HOMs for Superconducting Deflecting and Crabbing Cavities

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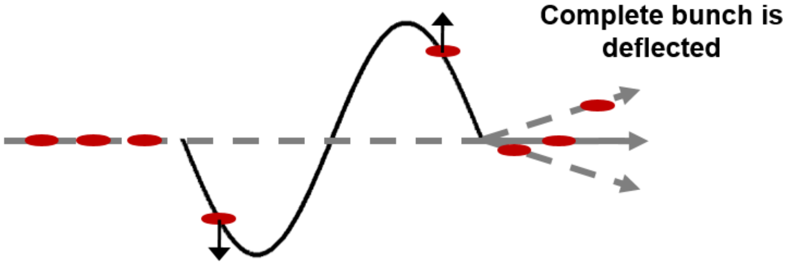
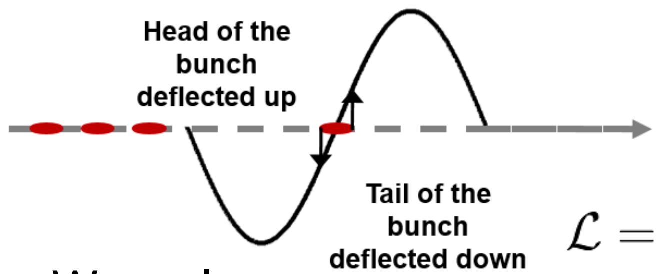
Deflecting / Crabbing Concept



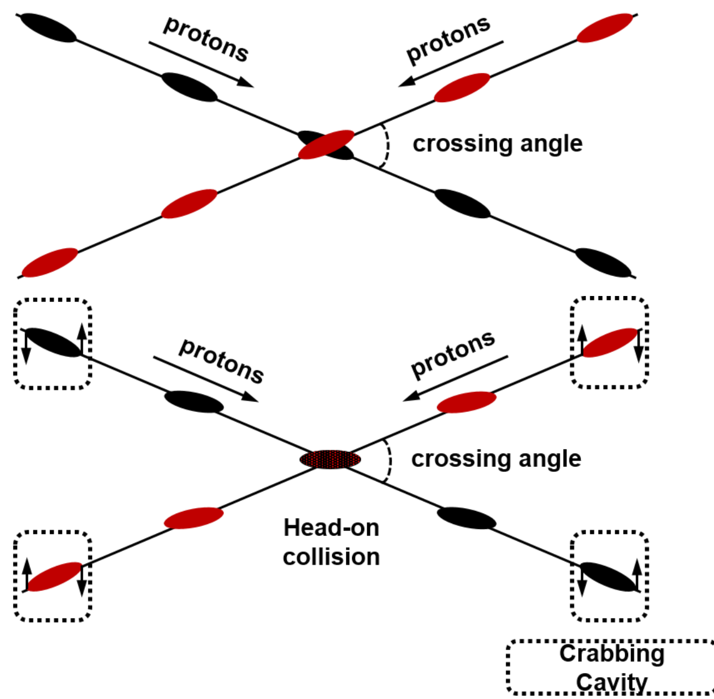


$$\mathcal{L} = \frac{N_1 N_2 f_c N_b}{4\pi\sigma_x\sigma_y}\frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x}\right)^2}}$$

- Concept of rf separation – Panofsky-Wenzel theorem

  W.K.H. Panofsky and W.A. Wenzel, Rev. Sci. Instrum, 27, 967 (1956)
- Deflecting cavities: Separates beam into multiple beams
- Crabbing cavities:
  - Luminosity management in linear or circular colliders with head on collision → Crab crossing
  - Emittance exchange in beams
  - X-ray pulse compression
  - Beam diagnostics
- Crab crossing – Proposed by R.B. Palmer

  R.B. Palmer, Energy scaling, crab crossing and the pair problem, SLAC-PUB-4707



Superconducting Crabbing Cavities

- All superconducting crabbing cavities are for collider applications

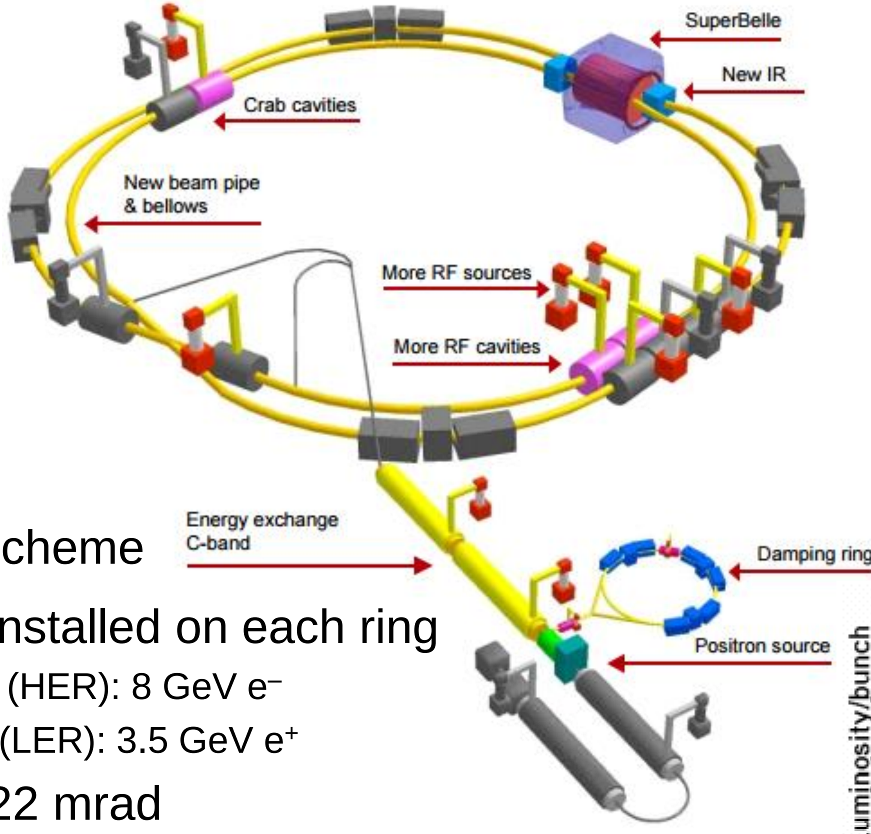
<u>Past, Present and Future Crabbing Systems</u>

- KEK Crabbing Cavity for KEKB Factory
- SPX Crabbing Cavity
- LHC High Luminosity Upgrade
  - 4-Rod Crabbing Cavity
  - Double Quarter Wave (DQW) Crabbing Cavity
  - RF-Dipole Crabbing Cavity
- Future Colliders
  - eRHIC
  - JLEIC

Crabbing System for KEKB Factory

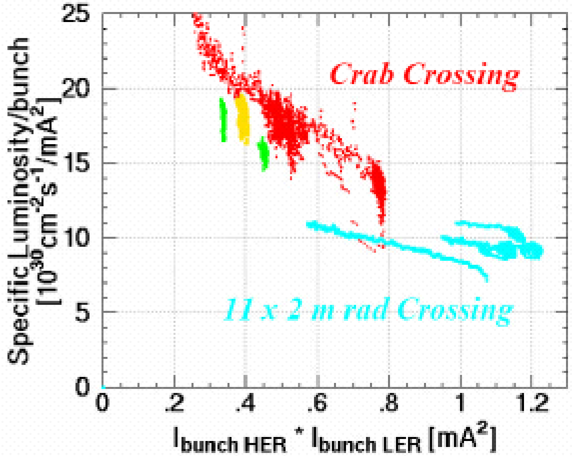
Crab cavity for HER

SuperKEKB Schematic Layout*



Crab cavity for LER

$$L_{sp} = \frac{N_b L_{peak}}{I^+ I^-} \left[cm^{-2} s^{-1} / A^2 \right]$$



- Global crabbing scheme
- One crab cavity installed on each ring
  - High energy ring (HER): 8 GeV e^-
  - Low energy ring (LER): 3.5 GeV e^+
- Crossing angle: 22 mrad
- Crab cavities operated under high current beam from 2007-2010
- Peak luminosity achieved: 21.1×10^{33} /cm^2/s

*Accelerator Design Report, KEK SuperB Factory (2004)

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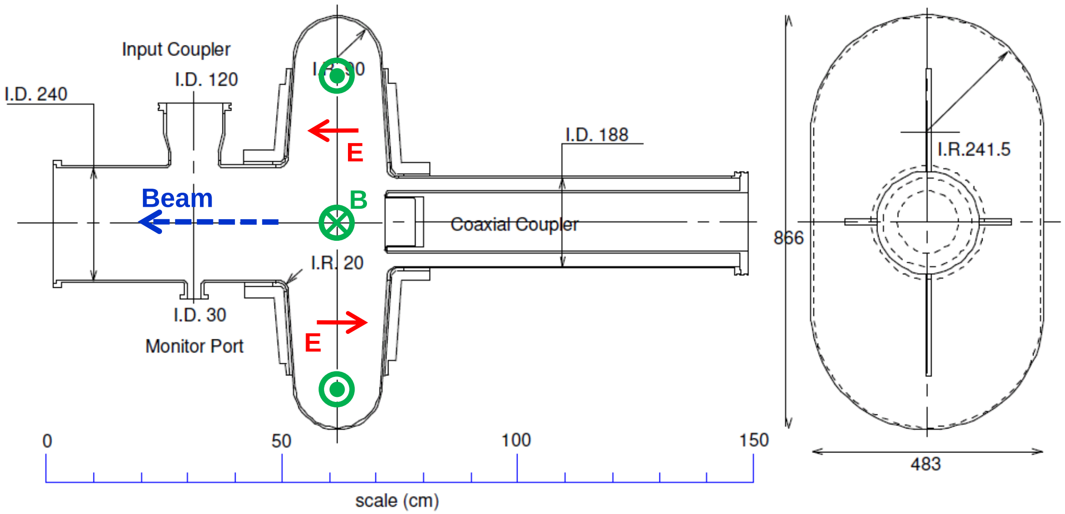
KEK Crabbing Cavity

- Operating frequency – 508.9 MHz
- Squashed elliptical cavity operating in TM_{110} mode
  - Crabbing mode is not the lowest mode
  - Separates the modes with same polarization



Transverse Voltage[#]	HER	LER
Test at Vertical Cryostat	1.9 MV	2.7 MV
At Test Stand	1.8 MV	1.93 MV
Operational	1.7 MV	1.43 MV

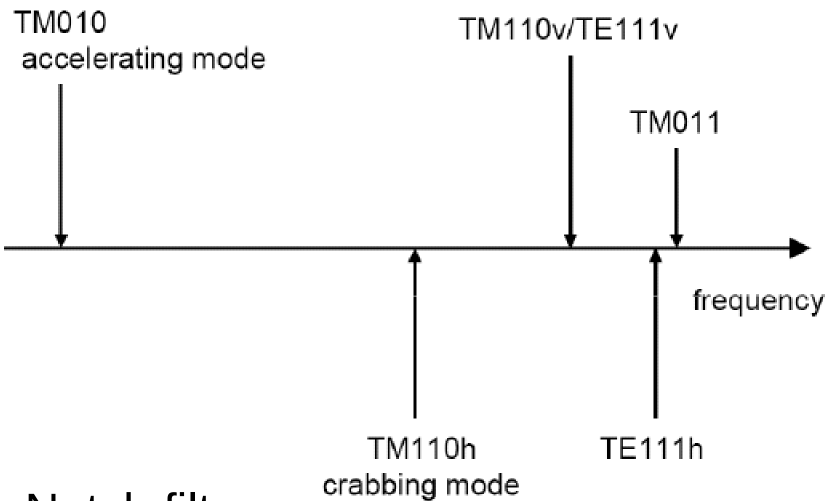
KEK Crabbing Cavity – RF Properties*

Frequency	**508.9**	**MHz**
LOM	410.0	MHz
Nearest HOMs	630.0, 650.0, 680.0	MHz
E_p^*	4.24	MV/m
B_p^*	12.23	mT
B_p^*/E_p^*	2.88	mT/(MV/m)
$[R/Q]_T$	48.9	Ω
Geometrical Factor (G)	227.0	Ω
$R_T R_S$	1.11×10^4	Ω^2
At $E_T^* = 1$ MV/m		

