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LHC crab-cavity aspects and strategy

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Abstract

The 3rd LHC Crab Cavity workshop (LHC-CC09) took place at CERN in October 2009. It reviewed the current status and identified a clear strategy towards a future crab-cavity implementation [1]. Following the success of crab cavities in KEK-B and the strong potential for luminosity gain and leveling, CERN will pursue crab crossing for the LHC upgrade. We present a summary and outcome of the various workshop sessions which have led to the LHC crab-cavity strategy, covering topics like layout, cavity design, integration, machine protection, and a potential validation test in the SPS.

INTRODUCTION

Operating at the beam-beam limit, the luminosity upgrade of the LHC is foreseen as a combination of an increase in the bunch intensities beyond the nominal ($\times 1-5$) and reduction of β^* with a simultaneous compensation of Piwinski angle as depicted in Fig. 1 with crab cavities [2].

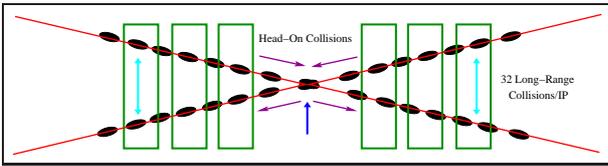


Figure 1: Schematic of the LHC interaction region triplets to depict the crossing scheme required to minimize parasitic collisions with reducing β^* .

Although, challenges confront all paths, crab crossing in the LHC is most attractive due to three main reasons:

- Recover the geometrical luminosity loss from increasing crossing angle due to long-range interactions independent of bunch intensity. This alleviating the requirement to substantially increase in bunch intensities or reduce the emittances which pose several challenges for the injector chain and the LHC.
- Natural luminosity leveling knob to maintain a constant luminosity during a physics store and substantially reduce the radiation damage of IR region SC magnets and detectors.
- Enable anti-crabbed ($\times 2$ crossing angle) to full head-on collisions to reach beyond the beam-beam limit.

Table 1 shows some relevant parameters for the nominal LHC and foreseen upgrade. Table 2 lists the corresponding luminosity gain for different operational scenarios of interest to the LHC. The success of crab crossing at KEK-B

Table 1: Relevant LHC nominal and upgrade parameters.

	Unit	Nominal	Upgrade
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	1.0-3.75
σ_z (rms)	[cm]	7.55	7.55
IP _{1,5} β^*	[m]	0.55	0.14-0.25
Betatron Tunes	-	{64.31, 59.32}	
Piwinski Angle	$\frac{\theta_c \sigma_z}{(2\sigma^*)}$	0.64	0.75
BB Parameter, ξ	per/ip	0.003	0.005
X-Angle: θ_c	[mrad]	0.3	0.5
Main RF	[MHz]	0.4	0.4
Crab RF	[GHz]	0.4	0.4
Crab Voltage	[MV]	5-10	
Peak luminosity	[$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	1.0	3-5

Table 2: Scenarios and luminosity increase compared to without 400 MHz crabs for different β^* and energies in the LHC. The integrated luminosity assumes a run time of 10 hr/store for 220 days and turn-around-time of 5 hrs [3].

β^* [m]	θ_c [μrad]	E_b [TeV]	L/L ₀	Int Δ L/yr
0.14	784	7.0	190%	31%
0.25	439	7.0	63%	22%
0.30	401	7.0	40%	19%
0.55	296	7.0	10%	NE
10.0	273	0.45	0.12%	NE

has significantly boosted the case for an LHC implementation. The geometric luminosity gain from crab crossing was immediately realized at KEK-B [4]. However, a gain predicted from an increase in the head-on beam-beam tune shift was only realized after a long commissioning period (~ 1.5 years) mainly due to bad lifetime at high currents. The origin of this phenomenon was traced to aperture limitations at the crab locations, later fixed by appropriate optics and a peculiar chromatic coupling at the IP corrected by using skew sextupoles [4]. The beam-beam tune shift is now increased to 0.09 from the previous 0.056 without crab cavities.

LHC BOUNDARY CONDITIONS

The LHC poses two main boundary conditions for the implementation of crab crossing: 1) Long bunches of 7.55 cm ($1\sigma_z$), which confine the maximum RF frequency of a deflecting cavity to about 800 MHz. 2) Beam-to-beam separation of 194 mm along the 27 km with only a few exceptions like the IR4 region. For example, a conventional elliptical cavity at 800 MHz radially measure about 250 mm making them incompatible in most of the LHC ring.

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Therefore, a new design with a smaller transverse diameter (Table 3) is essential.

