EIC and SRF Device Development at Brookhaven

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On behalf of the EIC & C-AD SRF Groups

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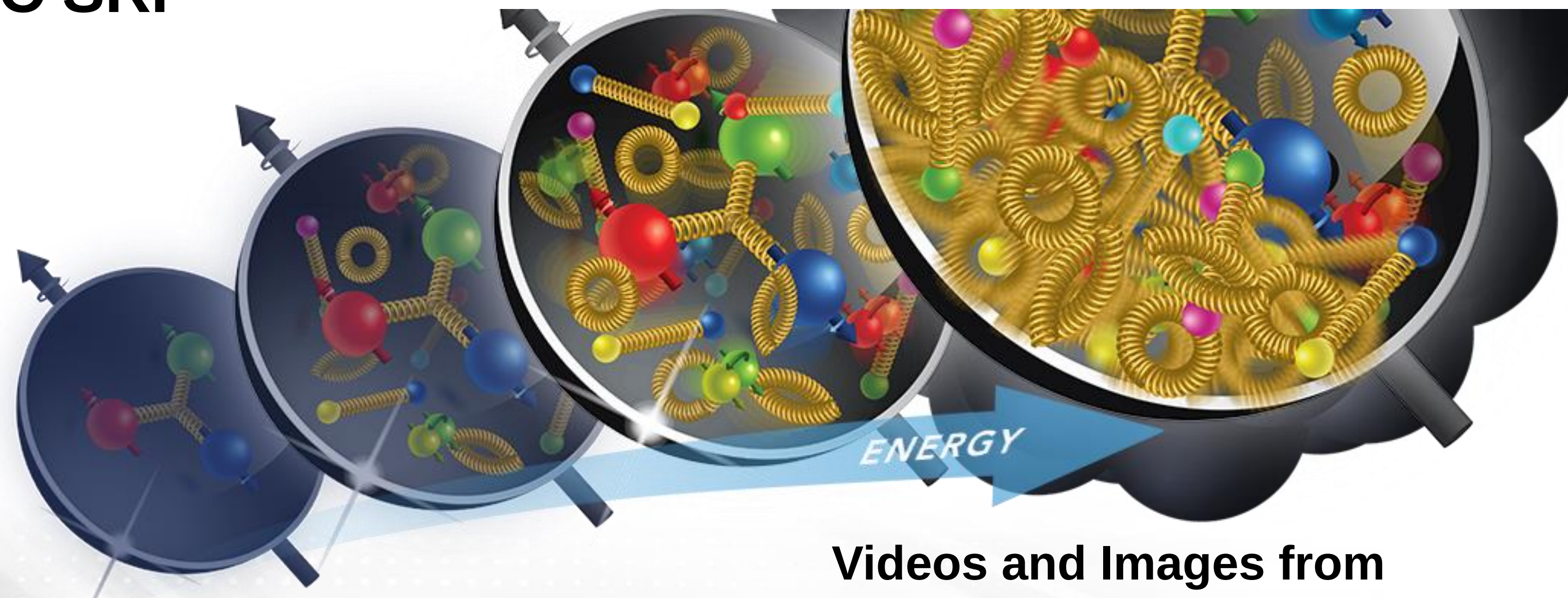
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN SCIENCE ASSOCIATES

Overview

- Electron Ion Collider (EIC) Motivation
- EIC Design
- EIC SRF
- EIC Technology Developments @ BNL
- BNL-RHIC 56 MHz SRF System

