Luminosity leveling with angle

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Abstract

The very high luminosity foreseen for the LHC luminosity upgrade entails in all cases a significant luminosity decrease during a few hours run. We present in this note a new method of luminosity leveling, based on the on-line adjustment of the crossing angle, while keeping the optics unchanged. It is implemented using the D0 dipole of a possible Early Separation Scheme and an orbit corrector. The whole bump is confined in the experimental drift space. It should be operationally simple as it avoids most complicated side effects that other leveling principles would produce.

INTRODUCTION AND CONCEPT

The LHC luminosity upgrade aims at increasing significantly the peak and average LHC luminosity [1]. In all scenarios, the decay of the luminosity due to the beam-beam interaction becomes dominant over other mechanisms and very significant as compared to the nominal LHC parameters. This is particularly true for the most efficient and economical scenarios where the luminosity increase is obtained by other means than a beam current increase. A large variation of the luminosity over a few hours run shows many drawbacks, both for the detectors and the machine components. From the machine point of view the main issues are the peak and average power deposition in the superconducting triplets and ancillary magnets. To prevent a quench, it has to be designed for the maximum instantaneous luminosity. The present knowledge shows that the capability of Nb-Ti appears significantly exceeded while the Nb_3Sn technology could face it though with additional improvements of the shielding efficiency. For the experiment itself, the high initial peak luminosity produces a higher multiplicity and a stronger background. To cope with it, either the detector has to be designed for the peak multiplicity that is significantly above the design goals of the present detectors or a fraction of the running time will not be used efficiently for data taking.

An answer to this challenge is luminosity leveling. It is traditionally proposed to adjust in real time the beam size at the crossing point to obtain this result. The authors ignore whether this was ever made operational in practice. While a modulation of the focusing is indeed a priori simple in principle, it shows a large potential of side effects that is bound to make it delicate in practice: when the focusing is modified, its chromatic correction has to be adjusted. As it is not locally corrected, all the lattice sextupoles have to be ramped, with unwanted feed-down effects on the betatron tunes and closed orbit all around the machine, including in the collimation sections. Likewise, the modification of the β-function at the place where it reaches its maximum requires strictly local correction of alignment or tilt imperfections, rarely obtained in practice, resulting, e.g. in closed orbit distortions propagating to the whole machine. In the LHC the situation is further complicated by the presence of a crossing angle that extends up to Q4/Q5 and that create feed-down effects depending on the detail of the optics, of the imperfections and of their correction strategy or capability. While this method is certainly not impossible, its complexity may require a long time (i.e. integrated luminosity) to make it operational.

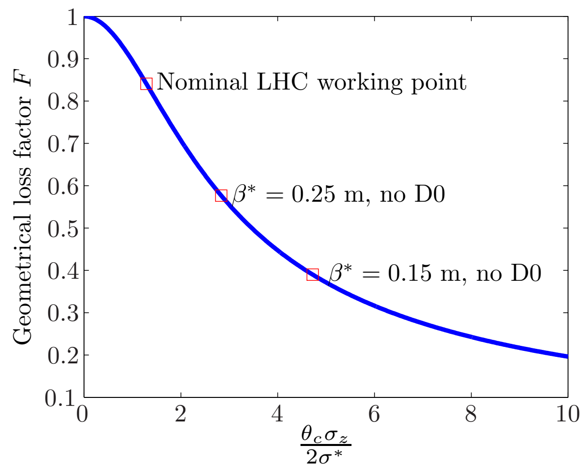

Figure 1: The geometrical loss factor as function of the Pinwiski parameter.

