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CRAB CAVITIES: PAST, PRESENT, AND FUTURE OF A CHALLENGING DEVICE*

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Abstract

In two-ring facilities operating with a crossing-angle collision scheme, luminosity can be limited due to an incomplete overlapping of the colliding bunches. Crab cavities then are introduced to restore head-on collisions by providing the destined opposite deflection to the head and tail of the bunch. An increase in luminosity was demonstrated at KEKB with global crab- crossing, while the Large Hardron Collider (LHC) at CERN currently is designing local crab crossing for the Hi-Lumi upgrade. Future colliders may investigate both approaches. In this paper, we review the challenges in the technology, and the implementation of crab cavities, while discussing experience in earlier colliders, ongoing R&D, and proposed implementations for future facilities, such as HiLumi-LHC, CERN's compact linear collider (CLIC), the international linear collider (ILC), and the electron-ion collider under design at BNL (eRHIC).

INTRODUCTION

Adopting head-on collision scheme is a straight-forward option for providing the highest possible luminosity at a given beam intensity. However, the particles and the debris from collisions travel towards the next bunch in the opposing beam after the interaction point (IP) [1]. To avoid long-range beam-beam collisions and possible damage to the instrumentation and detectors, it is necessary to separate bunches from their original travel orbit over a very short time. Depending on the bunch repetition rate, the substantial separation requirement could be within nano seconds, which is challenging for the designing the interaction region.

A crossing angle is introduced into colliders to avoid such drawbacks of the head-on collision; however, it also decreases luminosity due to reducing the geometric overlap of the colliding bunches. As shown in Figure 1, θ_c is defined as the full crossing angle.

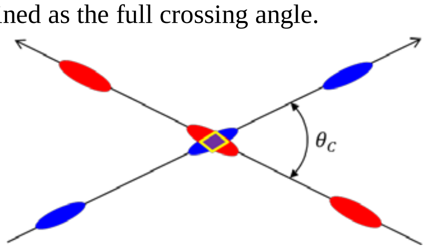

Figure 1: Beam collisions with crossing angle.

In 1988, Robert Palmer introduced the concept of crab cavity as a countermeasure to the geometric reduction in luminosity caused by the crossing angle in colliders [2]. The crab cavity imparts a transverse momentum kick, proportional to the longitudinal position of the particle. Transverse oscillation translates the longitudinally dependent kick to a transverse offset at IP. The offsets of the two beams cancel the reduction in luminosity caused by the crossing angle, and restore the head-on collision. Figure 2 illustrates the beam collision with the crab cavities [3]. The offset of the particles, x_{IP}, at the IP is a function of β_x at the crab cavity's location, $\beta_{x,cc}$, which is

$$x_{IP} = x' \sqrt{\beta_{x,cc}\beta_x^*} \sin \varphi$$

where φ is the phase advance from crab cavity to the IP.

The concept of the crab-crossing is appealing since it enables fast separation of the two colliding beam, has a compact interaction design, and small β^* at the interaction point (IP).

A few years after the concept was published, the first design of a superconducting RF (SRF) crab cavity started by KEK-Cornell University collaboration for CESR-B and later adopted at the High Energy Accelerator Research Organisation (KEK) in Japan for the electron-positron collider (KEKB). Since then, crab cavities have been added to many new collider designs as an essential element for pursuing higher luminosity.

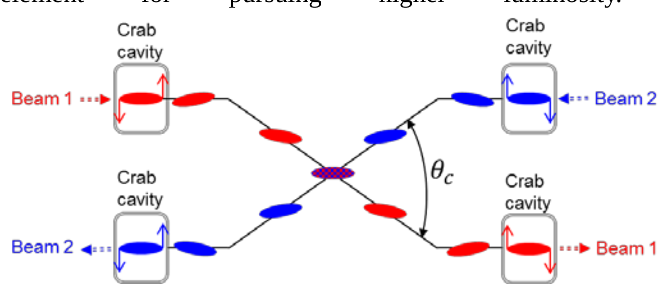

Figure 2: Beam collisions with crab cavity.