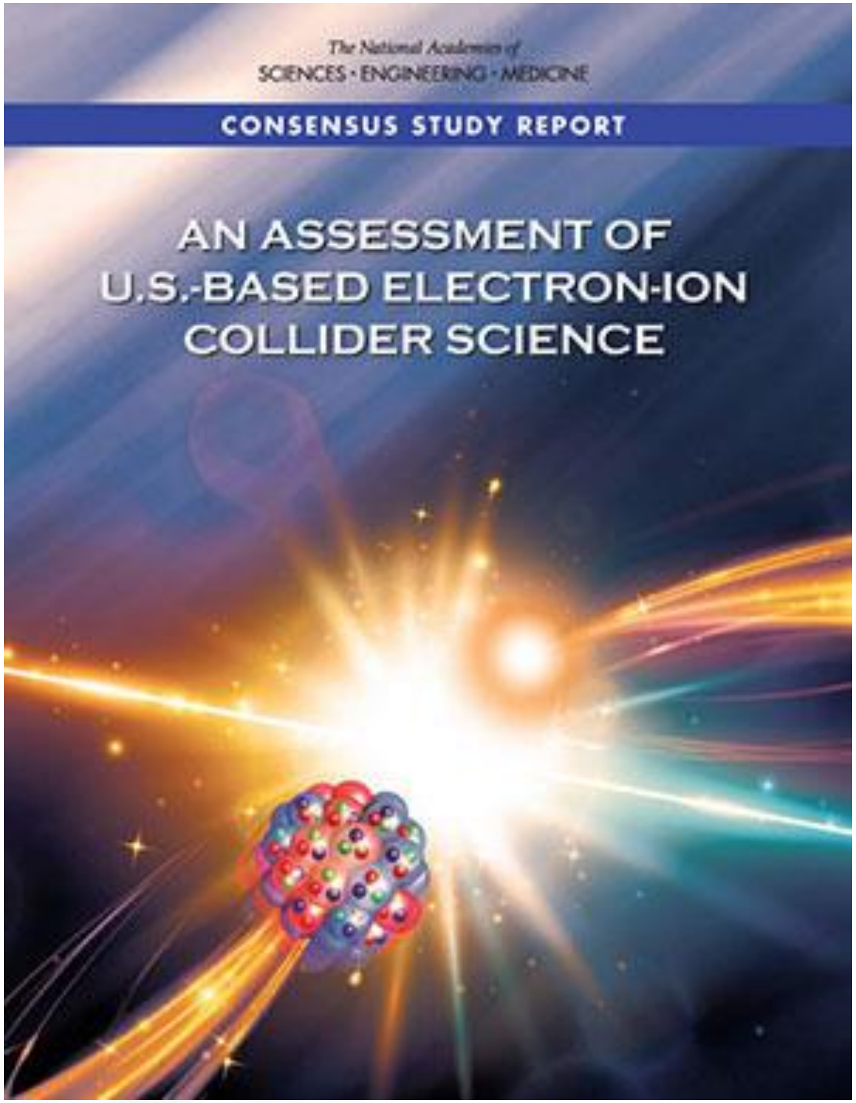


Videos and Images from www.bnl.gov/eic

EIC Motivation

- **EIC will collide e^- with p and nuclei (up to U) to produce snapshots of the hadon's internal structure.**
- **EIC science unanimously supported by the National Academy of Science:**

"The US nuclear science community has been thorough and thoughtful in its planning for the future… Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction <u>following the completion of the FRIB at MSU.</u>



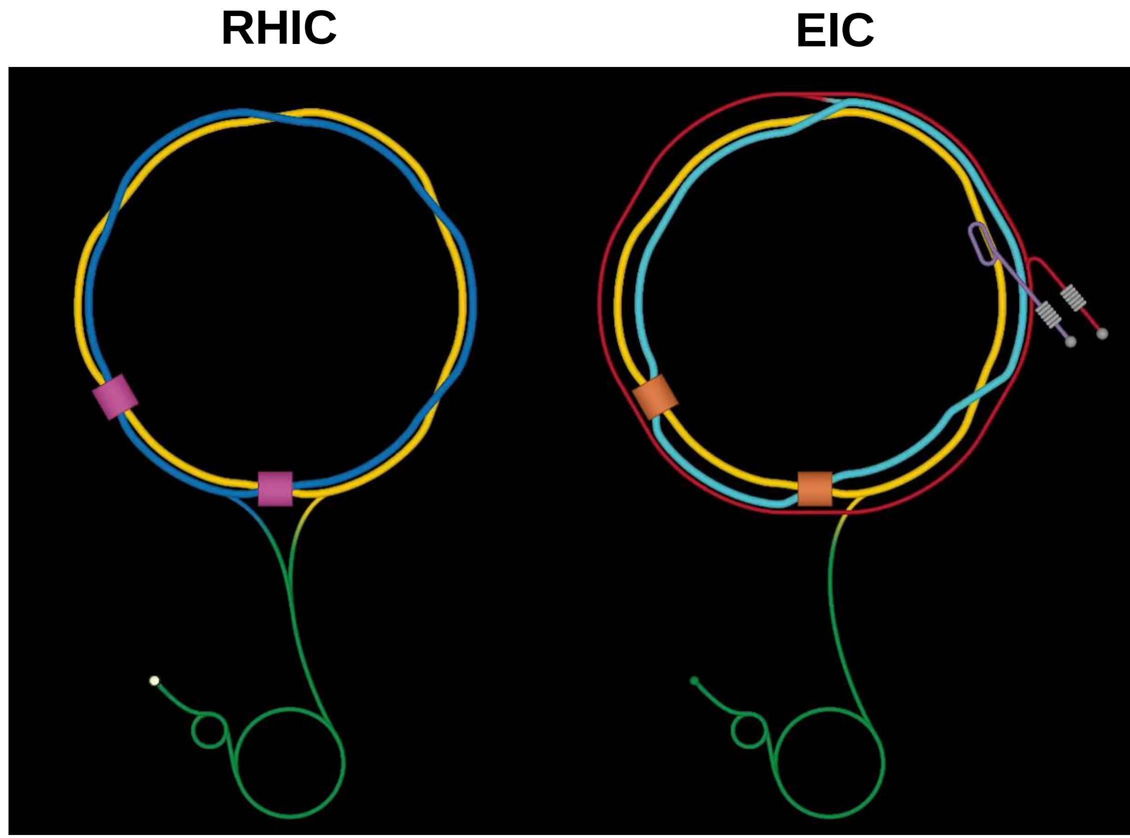
EIC Design - I

- EIC designed to meet NSAC and NAS Requirements:
    - A. Seryi @ EIC Workshop – Promoting Collaboration on the EIC, 7 October 2020.
- Will build upon RHIC @ BNL.

- CM Collisions @ 20 – 140 GeV.
- Maximum luminosity: 10^{34} $cm^{-2}s^{-1}$
- Hadron beam polarization > 70%.
- Electron beam polarization > 70%.
- Ion species range: p to U
- # of interaction regions = up to 2.

