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Crab Cavity Systems for Future Colliders

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Crab Cavity Systems for Future Colliders

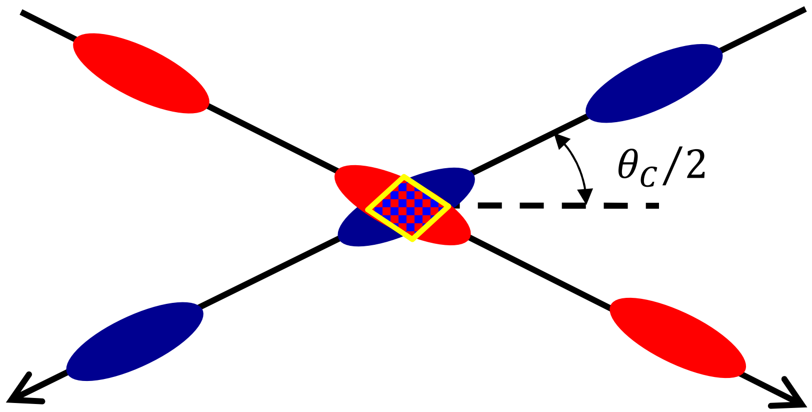
OUTLINE

- Motivation
- First implementation at KEK-B
- Crab cavity systems for linear colliders
- Crab cavity systems for circular colliders
- Summary and outlook

A crossing angle to reduce undesired interactions

The Linear Collider Problem:
if head-on collisions, undesired interaction of debris and particles with machine.

→ Introduce a **crossing angle θ_C**:



Piwinski angle

$$\phi = \frac{\theta_C \sigma_z}{2\sigma_x}$$

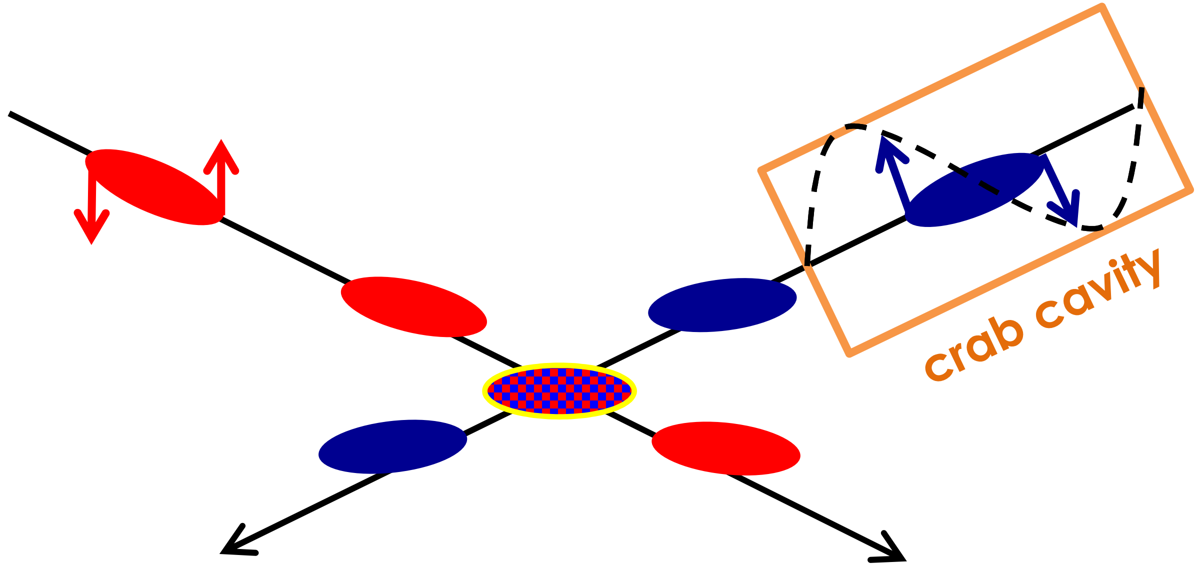
- ✓ **Avoid interaction** of **debris** with machine and incoming bunches
- ✓ **Minimize long-range beam-beam** interaction
- ✓ Move **triplet closer to IP for smaller β^***

✗ Ineffective overlap leading to peak **luminosity reduction:**
($F = 1$ for head-on collisions)

$$F = \frac{1}{\sqrt{1+\phi^2}}$$

Restore head-on collisions – the crab crossing scheme

→ **Crab crossing** to restore head-on collision for maximal peak luminosity [R. Palmer, 1988]



→ Kick by **crab cavities:**

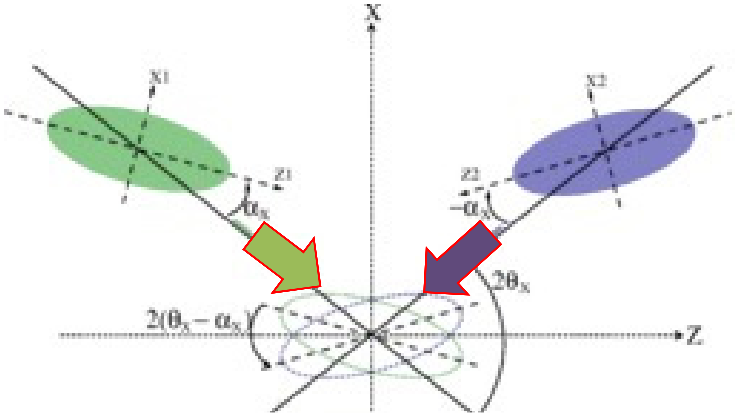
- Deflecting cavity operated with bunch center at cavity center for $\Psi = 0$
- Bunch length < half-wavelength for linear kick
- Transverse kick conversion into position kick after a drift

$$x_c' = \frac{\Delta p}{mc} = \frac{V_{max}}{E_o}\sin(\omega t) \qquad x_{ip} = R_{12} x_c'$$

Crab cavities – not only peak luminosity increase

also allow techniques for luminosity leveling and reduction of pile-up density

- Adjusting the crabbing as bunches depopulate with every collision

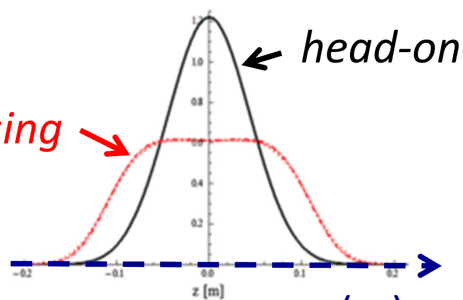


- **Crab kissing** [S. Fartoukh, 2014]

Special crab configuration and operation to overlap bunches in the other transverse plane

