CRAB COMPENSATION FOR LHC BEAMS *

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Abstract

An R&D program to establish a road map for the installation of crab cavities in the LHC is rapidly advancing. Both local and global crab schemes are under investigation to develop cavities that will be compatible with the LHC optics and meet the aperture requirements. Space and aperture constraints to accommodate a prototype crab cavity in the LHC along with related optics issues are presented. The design of a prototype TM_{110} cavity and pertinent RF requirements including impedance estimates and damping are discussed.

INTRODUCTION

A small angle ($\sim$ 0.3-0.5 mrad) crab scheme has been defined as the first step to realize a full crab crossing scheme for the LHC IR upgrade [1, 2]. The luminosity increase solely from crab cavities is expected to be 12-18% for the nominal LHC with $\beta^* = 55$ cm and 43-62% for the upgrade with $\beta^* = 25$ cm for cavity frequecies of 400-800 MHz respectively. Due to space constraints and technical ease, a global scheme at the LHC is considered as the best choice for the first experimental test of crab cavities in hadron colliders. In this scheme the cavities are placed in the accelerating RF section (IR4) to provide head-on collision at one of the interaction points in the LHC. A first mini-workshop (LHC-CC08) took place in February 2008 to discuss several beam dynamics and RF issues and build a global collaboration to establish a road map for the R&D prototype. A large collaboration spanning three continents is now in place to develop an optimized cryomodule compatible with the LHC and IR4 requirements. A tWiki page is set up to maintain a central repository and coordinate the project at an international level [3]. The objective of the repository is to provide easy access to latest developments related to LHC crab cavities and to share information with crab cavity developments from the ILC and light sources for mutual benefit. Regular meetings over the web enable discussions about the latest progress of the cryomodule. In this paper the installation issues at IR4, nominal cavity design, impedance and damping requirements are discussed.

APERTURE & COLLIMATION

The tight aperture constraints imposed by the LHC collimation system for machine protection and quench prevention leaves very little or no margin for additional aperture [4]. A global crab scheme would approximately require an additional 0.5σ of aperture (see orbits in Fig. 1) to accommodate the tilted bunch. The horizontal retraction of the collimators would be reduced with the consequence of even tighter tolerances and perhaps larger losses [6]. The impact of the global crab scheme on LHC collimation is under study to define the exact retraction and associated tolerances. Fig. 2 shows the additional beta-beat for a globally crabbed beam with nominal LHC parameters which is compared to the off-momentum β-beat. The crabbed beam β-beat is approximately a factor of 10 less and is not foreseen to be an issue. However, the tolerance imposed by large off-momentum β-beat is very severe. Mitigation of this β-beat with appropriate optics solution is essential for any IR upgrade scenario. A solution which significantly reduces the off-momentum beta beat at the collimators (down to $\beta^* \sim 0.2$ m) has been recently been developed by special powering of all arc sextupoles and optimizing phase

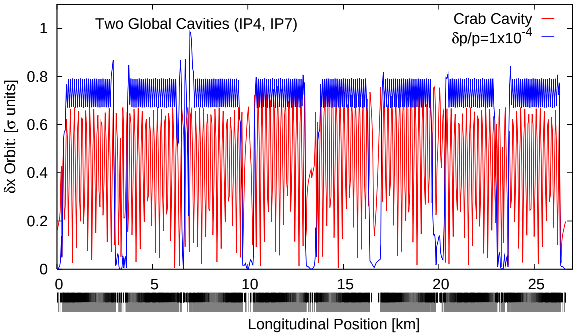

Figure 1: Orbit deviation of a $1\sigma_z$ particle for a globally crabbed beam compared to deviation of a particle at $1\sigma_{\delta p/p}$.