Relativistic Heavy Ion Collider @ BNL

EIC Design - II

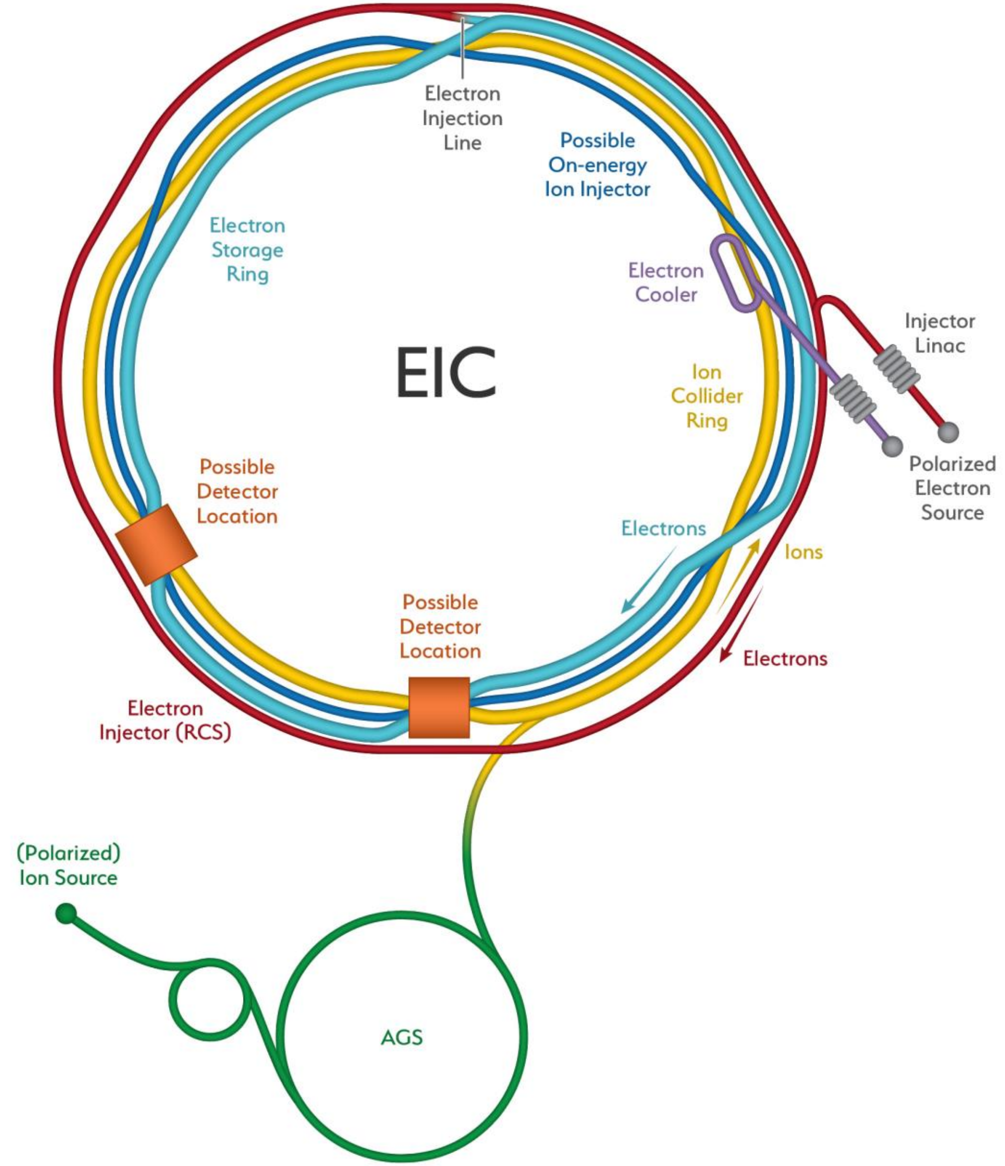


- **EIC design is based on existing RHIC & RHIC is a well-maintained complex operating reliably.**
- **Hadron Storage Ring, p @ 41-275 GeV, ions 41 to 110 GeV/u (existing)**
- **Electron Storage Ring, 2.5 – 18 GeV (new)**
  - **Large beam current (~2.5 A) = 10 MW syn rad.**
- **Electron Rapid Cycling Synchrotron with polarized source (new)**
- **High Luminosity Interaction Region(s) (new)**
  - **25 mrad crossing angle with crab cavities.**
- **Strong Hadron Cooling (new)**

EIC Design - III

- **EIC design team comprised of 2 major partners, BNL and JLAB.**
  - **Other major contributions from SLAC, LBNL, FNAL, MSU, ODU and Cornell.**
  - **A. Seryi's Presentation at the EIC Workshop – Promoting Collaboration on the Electron-Ion Collider, 7-9 October 2020.**
- **BNL-TJNAF Partnering Agreement Approved - May 7, 2020**
  - **J. Yeck's Presentation at the EIC Workshop – Promoting Collaboration on the Electron-Ion Collider, 7-9 October 2020.**

EIC Schematic



EIC SRF (Developing)