Given the LHC constraints, two schemes can be conceived for crab crossing in the LHC. Only the high luminosity regions (IP1, IP5) are considered for this study. The nominal and most flexible option without severe optical constraints is realized with a fully local crab crossing scheme at each IP. A dogleg to accommodate conventional elliptical cavities (see Fig 2) is too expensive and impractical [5]. Therefore, a compact cavity is mandatory.

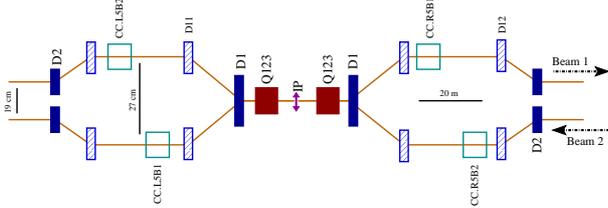


Figure 2: Schematic of the IR1 and IR5 layout in the LHC. A dogleg is required to accommodate conventional technology.

An alternate global scheme with a minimum of one cavity per beam placed in the IR4 dogleg region is a viable option. The IR4 region has the advantage of larger beam-to-beam separation (Table 3). However, this scheme poses severe constraints on the possible phase advances between IP1, IP5 and the crab cavities. Additional constraints on the crossing scheme at the two IPs maybe undesirable which is used to partially compensation of parasitic interactions. Some of the constraints can be eased with an additional dogleg elsewhere in the ring. Due to the available cavity voltage, the IR4 optics may also require an β -antisqueeze simultaneous to the β -squeeze at the IPs. An optics unsqueeze is in place and further optimization by adding a few additional bi-polar power supplies is possible [5].

Table 3: Aperture specifications for the IR4 dog-leg region for the global scheme and IR1 and IR5 high luminosity regions for a local scheme.

	Magnet	Aper-H [mm]	B1-B2 sep [mm]	Outer, R [mm]	L [m]
IR ₄	D ₃	69	420	395	9.45
	Crabs	84	220-300	195	10
	D ₄ , Q ₅	73	194	169	15.5
IR _{1,5}	D ₁	134	-	-	10
	Crabs	84	194	150	10
	D ₂	69	-	-	10

IMPEDANCE & RF TECHNOLOGY

Impedance budget of the LHC for crab cavities at 450 GeV is defined by the 200 MHz ACN RF system to 60 k Ω . This is reduced to 10 k Ω for upgrade intensities (1.7×10^{11} p/bunch). 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. In the transverse plane the impedance budget is given as 2.5 M Ω /m defined by the damping time of 60 ms at 450 GeV for nominal intensity. For upgrade intensities this is

reduced to 0.8 M Ω /m. An additional factor of $\beta/\langle\beta\rangle$ is needed to account for the local β -function. The natural frequency spread, chromaticity, bunch-by-bunch transverse damper and Landau octupoles should also damp potentially unstable modes above 2 GHz.

A two-cell conventional elliptical cryomodule at 800 MHz compatible with the impedance requirements and the IR₄ global scheme was developed as an initial step [2]. As a local crab scheme requires small cavities, deflecting structures with a compact footprint (see Table 3) are under investigation. The effort to compress the cavity footprint recently resulted in several TEM and other deflecting mode geometries. Apart from being smaller than the elliptical counterparts, the deflecting mode is also the primary mode in some of these structures. This paves the way to a new class of deflecting cavities at lower frequencies (400 MHz), also optimum for longer bunches due to reduced RF curvature(see Fig. 3).

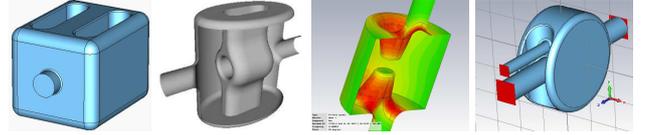


Figure 3: Left to right: Half wave double rod [6], half wave single rod [6], double rod loaded [6], rotated pill-box Kota cavities [6].

The ratio of the peak surface fields to kick gradient for some designs are lower by a factor of 2 or more than for the elliptical counterpart. Therefore, one may theoretically expect a larger kick voltage assuming the surface field limitations are similar to elliptical cavities. Some designs also have the added advantage of large separation in frequency between the deflecting mode and other higher order modes, thus making HOM damping simpler. Nevertheless, the coupler concepts developed for the elliptical design are being adapted to achieve a similar level of damping for the compact cavities. Prototypes of some compact designs are underway to validate the RF properties.