CRAB CAVITIES AT KEKB

In 2007, researchers at the KEKB demonstrated the first operational crab cavity, and observed a corresponding increase in luminosity [4][5].

The final configuration was a global crabbing scheme wherein a single cavity was used for each ring to compensate for a horizontal crossing angle of 22 mrad, Figure 3. In a global crabbing scheme, the crab cavity is installed at a particular location and generates transverse bunch oscillations around the ring. This scheme saved the cost by installing fewer cavities and utilization of the existing cryogenic system at Nikko.

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Cavity Design

In this crab cavity design, a squashed cell shape was adopted for delivering 0.8-1.6 MV crabbing voltage in TM110 mode at a frequency of 509 MHz, as shown in Figure 4. The cavity is elongated in one direction to separate the crab mode from its degenerative mode, and the latter is pushed up to 700 MHz. The squashed cell shape cavity scheme was studied extensively at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell collaboration [6][7].

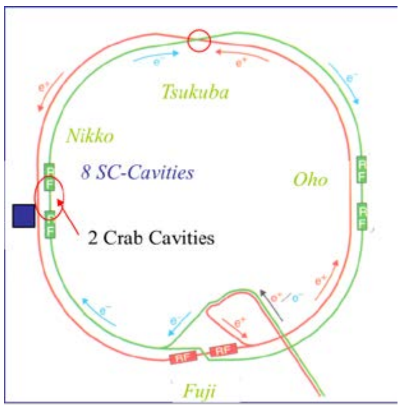

Figure 3: Crab cavity location for KEKB.

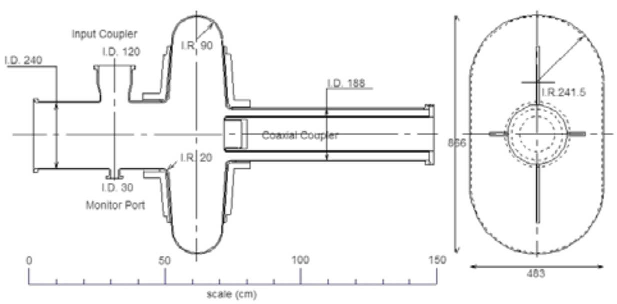

Figure 4: The KEKB crab cavity design.

The fabrication of the niobium cavities was challenging due to the non-axially-symmetric geometry, and the large dimensions. Special toolings were made for inserting the coaxial coupler with high precision. Both cavities were conditioned up to 1.8 MV crabbing voltage at 4 K with an unloaded Q above 10^9 at the designed voltage, 1.4 MV [8]. Multipacting occurred at a low RF field in the coaxial coupler region, and was easily conditioned away within one hour.

Cavity Operation

The crab cavities successfully delivered horizontal RF kicks to both beams as designed to restore the head-on collisions. The tilt of the bunches was recorded by streak cameras located in both rings; the tilt angles were correlated with the RF phase of the cavities, as predicated by simulations.

A maximum peak luminosity of 21.1×10^{33} cm^{-2}s^{-1} was achieved with the crab cavity in operation, which set the record for colliders in the year 2009. However, the measured beam-beam tune shift of 0.088 was lower than the expected value, 0.15. KEKB is the only facility that has implemented crab crossing to date.

CRAB CAVITIES FOR LHC

In CERN's 10-year plan approved in early 2011, the peak luminosity of LHC will reach above 2×10^{34} cm^{-2}s^{-1} by 2021, which corresponds to an integrated luminosity of 300 fb^{-1} [9]. Plans are that the machine then will enter a new stage of high luminosity LHC (HL-LHC), aiming to delivering a peak luminosity of 5×10^{34} cm^{-2}s^{-1} until the year of 2035. This goal will enable the integrated luminosity over the twelve years after the upgrade to reach more than 10 times that during the first ten years of the LHC lifetime.