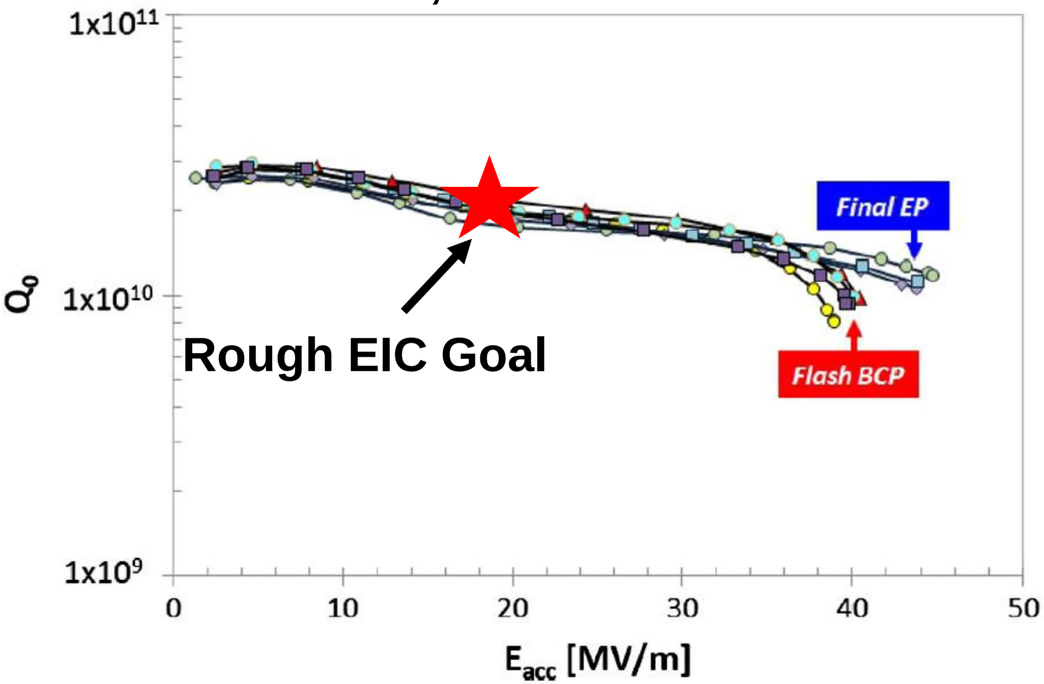
SRF System	SRF Sub-System	Frequency	Cavity Type	Quantity
ESR	H1 Fundamental	591 MHz	2-Cell ECR	14
RCS	H1 Fundamental	591 MHz	5-cell ECR	3
HSR	Bunch Compression	591 MHz	5-cell ECR	2
Interaction Region	Crab Cavity 1 (e^-/p)	394 MHz	RFD/DQW	6
Interaction Region	Crab Cavity 2 (p)	197 MHz	RFD/DQW	8
Strong Hadron Cooling	Injector	591 MHz	5-cell ECR	2
Strong Hadron Cooling	ERL	591 MHz	5-cell ECR	9

Peak surface fields for all SRF resonators ~40 MV/m and ~80 mT.
Hoping for residual surface resistances of < 10 nΩ.

ESR = Electron Storage Ring, RCS = electron Rapid Cycling Synchrotron, HSR = Hadron Storage Ring, ERL = Energy Recovery Linac, ECR = Elliptical Cell Resonator, RFD = Radio Frequency Dipole, DQW = Double Quarter-Wave Resonator

