PLANS FOR HIGH BETA OPTICS IN THE LHC

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Abstract

Based on what has been learned with the $\beta^* = 90\,\mathrm{m}$ commissioning and operation in 2011, we describe the potential and practical scenarios for reaching very high β^* in the LHC in 2012 and beyond. Very high β^* optics require dedicated running time and conditions in the LHC. We describe a planning which is optimized to maximize the physics potential in a minimum of dedicated running time.

INTRODUCTION

The top priority for 2012 LHC operation is to maximize the integrated luminosity. The current LHC schedule foresees about 129 days of standard proton running, 22 days for machine development and about 8 days for special running which is operation at high β^* as discussed here and luminosity normalization using separation scans in a couple of special physics fills. This leaves relatively little beam time for new optics developments, which will therefore have to be well targeted to allow to reach realistic goals in a small number of dedicated fills.

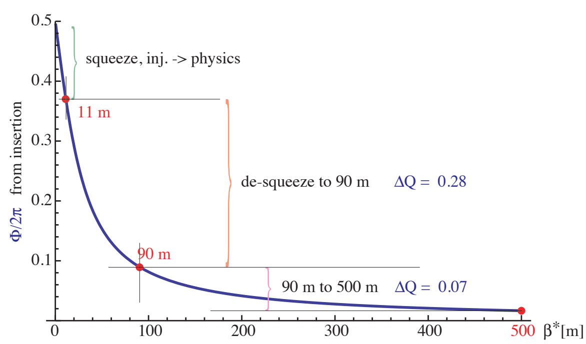

Figure 1: Tune contribution from the insertion $\pm 26\,\mathrm{m}$ from the interaction region as relevant for the LHC.

One major challenge in the de-squeeze from the standard injection optics to high-β is the significant change in phase advance which requires external tune compensation [1, 2].

A low-β insertion with $\beta^* \ll \ell$, where ℓ is the distance between the interaction point (IP) and the centre of the first quadrupole, contributes with a phase advance of π and tune of 0.5. For very high $\beta^* \gg \ell$ instead, the phase advance and tune contribution of the drift space between the first quadrupoles drops to zero. This is illustrated in Fig.1. We see that the local tune change from the free space between the low-β quadrupoles for the squeeze from 11 m to 0.55 m as relevant for the standard physics optics is approximately +0.1. This can be compensated internally in the insertion (by a rematch in the insertion between Q13 left and right of the interaction point) such that the overall LHC optics does not change during the normal squeeze to low β^*. The tune reduction in the de-squeeze is much larger and requires external tune compensation which modifies the optics of the entire LHC.

The experience with the 90 m optics has been very positive in 2011. We succeeded to reach 90 m by de-squeezing from the standard 11 m injection and ramp optics in a single fill [3] using the main quadrupoles of all LHC arcs for the external tune compensation and to commission the new 90 m optics with parallel separation bumps to allow to adjust for collisions in the second fill [4, 5].

STRATEGY FOR 2012

The de-squeeze to $\beta^* = 90\,\mathrm{m}$ will be extended to higher β^*. This allows to maintain the 90 m for further operation as requested by TOTEM and to minimize the extra beam-time required for the commissioning of the higher-β^* optics.

From 90 m to 500 m

The extension to higher β^* is done using sufficiently small steps of approximately 15% in β^* (105 m, 120 m, 140 m) for a smooth transition in the de-squeeze. The phase advance between the IP and the relevant roman pots (at 220 m from IP5 for TOTEM) is kept at $\pi/2$ in y for all steps above 90 m, while the phase advance in x is not constraint.

The matching was first done for beam 1 in IP5 and then for beam 2. The start values for the strength in beam 2 are taken from beam 1 after exchanging left and right sides. Finally, a second version of these files was produced for IP1, by re-matching for a phase advance of $\pi/2$ in the vertical plane to the roman pot at 240 m, as done last year for the IP1 version of the 90 m optics [6]. The other optics parameters are all very similar for IP1 and IP5.

Ratio constraint

The interaction region quadrupoles use a single return cable, which restricts the current ratio for the main insertion quadrupoles (from Q10 left to Q10 right) to $0.5 < \mathrm{beam1/beam2} < 2$. This is generally fine for the beam1/beam2 and left/right (anti)-symmetric lower-β optics, but instead a major restriction for the high β-optics

