

## Small angle crab crossing for the LHC \*

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### Abstract

A small angle crab compensation ( $\sim 0.5$  mrad) is foreseen to improve the LHC luminosity independently of the IR upgrade paths to enhance the luminosity of the LHC by 15% for the nominal and factor of 2-3 for various upgrade scenarios. Crab cavities ensure head-on collisions and recover the geometric luminosity loss from the presence of a finite crossing angle at the interaction point (IP). An R&D program is underway to design and fabricate superconducting RF (SRF) prototype cavity at 800 MHz to test several SRF limits in the deflecting mode. If the prototype is installed in the LHC, it can be used for a first demonstration of crab crossing in hadron beams to understand potential emittance growth mechanisms due to crab cavities.

### INTRODUCTION

The upgrade plans (phase I & II) of the LHC aim to increase the luminosity by a factor of 2-10. The luminosity gain is achieved mainly via an interaction region (IR) upgrade along with an increase of the bunch current. The IR upgrade involves reducing the collision point  $\beta$ -functions from a nominal  $\beta^*$  of 0.55 m to a  $\beta^*$  of 0.25 m or in some extreme cases to a value as small as 0.08 m. Some relevant parameters of the LHC for both nominal and upgrade options are listed in Table .

Regardless of the final choice of magnet technology and optics layout, most schemes will have a finite crossing angle with which the bunches collide at the IP. This crossing angle translates to a geometric luminosity reduction factor which increases steeply with decreasing  $\beta^*$  as

$$\frac{L}{L_0} \approx \left[ 1 + \left( \frac{\sigma_z}{\sigma_x^*} \tan(\theta_c/2) \right)^2 \right]^{1/2}$$

An elegant mitigation using crab cavities, first proposed by Palmer in 1988 for linear colliders, and later extended to circular colliders by Oide and Yokoyama is expected to compensate the geometric luminosity loss due to the finite crossing angle. Crab crossing has been demonstrated at KEK-B ( $e^-/e^+$  storage ring) and is actually operational since April 2007. Fig 1 shows a plot of the luminosity gain as a function of reduced  $\beta^*$  for the LHC with and without crab crossing.

The effect of crab cavities become clearly evident when the curves with crab crossing is compared to the red curve

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resulting from an upgrade without crab crossing. The crossing angle has to be increased in proportion to the reduction of  $\beta^*$  to provide the required beam separation to combat long range beam-beam effects. Therefore, without crab cavities the effective gain in the luminosity is significantly less than the case with crabs as seen in Fig. 1. The finite RF wavelength in the crab cavities gives rise to an associated residual reduction factor which is included in the luminosity calculation. This reduction factor is small for small crossing angles ( $< 1$  mrad) but it may become significant for larger crossing angles at higher frequencies [1]. A large angle crab scheme (8 mrad) proposed in 2006 [1]

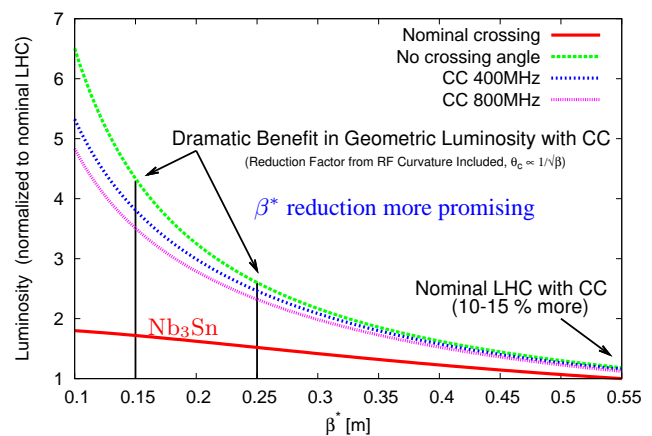


Figure 1: Luminosity scope showing the dramatic benefit of the crab compensation at smaller  $\beta^*$ . Note that the effect of RF curvature of the crab cavities is included.

was deemed risky since the feasibility of the upgrade would solely depend on the crab cavities which have never been tested in hadron machines. Therefore, a small or a moderately increased angle crab scheme is proposed to compensate the existing crossing angle. Two different crab schemes and related technological issues will be discussed in the following sections.

