HIGH BETA OPERATION SCENARIOS FOR CRAB CAVITIES IN THE INSERTION REGION 4 OF THE CERN LARGE HADRON COLLIDER

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Abstract

IR4 is a potential candidate for the installation of crab cavities in the CERN Large Hadron Collider. In this paper we present several operational scenarios in which the effect of the kick imparted by the cavity is enhanced by performing a dynamic blowup of the beta function at collision energy. Linear optics; power supply requirements; beam aperture and finally potential luminosity increase studies will be discussed in order to rank and assess the feasibility of the various options.

INTRODUCTION

Crab cavities have been proposed [1] to enhance the LHC luminosity for large crossing angle scenarios, i.e. if an interaction region upgrade would allow operation with $\beta^* < 55$ cm.

Crab crossing can be implemented in two fashions [2]: a local bump generated by two pairs of crab cavities that closes around the interaction region (IR) or a global distortion generated by a single crab cavity around the machine. Both approaches have pros and cons and in this paper we will concentrate on the feasibility of the latter, proposing and analysing different scenarios.

HARDWARE CONSTRAINTS

The global option needs at least one cavity assembly per beam per plane of crossing. The ideal location should:

- be free from other equipment (present and planned)
- allow easy access to cryogenic lines
- allow easy installation of RF power lines
- allow easy installation in the neighborhood of RF power converter
- not be affected by high level of radiation
- allow quick installation of crab cavities
- do not require major hardware changes
- have large separation between beams
- have large beta function in the plane of the kick

The last item is justified by the fact that the bunch rotation due to the crab cavity kick is given by (assuming crossing in the horizontal plane):

$$\frac{\theta_c}{2} = \frac{V_{\rm full}\omega_{\rm RF}}{2cE_0}\frac{\sqrt{\beta_{\rm crab}\beta^*}\cos(2\pi(\psi^x_{\rm cc\to IP}-\mu_x/2))}{\sin(2\pi\mu_x/2)} \quad (1)$$

where $\beta_{\rm crab}$ and β^* are the β function at the location of the crab cavity and the interaction point (IP), respectively, $\psi^x_{\rm cc\to IP} = |\psi_x(s_{\rm IP}) - \psi_x(s_{\rm cc})|$ is the phase advance between them, E_0 is the beam energy, $\theta_c = d_{sep}\sqrt{\epsilon/\beta^*}$ the crossing angle defined in terms of the required beam separation, $\omega_{\rm RF}$ is the crab cavity RF frequency and μ_x is the horizontal tune.

IR4 has been identified as an ideal candidate to host the crab cavities because it already hosts the LHC RF systems, which shares with the RF cavities, some of the requirements: larger than nominal separation and existing RF infrastructure.

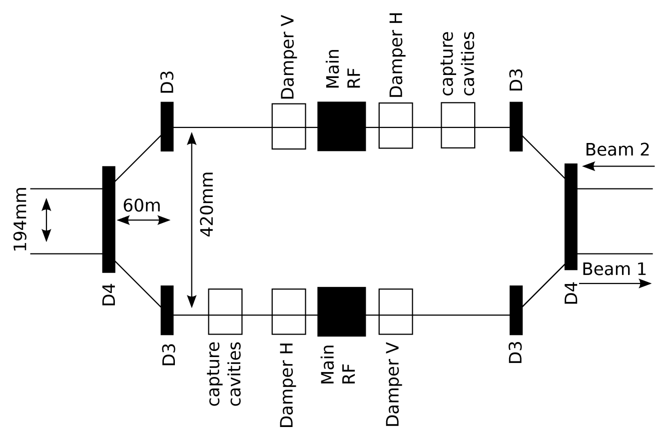

Figure 1: LHC IR4 Schematic layout.

IR4 offers several locations as seen in Figure 1:

- in the reserved space of capture cavities
- in the reserved space of additional damper kicker
- in the dogleg region (D3-D4)
- close to D3 after displacing the dogleg further away from the IP
- close to D3 after reducing the dogleg length with new dipole

None of them is ideal, because either the space is reserved for equipment that may or may not be needed (see [3]) or it requires hardware modifications.

As baseline for this paper, we propose to install one crab cavity module in the capture cavity region on the left part of IR4 for Beam 1 and in the right part for Beam 2. The polarity of the quadrupoles (and therefore the orientation of the beam scream) suggests that the most efficient plane for crab crossing is the horizontal plane. We assume the crab crossing will occur in IP5.

The region starts from 33.822 m to 42.384 m left and right with respect to IP4. In the following studies the position of the crab cavity is fixed at 40m from IP4.

