Crab Cavities: Past, Present, and Future of a Challenging Device

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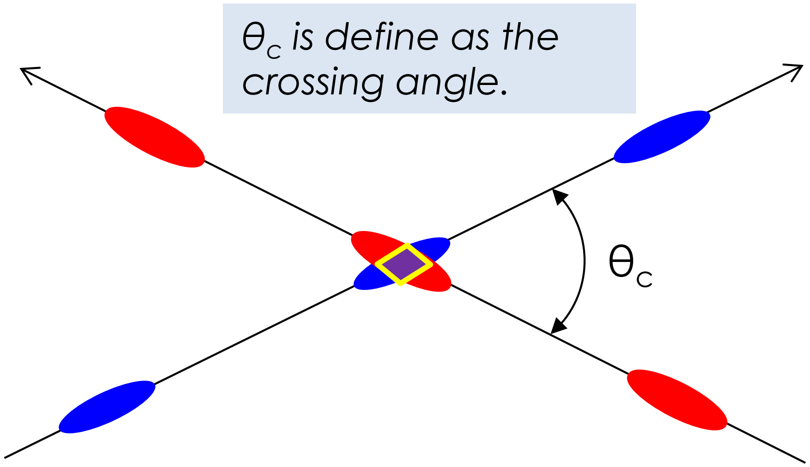
Outline

- Introduction to crab cavity
  - The motivation
  - Solution and challenges
- Footprints of crab cavity
  - Commissioned: KEKB
  - In design: Hi-Lumi LHC, ILC, CLIC
- Unwanted mode damping in crab cavities
- Future and beyond
- Summary

Introduction

geometry
Piwinski angle
KEKB
eRHIC
hadron
luminosity
LHC
beam
CRAB
Future Circular Collider
mrad
Synchronization
ILC
MEIC
collider
deflecting
CLIC
system
CAVITY
Hi-Lumi LHC
crossing angle
phase
electron
Nb
magnetic field
frequency
pressure vessel code
EB WELDING
LLrf
SRF
Q_0
amplifier
shielding
stress
installation
4K
damping
coupling
tuning
HOM
COPPER
thermal
dewar
fabrication
electric field
signal
tolerance
cryomodule
stiffening
2K
WINDOW
helium vessel

Motivation



Crossing angle is introduced to

- minimize the long range beam-beam interaction
- move triplet closer to IP to achieve smaller β^*
- avoid collision debris pass up to the opposing linac

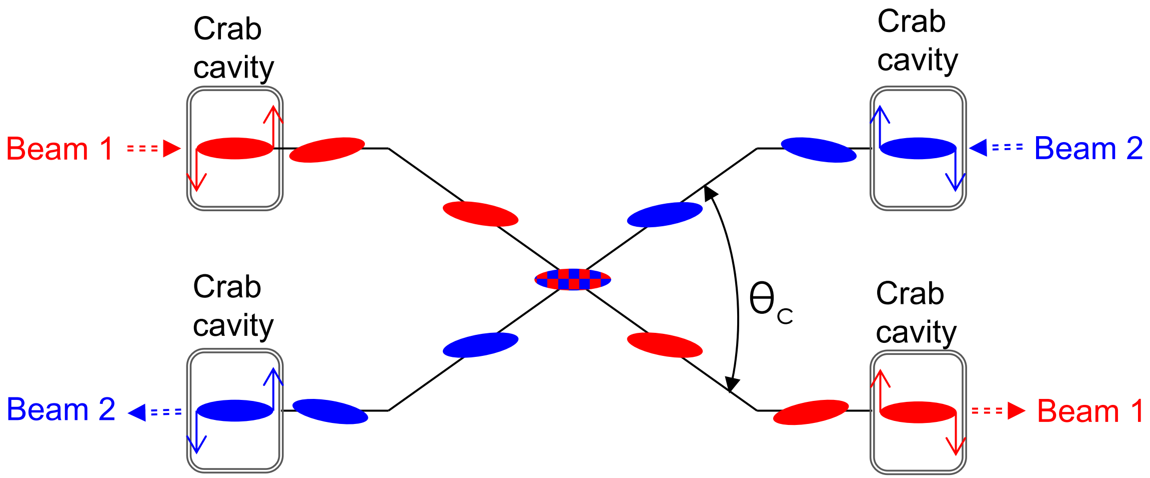
However crossing angle will also lead to geometric luminosity reduction

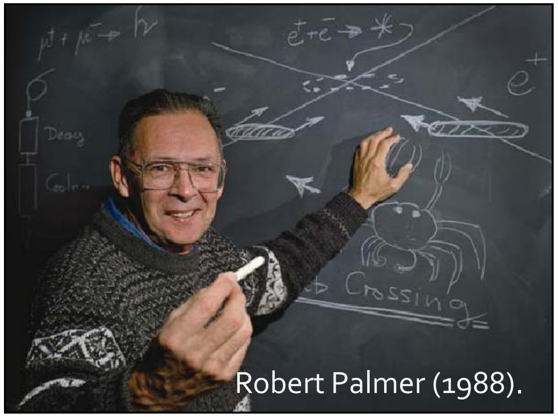
The luminosity reduction due to crossing angle is described by:

$$R = \frac{L}{L_0} = \frac{1}{\sqrt{1+\phi^2}}$$

Where $\phi = \frac{\theta_c \sigma_z}{2\sigma_x}$ Is called the Piwinski angle

Solution and Challenges




Robert Palmer (1988).

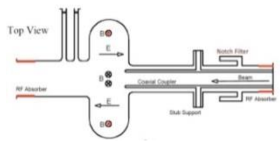
- Proposed by Robert Palmer in 1988 in luminosity study for linear colliders with CM energy between 10 GeV and 1 TeV.
- Crab cavities provide transverse kick inside the bunch base on its longitudinal location. The transverse offset at the IP due to the kick cancels the geometric luminosity reduction due to the crossing angle.

Challenges:

- High field
- Compact
- Synchronization
- Lattice
- HOM damping
- Fabrication

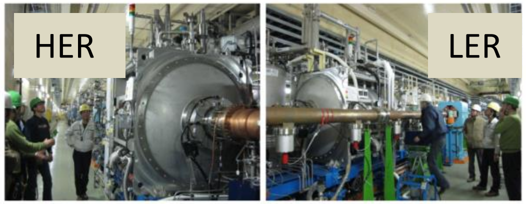
Footprints of Crab Cavity

KEK-Cornell Collaboration on CESR-B (1991-1992)