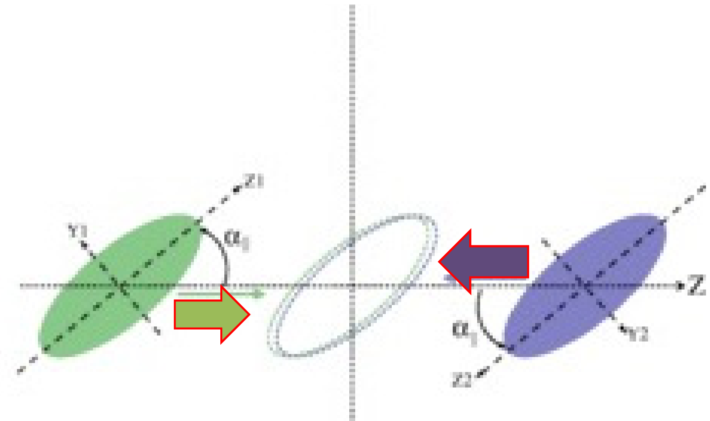
probability of collision

kissing



head-on

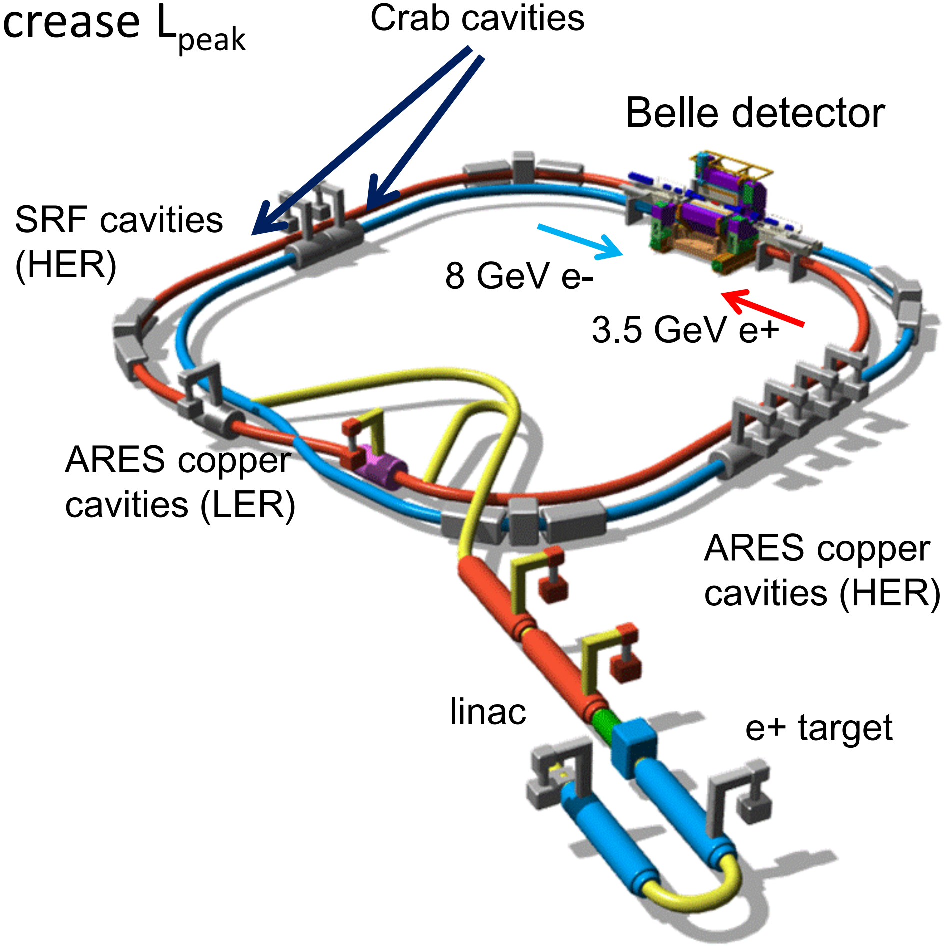
z (m)



First implementation at e-e+ KEK-B collider

MOTIVATION

- Simulations suggested **head-on collisions** to:
  1) maximize geometric overlap → increase L_{peak}
  2) increase b-b tune shift



CRAB CAVITY SYSTEM

- **Global scheme**: less cavities *but*

bunch wiggles around the whole ring

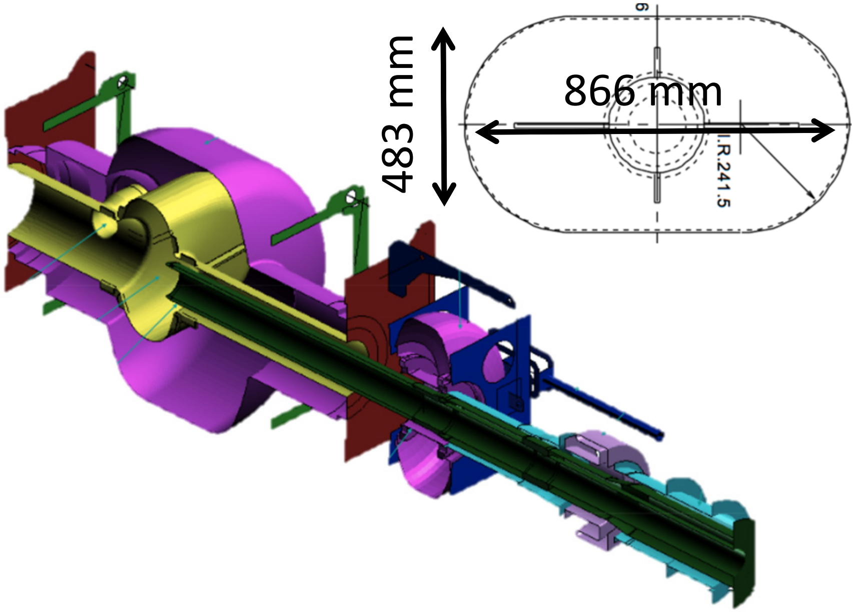
Crossing angle	22	mrad
RF frequency	509	MHz
Required Vt	2.8	MV
Cavities / ring	1	

KEK-B crab cavity – design and performances [Y. Funakoshi, 2014]

CAVITY DESIGN

- Squashed cell to select polarization mode; degenerated mode at 700 MHz
- Coaxial coupler to extract the lower order TM010 mode at 324 MHz

Crabbing mode	TM110	
RF frequency	509	MHz
Required Vt	2.8	MV
Operation temperature	4.2	K

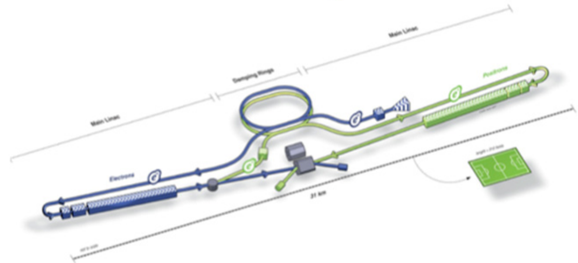


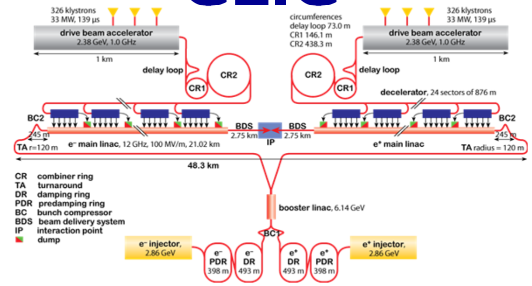
CRAB CAVITY SYSTEM PERFORMANCES

- 3 years operation under high current
- Bunches were successfully crabbed and overlaping with full geometric factor;

  L_{peak} =2.11 x 10^{34} /cm^2/s (with crabs)
- KEK-B operation terminated in June 2010 for the upgrade towards SuperKEKB

