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FPC and HOM couplers performance and power capabilities for RCS SRF cavity

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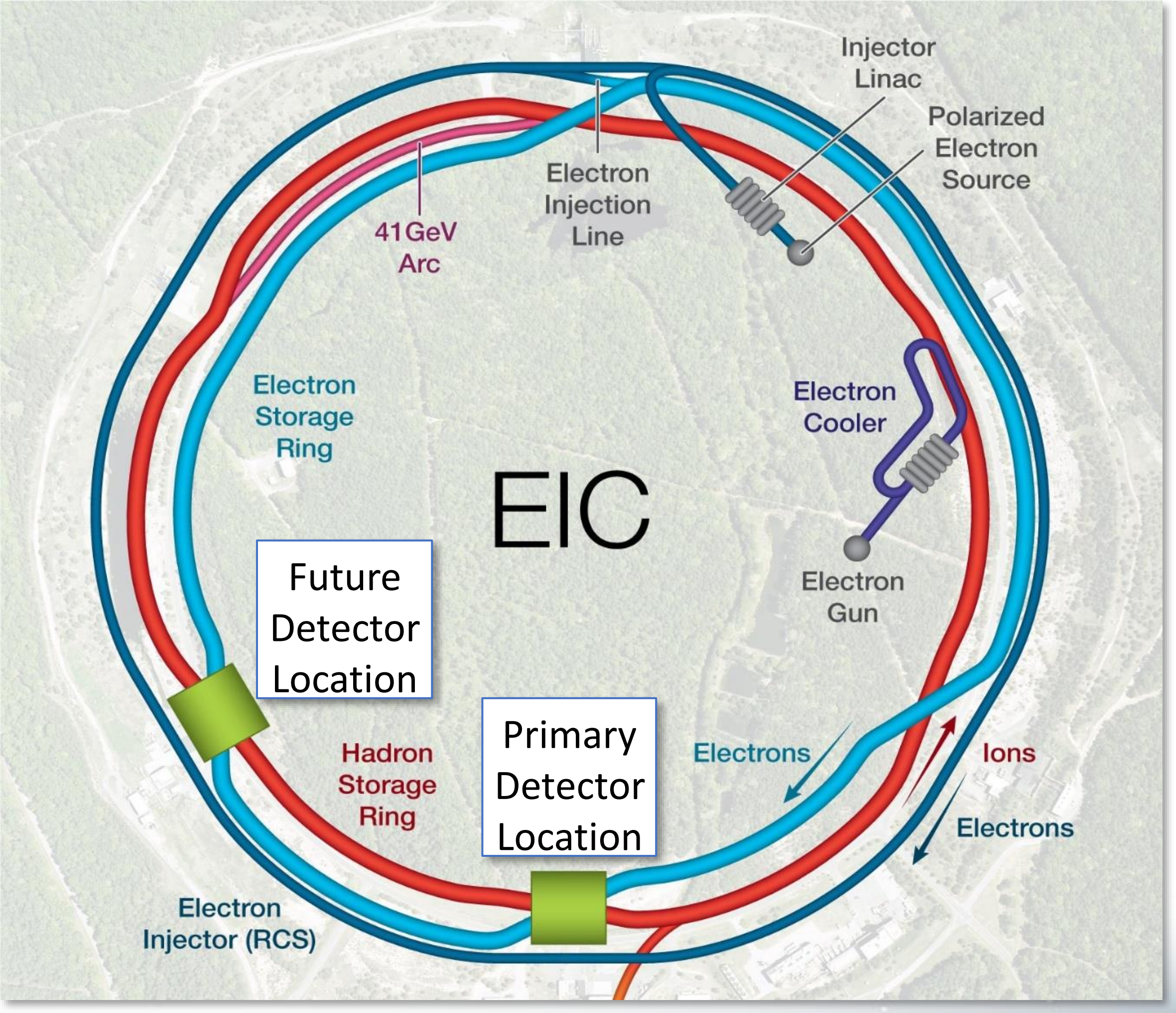
Outline

- Brief introduction of EIC
- RF systems in EIC
- SRF in EIC RCS
- FPC development for EIC
- HOM development for EIC
- Summary

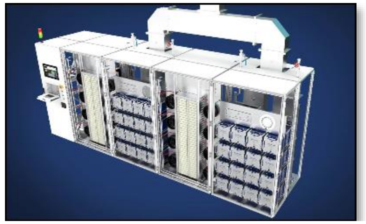
About EIC

- EIC is an Electron-Ion Collider, to be built at BNL in a partnership between BNL and TJNAF.
  - High Luminosity: L= $10^{33} – 10^{34} cm^{-2} sec^{-1}$
  - Highly Polarized Beams: 70%
  - Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
  - Large Ion Species Range: protons – Uranium
  - Accommodate a Second Interaction Region (IR)
- Hadron Storage Ring (HSR) provides ion beams, which is to upgrade the existing RHIC accelerator.
- Electron Storage Ring (ESR) provides 5-18 GeV of high current electron beam, which is a new accelerator, including pre-injector, RCS and ESR.
- The EIC will be a game-changing resource for the international nuclear physics community, but it is very challenge to archive all goals.

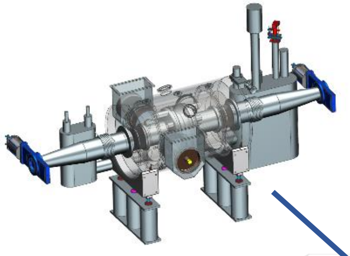


EIC CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

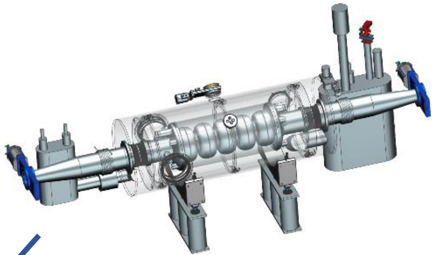
EIC RF Systems



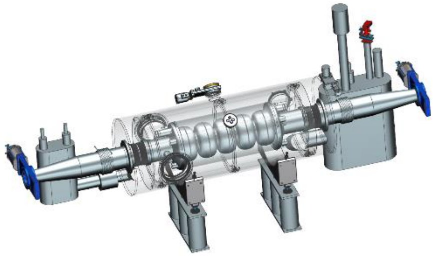
RF power and distribution 400kW×34 new SSAs for ESR 591MHz cavities, various power level for other cavities



Electron - 591 MHz electron storage cavity
17 CMs, IR10



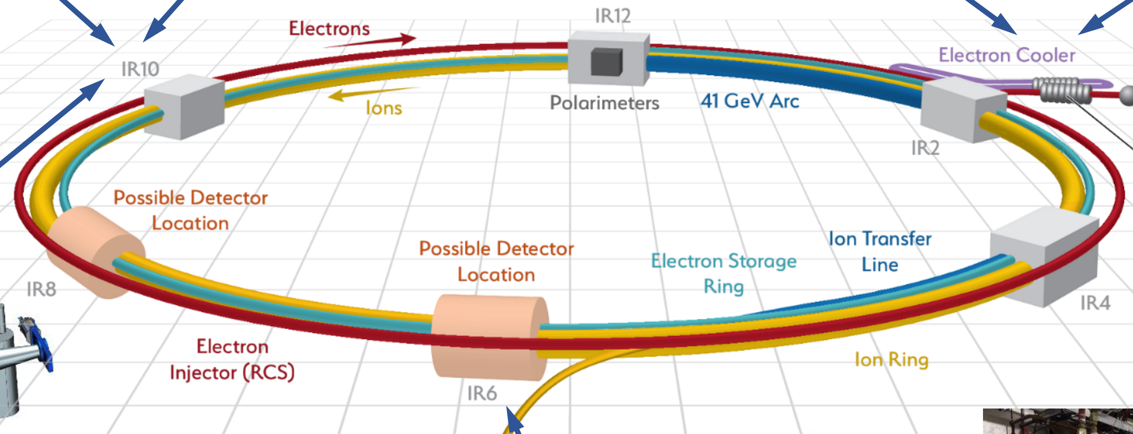
Hadron - 591 MHz bunch compression cavity
2 CMs, IR10

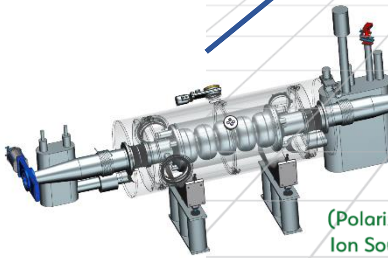


Hadron Cooling - 591 MHz acceleration cavity
10 CMs, Electron Cooler

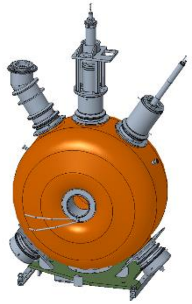
1773 MHz 3rd Harmonic (4) Cavities (Not shown)
1 CM, Electron Cooler