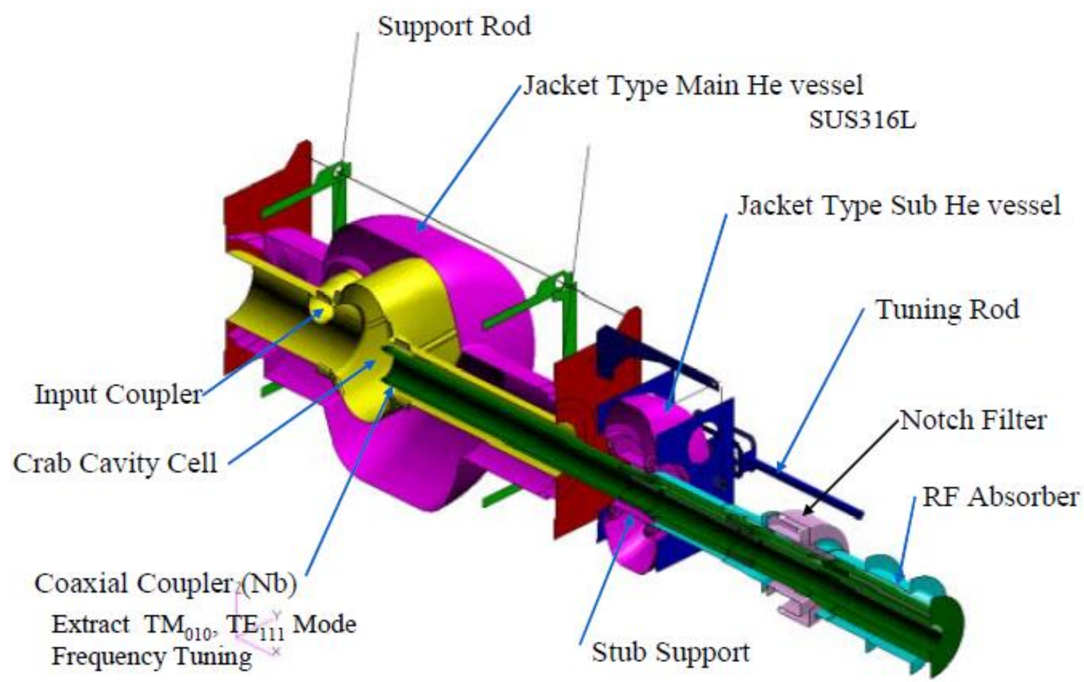
* K. Hosoyama et al, "Crab Cavity for KEKB", Proc. of the 7th Workshop on RF Superconductivity, p.547 (1995)

[#] K. Oide, "Status of SuperKEKB", March 2007

HOM Damping for KEK Crabbing Cavity

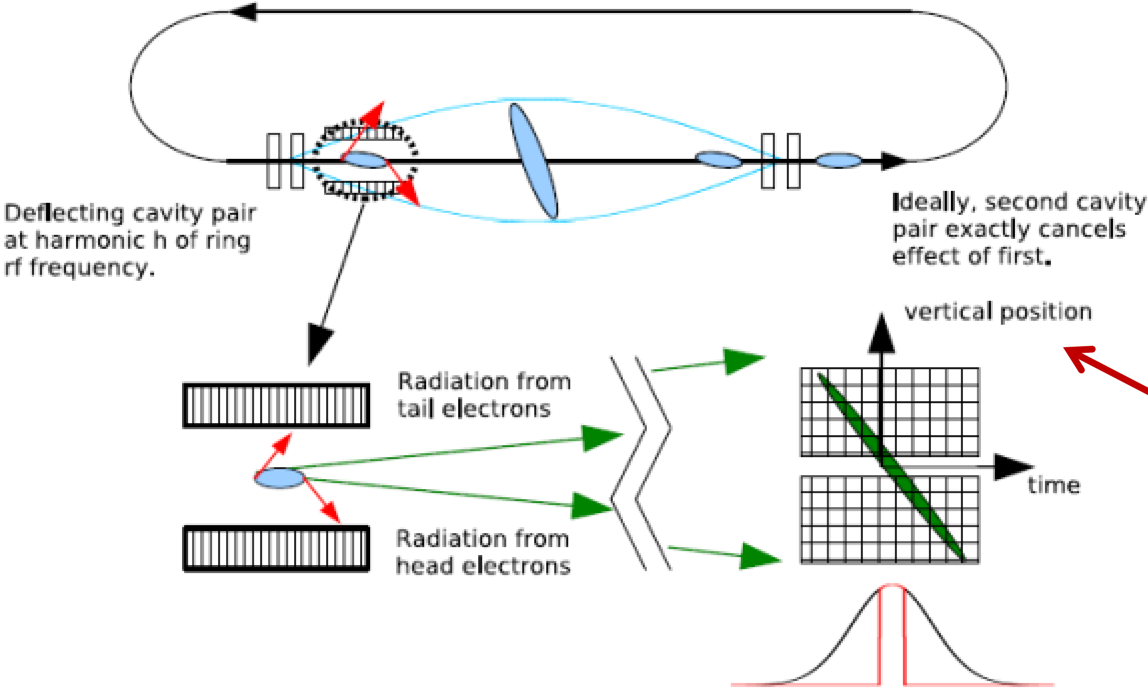


- Low impedance due to low Q_{ext}
- Coaxial coupler:
  - Designed to extract the lower order mode (TM_{010}) and TE_{111} mode
  - Multipacting observed at low RF levels and processed in about 1 hour
  - Centered accurately to prevent propagation of crabbing mode



- Notch filter:
  - Placed at the end of the coaxial coupler rejects crabbing mode flow
- RF Absorbers:
  - HOMs induced by high current beam are extracted from the cavity through the large beam pipe and damped by the ferrite absorbers
- Total HOM power per cavity: 16 kW

Crabbing Cavity for Short Pulse X-ray (SPX) Project



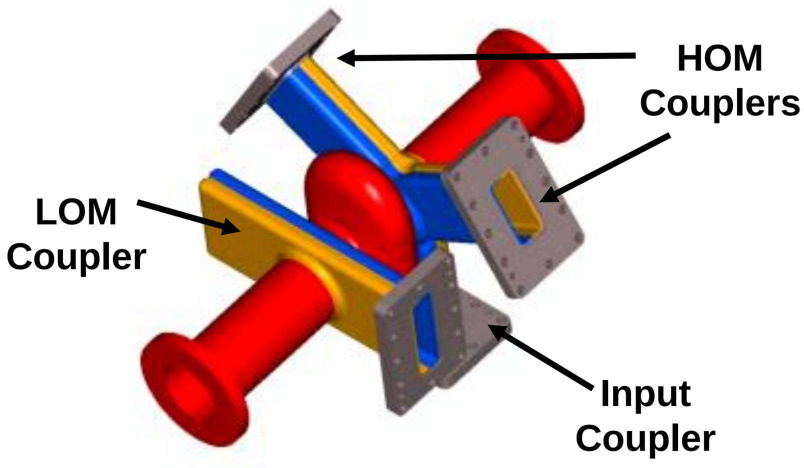
- Generate short x-ray pulses using crabbing cavities
- Beam energy – 7 GeV
- Beam current – 202 mA

Cavity specifications:

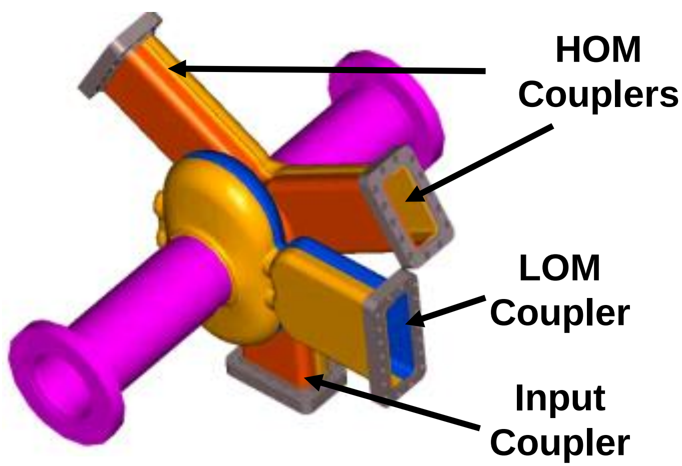
- RF Frequency – 2815.4856 MHz (8th harmonic)
- Transverse voltage per cavity – 0.5 MV

*A. Nassiri, "APS SPX Design Study", July, 2010

Crabbing Cavity for SPX Project



Baseline Design (MARK I)



Alternate Design (MARK II)

RF Properties*

Parameter	Baseline Design	Alternate Design	Units
Frequency	2.815		GHz
Beam iris	25		mm
V_t	0.5		MV
B_p/V_t	195.6	200.8	mT/MV
E_p/V_t	82	81.5	1/m
$[R/Q]_t$	35.8	37.1	Ω
G	227.5	227.8	Ω
Material thickness	3 Nb Sheet	4 Nb Block	mm

Cavity Comparison	MARK I	MARK II
Beam impedance margin	Meets Specs	Excellent
LOM Coupling	on beam pipe	on cavity cell
RF Kick Performance	same	same
Size		Compact
Induced HOM power	Meets Specs	Better

*H. Wang, “SPX Crab Cavity Development and Testing Result”, TTC Meeting, Nov, 2012
#J. Mammosser, “SPX Cryomodule Design”, APS-U Lehman Review, May 2011

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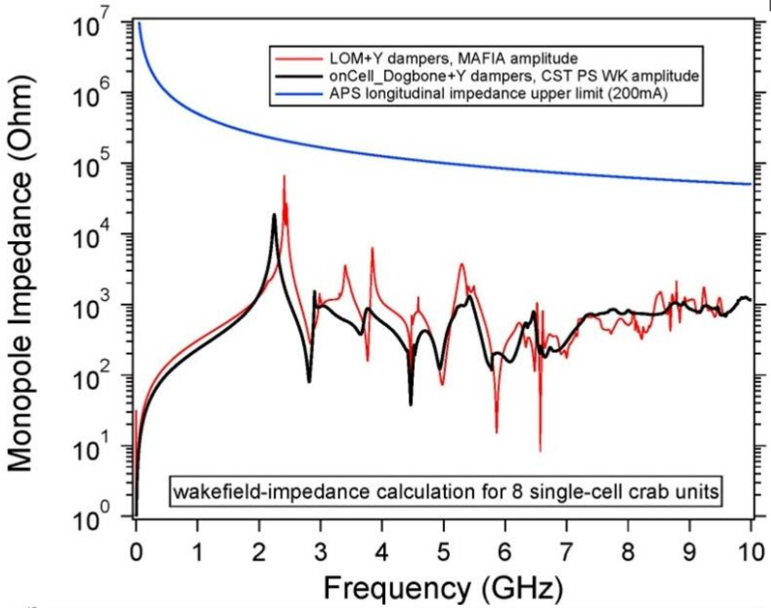
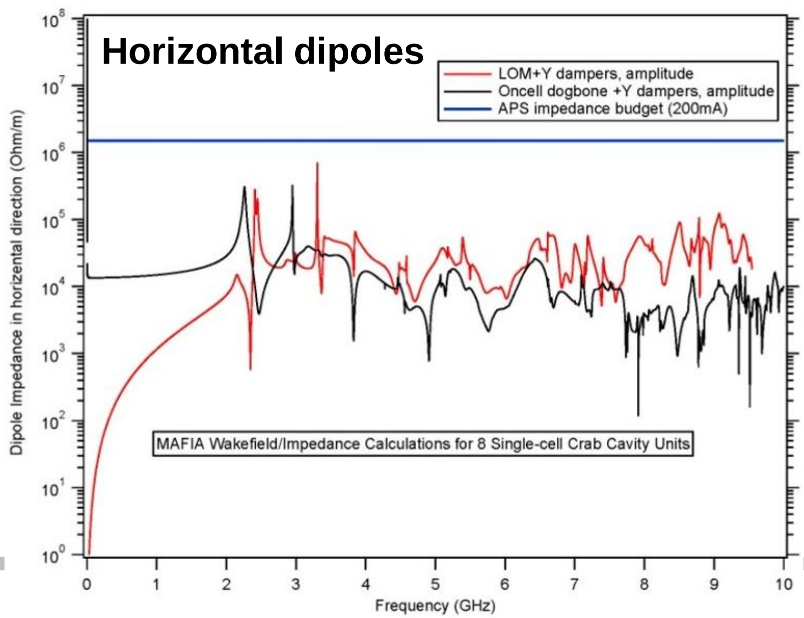
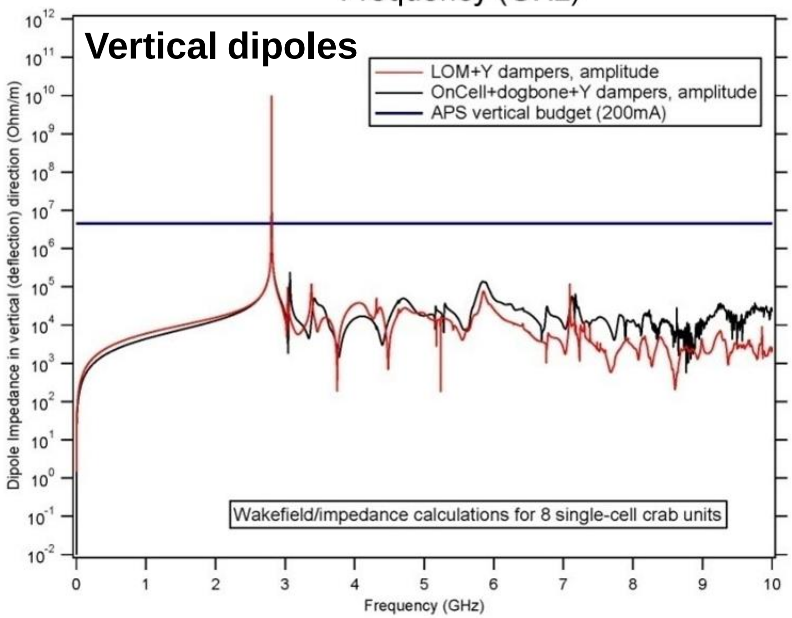
HOM Damping of SPX Crabbing Cavity