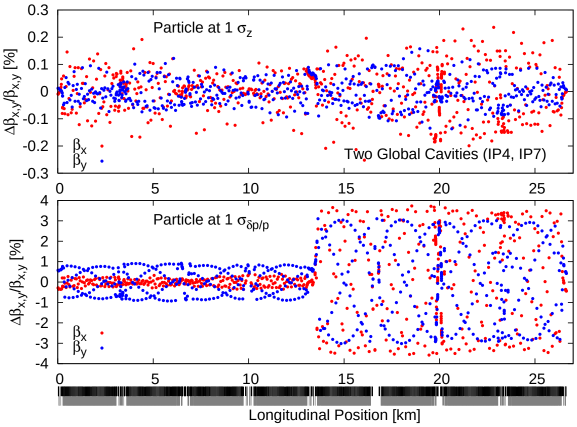

Figure 2: Top: β-beat of a $1\sigma_z$ particle for a globally crabbed beam compared to a particle at the center of the bunch. Beta beat of particle with momentum deviation of $1\sigma_{\delta p/p}$ compared to synchronous a particle.

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advances between the arcs [5].

IR4 INSTALLATION & ISSUES

The nominal beam line separation between the two beams in the LHC is 19 cm for the most part of the ring. This makes it difficult to transversely accommodate conventional RF cavities with a frequency of 800 MHz or smaller. The IR4 region, currently hosting the LHC main RF, has a special dog-leg to horizontally separate the two beam lines to 42 cm which removes this constraint. Two locations of 5m length as depicted in Fig. 3 have been identified as potential locations that can be used unless the equipment originally foreseen for these points become essential for LHC operation [7]. IR4 also provides another significant advantage as the existing RF infrastructure can be adapted to the crab cavities including the cryostat design, waveguides, power sources and controls while conforming to LHC technical and mechanical specifications.

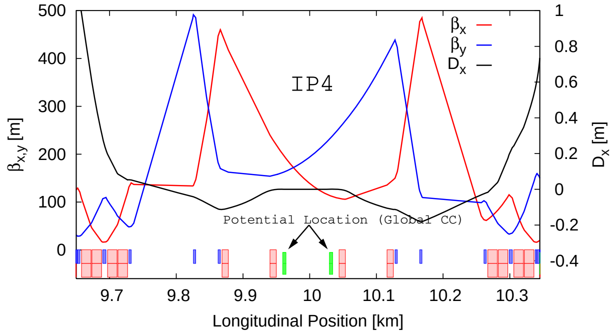

Figure 3: Nominal optics and magnetic elements in the IR4 region of the LHC. The two green blocks represent the potential locations (∼10 m) for cavities in the global scheme.

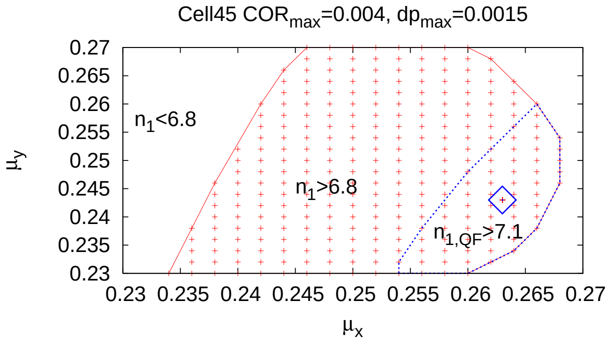

Figure 4: Tuning range of the LHC betatron phase advance. The horizontal and vertical axes of the plot are the horizontal and vertical phase advances per arc cell with the LHC operating point marked in a square.

Fig. 4 presents the tuning range of the betatron phase advance in the nominal LHC. The figure shows the horizontal and vertical phase advances per arc cell, respectively. The red line delimits the accessible values of the phase advances as constrained by aperture limitations and the nominal closed orbit and aperture assumptions for the LHC within the cell. A tighter aperture cut would yield the area within the blue line. A wide range for phase advance tunability is available when using the usual aperture assumptions for the LHC thus providing margin for operation and the cavity voltage. Small changes in IR4 quadrupole strengths can provide additional margin via local β-function modification.