R&D of crab cavity for KEKB

KEKB crab cavity construction & commissioning



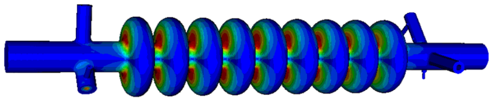
CLIC crab cavity design

CLIC crab cavity started high power test @ Xbox-2 @ CERN

1994 · 2004 · 2008 · 2009 · 2010 · 2011 · 2012 · 2013 · 2014 · 2015

Future Projects

ILC crab cavity design



First LHC crab cavity workshop held at BNL

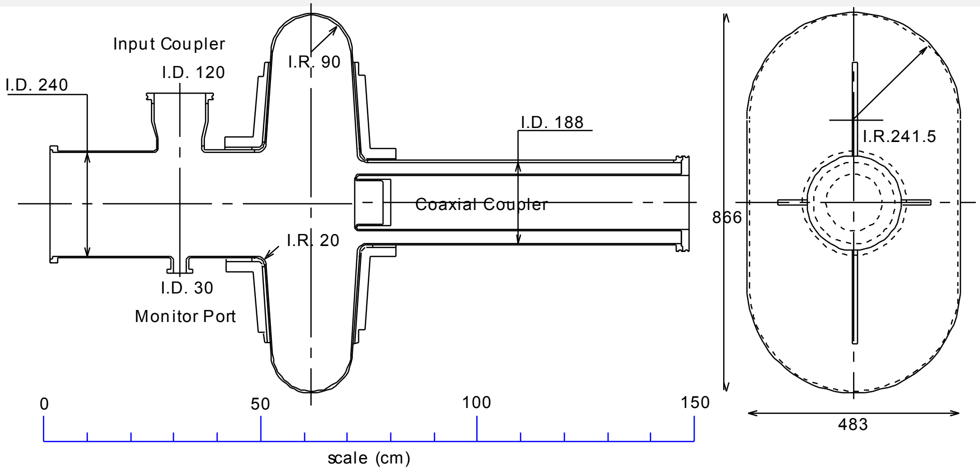
High Luminosity LHC

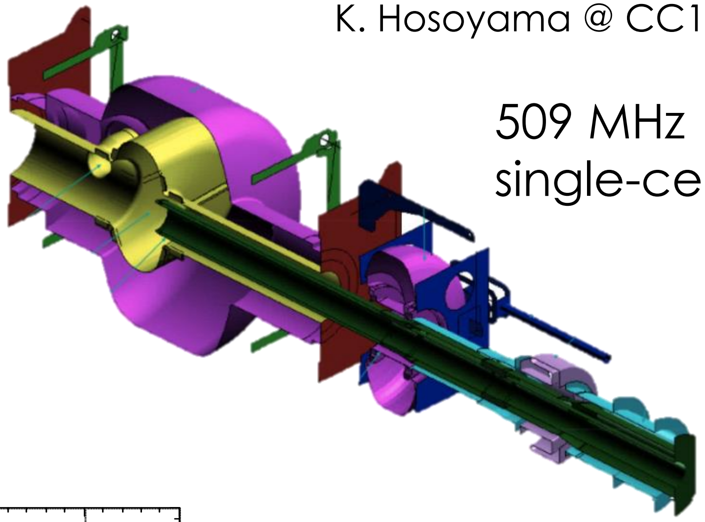
LARP

Design and testing of Proof of Principle (PoP) crab cavities for LHC

Start fabrication of Prototype LHC crab cavities

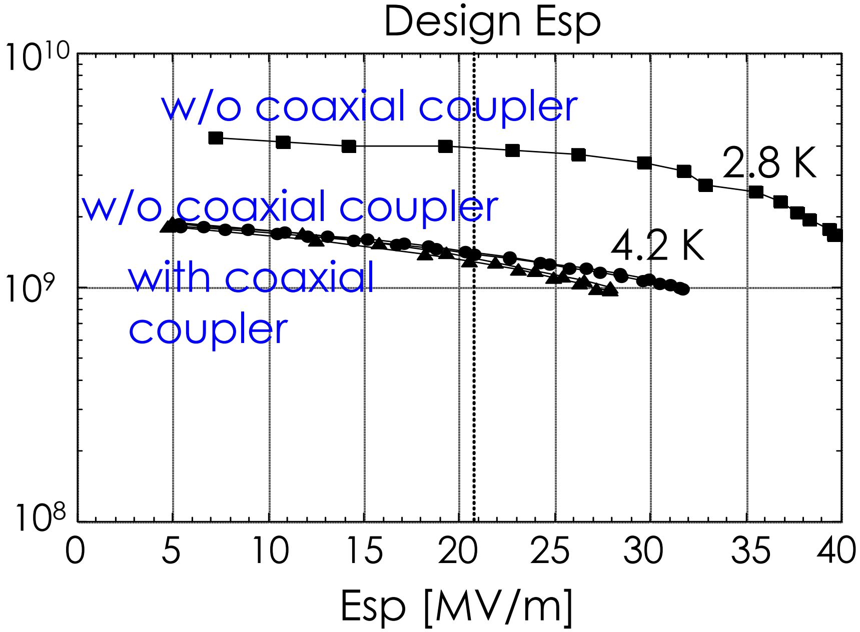
Crab Cavities at KEKB





K. Hosoyama @ CC10

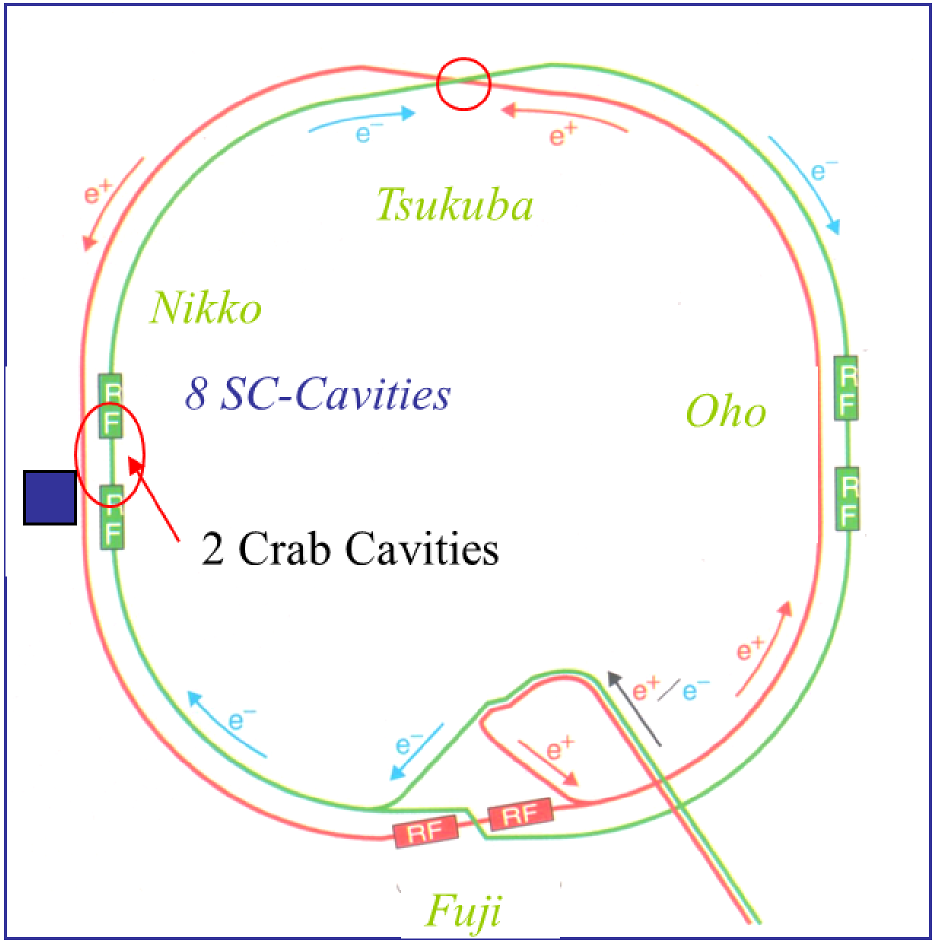
509 MHz single-cell



Assemble of the complete system

Crab Cavities at KEKB

Full crossing angle θc = 22 mrad



HER

LER

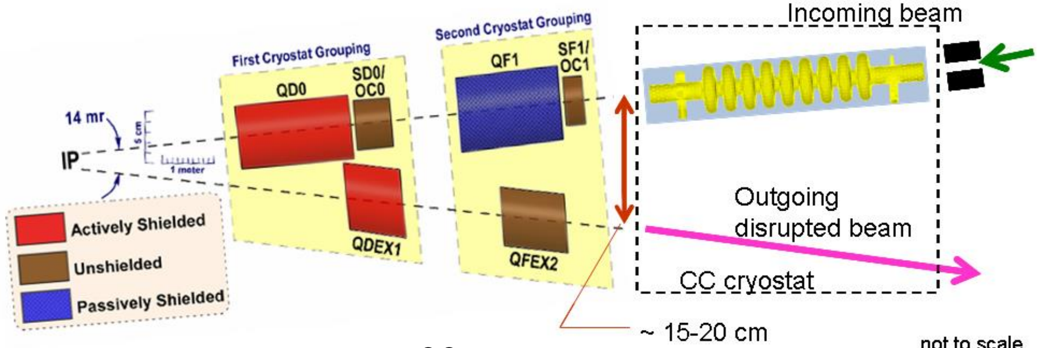
- 2 crab cavities were designed, constructed and installed in KEKB, and operated about 3 years under high current beam.
- Peak luminosity L_{peak} =21.1 x 10^{33} /cm^2/s attained under crab on operation (peak luminosity world-record 2009).

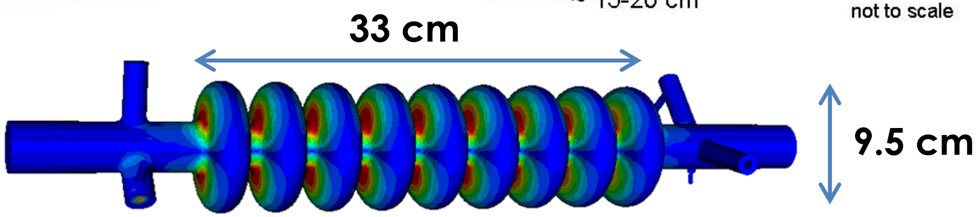
KEKB operation terminated in June 2010 for the upgrade towards SuperKEKB.