The early separation scheme proposed to modify the beam crossing layout [3] potentially allows another approach to luminosity leveling that appears much easier to implement. The principle is to adjust the crossing angle in real-time with an adjustment of the beam trajectories only in the experimental straight section between the left and right Q1 quadrupoles. In this way advantage is made of the significant influence of the crossing angle or rather geometrical loss factor F on the luminosity, as shown on Figure and Equation 1

$$F \approx \frac{1}{\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}} \qquad (1)$$

where θ_c is the full crossing angle, σ_z is the RMS bunch length and σ^* is the RMS beam size at the IP (in the round beam hypothesis). All the side-effects met when modulating the focusing and introduced before are suppressed. Other side effects are nevertheless present:

- a modulation of the length of the luminous region
- a modulation of the beam-beam tune shift, always toward lower values
- a modulation of the excitation of beam-beam driven synchro-betatron resonances.

The two former issues are discussed in this note while the latter is a general issue for the luminosity upgrade that goes beyond this study.

This method assumes that, in addition to the early separation dipoles that would be embedded in the detectors, a standard closed orbit corrector is installed ideally in front of Q1 towards the IP.

THE LUMINOSITY LIFETIME

In order to describe the evolution of the luminosity we numerically implement a simple model assuming that the luminosity will be dominated by the three following mechanisms

- the protons burning
- the intra beam scattering
- the rest gas scattering.

As shown in the following the previous phenomena are coupled.

The protons burning

The equation that describes the proton burning is

$$\dot{N_b}(t) = -\frac{\sigma\, n_{exp}}{n_b} L(t) \quad (2)$$

where $N_b(t)$ is the number of protons per bunch, n_b is the number of the bunches, n_{exp} the number of experiments considered at the luminosity $L(t)$ and σ is the p–p cross-section. In the following we assume $n_{exp} = 2$ and $\sigma = 80$ mbarn [1].

The intra beam scattering

The equation that describes the intra beam scattering is [2]

$$\dot{\epsilon}(t) = \frac{1}{\tau_{IBS}} \frac{N_b(t)}{N_{IBS}} \epsilon(t) \quad (3)$$

where $\epsilon(t)$ is the beam emittance, τ_{IBS} is the time constant for intra beam scattering relative to N_{IBS} protons per bunch, $N_b(t)$ is the number of protons per bunch considered. In the following we assume $\tau_{IBS} = 91.3$ h at $N_{IBS} = 1.15\ 10^{11}$ [1].

The rest gas scattering

The equation that describes the rest gas scattering is [2]

$$\dot{N_b}(t) = -\frac{n_b}{\tau_{RGS} N_{RGS} n_{RGS}} {N_b}^2(t) \quad (4)$$

where τ_{RBS} is the time constant for rest gas scattering relative to N_{RBS} protons per bunch and n_{RBS} bunches, $N_b(t)$ and n_b is respectively the number of protons per bunch and the number of bunches considered. In the following we assume $\tau_{RGS} = 78.35$ h, $N_{RGS} = 1.15\ 10^{11}$ and $n_{RGS} = 2808$ [1].

THE LUMINOSITY LEVELING INSERTION

In order to vary **locally** the crossing angle we propose to install one dipole and one orbit corrector between the IP and the triplet. The baseline crossing angle bumps extends beyond Q5: if we use this bump for leveling, the beam closed orbit in the quadrupoles will change with similar drawbacks as using a variable β^*. We performed the computations in the thin dipole approximation: the dipole is at l_1 from the IP and the orbit corrector at l_2. The angular kicks that should be provided by the two magnets in order to close the bump can be easily obtained by geometrical considerations:

$$\begin{aligned}
\theta_1 &= atan\left(\frac{l_2\, tan(\frac{\theta_{tripl}}{2}) - l_1\, tan(\frac{\theta_c}{2})}{l_2 - l_1}\right) - \frac{\theta_c}{2} \\
\theta_2 &= \frac{\theta_{tripl}}{2} - \frac{\theta_c}{2} - \theta_1
\end{aligned}$$

where θ_{tripl} is the angle between the beams in the triplet needed to preserve the 9.5 σ separation. The inequality $l_1 < l_2 \leq l^*$ should be respected. In the following we assume that $l_1 = 6$ m and $l_2 = 19$ m: this choice is just a starting point. The dipole position (l_1) is crucial since it determines the number of parasitic encounters at reduced distance: this has to be chosen keeping in mind the integrability issues in the detector areas and the beam stability constraint (hopefully to be confirmed by experimental results). In any case the dipole cannot approach the IP more than 3.5 m due to the inner detector presence: in the 25 ns time spacing scenario at least one parasitic encounter would occur at reduced distance.

