A PROPOSAL FOR THE OPTICS AND LAYOUT OF THE HL-LHC WITH CRAB CAVITIES

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Abstract

The LHC upgrade studies have been recently formalized into the so-called HL-LHC project. This project relies on the availability of new technologies such as crab cavities which would be installed in the interaction region (IR) of the new ATLAS and CMS experiments, and high-field and large aperture inner triplet quadrupoles equipped with Nb_3Sn super-conducting cables. This paper presents and analyzes a possible layout and optics for the new IRs, with a β^* squeezed down to 15 cm in collision using the Achromatic Telescopic Squeezing (ATS) scheme [1].

INTRODUCTION

In the LHC the bunch trains are separated just after the collision point thank to a crossing angle proportional to $1/\sqrt{\beta^*}$. Therefore, at constant bunch length, the luminosity gain with β^* rapidly saturates due to the reduction of the overlap integral between the two beam distributions. RF deflecting cavities (so-called crab cavities) can however restore this overlap (see e.g. [2]).

The ATS scheme, together with new large aperture magnets that will be developed for the HL-LHC project [3], has the potential to reach β^* values of the order of 15 cm or lower. The corresponding geometric luminosity loss factor is of the order of 0.35 for the LHC. Therefore an ideal crab-crossing would boost the luminosity by a factor of ~ 3. Compared to a possible back-up solution without crab cavities but based on flat optics [1, 4], the relative gain would still be of the order of 40-50%.

An upgraded layout of the LHC high-luminosity IRs will be presented, where two crab cavities per beam are installed on either side of the interaction point (IP) and generate a closed RF orbit bump with the appropriate bunch rotation in the $(x - z)$ plane induced at the IP (so-called local crab cavity scheme). The specifications on the optics parameters and new beam line elements will be described. Finally, we will also emphasize the need of cavity re-alignment in the presence of variations of the crossing angle and parallel separation, and will propose an alternative crossing scheme which eliminates the problem, while improving as well the mechanical acceptance of the new insertions.

CRAB CAVITY HARDWARE INTEGRATION

The local crab cavity scheme is based on two RF kicks spaced by $\pm\pi/2$ in betatron phase with respect to the IP of the ATLAS and CMS experiments (IR1 and IR5). RF related constraints impose however that the crab cavities are not in common to the two LHC beams, and that the beam separation is at least nominal (194 mm) in order to allow the hardware integration. The best compromise has been found between Q4 and D2, where the above $\pm\pi/2$ phase advances are still valid, and with D2 being moved towards the IP in order to maximize the β-functions at the crab cavity location, thus reducing the required cavity voltage (see Figures 1 and 2).

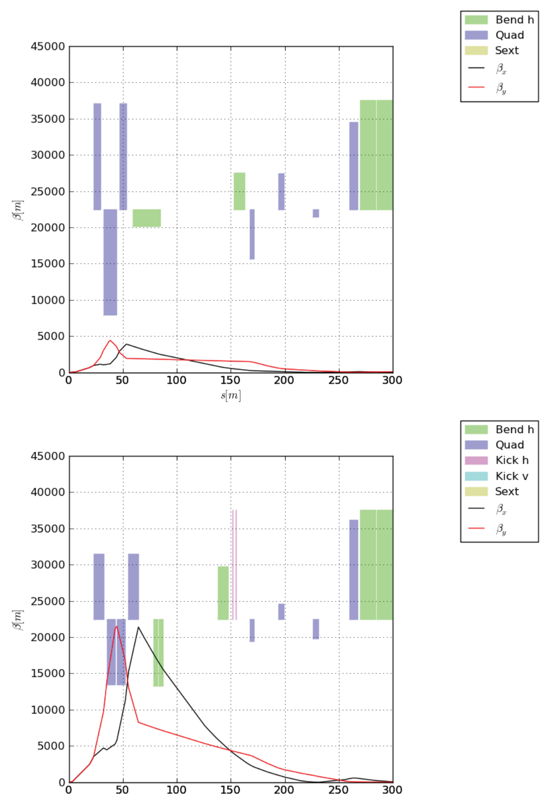


Figure 1: Nominal (top) and upgrade (bottom) IR1-5 layout and optics ($\beta^* = 55$ cm and 15 cm, respectively).

OPTICS AND LAYOUT

When β^* is pushed below $35 - 40$ cm [5], the nominal LHC suffers for serious optics limitations that are related to 1) the aperture of the triplet, D1 and D2 separation dipoles, Q4 and Q5 matching quadrupoles, 2) the matching quadrupoles which are pushed to maximum or very low gradients (if not change of polarity), 3) the chromatic aber-