Crab cavity systems for linear colliders

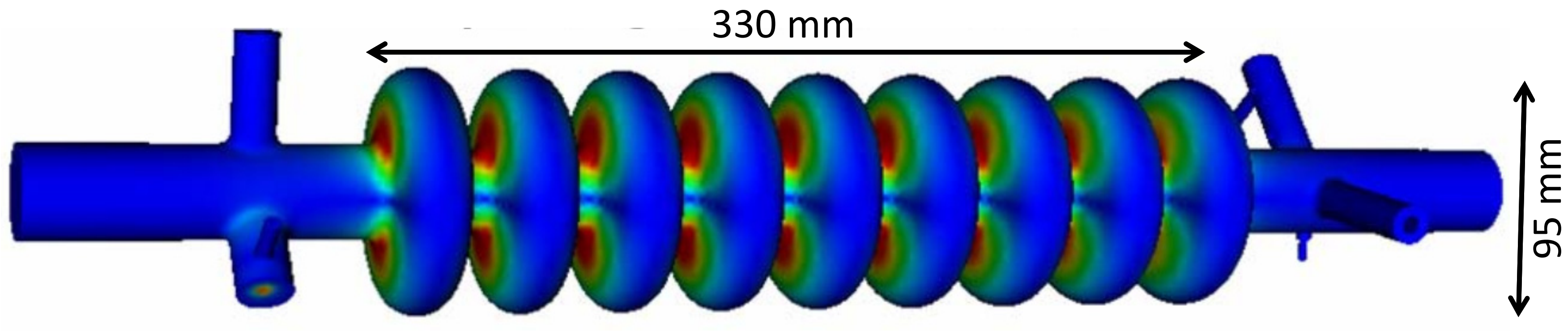




Future linear colliders	ILC	CLIC
RMS bunch length (mm)	0.3	0.044
RMS bunch width (nm)	474	45
Crossing angle (mrad)	14	20
Piwinski angle	4.4	9.8
Lumi reduction F (% of $L_{head\text{-}on}$)	22	10

- Bunches have one **single chance** to collide
- Use **well focused beams** to increase luminosity
- **Crab crossing** to compensate the crossing angle and recover head-on collisions

Crab cavity system for ILC [C. Adolphsen, 2007]



3.9 GHz TM110 TW 9-cell niobium cavity in π-mode operated at 1.8 K

- **Two** cavities per beam
- **5 MV/m peak deflection** each cavity

Challenges:

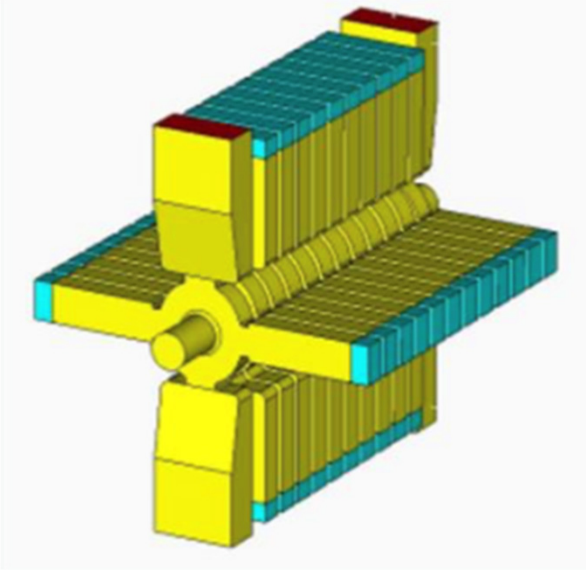
- Synchronization between cavities to **limit luminosity loss to 2%**:
  - **Requires phase control** within **0.086 deg** (61 fs)
  - **Demonstrated 0.052 deg** (37 fs) control for 7-cell 1.5 GHz prototype tested at JLab
- Requires **damping for LOM, HOM and vertical** polarization **of SOM**

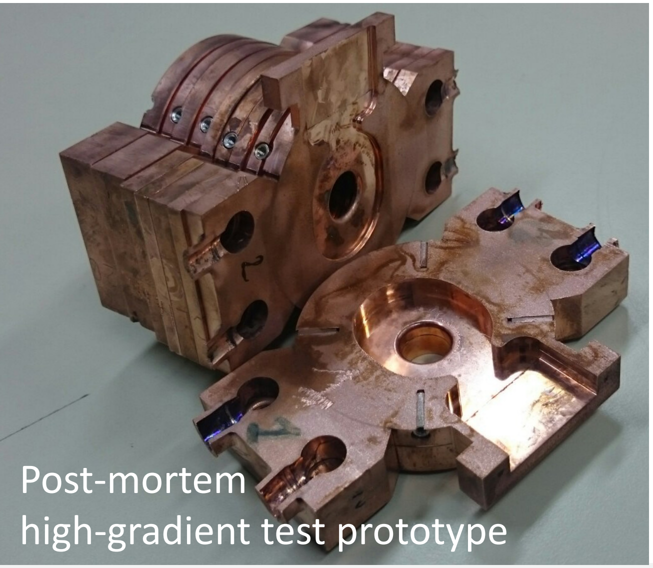
Crab cavity system for CLIC [B. Woolley, 2015] [N. Catalan-Lasheras, 2014]

11.994 GHz 12-cell race-track TW CI structure in copper with waveguide dampers

Challenges:

- Synchronization between cavities:
  phase control within **0.02 deg** (4.6 fs)
- Requires **HOM damping**, esp. vertical wakefield kicks
- E_{peak} ~ 88.8 MV/m for 2.55 MV kick: **verify BDR**





High-gradient RF tests performed in Xbox2 (CERN):

- Different coupler, no dampers
- 43 MW, 200 ns flat-top, breakdown rate < 10^{-6} bd/pulse: **well beyond nominal 13.35 MW**

Crab cavity systems for circular colliders

In LHC for proton-proton collisions:

- **HiLumi LHC** (the High-Luminosity upgrade of LHC)

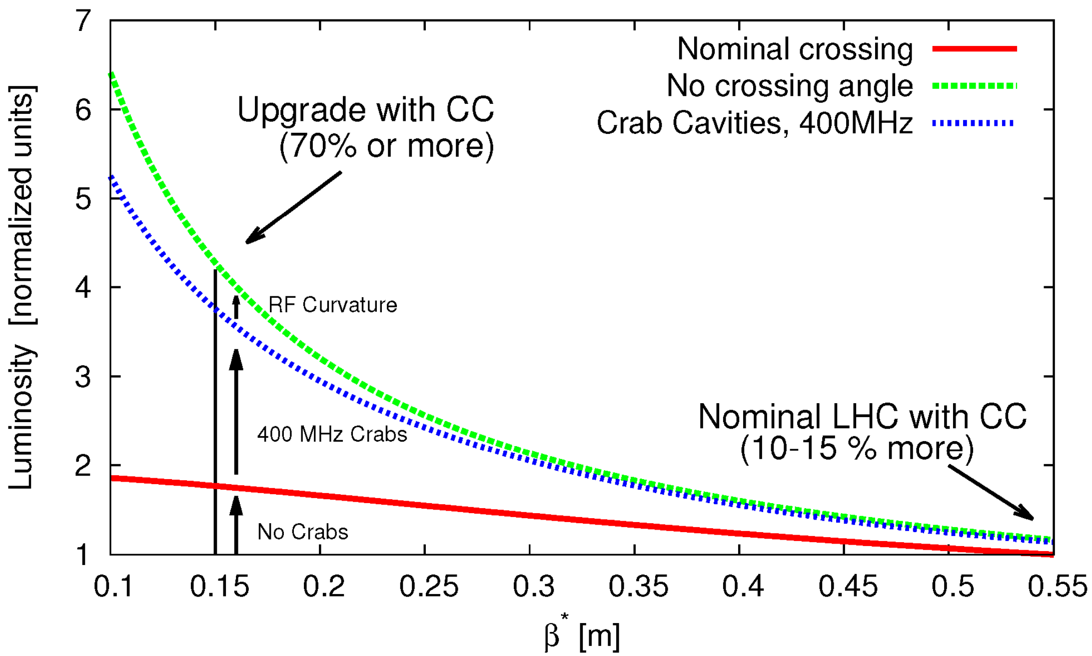
In the two competing designs to become the next electron-ion collider:

- **JLEIC** (Jefferson Lab electron Ion Collider)
- **eRHIC** (electron Relativistic Heavy Ion Collider)

Crab crossing for full exploitation of HiLumi LHC

LHC upgrade: decrease β^* (0.55 → 0.15 m); **increase θ_c** (0.280 → 0.590 mrad)

- Potential luminosity increase with crab cavities:



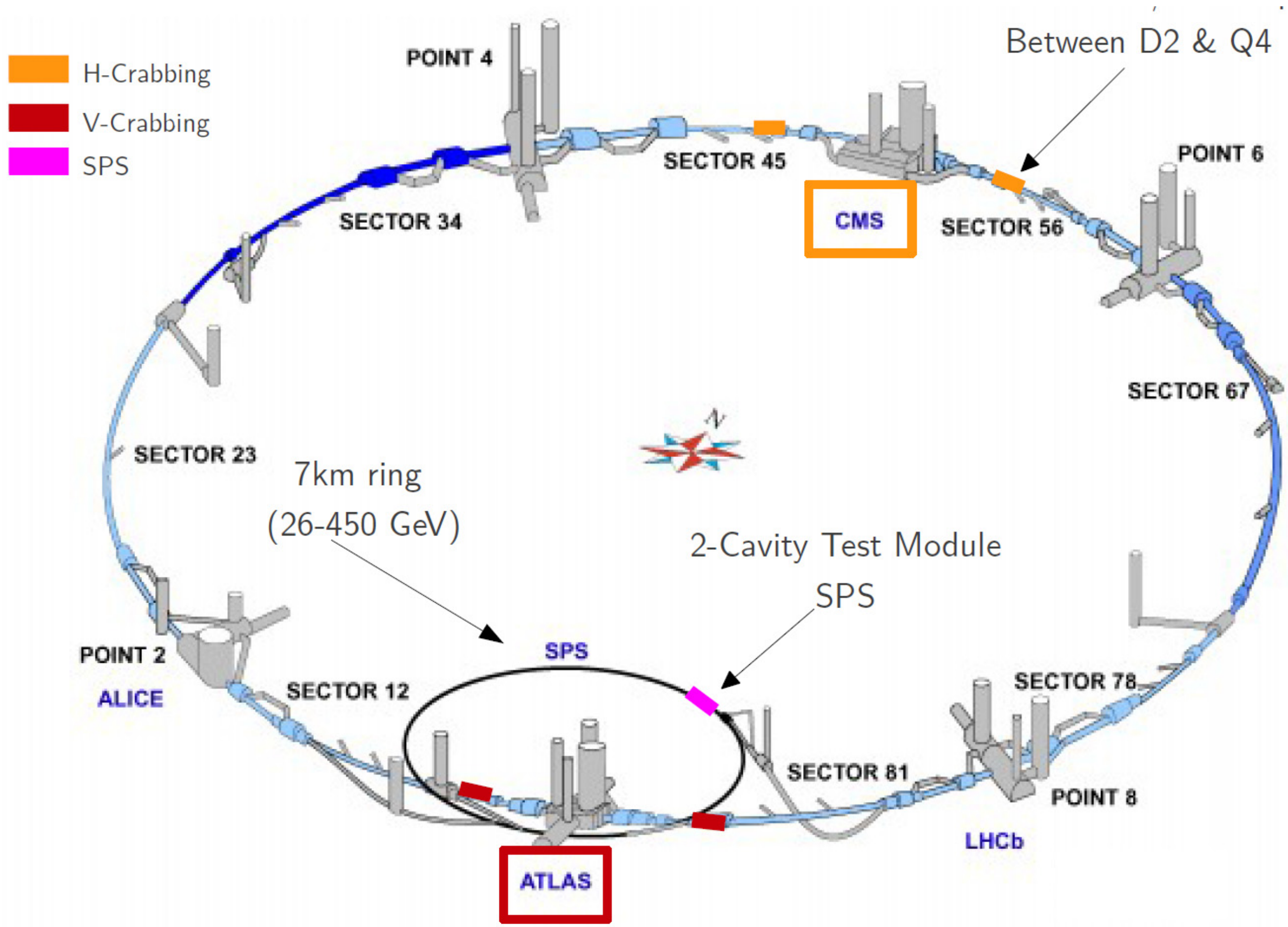
- Include **crab cavity system** for **crossing angle compensation**

Bunch length	(mm)	75.5
Bunch width	(mm)	0.007
Crossing angle	(mrad)	0.590
Piwinski angle		3.18

Crab cavity system for HiLumi LHC

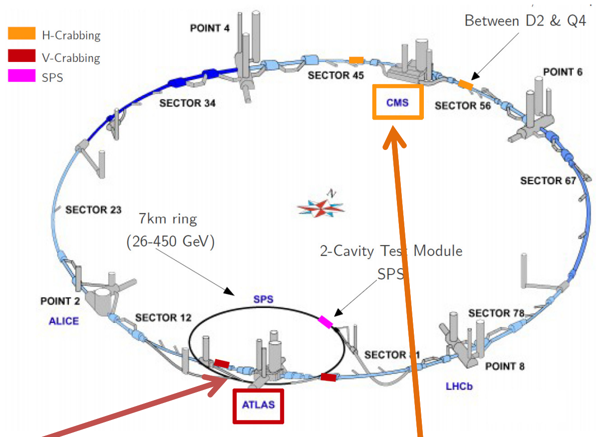
CRAB CAVITY SYSTEM

- Local scheme
- 16 crab cavities + 4 spare



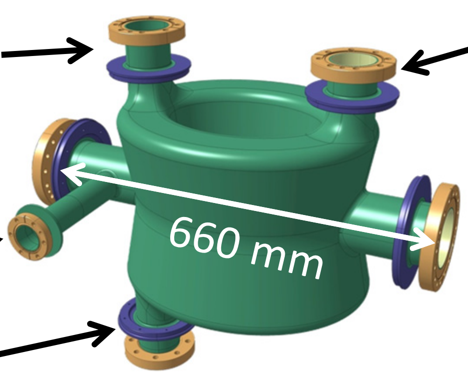
Crab cavity system for HiLumi LHC

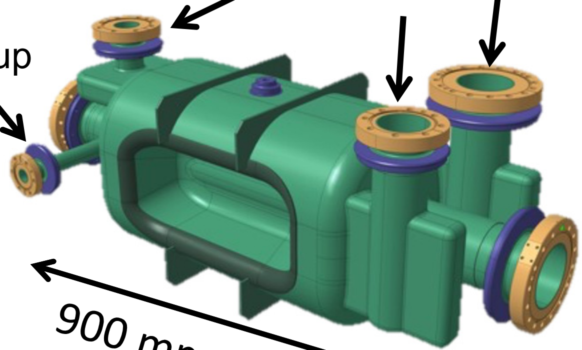
- **400 MHz** niobium cavities operated **at 2 K** providing **Vt = 3.34 MV per cavity**
- Requires **HOM damping** (crabbing provided by fundamental mode in DQW and RFD)
- **Two designs**, each better adapted for an IP:



Double-Quarter Wave (DQW)
by BNL/CERN

RF dipole (RFD)
by ODU/SLAC

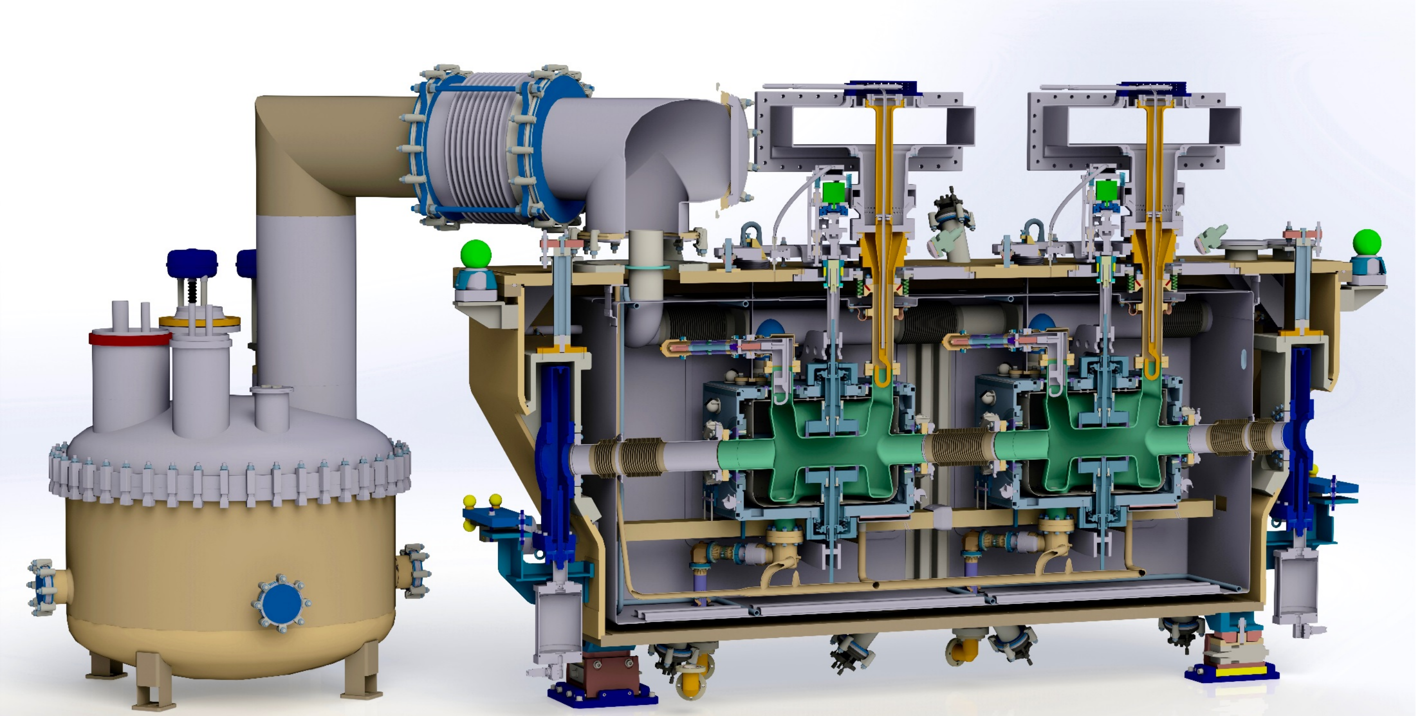




Crab cavity system for HiLumi LHC

Towards beam test in SPS of a cryomodule with 2 fully-equipped DQW crabs

- Deflecting kick, bunch rotation, transparency, emittance growth, multipacting, HOM damping
- Evaluate cryogenic loads, machine protection, vacuum, LLRF controls, system alignment



Cryomodule for SPS tests of 2 fully-equipped DQW crab cavities

Crab cavity system for HiLumi LHC

Towards beam test in SPS of a cryomodule with 2 fully-equipped DQW crabs

PRODUCTION

- 2 bare DQW cavity prototypes by US-LARP
- 2 DQW cavities built in-house at CERN
- Other equipment: He tanks, magnetic and thermal shields, tuner, HOM filters, etc

HOM filter (CERN)

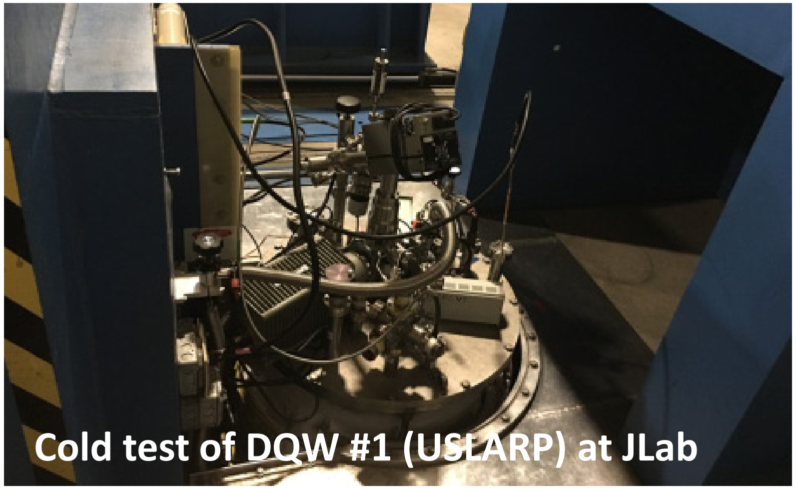
FPC (CERN)

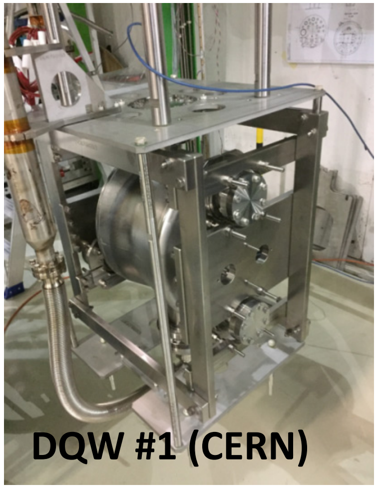
Vacuum vessel (CERN)

Successful bare cavity cold tests of DQW and RFD

- Transverse voltage beyond nominal (3.4 MV); FE onset beyond 3.4 MV.