To achieve this jump in luminosity, 19 work packages have been launched by the international collaboration community, with the crab cavity being one of them. Studies show that with β^* of 15 cm, the peak luminosity of LHC will increase by 70% from sole contribution of crab crossing at 400 MHz, as shown in Figure 5, to compensate a crossing angle of 0.59 mrad [10].

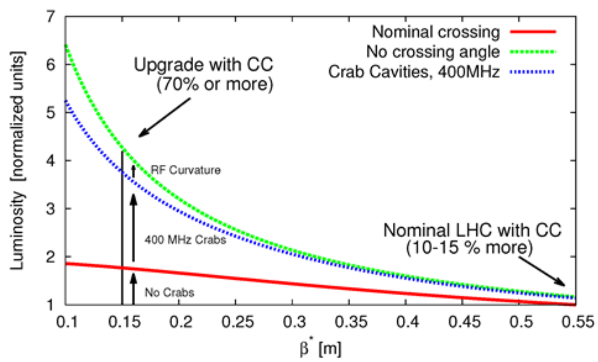

Figure 5: Luminosity dependence on $\boldsymbol{\beta}^*$ for LHC.

Cavity Design

The work package for the crab cavity focuses on installing local crab cavities at IP1 (vertical crabbing) and IP5 (horizontal crabbing). In such scheme, the bunches will receive a transverse kick shortly before arriving at the IP, and the tilt angle is cancelled by the crab cavities installed on the symmetrically opposing side of the IP. The current plan has four cavities on each side of the IP per ring, and the sum of the crabbing voltage they deliver should be 12-14 MV, depending on the final lattice.

The tight spacing of less than 20 cm between the centers of two beam pipes at the cavity location excluded the possibility of adopting KEKB type cavities [11]. High crabbing voltage and limited space along the beam pipe resulted in choosing SRF technology. Multipole novel design ideas emerged over 4 years, and three of them were supported by the US LHC Accelerator Research Program and the Cockcroft Institute along with Lancaster University of UK respectively to continue into the stage of cold testing a proof of principle (PoP) niobium cavity at 2 K [12][13][14]. All three PoP cavities delivered crabbing voltage above the designed voltage of 3 MV in the vertical tests. Figure 6 shows the three PoP cavities proposed for the LHC.

Figure 6: PoP crab cavities for LHC.

Successful cold tests encouraged the design of prototype cavities, for which beam tests are planned in the Super Proton Synchrotron (SPS) at CERN. The 4 Rod crab cavity currently is on hold in order to focus the efforts of the collaboration on the other two cavities, and thereby to increase the chance for success of the SPS test. Thorough studies for the Double Quarter Wave (DQW) crab cavity and the RF Dipole crab cavity (RFD) include optimization of their RF properties, stiffening and tuning of the cavity body, addressing thermal issues with available cryogenic capability, machining tolerances, integration into the helium vessel, and preliminary cryomodule design [15]. The final designs of these two cavities for SPS test are shown in Figure 7. Initiated by CERN, extensive joint efforts between various international research facilities are combined for all the studies. Both designs were finalized in 2014, and the prototype cavities are under fabrication.

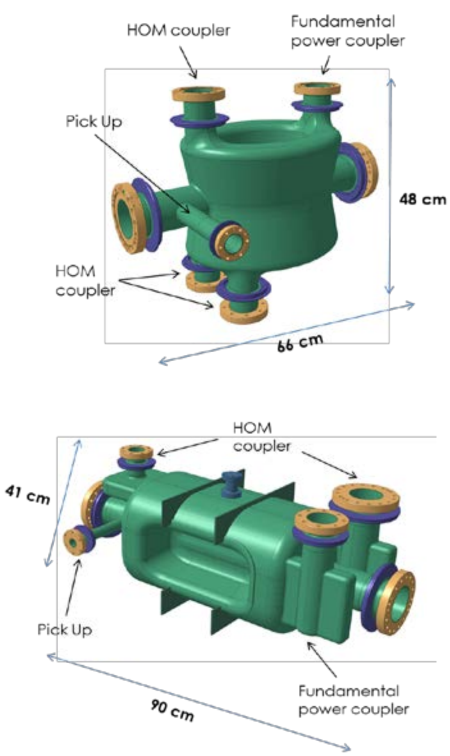

Figure 7: DQW (top) and RFD (bottom) prototype crab cavity designs.