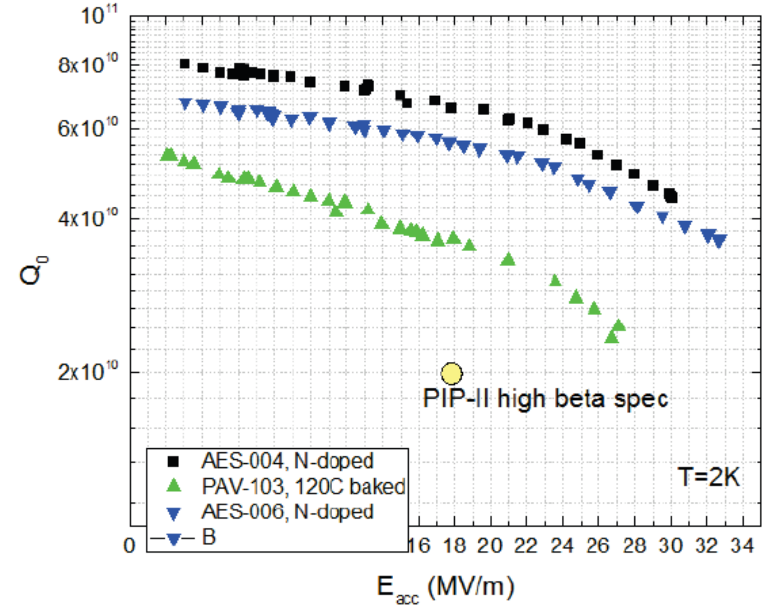
SRF Field Performance

2.0 K, 1.3 GHz 9-cell TESLA



W. Singer et al., PRST-AB 19, 092001

2.0 K, 650 MHz 5-Cell PIP-II

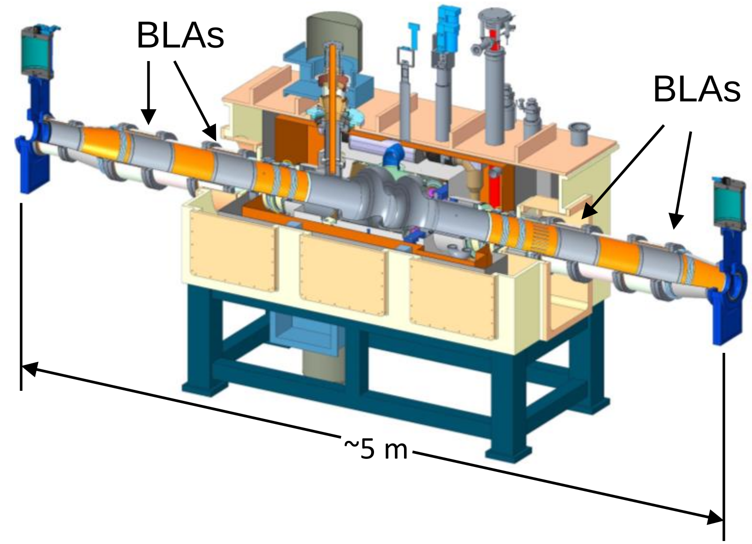


A. Grasselino et al., SRF15

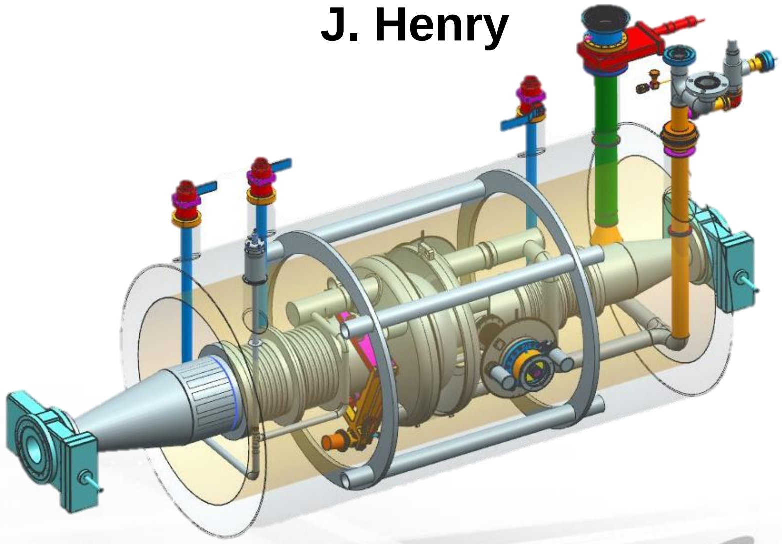
ESR Cryomodule

- **2K Operation.**
- **12.75 MW total installed power**
  - **10 MW synchrotron radiation**
- **68.1 MV of total installed voltage.**
  - **37.8 MV synchronous voltage.**
  - **826 kW forward power per cavity**
- **9 W dynamic losses @ 10 nΩ R_{res}**
- **1 vs 2 cell final design is being modeled by JLAB now.**
- **80 kW of HOM dampers per 2-cell cavity.**
- **Dual 500 kW fundamental power couplers per cavity.**