THE DYNAMIC RANGE OF THE θ_C

We found two mechanisms that limit the θ_c range. The minimum θ_c is constrained by the encounters at reduced distance: after some preliminary experimental results, we propose that the minimum distance should be consider equal to half the nominal that is to say around 5 σ. Reducing it below this threshold we assume that strong compensation should be implemented. The maximum θ_c is limited by possible synchro-betatron resonances: this problem should be addressed in a general study.

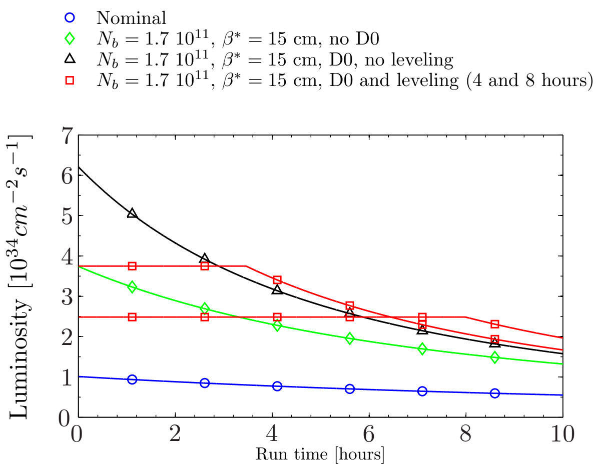

Figure 2: The luminosity behavior during the run time.

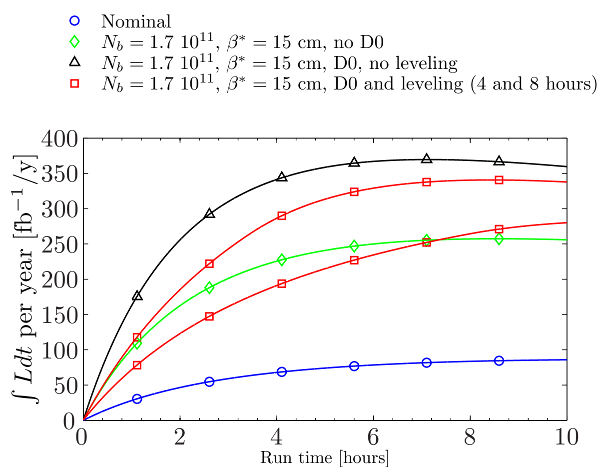

Figure 3: The integrated luminosity in a year considering 200 working days and 5 h of turn-around-time.

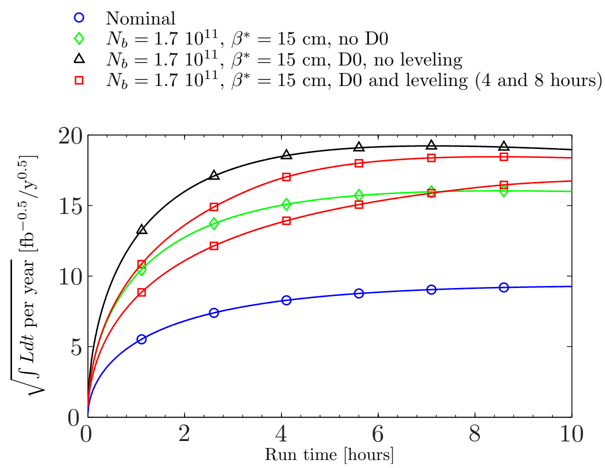

Figure 4: The square root of the integrated luminosity considering 200 working days and 5 h of turn-around-time.

