DESIGNING AND BUILDING A COLLIMATION SYSTEM FOR THE HIGH-INTENSITY LHC BEAM

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Abstract

The Large Hadron Collider (LHC) will collide proton beams at 14 TeV c.m. with unprecedented stored intensities. The transverse energy density in the beam will be about three orders of magnitude larger than previously handled in the Tevatron or in HERA, if compared at the locations of the betatron collimators. In particular, the population in the beam halo is much above the quench level of the superconducting magnets. Two LHC insertions are dedicated to collimation with the design goals of preventing magnet quenches in regular operation and preventing damage to accelerator components in case of irregular beam loss. We discuss the challenges for designing and building a collimation system that withstands the high power LHC beam and provides the required high cleaning efficiency. The present design choices and the work ahead are discussed.

INTRODUCTION

Each of the two LHC [**?**] rings will store 2808 bunches, each populated with $1.1 \cdot 10^{11}$ protons at energies of up to 7 TeV (nominal design parameters). The stored energy amounts to 350 MJ, two orders of magnitude beyond the achievements in the Tevatron or HERA. Comparing transverse energy densities, LHC advances the state of the art by even three orders of magnitude, from 1 MJ/mm^2 to 1 GJ/mm^2. At the same time the superconducting magnets in the LHC would quench if small amounts of energy (on the level of 30 mJ/cm^{-3}, induced by a local transient loss of 4×10^7 protons) are deposited into their cold parts [**?**].

It is seen that the energy stored in the LHC beams must be kept circulating while avoiding any significant beam loss into the cold aperture. However, beam losses cannot be completely avoided. A so-called ”primary beam halo” will continuously be filled by various beam dynamics processes and the beam current lifetime will be finite [**?**]. The handling of the high intensity LHC beams and the associated high loss rates of protons requires the usage of a powerful collimation system. It must provide the following functionality:

1. Efficient cleaning of the beam halo such that magnet quenches are prevented during regular operation.
2. Tuning of the experimental backgrounds induced by the beam halo.
3. Passive protection of the machine aperture in case of irregularities.

In addition the integrity of the system must be maintained during regular and irregular operational conditions. The challenges for designing and building an appropriate system are discussed.

DESIGN CONSTRAINTS

The collimation system must fulfil a number of important design constraints, which are listed below for protons and the limiting beam energy, usually 7 TeV. Similar constraints must be fulfilled for operation with ions.

Beam loss rates Regular LHC operation is assumed to include short periods of reduced beam lifetime. At 7 TeV the collimation system should be accepting $4.1 \cdot 10^{11}$ p/s (0.2 h lifetime) for 10 s or $0.8 \cdot 10^{11}$ p/s (1 h lifetime) continuously.

Cleaning efficiency Assuming the above beam loss rates, the expected quench levels and nominal intensity, the required local cleaning inefficiency is calculated to be $2 \cdot 10^{-5}$ m^{-1} [**?**]. The local inefficiency is defined for the LHC as the inefficiency (number of halo protons reaching $\geq 10\sigma$ per impacting primary proton) divided by the length over which losses are spread (e.g. 50 m).

Number of collimators and phase advance requirements The above mentioned excellent cleaning inefficiency can only be achieved with a cleaning system that has at least two stages with special optics requirements [**?**]. Momentum and betatron cleaning must be performed separately. For each of the LHC beams the following collimators are presently foreseen for providing the required efficiency:

1. Momentum cleaning in IR3 with 5 collimators (1 primary and 4 secondaries).
2. Betatron cleaning in IR7 with 20 collimators (4 primaries and 16 secondaries).

Some additional absorbers are required to capture the proton induced showers in the cleaning insertions. An eventual opening of collimator gaps would require additional collimators at the experimental insertions.

Beta functions in cleaning insertions Ideally, beta functions should be large at the collimators in order to alleviate the consequences if some bunches impact on the jaw. However, the limited space in the warm cleaning insertions restricts the beta functions to values of 50 m to 350 m (IR7) [**?**]. Corresponding transverse beam sizes are small, about 200 μm at 7 TeV.