### LOCAL & GLOBAL SCHEME

For the upgrade, two crab schemes are under consideration that address different spatial and technological constraints posed by the LHC lattice. In a local scheme the conventional crab crossing layout is employed where two cavities are placed  $\pi/2$  in phase advance on either side of the interaction point (IP). The first cavity tilts the incoming bunch with finite crossing angle to ensure an effective head-on collision and the second cavity tilts the head and the tail of the bunch back to its original closed orbit leaving the rest of the machine unperturbed. The transverse kick volt-

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

Parameter	Unit	Nominal	Upgrade
Circumference	[km]	27	27
Beam Energy	[TeV]	7	7
Number of Bunches	$n_b$	2808	2808
Protons/Bunch	$[10^{11}]$	1.15	1.7
Average current	[Amps]	0.58	0.86
Bunch Spacing	[ns]	25	25
Norm Emmit: $\epsilon_n$	$[\mu\text{m}]$	3.75	3.75
Bunch Length, $\sigma_z$ (rms)	[cm]	7.55	7.55
IP <sub>1,5</sub> $\beta^*$	[m]	0.55	0.25
Betatron Tunes	-	{64.31, 59.32}	{64.31, 59.32}
Beam-Beam Parameter, $\xi$	per/ip	0.003	0.005
Effective Crossing Angle: $\theta_c$	$[\mu\text{rad}]$	285	445
Piwinski Parameter	$\frac{\theta_c \sigma_z}{(2\sigma^*)}$	0.64	0.75
Main RF Frequency	[MHz]	400.79	400.79
Harmonic Number		35640	35640

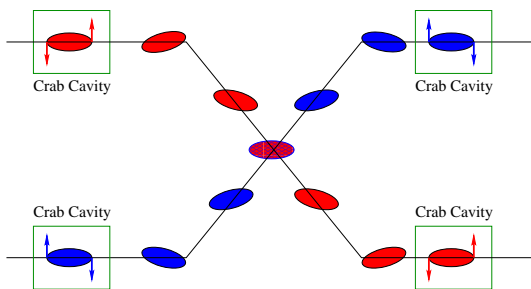


Figure 2: Local crab compensation scheme using transverse deflecting cavities near the IP to provide head-on collisions.

age required is

$$V_{crab} = \frac{cE_0 \tan(\theta_c/2)}{\omega_{RF} \sqrt{\beta_{crab} \beta^*}} \quad (1)$$

where  $E_0$  is the beam energy,  $\omega_{RF}$  is the RF frequency of the cavity,  $\beta_{crab}$  and  $\beta^*$  are the beta-functions at the cavity and the IP respectively. The nominal beam-to-beam line separation is  $< 20$  cm in most of the LHC ring except for the region near IR4 where it is  $\sim 40$  cm [3]. Conventional elliptical cavities with frequencies  $< 1$  GHz may become difficult to accommodate transversely. However, the effect of the finite RF curvature and long bunches prefer lower frequencies. Therefore, a compromise between the physical and RF constraints may require a frequency choice of 800 MHz with some IR beam line modifications unless a new compact design with a frequency of  $< 800$  MHz can be conceived.

An alternate version of the crab compensation where cavities located elsewhere in the ring satisfy certain phase advance conditions to the IP can alleviate some of the space constraints in the local scheme. This concept was successfully commissioned and now in operation at KEK-B [2].

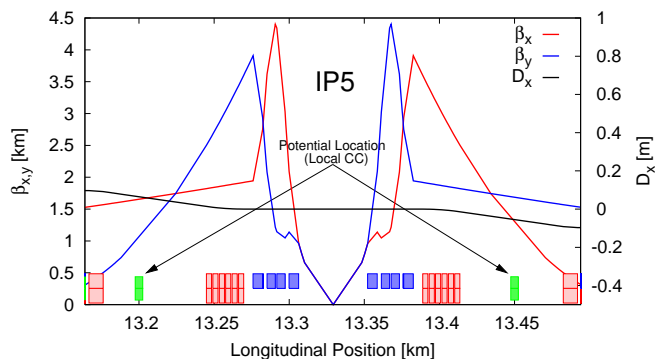


Figure 3: Optics function for the nominal LHC collision in IR5 region and potential locations for local crab cavities. The IR1 will have a similar configuration.

In this scenario, the head and the tail of the bunch oscillate around a reference closed orbit around the ring with an effective head-on collision at the IP. The transverse kick voltage required for one IP with a single cavity in the global case is given by

$$V_{crab} = \frac{2cE_0 \tan(\theta_c/2) \sin(\mu_x/2)}{\omega_{RF} \sqrt{\beta_{crab} \beta^*} \cos(\psi_{cc \rightarrow ip}^x - \mu_x/2)} \quad (2)$$

where  $\psi_{cc \rightarrow ip}^x$  is the phase advance from the cavity to the IP and  $\mu_x$  is the betatron tune. For  $n$  IP's with  $m$  cavities, a system of linear equations can be solved to derive the respective voltages for the cavities, using an obvious generalization of Eq. 2.

