BEAM COLLIMATION AND CONTROL IN THE LHC HIGH ENERGY INJECTORS

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Abstract

The design and construction of new injectors will allow to boost the luminosity of the LHC. Two consecutive machines capable to inject into the LHC ring at 1 TeV are being considered. Based only on the expected performance of the injectors, the beam loss handling in these high intensity machines will be a challenge and the introduction of collimation systems seems necessary. The need to reduce the beam losses and allow an efficient collimation system has to be implemented from the beginning of the design. The energy ramping in stages requires different approaches for removing the proton halo. Some studies are still necessary to define the hardware. The study performed in this paper as well as the conclusions will only slightly differ when applied to another scenario.

INTRODUCTION

The fundamental scenario on which this work is based consists of two machines installed in the SPS tunnel. A low energy ring with conventional technology would accelerate protons from the PS top energy (25 GeV) up to 150 GeV. A second high energy ring would use superconducting magnets to reach 1 TeV. The amount of uncontrolled losses should be comparable to the heat load in the cryogenic system, i.e. 20 kW [1].

In this paper, we try to determine what level of beam losses is expected and thereby the necessity of designing a collimation system. At this stage of the study, the loss mechanisms are not yet known but a first estimation can be done based on the experience in similar machines. We will stress the main issues to be kept in mind during the design of the machine in order to minimise the losses and allow the introduction of an efficient collimation system.

Consequently, a detailed design of the collimation system is not adequate. It is a known however; that the injection complex will use two distinct rings and define three very different ranges of energies, corresponding to injection and extraction of both machines. We will investigate the differences between these energy ranges and how they demand a different approach of the collimation system.

A first proposal for the two machines is sketched in the last section, together with a list of remaining issues which need to be addressed during the hardware design.

EXPECTED LOSSES

There are several limitations in the total and distributed beam losses that should be considered:

- **Heat load**. The heat load due to the beam losses in the machine will add to the cryogenic load, produced mainly by the fast ramping of the magnets. An equal contribution can be assumed, i.e. 20 kW of beam power distributed homogeneously along a circumference of 6 km. This yields a practical limit of 3 W/m
- **Quench levels**. In the high energy machine, the use of superconducting magnets imposes a limit in the amount of localised losses that can be tolerated before the magnets quench. As a first approximation, the same figures as for the LHC are taken, which corresponds to a maximum beam power of 10 to 50 W/m.
- **Activation and maintenance**. To allow fast interventions in the machine and minimize intervention time, the level of losses should not be larger than 1-10 W/m. This number depends on the actual energy of the beam, the geometry and the materials located next to the beam loss but it is a good estimate based on simulations and experience in high intensity machines [2].

The first two limitations, affect the superconducting ring while the third one is also a concern for the low energy ring. The heat load limit needs to be considered

	# of bunches	ppb	Energy [GeV]	Beam energy [MJ]	Cycle time [s]	Beam power [MW]
LHC nominal	2808	$1.15\cdot10^{11}$	7000	362	-	-
LHC ultimate	2808	$1.7\cdot10^{11}$	7000	535	-	-
LHC upgrade	5616	$1.7\cdot10^{11}$	7000	1000	-	-
SSPS inj.	288	$1.7\cdot10^{11}$	150	1.2	10	0.2
SSPS extr.	288	$1.7\cdot10^{11}$	1000	7.8	10	0.8

Table 1: beam energy and beam power of the LHC machine and the high energy injector

globally while the quench levels or activation are local limits. In practice, one should take into account all three criteria.

As was just discussed, the limits on beam losses are given in power per meter. Table 1 lists the beam energy and beam power of the different scenarios together with those of the LHC and its upgrade. For the injectors, the beam power becomes significant considering that they will continuously deliver beam for the fixed target experiments, CNGS and other projects.

From [3], the losses observed in similar machines like BNL-AGS, Fermilab-Main Ring or the Tevatron range from 1% to 6.5% and take place mainly during injection and extraction. Transition crossing is also a large source of losses for those rings that cross it. The losses observed in the current CERN machines at injection and extraction, are also at the level of a percent. From Table 1, it is evident that the total power will quickly reach 20 kW with no guarantee that the losses will be evenly distributed along the ring. Also the time dependence of the losses is unlikely to be uniform with loss peaks at injection, transition or extraction. It is clear that a collimation system needs to be included in the design of the new injectors at least in the high energy ring. In the low energy ring, the total power is considerably smaller and collimation would only be necessary to avoid excessive activation or at extraction.