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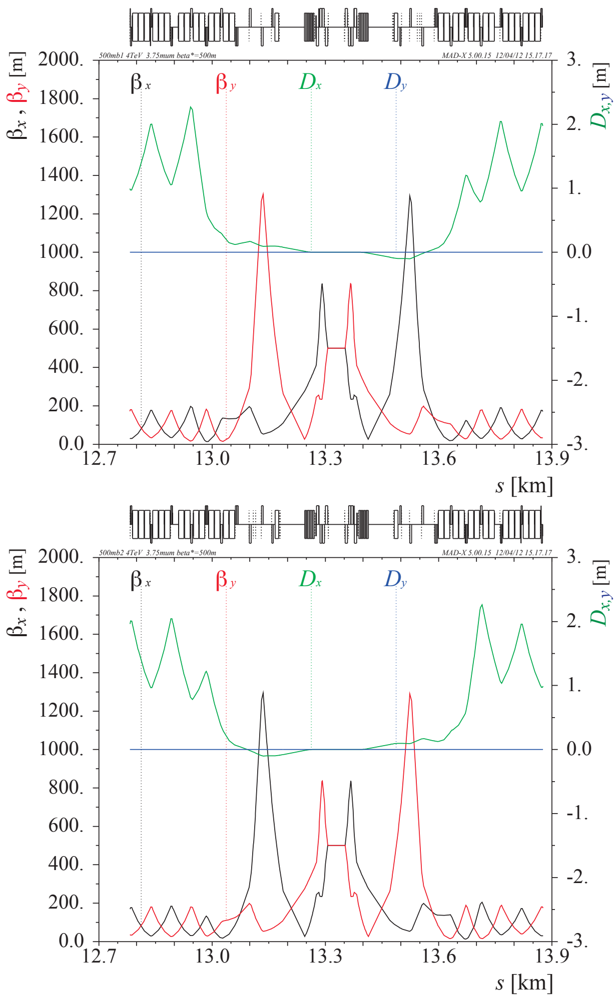

Figure 2: 500 m optics in IP5. Up for Beam 1 and down for Beam 2.

which have to respect single sided phase advance constraints to the roman pots. The strength ratios in the 90 m optics as used in 2011 and planned to be re-used in 2012 are listed in Table 1. The beam1 / beam2 ratios are already close to the limits for Q7 and Q8.

Table 1: Beam 1 / beam 2 current ratios at 90 m

Quadrupole	left	right
Q4	0.971	1.11
Q5	1.04	0.961
Q6	1.05	0.939
Q7	1.58	0.525
Q8	1.33	0.572
Q9	1.03	0.964
Q10	0.95	1.054

The 500 m optics proposed for this year is shown in Fig. 2.

Going well beyond 90 m required many matching iterations to respect the ratio constraint and required to accept some compromises : the continuity during the de-squeeze (i.e. quadrupoles moving only up or down during the de-squeeze) could not be fully assured and the difference in horizontal phase advances between beam 1 and beam 2 increased. The current ratios at 500 m are listed in Table 2.

Table 2: Beam 1 / beam 2 current ratios at 500 m

Quadrupole	left	right
Q4	1.10	1.07
Q5	0.997	1.01
Q6	0.974	1.03
Q7	1.86	0.563
Q8	1.56	0.641
Q9	1.12	0.879
Q10	1.09	0.914

Table 3 shows main optics parameters at 90 and 500 m – the β functions at the IP and the roman pots, the effective length $L_y = \sqrt{\beta_y^* \beta_{y,\mathrm{RP}}} \sin(\mu_{y,\mathrm{RP}})$ (equivalent to the off-diagonal element R_{34} of the transport matrix) between the IP and the roman pot, and the tune reduction compared to the standard optics.

Table 3: Optics parameters at 90 m and 500 m in IP5 for the roman pot at 220 m from the IP, and the tune reduction compared to the standard optics. Beam sizes are given for a beam energy of 4 TeV and the design emittance $\epsilon_{\mathrm{N}} = 3.75\,\mu$m.

Optics	90 m		500 m	
Beam	1	2	1	2
$\beta^*_{x,y}$, m	90	90	500	500
$\sigma^*_{x,y}$, mm	0.281	0.281	0.663	0.663
$\beta_{x,\mathrm{RP}}$, m	313.4	313.4	508.7	507.3
$\beta_{y,\mathrm{RP}}$, m	769.5	769.5	152.8	152.9
L_y, m	263.2	263.2	276.4	276.5
$\mu_{x,\mathrm{RP}}/2\pi$	0.500	0.500	0.487	0.487
$\mu_{y,\mathrm{RP}}/2\pi$	0.250	0.250	0.250	0.250
ΔQ_x	0.2219	0.2203	0.2251	0.2175
ΔQ_y	0.0546	0.0528	0.2292	0.2290

Aperture

Fig. 3 shows the aperture in terms of n_1 (number of σ including tolerances) around the interaction region. At 90 m, the aperture in the triplet region was not an issue and in fact larger than in the LHC arcs [2]. At 500 m, the aperture bottleneck moves to the TAS region, but remains still larger than the usual $n_1 = 7$ specification shown as green lines.