Collimator gaps The available LHC physical aperture is about 10 σ both at injection (limited in arcs) and 7 TeV (limited at triplets). The primary and secondary collimators must then be closed to nominally 6 σ and 7 σ for providing the required cleaning inefficiency at 10 σ. The corresponding collimator full gaps are small at 7 TeV, ranging from 2.2 mm to 4.4 mm. It is noted that there is some limited flexibility in the collimator settings [**?**].

Operational and mechanical tolerances The relevant tolerances derive directly from the difference in settings between primary and secondary collimators ($1\sigma \approx 200\mu$m), as well as from the impact parameter at the secondary collimators (average impact parameter is 200 μm). Tolerances are a fraction of these values. For example, the tolerances for transient orbit movements and transient beta beat were determined to be 0.6σ and 8%. Tolerances can be estimated for jaw surface flatness ($\approx 25\mu$m), reproducibility of jaw settings ($< 20\mu$m), resolution in jaw movements (μm, μrad) and knowledge in collimator gap $< 50\mu$m. Some trade-off between different tolerances is possible.

Impedance The collimators can produce significant transverse resistive impedance due to the small gaps at 7 TeV (impedance scales inversely proportional to the third power of gap size). The LHC octupoles allow handling of a total collimator impedance of up to 110 MΩ/m, to be compared with an impedance of 100 MΩ/m generated by the rest of the ring.

Shock beam impact In case of irregular beam dumps several bunches can be deflected on a collimator jaw. Any jaw can be hit, because the primary collimators only cover one phase space location and the overall LHC tune should be allowed to vary. The collimator hardware should withstand beam impact during irregular dumps. The expected maximum beam impact was calculated to be about 20 bunches [**?**]. Recently this value was reduced to about 8 bunches, due to a substantial improvement in the dump re-trigger time [**?**]. The presently ongoing material studies still include the now pessimistic, old scenario.

Reliability and maintenance The lost protons will activate the cleaning insertions with dose rates varying between 1-15 mSv and even higher values on the jaws themselves. Human interventions in the cleaning insertions must be restricted to the absolute minimum and the collimators must be designed for maximum reliability. More detailed studies are ongoing.

Vacuum aspects The collimators must be bakeable and outgassing rates must remain acceptable. For example, for a Graphite collimator this imposes special heat treatment, careful outbaking, and a maximum jaw temperature of 50°C, to be assured by collimator cooling. Graphite dust is believed to be uncritical. The magnitude of a local e-cloud and its possible effects are being studied. Outgassing measurements are being performed.

The design of the collimation hardware should address these constraints in a consistent way, even though some constraints support conflicting preferences.

MATERIAL STUDIES

The present baseline collimation system for the LHC relies on Aluminium and Copper jaws, as used in LEP. These choices do not allow collimator survival e.g. during irregular dumps. Copper would become damaged if about 10^{-5} of the stored 7 TeV beam intensity is lost in a single turn on one Cu collimator. The losses during irregular dumps are more than two orders of magnitude above this damage threshold.

Energy Deposition in Various Materials

The expected beam impact distribution for irregular dumps [**?**] was used to calculate the energy deposition versus jaw length in various materials. FLUKA [**?**] was used to perform a full shower study. The results are shown in Fig.1. It is seen how the shower develops along the length of the jaw. The length of secondary jaws, as required for achieving the desired cleaning efficiency, varies between 0.5 m for Cu and 1.0 m for C or Be. The temperature rise for these lengths is large, ruling out high Z materials, even for possible coatings. Shorter primary jaws (a few cm to 20 cm) are less critical. As possible candidate materials C and Be are retained.

Other FLUKA studies have been performed (required thickness of C layer, injection impacts) and some others are under preparation (fiber-reinforced C, Cu doped C, ions, slow losses in 200 nm surface layer, energy deposition downstream of jaw, input for e-cloud estimate).

Fatigue and Stress Analysis

The FLUKA results are used in ANSYS [**?**] to predict stresses. The static stresses were calculated for fine-grain C and Be (for the 7 TeV irregular dump). It was found that static stresses for C are about a factor of 2 and for Be about a factor of 5 beyond the engineering tolerance. Dynamic stresses usually further increase the stress values by a factor of 2. Detailed dynamical calculations are being done. In addition, ANSYS calculations are planned for fiber-reinforced C, Cu doped C, ions and injection cases.