The required efficiency of such systems cannot be calculated at this stage without a clear design, lattice and aperture model. The final machine design will define how well many loss mechanisms are minimized (space charge, IBS and Touscheck effect, beam-gas scattering, slow resonance extraction, RF capture, transition crossing, etc.). Accidental losses as miss-injection or kicker failures are sufficient to destroy a magnet and need to be taken into account at the design stage. Last but not least, the acceptance of the ring is the factor by which the beam halo will be transformed into beam losses. An optimisation of the lattice and the magnet aperture needs to be done in order to maximise the acceptance.

DEPENDENCE WITH ENERGY

Although other forms of collimation exist, we will consider here the simplest approach consisting on intercepting the beam halo with solid blocks of material called jaws. Several of these jaws will form a multi-stage collimation system [4]. The main processes taking place inside a jaw are ionization, multiple Coulomb scattering and nuclear reactions. These three mechanisms depend heavily on energy [5].

The energy loss by ionization in the collimator is described by the well known Bethe-Bloch equation. If an important fraction of the energy is lost in the jaw, it may put the proton outside the momentum acceptance. A hot spot will then be created at the next dispersion maximum, unless an additional absorber is provided downstream. The length of material needed to slow down a proton by 10^{-3} of its original momentum is plotted in figure 1. This length first depends on the material and decreases linearly with energy. It varies from some centimetres for most materials at low energy (25GeV) up to about one meter for light materials at high energy (1 TeV). From this, it is clear that the use of scrapers would be the preferred solution in the low energy ring at 25GeV but also at 150 GeV. The use of a long jaw (about 25 cm of graphite or 5-7 cm of copper) as primary collimator would prevent an efficient cleaning of escaping protons as they will have a large energy spread that will translate in a downstream spray of losses.

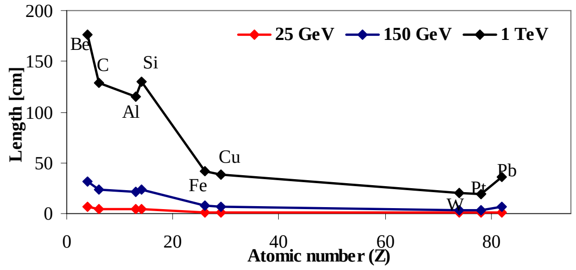

Figure 1: Length of material needed to slow-down a protons below its momentum aperture (dp/p=10^{-3}).

Taking this maximum length for each material and beam energy, we calculate the angular spread produced by multiple Coulomb scattering (figure 2). Finally, we calculate for that same adjusted length, the fraction of protons removed after experiencing a nuclear collision. This last calculation is shown in figure 3.

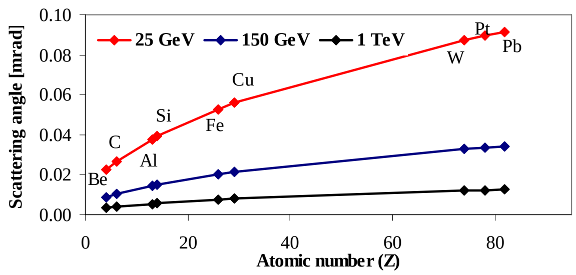

Figure 2: Angular deflection of the beam due to multiple Coulomb scattering depending on jaw material and beam energy.

The angular spread of the beam after traversing the jaw decreases with energy as protons are more rigid. For the same energy, higher Z materials increase the kicking angle produced in the jaw and are thus better candidates for scrapers.

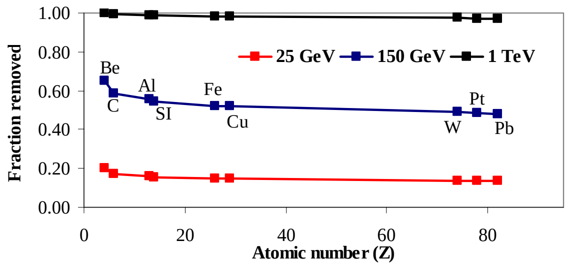

Figure 3: Fraction of protons undergoing a nuclear collision in the jaw depending on jaw material and beam energy.

On the other hand, and partly because longer collimators are used, the nuclear absorption increases with energy. A fraction of the energy of the impinging proton will be transferred to the jaw through the hadronic shower created after the first inelastic interaction. In practice, the heat deposited in the material will be the limiting factor to decide the length of the jaw as well as the material used. Decreasing the jaw length will decrease the efficiency and the heat load but the surviving protons will also have a smaller angular spread. Higher energy collimation systems are thus very sensitive to misalignments and orbit deviations which are comparable to the scattering angle.

