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STUDIES ON COMBINED MOMENTUM AND BETATRON CLEANING IN THE LHC

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Abstract

Collimation and halo cleaning for the LHC beams are performed separately for betatron and momentum losses, requiring two dedicated insertions for collimation. Betatron cleaning is performed in IR7 while momentum cleaning is performed in IR3. A study has been performed to evaluate the performance reach for a combined betatron and momentum cleaning system in IR3. The results are presented.

INTRODUCTION

The LHC collimation system is designed to provide both betatron and momentum collimation [1]. Unavoidable losses of protons or ions with high betatron amplitude or high momentum offset must be intercepted at collimators and absorbed with very high efficiency in order to prevent quenches in the super-conducting magnets of the LHC. Maximum efficiency is achieved by implementing these two functions in two separate insertion regions. The complete separation of betatron and momentum collimation also provides maximally orthogonal phase space cuts.

There are no accelerator physics reasons for installing a given function (momentum or betatron collimation) into a given insertion region (IR). The choice of the IR's has been made at the end of the 1990's, based on ideas to minimize water activation. The final design choice placed momentum collimation into IR3 and betatron collimation into IR7, at opposite extremes of the LHC ring. This is shown in Figure 1.

MOTIVATION FOR COMBINED FUNCTION CLEANING

The first beam operation of the CNGS pointed to the weakness of several electronics equipments used for the LHC with respect to radiation damage (single-event effects) [2]. In order to minimize radiation damage to electronics for a given loss of primary accelerator beam, one can define an effective radiation dilution area A_{rad}:

$$A_{rad} = \frac{R_{beam-loss}}{F_{elec}}$$

It is a function of the beam loss rate $R_{beam\text{-}loss}$ at primary collimators (e.g. in number of protons per year) and the resulting peak flux F_{elec} through the electronics components in underground caverns (e.g. in number of hadrons above 20 MeV per cm^2 per year). A detailed description of radiation to electronics is found in [3].

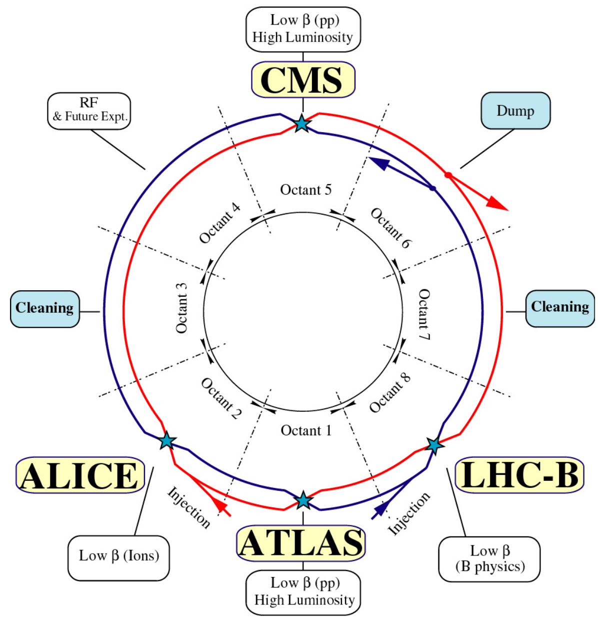

Figure 1: Schematic layout of the LHC and the functions of the various insertion regions. Beam cleaning (or collimation) is implemented separately for betatron collimation in IR7 and momentum collimation in IR3.

Ideally one would like to allow the highest possible losses of primary beam at the collimators while having at the same time the lowest possible radiation to electronics in underground areas. Goal is therefore to maximize the effective radiation dilution area.

Radiation to electronics in underground areas of the LHC has been calculated in 2005, both for IR3 and IR7 [4,5]. It was shown that the radiation to electronics in the underground electronics caverns from losses on primary collimators is strongly different for the two cleaning insertions:

- IR7: For 4×10^{16} p lost at primary collimators the peak radiation to electronics was calculated to be 1×10^{8} (RR73/77) and 8×10^{8} (UJ76) hadrons above 20 MeV per cm^2 [4]. The radiation dilution area is then in the range of **(0.5-4.0) $\times 10^8$ cm^2** in IR7.
- IR3: For 10^{16} p lost at primary collimators the peak radiation to electronics in UJ33 was calculated to be 2×10^{6} hadrons above 20 MeV per cm^2 [5]. The radiation dilution area is then **5×10^9 cm^2** in IR3.