It should be noted that constraints from dynamic aperture and collimation limit this scheme to small crossing angles ( $< 1$  mrad) because of the additional z-dependent closed orbit introduced by the oscillating bunch [1].

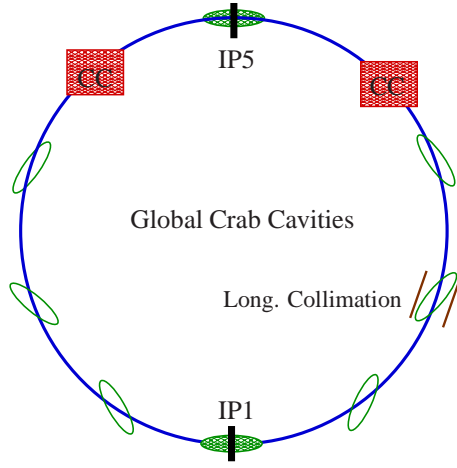


Figure 4: Schematic of a possible global crab crossing scheme to have head-on collisions at IP1 and IP5.

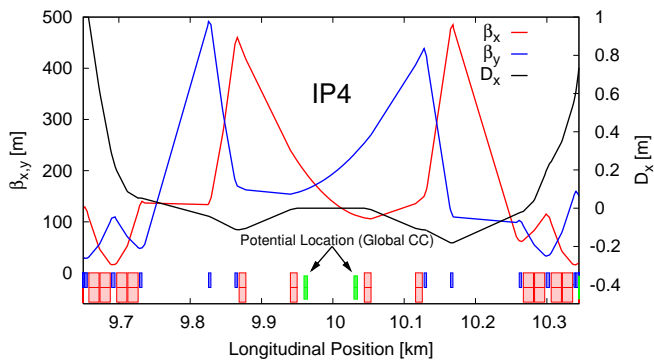


Figure 5: Optics function for the nominal LHC at 7 TeV and potential locations for a global crab cavity in the IR4 region.

## CAVITY DESIGN

An LHC baseline design with superconducting RF elliptical cavities conceptually similar to KEK-B design is considered. In the view of the bunch length and RF curvature lower frequencies are more desirable. However, the cavity dimensions and space constraints prefer a higher frequency. An initial crab crossing proposal with large crossing angle (8 mrad) lead to a development of a 400 MHz design [1]. For small crossing angles ( $\sim 0.5$  mrad) which is the current baseline, an 800 MHz cavity appears to be a good compromise. The corresponding geometric luminosity reduction is as seen in Fig ???. A coupled two-cell cavity is being considered as a fundamental unit in the  $\pi$  mode to impart a total kick of  $\sim 2.5$ - $3.0$  MV per module ( $\sim 2.5$ - $3.0$  MV/m including cryostat). For reference, the KEK-B cavities achieved a field gradient of approximately 2 MV/m or a bit higher, limited mainly by multipacting and/or field emission near the iris region consisting of co-axial coupler [4]. A schematic of the original semi-optimized two-cell LHC cavity at 400 MHz and a scaled 800 MHz prototype is shown in Fig. 6. The relevant geometrical param-

eters of the cavity structure are listed in Table 2.

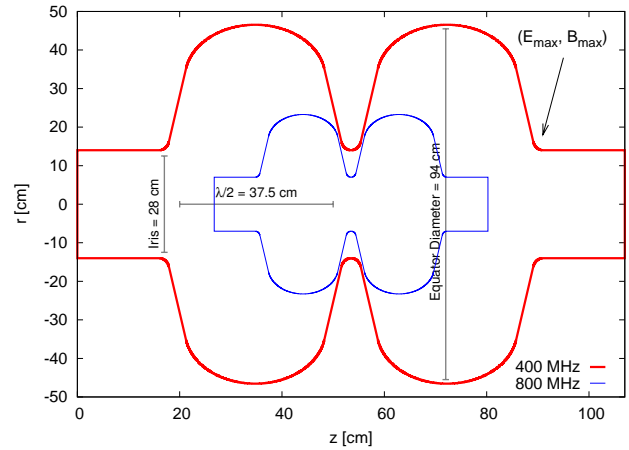


Figure 6: Graphic of the proposed two-cell 400 MHz cavity and a scaled 800 MHz cavity.

Table 2: Cavity geometrical parameters for inner and outer  $\frac{1}{2}$  cells for 400 MHz. The 800 MHz cavity is a scaled model with same geometrical ratios.