OUT-SCATTERING

In figure 4, we plot the fraction of protons absorbed in a copper jaw as a function of its length. The impact parameter has been adjusted to the beam energy.

The fraction of protons absorbed increases with the jaw length and reaches a plateau after L~45 cm. There is an effective maximum length after which the efficiency increase is negligible. This length is the same for all energies and depends only on the nuclear interaction length of the material.

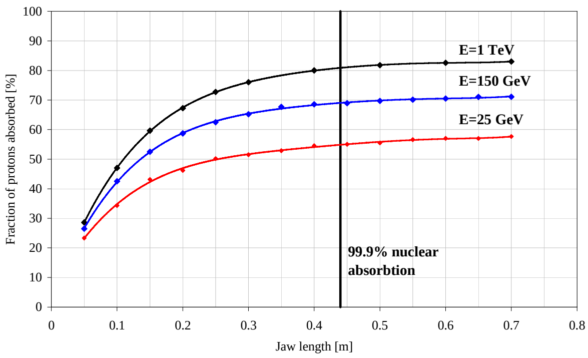

Figure 4: Fraction of protons undergoing a nuclear interaction in a copper jaw as a function of the jaw length.

Theoretically 99% of all 1 TeV protons should undergo a nuclear interaction after traversing 45 cm of copper. The difference between this value and the ~80% in the simulation comes from two mechanisms

a) Elastic nuclear scattering which does not account for absorption. Actually, elastic scattering produces large scattering angles and most of these protons will be lost within the vicinity of the collimator.
b) Protons which escape the jaw sideways without fully traversing it. This phenomenon, known as out-scattering [6] strongly depends in the impact parameter and on the impact angle on the jaw, which in turn, depends on the energy.

To study exclusively the effect of out-scattering we take a sufficiently long jaw (0.3 m of copper). The fraction of particles leaving the jaw before a full traversal (figure 5) is quite large and becomes more important as the energy decreases.

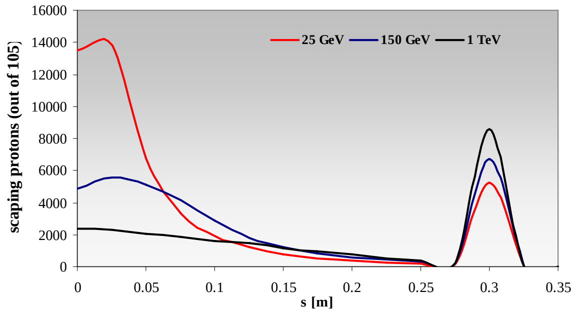

Figure 5: Longitudinal distribution of the escaping protons in a copper jaw.

Figure 6 shows the angular distribution of the escaping halo for all three energies. The halo in the left part of the figure is out-scattered while the part in the right is traversing the jaw without being absorbed. We see that the efficiency of a single jaw is much higher with high energy.

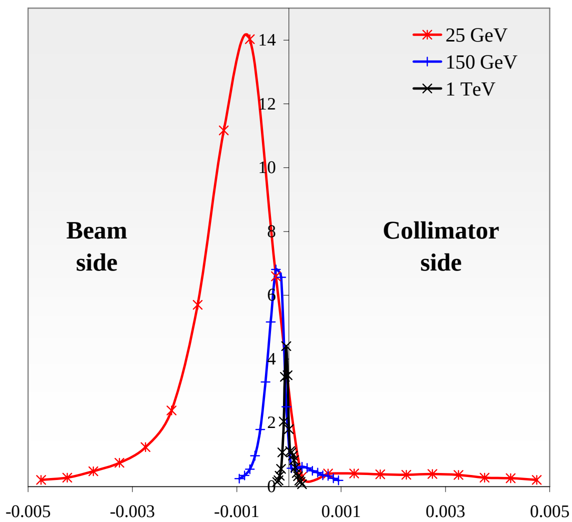

Figure 6: Angular distribution of the secondary halo escaping from a 30 cm copper jaw.

From this figure is also evident that allowing secondary collimators to efficiently catch the secondary halo requires a specific acceptance that decreases with increasing energy. The aperture of the machine not only determines the required efficiency but also its actual value.

LOW ENERGY AND HIGH ENERGY RING COLLIMATION SYSTEMS

We have seen that the cleaning of protons using a single collimator is more efficient for high energy beams. A low energy multi-stage beam collimation system has also a naturally lower efficiency as most of the protons escaping the jaw will have a high momentum deviation, and a high angular dispersion. The escaping protons have a high probability of hitting the aperture before reaching either the primary or a secondary collimator. Low energy collimation is a few turns mechanism.