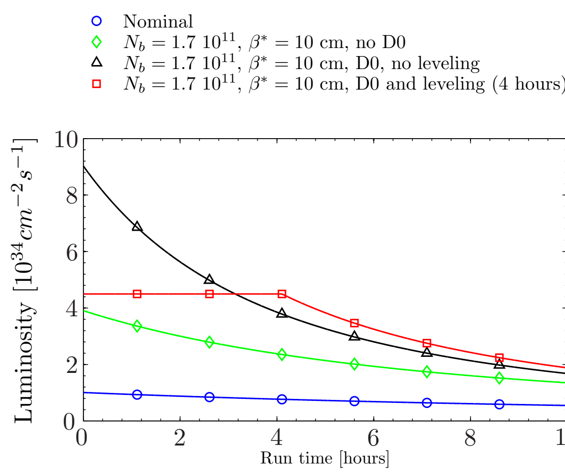

Figure 5: The luminosity behavior during the run time.

SCENARIOS, PERFORMANCE AND SIDE EFFECTS

Scenarios and Performance

In the following we present a possible scenario of upgrade considering a $\beta^* = 0.15$ m at the ultimate current ($n_b = 2808$ and $N_b = 1.7\ 10^{11}$) and therefore a bunch spacing of 25 ns. The former is just one scenario among others with the only aim to provide an example.

In Figure 2 we show the luminosity behavior during the run in different configurations. Without implementing the D0 (or alternative solutions that reduce the crossing angle, such as Crab cavities) the gain in peak luminosity is about a factor 4. With the D0 and a fixed crossing angle we reach a factor 6; with the leveling, partially reducing the integrated luminosity, we reduce the peak luminosity of a factor 2. In Figure 3 we show the integrated luminosity achievable considering our model and in Figure 4 its square root. It is evident that we reduced the peak luminosity with a cost in term of integrated luminosity. However our computation of the integrated luminosity is simplistic: it assumes 100% efficiency in using the collisions at all times and a luminosity decay only due to the above mentioned well defined sources. The apparent loss of luminosity due to leveling may well be overestimated.

To analyze the scheme potential in presence of even more challenging scenario we can look at the Figures 5 and 6. Here we consider the ultimate current, a $\beta^* = 0.10$ m and and the minimum distance between the beams of 3.3 σ. To reach that configuration without impacting on the beam lifetime strong compensation scheme are probably needed (electron lenses) or the use of weak crab cavities as auxiliary system of the D0's task. The peak luminosity and the integrated luminosity are summarized in Table 1: for the computation of the integrated luminosity we assumed 200 working days per year and a turn-around-time of 5 h (we

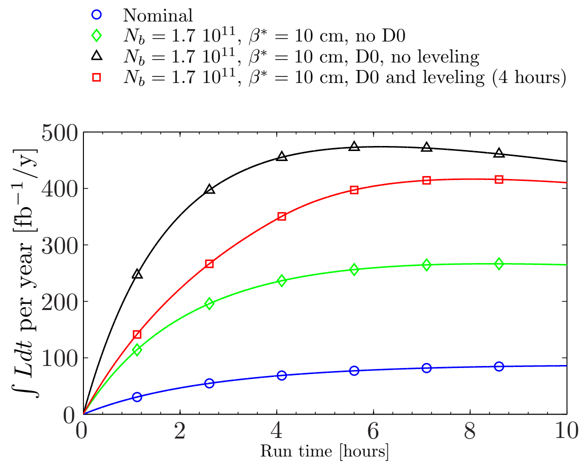

Figure 6: The integrated luminosity in a year considering 200 working days and 5 h of turn-around-time.

Table 1: Performances in term of luminosity (L) of the different schemes

		Integrated L [fb^{-1}]
Nominal scenario		86.37
$\beta^* = 0.15$ m	no D0	257.37
$\beta^* = 0.15$ m	D0, no leveling	369.65
$\beta^* = 0.15$ m	D0 and leveling	340.70
$\beta^* = 0.10$ m	no D0	266.49
$\beta^* = 0.10$ m	D0, no leveling	473.87
$\beta^* = 0.10$ m	D0 and leveling	416.54

consider as turn-around-time the distance in time between the beam dumping and the first collisions).