- HOM power (w/beam) – 492 W
- LOM power (w/beam) – 1800 W
- Long. threshold: $R_s \times f_p$ < 0.44 MΩ – GHz
- Horz. Dipole threshold: R_t < 1.3 MΩ/m
- Vert. dipole threshold: R_t < 4.5 MΩ/m
- Red line – Baseline Design
- Black line – Alternate Design







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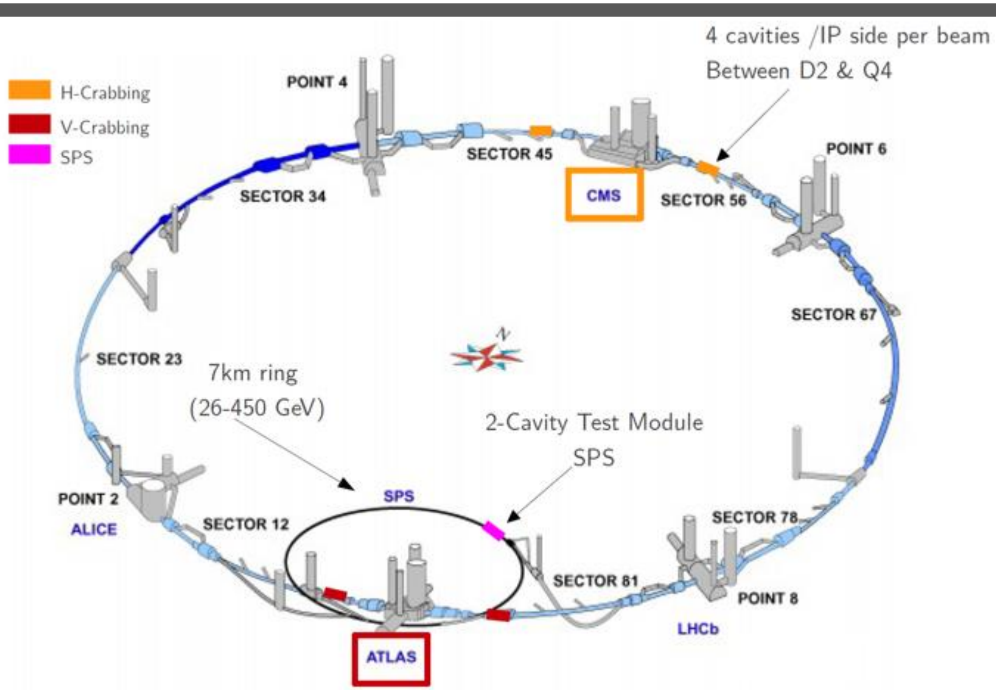
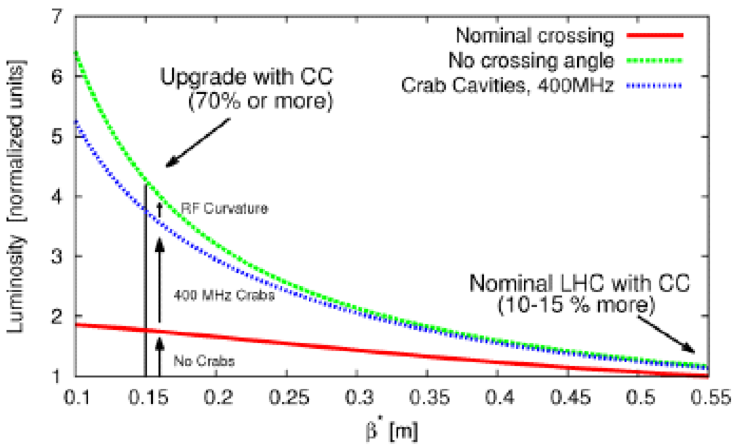
H. Wang, "Wakefield/Impedance Considerations for APS and LHC Crab Cavities", July 2012

Crabbing Cavities for LHC High Luminosity Upgrade

- Proton beam energy: 7 TeV
- Crossing angle: 0.59 mrad
- Requires two crabbing systems at:
  - IP_1 (ATLAS) – Vertical crabbing
  - IP_5 (CMS) – Horizontal crabbing
- RF frequency (f_c) = 400.79 MHz
- Total transverse voltage (V_t) per beam per side = 13.4 MV
- Total 16 crabbing cavities per type
- Transverse voltage per cavity = 3.4 MV





Luminosity increase due to crab cavities

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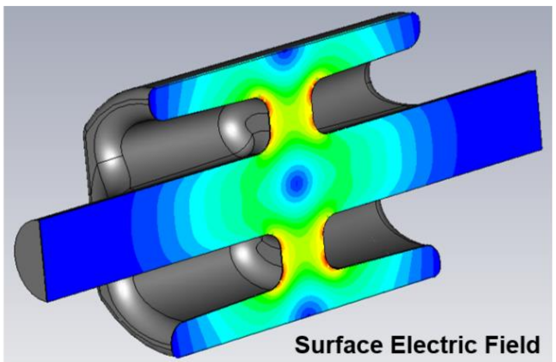
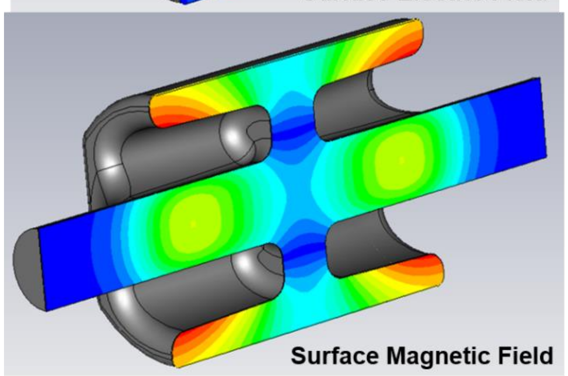
LHC Crabbing Cavities

- Requires compact designs due to low operating frequency
- TM_{110} squashed elliptical geometries are not favorable
- Solution: Designs operating in TEM or TE-like modes

<u>4-Rod Cavity</u>

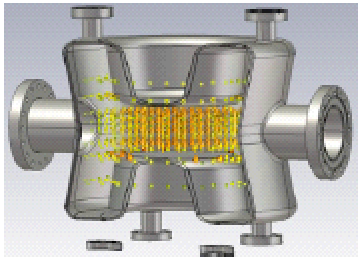
Operating in TEM mode



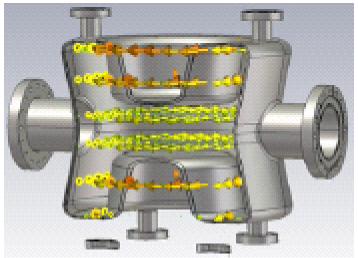


<u>Double Quarter Wave Cavity</u>

Operating in TE-like mode



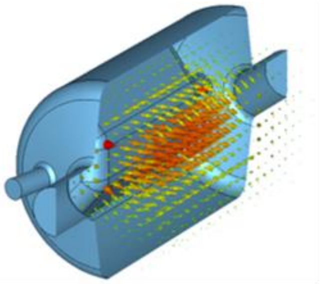
E Field



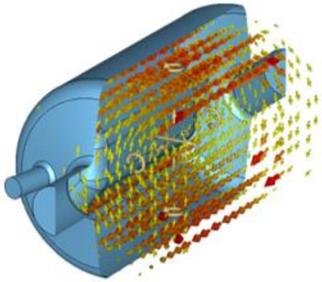
B Field

<u>RF-Dipole Cavity</u>

Operating in TE-like mode



E Field

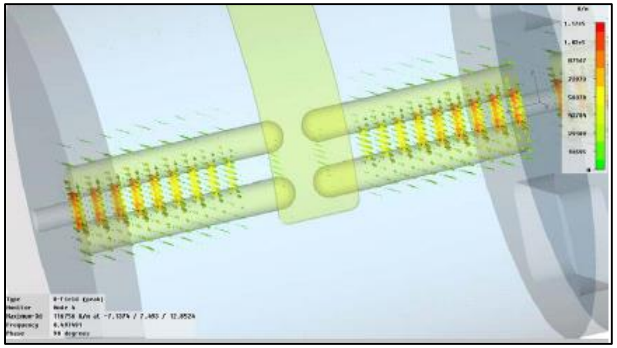


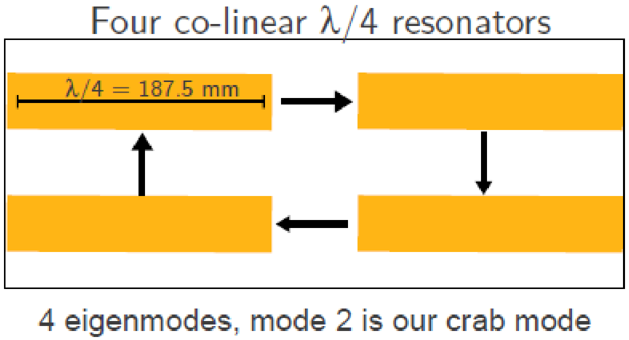
B Field

4 – Rod Crabbing Cavity

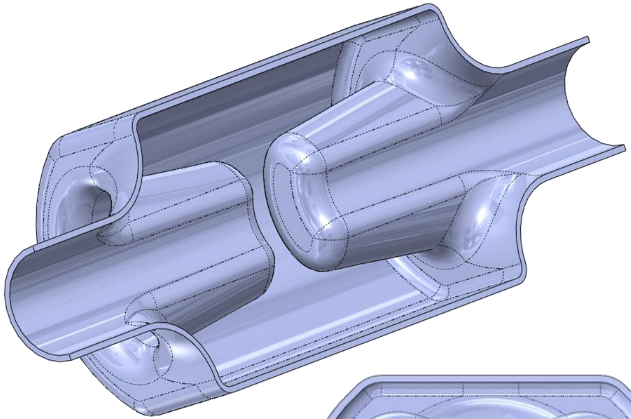
Courtesy: G. Burt (Lancaster University)

- Initial concept from Jefferson Lab normal conducting 499 MHz rf separator

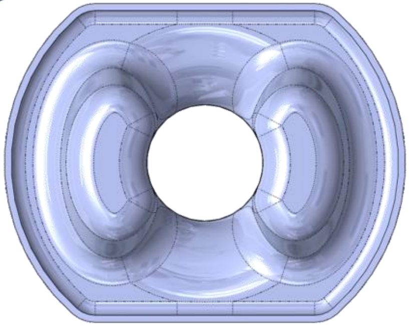




- Improved design:
  - Increased separation between the rods and wider rods
  - Makes rods closer to the outer wall of the cavity
- Proof-of-Principle Cavity