RCS injection harmonic RF kicker



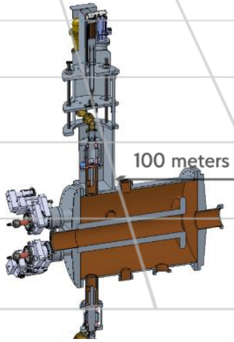


Rapid Cycling Synchrotron - 591 MHz acceleration cavity
3 CMs, IR10

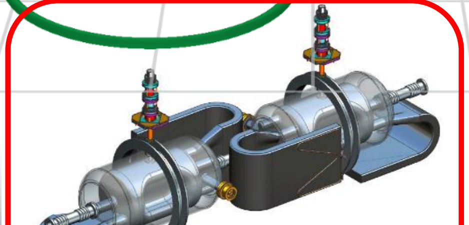


Hadron - 197 MHz bunch compression cavity

Hadron – 24.5 MHz acceleration cavity

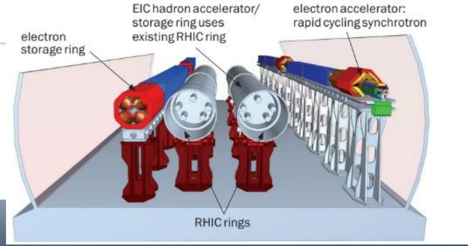


Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity



Both rings – Crab cavities

Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2



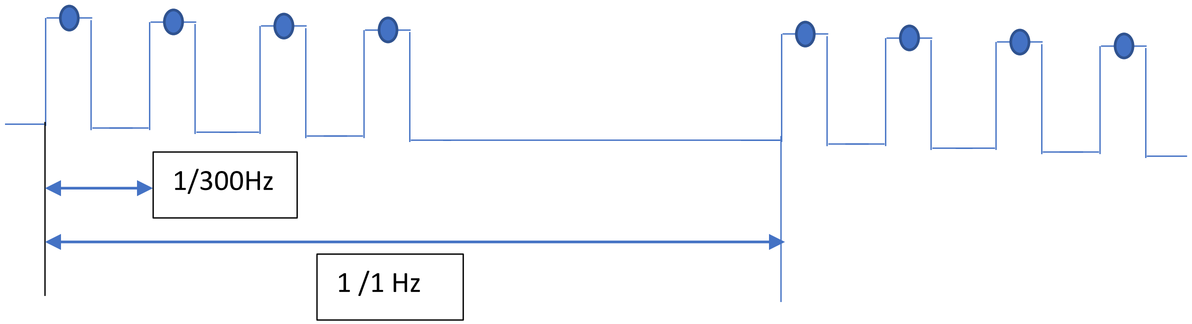
EIC RF – Systems (By Type & Number)

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities
Electron Storage Ring	Accel / Store	591	SRF, 1-cell	IR-10	17
Rapid Cycling Synchrotron (RCS)	Accel / Store	591	SRF, 5-cell	IR-10	3
	Harmonic Kickers	591	NCRF, QWR, 1-mode NCRF, QWR, 2-mode	IR-2 or IR-12	1 1
	Bunch Merge Type 1	295	NCRF, Reentrant	IR-4	2
	Bunch Merge Type 2	148	NCRF, Reentrant	IR-4	1
Hadron Storage Ring	Capture / Accel	24.6	NCRF, QWR	IR-4	4
	Bunch Split 1	49.2	NCRF, QWR	IR-4	2
	Bunch Split 2	98.5	NCRF, QWR	IR-4	2
	Store 1	197	NCRF, Reentrant	IR-4	7
	Store 2	591	SRF, 1- or 2-cell	IR-10	5 or 3
Strong Hadron Cooling ERL Design remains very fluid	ERL Injector	197 591	SRF, QWR SRF, 1-cell	IR-2	2 1
	ERL Low Energy Linac	197 591	SRF, QWR SRF, 1-cell	IR-2	4 2
	ERL Fundamental	591	SRF, 5-cell	IR-2	10
	ERL Third Harmonic	1773	SRF, 5-cell	IR-2	4 (1 CM)
Crab Cavities	Hadron	197	SRF, RFD	IR-6	8 (4 CM)
	Hadron/Electron	394	SRF, RFD	IR-6	6

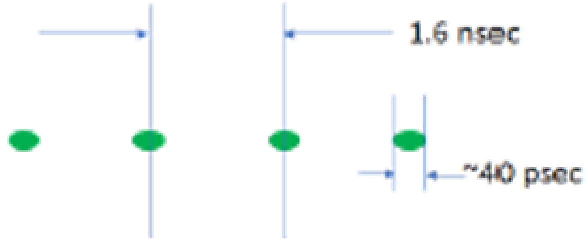
Bunch pattern in EIC RCS

- Bunch injection:
  - Four, 400 MeV 7 nC bunches
  - Bunch spacing 1/300Hz
  - Pre-injector chills for the rest of 1 second.
- Bunch in RCS
  - These 4 bunches are placed in RCS with 1.6 nS spacing (591 MHz), by harmonic kicker.
  - They are ramped to 1 GeV.
  - These four bunches will merge to one 28 nC bunch
  - The 28 nC bunch will be ramped to top injection energy: 5- 18 GeV.
- Bunch extraction
  - Every second, a 28 nC bunch will be extracted from RCS and injected to ESR.

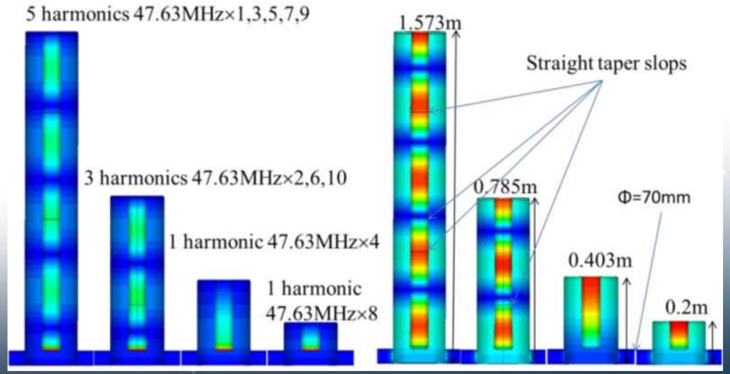
Bunch pattern in pre-injector



Bunch pattern in RCS for ramping



RCS harmonic kicker:

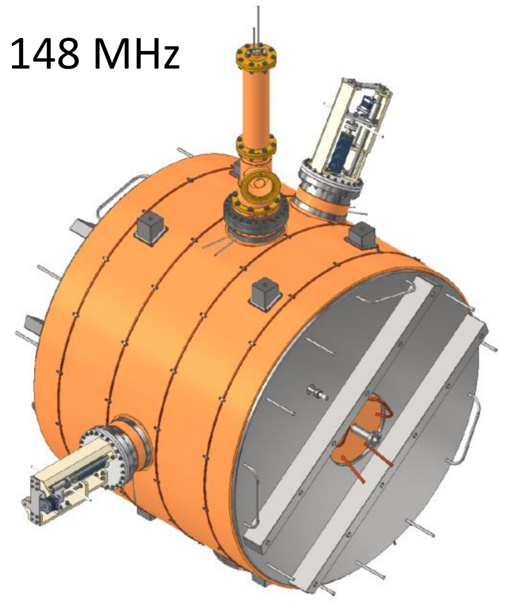


RCS NCRF Design & Cavity Parameters

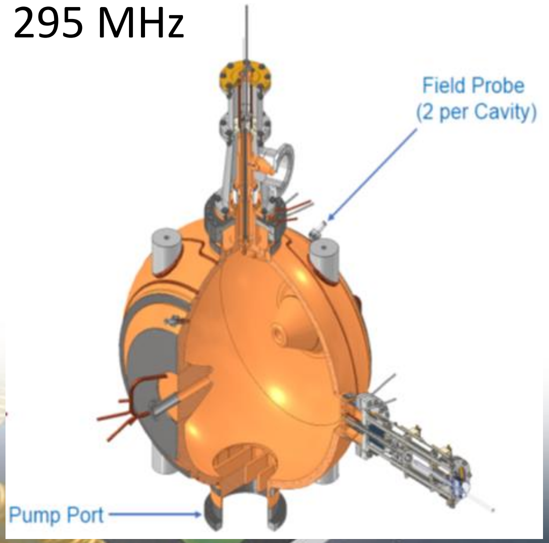
Parameter provided by Physics	Type 1	Type 2
RF frequency [MHz]	295.5	147.75
Harmonic number	3780	1890
Installed voltage [MV]	1.3	0.7
FPC Coupling Beta	1	
Tuning [±kHz]	50	
Beam pipe diameter [cm]	3.29	
Longitudinal instability threshold	1.59MΩ (<1GHz) & 1.59MΩ*GHz (>1GHz)	
Transverse instability threshold	12MΩ/m	

147.75 MHz cavity			295.5 MHz cavity	
Type			Type	
Simple pill box			Rounded pill box	
φ	20°		**φ**	30°
h	27.5 cm		**h**	12.5 cm
g	48.9 cm		**g**	28.1 cm
L	103.9 cm		**L**	53.1 cm
D	133.7 cm		**D**	80.1 cm
Rsh	14.62 MOhm		**Rsh**	10.32 MOhm
Q	63735		**Q**	54540
R/Q	229.3 Ohm		**R/Q**	189.2 Ohm
Rsh*0.85	11.69 MOhm		**R**sh*0.85	7.94 MOhm
Q*0.85	50990		**Q***0.85	46030
P@0.7MV	18.07 kW		**P**@0.65MV	24.08 kW
Emax@0.7MV	5.78 MV/m		**E**max@0.65MV	8.18 MV/m
Hmax@0.7MV	2575 A/m		**H**max@0.65MV	3840 A/m