However, the difficulty for the high energy collimation is the high efficiency demanded. While loosing one particle in a thousand could be tolerated at 25 GeV or 150 GeV it is not admissible at 1 TeV. Catching the secondary halo in high energy machines implies multiple passages of the protons though the primary collimator and a slow and controlled angular diffusion towards the secondary collimation system. The less controlled the diffusion, the larger the amount of secondary collimators necessary to reduce the halo.

As a first proposal, if a collimation system is needed in the low energy machine, it should use heavy material, thin scrapers as primary collimators. Special attention needs to be paid to momentum losses that would occur either during ramping or would be induced by the scrapers themselves. Secondary collimators could then be located at the right phase advance but also in dispersive regions to avoid betatron cooling in part of the halo. A high loss area seems unavoidable some meters after the collimator itself.

For the high energy ring, a multistage collimation system similar to the LHC would be necessary. Primary collimators need to be dimensioned to the injection energy, while the number and length of secondary collimators would be adapted to the required efficiency at extraction energy. The primary collimators could be done using light materials to minimize nuclear absorption while maximizing the angular scattering. The use of long collimators or scrapers needs to be weighted against the number of turns needed to remove the proton.

The eventual co-habitation of the low and high energy rings in the same tunnel will translate in short transfer lines whose protection becomes very difficult due to lack of space.

REMAINING ISSUES

Jaw material

For this preliminary study, we have chosen copper as the jaw material as an example. The choice of final material needs to be addressed taking into account the level of expected losses, their time pattern, the beam spot size, and the beam energy. Simulations are not always reliable considering the fact that reproducing the exact conditions of the loss is extremely difficult. An outstanding progress has been achieved recently through dedicated experimental studies [7]. Composite materials and layered collimators may be used to solve engineering concerns like cooling of the jaw or neutron absorption [8]. The use of bending crystals as primary scrapers also deserves to be considered.

Cross-talk between rings

The typical length of a hadronic shower in copper or steel is about one meter. In the current scenario where the low and the high energy rings share the same tunnel, losses in the low energy normal conducting ring may be seen by the superconducting ring. Their contribution needs to be pondered and added to the existing losses. At the same time, activation in the ring will be caused by both rings reducing yet loss limits.

Accidental losses

As calculated in the LHC, and experienced in the SPS machine at 450 GeV, the high energy beam can damage the accelerator in case of an accident. All the possible scenarios need to be studied, if possible at the same time as the kickers design or the injection optics.

Maintenance

Residual radiation and hands on maintenance requirements need to be defined. The shielding and maintenance procedures to repair and exchange the collimators are better considered sooner than later. The location of the collimation system with respect to access and passage also need to be considered.

CONCLUSIONS

Collimation seems to be necessary for heat load, machine protection and activation concerns. It is mandatory for the high energy part of the injectors but it could also be necessary in the low energy ring to minimize activation.

The collimation system needs to be designed in parallel with the rest of the machine, starting from the lattice definition until the study of eventual instabilities. The design of the machine will define the level of expected losses and the final efficiency required. The implementation of a collimator system in an old machine is therefore more difficult and less effective than in a new machine.

Aperture and acceptance of the machine is a key parameter that defines the required and effective efficiency of the collimation system.

The collimation system definition and final efficiency depends strongly on the energy. Scrapers are preferred for low and intermediate energy where the energy loss by ionization may be comparable to the momentum aperture. Independent systems may need to be used for injection and extraction in the high energy ring with common elements. The protection of the transfer lines remains to be studied.

Concerning the hardware and material choices, the high energy part is challenging but a lot can be learned from current and future machines like HERA, the Tevatron and the LHC.

REFERENCES

[1] W. Scandale. These proceedings

[2] "7th ICFA mini-workshop on high intensity, high brightness beams. Beam Halo and scraping" Lake Como, WI, Sept. 1999

[3] "Summary of the 2nd Mini-Workshop on Particle Losses, December 9-11 1996, KEK"

[4] T. Trenkler and J.B. Jeanneret, Part. Accel. 50 (1995) no. 4, pp.287-311

[5] "Passage of particles through matter" in S. Eidelman et al., Phys. Lett. B 592, 1 (2004)

[6] A. Van Ginneken, Phys. Rev. D **37**, 3292-3307 (1988)

[7] V. Kain et al.,"Material Damage Test with 450GeV LHC-type beam", LHC-Project-Report-822; Geneva: CERN, 25 Jul 2005

[8] N. Simos et al."Double-Wall Collimator Design of the SNS Project" PAC '01, Chicago, IL, USA Jun 2001