PRINCIPLES FOR GENERATION OF TIME-DEPENDENT COLLIMATOR SETTINGS DURING THE LHC CYCLE

R. Bruce*, R.W. Assmann, S. Redaelli
CERN, Geneva, Switzerland

Abstract

The settings of the LHC collimators have to be changed during the cycle of injection, ramp and squeeze to account for variations in the orbit, beam size and normalized distance to the beam center. We discuss the principles for how the settings are calculated and show a software tool that computes them as time-dependent functions from beam-based data and theoretical optics models.

INTRODUCTION

The LHC uses a multi-stage collimation system to intercept unavoidable beam losses and to provide passive machine protection [1, 2, 3]. The collimators installed in the cleaning insertions IR7 and IR3 are primary (TCP), secondary (TCS) and absorbers (TCLA). Furthermore, there are tertiary collimators (TCT) in the experimental interaction regions (IRs), dump protection (TCS and TCDQ) in IR6 and special injection protection collimators. The collimators must at all times be positioned in such a way that the cold aperture is protected and that the hierarchy between the different stages is preserved. This means that the TCPs must be the primary aperture bottleneck and have a smaller aperture than the TCSs and that they must shadow the dump protection, which in turn shadows the TCTs. Therefore, the collimator settings must be changed routinely during the standard operational cycle: i) Beams are injected at 450 GeV, ii) The energy is ramped (to 3.5 TeV in 2011), iii) The optics is changed so that the β-functions at the interaction point (IP) is reduced ("squeeze") from 11 m to a smaller value (1.5 m in 2011), iv) The parallel separation at the IP is collapsed so that the beams are put into collision, and v) At the end of the fill, the beams are dumped, the magnets ramped down and the cycle restarts.

To determine the settings of the collimators, the theoretically calculated settings in beam σ have to be adjusted for orbit offsets and possibly corrected with the ratio of the real beam size to the theoretical beam size. To determine the centers, the collimators are aligned using a beam-based calibration [4], which is called a collimation setup. This is done by touching the beam halo with both jaws to create losses seen by the beam loss monitors. From the setup, both the center of the beam and the effective beam size can be deduced [4]. The measured beam size is used only at injection. At top energy the error on the measured beam size becomes significant [5], and since the β-beat is small, the nominal beam size is used instead.

Collimation setups are performed in several machine configurations during the cycle: at injection, after the ramp, after the squeeze (only TCTs are aligned) and in collisions (only TCTs are aligned). At these points, all beam centers and beam sizes are clearly defined. Between the setup points, the machine is performing a smooth transition between different configurations. To ensure optimal performance, the collimators have to follow smoothly. This is done through time-dependent functions, which provide the settings for all collimators.

In the following sections, we describe how the functions are calculated and generated for the different stages.

RAMP FUNCTIONS

For the nominal machine design, the collimator settings are determined beforehand in units of the *nominal* beam size σ in the collimation plane. Assuming a bi-Gaussian beam distribution, σ can be calculated to

$$\sigma = \sqrt{\sigma_x^2 \cos^2 \theta + \sigma_y^2 \sin^2 \theta} \tag{1}$$

for a collimator with beam size σ_u in plane u and a tilt angle θ.

Several parameters change between the start (denoted by subscript 0) and the end of the ramp (denoted by subscript 1) . When the energy is increased, the beam size shrinks due to adiabatic damping. Furthermore, although the theoretical optics stays the same, different collimator centers are found in the setups at injection and top energy and the effective β-beat changes at the collimators. The σ at the collimators is also different because of the use of the measured beam size at injection and the nominal beam size at top energy.

In order to calculate the settings during the ramp, we have to make several assumptions. For simplicity we make a linear interpolation as a function of the relativistic parameter γ for the parameters: i) beam center v at a collimator, ii) the chosen setting n in units of σ (for the collimators where this changes), and iii) the normalized beam size (defined as $\tilde{\sigma} = \sqrt{\beta \epsilon_n}$ as opposed to the geometric beam size $\sigma = \tilde{\sigma}/\sqrt{\gamma}$). Here β is the optical function of the lattice and ϵ_n the normalized emittance. Note that i) and iii) are approximations. The collimator setting u_i at an intermedi-

ate position i during the ramp thus becomes

$$u_i = v_i \pm n_i\sigma_i = v_0 + \frac{v_1 - v_0}{\gamma_1 - \gamma_0}(\gamma_i - \gamma_0)\pm$$

$$\left(n_0 + \frac{n_1 - n_0}{\gamma_1 - \gamma_0}(\gamma_i - \gamma_0)\right) \times$$

$$\left(\tilde{\sigma}_0 + \frac{\tilde{\sigma}_1 - \tilde{\sigma}_0}{\gamma_1 - \gamma_0}(\gamma_i - \gamma_0)\right)\frac{1}{\sqrt{\gamma_i}}. \quad (2)$$

The nominal collimator settings demand a high stability in other machine parameters (orbit, optics). In order to relax the tolerances and the sensitivity to imperfections during a trasition period, another scheme of settings, which we call intermediate, has been put into operation [6]. Here only the TCPs arrive at their nominal top-energy settings while other collimators have more relaxed settings. In 2011 an updated version of this scheme, based on the observed machine stability, is in use [7].