148 MHz



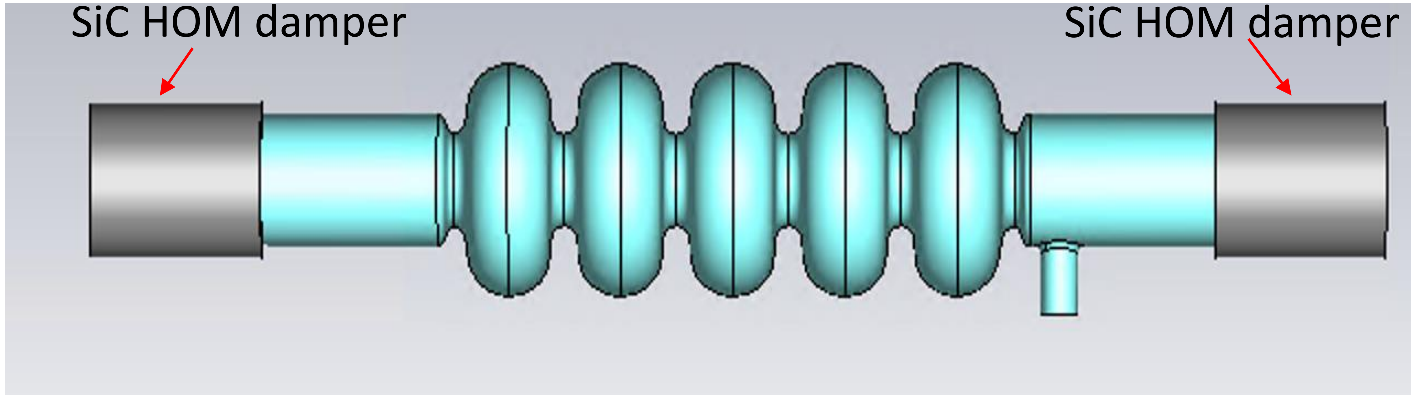
295 MHz



- Maximize shunt impedance to minimize RF power.
- Same FPC for both cavity
- No HOM damper needed for 148 MHz.
- HOM damper for 295 MHz is under estimation.

RCS SRF cavity: 5-cell 591 MHz SRF cavity

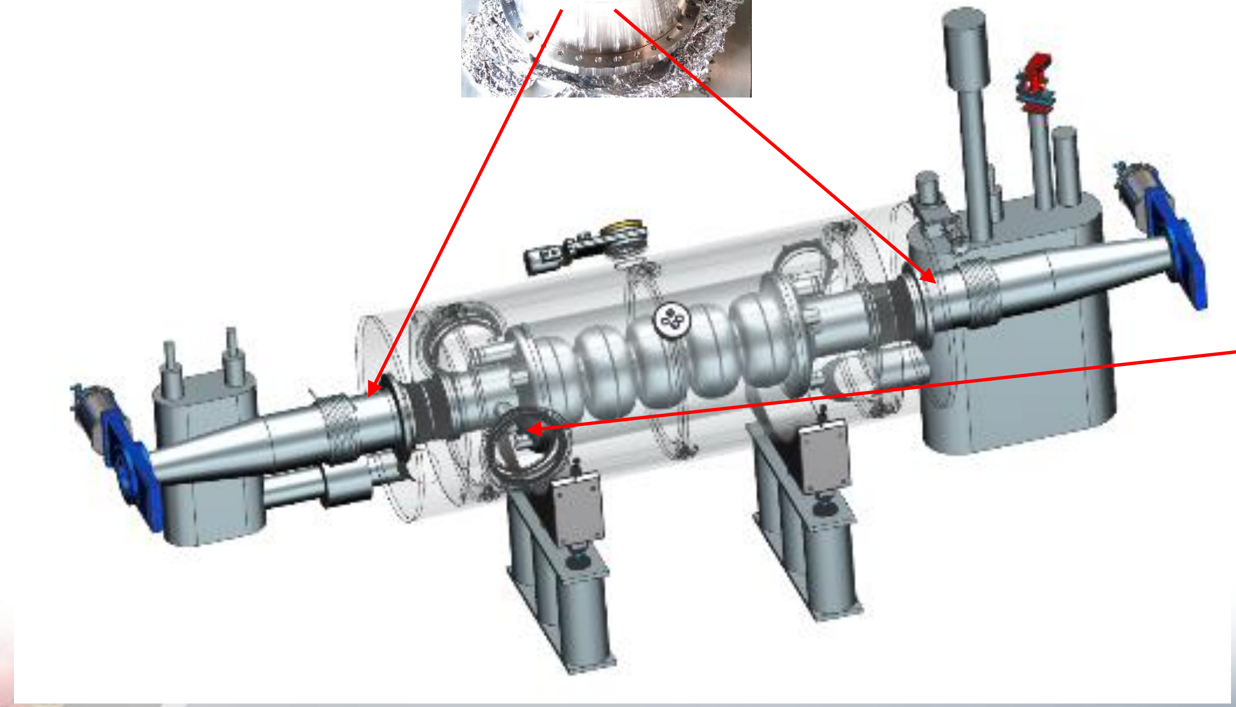
- RCS requirements for 5-cell 591 MHz SRF cavity.
  - Total voltage 60 MV for 3 cavities.
  - Ramping of electron bunch energy requires cavity resonant frequency fast tuning up to 4 kHz in ~ 100 ms.
  - Couple bunch instability requires longitudinal impedance < 1.6 M Ω (bunch merging at 1 GeV).
  - Transversal bunch instability requires impedance < 12 MΩ/m.
- Scaled from the high current 650 MHz SRF linac cavity design for eRHIC (previous BNL version of EIC).
- A Copper 650 MHz cavity was built for HOM study.
- A 650 MHz Nb cavity was prototyped, processed and tested vertically up to 18.2 MV, limited by radiation.
- The 650 MHz Nb cavity serves as a practicing cavity for EIC, and we are reprocessing the cavity and retesting the cavity soon.

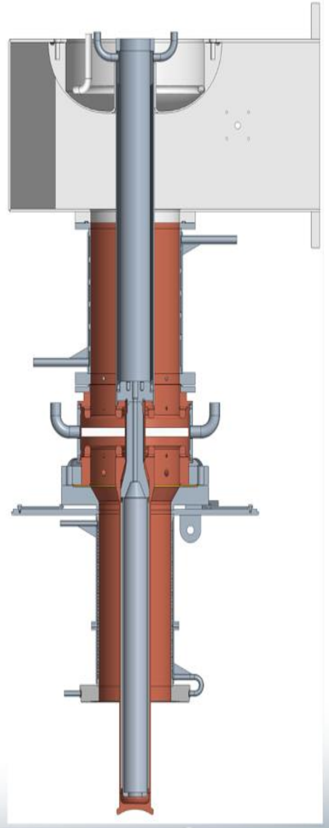


Frequency	591 MHz
R/Q	502 Ω
Geometry factor	273
Epk/Eacc	2.27
Bpk/Eacc	4.42 mT/(MV/m)
Coupling factor	2.8
Wall thickness	4.4 mm
Tuning range	+/- 174 kHz (+/-2mm)
Lorentz detuning factor	0077 Hz/(MV)^2
First modal frequency	> 107 Hz