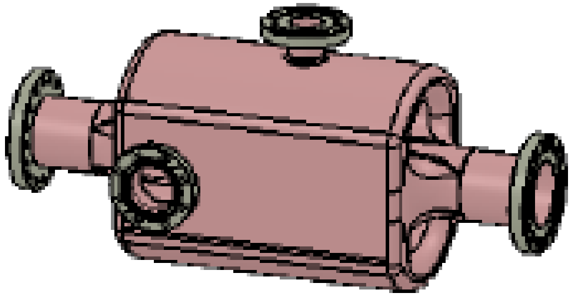


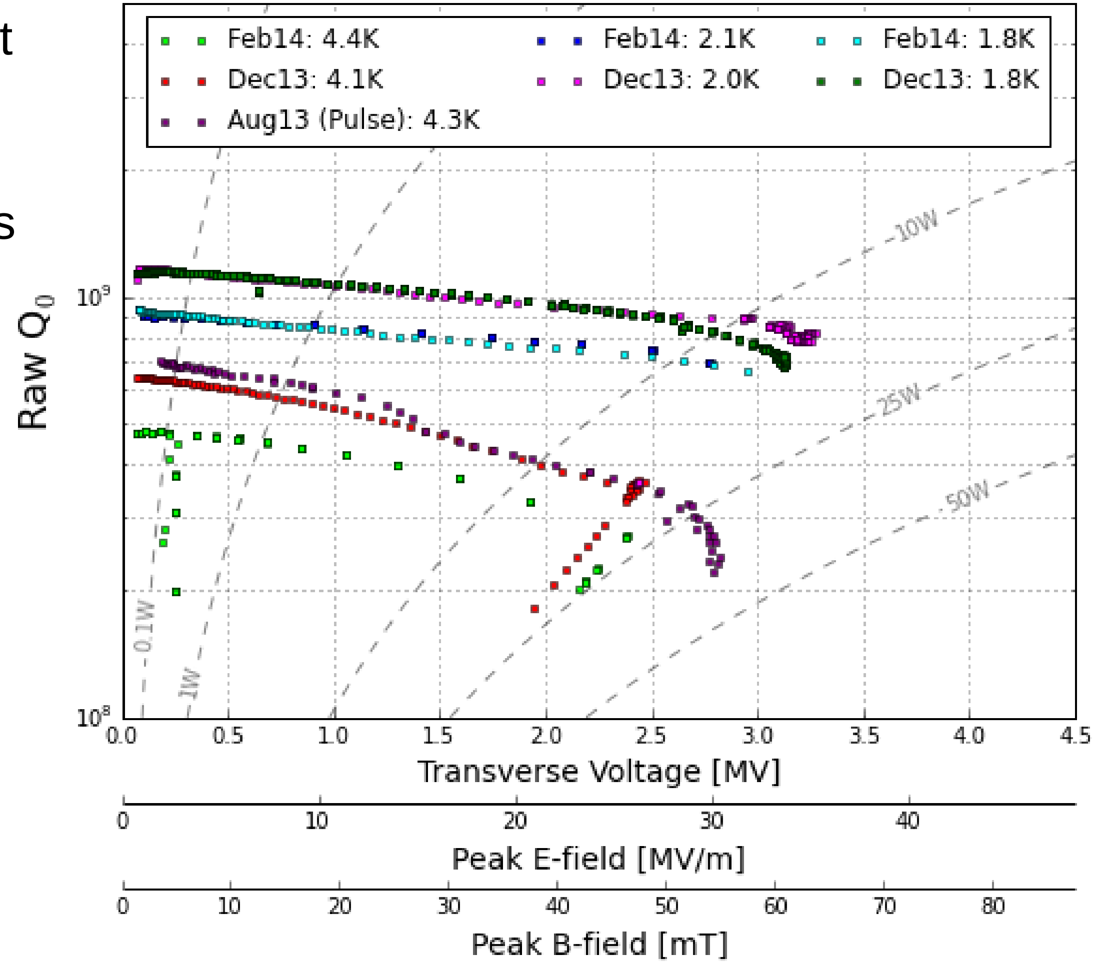
- LOM – 375.2 MHz
- Nearest HOMs - 436.6, 452.1 MHz



4-Rod P-o-P Cavity Cold Test

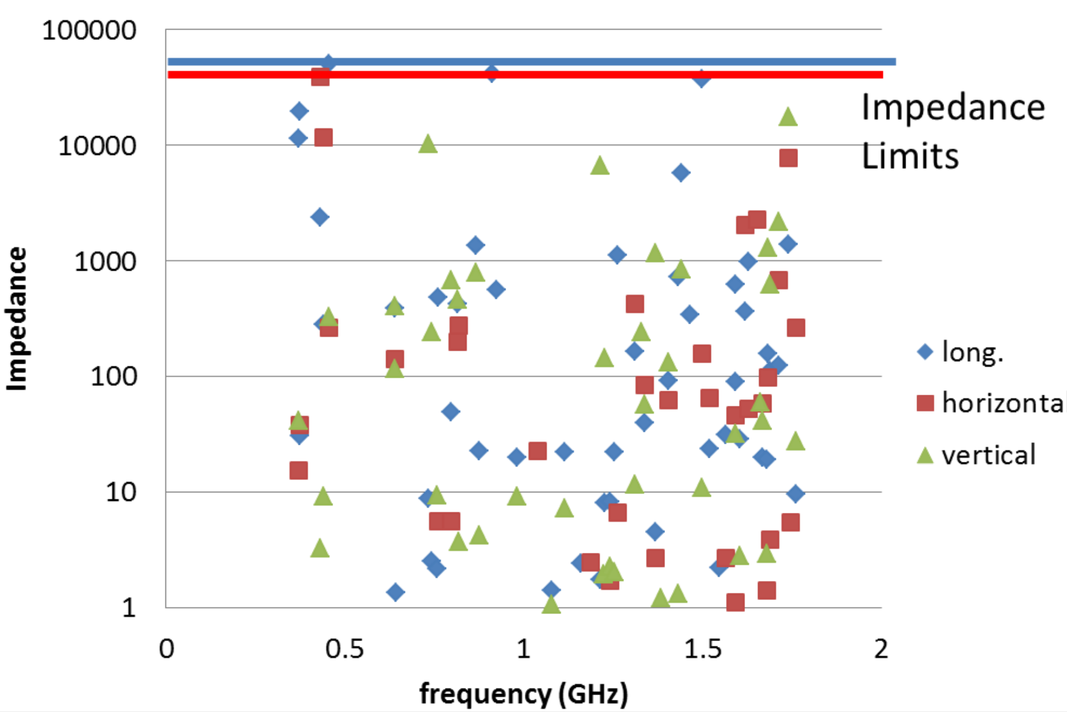
- RF test performed at CERN
- Cavity reached operating gradient with a high residual resistance
- Possible contribution to losses due to the stainless steel couplers
  - Copper
    - $Q_0 = 7.189E9$
    - $R_s = 8.3$ nOhm
  - Stainless Steel
    - $Q_0 = 2.737E9$
    - $R_s = 22.0$ nOhms

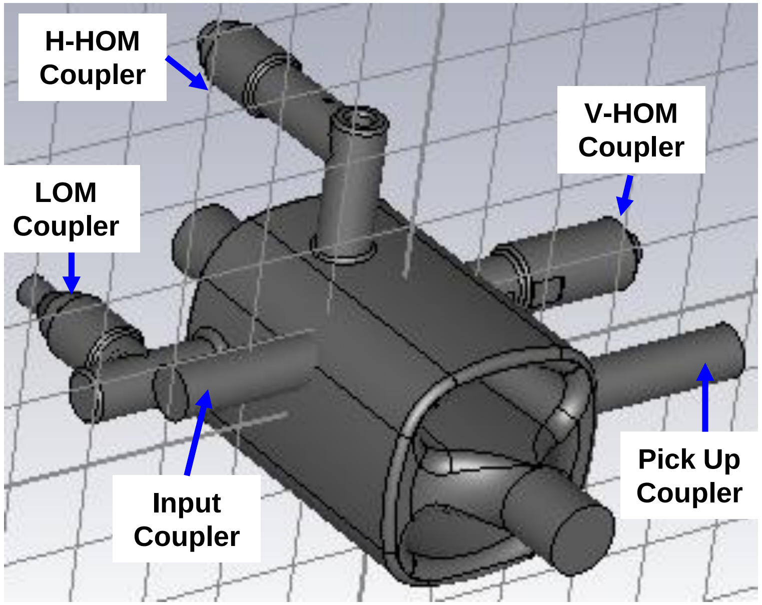




4 – Rod Prototype Crabbing Cavity

- Three HOM couplers
  - LOM coupler
  - Horizontal HOM (H-HOM) coupler
  - Vertical HOM (V-HOM) coupler
- All the couplers are in low magnetic field regions





- **All modes up to 2 GHz are damped up to the required impedance**
- CST calculates few spurious non-existent modes in the couplers
- All 3 components are calculated for each mode

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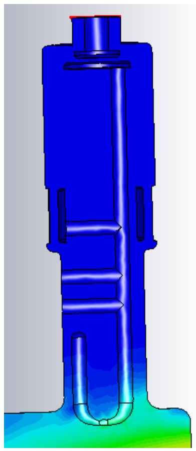
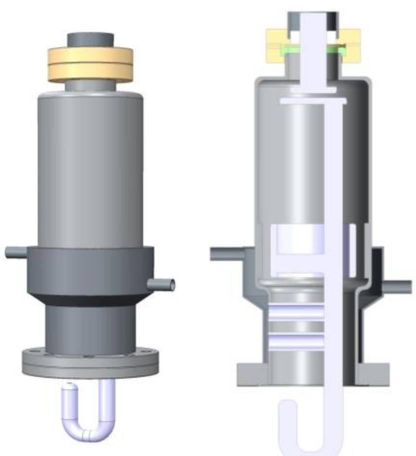
HOM Coupler Designs of 4-Rod Cavity

LOM Coupler

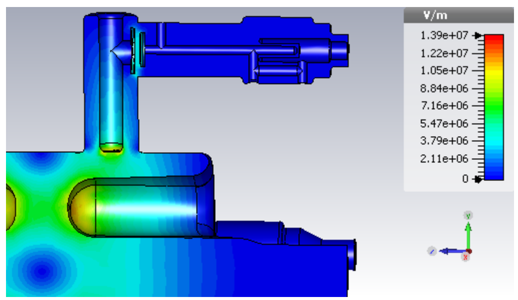
- Sees very little crabbing mode

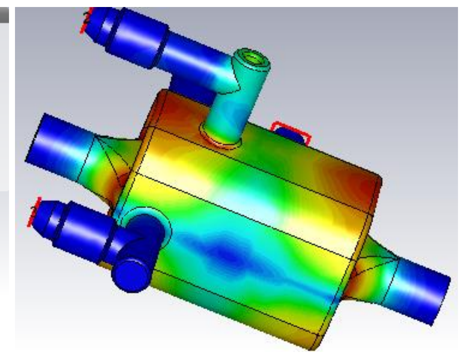


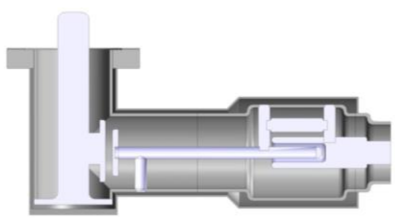


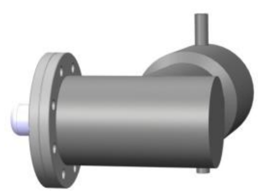
H-HOM Coupler

- Sees very little crabbing mode
- Sees some electric field
- Low magnetic field



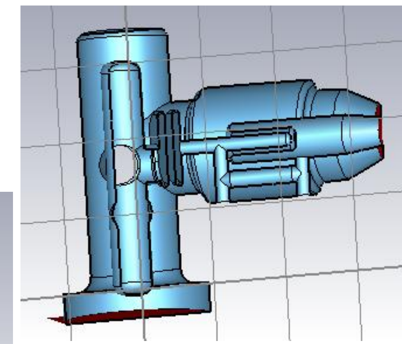


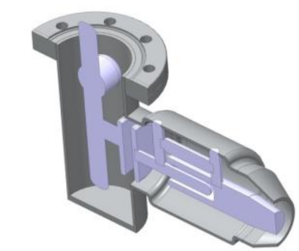




V-HOM Coupler

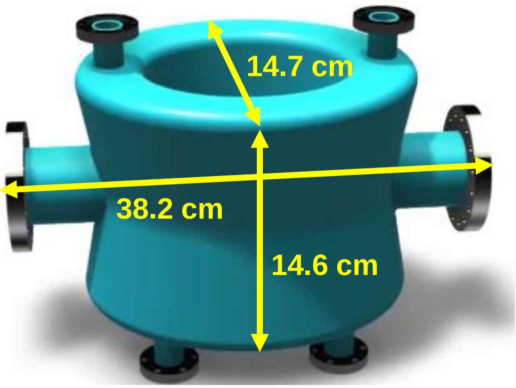
- All the couplers are in low magnetic field region



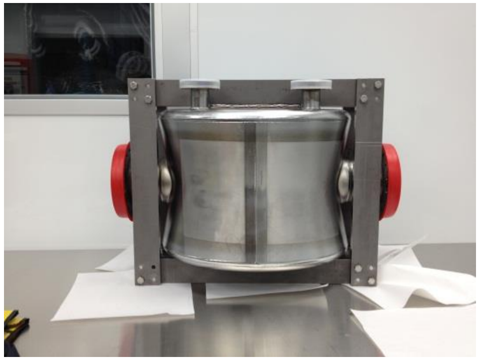


Double Quarter Wave Crabbing Cavity

Proof of Principle Cavity

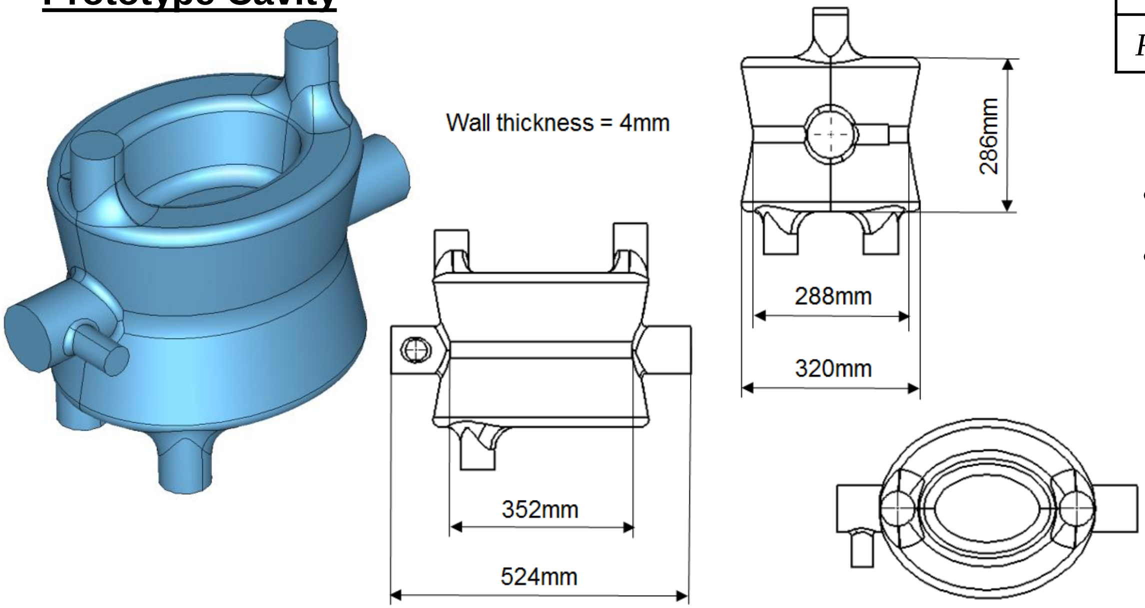


Courtesy: Q. Wu (BNL)