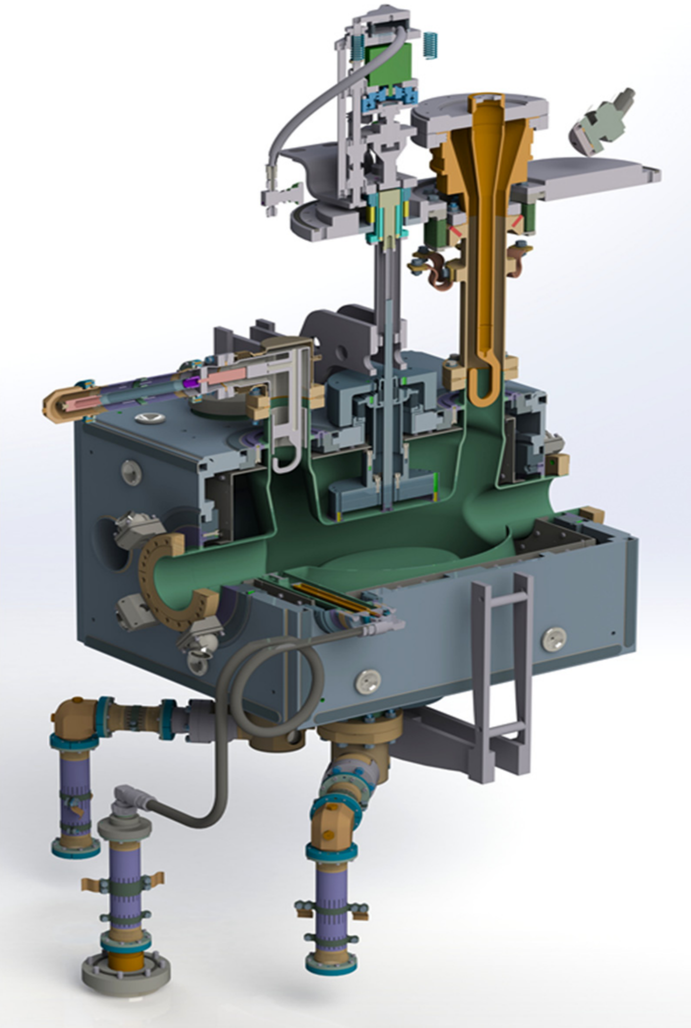
		DQW #1 (CERN)	DQW #2 (CERN)	DQW #1 (USLARP)	DQW #2 (USLARP)	RFD #1 (USLARP)	RFD #2 (USLARP)
Max.Vt	(MV)	**5.04**	**4.8**	**5.8**	TBD	**4.4**	TBD
E_{peak}	(MV/m)	56	54	65		42	
B_{peak}	(mT)	109	103	125		73	
Min. Rs	(nΩ)	10	10	9		11	
Rs at 3.4 MV	(nΩ)	15	18	15		13	
FE onset	(MV)	4.0	3.5	4.5		No FE	

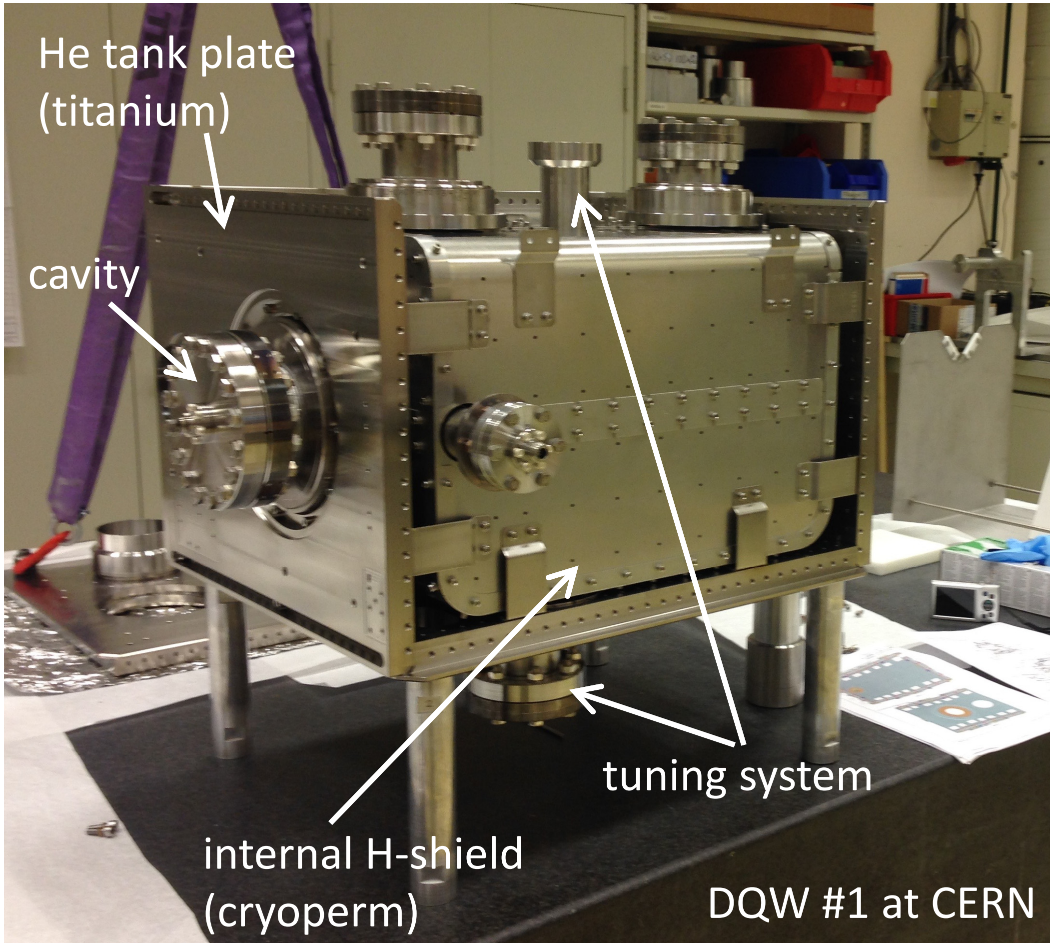




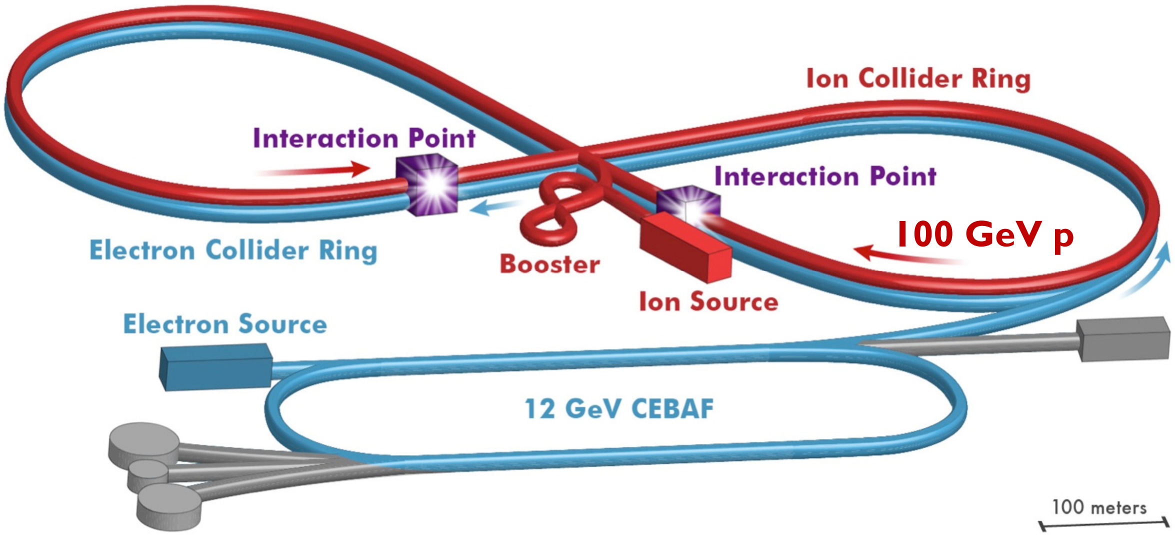
Moving forward: preparing for cold test of fully dressed cavity

- **Finalized dressing** DQW #1 (CERN): internal H-shield, He tank, tuning system.
- **Completed pre-tuning** and now getting prepared for **cold test in SM18**.