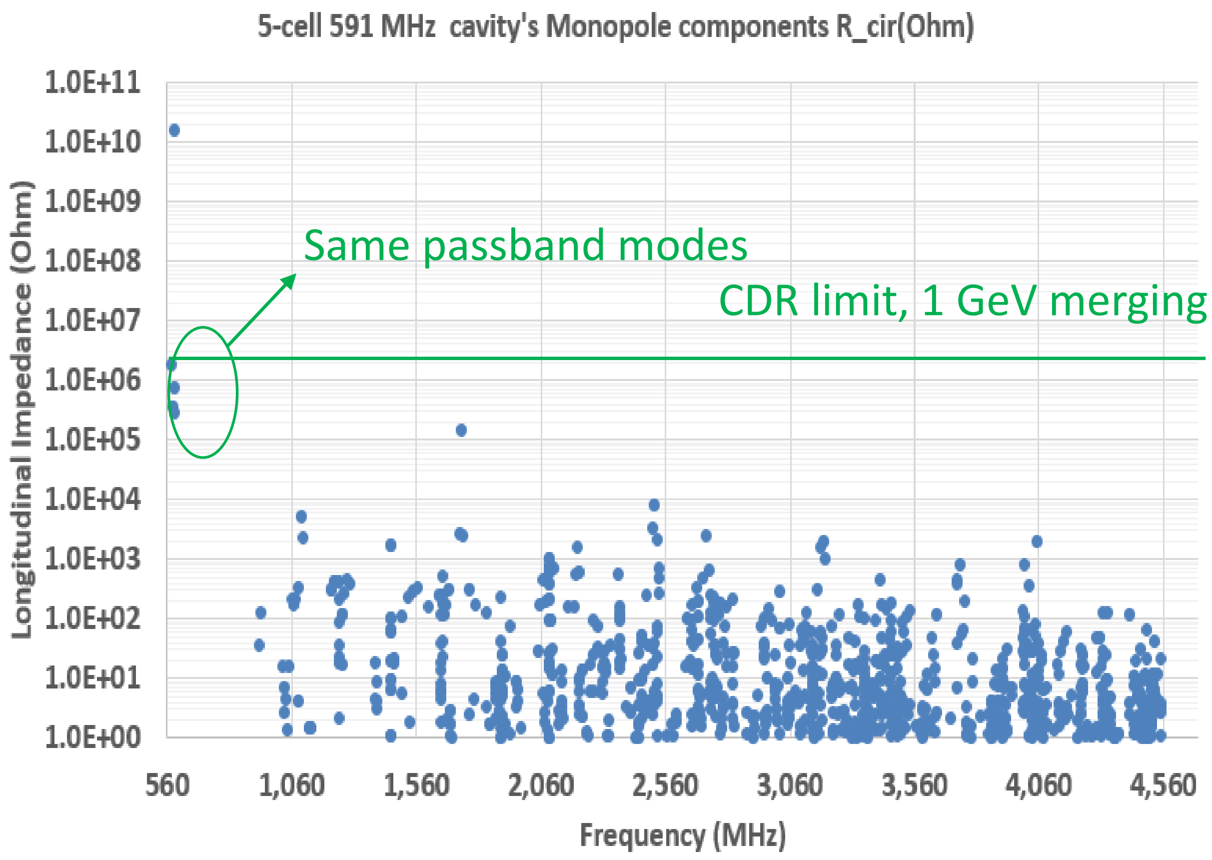
Preliminary design of RCS cryomodule

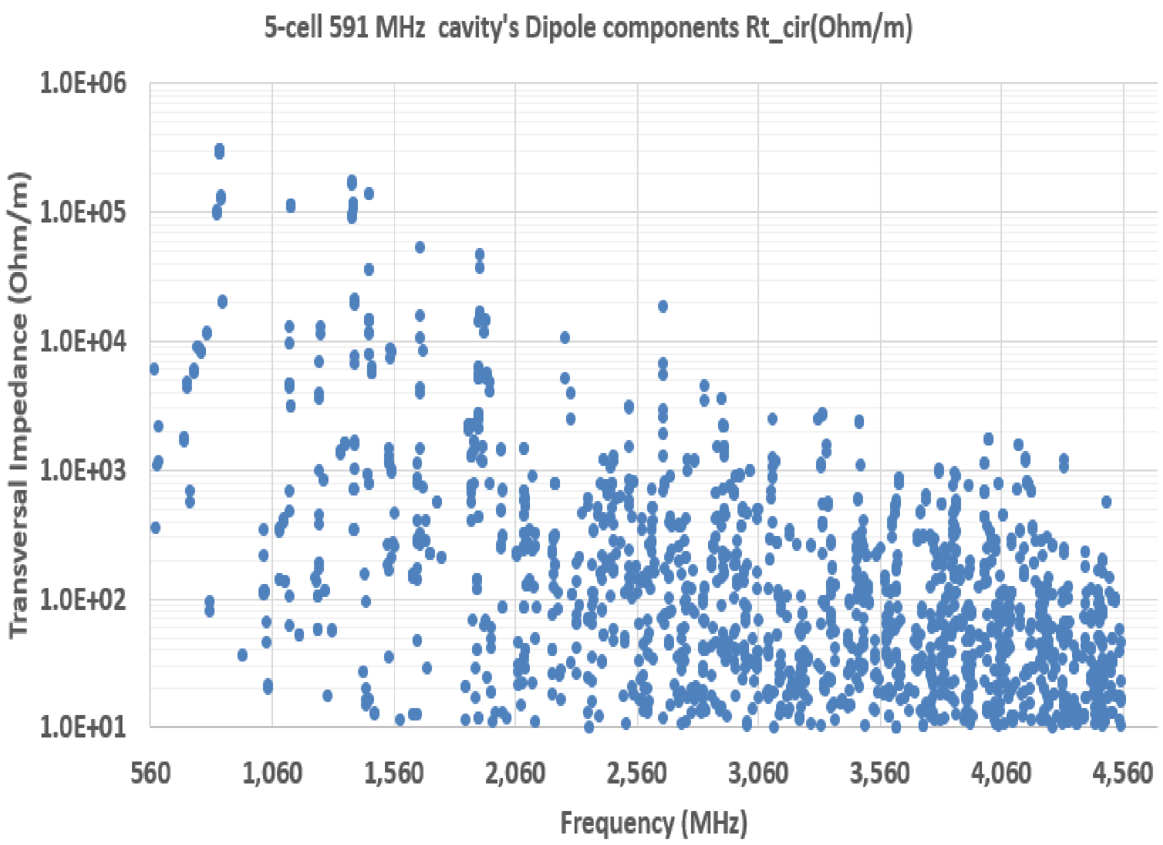
- One 5-cell cavity per cryomodule
- One high power FPC per cryomodule
  - Details in next two slide
- SIC HOM damper at both end of the cryomodule
  - Details in later slide
- Operating temperature: 2K





Longitudinal and transversal impedance



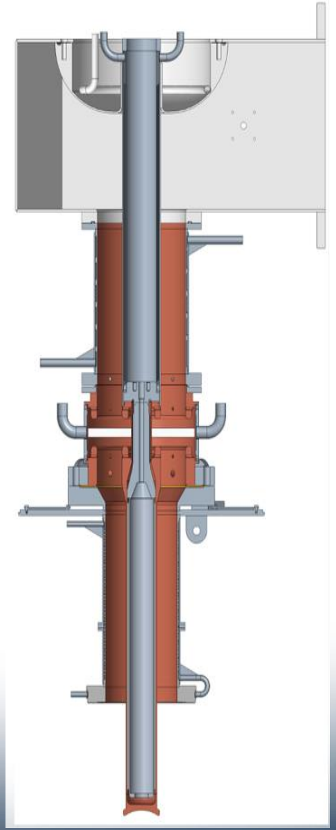


- Longitudinal HOMs are below the CBI threshold
- Same passband modes are close to the limit because of the cut off frequency of the beampipe.
- The fundamental mode impedance will be reduced by direct feedback.
- Transverse modes are all below the threshold, 12 M Ω/m

High Power FPC for RCS

- FPC requirement for RCS:
  - Beam current in RCS is very small: 28 nC X 78 kHz = 2.2 mA
  - Energy loss per turn in RCS is 40 MeV, so the required RF power is 88 kW.
- The FPC for RCS will use the same FPC for ERS 591 MHz cavity, which requires to deliver up to 400 kW of RF power per coupler.

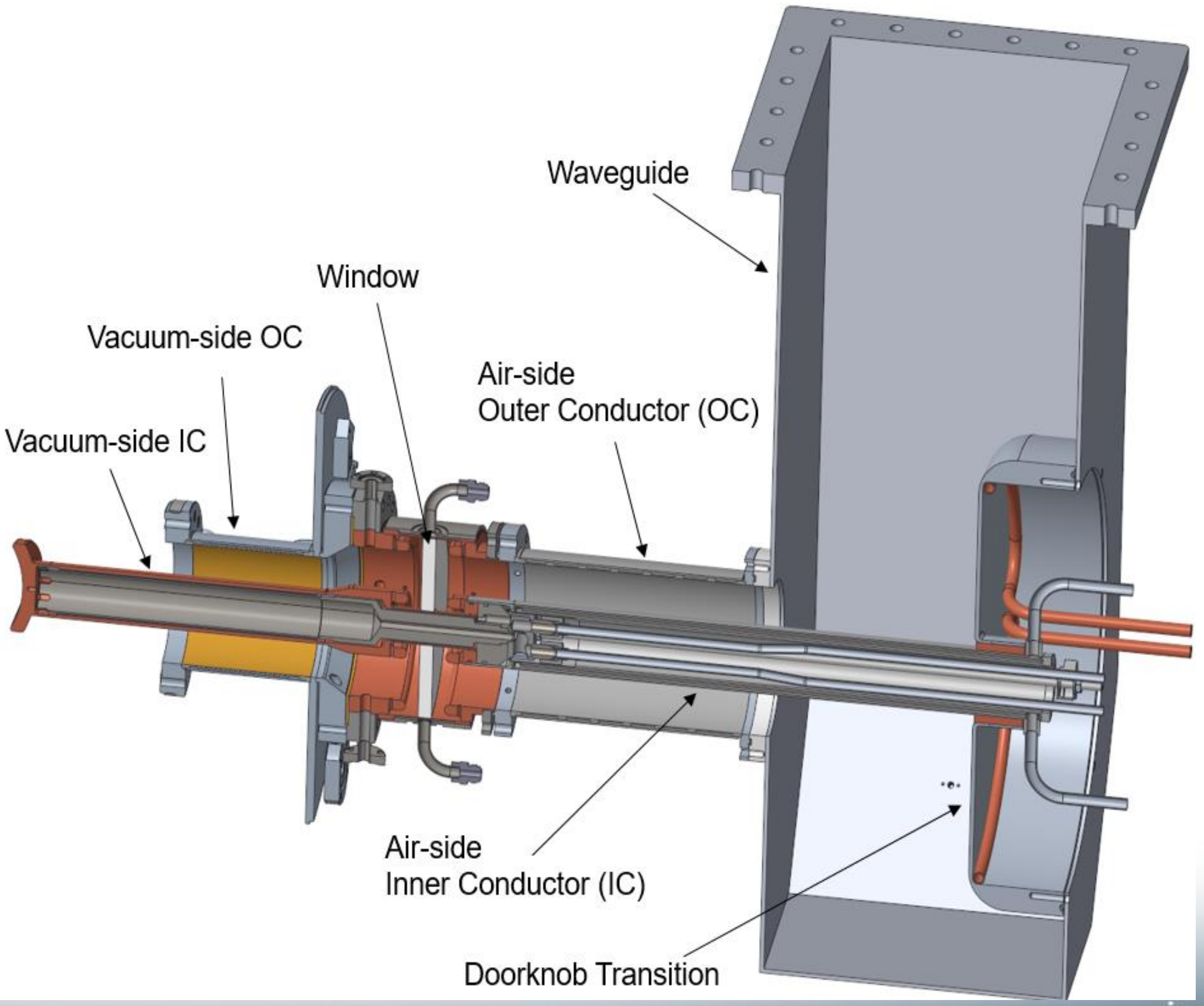
	Requirement for ESR	FPC Design
Average RF power	379 kW	1 MW, traveling wave 500 kW, full reflection
Peak Power (during full reflection)	1.5 MW, equivalent	2 MW, equivalent
Frequency	591 MHz	Broadband window design, good for EIC cavities below 591 MHz
Shock load	5g, In any orientation	5g, In any orientation
Modal frequency	> 60 Hz	100 Hz
Inner conductor length	289 mm	425 mm



