STATUS OF LHC CRAB CAVITY SIMULATIONS AND BEAM STUDIES *

R. Calaga, R. De-Maria (BNL), R. Assmann, J. Barranco, F. Caspers, E. Ciapala, T. Linnecar, E. Metral, Y. Sun, R. Tomás, J. Tuckmantel, T. Weiler, F. Zimmermann (CERN), N. Solyak, V. Yakovlev (FNAL) Y. Funakoshi, N. Kota, O. Yukioshi, A. Morita, Y. Morita (KEK), G. Burt (LU), J. Qiang (LBL), P .A. McIntosh (DL/ASTeC), A. Seryi, Z. Li, L. Xiao (SLAC)

Abstract

The LHC crab cavity program is advancing rapidly towards a first prototype which is anticipated to be tested during the early stages of the LHC phase I upgrade and commissioning. The general project status and some aspects related to crab optics, collimation, aperture constraints, impedances, noise effects, beam transparency and machine protection critical for a safe and robust operation of LHC beams with crab cavities are addressed here.

INTRODUCTION

The LHC crab crossing scheme is proposed in two phases, a single prototype structure per beam to perform the first ever test in a hadron collider and a subsequent full crab crossing scheme for the luminosity upgrade. The luminosity reach including the natural luminosity leveling and the associate technological challenges is discussed in detail in Ref. [1]. Table 1 shows some relevant parameters for crab cavity (CC) prototype and subsequent phase II upgrade in the LHC.

Table 1: Some relevant parameters for the LHC nominal and upgrade lattices.

	Unit	Prototype	Phase II
Energy	[TeV]	3-7	7
P/Bunch	[10^{11}]	1.15	1.7
Bunch Spacing	[ns]	50-25	25
ϵ_n (x,y)	[μm]	3.75	3.75
σ_z (rms)	[cm]	7.55	7.55
IP$_{1,5}$ β^*	[m]	0.25-0.3	0.15-0.25
Betatron Tunes	-	{64.31, 59.32}	
Main RF Frequency	[MHz]	0.4	0.4
Crab Frequency	[GHz]	0.8	0.4-0.8

PHASE NOISE & KEK EXPERIMENTS

Strong-strong beam-beam simulations (3D) were carried out to study phase noise effects and emittance growth of colliding beams with a local crab compensation at IP$_5$ in the LHC (β*=0.25m, θ_c=0.522 mrad). The simulations were performed with 2.5 million macro-particles per beam, a 128×128 transverse grid, and 10 longitudinal slices. A 400 MHz local crab scheme, anticipated for the phase II upgrade, is modeled as a thin nonlinear kick located $\pi/2$ in phase advance before and after the collision point. Measurements at KEK-B show the side bands of the RF spectrum due to modulated phase noise at frequencies from 50 Hz to 32 kHz. This phase noise leads to dynamic offsets at the collision point with high frequencies being more dangerous [2]. Simulations with phase noise at 32 kHz suggest collision offsets to be $\leq 0.1\sigma$ for an emittance growth below 10% per hour. Simulations with a phase error at 32 kHz resulting in offset collisions should be controlled to $\leq 0.1\sigma$ to keep the emittance growth below 10% per hour.

Following the successful commissioning of the KEK-B crab cavity [3], experiments targeted to assess the impact of the RF phase noise and other measurements relevant to crab cavity beam dynamics were performed. The noise studies consisted of scanning the RF phase noise in the CCs and measure the corresponding beam size blow-up. Figure 1 summarizes the scans on the two rings (LER and HER) at frequencies close to the horizontal betatron tunes. The first visible effects occur at about -60dB for both rings. This corresponds to about 0.1° RF phase noise. However, the blow-up of the vertical beam size in the HER ring is more striking. This was initially believed to originate from transverse coupling. However, adjustment of vertical tune and the machine coupling does not qualitatively affect the observation. Similar scans were carried out with the beams in collision and observing the luminosity in the Belle experiment. The luminosity is recorded as a function of RF phase noise while exciting the LER and HER CCs individually. First visible effects appear at -70dB, which corresponds to about 0.03°. This value can be extrapolated to the LHC CC tolerances as a high ceiling, i.e. the LHC cavity phase noise must be much smaller than 0.03° since the radiation damping in LHC is almost negligible.