Parameter	Crab Cavity	
	Middle Cell	End Cell
Frequency [MHz]	400	400
Iris Radius, $R_{iris}$ [cm]	14	14
Wall Angle, $\alpha$ [deg]	10	10
Equatorial Ellipse, $R = \frac{B}{A}$	1.0	1.0
Iris Ellipse, $r = \frac{b}{a}$	1.5	1.5
Cav. wall to iris plane, $d$ [cm]	1.5	1.5
$\frac{1}{2}$ Cell Length, $L = \frac{\lambda\beta}{4}$ [cm]	18.75	18.75
Equator Height, $D$ [cm]	50	50
Cavity Beta, $\beta = v/c$	1.0	1.0

An extensive scan of the cavity geometric parameters was performed to obtain the optimum RF characteristics for the inner and outer half-cell of the two-cell cavity. The relevant RF parameters for the superconducting cavities are plotted as a function of the respective geometrical parameters in Fig. 7.

For crab cavities, the ratio of the peak surface fields to total kick voltage is much larger than a typical accelerating cavity. It must be noted that the tabulated geometrical values are not final. As a first step the same geometrical parameters are chosen for both middle and end cells. The final optimization will be based on higher order mode (HOM) damping, peak field specifications, and mechanical constraints. For example, the maximum achievable kick voltage for the two cell cavity will be limited by the peak surface magnetic field. An increase in wall angle ( $\alpha$ ), iris ellipse ratio ( $r$ ), and cavity wall distance to the iris plane ( $d$ ) can significantly reduce the magnetic field without compromising the other RF parameters. If a further decrease

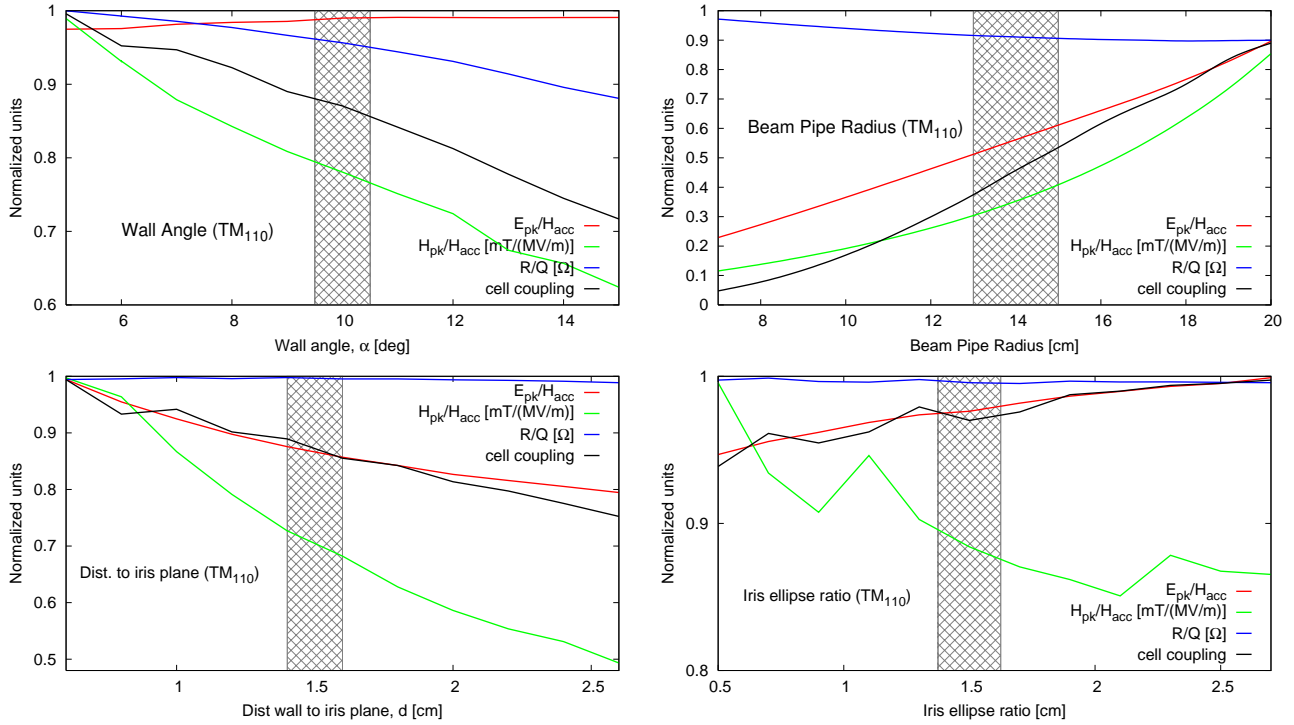


Figure 7: Cavity geometrical parameters as a function of relevant RF parameters leading to an input for optimization of the  $\frac{1}{2}$  cell geometry.

in peak fields is needed, a reduction in the beam pipe is necessary. However, this might lead to the trapping some HOMs. A fine tuning of the cavity shape may increase the kick gradient providing for margins for optics as well as longitudinal space requirements.