FPC for EIC ESR SRF Cavity

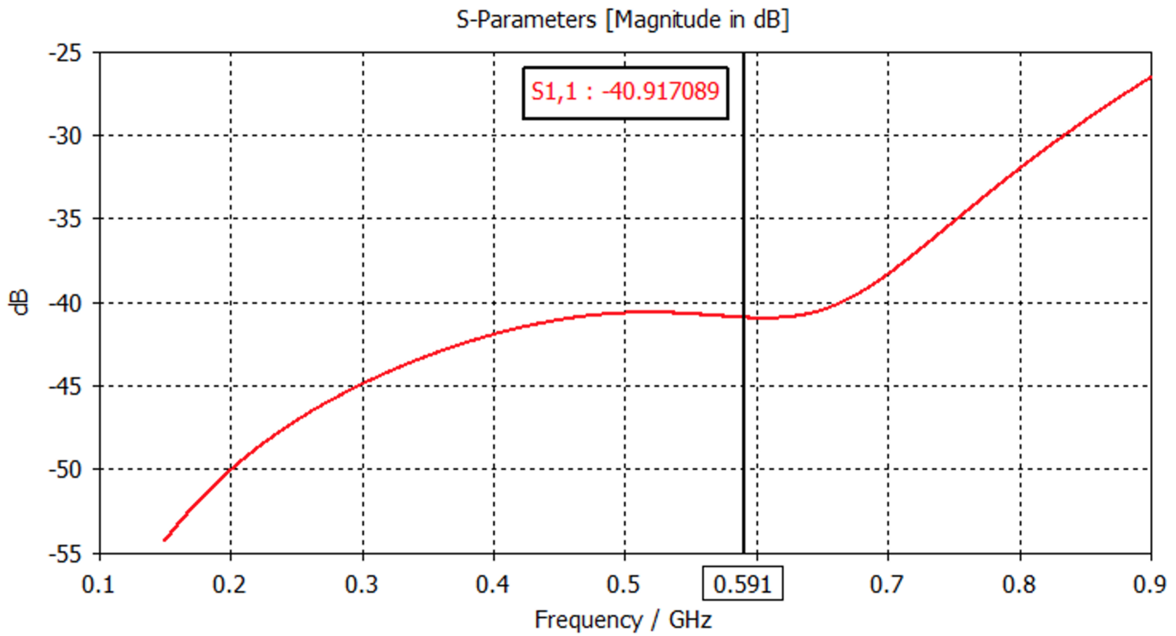
- FPC design is a variation of KEKB/ Tristan/SNS/BNL BeO high power window.

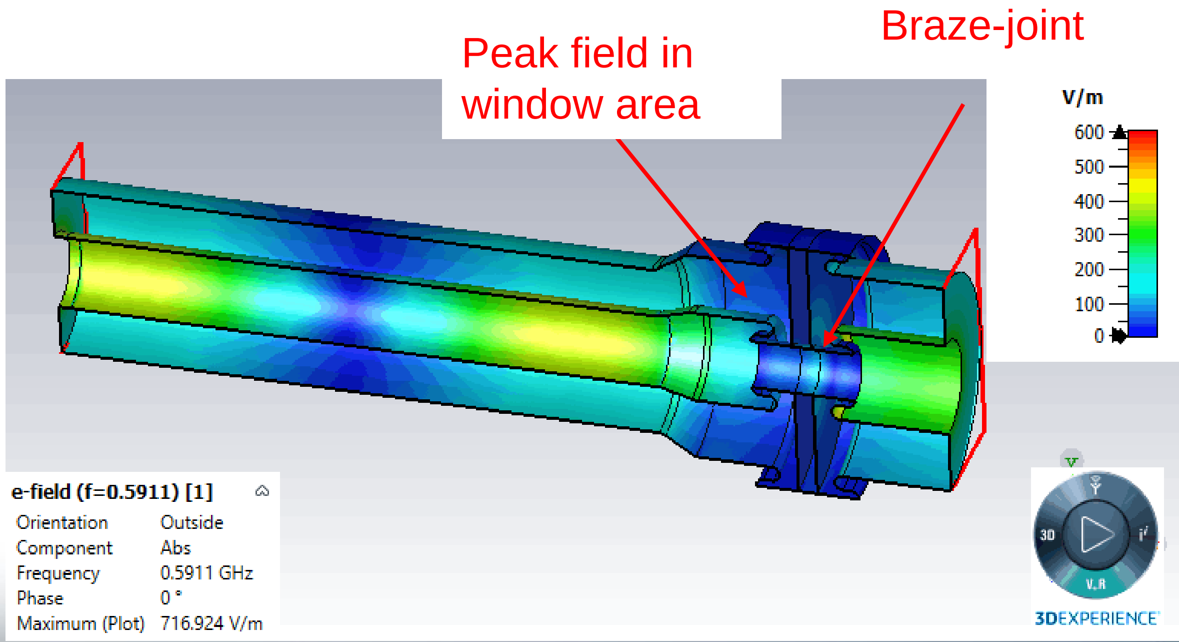
- Particularly, this Al2O3 window FPC improved various aspects based on lesson and learn from design and operating experiences of BNL BeO window, so that it can satisfy the EIC requirements.
  - Replace BeO window with 99.5% Al2O3 for safety and maintenance considerations.
  - Increase choke to window distance for better TiN coating and inspection.
  - Optimized coaxial line to increase power handling and coupling with cavity.
  - Larger ceramic ID to survive 5 g shock load in any direction.
  - Improve cooling channel design.
  - Improve instrumentations on FPC.
  - 4.5 kV bias will be ready to apply.



High Power Broadband RF window Design for EIC

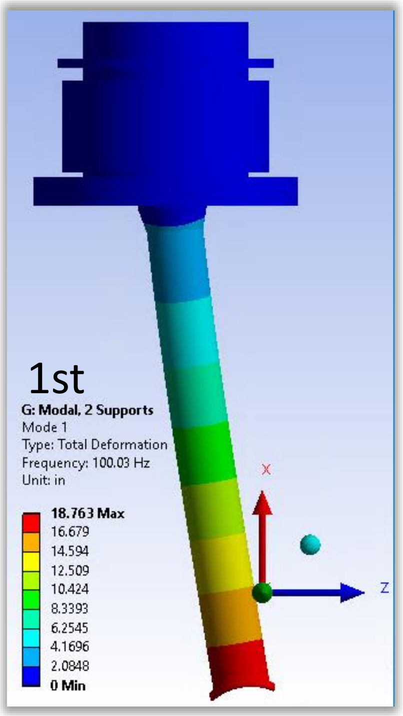
- Broadband RF window design for EIC RF/SRF applications, including 197/394 MHz crab cavities, 591 MHz multicell cavities for RCS, HSR, ERL in EIC.
- The peak field at the braze-joint is 367 kV/m (with 1 MW input), which is reasonable.
- Maximum E field occurs on the outer surface of choke, the same as other similar coupler design.