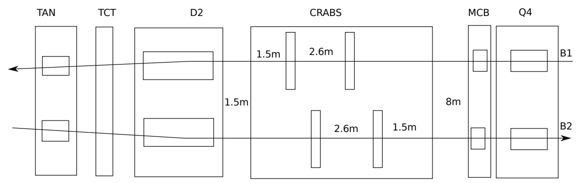


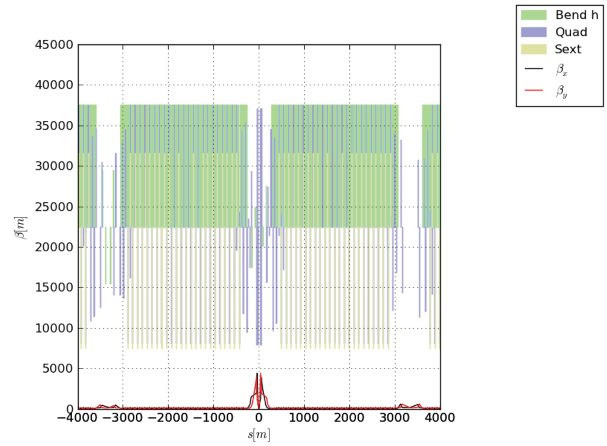
Figure 2: Tentative layout of the crab cavity area. The cavities of both beams are interleaved to equalize the voltage needed for Beam 1 and Beam 2 on the left and right sides of the IP. The assembly is pushed towards D2, and D2 is eventually pushed towards the IP to gain in voltage efficiency, thanks to larger beta functions.

Table 1: Specifications (first estimates) for the new equipments needed in IR1 and IR5. Orbit and non linear corrector package are not included. The layout of the inner triplet (IT) is based on [5]. Lower or higher IT gradients (e.g. 100 or 150 T/m for a 14% longer Nb-Ti or a 12% shorter Nb_3Sn triplet of $\sim$ 150 mm aperture) are possible, with marginal impact on the specifications of the other magnets.

Element	length [m]	field	coil ID [mm]	sep. [mm]
Q1	9.145	123 T/m	150	n/a
Q2a,Q2b	7.735	123 T/m	150	n/a
Q3	9.145	123 T/m	150	n/a
D1	7.4	5.1 T	165	n/a
TAN	3.7	n/a		145
D2	9.45	4.0 T	105	186
Q4	3.4	160 T/m	85	194
Q5	4.8	160 T/m	70	194

rations (non-linear chromaticity, off-momentum β-beating, spurious dispersion due to the crossing angle) which can no longer be corrected and reduce the momentum acceptance of the ring. The first limitation can be addressed by building and installing new magnets of larger aperture (see Table 1). The last two issues have been recently solved by the ATS scheme, a novel optics concept. In this scheme the two insertions on either side of the high-luminosity insertions participate to the squeeze of IR1 and IR5. As a result, the optics is mismatched in the arcs surrounding the low-β insertions, with peak values increased by a factor of up to 4 with respect to a standard FODO optics (see Fig. 3).

This effect poses new challenges for the control of the dynamic aperture (DA). The impact of the field quality of the arc magnets, which is in general negligible for the LHC at flat top energy, shall be in the shadow of the other contributions, in particular those coming from the triplet and the other magnets of the low-β insertions. A target DA for the field quality of the new magnets at 7 TeV is estimated to be 10σ and 6σ without and with beam-beam effects, respectively. Therefore the target dynamic aperture without the new elements should be substantially higher. Some geometric aberrations can be canceled by adding new main sextupoles at Q10 in IR1 and IR5. This scenario offers as



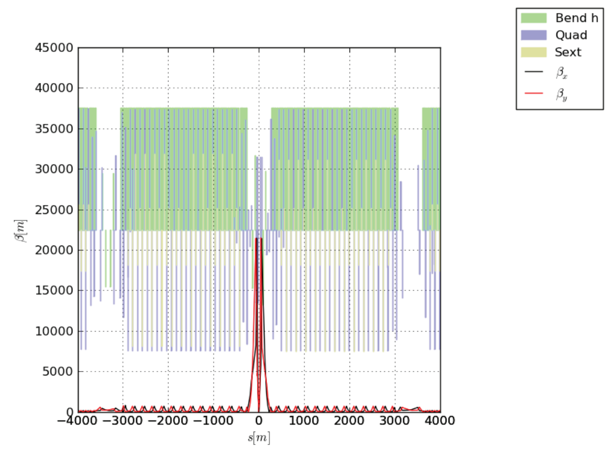


Figure 3: Nominal (top) and upgraded (bottom) collision optics for the low-β IR and surrounding sectors.

well a smaller tune spread compared to the nominal sextupole scheme. A minimum dynamic aperture of 15σ has been found in this configuration [6].

ALTERNATIVE CROSSING SCHEME

A crossing angle is needed to ensure a sufficient beam-beam separations at the parasitic encounters. The required crossing angle is 580 μrad for $\beta^* = 15$ cm and the nominal LHC emittance ($\gamma\epsilon = 3.75\,\mu$rad), corresponding to a beam-beam separation of $10\,\sigma$ till the entry of Q1 (and a few parasitic encounters at $7\,\sigma$ in the triplet). A crossing scheme using orbit correctors at Q3, Q4, Q5 and Q6 is generated and shown on the top of Figures 4.

The spurious dispersion induced by the crossing angle can be as large as 15 m in the triplets, but it can be effectively corrected in both planes by a closed orbit oscillation in the arcs surrounding IP1 and IP5, which is a by-product of the ATS scheme [7].