Files have been matched up to $\beta^* = 1000$ m for study purposes. At 1000 m, we have $n_{1,\mathrm{min}} = 6.3$ which is below specification. In addition, it will be difficult to maintain

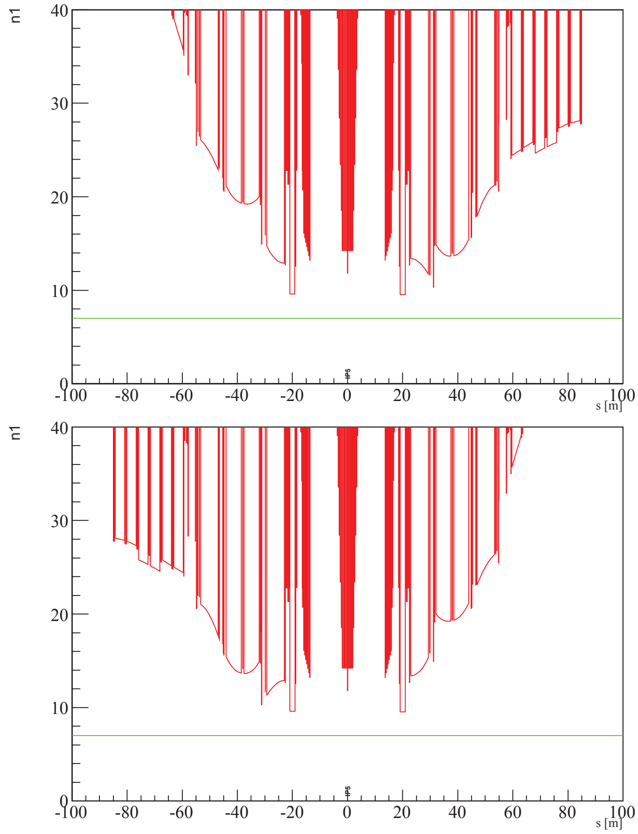

Figure 3: Aperture at 4 TeV, for the design emittance $\epsilon_\mathrm{N} = 3.75\,\mu\mathrm{m}$ at $\beta^* = 500\,\mathrm{m}$ around IP5 including $\pm 2\,\mathrm{mm}$ parallel separation. Top is for beam 1 and bottom for beam 2.

sufficient parallel separation during the de-squeeze beyond a β^* of 500 m.

Given the limited beam time and many constraints, an ambitious but not too unrealistic goal for 2012 is to aim for a $\beta^* = 500\,\mathrm{m}$ for high-β^* for physics operation in 2012. If things go extremely well and beam time would be available, studies could be extended towards 1000 m.

HOW TO GET TO THE COULOMB INTERFERENCE REGION ?

Getting to the Coulomb interference region, that is down to a momentum transfer of $-t \approx 6.5 \times 10^{-4}\,\mathrm{GeV}^2$ is known to be extremely challenging at LHC energies [7]. With $-t \approx= p^2\,\theta^2$, where p is the beam momentum and θ the scattering angle, this corresponds to measuring down to $\theta_C = \sqrt{6.5 \times 10^{-4}}\,\mathrm{GeV}/p$ or $3.6\,\mu\mathrm{rad}$ at 7 TeV. For comparison, the Coulomb region was reached at $\theta_C = 120\,\mu\mathrm{rad}$ at the Sp$\bar{\mathrm{p}}$S collider[8].

Measuring these small angles requires to minimize the beam divergence and to bring the roman pots very close to the beam. The beam divergence at the interaction point is $\sigma' = \sqrt{\epsilon/\beta^*}$, where ϵ is the geometric emittance, related to the normalized emittance ϵ_N by the Lorentz factors β, γ according to $\epsilon = \beta\gamma\epsilon_N$.

Numerical values are given in Table 4 for a normalized emittance of $\epsilon_N = 2\,\mu\mathrm{rad}$. The Coulomb region would be reached an angle which is about 7 times the beam divergence.

Table 4: Scattering angle θ_C required to reach the Coulomb region and beam divergence for $\epsilon_N = 2\,\mu\mathrm{rad}$

p TeV	β^* m	σ' μrad	θ_C μrad	θ_C/σ'
4 TeV	500	0.969	6.37	6.6
7 TeV	1000	0.518	3.64	7.0

The roman pots of TOTEM and ALFA start to be sensitive after $\sim 0.5\,\mathrm{mm}$ and would have to be moved to less then $5\,\sigma$ to reach the Coulomb interference region.

SUMMARY

Based on the successful commissioning and operation at 90 m in 2011, we developed sets of optics files for commissioning and operation in 2012 which extend to higher β^*. As an already ambitious but not too unrealistic goal, that should be reachable within few shifts of dedicated beam time, we aim for a target $\beta^* = 500\,\mathrm{m}$, to be reached by simultaneous de-squeeze in both IP1 and IP5. If things go extremely well and more beam time would be available, studies could be extended this year in the LHC towards $\beta^* = 1000\,\mathrm{m}$.

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