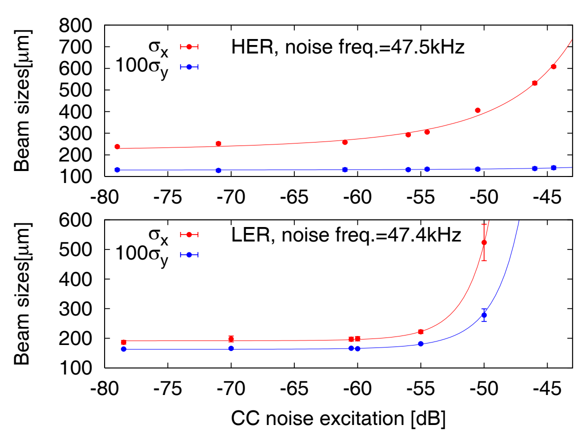

Figure 1: Beam size versus RF phase noise when exciting the LER and HER CCs individually.

* This work was partially performed under the auspices of the US Department of Energy, We also acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 ”Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395)

CAVITY IMPEDANCE & DAMPING

The LHC impedance is dominated by the numerous collimators [5] but additional impedance (both narrow band and broadband) from sources like crab cavities need to be minimized. 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 from Refs. [6]. 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 ($\mathrm{Re}\{\Delta Q\} < 3 \times 10^{-4}$, $\mathrm{Im}\{\Delta Q\} < 1.5 \times 10^{-4}$). Table 2 lists the corresponding tolerances assuming that the sampling frequency falls on the resonance.

Table 2: Impedance tolerances estimates.

Parameter	Unit	Longit.		Trans
		Inj	Top	
Coup bunch, R_{sh}	kΩ	137	196	$\ll 2\ \frac{\mathrm{M}\Omega}{\mathrm{m}}$
Coup bunch, Q_{ext}		< 200		-
Broadband, $\mathrm{Im}\{Z/n\}$	Ω	0.24	0.15	-

A two-cell cavity was optimized at 800 MHz for various RF characteristics which will serve as a baseline cavity for a complete cavity-coupler(s) design. Due to the unprecedented damping needs ($Q_{ext} \sim 10^2$), aggressive damping mechanisms were proposed to damp TM_{010} mode (LOM), the sister TM_{110} mode (SOM) and other HOMs. Three such designs which fulfill the damping criteria are under consideration [1]. These designs aim at providing a robust RF, mechanical and thermal performance. Detailed studies are underway (see Refs. [4]) to determine the merit of these damping schemes and converge to a final design compatible with LHC needs.

Some important modes {monopole: 0.54, 0.70} GHz with R/Q values of {35.2, 194.5} Ω and {dipole: 0.8, 0.81, 0.89, 0.9} with R/Q values {117.3, 0.46, 93.4, 6.7} Ω are studied in detail. Simulations were carried out to determine the thresholds for transverse modes leading to coupled-bunch instabilities. For a single crab cavity (β_{cc}=3 km), the (minus) imaginary part of the tune shifts for the 4 trapped modes respectively, assuming first a $Q = 10^6$ for all the modes, are approximately $\{90.3, 0.3, 55.0, 3.7\}\times 10^{-4}$. The minimum Q-values needed to enter the stability region (assuming only these trapped modes) would be approximately $\{16.6, 5000, 27.3, 405.4\}\times 10^3$ for the 4 modes respectively. However, these modes are not the only impedance contributions of the machine, and their effects should be minimized. A reasonable target would be to have a margin of 2 orders of magnitude, which would lead to maximum Q-values of few $\{10^2, 10^4, 10^2, 10^3\}$ for the 4 modes respectively. For example, taking the maximum value of the computed instability growth rate for the 1^{st} trapped mode ($\tau^{-1} \sim 0.63$, $Q = 10^3$) and dividing it by the revolution (angular) frequency yields an imaginary part of the tune shift of $\sim 0.09 \times 10^{-4}$. The impact of a trapped mode can be approximated as $\frac{\beta_\perp}{\beta_\perp^{Av}} R_\perp \ll 1\mathrm{G}\Omega/\mathrm{m}$, where $\beta_\perp$ is the transverse β-function at the location of the trapped mode, $\beta_\perp^{Av}$ = R/$Q_\perp$ is the average transverse betatron function of the machine (with R the machine radius and $Q_\perp$ the transverse tune), and $R_\perp$ is the transverse shunt impedance of the trapped mode. The value of 1 GΩ/m corresponds to the situation where the mode is close to the limit of the stability diagram.