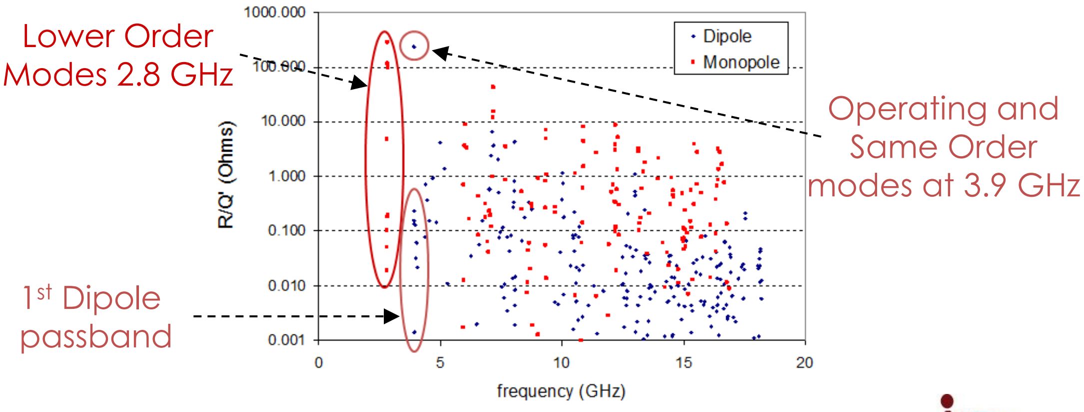
K. Hosoyama @ CC10

Crab Cavity for ILC

Amos Dexter @ LC-ABD Review, March 2009

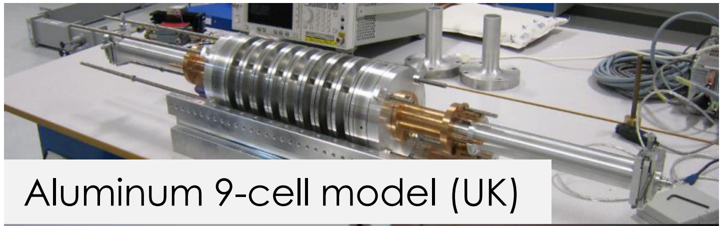




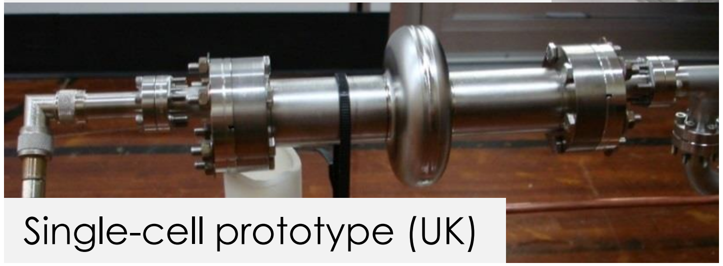


Full crossing angle θ_c =14 mrad

Crab cavity just behind the Final Doublet



Aluminum 9-cell model (UK)



Single-cell prototype (UK)

Challenges:

- Lower order mode damping
- Higher order mode damping
- Tight phase tolerance

CERN Fermilab SLAC The Cockcroft Institute of Accelerator Science and Technology Jefferson Lab BROOKHAVEN NATIONAL LABORATORY

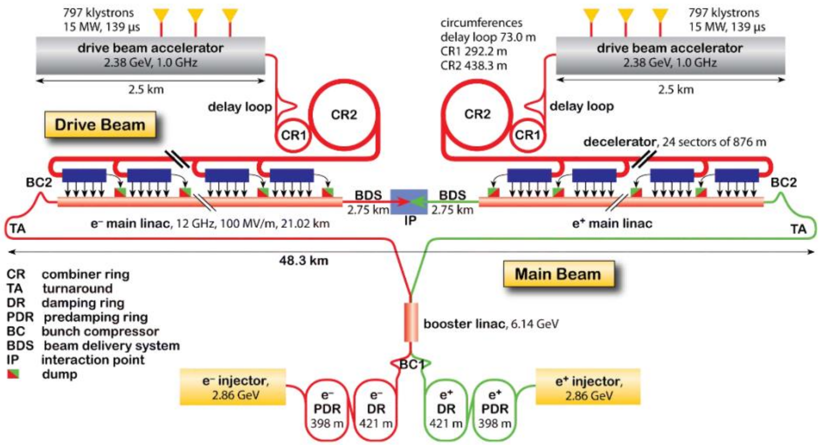
Crab Cavities for CLIC

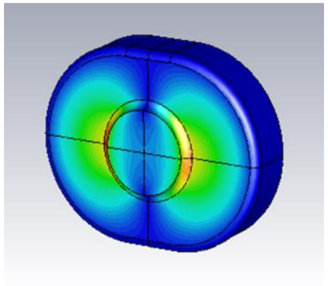
CLIC

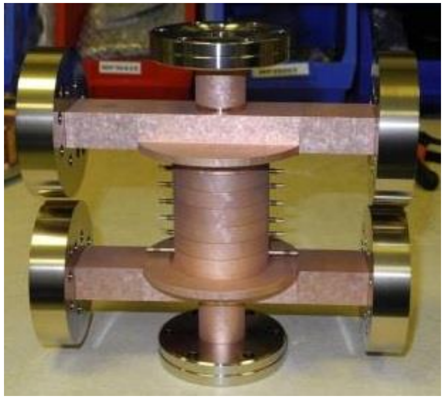
Full crossing angle θ_c = 20 mrad

crabs increase ***L*** to *95% of head-on case*

V_{defl} = 2.55MV at 11.9942 GHz





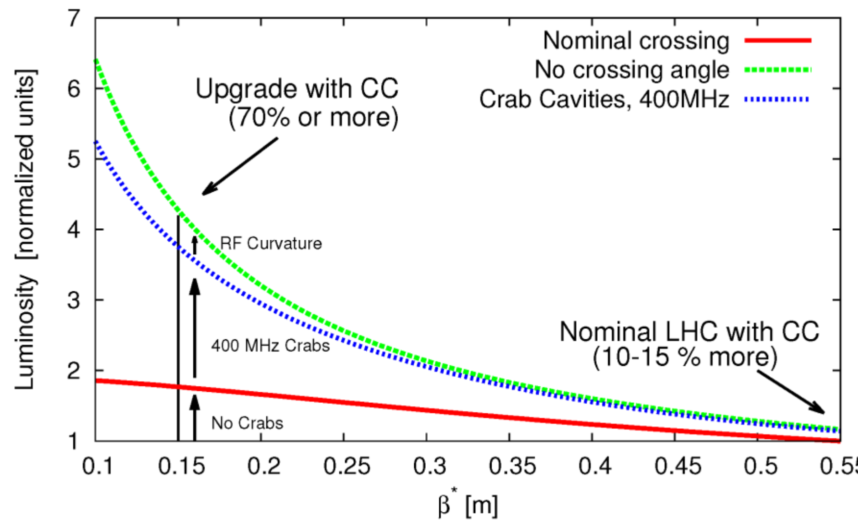


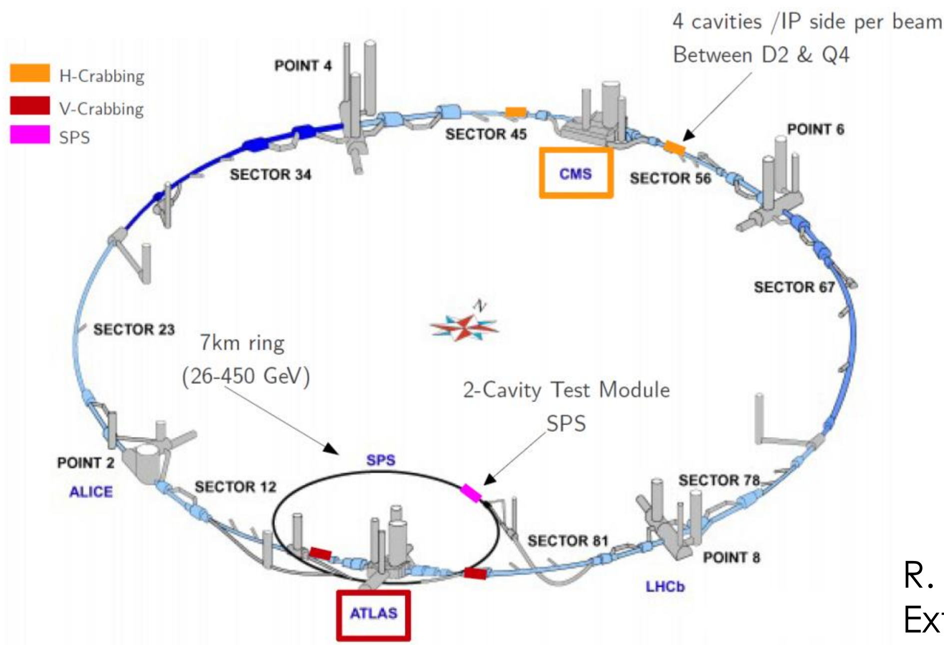
12-cell TW race-track structure in copper, currently installed at XBox2 (CERN) for high gradient testing

B. Woolley et al., CLIC UK Collaboration Meeting, May 2012
IPAC15 WEPHA057

Crab Cavities for LHC

Potential Luminosity increase from crab cavities:



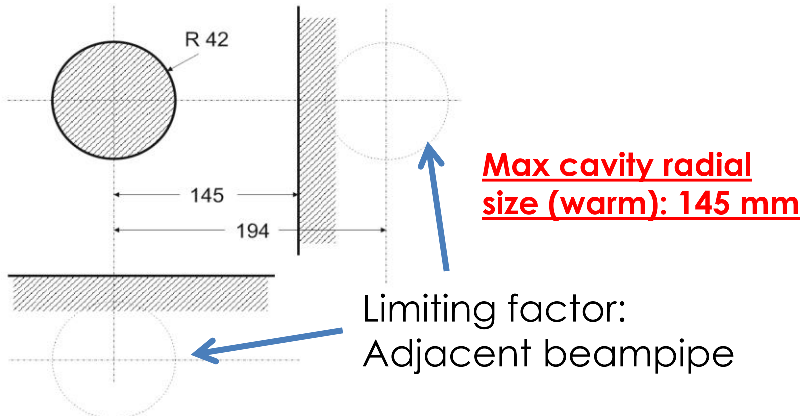


Full crossing angle θ_c =0.59 mrad

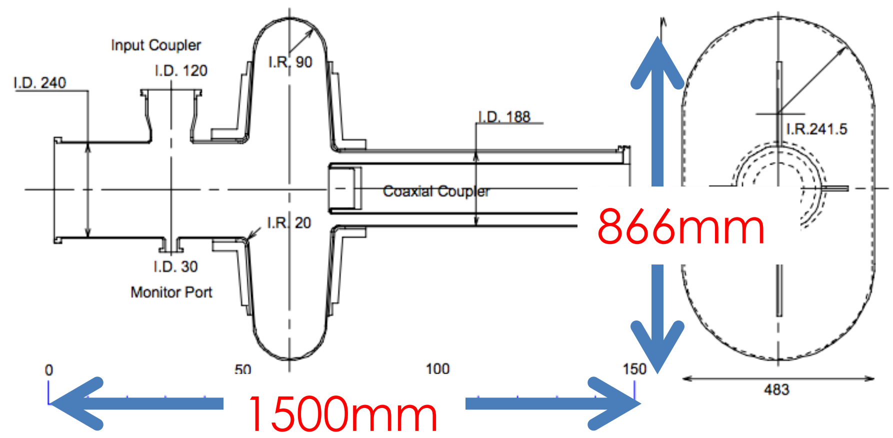
R. Calaga @ HiLumi-LHC/LARP Crab Cavity System External Review, May 5-6 2014

Limitations in LHC for crab cavities

Geometry Constrain

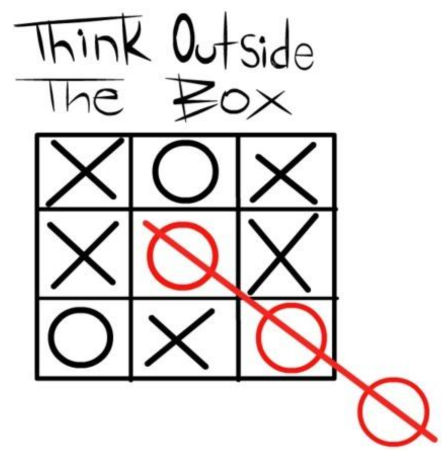


KEK 509 MHz crab cavity :



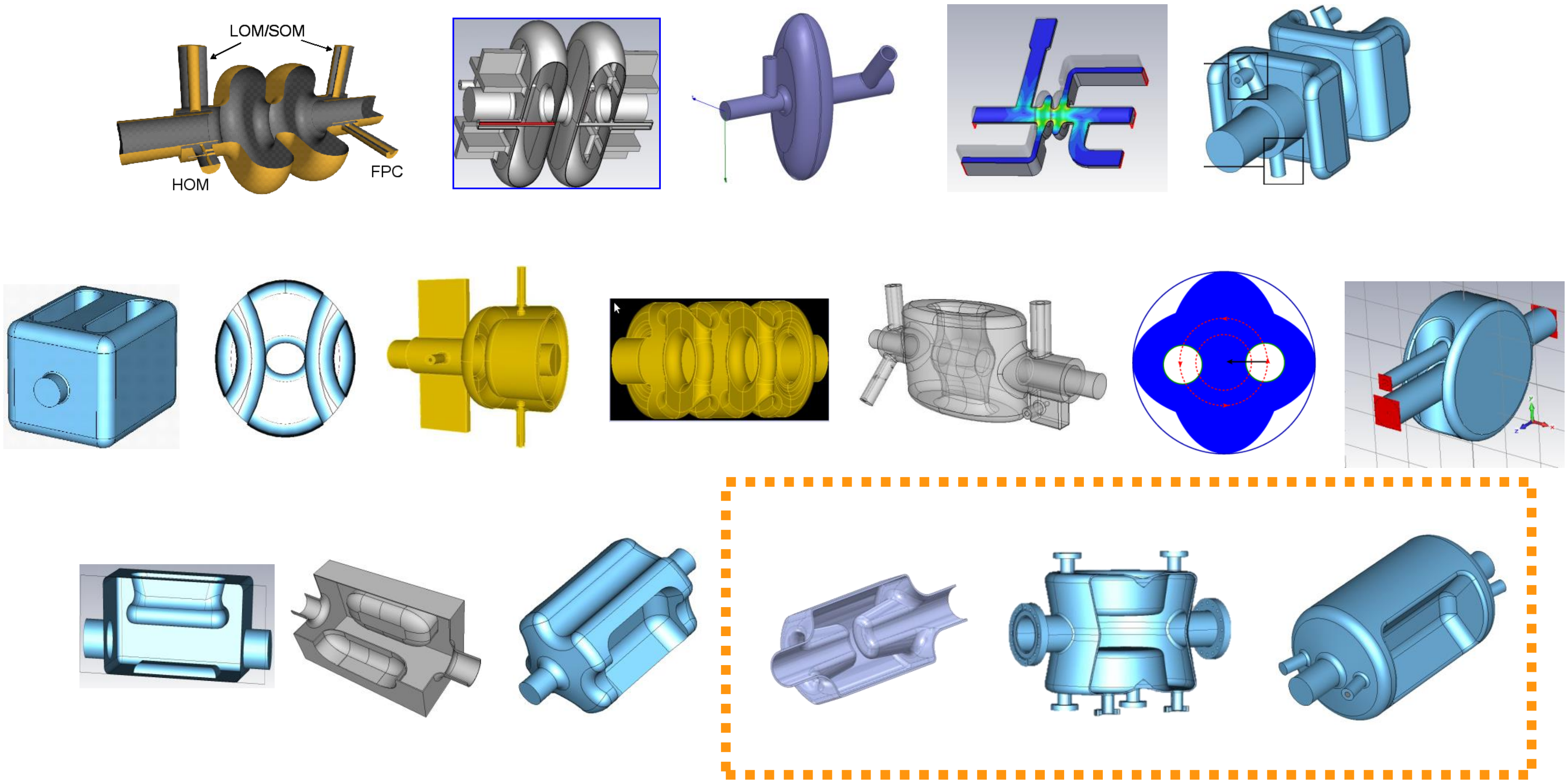
Fit in 8 cavities for both beamlines along with their helium vessels and cryostat within 10 meters

Parameters for each cavity	Value
Resonance frequency	400 MHz
Nominal kick voltage	3.34 MV
R/Q	300 Ω … 900 Ω
Q_0	10^{10}
Q_L	$10^5 \ldots 10^6$



Meet the candidates

R. Calaga, Chamonix '12

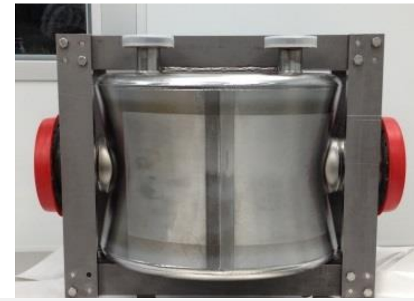


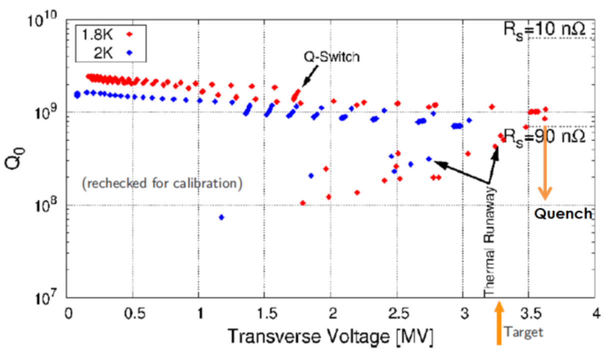
Exotic zoo of crab cavities developed in about 4 years (BNL, CERN, CI-JLAB, FNAL, KEK, ODU/JLAB, SLAC)
Three cavities remaining after down-selection.