Crab cavity system for JLEIC



JLEIC		*proton*	*electron*
RMS bunch length	(mm)	22	10
RMS bunch width	(mm)	0.03	0.03
Crossing angle	(mrad)	50	
Piwinski angle		18.6	8.4

- **Crab crossing** in the two IPs for Luminosity ~ 10^{34} $cm^{-2}s^{-1}$
- Uses **local scheme**

Crab crossing for JLEIC

[J. Delayen, 2017] [V. U. Morozov, 2017]

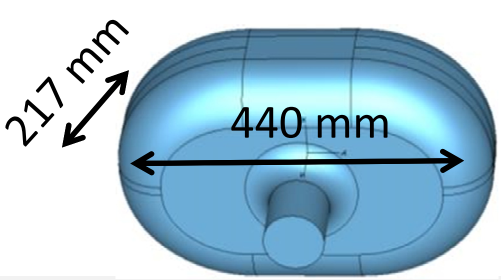
TRANSVERSE VOLTAGE

	proton	*electron*	
Beam energy	**100**	**10**	GeV
β-function at crabs	**750**	**200**	m
β-function at IP	0.1		m
Crossing angle	50		mrad
RF frequency	**952.6**		MHz
Transverse voltage	**14.5**	**2.8**	MV

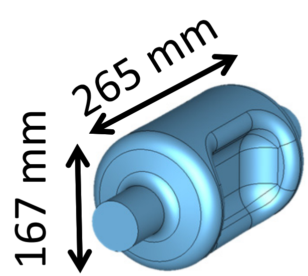
$$V_{\perp} \simeq \frac{\theta_C E_0 c}{2\omega_{RF}\sqrt{\beta^* \beta_{crabs}}}$$

FREQUENCY CHOICE: 952.6 MHz

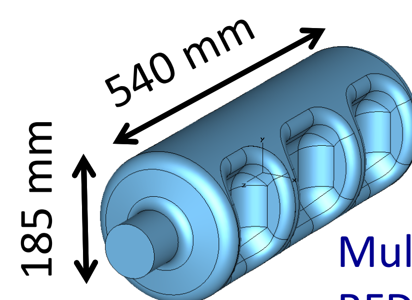
- High bunch repetition rate: 476.3 MHz
- Space constraints in transverse and longitudinal: compact cavities
- Multiturn simulations with 10 mm long bunch - reduced banana-shaping



squashed elliptical

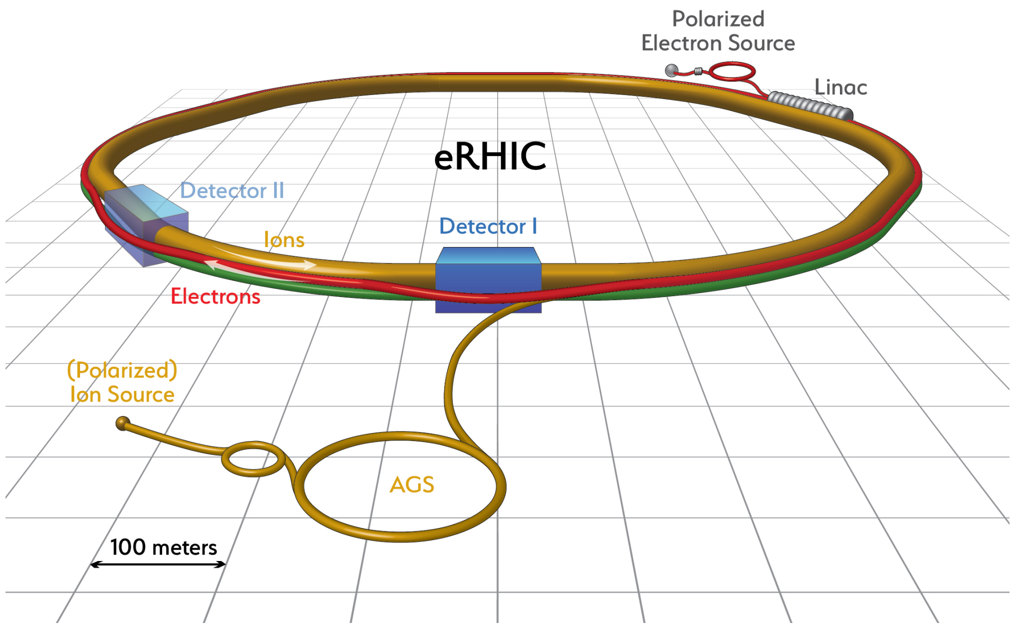


RFD



Multicell RFD

Crab cavity system for eRHIC



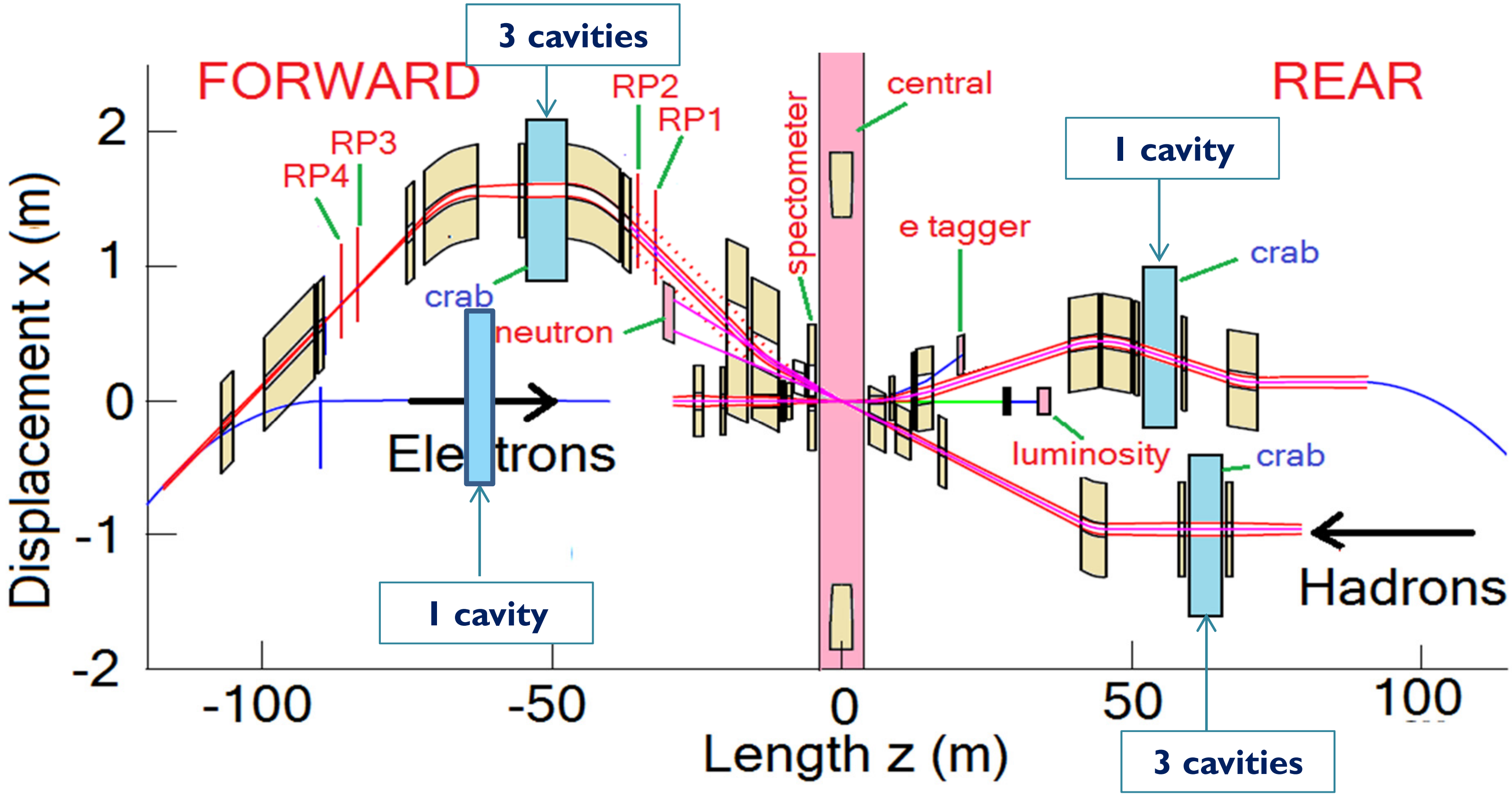
eRHIC		*proton*	*electron*
RMS bunch length	(mm)	70	4.3
RMS bunch width	(mm)	0.123	0.123
Crossing angle	(mrad)	22	
Piwinski angle		6.26	0.38