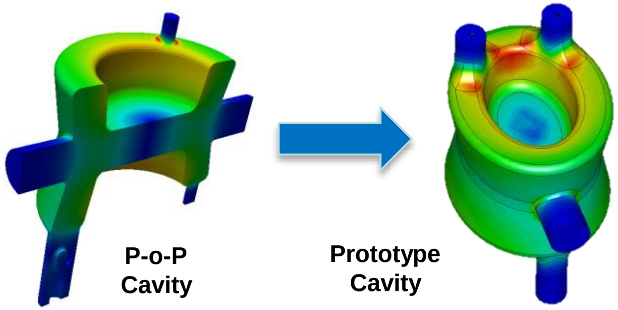
	P-o-P Cavity	Prototype Cavity	
Frequency	**400**	**400**	**MHz**
1st HOM	579	580	MHz
V_t	3.34		MV
E_p	49	40.7	MV/m
B_p	80	70.9	mT
$[R/Q]_t$	406	430	Ω
G	85	89	Ω
R_tR_s	3.45×10^4	3.83×10^4	Ω^2

Prototype Cavity



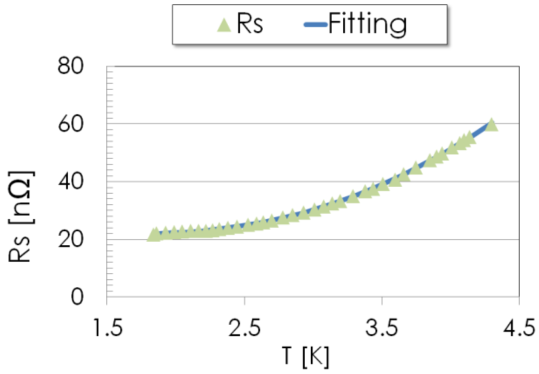
Prototype cavity

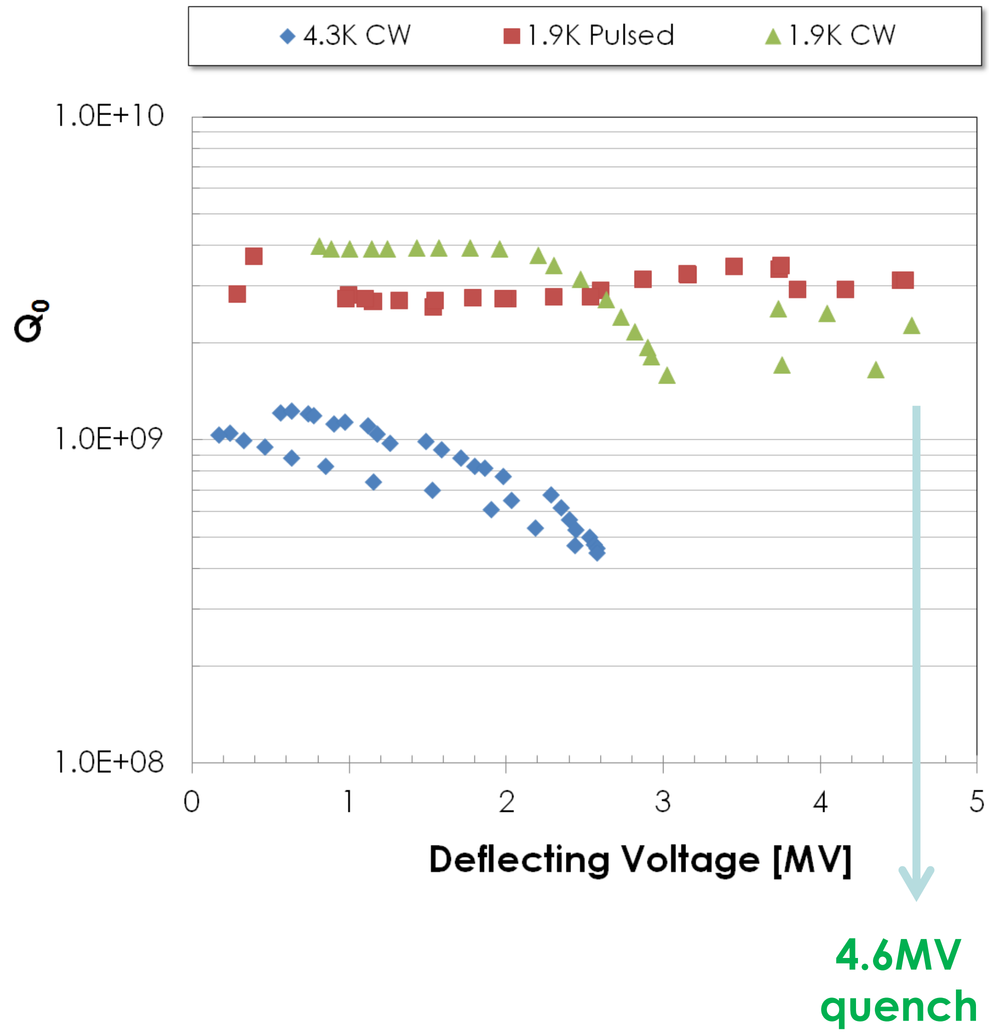
- More compact design
- Lowered peak magnetic field



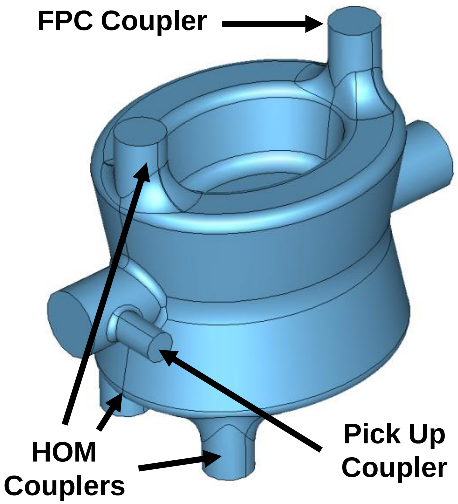
DQW P-o-P Cavity Cold Test

- Q_0 reached 3×10^9 at low field at 2K
- Multipacting is conditioned within 30 minutes
- Reached 4.6MV kick in CW with Q_0 above 2×10^9, limited by quench
- Quench field at ~110mT, with peak E field at 52.8MV/m
- R_s at 4.3K: 57nΩ and at 1.9K: 21.6nΩ
- R_{res} is 21.5nΩ

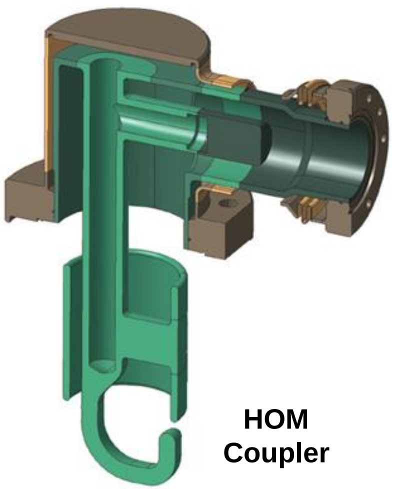




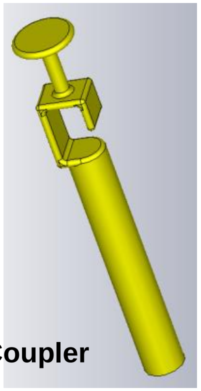
HOM Coupler Designs of DQW Cavity



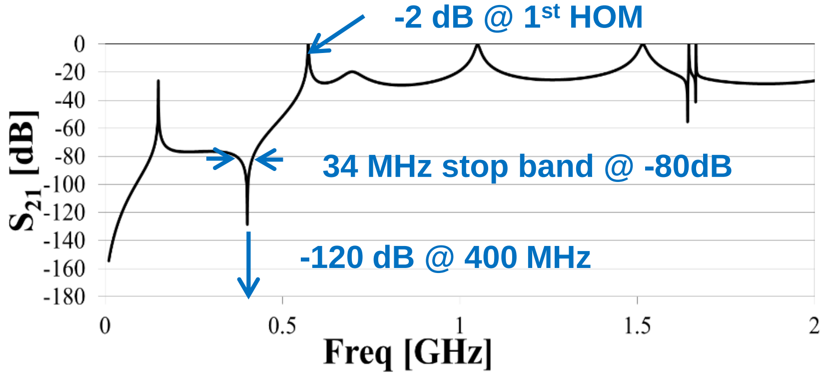
- Three identical HOM couplers
  - Maximum magnetic field on the HOM coupler is 52 mT
  - Maximum HOM power of 1 kW/coupler
- Locations of the couplers are specifically chosen to allow sufficient coupling to all HOMs (with extra damping from Pick Up coupler)
- Coupler hook and filter will be actively cooled by liquid helium
- Pick-up coupler provide damping for a specific HOM at 1.75 GHz



HOM Coupler

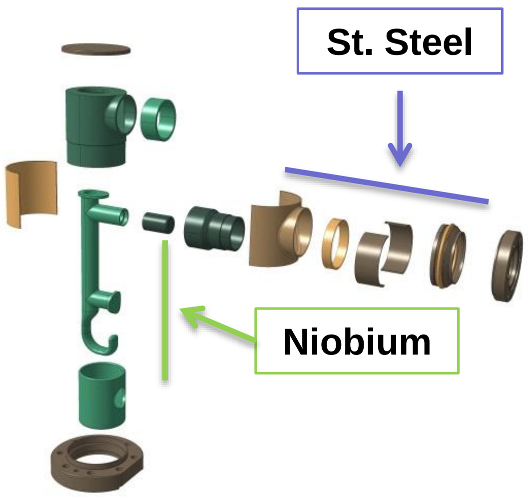


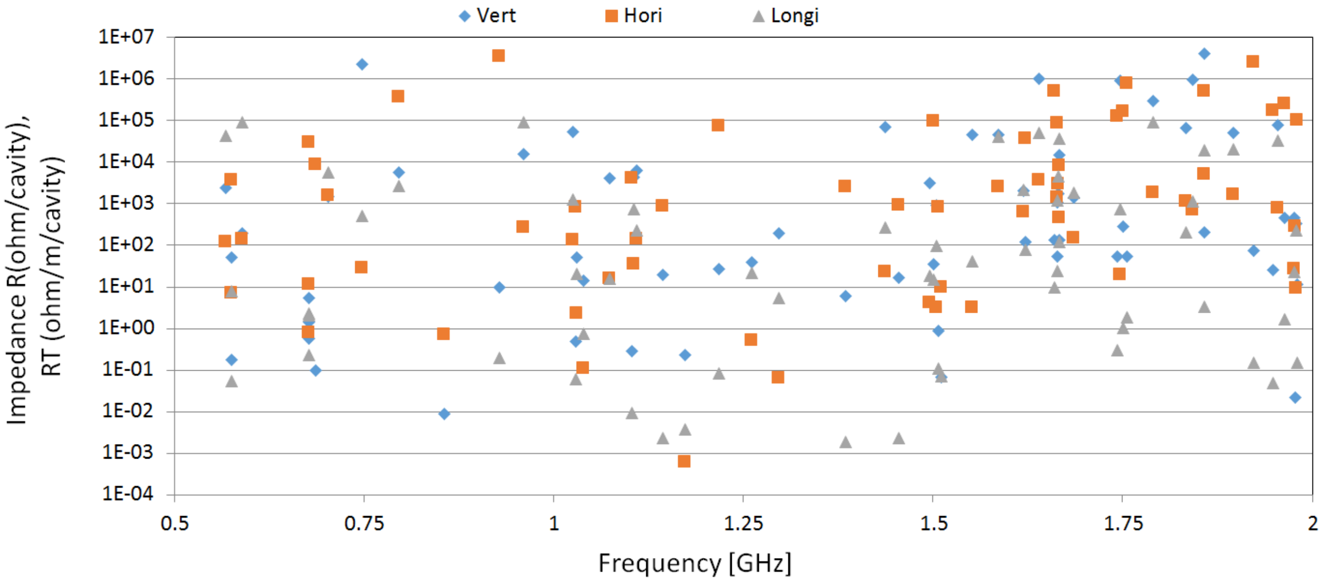
Pick Up Coupler



HOM Damping of DQW-HOM Couplers

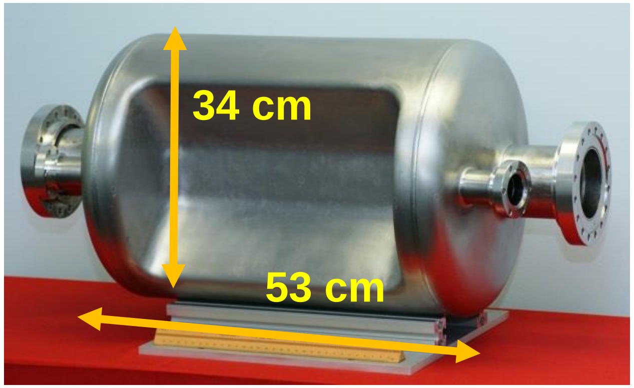
- Impedance of all <u>longitudinal</u> modes are damped below 1e5 Ohm
- Impedance of all <u>transverse</u> modes are damped below 4e6 Ohm/m.
- Liquid He jacket and hollow channels provides direct cooling to high magnetic field region.
- Wide stop-band at 400 MHz allows reasonable fabrication and assembly errors