Cut-Away View of BNL ECR Cryomodule Concept: D. Holmes

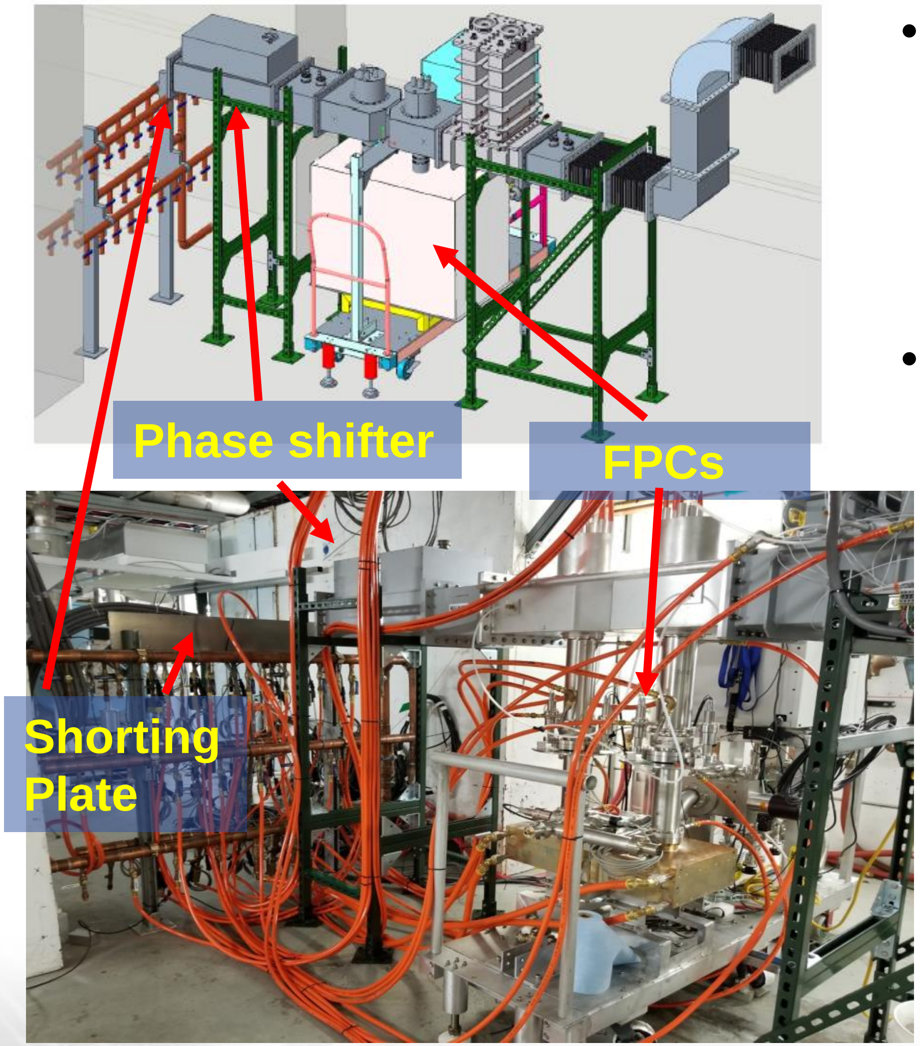


JLAB RCS Cryomodule Concept: J. Henry



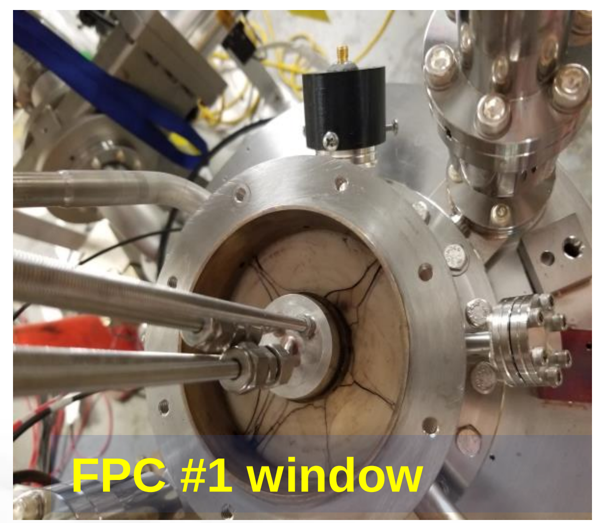
500 kW Power Couplers & Tuner

500 kW Coupler Testing



- FPC Offline Testing/Conditioning
- 20 ms pulse-on, low duty cycle to CW operation are increasing $P_{forward}$ (170, 300, 400, 500 kW) while scanning phase over an 80 degree window.
- 500 kW forward power reached for 1 setting of the phase shifter.

Window After Test



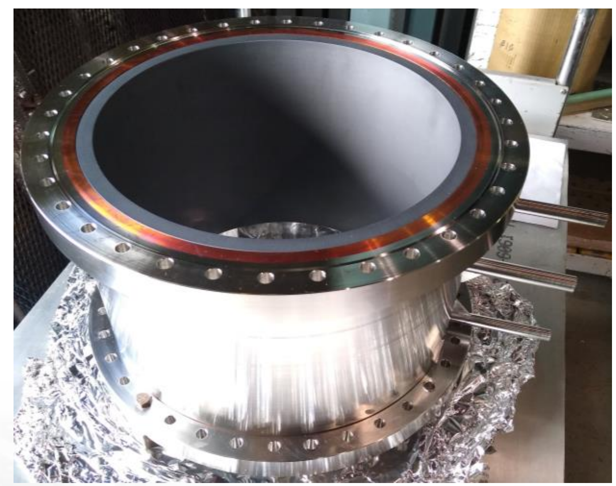
W. Xu et al., TTC2020, February.

20 kW BLA R&D

- CoorsTek SC-35 SiC Cylinder: 308 mm ID, 336.5 mm OD, 240 mm length, 11.4 kG
- Shrink fit into water cooled copper cylinder with stainless steel jacket. Full assembly = 55.4 kG.
  - R. Eichhorn et al., SRF2015
  - S.-h. Kim et al., THPB073, SRF15.
- D. Holmes et al., TTC2020, February.

20 kW BLA Parts

20 kW BLA Assembly



Photos: D. Holmes

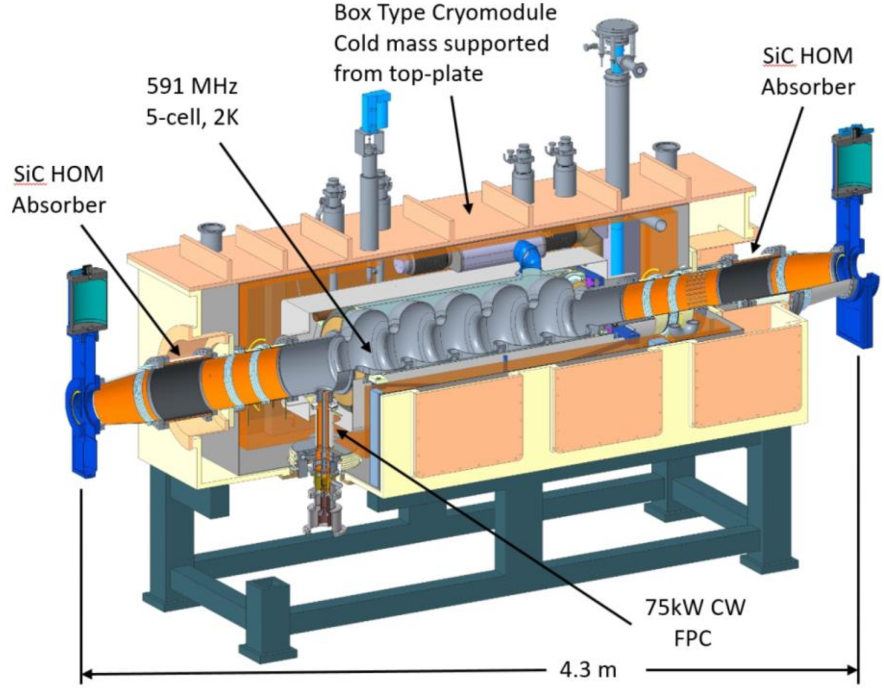
5-Cell ECR RF Systems

- **The HSR, RCS and SHC ERL SRF systems provide an opportunity to leverage design commonality.**
- **All systems require high voltage:**
  - **HSR each SRF cavity > 20 MV.**
  - **RCS with 100 ms ramp rate (2 MV/turn) and high synchrotron radiation loss per turn (38 MeV at 18 GeV).**
  - **SHC ERL at 150 MeV – reduce required linac tunnel length.**
- **All systems require heavy Higher Order Mode (HOM) damping**
  - **HSR beams have no intrinsic damping and are planned to operate up to 1 A with 6 cm rms bunch length.**
  - **RCS with only 2 bunches (28 nC/bunch) must still control long range wake fields.**
  - **SHC ERL with 100 mA beam, 1 nC per bunch, maintain $\Delta E/E$ = 1e-4 and maximize BBU threshold.**