Future Plans

During the SPS tests, a cryomodule for each cavity type will be installed and tested with beam in the ring. The cryomodules will be cavity-specific and house 2 cavities each. All cavities will be equipped with tuners, fundamental RF power couplers, and HOM dampers to ensure a complete system test. At the same time, all issues related to the operation of the cavity, such as system alignment, low level RF control, machine protection, vacuum, cryogenic system, also will be tested.

In the design of the prototype cavity, the DQW crab cavity delivers a vertical kick, while the RFD cavity tilts bunches horizontally. Further study is planned for converting each prototype cavity to crab in the other direction, while having both types of cavities operate at the corresponding IP is another option.

The designing of the LHC cryomodule will start in 2017, in parallel with the SPS experiments. The production and testing of the LHC cryomodules are scheduled to be completed within six years from the start of the design, so that the installation can begin in 2023 [15].

CRAB CAVITY FOR ILC

Since the bunch transverse size to length ratio envisioned for the single collision point in ILC is in the order of 10^4, precise crabbing is proposed for compensating the crossing angle of 14 mrad to boost the luminosity [16]. The crab cavities should provide a strong kick of 4.1 MV maximum to the bunch trains horizontally. This re-establishes head-on collision for a 500 GeV beam, leaving 100% redundancy for a 250 GeV beam. The transverse dimensions at the location of the crab cavity are limited because the opposing beam line is 15-20 cm away. Another challenging specification of the crab cavity system is on the uncorrelated phase jitter between the two sets of cavities from each beam line. Precise control must ensure that the jitter is less than 61 fsec in order to maintain optimized collisions.

Cavity Design

In the latest design, an elliptical superconducting RF 9-cell cavity is optimized at the frequency of 3.9 GHz. Figure 8 shows the 3D cavity model with the dipole crabbing mode field pattern and the single-cell prototype fabricated at Fermilab.

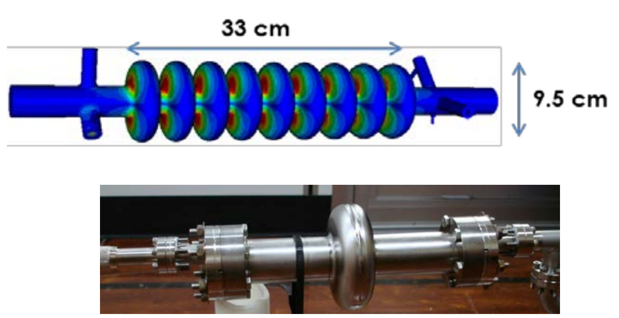

Figure 8: Top: 3D model of the 3.9 GHz 9-cell crab cavity for ILC. Bottom: Single-cell prototype.

Two cryomodules will be placed ~15 m from the IP, one for each beam line, with two cavities in each cryomodule. De-crabbing is not necessary for linacs, since the beam is dumped after the collision. Experience at Fermilab show that elliptical cavities operated at 3.9 GHz can be fabricated and can achieve a 7.5 MV/m peak accelerating field, which is above the required 5 MV/m for the crab cavity [17].

The research on the crab cavity in the United States and UK were put on hold in about 2010. Further optimization and development of couplers will be continued when the project resumes.

CRAB CAVITY FOR CLIC

Compared to the ILC, CLIC has an even slender beam. With 20 mrad crossing angle, the crab cavity in CLIC becomes a critical device for increasing the luminosity to 95% of the head-on scheme. Horizontal crabbing requires the cavity to provide a voltage of 2.55 MV [18]. The crab cavity is located before the final dipole, but sufficiently closes to be at 90 degrees phase advance from the IP.

