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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).

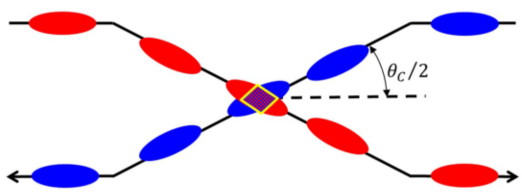

Figure 1: Collision scheme with crossing angle.

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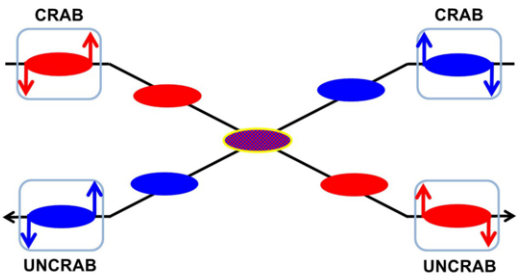

Figure 2: Crab crossing scheme: full bunch overlapping for maximal geometric factor.

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 $21.1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. 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 $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, twice the nominal peak luminosity, with 14 TeV energy collisions by 2023 (expected integrated luminosity of 300 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, β^* 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 β^* 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 β^* is 0.15 m, about 70%. Fig. 3 shows the luminosity dependence on β^* for the scenarios with normal crossing, no crossing angle and with crab cavities.

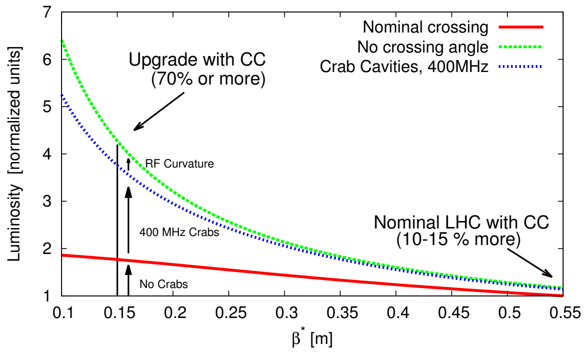

Figure 3: Luminosity dependence on β^* for different scenarios.

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].

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