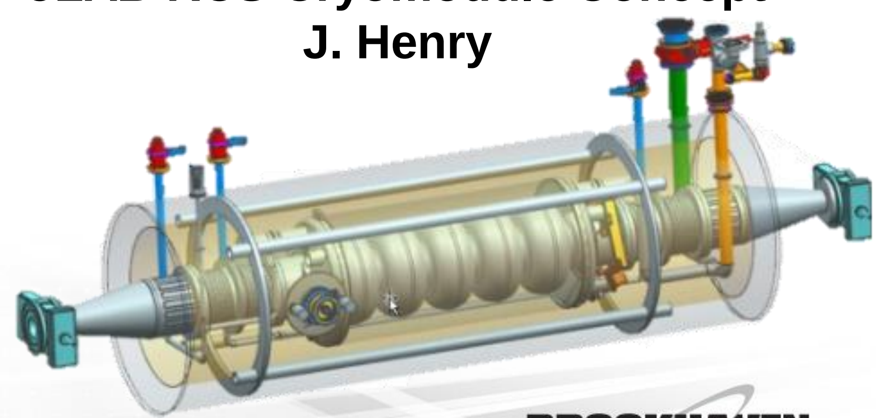
5-Cell Cryomodule

- **The EIC 591 MHz 5-cell cavity design is scaled from the 650 MHz 5-cell prototype developed for BNL's linac-ring collider's ERL.**
    - **Wencan Xu, et al. IPAC'2012**
- **The EIC 591 MHz 5-cell cavities duplicate the large beam pipes of the ESR cavities which do not trap any HOM and extend to external Silicon Carbide (SiC) Beam Line Absorbers (BLAs).**
- **The 650 MHz Nb and copper cavities are being used for R&D to validate the HOM damping scheme.**