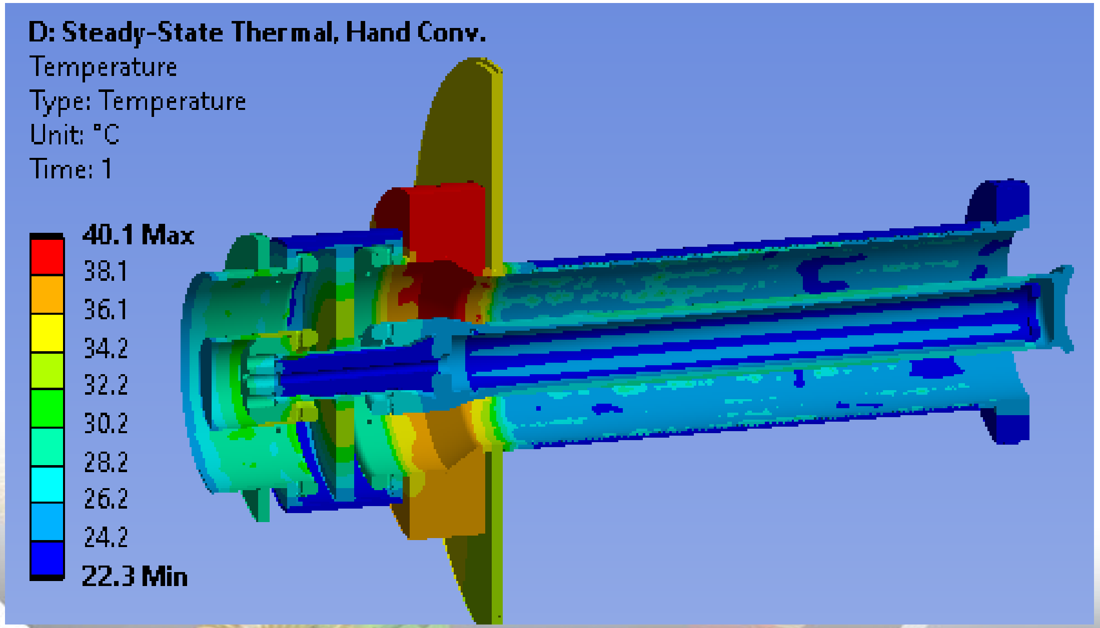


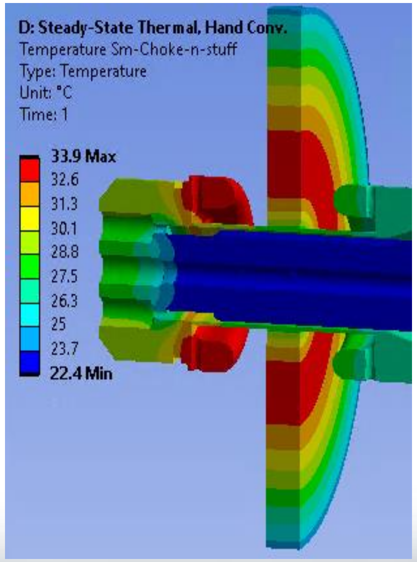


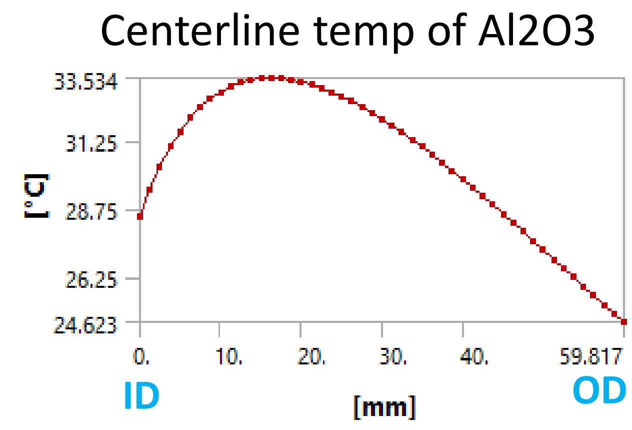
Summary of FPC Thermal and Mechanical Design

- 1st modal frequency is 100 Hz.
- Survive 5g shock load in any direction.
- Conservative thermal simulation.
  - CW 1 MW travel wave.
  - Temperature differential on the ceramic is 10 degree.



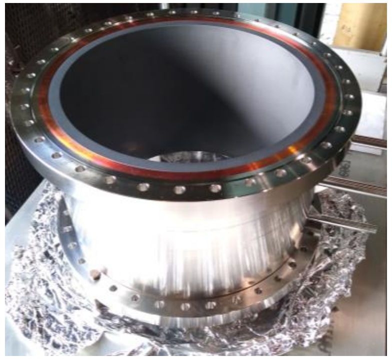




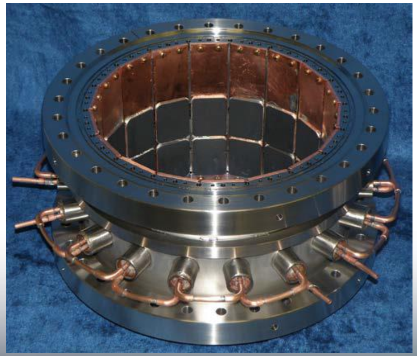


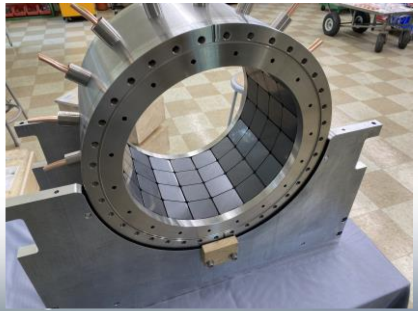
SiC HOM Absorber Prototyping

- R&D on SiC as EIC SRF cavity RT HOM absorber is ongoing at BNL: Test manufacturing of large SiC HOM damper, measure its bandwidth and power handling capability.
- Two techniques for prototyping HOM absorbers were studied.
  - Shrink-fit a solid cylindrical SiC HOM damper
  - Brazing SiC tiles on Cu base



Solid cylindrical SiC HOM damper

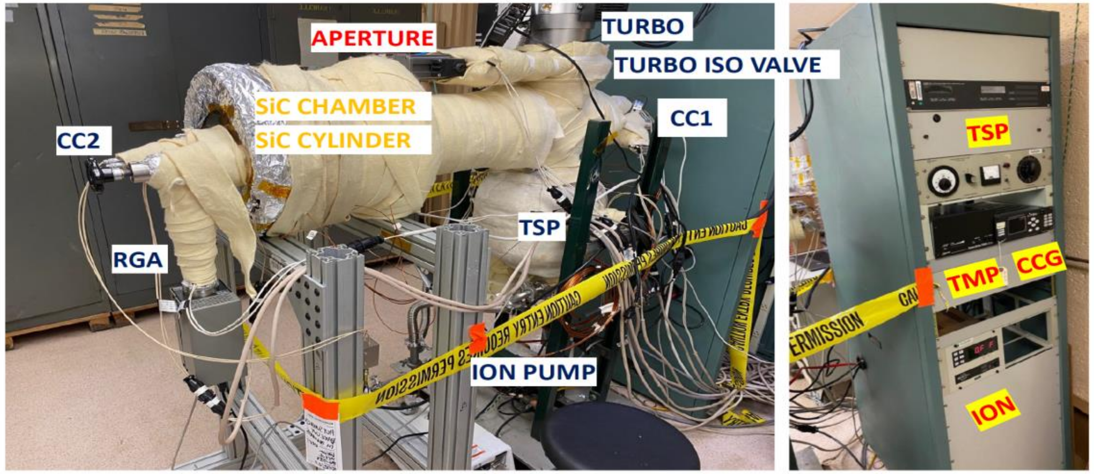




Tile-style SiC HOM damper (Courtesy: T. Schultheiss)

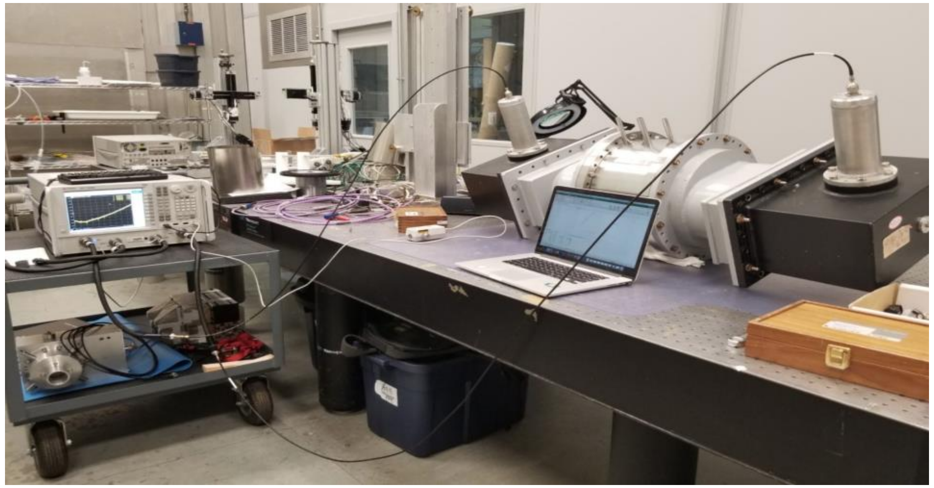
Test for application in a SRF cavity

- Outgassing test was completed with solid SiC HOM damper.
  - Outgassing rate is 2.2e-10 torr-liters/sec-cm^2
  - Demonstrated interference-fit SiC assembly satisfies the high vacuum needs in EIC SRF cavities.
- SRF cleaning test
  - SRF cleaning procedure test on the SiC HOM damper
  - Demonstrated SRF handling criteria.