Based on the semi-optimal choice of geometrical parameters listed in Table 2, some relevant RF characteristics of the final two-cell cavity design are listed below:

- Peak Fields ( $B_{kick}$ : 2.5 MV, 400-800 MHz):
  - $E_{peak} \sim 18-30$  MV/m. The highest surface fields so far have been demonstrated in TESLA cavities which reached 70-90 MV/m. The limitation is believed to be due to field emission.
  - $B_{peak} \sim 93-125$  mT. The highest surface fields have again been demonstrated in TESLA cavities which have reached upto 150-190 mT. The theoretical limit in type II superconductors like Nb is approximately 220mT which is caused due to breaking of cooper pairs.
  - The ratio  $B_{peak}/B_{kick} \approx 12$  is large compared to typical accelerating cavities with a ratio of 4-5. Modifications to the cavity geometry suggested above can be used to reduce the peak magnetic field.

- The transverse shunt impedance is given by

$$\frac{R_{\perp}}{Q_0} = \frac{1}{(kr)^2 \omega U} \int_0^L E_z(r=r_0) e^{ikz} dz \quad (3)$$

$$\approx 120 \Omega \{800\text{MHz}, 2\text{Cells}\} \quad (4)$$

- An orbit offset of the crab cavity can result in beam loading which is given by

$$V_b \approx Q_L I_b \frac{R_{\perp}}{Q} (\delta x) \quad (5)$$

$$\approx 0.1 \frac{MV}{mm} \{Q_L = 10^6, I_b = 0.85A\} \quad (6)$$

Local orbit correctors around the cavity can be envisioned to control the beam orbit at the sub-millimeter level. The input and HOM power from the cavity naturally provide a feedback signal to precisely center the beam in the magnetic center of the cavity.

- A Power of 2-20 kW may be required ( $Q_L = [10^5 - 10^6]$ ) for beam loading, cavity conditioning, microphonics, Lorentz force detuning and other mechanical effects. Sources at these power levels for 800 MHz frequency are commercially available in the form of inductive output tubes (IOTs).

Since the mode of choice is a dipole mode, the parasitic mode with the orthogonal polarization needs to be well separated in frequency and damped to avoid creating a spurious crossing angle in the other transverse plane. A mode

separation of about 50 MHz for the 400 MHz design and of a similar magnitude for the 800 MHz can be achieved by squashing the cavity transversely by design to a ratio of 0.75 [1]. The beam harmonics are separated by 40 MHz (bunch spacing 25ns). Therefore, there is sufficient frequency space to adequately separate the orthogonal mode and avoid overlap with beam harmonics.

### COUPLERS & TUNERS

A combination of couplers and beam pipe ferrites need to be employed to both supply the input power for the mode of operation and to extract lower order (LOM) and higher order modes (HOMs). Some possible options for the required couplers are:

- A co-axial coupler will be used to provide the input power for the deflecting operating mode. Dual couplers and contoured co-axial tips as shown in Fig. 8 can be used to minimize the coupler kicks and wake-field effects.

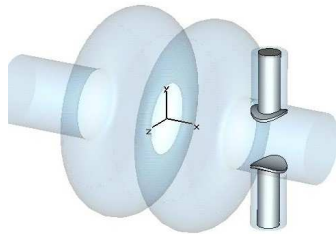


Figure 8: Dual coaxial couplers with optimized pringle shaped tips to reduce the effect of short range wakes and transverse coupler kicks.

- A beam Pipe co-axial line as depicted in Fig. 9 can be used to extract both the LOM and HOMs similar to the KEK-B damping scheme. A choke rejection filter can be tuned for the operating mode and all the other modes can be transmitted to a room temperature ferrite absorber. Damping of most modes to  $Q_{ext} \sim 10^2$  has been demonstrated at KEK-B with such a scheme. However, the assembly of this coupler is fragile and poses significant technical challenges in addition to leading to potential multipacting near the high field region.
- A waveguide coupler can be substituted for the beam pipe coax (see Fig. ??) but the damping is limited to  $Q_{ext} \sim 10^3$  [5]. This setup is structurally robust and longitudinally compact, but it has yet to be determined if the damping provided by the waveguides is sufficient for high current operation in the LHC.
- New concepts (for example: radial beam-pipe coax) may need to be developed to provide the equivalent damping of the beam-pipe coaxial line while having the virtue of being compact and more robust like

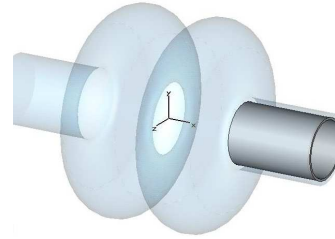


Figure 9: Beam pipe coax with a choke rejection filter to reject the kick mode ( $TM_{110}$ ) and to couple to all other modes strongly.

