

## A Novel Collimation Method for Large Hadron Colliders (Postprint)

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### Abstract

This paper proposes a novel collimation method for large hadron colliders by arranging betatron and momentum collimation systems in the same insertion to improve the overall cleaning efficiency. The method has the potential of avoiding beam losses at the downstream dispersion suppression section following the conventional betatron collimation section, which is caused by those particles with single diffractive scattering at the collimators. Evident beam loss in arc sections should be avoided to protect the superconducting magnets from quenching, especially when the stored beam energy is up to hundreds of MJ level or even higher in modern proton-proton collider. Our studies show that it is beneficial to arrange the momentum collimation system just after the betatron collimation system so that it can clean the particles with lower momentum due to the single diffractive scattering in the betatron collimators. This method is being applied to the future proton-proton collider SPPC. Preliminary multi-particle simulations are presented with the Merlin code.

### Full Text

## A Novel Collimation Method for Large Hadron Colliders

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This paper proposes a novel collimation method for large hadron colliders that improves overall cleaning efficiency by arranging betatron and momentum collimation systems within the same insertion. This approach has the potential

to avoid beam losses in the downstream dispersion suppression section following conventional betatron collimation sections, which are caused by particles undergoing single diffractive scattering at the collimators.

Evident beam loss in arc sections must be avoided to protect superconducting magnets from quenching, particularly when the stored beam energy reaches hundreds of MJ or higher in modern proton-proton colliders. Our studies demonstrate that positioning the momentum collimation system immediately after the betatron collimation system effectively cleans particles with reduced momentum resulting from single diffractive scattering in the betatron collimators. This method is currently being applied to the future proton-proton collider SPPC. Preliminary multi-particle simulations using the Merlin code are presented herein.

## I. Introduction

In large hadron colliders, the stored beam energy is extremely high, making the beams highly destructive. Even a tiny fractional loss of the full beam in a superconducting magnet could cause a quench, and substantial beam losses could inflict serious damage on accelerator components. However, beam losses are unavoidable in colliders where beam-beam collisions represent the primary loss source. Therefore, beyond strictly controlling beam losses and implementing highly reliable beam abort systems, a robust and extremely efficient collimation system is essential for safely disposing of beam losses.

The performance of the collimation system is quantified by the local cleaning inefficiency, defined here as:

$$\eta_{local} = \frac{N_{lost}}{N_{abs}} \quad \text{over a length of } \Delta s = 10 \text{ cm}$$

where  $N_{lost}$  is the number of particles lost locally and  $N_{abs}$  is the total number of particles absorbed in the collimation system.

Figure 1 [Figure 1: see original paper] shows the layout of the LHC collimation system, which represents state-of-the-art performance. The system includes 108 movable collimators: primary collimators (TCPs), secondary collimators (TCSGs), absorbers (TCLAs), tertiary collimators (TCTs), and other protection collimators [1]. With the design stored energy of 360 MJ, the local cleaning efficiency can reach up to 99.993%, ensuring that only about  $10^{-5}$  of particles are lost at local superconducting magnets [2]. However, this performance is considered insufficient to prevent superconducting magnet quenching when the LHC is upgraded to HL-LHC [3] with stored energy up to approximately 700 MJ.

The primary challenge arises from beam loss in the downstream dispersion suppression (DS) section following the betatron collimation insertion (IR7), which becomes excessively significant and has been attributed to the single diffractive

(SD) effect [4]. Consequently, the collimation system must be upgraded to meet the challenges at HL-LHC.

## II. A Novel Collimation Strategy for Future Proton-Proton Colliders

A novel collimation method for large hadron colliders is proposed to address the problem of requiring extremely high collimation efficiency. The concept involves arranging both betatron and momentum collimation systems within the same cleaning insertion to prevent significant beam losses in the downstream DS region due to SD effects. The momentum collimation system will clean those particles that lose substantial energy in the primary betatron collimators but survive the secondary collimators and absorbers.