It is seen that losses at primary collimators in IR3 are predicted to induce 12-100 times less radiation to electronics in underground caverns, if compared to the same losses in IR7. The differences between IR3 and IR7 are related to different tunnel layouts in the areas and in particular a larger distance between the LHC accelerator beam line and the UJ33 electronics cavern in IR3.

In case of problems with radiation damage for LHC electronics, the allowable integrated beam losses in the IR7 cleaning insertion could be limited to below the damage threshold of the electronics. The maximum LHC beam intensity is at least linearly proportional to the allowable beam loss rate and can therefore also be limited. It would then be strongly beneficial to combine all losses in IR3, i.e. to operate a combined momentum and betatron cleaning system in IR3. Such a solution could allow recovering a factor 12-100 if intensity is limited by radiation to electronics.

IR3 FOR COMBINED BETATRON AND MOMENTUM CLEANING

The IR3 momentum collimation system implements a horizontal collimation system in a dispersive area of the LHC machine, already prepared for a phase II installation of additional collimators for system completion. It includes per beam:

1. One robust primary horizontal collimator TCPH with carbon-based jaws at the start of the insertion.
2. One prepared location for a scraper (phase II).
3. Four robust secondary horizontal collimators TCSGH with carbon-based jaws along the insertion.
4. Four prepared locations for phase II secondary collimators.
5. One vertical TCLAV and three horizontal collimators TCLAH with tungsten jaws at the end of the cleaning insertion.

This horizontal system can only be used for horizontal combined momentum and betatron cleaning. In order to also perform vertical betatron cleaning it would need to be upgraded with vertical collimators. For this purpose one could conveniently use the already prepared phase II slots with existing cables, water connections and supports. The following collimators would be added:

1. One robust primary vertical collimator TCPV into the prepared location for a scraper (phase II).
2. Four robust secondary vertical collimators TCSGV with carbon-based jaws into the prepared locations for phase II secondary collimators.

It is noted that this would need to be implemented for both beams, bringing the total number of additional vertical collimators to 10. Such a system could initially be implemented by reducing the number of collimators in IR7 and by using spare collimators. However, in the longer term these additional collimators would need to be produced and additional electronics would need to be procured and installed. Such an upgraded IR3 collimation system was implemented for simulating the achievable cleaning performance for protons and ions.

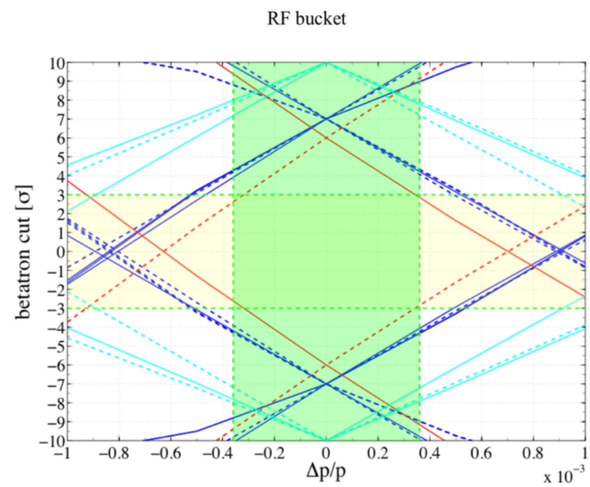

Figure 2: Collimator lines versus betatron and momentum cuts with a combined betatron and momentum cleaning system in IR3. The red lines indicate cuts from primary collimators TCPH, blue lines from secondary collimators TCSGH and turquoise lines from TCLAH collimators. The RF bucket size and the 3 σ betatron size are indicated with colored areas.

COUPLED PHASE SPACE CUTS

The modified cleaning system was studied with the following collimator settings, expressed in terms of betatronic beam size σ_β for on momentum particles $\Delta p/p=0$:

1. TCPH, TCPV at 6 σ_β.
2. TCSGH, TCSGV at 7 σ_β.
3. TCLAH, TCLAV at 10 σ_β.

The resulting phase space cuts are shown in Figure 2, taking into account the chromatic Twiss functions (therefore we see a curvature of the lines representing the phase space cuts). The algorithm for creating such phase space plots is described in [6].

It is seen that a combined system is feasible with the settings listed above. However, the particle distribution is cut close to 3 σ_β at the edge of the RF bucket. Settings cannot be reduced below the once listed above in order to avoid that collimators cut into the core of the beam distribution and to prevent a reduction in beam lifetime and an increase in beam loss rates.