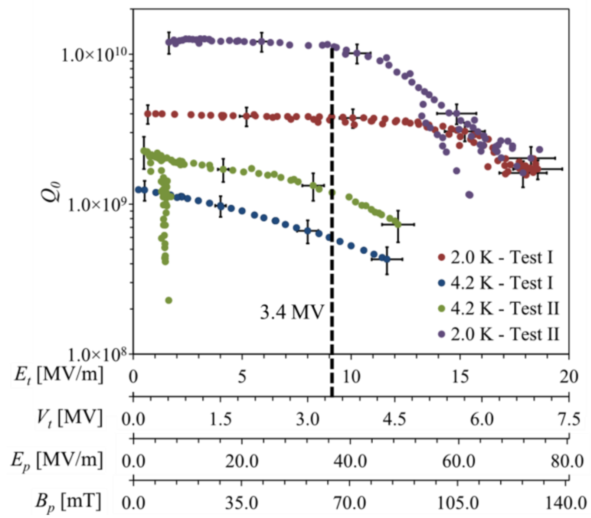
Successful Cold Testings

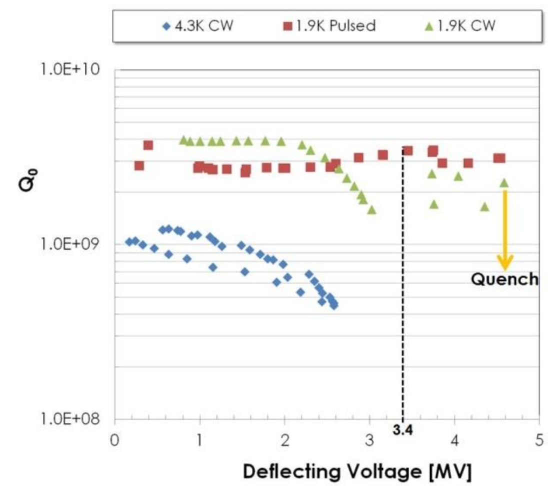

4 Rod


RF Dipole


Double Quarter Wave



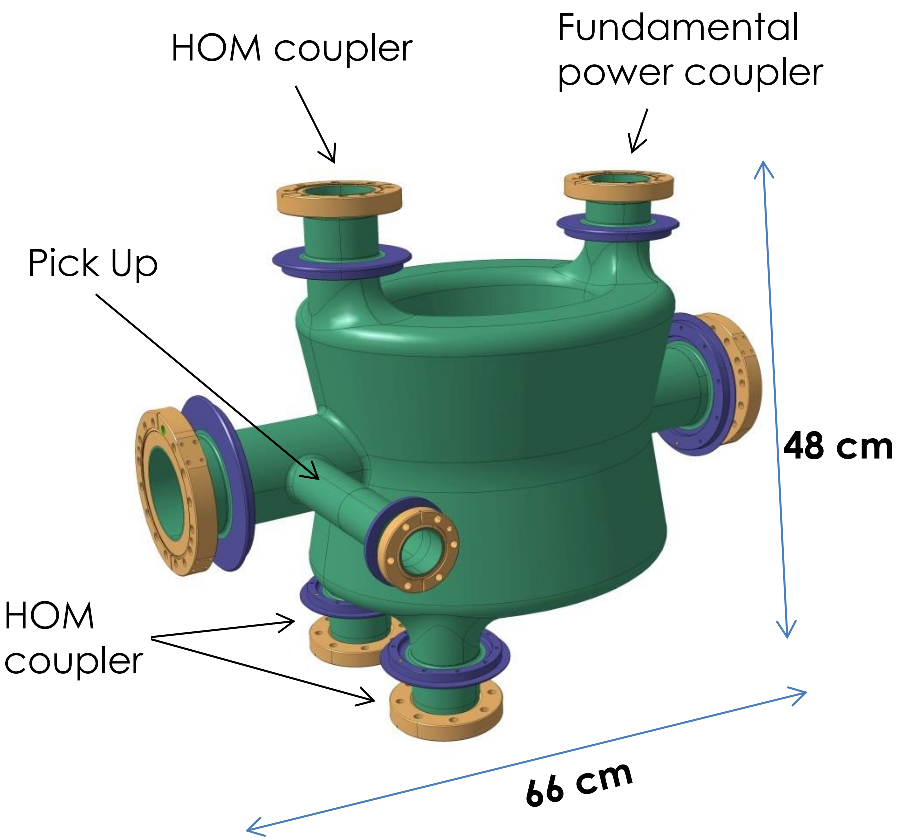




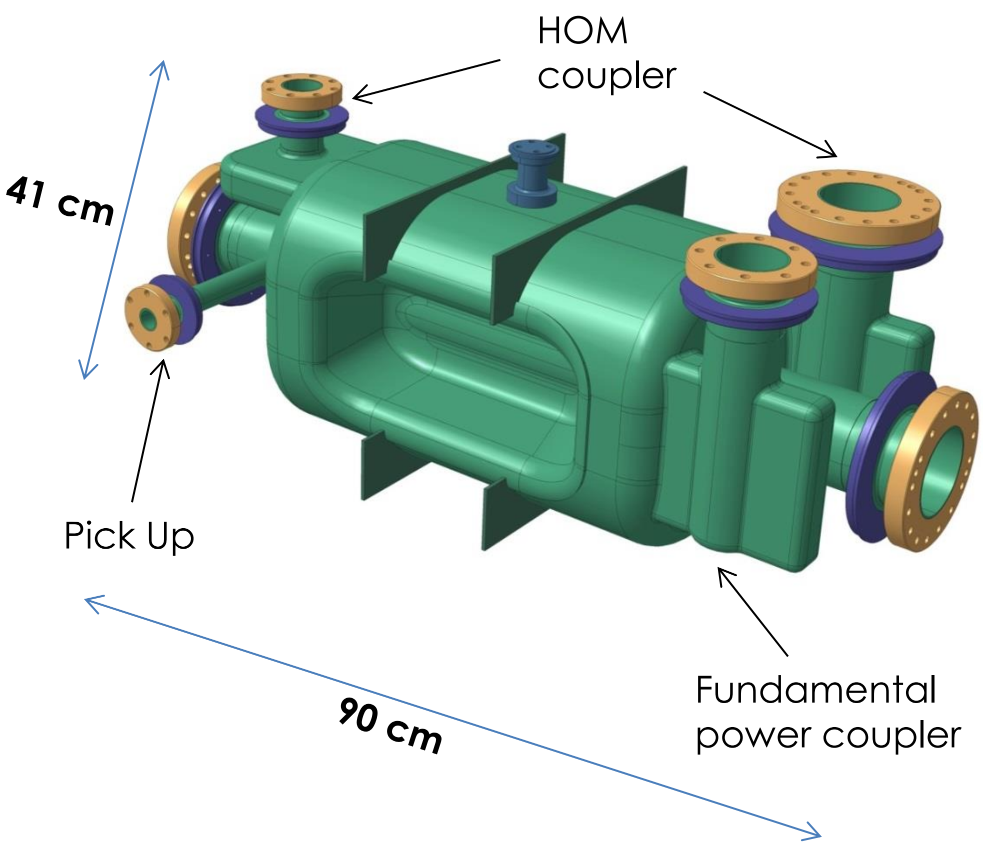
HiLumi-LHC/LARP Crab Cavity System External Review, May 2014
WEPWI036, WEPWI060, IPAC15

Prototype Designs

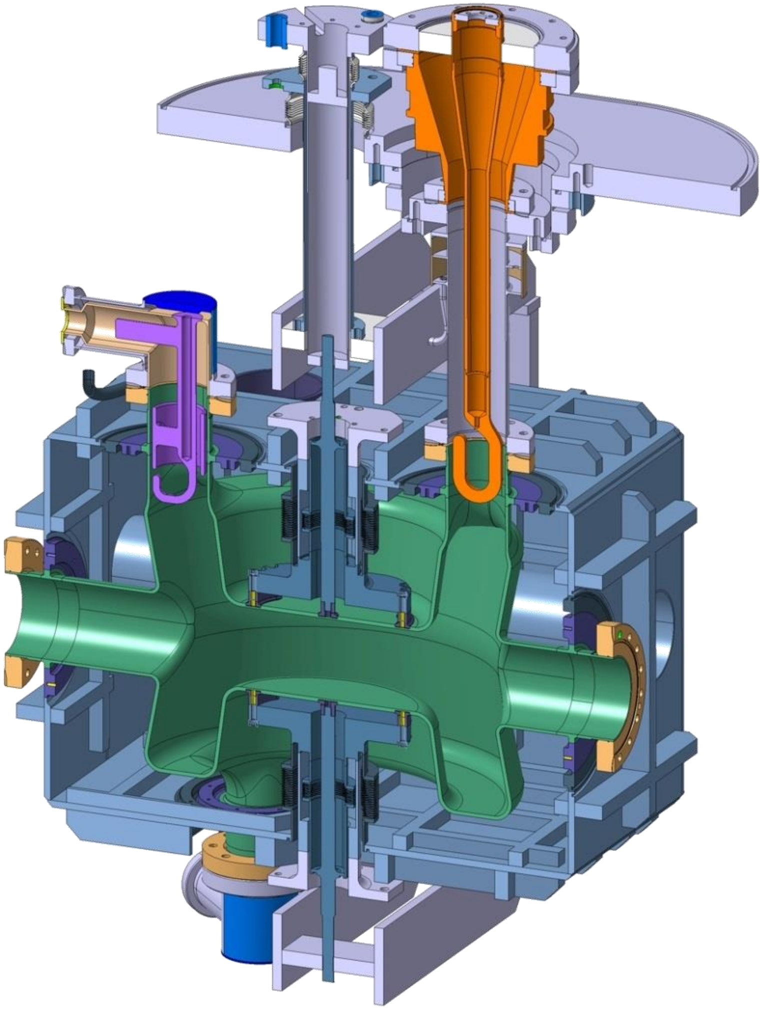
Double Quarter Wave (DQW)