Only protons with  $\Delta p/p < 0.5\%$  would escape the DS region without local collimators in the case of the LHC [6]. The maximum momentum deviation  $\delta_{max}$  that can pass the primary momentum collimator is defined by:

$$\delta_{max} = \frac{n_1 \sqrt{\varepsilon}}{\eta_D}$$

where  $n_1$  is the primary momentum collimator aperture (in units of rms beam size),  $\varepsilon$  is the geometric emittance, and  $\eta_D$  is the normalized dispersion at the collimator.

If the maximum normalized dispersion in the momentum collimation section is larger than that in the DS section or the entire arc section, there will theoretically be minimal beam losses in the downstream DS section or even throughout all arc sections. With betatron and momentum collimations sharing the same long straight section, generating the required dispersion for momentum collimation becomes a key issue. Unlike the momentum collimation section at the LHC where dispersion is intentionally designed to be non-zero between two adjacent DS sections, this novel approach requires an achromatic end at the joint between the momentum collimation and transverse collimation sections.

As shown in Figure 3 [Figure 3: see original paper], one can see that each SPPC ring is composed of eight arcs and long straight sections (LSSs), with LSS1 serving as the collimation insertion. Different from the momentum collimation section at the LHC where dispersion is intentionally designed non-zero between the two adjacent DS sections, here it is required to have an achromatic end at the joint between the momentum collimation and transverse collimation sections. This means that cold dipole magnets are needed to produce the required dispersion for momentum collimation and cancel the dispersion at the section end.

Necessary protection from local beam loss and sectional radiation for these cold dipole magnets is indispensable. Some protective collimators (TCPs) are used

to intercept particles with very large momentum deviation. Another limitation is that betatron collimation typically requires significantly longer space for multi-stage collimation, and the two proton beams run in opposite directions. Finally, the two ends of the long straight section connecting the adjacent arcs should not be affected by the introduced dipoles. Altogether, a chicane structure for the momentum collimation can be envisioned. The cryostats for the superconducting magnets are connected by warm vacuum tubes, and some local shielding is provided to protect the superconducting magnets.

### III. Applying the Novel Collimation Method to the SPPC

#### A. Brief Introduction to the SPPC

SPPC (Super Proton-Proton Collider) is a next-generation proton-proton collider designed for energy-frontier physics, particularly for beyond-Standard Model research. It represents the second phase of the CEPC-SPPC project proposed by Chinese scientists, with both colliders sharing the same tunnel [7]. Figure 4 [Figure 4: see original paper] shows the layout of the SPPC, and Table 1 presents some main parameters of the preliminary baseline design.

The stored beam energy per beam will reach up to 6.7 GJ, posing an extreme challenge to both the beam abort system and collimation system. The local cleaning inefficiency should achieve  $10^{-6}$  or even lower to prevent quenching of superconducting magnets. A multi-stage collimation system for both transverse and longitudinal planes is employed at the SPPC, similar to the LHC scheme, but with both collimation systems arranged in one long straight section as explained in Section II.

#### B. Beam Collimation Method and Local Lattice at the SPPC

The transverse collimation is illustrated in Figure 5 [Figure 5: see original paper], perhaps with one more stage than the LHC scheme. Figure 6 [Figure 6: see original paper] shows the betatron and dispersive functions throughout the cleaning insertion. Warm quadrupoles are used for the transverse collimation section, while superconducting dipoles and quadrupoles are used in the momentum collimation section.

To protect the arc aperture from off-momentum particle losses, the normalized dispersion at the primary momentum collimator must satisfy [1]:

$$|\eta_{D,prim}(n_1)| \geq \frac{n_1 \eta_{D,arc}}{A_{arc,inj}(\delta_p = 0) - (n_2^2)^{1/2}}$$

where  $A_{arc,inj}(\delta_p = 0)$  is the arc aperture for on-momentum particles;  $\eta_{D,arc}$  is the normalized dispersion with errors in the focusing quadrupole magnets; and  $n_1$ ,  $n_2$  are the apertures of primary and secondary collimator jaws in multiples of rms beam size.

For the present SPPC design,  $A_{arc,inj}(\delta_p = 0) = 22.3$ ,  $\eta_{D,arc} = 0.246 \text{ m}^{1/2}$ ,  $n_2 = 7.5$ ,  $n_1 = 5.5$ , thus requiring  $|\eta_{D,prim}(n_1)| \geq 0.079 \text{ m}^{1/2}$ .