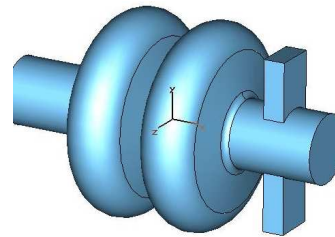


Figure 10: Waveguide couplers to extract LOM & HOM modes from the cavity.

waveguides. Simulations are underway to test the effectiveness of radial type couplers.

- TESLA type loop couplers can be used but perhaps limited by their inability of handing CW power. The cavity design along with the beam-pipe will be optimized to effectively propagate most HOMs through the beam pipe to a room temperature ferrite which can handle power levels of 10-20 kW.

Tuning of the operating mode, the LOM and the relevant HOMs may become necessary to minimize input power and to avoid the overlap of harmful resonances with beam harmonics. The two available tuning mechanism are:

- A beam-pipe coaxial coupler can also be used for tuning. This system is used in the KEK-B cavities where it has proven to be effective and simple during operation. This system also allows a large tuning range due the direct coupling to electro-magnetic fields.
- Conventional tuners (for example: mechanical push-pull) have been demonstrated extensively on accelerating cavities. In addition, the presence of both peak magnetic and electric fields at the iris of the cavity can be exploited by “iris based tuners” which deform only the irises of the cavity. The latter may provide a more efficient and larger tuning range compared to conventional cavity body tuners.

### PHASE NOISE & EMITTANCE GROWTH

Several sources of emittance growth due to imperfections of crab compensation have been identified. The effect

of amplitude (or voltage) jitter is negligible and can be easily compensated with available low-level RF technology as shown in Table . However, phase jitter from the RF sources is of major concern. A phase error in the RF wave causes an offset of the bunch rotation axis translating into a transverse offset at the IP as shown in Fig. 11. The offset at the IP is given by

$$\Delta x_{IP} = \frac{c\theta_c}{\omega_{RF}} \delta\phi \quad (7)$$

where  $\theta_c$  is the full crossing angle and  $\delta\phi$  is the phase error.

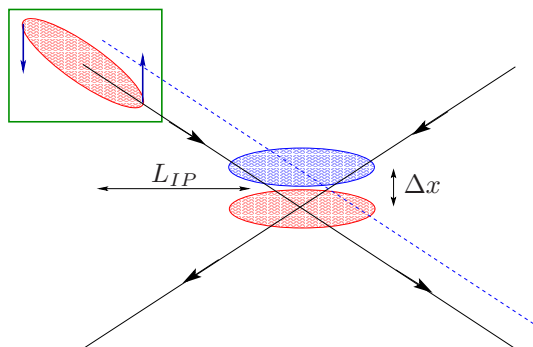


Figure 11: RF phase jitter of the crab compensation results in a transverse offset of the bunch at the IP.

This random offset at the IP is potentially severe due to beam-beam effects. In addition the phase jitter can lead to random dipole kicks on the beam which is expected to result in an even more severe emittance growth than the random IP offsets. For nominal LHC upgrade parameters, and for a maximum emittance growth of 1%/hr and a feedback gain of approximately 0.2, Table shows a list of tolerances derived from analytical estimates [1, 6, 7] using random uncorrelated phase noise (white noise) and some corresponding strong-strong simulations results which represent the most pessimistic scenario. Tolerances feasible by today's technology are also listed.

However, measurements of the phase jitter from the KEK-B crab cavities show that the noise modulation is not "white" but has a frequency spectrum as shown in Fig. 12 (courtesy K. Akai). Sidebands of -65 db below the main RF signal (509 MHz) are visible in a 200 Hz span (32Hz, 37Hz, 46Hz, 50Hz, 100Hz) and sidebands of almost -80db down are visible in a 200 kHz span (32 kHz, 64kHz). A wider span of 3MHz show no visible sidebands above the noise level.