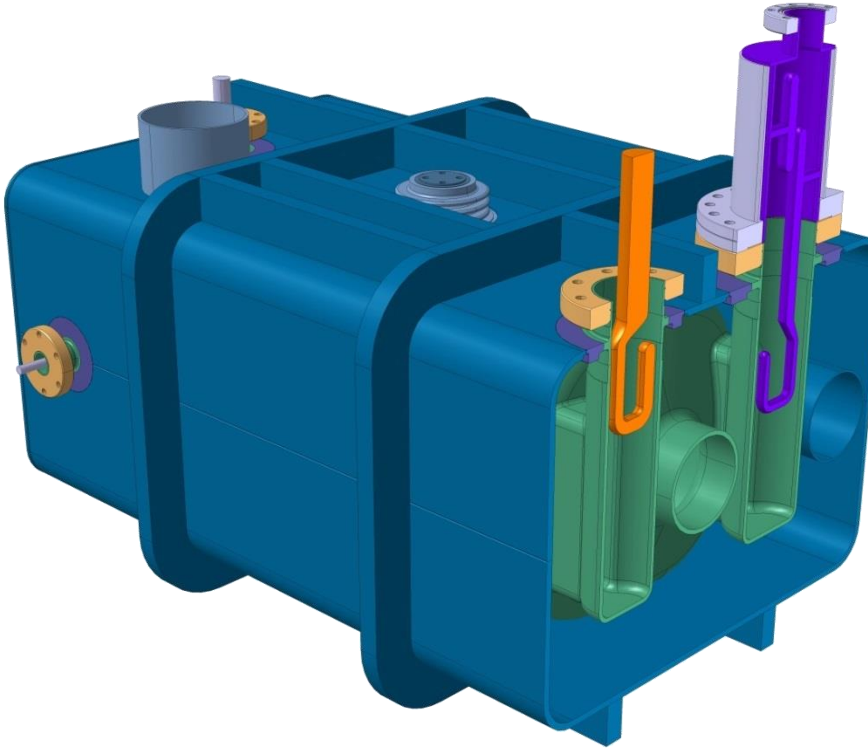
RF Dipole (RFD)



Dressed Cavities



Same approach for helium vessel design & manufacturing to be considered



O. Capatina, Crab Cavity Manufacturing Readiness Meeting, Oct 2, 2014

Next Step

Short term plans

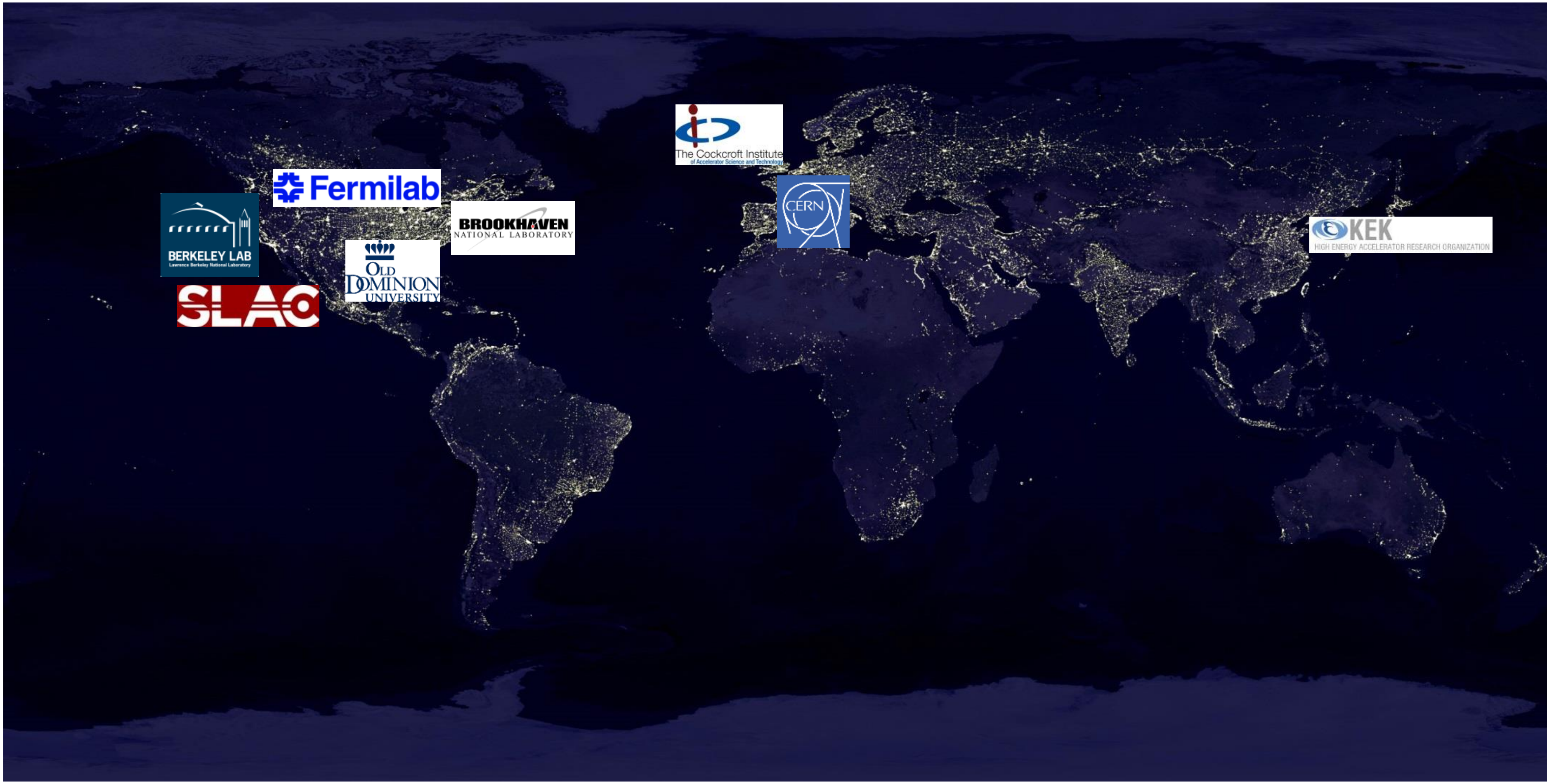
- Complete cavity and couplers fabrication in summer/fall 2015
- Build two fully dressed cavities of each kind
  - Include helium vessel, HOM filters, tuners – No FPC
  - Vertical test @ US lab before shipping
- Integrate cavities in cryomodule(s) for SPS test to begin in 2017
- Ambitious, in light of current progress

Long term plans

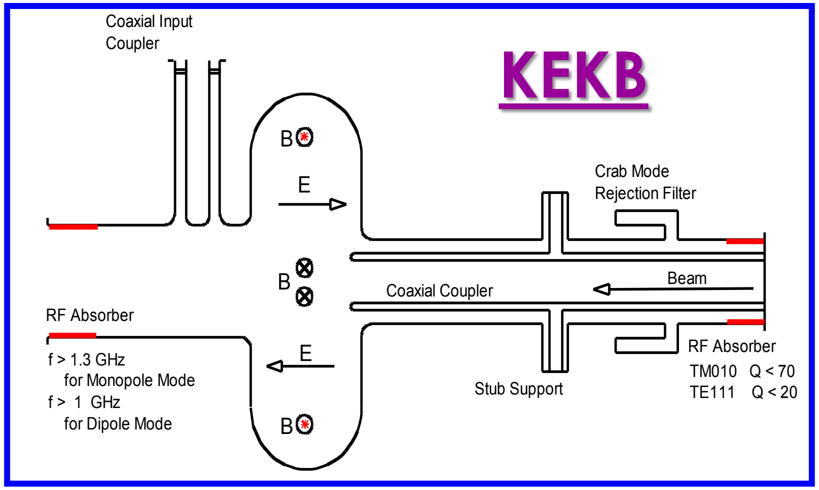
- Design and build LHC prototype CMs (2017-2020)
  - Must start while SPS test are ongoing
  - Need to freeze requirements and baseline by mid 2016
- Build production cryomodules (2020-2023)
  - Start upon successful horizontal test of prototypes
  - Includes spares
- Installation (2023-24)

A. Ratti, 4th Joint Hilumi/LARP Annual Collaboration Meeting, Nov 17-21, 2014

The Current Community



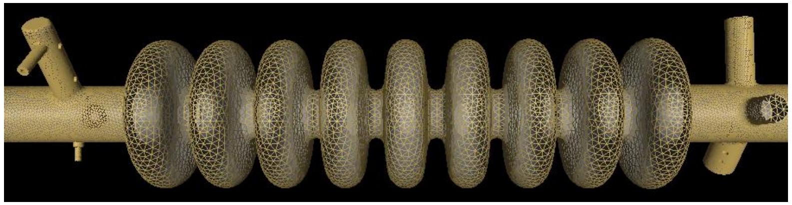
Unwanted Mode Damping

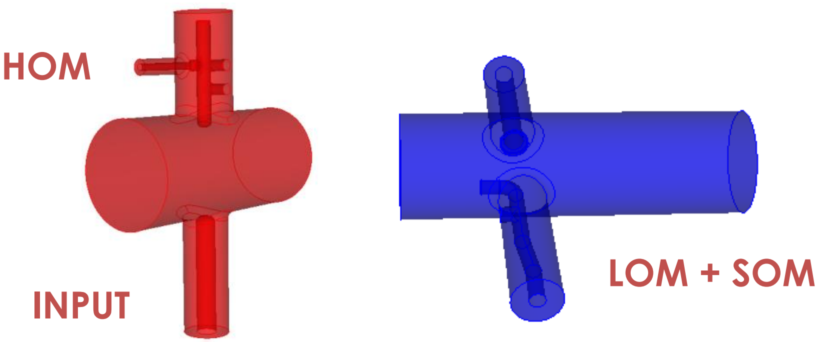


K. Hosoyama, EPAC08, pp. 2927-2931

- "Squashed cell shape" design is adopted to push up the unwanted same order mode
- Large beam pipe is designed for HOM damping
- Coaxial coupler is put into the cell through beam pipe for the lowest TM010 acceleration mode damping
- Notch filter in the coaxial coupler reject outgoing crab mode