In the following we always consider the more conservative scenario with ultimate current, $\beta^* = 0.15$ cm and $4.75\ \sigma$ minimum separation.

The leveling will modify the crossing angle and consequently the geometrical loss factor during the run as described in Figure 10 and 11.

The requested integrated magnetic field on the dipole and the orbit corrector is shown in Figure 12 and 13 respectively.

We plotted in Figure 14 and 15 the evolution of the beam current and of the beam normalized emittance.

Side effects

In the previous section we underline the fact that using a leveling we have the advantage of reducing the peak luminosity with the drawback of losing some integrated luminosity. We have to stress that this is a result obtained from simple models: it doesn't take into account effect that can be dominant in real life. For instance the first parts of the run can be dedicated to the tuning of machine setup or of experimental instrumentation: therefore cannot be considered as useful luminosity. In any case the hardware needed for the leveling is definitely compatible with the run that doesn't change the crossing angle.

A very important aspect to investigate is the required distance between the beams (Figure 7): the impact of the reduced distance at parasitic encounters should be hopefully addressed with an experiment at RHIC. An other possible

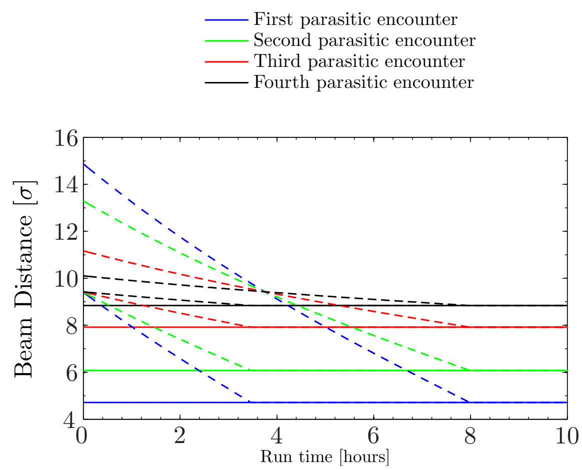

Figure 7: The distance between the beams at the first four encounters with the D0 without leveling (*solid line*) and with leveling (*dotted line*).

drawback is the change of longitudinal size σ_{lum} of the luminous region [4]

$$\frac{1}{\sigma_{lum}} \approx \sqrt{\frac{2}{\sigma_z^2} + \frac{\theta_c^2}{2\,\sigma^{*2}}} \tag{5}$$

that is to say

$$\sigma_{lum} \approx \frac{\sigma_z}{\sqrt{2}} F. \tag{6}$$

As shown in Figure 8 the leveling has a significant impact that ought to be investigated.

On the other hand in Figure 9 the tune shift ξ due to the head on

$$\xi = \frac{N_b r_p}{4\pi\epsilon_n} F \tag{7}$$

where N_b is the number of protons per bunch, r_p is the classical radius of the proton, ϵ_n in the beam normalized emittance and F the geometrical loss factor. It seems that the impact of the leveling on the head-on tune shift is not more severe than in the other configurations that do not implement the Early Separation Scheme.

CONCLUSION

In this work we presented the concept and the performance of a leveling scheme for the LHC luminosity upgrade. With the early separation scheme it is possible to vary the crossing angle between the beams during the run: there is no impact on the optics of the machine itself. In general, limiting the peak luminosity has some negative

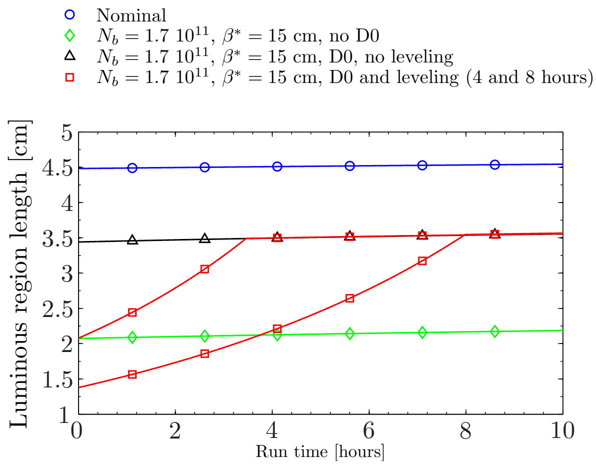

Figure 8: The luminous region size during the run time.