The bunch train for CLIC contains 312 bunches, and will pass the cavity in 156 ns. The synchronisation of the two cavities on each beam line, which are 50 m apart, requires a phase jitter better than 4.4 fs and an amplitude control of less than 2%. This is a very challenging specification for instrumentation.

Cavity Design

Unlike the superconducting crab cavities in other projects, CLIC adopted normal conducting copper cavities. A racetrack shape was chosen for setting the SOM frequency to fall in half way in between two bunch harmonics to reduce the multi-bunch wake. Figure 9 shows the prototype 12-cell travelling-wave cavity optimized at 11.994 GHz [19]. The cavity is undergoing testing at the high power X-band test station at CERN, Xbox2. The incident power reached up to 30 MW, which is 2.5 times the operation power, at a breakdown rate of 1.8e-6.

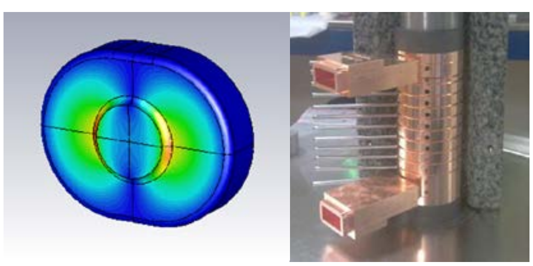

Figure 9: 12-cell copper travelling-wave structure for crabbing in CLIC. Left: Distribution of the electric field in one cell. Right: Prototype copper cavity.

DAMPING OF UNWANTED MODES

Other than the crabbing mode, beam will also interact with other modes in the cavity during operation. Similar to other RF devices, any unwanted mode in the crab cavity would excite beam instability once the mode's impedance is above a certain threshold. Damping all unwanted modes is a critical issue, relevant to all crab cavity projects.

Due to different design and operation requirements, unwanted mode damping focuses on various aspects for each crab cavity.

The KEKB crab cavity has one lower order mode (LOM) at 413 MHz, and the first higher order mode (HOM) is located near 650 MHz. The HOMs propagated out via the large beam pipes and are dissipated at the ferrite absorbers on both sides of the cavity. The TM010 LOM is extracted by the coaxial coupler inserted into the cavity cell. The coaxial coupler has a cut-off frequency of 600 MHz for dipole modes, which is above the operating frequency at 509 MHz. This allows the dipole modes, including the 700 MHz SOM, to couple out through both beam pipes [8].

The LOM and SOM damping issues also exist in ILC crab cavities due to their elliptical type geometry. The latest study focused on integrating the LOM and SOM couplers to simplify the installation. The HOM coupler still is under development [20].

Since the race track shape minimized the effect of the SOM on the beam, the CLIC crab cavity design focuses on damping the LOM and HOMs, and it achieves sufficient damping through the waveguide approach. Four waveguides are added to each of the cavity cells and are loaded with an RF absorbing material [19]. Two of the waveguides are specially designed with low cut-off frequency to extract the LOM, and both are oriented vertically to prevent leakage of the crabbing mode.