RF test

- Narrow band measurement on solid SiC HOM damper with waveguide transition at each side.
  - The result is close to expectation. ➔ We will need 62 kW to test the 24 kW absorption at 704 MHz.



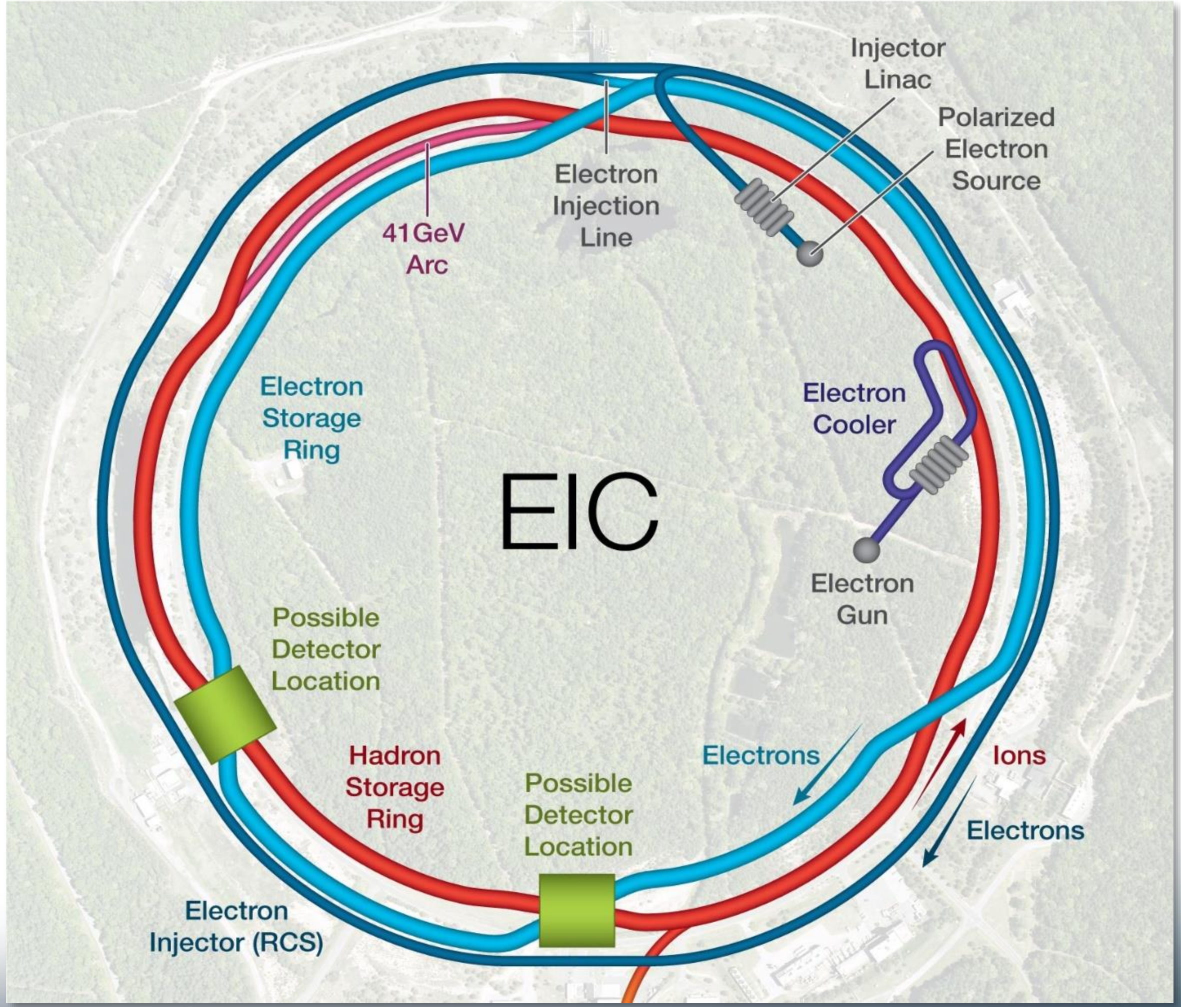
- High power test at 704 MHz to verify power handling.

Summary

- EIC is a challenging machine, particularly, RF system is quite complicate.
- EIC RCS RF has unique requirement for longitudinal and transversal impedance, which can be satisfied with SIC HOM damper at the both ends of the cryomodule.
- RCS FPC requirement is much lower than the FPC for ESR, so we are able to use the same design for ESR.
- SIC HOM damper prototype and test is ongoing, and the last check box left is high power RF test.

Acknowledgements

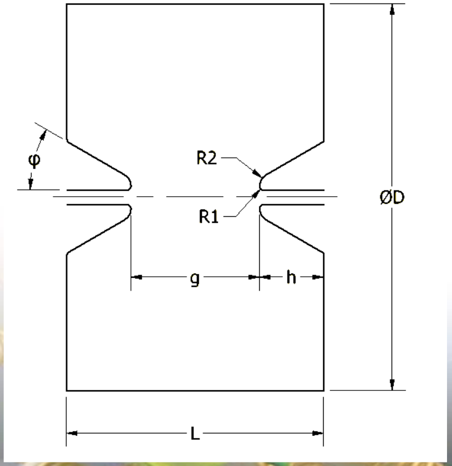
- BNL – K. Smith, B. Xiao, D. Holmes, A. Zaltsman, Z. Conway, Vahid Ranjbar, S. Andres-Verdu, Q. Wu and many others
- JLAB –E Daly, J. Guo, J. Henry, J. Matalevich, R. Rimmer, and many others

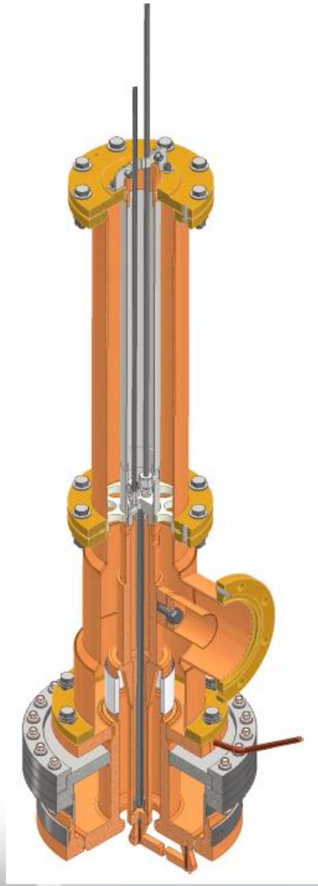


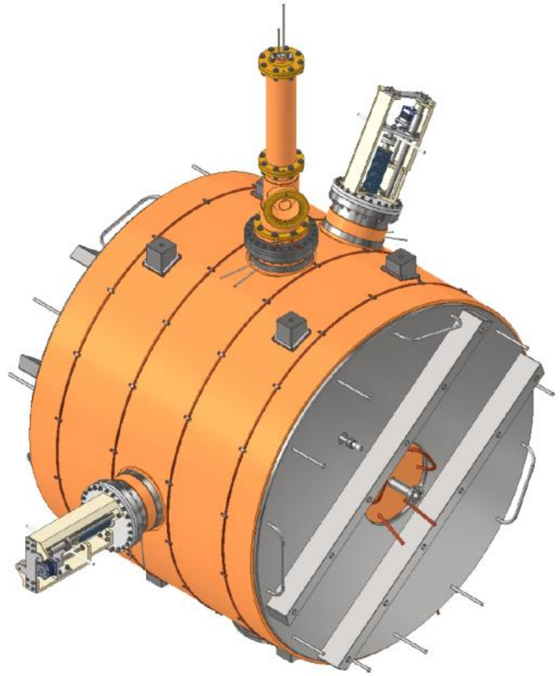
Backup Slides

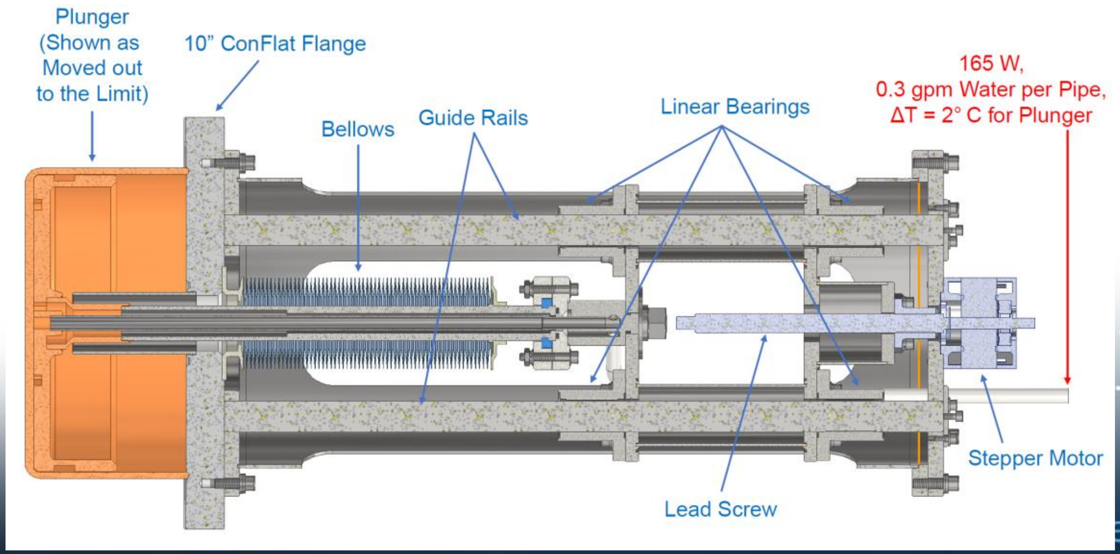
RCS 147.75 MHz Bunch Merge (Binping Xiao)