The combined system gives up on orthogonal cuts for momentum and betatron space in the horizontal plane. Some freedom can be recovered by going to one-sided cleaning. One side of the two-sided primary collimator (the one in the direction of dispersive offsets) is used for momentum cleaning while the opposite side is used for betatron cleaning. The jaws can be set asymmetrically around the beam, choosing independently momentum and betatron cuts. Alternatively, the beam could be shifted by an orbit bump in the primary collimator.

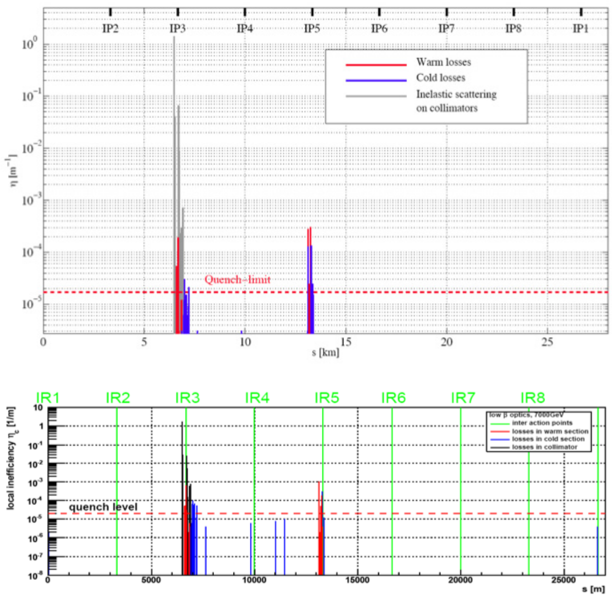

Figure 3: Proton beam loss maps, showing local cleaning inefficiency (leakage) around the ring for horizontal (top) and vertical (bottom) cleaning with a combined IR3 system. The blue lines indicate losses in super-conducting magnets. A quench level is indicated for nominal LHC intensity and nominal peak loss rate (0.1%/s).

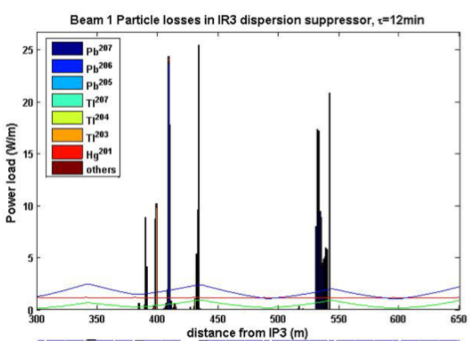

Figure 4: Loss map of ion fragments downstream of IR3. The corresponding quench limit is 8.5 W/m for nominal intensity.

EFFICIENCY OF COMBINED BETATRON/MOMENTUM CLEANING

The achievable cleaning efficiency was calculated for horizontal and vertical betatron cleaning. It is here expressed as cleaning inefficiency, the leakage of collimation losses to downstream accelerator equipment. The results are shown are shown in Figures 3 and 4. The losses in IR5 will be handled with tertiary collimators in this insertion (not included in this simulation) and should therefore be ignored. Important are the losses immediately downstream of the IR3 cleaning insertion. It was found that collimation efficiency is reduced for a combined momentum and betatron collimation system as follows:

- Horizontal betatron cleaning for protons: Ideal **efficiency is reduced by factor 2** if compared to IR7. Ideal performance reach: up to 40% of nominal intensity.
- Vertical betatron cleaning for protons: Ideal **efficiency is reduced by about a factor 2** if compared to IR7. Ideal performance reach: up to 20% of nominal intensity.
- Betatron cleaning for ions: Ideal **efficiency is reduced by about a factor 3-5**. Ideal performance reach: up to 20% of nominal intensity.

A combined betatron and momentum cleaning system in IR3 provides acceptable cleaning performance both for betatron and momentum losses, though the performance is reduced with respect to the achievable performance with two independent cleaning systems. The reduction in cleaning performance (factor 2) is much lower than the gain in radiation to electronics (factor 12-100).

CONCLUSIONS

A combined betatron and momentum collimation system was studied for the LHC. It was shown that such a combined system could be implemented into IR3, making use of the existing preparations for the phase II of LHC collimation. In particular, replacement chambers, electrical cables, water connections and supports are in place in the tunnel.

The performance of such a combined system was simulated. It was shown that it would work properly for both protons and ions. The performance reach of LHC collimation would be reduced by about a factor 2. At the same time, collimation-related radiation to the electronics in underground caverns of the LHC would be reduced by a factor 12-100 for the same collimation losses.

It is concluded that a combined momentum and betatron collimation system in IR3 can provide a viable solution in case that radiation to electronics from beam losses on collimators would limit the LHC beam intensity.

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