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ScienceDirect
Nuclear and Particle Physics Proceedings 273–275 (2016) 193–197
www.elsevier.com/locate/nppp

# Crab cavities for colliders: past, present and future

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## Abstract

The numerous parasitic encounters near interaction points of some particle colliders can be mitigated by introducing a crossing angle between beams. However, the crossing angle lowers the luminosity due to reduced geometric overlap of the bunches. Crab cavities allow restoring head-on collisions at the interaction point, thus increasing the geometric luminosity. Crab cavities also offer a mechanism for luminosity leveling. KEKB was the first facility to implement the crab crossing technique in 2007, for the interaction of electron and positron beams. The High Luminosity Large Hadron Collider (HL-LHC) project envisages the use of crab cavities for increasing and leveling the luminosity of proton-proton collisions in LHC. And crab cavities have been proposed and studied for future colliders like CLIC, ILC and eRHIC. This paper will review the past, present and future of crab cavities for particle colliders.

*Keywords:*
Crab cavity, crab crossing, head-on collision, particle collider, luminosity upgrade, luminosity leveling

## 1. Introduction - first ideas

A crossing angle is sometimes introduced between beams at the interaction point of colliders in order to mitigate parasitic collisions and/or get rid of the spent beam and debris from the collision. The crossing angle however reduces the peak luminosity of the collisions because it reduces the geometric overlap of colliding bunches as shown in Fig. 1.

In 1988 R. B. Palmer proposed the crab crossing scheme for an electron-positron linear collider [1], but actually it applies to any kind of collider. The scheme allows large crossing angles without loss in luminosity as it reestablishes head-on collisions. Fig. 2 illustrates the crab crossing scheme.

A crab cavity is a deflecting cavity operated such that the phase is zero when the bunch is at the cavity center. The center of the bunch will receive a null kick whereas its head and tail will receive opposite kicks. The bunch will wiggle along its path due to the crabbing kick. The phase advance between the crab cavity and the IP location must be 90 degrees so that the momentum kick provided by the crab cavity fully transforms into a rotation of the bunch in the IP. The bunch can be uncrabbed by another set of crab cavities after the IP (local scheme) or can wiggle all around the accelerator (global scheme).

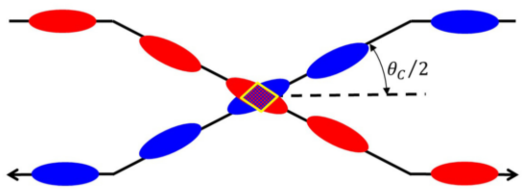


Figure 1: Collision scheme with crossing angle.

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http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.025

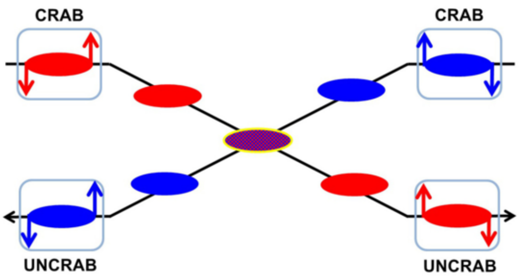


Figure 2: Crab crossing scheme: full bunch overlapping for maximal geometric factor.

## 2. First implementation of crab crossing technique

The B-factory KEKB was the first collider in implementing the crab crossing scheme in 2007. Beam-beam studies had predicted that head-on collisions would increase the beam-beam tune shift from 0.055 to about 0.15 leading to higher luminosity gain than just the geometric luminosity gain [2].

KEKB was a 8 GeV electron and 3.5 GeV positron circular collider with a single IP. A global crab crossing scheme was implemented to reduce costs of cavities and cryogenics. There was only one crab cavity per ring. The required deflecting voltage per cavity was 1.4 MV at 500 MHz to compensate for a horizontal crossing angle of 22 mrad.

The KEKB crab cavities were single cell structures working at 4.5 K and operating in the $TM_{110}$ mode at 509 MHz. The cavity had a coaxial coupler to extract the $TM_{010}$ (fundamental) mode and large beam pipes for the HOMs. The cell had a squashed shape to select the polarization mode [3].

The cavities successfully crabbed the KEKB bunches of high intensity beams to provide head-on collisions and maximize the geometric luminosity gain. The measured vertical beam-beam tune shift, 0.088, was however below the predicted value from simulations and the luminosity gain from beam-beam tune shift was therefore below the expected value [4, 5].