Simulations were performed including beam-beam offset (weak-strong) with frequency dependent noise like the ones in Fig. 12. Fig. 13 shows the emittance growth as a function of the amplitude for three different sine like effects similar to the ones observed in the KEK cavities. A quadratic fit to the 32 KHz (one of the fastest frequencies observed in KEK-B) line suggests a maximum tolerance of  $\sigma_{noise} \approx 6 \times 10^{-12}$  m corresponding to an emittance growth of 1% per hour. The measured amplitude of -80db

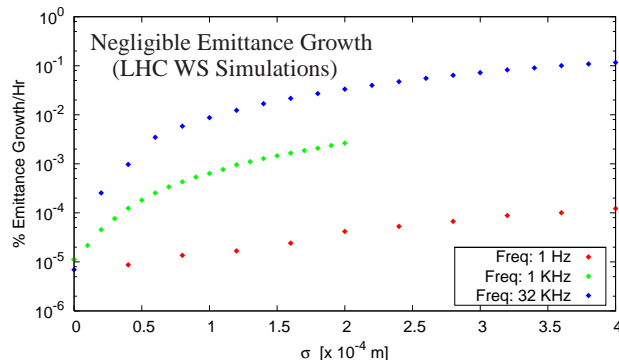


Figure 13: Simulated emittance growth for a beam-beam offset at two IPs modulation at different frequencies (1 Hz, 1KHz, and 32 KHz) at the IP ( $\beta^* = 0.25m$ ) as a function of the modulation amplitude.

translates to an IP offset of  $6 \times 10^{-13}$  m which is an order of magnitude smaller than the maximum tolerance for 1% emittance growth per hour. Also, preliminary simulations in Ref. [8] suggests that the tolerances can be relaxed linearly with the correlation time of the noise source. Since the slow noise sources are the dominant ones, the phase tolerance should be much less stringent than the naive estimates based on white noise. In addition a transverse feedback alleviates some of the tightest requirements.

## OPTICS & RF TOLERANCES

Orbit and lattice errors such as linear imperfections, non-linear imperfections, and coupling can impact the effectiveness of the crab crossing scheme.

- An additional z-dependent horizontal orbit and beta-beating can impact the efficiency of the collimation system and reduce the available aperture. However, the bunch oscillation around the closed orbit can provide an extra degree of freedom to collimate in the longitudinal plane as depicted in Fig. . Tracking studies are underway to determine the additional losses and produce loss maps in order to address the pertinent collimation issues.
- Error in optics functions ( $\beta_{crab}$  &  $\Delta\phi_{cc \rightarrow ip}$ ) are analogous to a voltage error ( $\Delta V_{crab}$ ) which results in residual crossing angle. For example, a betatron phase error ( $\Delta\phi_{err} \sim 0.25^\circ$ ) results in residual angle ( $\theta_{res} < 1 \mu\text{rad}$ ) which is negligible. The  $\Delta\phi_{cc \rightarrow ip}$  and/or voltage can be optimized with luminosity & lifetime measurements. An intentional voltage variation can be used for luminosity leveling via the crossing angle. A local  $\beta$ -function modification at cavity location is envisioned to provide an extra degree of freedom and some margin for cavity voltage.
- Betatron coupling in the lattice introduces a vertical crossing angle and offset at the IP. A preliminary estimate using a random tilt error of approximately 1

Table 3: For 1% Emittance Growth/Hr, gain=0.2 (Random turn-to-turn)

Jitter Estimate	Amp.	Phase	
		Beam-Beam	Dip. Kicks
Analytical Simulation (WS)	~ 0.04%	0.01° (0.006°)	0.006° (0.003°)
		0.002°	-
Simulation (SS, K. Ohmi)		< 0.001°	
Feasible Today	0.01%	0.003°	

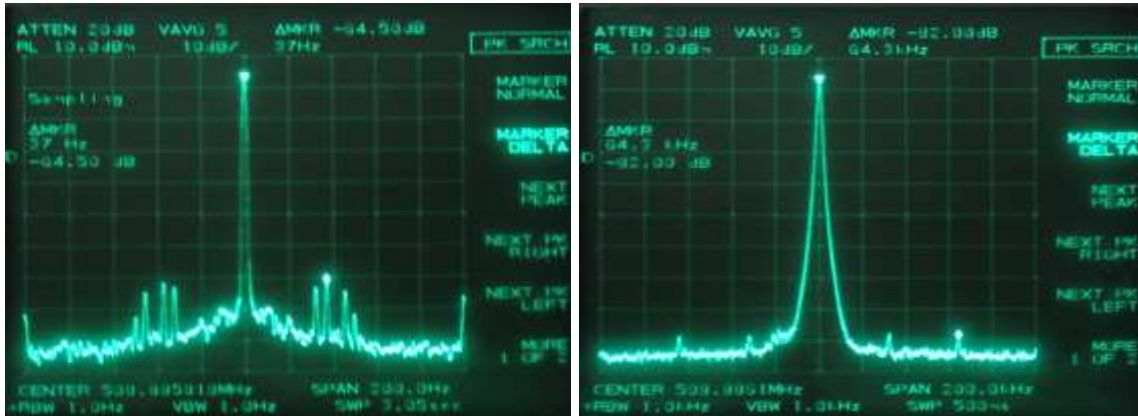


Figure 12: Spectrum of the KEK-B crab cavities during operation with a. frequency span of 200 Hz (left) and 200 kHz (right). The main frequency line is modulated by the side-bands which are approximately -60 dB and -80 dB below the main line (Courtesy KEK crab cavity group).

mrad in the quadrupoles, resulting in a  $\Delta Q_{min} = 1.5 \times 10^{-3}$ , introduces a vertical crossing angle of approximately  $6 \mu\text{rad}$  which is negligible. Tracking studies are underway to determine the tolerances on coupling errors for operating at the nominal working point.

