	0.125 g/cm^3
at 4.2 K, 5 atm	0.135 g/cm^3
at 1.8 K, 1 atm	0.145 g/cm^3
Mean one ion pair production energy	42.3 eV
Effective positive ion mobility	
at 4.2 K	0.06 cm^2 V^{-1} s^{-1}
at 1.8 K	0.17 cm^2 V^{-1} s^{-1}
Effective electron mobility	
at 4.2 K	0.025 cm^2 V^{-1} s^{-1}
at 1.8 K	0.12 cm^2 V^{-1} s^{-1}
Electrical strength	19 kV/mm
Relative dielectric constant	1.04–1.06

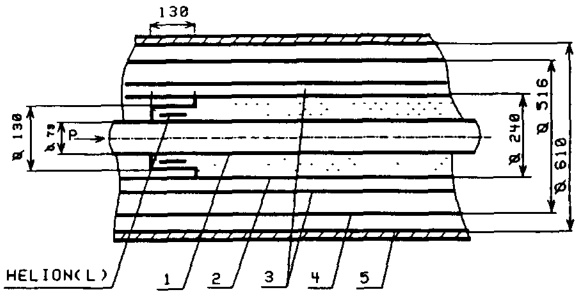

Fig. 3. The possible layout of the UNK SC quadrupole magnet, completed by the HELION(L). Sizes are given in mm. 1 – beampipe, 2 – LHe vessel, 3 – LHe flow vessels, 4 – cold (LN_2) screen, 5 – vacuum vessel of the cryostat.

μC/rad, i.e. 50 times greater. The factor of optimal (L) disposition is about 10^3, providing simultaneously much more accurate measurements of the energy deposition in the SC coil. The real volume of (L) is about 800 cm^3, i.e. 7 times greater. Thus, the common gain in the signal amplitude would be 0.35×10^6 and the expected signal of (L) at the above mentioned alarm beam loss level for the SSC dipole would be about 1.7 μC and have a higher accuracy, which seems very attractive. As a result, in addition to the quench protection, one will be able to observe the beam loss at quite low levels and to solve successfully all common tasks listed in the beginning of this article and some new tasks specific for the SC colliders.

The (L) resolution time τ_L may be determined as a maximum of $[\tau_+, \tau_-]$ – of the full collection times of free (+), (−) charges as well as the response time τ_f

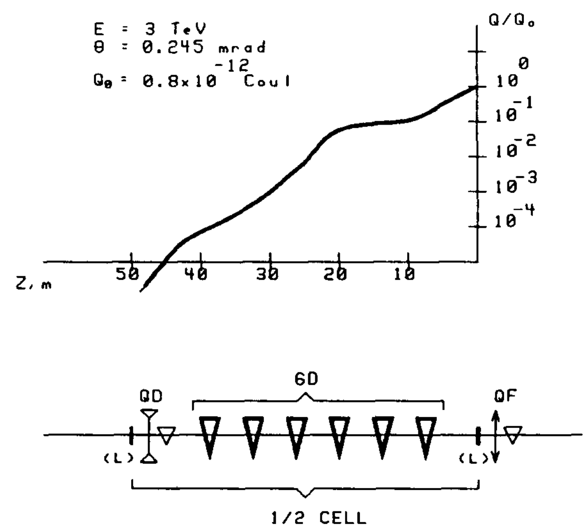

Fig. 4. HELION(L) response function, normalized to one incident proton from the 3 TeV thread beam, hitting the outer beam pipe wall at $\theta = 0.245$ mrad in the median plane. The function is calculated for the UNK-II regular lattice, presented below at the same scale.

from the front of (L) signal, which is expected to be of about submicrosecond range. Thus, the BLMS response time will be determined mainly by the electronics feasibilities and in the alarm real-time branch it may be, as we think, of about 1–10 μs. It is short enough to produce timely the alarm signal for beam dumping. The τ_L can be estimated as max of [0.5,1.2] ms for 4.2 K and of [0.15,0.2] ms for 1.8 K (for electrical field strength of 1 kV mm^{-1} and working gap 3 mm) [9]. These values are in a good agreement with both the big machines requirements (the same scale with the beam revolution time), and the time constant τ_C of the heat exchange process between the SC coil and cryoagent ($\tau_C \leq 5$–10 ms). It is very important and nice, that in liquid helium $\tau_+ \sim \tau_-$, resulting $\tau_L \sim \tau_C$ and $\tau_f \leq 1$ μs. The dose load will be integrated both in the coil with τ_C and in the HELION(L) with τ_L, and it allows one to create the simple and reliable real-time alarm branch of BLMS, which will use the fast τ_f and the common alarm threshold for both the fast and the slow beam loss.

Fig. 4 presents the response function of HELION (L), calculated for the 3 TeV thread proton beam under conditions of the UNK-II regular lattice. The half a distance between the lenses is observed well. One can expect that this function for the SSC case will be more extended. It seems to be expedient to have (L)s at points C in addition to points F and D in the SSC lattice [7] and in this case it will be a natural decision to complete the corresponding SSC corrector magnet design with (L).

HELION(L) will also have a unique electoral ability to reject the signal from the neighbouring ring. For example for the UNK case, where the distance between the rings is equal to 1.2 m, its electoral ability from the warm ring is expected to be of about 55 dB.

The problems, connected with the radiation resistance of this BLM type, are solved automatically. The electrodes are made from stainless steel, the ceramic insulators applied are very radiation resistive too, and the sensitive medium – liquid helium – is continuously renovated.

The increased sensibility of the BLM we have proposed also permit to solve some new tasks. For example, one will be able to provide the long-term beam stability in colliders by on-line study of the extremely low beam loss, occurring on the beam pipe wall or on the introduced matter. The set of (L)s, situated in low-β region near the QL1–QL3 lenses [1], may be used as the relative luminosity monitor in the pp-collision regime.

4. Conclusions

In this report only the main contours of the proposed BLM are described. Some serious problems have to be solved to implement HELION(L). But we do not see now any alternative (for SC accelerators) beam diagnostic instruments providing the detection of the beam loss at levels preventing the development of quench. We offer to complete the traditional quench protection system (QPS) by the "quench prediction one" (BLMS), where the first would be used mainly as an insurance to the second one. We believe, high-precision and sensitive BLMS, the key element of which we have proposed, will turn out to become an additional powerful tool to provide:

– the more comfortable and effective operational mode of SC colliders owing to the frequency reducing of unfounded beam abort system preventive switching on;

– the long-term beam stability in SC colliders by the operational mode optimizing from the viewpoint of beam loss;

– the additional luminosity and some other measurements.

We note that to implement HELION(L) there should be foreseen some space and environment (cables, connectors, feedthroughs) in the cryostat design to place the monitor in the vicinity of the beam pipe. We think, such a BLM must be an indispensable part of the chosen SC magnet components as it is the case with pickup electrodes for the beam orbit measurements.

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