ILC



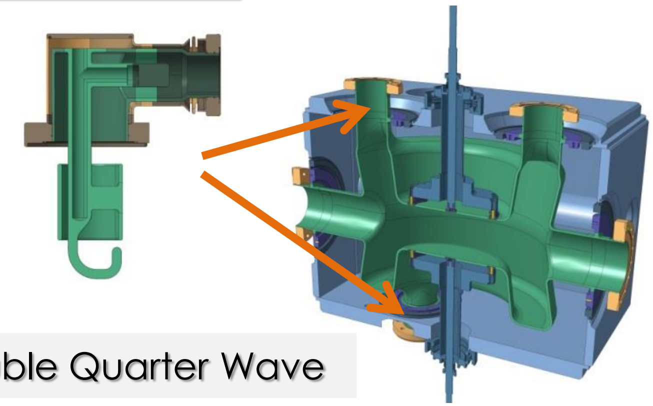


- The requirement for HOM damping is to damp both monopole and dipole Qext to less than 10^6.
- The LOM and SOM damper has joint together to simplify the assembly.
- Further optimization is needed to achieve damping requirements in every aspect.

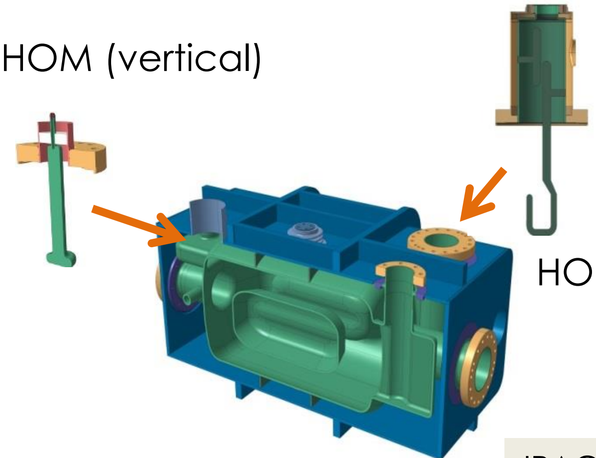
L. Xiao and Z. Li, ILC BDS meeting, March 2007

Unwanted Mode Damping

HiLumi LHC



Double Quarter Wave

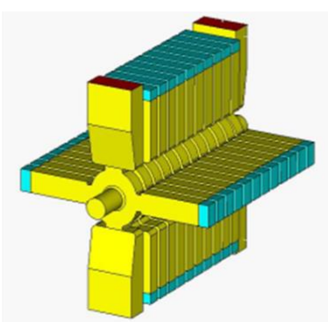


RF Dipole

- No LOM or SOM in crab cavities designed for LHC.
- The first HOM is more than 150 MHz higher than the operation mode.
- High-pass filters are essential for these couplers.
- Still working with beam dynamics group to verify the impedance of each mode is below threshold.
- The RF, thermal, and mechanical designs has been analyzed via international collaboration

IPAC15:
WEPWI004, WEPWI0037,
WEPWI0039, WEPWI0059

CLIC



- Four waveguides are added to each of the cavity cells and are loaded with an RF absorbing material.
- 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.

B. Woolley et al., CLIC UK Collaboration Meeting, May 2012

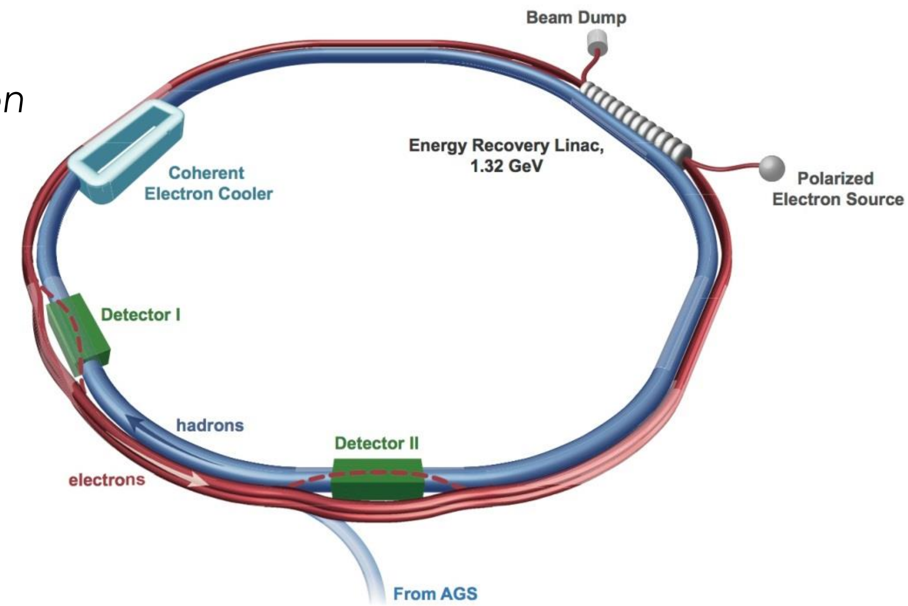
Crab Cavity Comparison

Parameters	KEK	ILC	CLIC	LHC
Operation Frequency [GHz]	0.509	3.908	11.994	0.400
Lower Order Mode (band) [GHz]	0.413	2.784	8.84	None
Same Order Mode [GHz]	0.700	3.912	13	None
1st Higher Order Mode (band) [GHz]	0.650	4.3	14	>0.575
Full Crossing Angle [mrad]	22	14	20	0.59
Crabbing Voltage per Cavity [MV]	1.4	2.05	2.55	3.34
Number of Cavities in Facility	2	4	2	16
Cavity Type	1-cell elliptical	9-cell elliptical	12-cell elliptical	DQW+RFD
Operating temperature	4 K	1.8 K	Room temp	2 K
Unwanted mode damping	Beampipe + Coupler	Coupler	Waveguide	Coupler

Crab Cavities for eRHIC

eRHIC

- *250 GeV polarized protons and 15.9 GeV electron*
- $\mathcal{L} \sim 5 \times 10^{33}\ cm^{-2}s^{-1}$



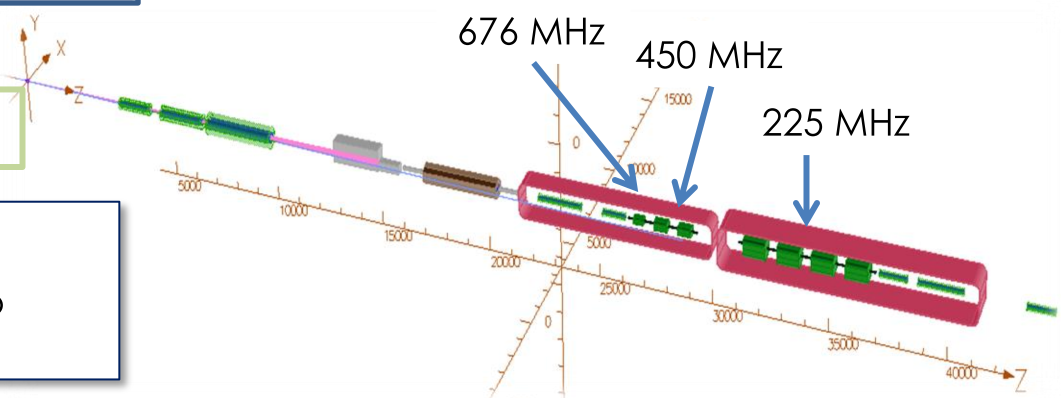
B. Parker @ EIC14

Based on DQWCC design *(SRF technology)*:

Crab cavities	250 GeV proton			15.9 GeV e-
freq [MHz]	225	450	676	676
$N_{cavities}$	4	2	1	1
V_{defl} [MV]	6.19	2.79	0.76	1.90

Full crossing angle θ_c *=10 mrad*

- *Horizontal local crabbing scheme*
- *Higher harmonic cavities are planned to* correct *non-linearity* kick.