KEKB operation terminated in June 2010 for the upgrade towards SuperKEKB. The maximum peak luminosity reached with the crab crossing scheme was $21.1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Up to date, KEKB has been the only facility were the crab crossing scheme has ever been implemented.

## 3. Crab cavities for the luminosity upgrade of LHC

LHC will reach a luminosity of $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, twice the nominal peak luminosity, with 14 TeV energy collisions by 2023 (expected integrated luminosity of 300 $\mathrm{fb}^{-1}$). The High Luminosity LHC project, or HL-LHC, aims at increasing the integrated luminosity of LHC by one order of magnitude by 2035.

The HL-LHC will require to install new magnets and collimators, update vacuum, cryogenics and machine protection systems, upgrade injectors, implement new beam optics and crossing schemes, among other actions [6]. As part of these upgrades, $\beta^*$ will be reduced from 0.55 to 0.15 m in order to increase the luminosity of LHC. As the two beams of LHC share the same vacuum pipe along a 120 meter-long section of each IP, a smaller beta function value at the IP will result in larger Long-Range Beam-Beam (LRBB) effects. The crossing angle will be almost doubled from 290 to 590 mrad in order to reduce these LRBB effects [7].

Crab cavities thus become instrumental to fully benefit from the $\beta^*$ reduction, as crab crossing can reestablish head-on collisions and so increase the peak luminosity. The expected improvement in peak luminosity by operating LHC with a 400 MHz crab cavity system is, when $\beta^*$ is 0.15 m, about 70%. Fig. 3 shows the luminosity dependence on $\beta^*$ for the scenarios with normal crossing, no crossing angle and with crab cavities.

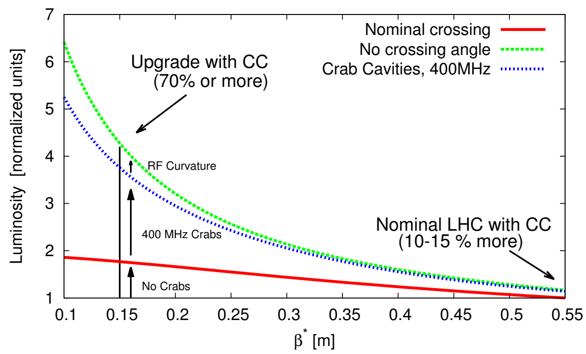


Figure 3: Luminosity dependence on $\beta^*$ for different scenarios.

Crab cavities also provide mechanisms for luminosity leveling. The crossing angle can be varied from a large value to head-on configuration as the particles burn off during collisions. Alternatively, crab cavities allow the implementation of the recently proposed crab kissing technique in which the two bunches collide over their longitudinal plane. This technique does not only allow for luminosity leveling but also pile-up density reduction [8].

The HL-LHC upgrade envisages the implementation of crab crossing at the IPs of both ATLAS and CMS (respectively, IP1 and IP5) following a local scheme configuration. Bunches from the two colliding beams will be crabbed before and uncrabbed after each IP. The local scheme requires twice the number of cavities than the global scheme but is preferred to avoid the severe phase advance constraints between IPs required by the global scheme.

The LHC crab cavity program consists in four main stages. The first stage initiated in 2003 and was dedicated to the conceptual design, feasibility study and development of the LHC crab crossing scheme.

The cavities will be SRF CW single-cell cavities operated at 2 K. The deflecting mode frequency is chosen to be 400 MHz as a compromise between compactness and reduced head-tail effect on the bunches. In the KEKB case, bunches were 5.8 mm long for the positron beam and 6.4 mm long for the electron beam, with the half-wavelength of the KEKB crab cavity deflecting mode being more than 46 times the bunch length of the KEKB beam. The half-wavelength of the LHC crab cavity deflecting mode will be only 5 times larger than the nominal LHC bunch length of 75 mm.

A total deflecting voltage of 12 MV must be provided at 400 MHz for full head-on collision. The present layout foresees that the delivery of total deflecting voltage is shared by 4 identical cavities.

The distance between the two beam pipes of LHC constrains the maximum width and height of the crab cavities to be 194 mm at room temperature for horizontal (CMS) and vertical (ATLAS) kick configuration, respectively. The cavities will be installed between D2 and Q4 at both sides of the IP1 and IP5. There are only 10 meters available at each crabbing site to fit in 8 cavities (4 per beam) with their helium vessels and cryostats. Design studies focused their efforts in providing very compact cavities that will satisfy the above mentioned space constraints in LHC [9].