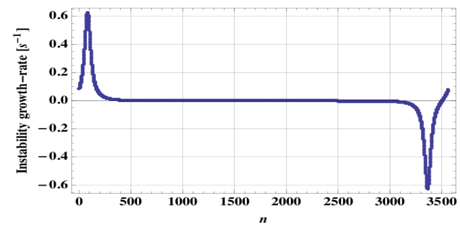

Figure 2: Instability growth rate vs. the transverse coupled-bunch mode number for the case of the 1^{st} trapped mode (only) with $Q = 10^3$.

COLLIMATION

Collimation efficiency and machine protection is a serious concern for LHC beams. The impact of collimation efficiency with the existing collimators setup in IR7 for betatron cleaning with globally crabbed beams needs detailed analysis. A single crab cavity is placed in the IR4 region to achieve head-on collisions at IP5. As a non-adiabatic increase in crab cavity kick results in emittance growth, the cavity voltage is ramped over 1000 turns after which the collimators are input in the tracking simulations. Results show no observable difference in the loss maps between nominal LHC and that with global crab cavities as envisioned for prototype tests.

Table 3: Impact parameters and particles absorbed on the primary collimator TCP.C6L7.B1 at IR7 with on-momentum (top) and off-momentum (bottom) from tracking 5×10^6 particles.

	Nominal		Crab Cavity	
	$2\sigma_z$	$3\sigma_z$	$2\sigma_z$	$3\sigma_z$
1^{st} turn [μm]	0.78	0.78	3.84	3.84
All turns [μm]	0.153	0.154	0.147	0.147
Part. absorbed.	70.2%	70.2%	68.5%	68.5%
1^{st} turn [μm]	50.61	59.82	76.16	79.03
All turns [μm]	36.1	40.44	66.47	67.03
Part. absorbed	96.5%	97%	99.56%	99.56%

The impact parameters (physical distance to the edge of a collimator) are listed in Table 3 for the globally crabbed beam and compared to the nominal LHC case. A typical value of 1-2μm is used for nominal beam (on-momentum particle) based on diffusion studies. The impact parameters for the crabbed beam in the 1^{st} turn are about a factor of 5 higher. However, for off-momentum particles, the impact parameters are similar to the nominal case and hence the effective cleaning inefficiency remains similar. More studies with similar impact parameters for on-momentum particles with crab cavities are underway to determine any change in efficiency. In addition, the hierarchy of the collimator family needs to be maintained for efficient cleaning. To properly account for lattice dispersion and crab dispersion, an effective amplitude function is defined as $A_z = \sqrt{\delta_p^2 + \delta_z^2}$. A phase space cut of all collimators was constructed as a function of the effective δ_p (with δ_z set as $1\sigma_z$) in the presence of crab cavities to determine the allowed region for beam. The constructed phase cut is similar to the one of the nominal LHC and maintains the hierarchy of the primary, secondary and tertiary collimators critical for efficient collimation.

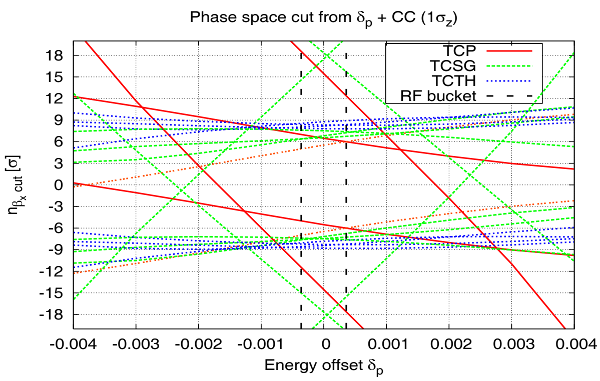

Figure 3: Phase space cut of all the collimators in the LHC with crabbed beams. The hierarchy of the primary (red), secondary (green) and tertiary (blue) collimators