CAVITY DESIGN

The cavity geometry first originated from an initial 400 MHz design via a geometrical parameter scan to reach some semi-optimal RF charateristics. After scaling to 800 MHz, an additional optimization was performed on the 800 MHz cavity to arrive at the two designs shown in Fig. 5. The optimized geometric and the corresponding RF parameters are shown in Table 1 and Table 2 respectively. The two geometries shown differ mainly in the wall angle of the cavity which subsequently affects the final optimum set of geometrical parameters. Typically, a finite wall angle of 6° or larger is preferred for cavity treatment. Fine tuning may be required to meet the final requirements related to surface fields, multipacting and coupler geometries.

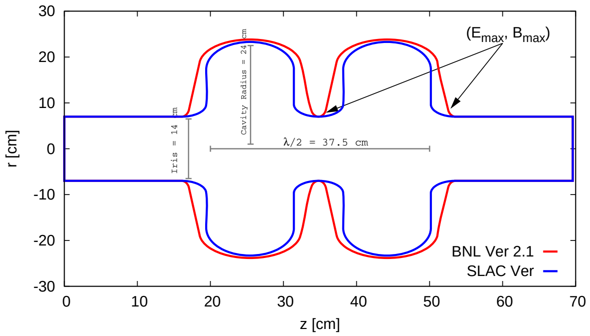

Figure 5: 800 MHz two-cell cavity from crab crossing for the LHC. An alternate version optimized by SLAC group (blue, geomterical parameters courtesy L. Xiao, Z. Li) achieves lower surface fields.

Table 1: Two optimized geometries for 800 MHz LHC-CC

Parameter	Crab Cavity	
	BNL v2.2	SLAC
Iris Radius, R_{iris} [cm]	7.0	7.0
Wall Angle, α [deg]	6.0	0.0
Iris/Eq. Ellipse, $r = \frac{b}{a}/R = \frac{B}{A}$	2.0/0.8	0.8/1.0
Cav. wall to iris, d [cm]	1.0	3.375
$\frac{1}{2}$ Cell, $L = \frac{\lambda\beta}{4}[cm]$	9.375	9.375
Eq. Height, D [cm]	23.8	23.3
Cavity Beta, $\beta = v/c$	1.0	1.0

Table 2: RF characteristics of the two geometries for a kick gardient of $B_{kick} = 6.6$ MV/m ($L_{active} \sim 37.5$ cm)

Parameter	Unit	Crab Cavity	
		BNL v2.2	SLAC
E_{peak}	MV/m	22	30
B_{peak}	mT	103	87
R/Q$_\perp$	Ω	112	118
$k_{\|\|}$	V/pC	0.54	0.43
$k_\perp$	V/pC/m	2.635	2.164

IMPEDANCE REQUIREMENTS

The impedance spectrum of BNL v2.2 cavity was calculated with ABCI [8]; see Fig. 6. A comparison between an 8cm and 6cm beam pipe radius is shown to roughly identify any trapped modes and the corresponding frequency shifts with aperture. The exact aperture will be chosen based on the optimum coupling-damping scheme while minimizing the number of trapped modes below the cut-off frequencies of the beam pipe.

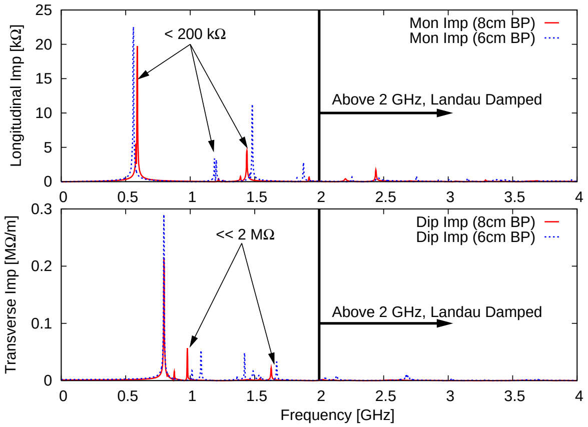

Figure 6: Longitudinal and transverse impedance spectrum of an 800 MHz two-cell from ABCI. A comparison between 8cm (red) and 6cm (blue) is shown.