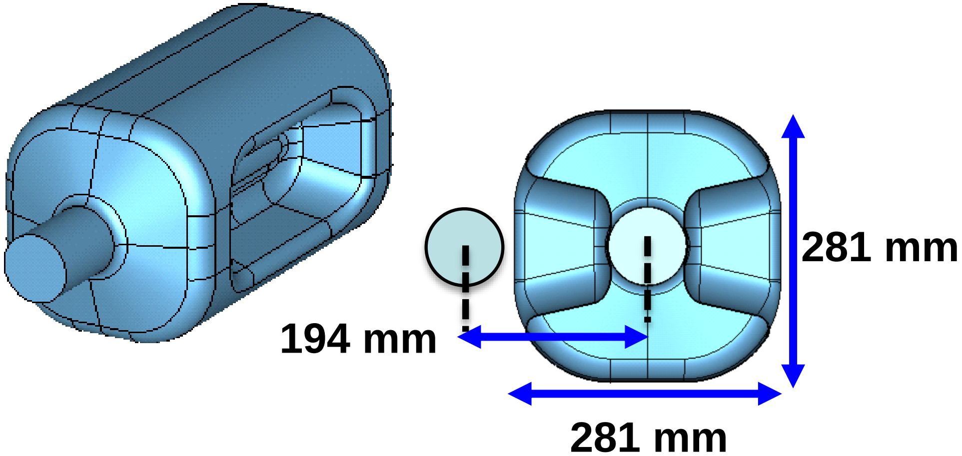


RF-Dipole Crabbing Cavity

Proof of Principle Cavity



Prototype Cavity



	P-o-P Cavity	Prototype Cavity	
Frequency	**400**	**400**	**MHz**
1^{st} HOM	590	633.5	MHz
V_t	3.4		MV
E_p	37	33	MV/m
B_p	64	57	mT
$[R/Q]_t$	287	430	Ω
G	141	107	Ω
R_tR_s	4.0×10^4	4.6×10^4	Ω^2

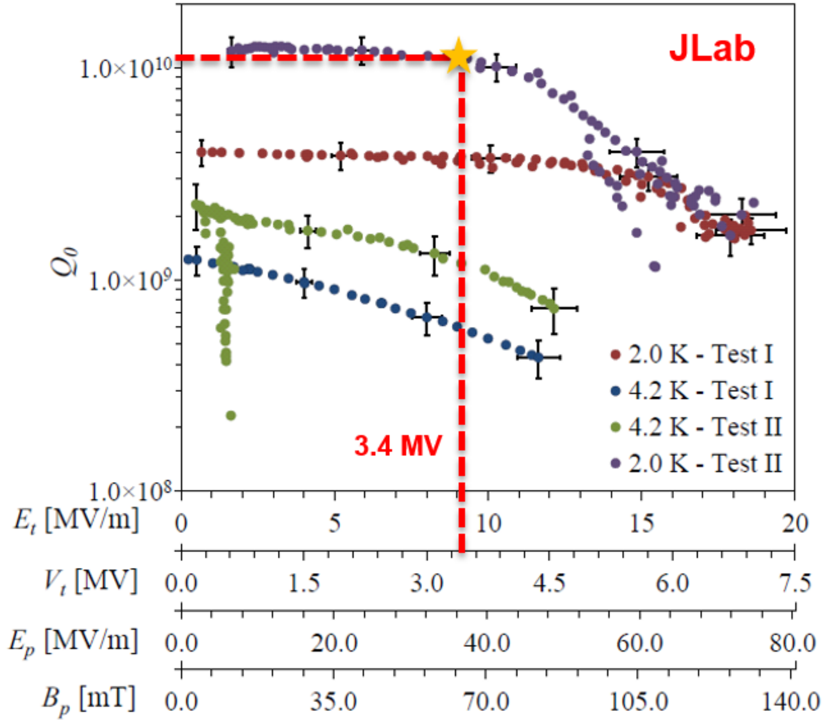
Prototype cavity

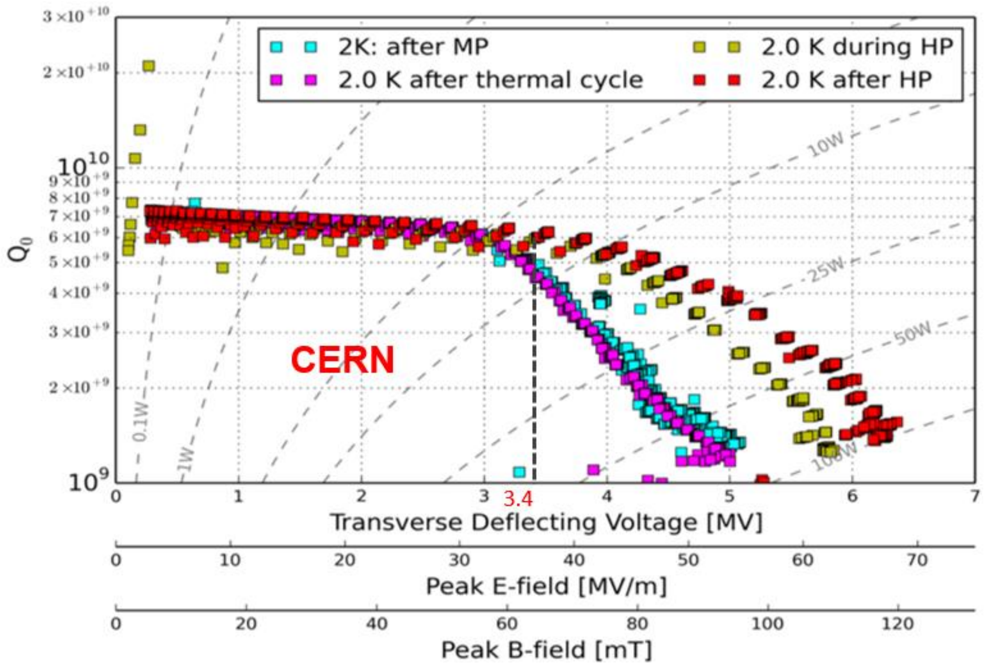
- Well separated HOMs
- Reduced surface electric and magnetic fields
- High shunt impedance
- Improved multipacting levels compared to P-o-P cavity
- Reduced multipole components

[*]S.U. De Silva and J.R. Delayen, PRAB 16, 012004 (2013)
[#]S.U. De Siva and J.R. Delayen, PRAB 16, 082001 (2013)

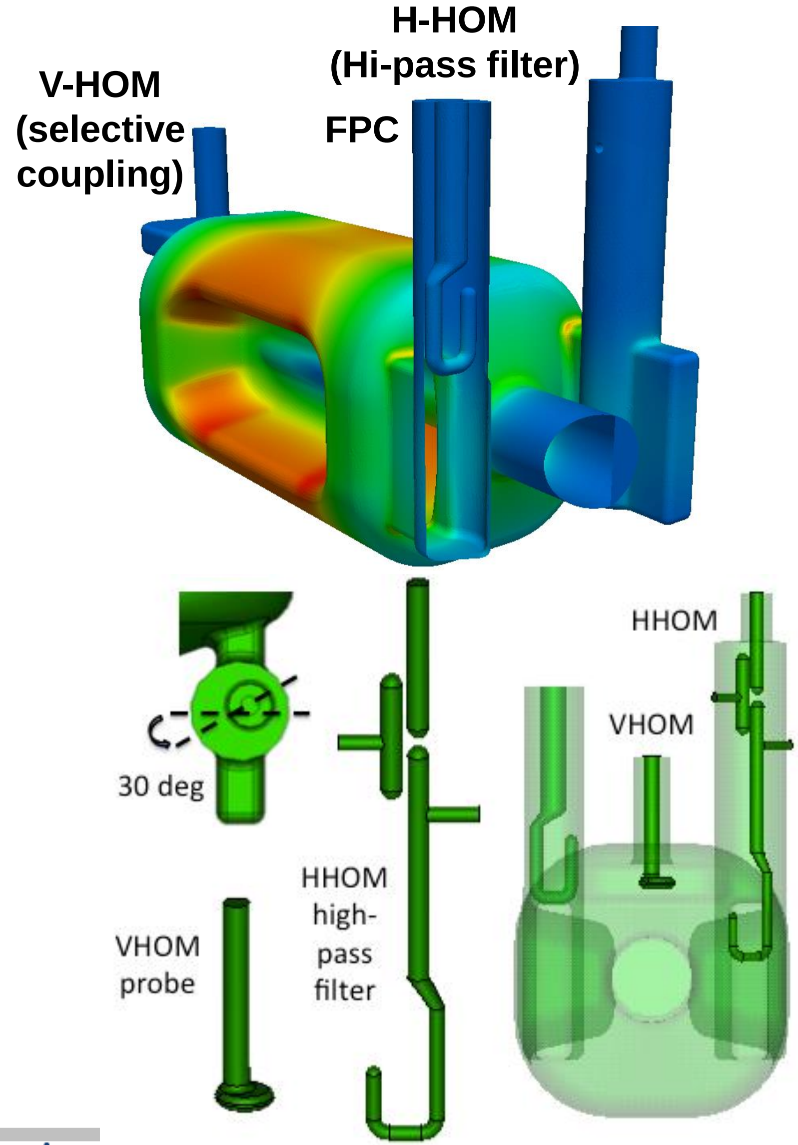
RFD P-o-P Cavity Cold Test

- Surface treatment and rf testing done at Jefferson Lab
  - Test I – April, 2012
  - Test II – June, 2014
- Test at CERN – October, 2014
  - Low Q_0 due no magnetic field compensation
- Cavity reached a V_t of 7.0 MV
  - Retested with Nb coated flanges provided by CERN
  - Q_0 increased by a factor of 3 from 4×10^9 to 1.2×10^{10}
- Multipacting was processed easily and did not reoccur





HOM Coupler Designs of RFD Cavity



- Two HOM couplers
  - Horizontal HOM (HHOM) coupler
  - Vertical HOM (VHOM) coupler
- Modes up to 2 GHz are well damped below requirement impedance
- Couplers at locations of low field region on cavity body
  - Minimizes RF heating on the coupler components
- Location preserves field symmetry
  - Electrical center moved by only 50 microns
- H-HOM coupler with 30 degree hook orientation with no change to filter elements
- Selective coupling (V-HOM) to reduce the number of filters
  - 7 mm offset incorporated into the probe tip to enhance coupling to the dipole modes at around 2 GHz
  - Small RF power leakage through the coupler, ~1.5W, due to asymmetry