The retraction r (in mm) between a collimator with beam size σ and a setting $n\sigma$ at injection, and the TCP with a setting $n_p\sigma_p$ is defined as

$$r = (n - n_p)\sigma. \quad (3)$$

In the intermediate scheme, r is kept constant during the ramp. This is achieved by increasing n_0 to n_i when γ goes from γ_0 to γ_i. With the intermediate beam size

$$\sigma_i = \sigma_0\sqrt{\frac{\gamma_0}{\gamma_i}}, \quad (4)$$

the condition for a constant retraction $r_0 = r_i$ becomes

$$(n_0 - n_{p0})\sigma_0 = (n_i - n_{pi})\sigma_0\sqrt{\frac{\gamma_0}{\gamma_i}}. \quad (5)$$

Eq. (5) can be solved for the half gap at γ_i:

$$n_i\sigma_i = \sigma_0\left(n_0 - n_{p0} + n_{pi}\sqrt{\frac{\gamma_0}{\gamma_i}}\right). \quad (6)$$

Using $\sigma_0 = \tilde{\sigma}/\sqrt{\gamma_0}$ and assuming again a linear interpolation of n_p and $\tilde{\sigma}$, and adding the linearly interpolated beam center, we arrive at the setting

$$u_i = v_i \pm n_i\sigma_i = v_0 + \frac{v_1 - v_0}{\gamma_1 - \gamma_0}(\gamma_i - \gamma_0)\pm$$

$$\frac{1}{\sqrt{\gamma_0}}\left(\tilde{\sigma}_0 + \frac{\tilde{\sigma}_1 - \tilde{\sigma}_0}{\gamma_1 - \gamma_0}(\gamma_i - \gamma_0)\right) \times$$

$$\left(n_0 - n_{p0} + \left[n_{p0} + \frac{n_{p1} - n_{p0}}{\gamma_1 - \gamma_0}(\gamma_i - \gamma_0)\right]\sqrt{\frac{\gamma_0}{\gamma_i}}\right). \quad (7)$$

It should be noted that for the TCPs, where $n_0 = n_{p0}$, Eq. (7) is equivalent to the nominal setting given by Eq. (2). For the TCP in IR7 $n_{p1} = n_{p0}$ in the intermediate scheme while $n_{p1} \neq n_{p0}$ in IR3. Table 1 shows settings n for different collimator groups at injection and top energy. Some examples of the settings used during operation for different collimators throughout the cycle are shown in Fig. 1.

Table 1: Settings in units of σ at injection and top energy before squeeze (nominal and intermediate scheme) of all LHC collimators.

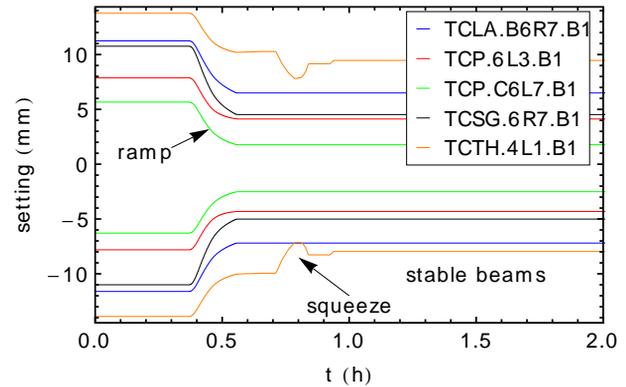| collimators	n_0	n_1 nominal	n_1 2011
TCP IR7	5.7	6.0	5.7
TCS IR7	6.7	7.0	8.5
TCL IR7	10.0	10.0	17.7
TCP IR3	8.0	15.0	12.0
TCS IR3	9.3	18.0	15.6
TCL IR3	10.0	20.0	17.6
TCT	13.0	8.3	26.1
TCS IR6	7.0	7.5	9.3
TCDQ IR6	8.0	8.0	9.8

Figure 1: The settings used in the machine during the start of a physics fill for a selection of collimators from different families. From the point of stable beams, the beams are left colliding for the rest of the fill.

SQUEEZE FUNCTIONS

During the squeeze the machine configuration changes in a different way: the energy is kept constant but the orbit and the optical functions in the experimental IRs are changing. Therefore, in the present scheme, the positions of the TCTs have to be adjusted, while all other collimators remain at the position from the end of the ramp.

In order to generate the TCT settings during the squeeze, we do as before a linear interpolation of the orbit offset at the collimator but this time in β^*. For σ on the other hand an exact calculation is done at each intermediate β^*-value in the squeeze. The calculation is performed using Twiss output files from MAD-X [8].