Three compact designs were selected: the RF dipole cavity designed by ODU-SLAC [10], the Double Quarter Wave (DQW) cavity designed by BNL [11] and the 4-rod cavity designed by Lancaster University [12]. Fig. 4 illustrates how compact the LHC crab cavities are by comparing the KEKB crab cavity with the DQW cavity.

The high bunch intensity of LHC requires a strong damping of HOMs. Dedicated HOM filters are being developed for the LHC crab cavities to mitigate the appearance of instabilities.

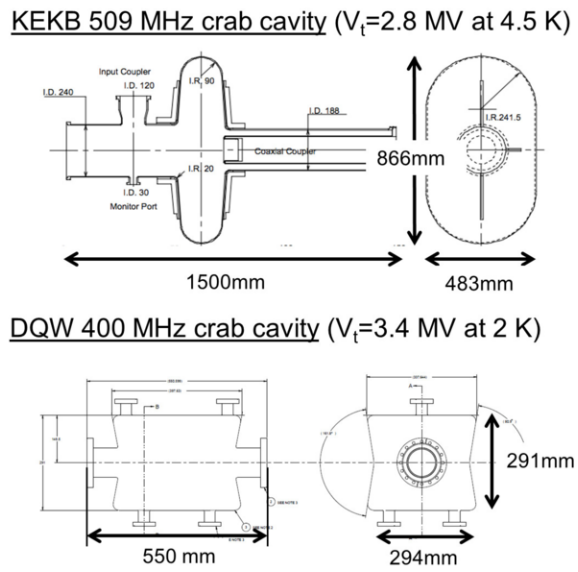


Figure 4: KEKB and DQW crab cavities for dimensional comparison.

The second stage comprised the design finalization, construction and cryogenic tests of one Proof-of-Principle (PoP) cavity for each of the three designs. All of them went through successful cryogenic tests reaching the nominal deflecting voltage of 3.4 MV, and exceeding it in the case of the RF dipole and the DQW cavities [11, 13]. Larger deflecting voltages than the nominal might be required to implement the crab kissing technique. Fig. 5 shows the three PoP cavities.

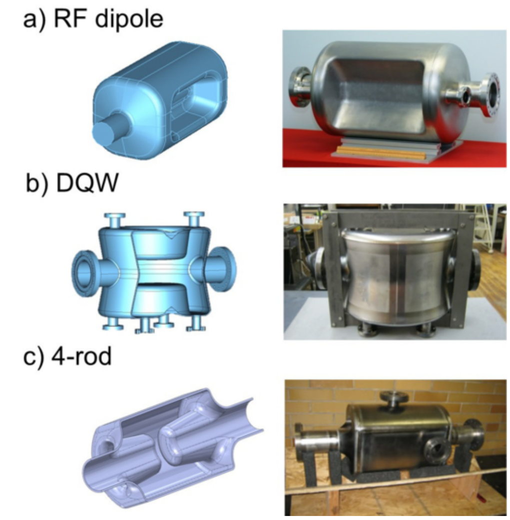


Figure 5: The three PoP cavities for cryogenic testing: a) RF dipole, b) DQW and c) 4-rod.

The third stage started in 2014 and is devoted to the design and manufacturing of prototype cavities and cryomodules for a validation test with beam in SPS by 2016-2017. It will be the first time that crab cavities are exposed to hadron beams. In this stage one cryomodule with two DQW cavities and another one with two RF dipole cavities will be tested. The test has the main scope of validating the cavity operation with beam: deflecting voltage, cryogenic performances, tuning system, HOM damping and impedances, effective bunch crabbing, performance limits, emittance growth and non-linearities of the cavity field.

LLRF controls are crucial for successful crab crossing. The phase synchronization between the crab cavities of the two colliding beams is important to avoid introducing any transverse offset and thus guarantee full head-on collision. Phase synchronization between the cavities at both sides of the IP is also important to crab and fully uncrab the bunches, in order to avoid the propagation of instabilities in the accelerator. The cavities at one side of the IP will be distributed along a non-uniform beta region, which may have implications for control and operation of the cavities. The control system will also need to deal with quench detection and response. Cavities must be able to become transparent to the LHC beam during injection, ramp and squeeze. The SPS tests will then need to validate the RF control systems for the crab-uncrab operation, quench detection and response. Machine protection mechanisms will also be evaluated. Important information can be extracted to prepare for different cavity failure scenarios and define instrumentation and interlocks for operation in LHC. Cavity transparency during injection, ramp and squeeze must also be proved.