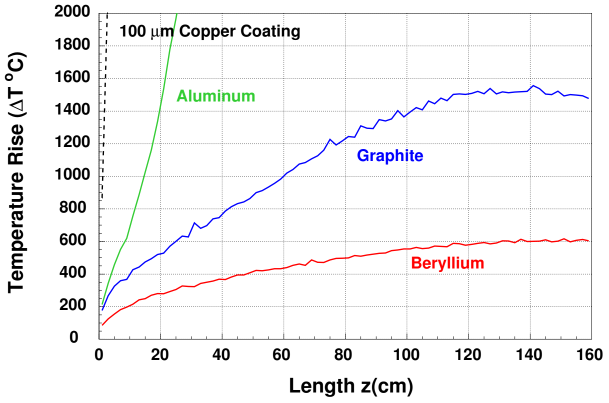

Figure 1: Temperature increase (peak) from 20°C versus collimator length for different materials. Input is the proton impact distribution from an irregular dump at 7 TeV (single-module pre-trigger with a 1.3 μs re-trigger time). Approximately 20 bunches impact on the jaw face.

The ANSYS results will allow selecting the material with the best mechanical properties for LHC collimation. It is too early for any final conclusions at this point, however, C looks most promising. Taking into account the recent factor 2.5 reduction in beam impact (improved LHC dump re-trigger time) and a factor of 2 increase for dynamic stress, it is seen that fine-grain C is be less than a factor of two away from the design target. These C jaws would survive most irregular dumps at nominal intensity and certainly would have appropriate robustness for running during the first years of the LHC. It is hoped that fiber-reinforced C will show even better mechanical resistance.

Impedance

The transverse resistive impedance was evaluated for the collimators, assuming nominal 7 TeV gaps, nominal intensity, and different materials. Large impedance was found, ranging from 100 MΩ/m for Copper jaws to 1050 MΩ/m for C jaws. While the Cu-based solution is acceptable for impedance and unacceptable for robustness, the C-based solution is almost acceptable for robustness but unacceptable for impedance. A full Be-based system has insufficient robustness. A solution with C jaws in the horizontal plane (the dump sweep is horizontal) and Be jaws elsewhere would allow reducing impedance to about 300 MΩ/m. This is still unacceptably large and in addition the use of Be would introduce additional safety concerns. The conflicting requirements prevent a straight-forward solution.

More complicated solutions are being investigated. For example, a C-based collimation system might have acceptable impedance with a different collimation strategy, where secondary collimators are opened to about 10 σ. Possibilities to achieve this without constraining the LHC performance are under study. It is also investigated whether Copper doped Graphite has a better impedance for similar robustness.

SUMMARY AND OUTLOOK

The design challenges for the LHC collimation system have been reviewed, giving a list of specific constraints. Possible jaw materials are being studied with the goal of building collimators that can survive the expected conditions during LHC operation, including irregular dump actions. This would avoid the use of more elaborate and more expensive concepts like ”consumable” or ”renewable” collimators. At present no appropriate jaw material could be identified. Graphite is very promising in terms of robustness but generates unacceptably high transverse resistive impedance. The use of a C-based collimation system would require a different collimation strategy that uses larger gaps. This is being studied but would require additional collimators close to the experimental interaction points. In addition hybrid solutions (C/Cu, C/Be) and more advanced materials (Cu doped C) are being investigated. Concepts of ”consumable” or ”repairable” jaws are considered with still lower priority.

The mechanical design of the collimator tanks, the jaws themselves, the cooling, . . . is being addressed in parallel to the material studies. Once a material has been selected and the mechanical layout has been chosen, a prototype will be built for April 2004. The production of 66 collimators and spares would take place in 2004 and 2005. The collimators would be installed in 2006 and be ready in time for LHC commissioning in 2007.

Collimation for the LHC is a difficult task offering many interesting challenges. The commissioning, operation, and understanding of the system will be an opportunity to learn about handling of high-intensity proton beams in a completely new regime.

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