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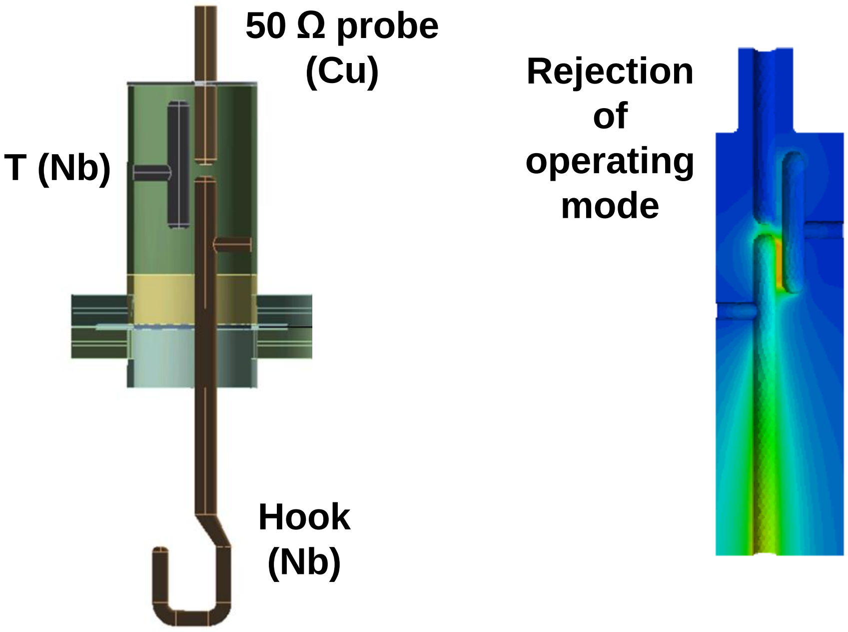
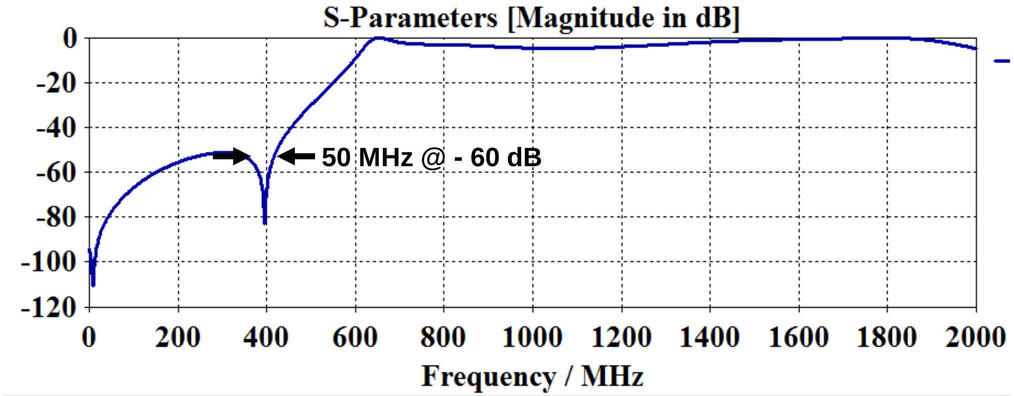
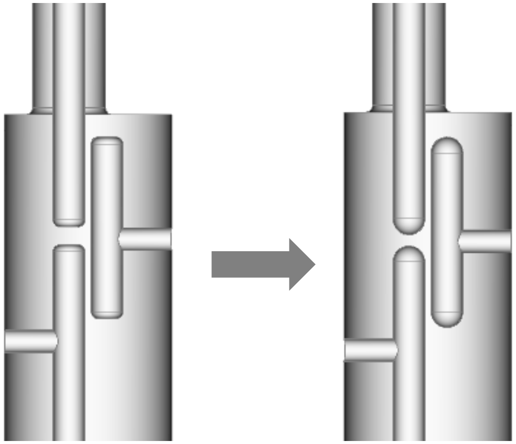
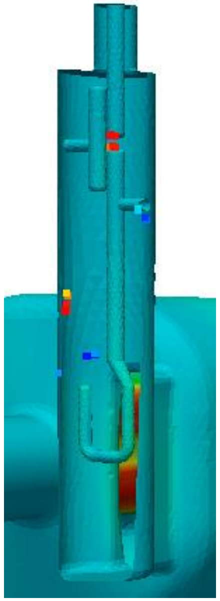
HHOM High Pass Filter



- High pass filter
  - Simple filter design → Cuts off fundamental mode
  - Damps horizontal deflecting and accelerating modes
  - Demountable coupler
  - Low fields in the filter

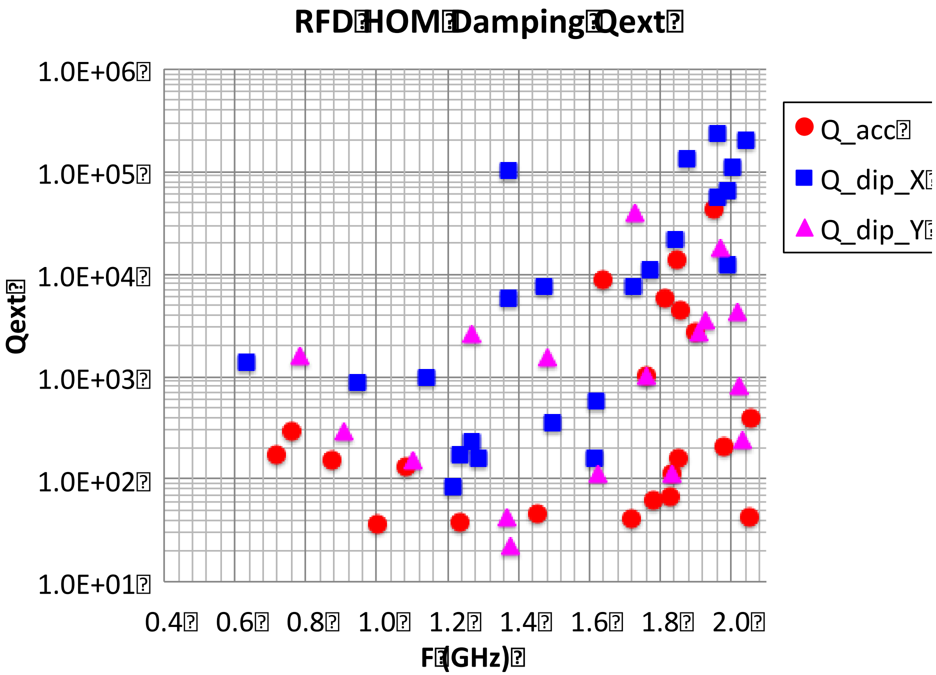


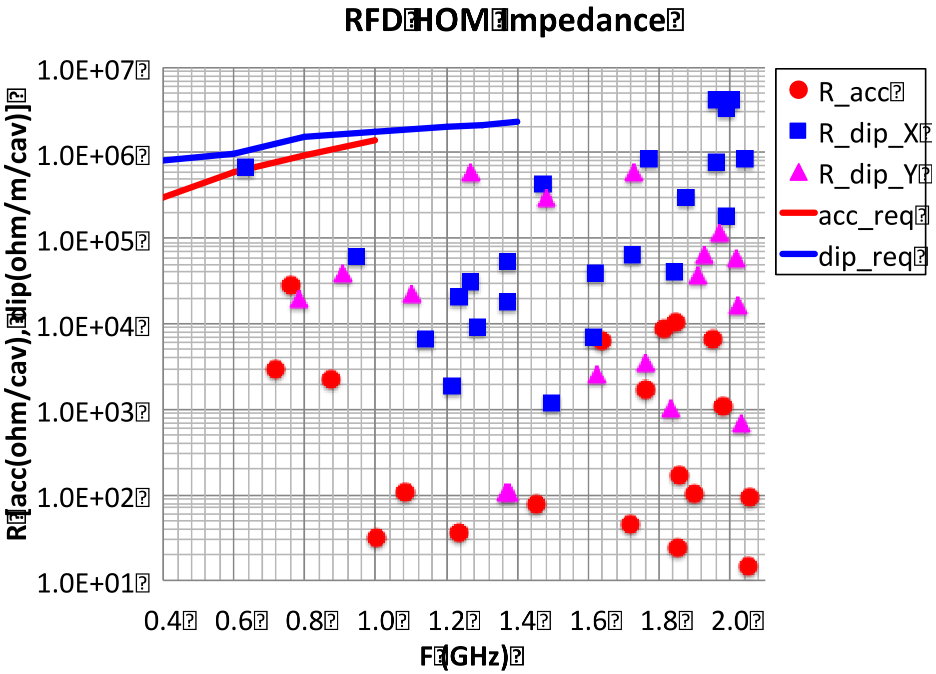




Multipacting trajectories in the gap removed

HOM Damping for RFD Cavity





- Q_{ext} calculated using Omega3P (SLAC ACE3P suite) for modes up to 2 GHz
- Solid lines are the impedance budget for dipole HOMs (blue) and accelerating HOMs (red) respectively
- Damping scheme meets the LHC High-Luminosity Upgrade impedance requirements

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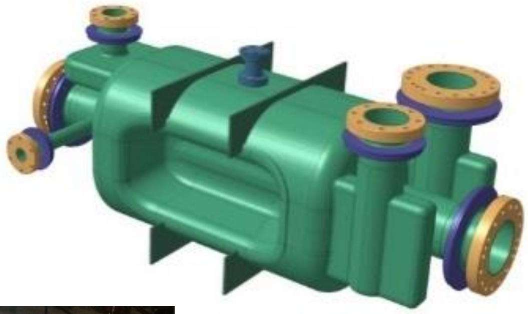
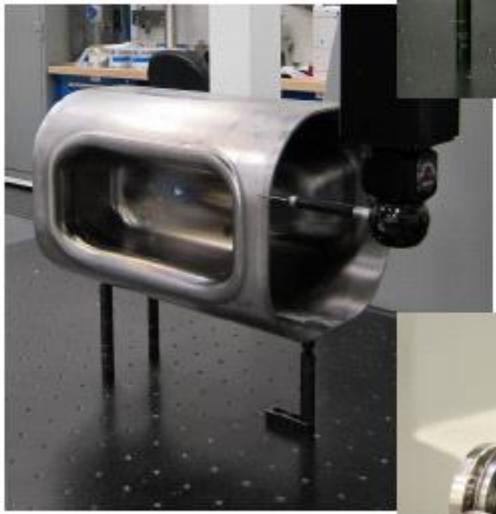
RFD Cavity & HOM Coupler Fabrication

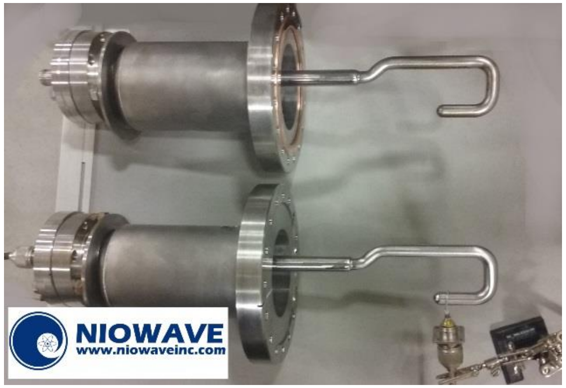
- Courtesy: Niowave Inc.
- Cavity sub-assemblies
- Fabricated Cu prototypes of
  - Demountable HHOM coupler
  - VHOM coupler probe



Cu HOM Couplers

Nb H-HOM Coupler





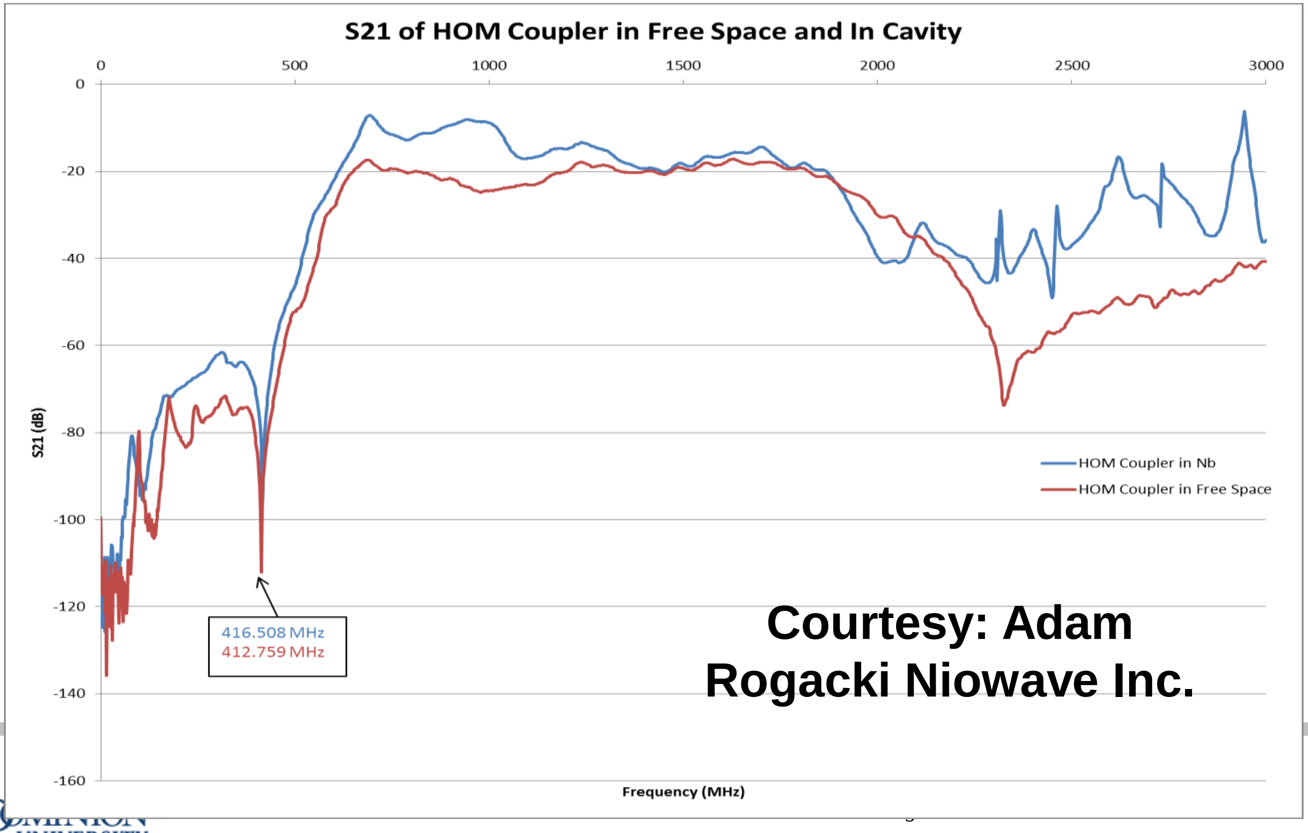
VHOM

HHOM

HOM COUPLER MEASUREMENTS

- Measurement of S_{21} of bare HOM coupler and with stacked cavity
- Complete rejection of fundamental mode