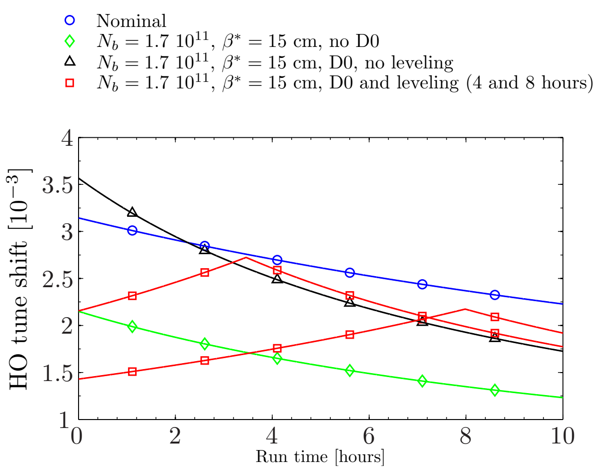

Figure 9: The HO tune shift during the run time.

impact on the integrated luminosity: the early separation scheme gives a lot of flexibility that can be adjusted to the experiments' needs. From first discussions there seems to be not significant problems with respect to the luminous region length and the HO tune shift, while synchro-betatron resonances still have to be addressed in a more general framework.

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[3] J.-P. Koutchouk and G. Sterbini, *"An Early Beam Separation Scheme for the LHC Luminosity Upgrade"*, EPAC06 Proceedings, Edinburgh.

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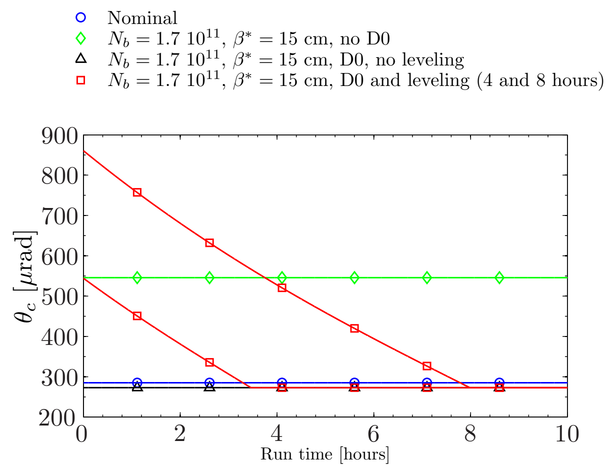

Figure 10: The θ_c behavior during the run time.

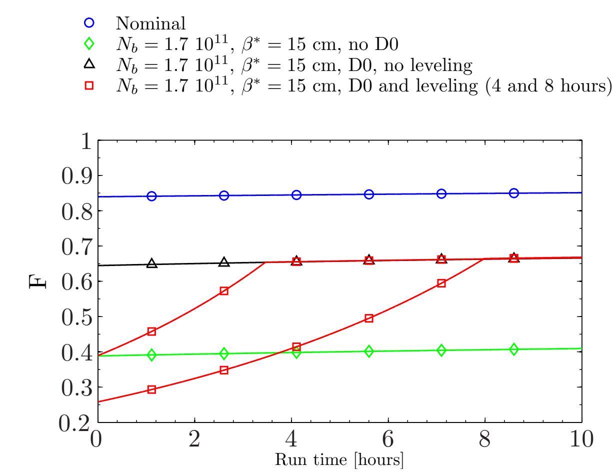

Figure 11: The geometrical loss factor during the run time.