Crab Cavities for MEIC

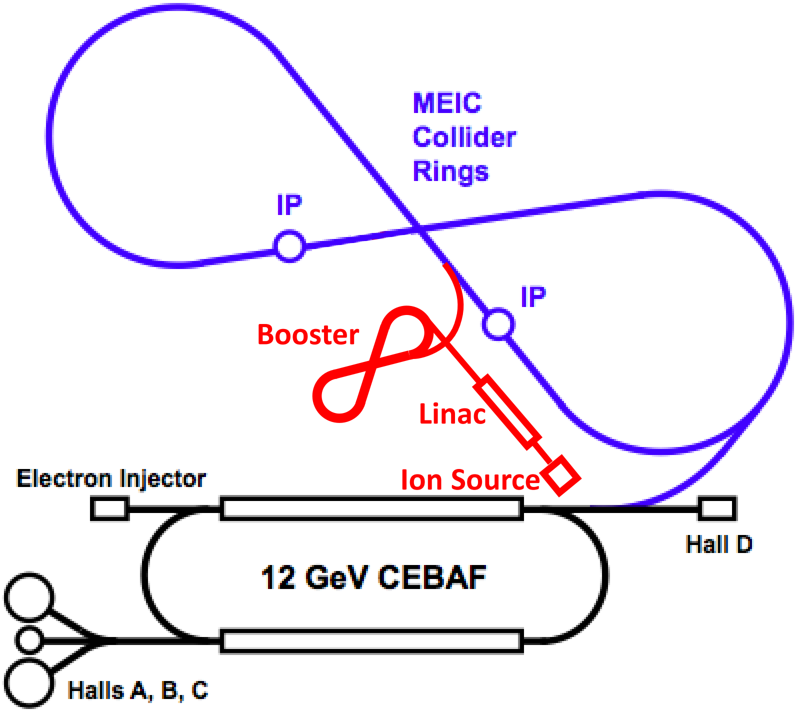
MEIC

- *Up to 100 GeV polarized protons and 10 GeV polarized electrons*
- $\mathcal{L} \sim 7.5 \times 10^{33}\ cm^{-2}s^{-1}$

Based on RFDCC design *(SRF technology)*:

Crab cavities	100 GeV proton	10 GeV e-
freq [MHz]	952	952
$N_{cavities}$	6	2
V_{defl} [MV]	14.48	1.76

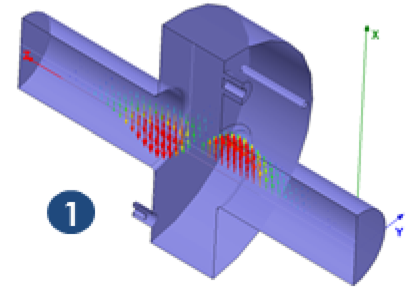
Full crossing angle θ_c =50 mrad



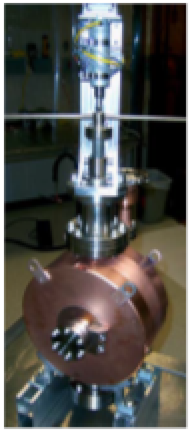
- *Horizontal local crabbing scheme*

Crab Cavities beyond Luminosity

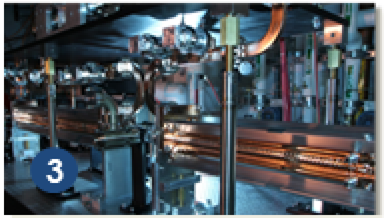
- **Longitudinal phase space diagnostics**
  - D. Alesini et al, Nucl. Instr. and Meth. A 568 (2006) 488–502
  - A. Falone et al., PAC09, pp. 2012-2014 [1]
  - S. Belomystnykh et al., Nucl. Instr. and Meth. A 614(2010) 179–183 [2]
  - C. Behrens *et al.*, Nat. Commun. 5:3762 (2014) [3]
- **Ultra-short synchrotron radiation pulse generation**
  - A. Zholents *et al.*, Nucl. Instr. and Meth. A 425 (1999) 385
  - D. Li and J. N. Corlett, PAC03, pp. 1249-1251
  - M. Borland *et al.*, PAC07, pp. 1127-1129
  - A. Lunin et al., LINAC14, pp. 966-968 [4]
- **Emittance Exchange**
  - M. Cornacchia and P. Emma, Tech. Report LCLS-TN-02-3, SLAC
  - J. Shi *et al.*, Nucl. Instr. and Meth. A 598 (2009) 388–393 [5]



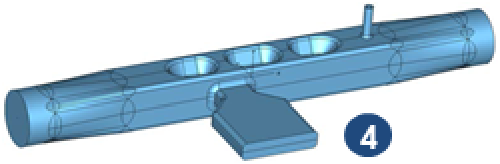
3 GHz RF deflector @ PSI


2

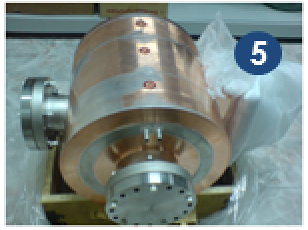
1.3 GHz deflecting cavity @ Cornell



X-Ban RF deflector @ LCLS



2.8 GHz HOM-free deflecting cavity @ ANL



1.3 GHz deflecting cavity @ ANL

In addition, crab cavities can be used as beam spreaders when operated with a 90° phase shift from the crabbing scheme.

Summary

- The crab cavity concept has been introduced to the community for almost 30 years.
- As the first facility commissioned crab cavity, KEKB demonstrated peak luminosity of 21.1 x 10^{33} /cm^2/s, which set the record of colliders in 2009.
- Broad and active international collaboration efforts are spent on crab cavity adoption in various projects, e.g. ILC, CLIC, and LHC.
- Unwanted mode damping always played an important role in the crab cavity development.
- Along with resolving many issues of the crab cavity with novel designs, new challenges emerge with increasing demand of physics.
- Crab cavities are essential to the success of future projects, and they function much more beyond increasing the luminosity in colliders.

Acknowledgement

Special Thanks to:

Sergey Belomestnykh, Ilan Ben-Zvi, Silvia Verdu-Andres, Binping Xiao

Alex Ratti

Rama Calaga, Ofelia Capatina, Teddy Capelli

Graeme Burt

Jean Delayen, Subashini Uddika De Silva, Hyekyoung Park

Yuantao Ding, Zenghai Li

Crabbing Related Papers in IPAC15 (incomplete list)

- ID: 2941 - MOBD2 Design and Prototyping of HL-LHC Double Quarter Wave Crab Cavities for SPS Test
- ID: 2831 - MOPWA049 Simulation of Crab Waist Collisions in DAFNE with KLOE-2 Interaction Region
- ID: 2399 - MOPWA059 Dynamic Aperture Studies for the FCC-ee
- ID: 2350 - MOPJE069 General Functionality for Turn-Dependent Element Properties in SixTrack
- ID: 1411 - TUYB3 Progress on the Design of the Polarized Medium-energy Electron-Ion Collider at JLab
- ID: 2717 - TUPTY018 Interaction region for crab waist scheme of the Future Electron-Positron Collider (CERN)
- ID: 3230 - TUPTY053 Roadmap towards High Accelerator Availability for the CERN HL-LHC Era
- ID: 2019 - TUPTY073 An Alternative High Luminosity LHC with Flat Optics and Long-Range Beam-Beam Compensation
- ID: 2539 - TUPTY076 Beam-Beam Simulation of Crab Cavity Noise Effects for LHC Upgrade
- ID: 4041 - TUPTY082 Scanning Synchronization of Colliding Bunches for MEIC Project
- ID: 2851 - TUPWI039 Modeling Crabbing Dynamics in an Electron-Ion Collider
- ID: 3062 - WEPMN065 Progress at the FREIA Laboratory
- ID: 3759 - WEPHA057 High Gradient Testing of an X-band Crab Cavity at XBox2
- ID: 3504 - WEPTY080 Development of 400 MHz Superconducting LHC Crab Cryomodules for the HiLumi LHC Upgrade at CERN
- ID: 3496 - WEPWI004 FPC and Hi-Pass Filter HOM Coupler Design for the RF Dipole Crab Cavity for the LHC HiLumi Upgrade
- ID: 2854 - WEPWI034 Effects of Crab Cavities' Multipole Content in an Electron-Ion Collider
- ID: 3557 - WEPWI037 Imperfection and Tolerance Analysis of HOM Couplers for ODU/SLAC Crab Cavity for LHC High Luminosity Upgrade
- ID: 2871 - WEPWI039 Engineering Study of Crab cavity HOM Couplers for LHC High Luminosity Upgrade
- ID: 3593 - WEPWI036 Design and Prototyping of a 400 MHz RF-dipole Crabbing Cavity for the LHC High-Luminosity Upgrade
- ID: 2953 - WEPWI059 Higher Order Mode Filter Design for Double Quarter Wave Crab Cavity for the LHC High Luminosity Upgrade
- ID: 2952 - WEPWI060 Cryogenic Test of Double Quarter Wave Crab Cavity for the LHC High Luminosity Upgrade
- ID: 1417 - THXB2 Crab Cavities: Past, Present, and Future of a Challenging Device
- ID: 2349 - THPF095 Limits on Failure Scenarios for Crab Cavities in the HL-LHC