- One loop FPC
- Two tuners
- No HOM damper
- PDR completed

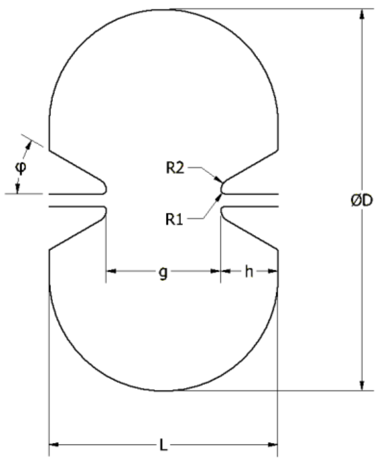




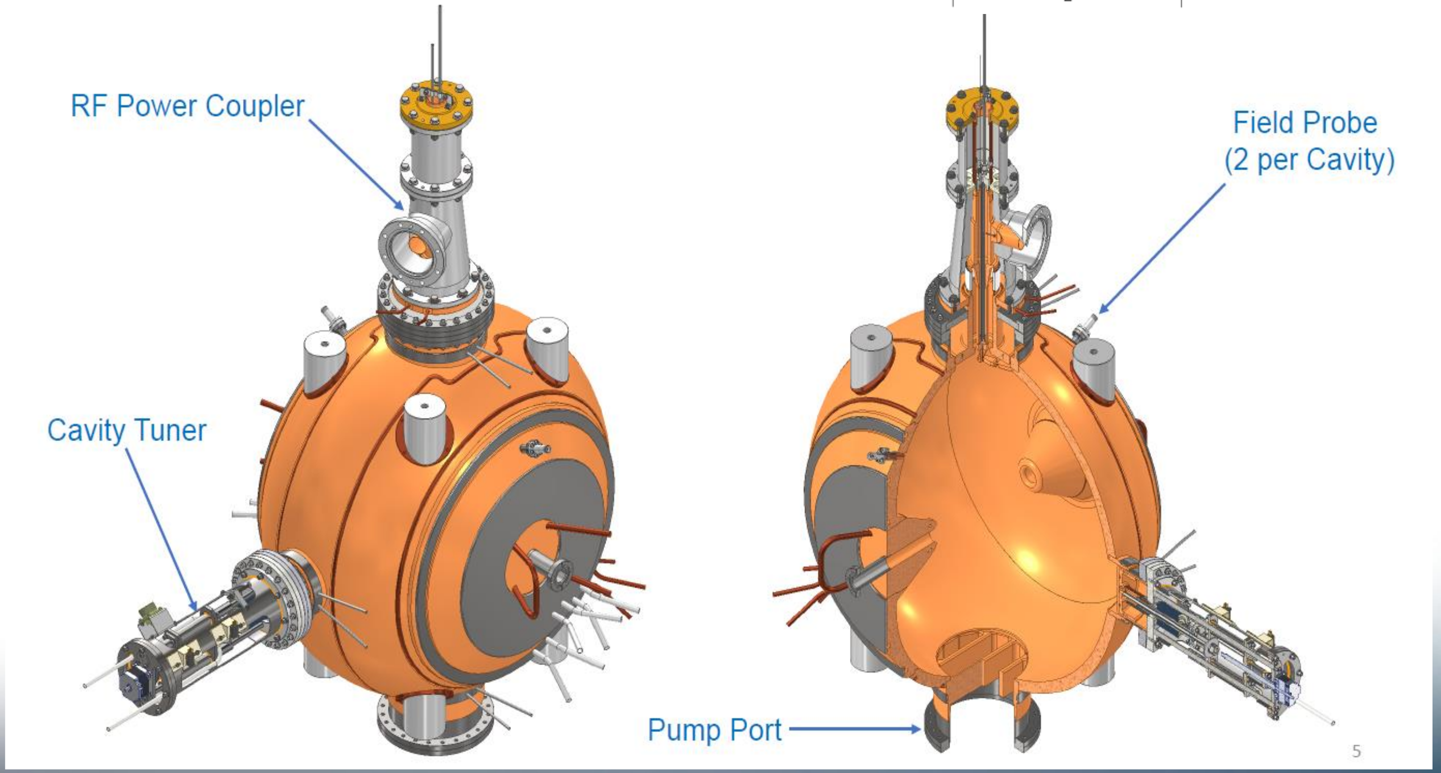




RCS 295.5 MHz Bunch Merge (Binping Xiao)

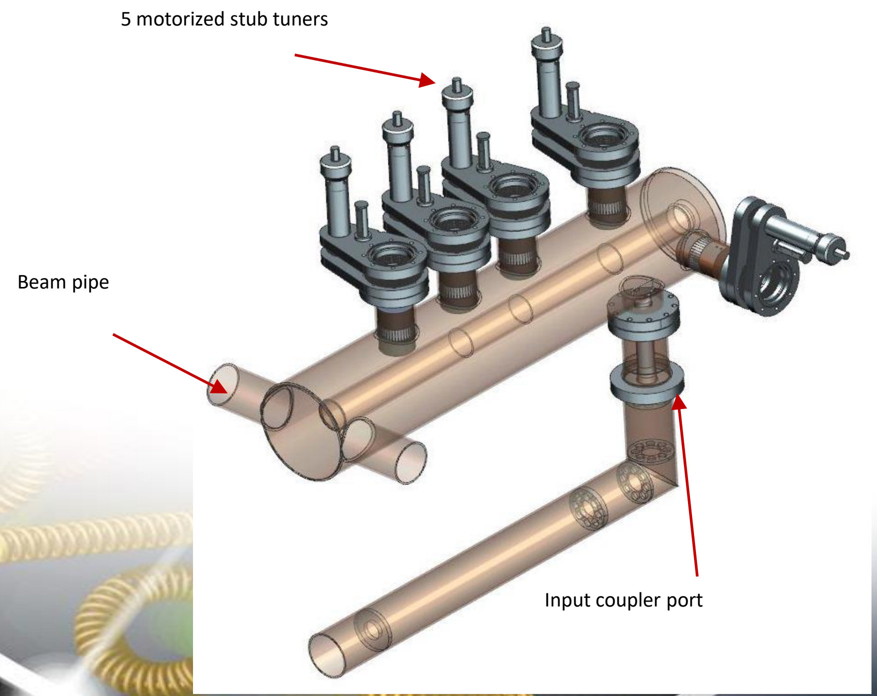


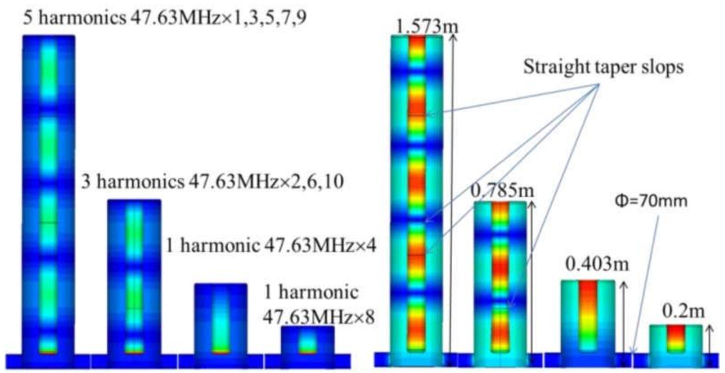
- Preliminary design on-going
- FPC brazing assembly the same as the 147.75MHz design, with different T-section and quarter wave stub that bolts onto the brazing assembly
- One tuner required
- Developing design for HOM damper



RCS Harmonic kicker (Jiquan Guo)

- All forward power are calculated to achieve desired kicker voltage in 10μs rise time
- Coupling optimized to minimize the forward power (may need ~20% margin for the 3rd harmonic simply due to constraint on coupling optimization)
- The baseline 0-slope scheme uses only ~1/3 power of the squarewave and the equal amplitude schemes
- Cooling is not required for the RCS kicker due to the low duty factor





0-slope, harmonic 1-3						
f (MHz)	Scaled from f (MHz)	R⊥/Q (Ω)	G (Ω)	β	V(kV)	P fwd (kW)
147.75	95.3 (Y. Huang C2)	1166	31	2.74	150	3.8
295.5	190.5 (Y. Huang C3)	975	55	1.90	100	1.2
443.25	285.8 (Y. Huang C2)	268	92	1.77	50	0.8
					total	5.8