In addition, to ensure that the cut of the secondary halo is independent of particle momentum, the following condition must be satisfied at the position of the primary collimator [8]:

$$\beta_{prim} = \beta_{sec}$$

Two pairs of dipole groups are used to produce sufficient dispersion for momentum collimation, with the final orbit returning to the same line as the betatron collimation section. A “magnet group” here denotes several magnet units arranged together, functioning as a single magnet of extended length. The first-version parameters are listed in Table 2 .

### C. Multi-Particle Simulations

Multi-particle simulations using the lattice parameters and collimator settings have been carried out with the code Merlin [9]. As an initial approach for the betatron collimator settings, similar physical gaps and phase advances as the LHC have been chosen to verify the effectiveness of the novel collimation method, particularly in cleaning particles related to the SD effect. The primary momentum collimator is placed at the middle quadrupole between the second and third groups of dipoles to satisfy Eq. (4), where the normalized dispersion is close to its maximum absolute value. The other momentum collimators are placed downstream with the same phase advances as the current LHC. The collimator positions can be found in Figure 7 [Figure 7: see original paper].

For simplicity, the interaction regions are replaced by simple FODO periods in the simulations. To increase simulation efficiency with a huge number of particles ( $10^8$ ), the initial beam distributions are chosen as a ring-type distribution in the horizontal plane and a Gaussian distribution in the vertical plane. Table 3 shows the initial beam parameters for the simulations, and Table 4 shows the basic parameters of the collimator settings for each beam.

Figure 7 [Figure 7: see original paper] shows the beam loss distribution in the cleaning insertion without additional protective collimators, revealing cold-area losses of about  $10^{-5} \text{ m}^{-1}$ . The reason is that after betatron collimation, the SD effect induces beam losses in the region where dispersion begins to rise, necessitating protective collimators (used as absorbers). Unlike placing protective collimators in the DS region where the lattice structure is very strict and tight, it is much easier to provide space for collimators at room temperature in the momentum collimation section.

Based on the positions of lost particles, three protective collimators made of Tungsten with apertures identical to the primary momentum collimator are placed to intercept the particles. The specific locations are as follows: one

protective collimator is placed between the second and third dipole magnets of the first dipole group to intercept particles with very large momentum deviation, with the cryostat for the dipole group split into two parts to allow insertion of the room-temperature collimator; another is placed before the quadrupole between the first and second groups of dipoles to protect the quadrupole; and the third is placed in front of the second group of dipole magnets.

Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper] show the beam loss distributions in the cleaning insertion and the full ring with protective collimators, respectively. These figures demonstrate that with suitable protective collimators, nearly all beam losses in the DS regions due to the SD effect disappear. Almost all lost particles are intercepted by collimators in warm regions. For the present design, considering only linear conditions, the maximum energy spread of particles that can pass through the primary collimator is about 0.1%.

The situation with energy spread is also simulated, as illustrated in Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper]. These figures show that even with maximum energy spread, the novel collimation method achieves extremely high cleaning inefficiency in the downstream DS regions, at least better than  $5 \times 10^{-7}$ , which meets the SPPC requirement.

#### IV. Conclusions and Discussions

A novel collimation method for large hadron colliders is proposed by arranging both betatron and momentum collimation systems in the same cleaning insertion to largely reduce beam losses in the downstream arc section, as beam loss in cold regions is considered a critical issue. This arrangement can utilize the momentum collimation system to clean very large off-momentum particles generated in the upstream transverse collimators by the single diffractive effect, along with its original function of cleaning particles with large momentum deviation that may arise from beam-beam collisions, intra-beam scattering, and instabilities. A very long straight section is required to host the two collimation systems, one for each of the two beams. Sufficiently large dispersion is required for the momentum collimation section, and protective collimators safeguard the superconducting magnets used in this region.

Preliminary studies including layout, linear optics, and multi-particle simulations with Merlin demonstrate that the method is very effective in eliminating beam losses in arcs. Further optimization of the method and benchmark simulations with the SixTrack code will be carried out in the next step.

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