In addition the effects of synchro-betatron resonance, finite energy spread and chromaticity in the presence of beam-beam effects require extensive simulations which are also underway.

## R&D OF CAVITY AND COMPONENTS

An international collaboration is being organized to establish a crab cavity team which will address the various beam dynamics and technical challenges associated with the development of the LHC crab cavities. As a first step towards this R&D, a prototype cavity at 800 MHz is being proposed in order to test several SRF limits with deflecting mode superconducting cavities like:

- $Q_0$  slope, Max kick gradient ( $B_{kick}$ ), Multipacting
- RF stability and Tuning
- LOM/HOMs damping to specifications

In addition the prototype will allow a first test of crab crossing with hadron beams and an investigation of the effects of RF curvature, phase noise and other relevant studies.

A preliminary R&D chart outlines the various tasks related to the development of the prototype and the subsequent path towards crab structures for the LHC upgrade is shown in Fig. 14.

## CONCLUSION

Extensive studies underway to investigate a small angle crab compensation (0.5 mrad) for the LHC upgrade. It foreseen to improve the LHC luminosity nominal LHC upto 15% and factor of 2-3 for the upgrade scenarios. Two different crab compensation schemes have been described in details along with the challenges associated with the integration of the cavities into the LHC. A preliminary cavity design and corresponding RF characteristics are presented. A prototype R&D program to design and fabricate superconducting RF cavities at 800 MHz both is seen as the first step of the R&D program which will subsequently lead to the crab compensation at the LHC.

## ACKNOWLEDGMENTS

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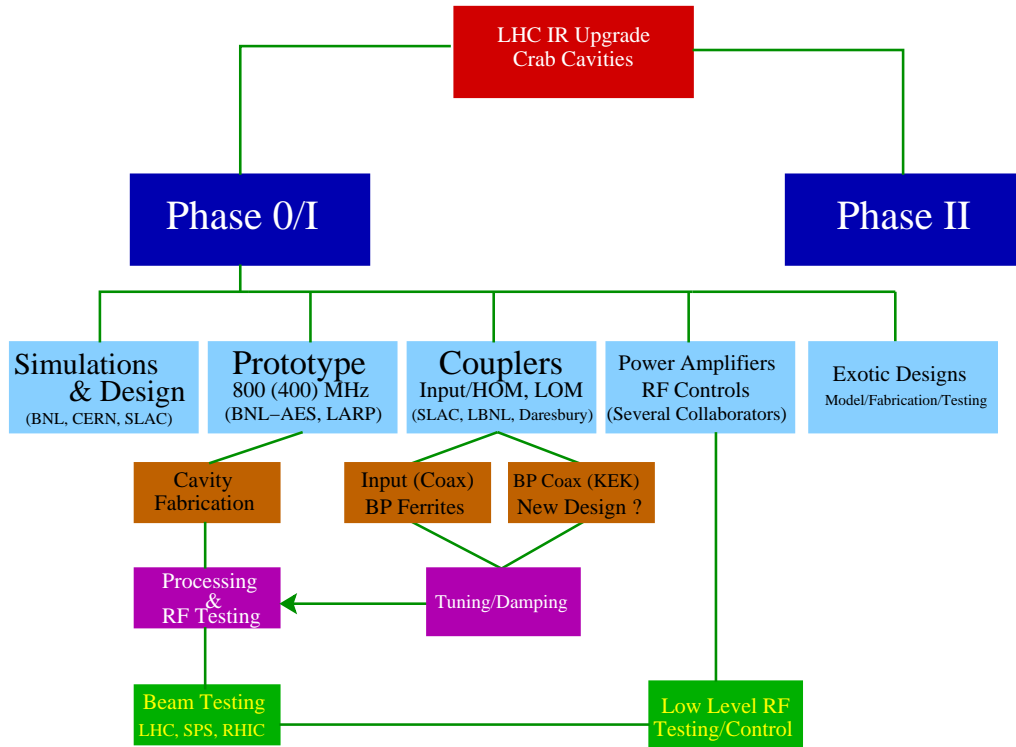


Figure 14: R&D chart for the LHC crab cavity prototype development and fabrication.

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