The crab cavity voltage required to rotate the beam by half of the crossing angle is around 10MV, which justifies the use of two cavities per beam on either side of the IP, each delivering 5MV. In principle there is room for a third module. The total installed voltage is therefore 80MV for

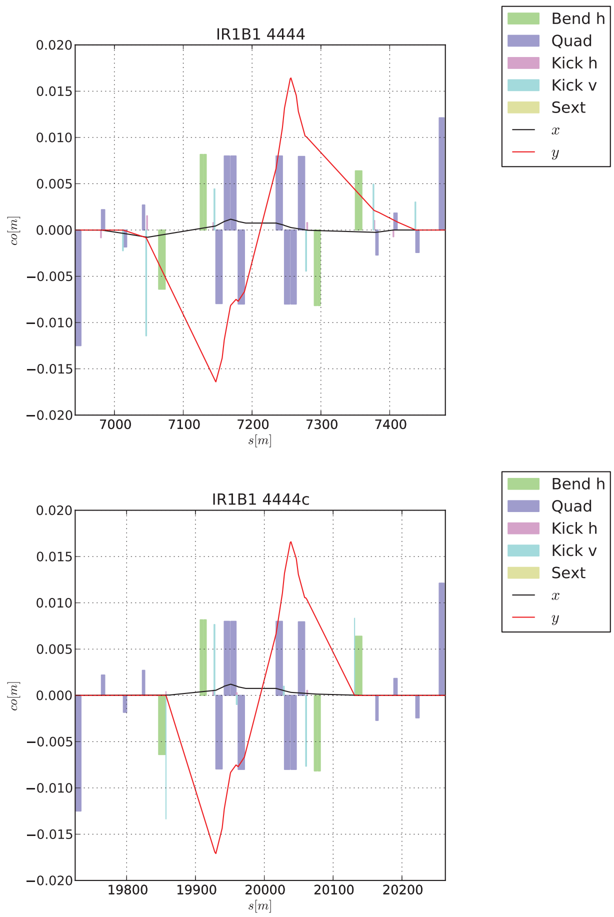


Figure 4: Baseline (top) and alternative (bottom) crossing parallel separation bumps, with corresponding orbit corrector strengths, for Beam 1 in IR1.

the two insertions and the two beams.

The orbit of the beam shall always be centered with respect to the axis of the cavities to avoid large beam loading. With the present crossing scheme, the crab cavities are installed inside the crossing angle and the beam separation bumps. Since they are expected to change during operation from injection to collision and during luminosity scans performed with the parallel separation bumps, the crab cavities would need to be realigned each time. In addition, the crossing angle specifications might change driven by beam dynamics issues (e.g. long-range beam-beam effects) or on request by the experiments (e.g. search of systematic effects) which would require periodical re-alignments.

The maximum closed orbit excursion at the crab cavity location is ± 3.35 mm for a half crossing angle of $5\,\sigma$ and ± 0.67 mm for a half parallel separation of 0.75 mm. This determines the range of alignment flexibility that the hardware should support.

However it is possible to solve completely the issue by implementing a crossing and parallel separation scheme that closes exactly on the IP-side of D2, thus upstream of the crab cavities. An additional advantage would then also be to reduce the aperture required for the new Q4 and D2. In order to prove the principle, we assumed a minimum of two nested orbit corrector MCBXHV per triplet on the IP-side of Q2 and non-IP-side of Q3, and HV 2-in-1 orbit correctors on the IP-side of D2, which would be non common to the two beams (see [6] for more details). The bottom picture of Fig. 4 shows the results in terms of orbit and corrector strengths. Some corrector strengths are particularly large: $150\ \mu\mathrm{rad}$ (or $3.5\ \mathrm{Tm}$ at 7 TeV) for the MCBX at Q3 and $250\ \mu\mathrm{rad}$ (or $5.9\ \mathrm{Tm}$) for the 2-in-1 orbit corrector at D2. For comparison, the D1 and D2 separation recombination dipoles provide $1620\ \mu\mathrm{rad}$ each.

CONCLUSIONS

A consistent layout and optics has been presented for an upgrade scenario of the LHC with a local crab cavity scheme and $\beta^* = 15$ cm. All matched optics respect the constraints for the existing elements and the main specifications for the new magnets are given. The chromatic aberrations and the spurious dispersion are well controlled thanks to the implementation of the ATS scheme. The dynamic aperture resulting from the field quality of the existing elements looks acceptable provided 4 additional sextupoles are installed at Q10 in IR1 and IR5 in order to minimise the geometric aberrations induced by the chromatic correction. Finally, an alternative crossing scheme has been developed showing the feasibility and the advantages of closing the bumps on the IP side of D2.

The layout can be completed, and β^* fine-tuned, with a wide range of triplet options (e.g. aperture and gradient) either based on the baseline Nb_3Sn technology or NbTi if necessary. Finally, the HL-LHC beam parameters will probably influence the detailed design of the area between D1 and Q4, based on radiation shielding, machine protection and collimation related criteria.

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