OPTICS AND OPERATIONAL ISSUES

The nominal (and phase I) optics in the IR_4 region have small β-functions and therefore require substantial cavity voltage. We propose an anti-squeeze in the crab cavity section of IR4 to reach the maximum β-functions for the prototype tests without altering the phase advance. The phase advances $\psi^x_{cc\to ip}$ for beam 1 and beam 2 are (7.636, 8.185) which are close to the optimum phase advances for the IR4 location which are (0.655, 0.155) respectively. The apertures for the anti-squeezed optics are within specification and require four quadrupoles to be powered by new bipolar power supplies. Detailed studies on the actual anti-squeeze sequence are underway to have a smooth path between injection and collision optics. Studies to compute dynamic aperture and effects of chromatic aberrations are underway.

The operation of the prototype cavity with beam requires a well defined scenario(s) for the prototype tests. The two primary goals are: 1. inject single and multiple bunches in the LHC to establish stable beam trajectory and lifetime without crab cavity related emittance growth. In addition, the beam quality should be maintained through the energy ramp and 2. demonstrate head-on collisions at top energy with an observable luminosity increase and the feasibility of luminosity leveling. These goals should also ensure the safety of the machine at all stages and therefore require detailed operational procedures and appropriate remedies for possible failure scenarios. During injection and the energy ramp, the β-functions at the crab cavity are minimum, and the cavity is detuned and maintained at a pre-determined minimum voltage with active feedback loops. Alternately, the RF phase can be set $\pi/2$ out-of-phase and "effectively" impart a dipole kick to the beam. This kick can be compensated with a corrector downstream to close the bump. If the frequency is detuned to avoid overlap of the beam spectrum, the effect of the cavity is negligible.

At collision energy, the cavity will be re-tuned to the exact harmonic of the beam frequency. Subsequently, the cavity will be ramped to the nominal voltage in 100 turns or longer to maintain adiabaticity. The technique of re-phasing can be employed at nominal voltage if the alternate scenario is used. Active orbit control of the cavity with local feedback system will be in place. The beam loading is computed to be approximately 0.1 MV/mm for the ultimate intensities (0.8 Amps). Therefore, an amplifier with a power 20 kW (60 kW available) is required to allow for orbit deviations of approximately a millimeter inside the cavity . Table 4 show test scenarios for different collision energies and corresponding optics schemes. A maximum of 2.5 MV kick is assumed as a nominal voltage for a single two-cell cavity which may limit the ultimate potential of the luminosity gain. This can be easily recovered with additional voltage. For example, with a factor of 2.2 increase in voltage, the luminosity gain can be increased from 21% to a maximum of 43% for case 1 in Table 4.

Table 4: Operational scenarios for three different β^* and collision energies in the LHC. The cavity voltage is set to 2.5 MV and the maximum achievable β_x at the crab cavity within the aperture limit is used to determine the approximate luminosity gain.

β_{cc} [km]	β^* [m]	θ_c [μrad]	E_b [TeV]	L/L$_0$ [%]
3.0	0.25	439	7.0	21%
3.0	0.30	401	7.0	19%
3.0	0.55	296	7.0	12%
2.0	0.42	401	5.0	15%
1.0	0.7	401	3.0	8%
0.2	10.0	273	.45	0.04%

ACKNOWLEDGMENTS

We would like to thank all the members of LHC-CC collaboration for valuable discussions and their contributions.

REFERENCES

[1] R. Calaga et al.,CARE-HHH 2008, Chavannes-de-Bogis.

[2] R. Calaga et al., PAC07, Albuquerque, NM, 2007.

[3] K. Oide et al., these proceedings (1108).

[4] B. Hall et al., in these proceedings, 2009 (2398); L. Xiao et al., in these proceedings, 2009 (3517).

[5] E. Métral et al., LHC project report 1015.

[6] E. Shaposhnikova, LHC Project Note 242 (2000); F. Sacherer, IEEE Tr. Nucl.Sci. NS-20 , 825 (1973); V. Balbekov et al., IHEP Preprint 91-14, Protvino (1991).