COLLIMATION AND PROTECTION

Collimation efficiency is a serious concern for LHC beams. The impact on collimation with the existing collimators setup in IR3 and IR7 is minimal for a local scheme. For a global scheme, studies were carried out with a single crab cavity placed in the IR4 region to achieve head-on collisions at IP5 [8, 2]. Results show no observable difference in the loss maps between the nominal LHC and that with global crab cavities [8, 2]. The impact parameters (physical distance to the edge of a collimator), also used as a figure of merit for cleaning inefficiency, is a factor of 5 larger after the 1st turn compared to the nominal case ($1-2\mu\text{m}$). However, for off-momentum particles, the impact parameters are similar to the nominal case and hence the effective cleaning inefficiency remains similar. The phase space cuts of all LHC collimators in the presence of a global crab cavity are similar to the ones for the nominal LHC. More im-

portantly, the hierarchy of the primary, secondary and tertiary collimators is also preserved. Suppression of synchrotron resonances was also clearly evident in the simulations with crab cavities. A maximum decrease by 1σ was calculated for the global scheme (nominal DA 13σ).

Due to the immense stored energy in the LHC beams at 7 TeV (350 MJ), protection of the accelerator and related components is vital. At 7 TeV and nominal intensity, 5% of a single bunch is beyond the damage threshold of the superconducting magnets [7]. Hundreds of interlocks with varying time constants ensure a safe transport of the beam from the SPS to the LHC and maintain safe circulating beams in the LHC. The time scale of the failure scenarios ranges from a single turn (kicker failure, fastest) to ten turns (NC magnet). Other failure scenarios typically have longer time scale. A best case scenario for detecting an abnormal beam condition is $40\ \mu\text{s}$ (half a turn), and the corresponding response time to safely extract the beams is about 3 turns. Therefore, induced beam losses from a crab cavity has to stay within the safety limits before the beam is ejected out of the machine (> 3 turns). Detailed tracking studies are needed to confirm the local and global loss maps in the case of abnormal failure scenarios such as abrupt cavity quenches and phase changes as well as the mitigation with appropriate feedback.

PHASE NOISE EFFECTS

This phase noise leads to dynamic offsets at the collision point and related emittance growth with higher frequencies being more dangerous [2]. Dedicated noise studies were performed in KEK-B by scanning the RF phase noise at frequencies close to the betatron tune with different amplitudes in the crab cavities to measure the corresponding beam size blow-up [10]. The first visible effects occur at about -60dB for both rings without beam-beam at -70 dB in the presence of beam-beam. This corresponds to about 0.1° and 0.03° in RF phase noise respectively and be extrapolated as a high ceiling for the LHC. The effect on the luminosity with colliding beams of induced noise as a function of noise frequency for different amplitudes was performed. Strong effects are observed close to the σ -mode while a weaker effect is observed close to the π -mode. Weak-strong with measured noise spectra from KEK-B cavities and strong-strong simulations using white noise indicate a tolerance of $\leq 0.1\sigma$ and $0.02\sigma\tau$ respectively for 10% emittance growth per hour [2, 9]. σ is the transverse offset and τ is the correlation time in units of turns. This is approximately consistent with KEK-B experiments. These values are within reach of the existing low-level RF technology.

SPS BEAM TESTS

As one of the vital conclusions from LHC-CC09, a test of crab cavities in the SPS was regarded as an important step to identify the differences between electrons and protons. A working group identified several aspects including integration, cryogenics, infrastructure and feasibility

of a test in the SPS [11]. No show stoppers were found with an additional possibility of using KEK-B crab cavity in the SPS for test purposes is found feasible after appropriate frequency changes to the cavity. A specific region near the LSS4 hosting the COLDEX experiment was identified as the best location for the crab cavity tests. This region consists of a movable horizontal bypass the COLDEX and cryogenic infrastructure thus posing minimum risk to the regular SPS operation. Preliminary tracking studies indicate strong effects in the SPS on emittance at the current working point (0.12, 0.18), but almost vanishing with changing working points [11]. Two collimators, TCSP.51934 and a SLAC collimator, are positioned ideally with respect to the crab cavity to see maximum and minimum orbit excursions. This setup enables detailed halo and impact parameter studies. Dedicated experiments are planned to establish the nominal lifetime at varying energies and bunch patterns in the SPS to be compared to potential future tests with crab cavities. Complementary machine studies include emittance growth, voltage ramp, intensity dependent effects and RF feedback during an energy ramp and at top energy. Machine protection pertinent to the LHC will be studied to determine different type of interlocks based on RF (fast) and orbit (slow) measurements. The effects on the beam of cavity failure scenarios such as cavity trips, multipacting, abrupt RF breakdown and phase changes will be studied. General operational aspects such as adiabatic voltage ramping, cavity transparency and other issues are also of interest.

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