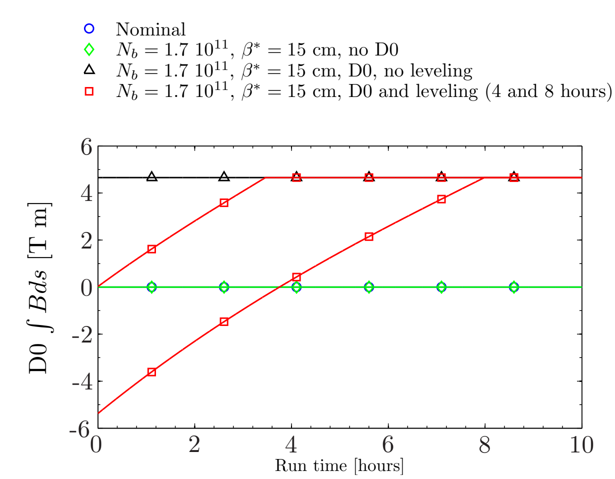

Figure 12: The integrated magnetic field request on the D0.

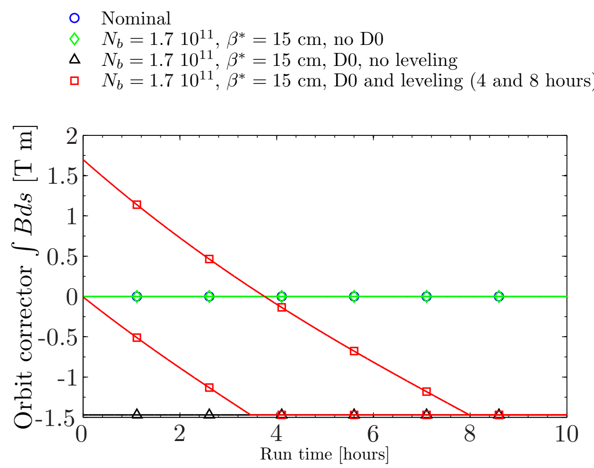

Figure 13: The integrated magnetic field request on the orbit corrector.

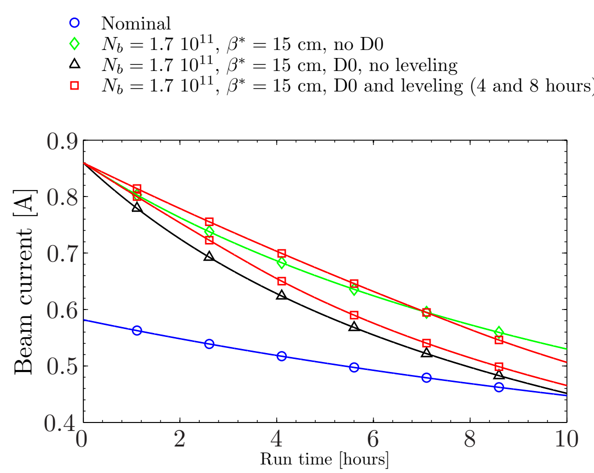

Figure 14: The current behavior during the run time.

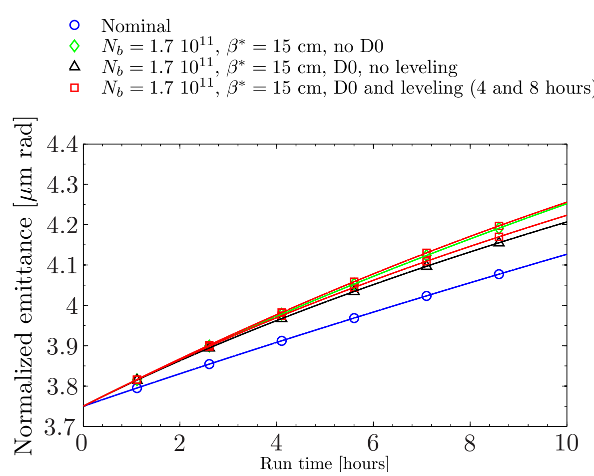

Figure 15: The beam normalized emittance during the run time.