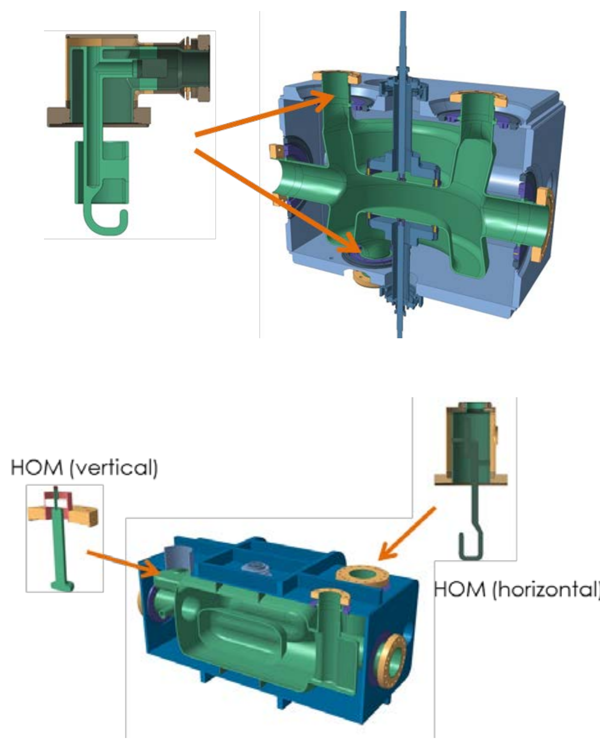

Figure 10: HOM couplers for DQW (top) and RFD (bottom) crab cavities with helium vessel.

Due to their novel designs, both the DQW and RFD crab cavities operate at the lowest RF mode at 400 MHz, and the first HOM is 180 MHz above the operating mode. Extensive effort was focused on studies of HOM damping [21][22][23]. Figure 10 shows the final designs of the couplers.

Depending on its location, each HOM coupler couples to different modes in the cavity. Those in the DQW crab cavity are identical and inserted from three locations into the high magnetic field region. Each coupler incorporates a high pass filter with -128 dB rejection to the fundamental mode. HOM damping of the RFD crab cavity is fulfilled by two different designs of couplers, which couple to the vertical and horizontal modes respectively. A high-pass filter is also included in the horizontal HOM coupler, while it is not necessary for the vertical coupler as the location of the latter determines that it does not couple to the fundamental mode. All couplers will operate at 2 K, as the high-pass filters are enclosed in helium jackets.

CRAB CAVITIES FOR FUTURE

Despite the fact that most of the reviewed projects are still under development, crab cavities have become a straight forward choice for future colliders.

In the design of the electron ion collider at BNL (eRHIC), crab cavities are installed to compensate for the 10 mrad crossing angle. These cavities are essential devices for reaching a luminosity of $4.9 \times 10^{33} cm^{-2} s^{-1}$ for the collisions of 15.9 GeV polarized electrons and 250 GeV polarized protons. eRHIC will have 2 IPs with local crabbing scheme and different cavity frequencies for electrons and ions [24].

The fundamental SRF crab cavity for the ion beam is set at 225 MHz, and four cavities will provide 15.9 MV for the deflection. To control the nonlinear effect from crabbing long bunches 2^{nd} and 3^{rd} harmonic crab cavities are added at the same location, and each will provide a defecting voltage of 2.8 MV and 0.8 MV. Due to the shortness of electron bunches, crabbing requirements are much more relaxed in the electron ring, where only one 676 MHz crab cavity is needed at each side of the detector.

SUMMARY

Over the past 27 years of the history of crab cavities, multiple colliders, linac and circular, have adopted this idea for compensating the luminosity loss caused by crossing angles. Although the missing factor between the measured increase in luminosity and the expectation is still under investigation at KEKB, the intention of correcting the beam back to head-on collision is a straight forward approach towards retrieving the lost collision events. Parameters of the available crab cavity designs are listed in Table 1.

In each design, the crab cavities are believed to deliver a major boost to luminosity, and they will be present in future accelerator projects as an important factor that facilitates the findings in physics.

Table 1: Parameters of available crab cavity designs.

Parameters	KEK	LHC	ILC	CLIC
Operation Frequency [GHz]	0.509	0.400	3.908	11.994
LOM [GHz]	0.413	None	2.784	8.84
SOM [GHz]	0.700	None	3.912	13
1^{st} HOM (Band) [GHz]	0.650	>0.575	4.3	14
Full Crossing Angle [mrad]	22	0.59	14	20
Crabbing Voltage per Cavity [MV]	1.4	3.4	2.05	2.55
Number of Cavities in Facility	2	16	4	2
Cavity Type	1-cell elliptical	DQW+RFD	9-cell elliptical	12-cell elliptical
Operating temperature	4 K	2 K	1.8 K	Room temp
Unwanted mode damping	Beampipe + Coupler	Coupler	Coupler	Waveguide

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