Table 1: Luminosity Gain Estimates using Crab Cavities

Beam energy (TeV)	β^* (cm)	θ_c (μrad)	$\frac{\mathcal{L}_{\text{ho}}}{\mathcal{L}_{\text{nocrab}}}$	V_{crab} (MV)	β_{crab} (km)	$\frac{V_{\text{crab}}}{V_{\text{fullcomp}}}$	$\frac{\mathcal{L}_{\text{cr}}}{\mathcal{L}_{\text{nocrab}}} - 1$
7	30	409	1.60	2.5	2.6	0.50	$\sim 18\%$
7	55	302	1.21	2.5	2.6	0.90	$\sim 13\%$
5	42	409	1.34	2.5	2.0	0.70	$\sim 15\%$
3.5	60	409	1.18	2.5	1.3	1.00	$\sim 10\%$

OPTICS SCENARIOS

As baseline we assume the optics developed for the SLHC phase 1 upgrade scenarios [4].

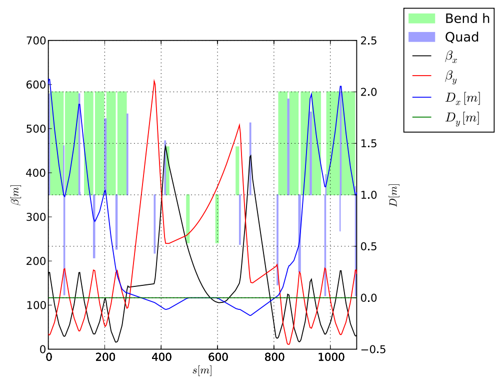

Figure 2: SLHC injection optics for IR4 Beam 1.

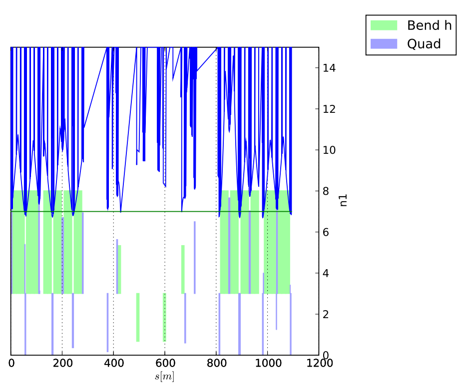

Figure 3: Aperture estimate in term of n1 for IR4 Beam 1.

Figure 2 and 3 show the SLHC optics and aperture for IR4 Beam 1.

Assuming an horizontal tune of $\mu_x = 63.31$ (integer part does not matter) we need to impose $\psi^x_{\text{cc}\to\text{IP}} \mod 1$ is 0.655 or 0.155 in order to get the maximum beam rotation at the IP. For minimal effect (e.g. IP1 that crosses in the other plane) the ideal $\psi^x_{\text{cc}\to\text{IP}} \mod 1$ is 0.405 or 0.905.

In the present case we have $\psi^x_{\text{cc}\to\text{IP}} = 7.687, 8.157$, for Beam 1 and Beam 2 respectively, that are already very close to the optimum.

For the β function we have: $\beta_{\text{crab}} = 204\,\text{m}, 260\,\text{m}$, which are small values compared to what we would need. Beta values at injection are restricted by aperture constraints and they cannot be further increased but at top energy aperture margins increase by a factor 4 in terms of sigma. Therefore we propose to blowup the beta function at constant phase advance before collision when the other insertion IR1 and IR5 perform the β squeeze.

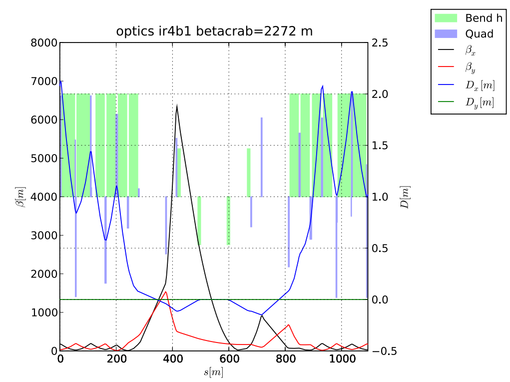

Figure 4: Final stage of the optics transition for IR4 Beam 1.

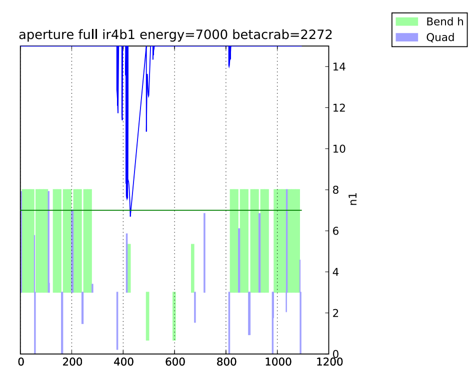

Figure 5: Aperture estimantes for the final stage of the optics transition for IR4 Beam 1: aperture.