It is estimated that single and coupled-bunch longitudinal modes above 2 GHz will be Landau-damped due to the frequency spread of synchrotron oscillations. Tolerances can be set by estimating the impedance requirements given by [9, 10, 11],

$$R_{sh,L} \quad < \quad \frac{\eta E}{e I_0 \beta^2} \left(\frac{\Delta}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} \frac{F}{f_0 \tau} G(f_r \tau) \quad (1)$$

$$Im\left(\frac{Z}{n}\right) \quad < \quad \frac{\eta E}{e I_b \beta^2} \left(\frac{\Delta}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} f_0 \tau. \quad (2)$$

In the transverse plane the natural frequency spread, chromaticity, bunch-by-bunch transverse damper and Landau octupoles should also damp potentially unstable modes above 2 GHz. The stability limit from Landau octupoles at 7 TeV can be formulated in terms of a maximum limit on tune shifts (Re$\{\Delta Q\} < 3 \times 10^{-4}$, Im$\{\Delta Q\} < 1 \times 10^{-4}$). Pessimistically assuming that the sampling frequency falls on the resonance,

$$R_{sh,T} \ll \frac{Z_0 C \gamma}{r_0 M N_b \beta} |Im\{\Delta Q\}|_{max} \quad (3)$$

Table 3 lists the corresponding tolerances.

Table 3: Impedance tolerances estimates

Parameter	Unit	Longitudinal		Trans
		Inj	Top	
Coup bunch, R_{sh}	kΩ	137	196	≪2 MΩ/m
Coup bunch, Q$_{ext}$		< 200		-
Broadband, Im$\{Z/n\}$	Ω	0.24	0.15	-

COUPLER GEOMETRIES

Very strong damping of lower and higher order modes are required to stay well below the LHC instability thresholds. In addition a robust design is paramount for stable operation and tuning. With these constraints and in view of the KEK-B operational experience four designs shown in Fig. 7 are presently under study. These designs and other ideas will be compared on a common basis to evaluate their effectiveness and ease of fabrication to reach the final design that will comply with LHC specifications.

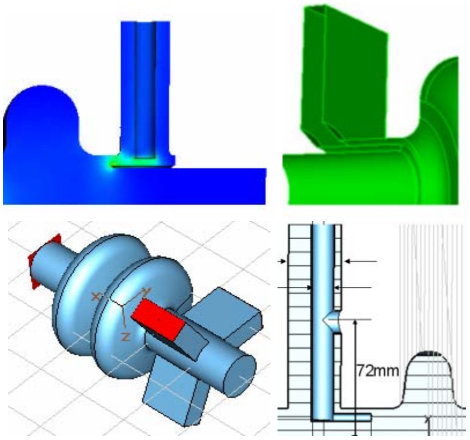

Figure 7: Potential coupler geometries to achieve strong damping with a robust design. Top: Coax-to-coax and waveguide-to-coax (courtesy X. Liling, Z. Li), bottom: multiple waveguides and coax-to-hook (courtesy G. Burt)

CONCLUSIONS

A low angle global crab compensation scheme located in IR4 is defined as the best option for a first experimental demonstration of crab cavities in hadron colliders and also for the phase I upgrade of the LHC to recover the geometric reduction of luminosity. A globally crabbed beam in the LHC requires an additional aperture of approximately 0.5σ. The associated collimator retraction and its impact on the collimation efficiency is under investigation. Optics scans indicate ample margin for tuning the phase advance and beta functions during machine operation. Two designs of a prototype TM$_{110}$ cavity and pertinent RF requirements including impedance estimates and damping requirements were presented.

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