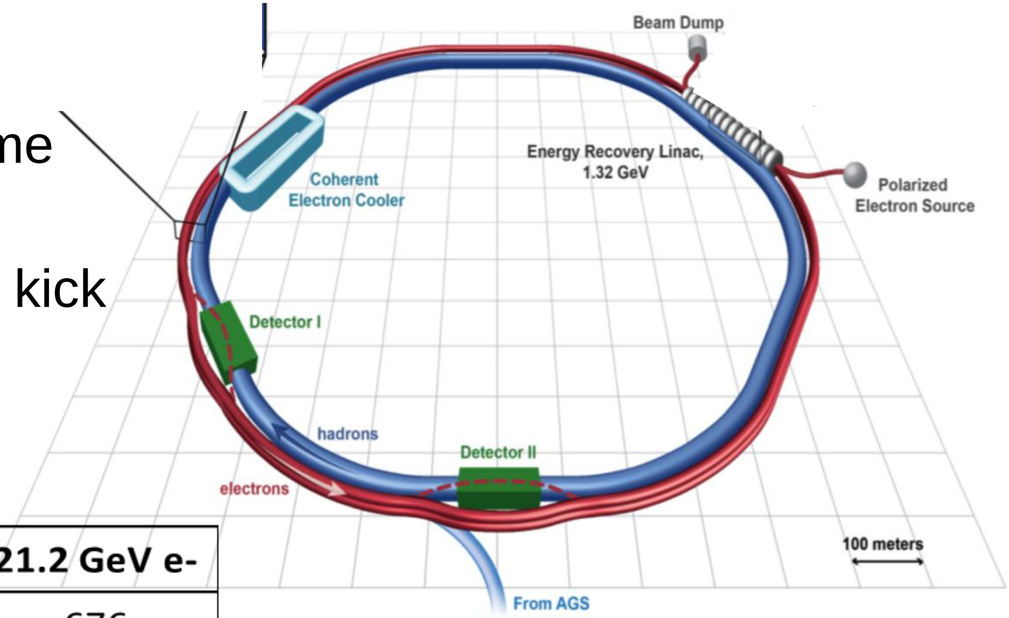
S21 Measurements of Soldered Assembly in Free Space



Courtesy: Adam Rogacki Niowave Inc.

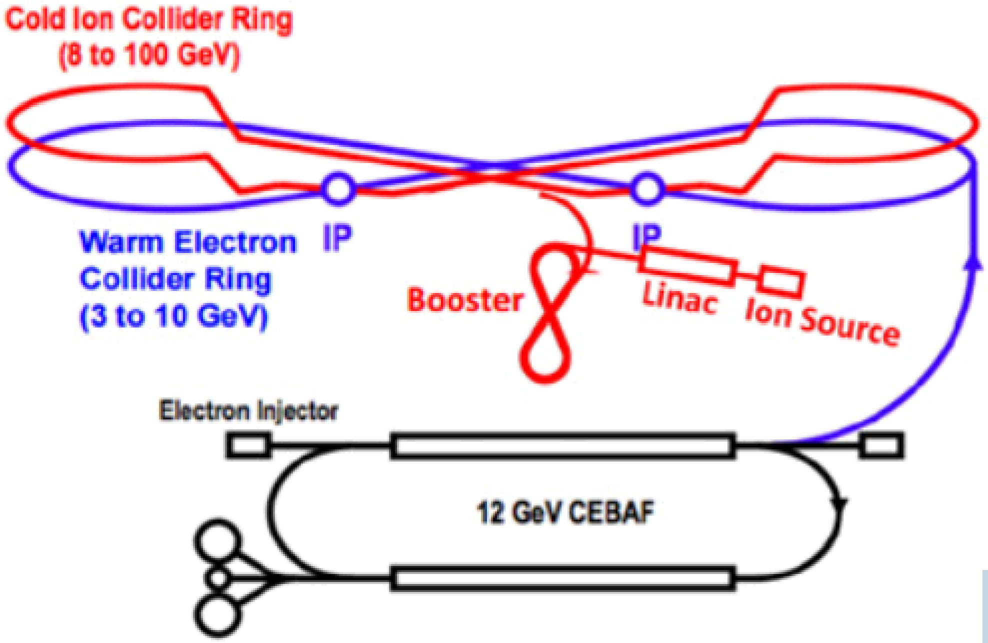
Crabbing Cavity for eRHIC - BNL

- 250 GeV polarized protons and 15.9 GeV electrons
- Crabbing system For both hadrons and electrons to avoid ~50 times loss of luminosity due to collisions at crossing angle
- $L \sim 5\times10^{33}\ cm^{-2}s^{-1}$
- Crossing angle – 10 mrad
- Horizontal local crabbing scheme
- Higher harmonic cavities are planned to correct non-linearity kick



Crab cavities for:	250 GeV proton			21.2 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

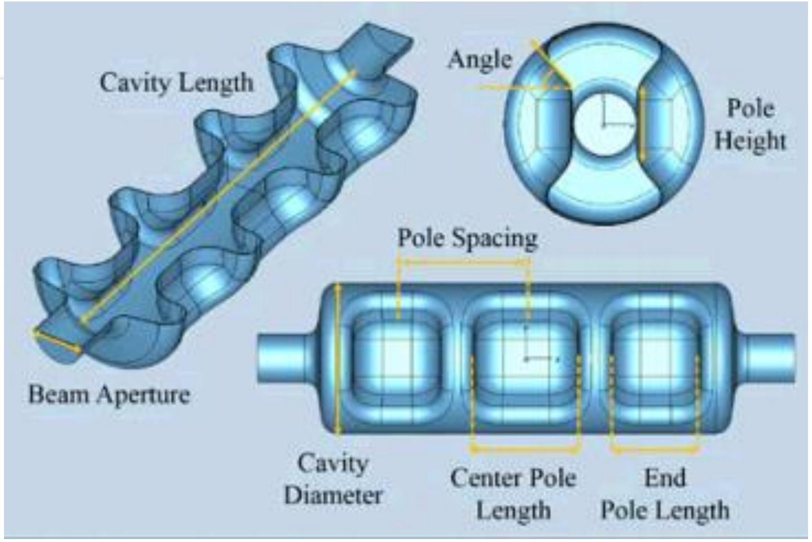
Crabbing Cavity for JLEIC - JLAB



- Local crab scheme
- Crossing angle – 50 mrad

Parameter	(A)	(B)	(C)	Units
Aperture diameter	50	60	70	mm
V_t per cavity	3.3	3.0	2.8	MV
E_p	33	33	33	MV/m
B_p	61	64	68	mT
No. of cavities (e/p) per side	1 / 6	1 / 7	1 / 7	

Parameter	Electron	Proton	Units
Beam energy	10	100	GeV
Beam current	0.72	5.0	A
Bunch frequency	952.6		MHz
Crab crossing angle	50		mrad
Betatron function at IP	10		cm
Betatron function at crab cavity	200	750	m
Integrated transverse voltage	2.8	18.4	MV



Summary

- KEK crabbing cavity – First demonstration of successful implementation and operation of a superconducting crabbing cavity
- No crabbing cavity has been demonstrated on a machine with proton beam
- Future compact crabbing cavities for LHC High Luminosity Upgrade
  - Double quarter wave cavity
  - RF-dipole cavity
- Concept has been successfully tested with Proof-of-Principle cavities
- Prototype cavity designs for SPS test at CERN are completed including FPC, HOM couplers and other ancillary
- Cavities and HOM couplers are being fabricated

Acknowledgements

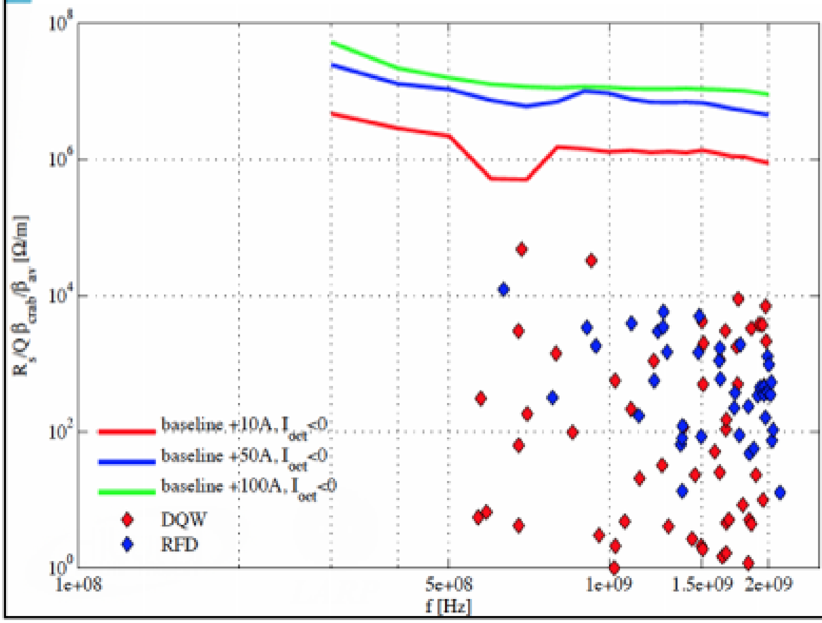
- BNL – Q. Wu, S. Verdu-Andres, B. Xiao
- ODU – Jean Delayen, HyeKyoung Park, Rocio Olave, Alex Castilla
- SLAC – Zenghai Li
- CERN – Benoit Salvant, Rama Calaga, Ofelia Capatina and the team
- Fermilab – Tom Nicol
- LBNL – A. Ratti

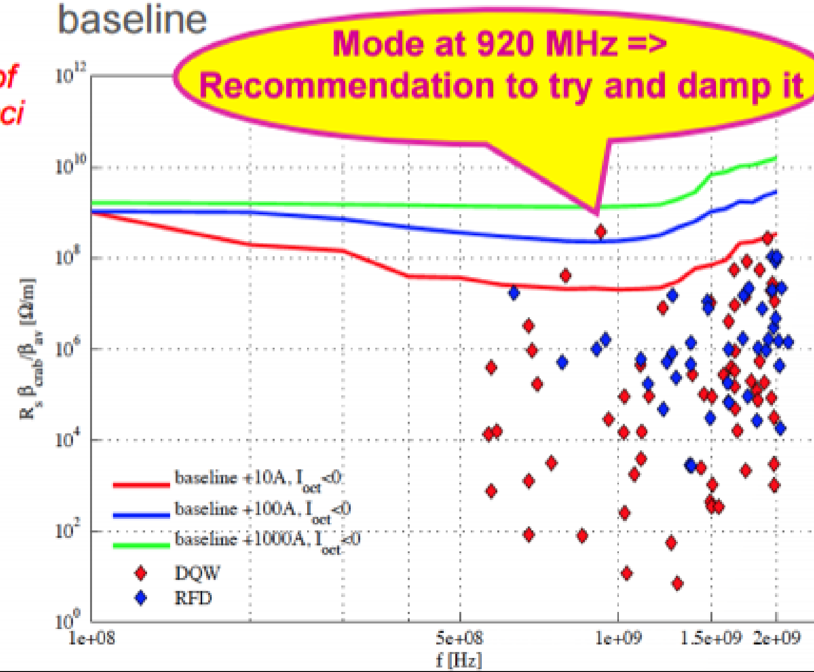
Impedance Budget

Reminder on the effect of Crab Cavities

- HOM of the DQW and RFD crab cavities and corresponding single bunch thresholds for the increase of octupole current over the machine baseline
- HOM of the DQW and RFD crab cavities and corresponding coupled bunch thresholds for the increase of octupole current over the machine baseline

Courtesy of N. Biancacci





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