Figures 4, 5 and 6 show the final stage of the optics transition with aperture and quadrupoles' strength evolution. The optics transition is compatible with strength and polarity of the insertion quadrupoles. The optics behavior shows how the insertion is not really designed for high beta operation because for obtaining 3 km of beta function at the crab cavity ones needs to accept 8 km of maximum beta.

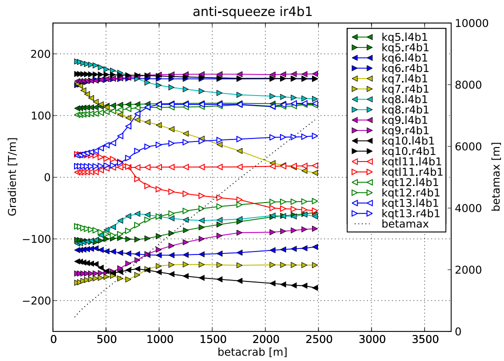

Figure 6: Evolution of the quadrupoles' strength for IR4 Beam 1 during the optics transition.

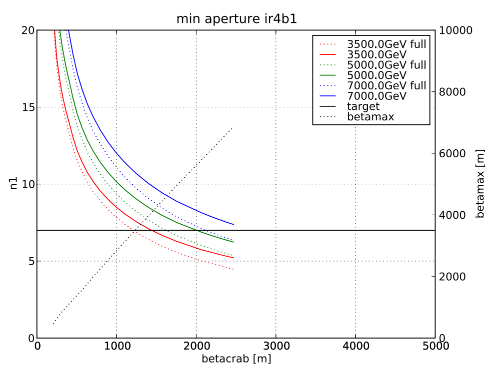

Figure 7: Summary of the aperture as a function of $\beta_{\rm crab}$ and beam energy for Beam 1 with and without spurious dispersion.

Figure 7 shows the evolution of the aperture as a function of $\beta_{\rm crab}$ and beam energy for Beam 1 with and without spurious dispersion. Apertures are evaluated using a closed orbit tolerance of 3mm and maximum $\delta p/p = 8.6 \times 10^{-4}$, using the present aperture model and tolerances. The target of $n_1 = 7$ is the same of nominal which is actually enforced only at triplets that have dedicated collimator). It is worth mentioning that SLHC Phase I aims at $n_1 = 10$. The aperture calculations do not include the effect of the crab cavity on the collimation.

LUMINOSITY ESTIMATES

LHC luminosity can be approximated by:

$$\mathcal{L} = \mathcal{L}_{\rm ho} \cdot F_{\rm geo} = \frac{N_b^2 n_b f_{\rm rev}}{4\pi\epsilon\beta^*} \cdot 1/\sqrt{\left(1 + \frac{\sigma_z \theta_c}{2\sigma^*}\right)^2} \quad (2)$$

The luminosity with the crab cavity is bounded between the head-on, $\mathcal{L}_{\rm ho}$, and crossing angle luminosity, $\mathcal{L}$.

Table 1 illustrates the expected effect of the luminosity on the crab cavity on various conditions.We assume moderate 2.5 MV max voltage, optimum phase advance, and nominal parameters such as $\epsilon_n = 3.75\text{mm mrad}$, $d_{\rm sep} = 10\sigma, N_b = 1.15 \cdot 10^{11}, \sigma_z = 7.55\text{cm}, n_b = 2808$, Gaussian beam, $V_{\rm fullcomp}$ is the required cavity voltage to compensate the total crossing angle. For additional details on luminosity estimates refer to [5].

CONCLUSIONS AND OUTLOOK

The scenarios presented allow efficient operation of the crab cavities installed in IR4. It does require additional hardware (beside the cavity) and it is compatible with aperture constraints and the quadrupole strength limit.

There is set of solutions compatible with a variety of parameters: requirements from collimation, top energy, values of beta crab. They allow to adapt to the machine parameter and they also offer knobs for gradual luminosity enhancement or reduction experiments.

The optics of IR4 is over pushed to the limit and it loses any flexibility. The beta-function increase may affect the instrumentation installed in the area. For the highest beta max in the cavities, IR4 becomes an additional aperture bottleneck at high energy and the machine protection needs to be re-evaluated.

A redesign of the region layout involving additional hardware changes is under study to reduce the peak beta function and keep some optics flexibility [6]. In particular additional quadrupoles (e.g. warm quadrupole in the dogleg region) and or a redistribution of them may restore part of the flexibility. A symmetric layout at the IP up to Q5 may may also reduce the peak beta function for the same beta values at the crab cavities at the cost of additional hardware changes.

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