The setting of a TCT at an intermediate position i during the squeeze (with starting point 0 and end point 1) therefore becomes

$$u_i = v_i \pm n_i\sigma_i = v_0 + \frac{v_1 - v_0}{\beta_1^* - \beta_0^*}(\beta_i^* - \beta_0^*)\pm$$

$$\left(n_0 + \frac{n_1 - n_0}{\beta_1^* - \beta_0^*}(\beta_i^* - \beta_0^*)\right)\sigma(\beta^*). \quad (8)$$
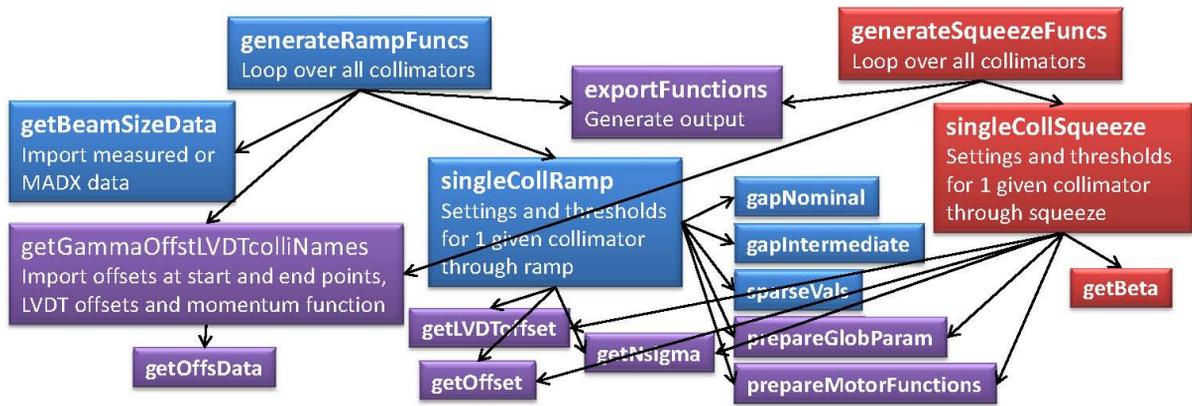
01 Circular Colliders

T19 Collimation

Figure 2: Schematic illustration of the different subroutines in the program used to generate the functions.

It should be noted that the squeeze functions differ between the experimental IRs, since the function $\beta^*(t)$ is not the same. Furthermore, since the setting is a product of n, which decreases during the squeeze, and σ, which increases, some functions may show a local minimum between the start and end points. This is shown in Fig. 1.

SOFTWARE FOR FUNCTION GENERATION

To automatically generate the collimator settings during ramp and squeeze, a software tool has been developed, which runs within Mathematica [9]. A schematic chart of the code is shown in Fig. 2. Other tools for generation of settings are available [10] within LSA [11].

The most important input parameters are the normalized emittance, n_0 and n_1 for each collimator family, if nominal or intermediate settings should be used, data files with the centers and beam sizes of all collimators at start and end point, MAD-X Twiss files with the optics at both points, tilt angles, and a data file with $\gamma(t)$ given as a vector.

The settings are calculated using the formulas in previous sections either for all collimators or for a subset. If the calculated setting is larger than a pre-defined maximum setting, the maximum setting is used instead. The functions are also filtered so that the smallest step used between two points is larger than a given minimum step size, which is given as an input parameter. That way, the output files are kept small so that the input into the control system is done smoothly.

The output is text files with vectors containing time and settings. The files can be imported directly into the control system. The program generates also the thresholds where either a warning is given or the signal for beam dump is given. These limits follow the functions with a constant offset, which is the sum of an offset given by the user as input and an offset between the LVDT sensor and motor steps. This difference has to be accounted for since the motor steps are used for the settings of the jaw while the thresholds are connected to the LVDTs. Further output includes specific tables with all settings at the start and end points as well as the top-level parameters σ_x, σ_y, n, and v. This allows for the settings to be changed more easily directly inside the control system.

SUMMARY

The LHC collimators must at all times during the operational cycle be positioned in such a way that the cleaning hierarchy is respected and the cold aperture protected. The settings are first determined through setups with beam-based alignment for the injection optics at 450 GeV and 3.5 TeV, and for the collision optics at 3.5 TeV after the squeeze, before and after putting the beams into collision.

During the time periods between the points where a setup has been done, a transition between different machine configurations takes place. For these periods, the collimator settings are generated in the form of vectors containing time and jaw position based on an interpolation between the clearly defined start and end points. We have shown formulas for how the settings are interpolated both in the case of nominal and intermediate collimator settings and for ramp and squeeze. We have also described a software tool running under Mathematica, which is used to automatically generate the settings.

REFERENCES

[1] LHC design report v.1. *CERN-2004-003-V1*.

[2] R.W. Assmann. *Chamonix XIV*, 2005.

[3] R.W. Assmann *et al.* TUODFI01. *EPAC06*.

[4] D. Wollmann *et al.* TUOAMH01. *IPAC10, Kyoto, Japan*.

[5] R.W. Assmann. *presentation in the LHC Internal Machine Protection Review*, 2010.

[6] C. Bracco. *PhD thesis*. PhD thesis, EPFL Lausanne, 2008.

[7] R. Bruce and R.W. Assmann. *Evian workshop*, 2010.

[8] http://cern.ch/mad/.

[9] http://www.wolfram.com.

[10] S. Redaelli *et al.* FR5REP007. *PAC'09, Vancouver, Canada*.

[11] G. Kruk *et al.* ICALEPCS2007, 2007.