The fourth stage extends from 2017 until 2023 and envisages the preparation of cavities and cryomodules for LHC, installation and commissioning. The baseline layout foresees two-cavity cryomodules to ease maintenance and reduce complications during operation. So a minimum of 32 cavities and their corresponding 16 cryomodules should be prepared. An alternative layout would consist of an eight-cavity cryomodule per side per IP for reduced warm-to-cold transitions.

## 4. Future of crab cavity technology

### *4.1. Future linear colliders: CLIC and ILC*

The two proposed future linear colliders, CLIC and ILC, will require crab cavities at the end of the linacs that reestablish head-on collisions for maximal peak luminosity. The crab cavities for both machines share common challenges related to synchronization and vertical wakefield kicks.

CLIC beams will collide in a single collision point with a 20 mrad crossing angle. Crab crossing will increase the luminosity to 95% of the head-on case.

The CLIC crab cavities will be located prior to the Final Doublet (FD) and at a distance of 90° phase advance from the IP. The cavities are normal conducting multi-cell traveling wave structures operating at 11.994 GHz. The deflecting voltage required at this frequency is 2.55 MV. Control of voltage phase and amplitude will have a major impact on luminosity. The phase must be controlled within 0.02 degrees (4.6 fs for 11.994 GHz cavities) for a luminosity loss of 2%. Higher order modes must be effectively damped to reduce impact of vertical wake filed kicks [14].

A CLIC crab cavity prototype is currently under preparation for being high-gradient tested soon in the XBox2 facility at CERN.

ILC will have a single collision point with a 14 mrad crossing angle in the horizontal plane [15].

Two 3.9 GHz superconducting 9-cell cavities will be located at 13.4 m from the IP. The cavities will deliver a 5 MV/m deflecting kick, enough to reestablish head-on collisions for 500 GeV beam. Phase jitter between cavities for positron and electron beams must be tightly controlled to ensure maximal bunch overlapping. A feasibility test of a 7-cell 1.5 GHz cavity conducted at JLab ERL showed that it is possible to maintain the phase jitter within 37 fs. Strong damping of higher and lower order modes as well as vertical polarization of same order mode are required to limit vertical deflection in the IP.

### *4.2. eRHIC*

The future electron-Relativistic Heavy Ion Collider (eRHIC) will have a crossing angle of 10 mrad in the horizontal plane. Crab cavities will be needed to reach a luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for collisions of 21.2 GeV electron beam and 250 GeV polarized proton beam [16]. The collider will have 2 IPs where crab crossing will be performed following the local crossing scheme.

Based on the DQW design, one crab cavity of about 676 MHz will be enough to provide 1.9 MV deflecting voltage required to tilt the bunches of the 21.2 GeV electron beam. The rms bunch length is 50 mm for 250 GeV proton beams [16], so several harmonic cavities will be needed to correct the non-linear kick.

One 676 MHz cavity will provide a deflecting voltage of 0.76 MV, two 450 MHz cavities will provide 2.79 MV each and four 225 MHz cavities will provide 6.19 MV each.

## 5. Overview

Crab cavities open the possibility to increase luminosity in colliders with finite crossing angle as well as they offer mechanisms for luminosity leveling and pile up density reduction.

The phase control of crab cavities and the appropriate damping of modes other than the deflecting one become the most important technical issues to guarantee a successful crab crossing. LHC crab cavities show additional challenges for fabrication and cleaning due to their complex geometries that at last may impact the cavity performances.

The development of compact crab cavities for LHC has given birth to a variety of cavities that might be of interest for other applications. Crab cavities can be used as deflecting cavities when operated at a different phase. In this context, an RF dipole cavity - similar to the RF dipole cavity for HL-LHC - has been recently proposed as alternative to the kicker currently under construction for the beam switching system of LCLS-II [17, 18].

## Acknowledgements

Work partly supported by the EU FP7 HiLumi LHC grant agreement No. 284404 and by the US DOE through Brookhaven Science Associates, LLC under contract No. DE-AC02-98CH10886 with the US LHC Accelerator Research Program (LARP).

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