- **Crab crossing** in the two IPs for Luminosity ~ 10^{34} $cm^{-2}s^{-1}$

Layout of eRHIC interaction region

[R. Palmer, 2017]

- **Crab crossing** in the two IPs using **local scheme**
- **3 crabs per side for proton beam; 1 crab per side for electron beam**



Crab crossing for eRHIC

[Y. Luo, 2017] [Y. Hao, 2017]

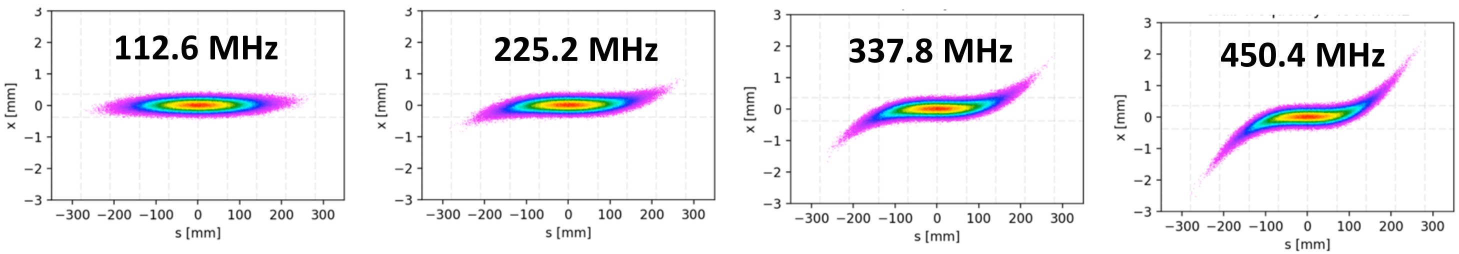
TRANSVERSE VOLTAGE

	electron	*proton*	
Beam energy	**18**	**275**	GeV
β-function at crabs	TBD	1200	m
β-function at IP	0.62	0.94	m
Crossing angle	22		mrad
RF frequency	**337.8**		MHz
Transverse voltage	**<4**	**13**	MV

$$V_{\perp} \simeq \frac{\theta_C E_0 c}{2\omega_{RF}\sqrt{\beta^* \beta_{crabs}}}$$

FREQUENCY CHOICE: 337.8 MHz

- Bunch repetition rate: 9.4 MHz
- No tight spacial constraints
- Crabs recover almost 90% $L_{head\text{-}on}$; loss does not increase over multiturn

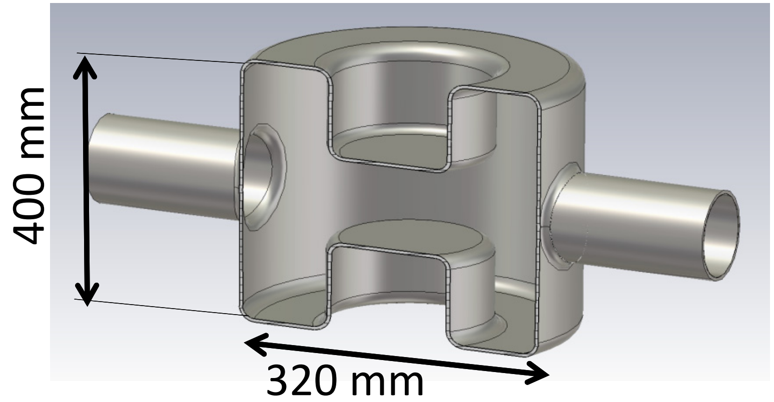


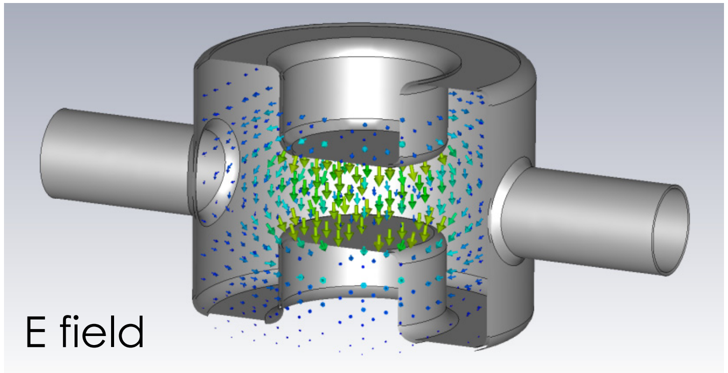
Crab cavity design for eRHIC proton beam

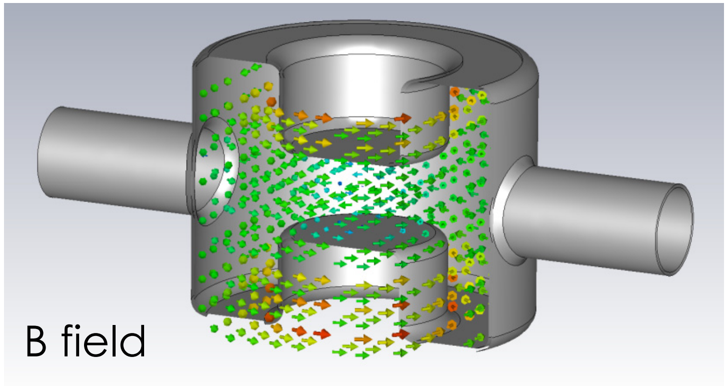
- Based on DQW for HL-LHC

Preliminary design

RF frequency	**337.8**	MHz
First HOM frequency	527	MHz
Rt/Q	373	Ohm
Geometry factor	**102**	Ohm
Epeak / Vt	**12.7**	m^{-1}
Bpeak / Vt	**17.5**	mT/MV







Summary: Crab Cavity Systems for Future Colliders

- **Initial proposal** in 1988 for TeV-range **linear colliders**
- **First implemented** in e-e+ **circular collider** KEK-B (2007 – 2010)
- Currently **many colliders include crab** cavities to compensate Xangle
  - Different crossing angles, frequencies, particles, beam energies and bunch dimensions
  - New, **compact cavity** designs proposed: DQW, RFD
- **First crab** cavity test with **proton** beam coming soon at **SPS in 2018**
- Crab/deflecting cavities **beyond luminosity**:
  - bunch compression, longitudinal phase space diagnostics, emittance exchange and ultra-short synchrotron radiation pulse generation

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Thanks for your attention

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