Cut-Away View of BNL RCS Cryomodule Concept: D. Holmes



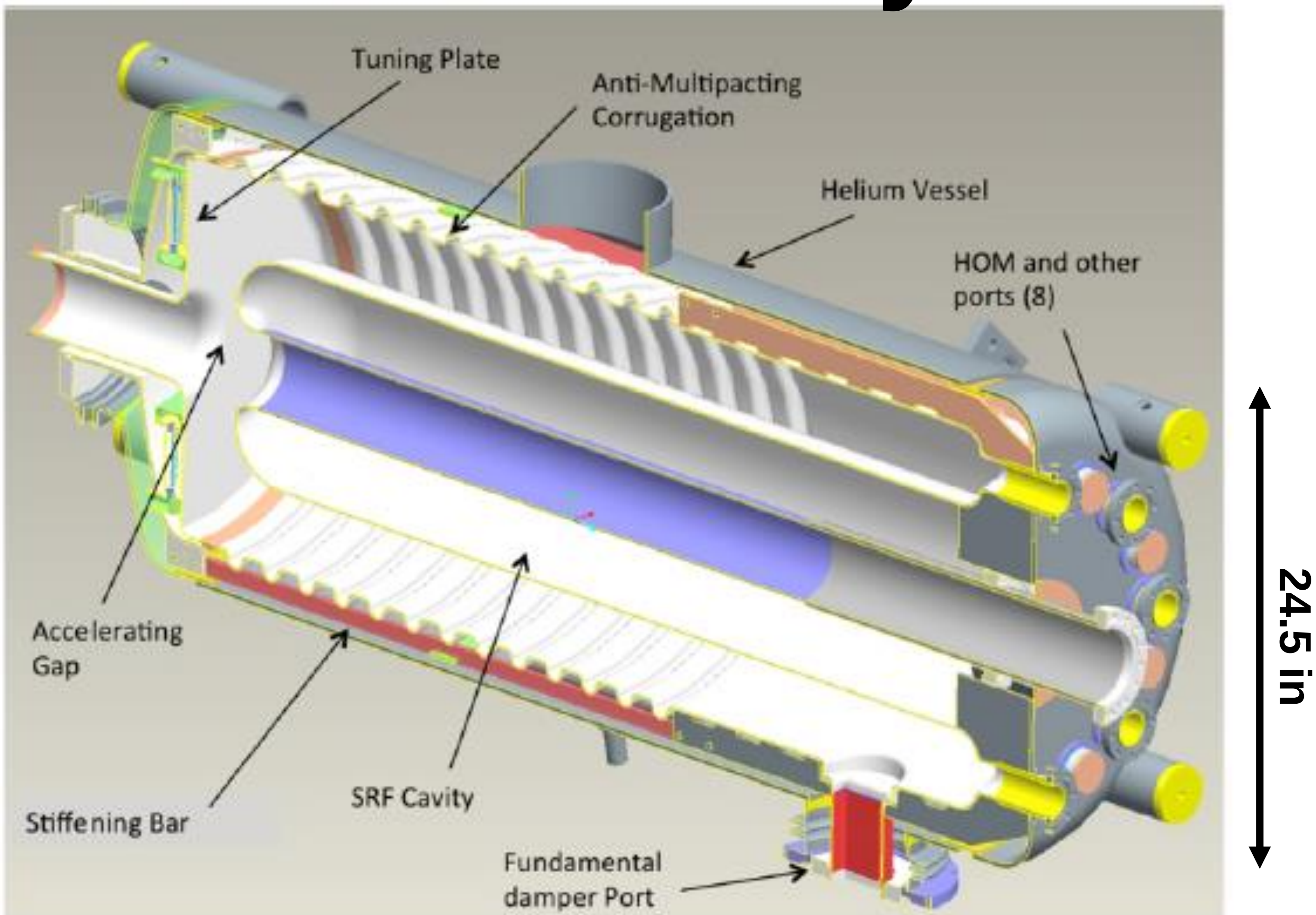
JLAB RCS Cryomodule Concept
J. Henry



Frequency Sweeps

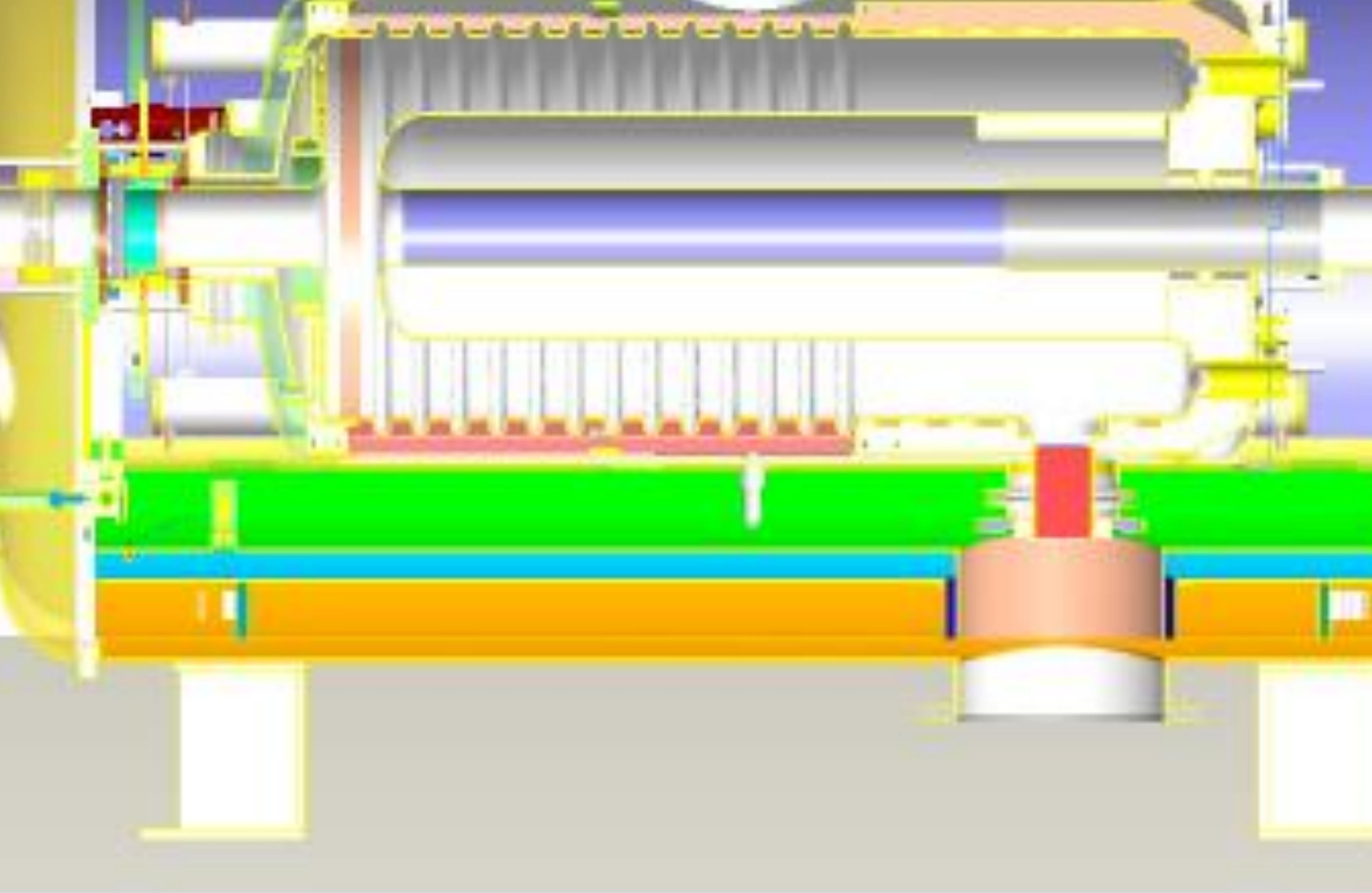
- **The Hadron Storage Ring:**
  - **Protons with final energy = 275 GeV, 0.1% Frequency Sweep**
  - **Ions with final energy = 110 GeV/A, 0.5% Frequency Sweep**
- **The electron RCS frequency sweep ~500 Hz for the 591 MHz system with operation from 400 MeV to 18 GeV.**
- **How to tune a 5-cell ESR? Need additional range to provide flexibility between operating modes and dynamic range.**
  - **Original design goals were 1-1.5%!**
  - **Revolution frequency = 78.2 kHz**
  - **Harmonic # for 591 MHz = 7560**
- **Can the tuner slew rate be high enough to track the beam?**
  - **Fast tuner possible for the RCS with 1-2 Hz rep rate and 500 Hz shift.**
- **<u>Damp the cavities so they are transparent to beam.</u>**

RHIC 56 MHz System



Q. Wu et al., PRAB 22, 102001

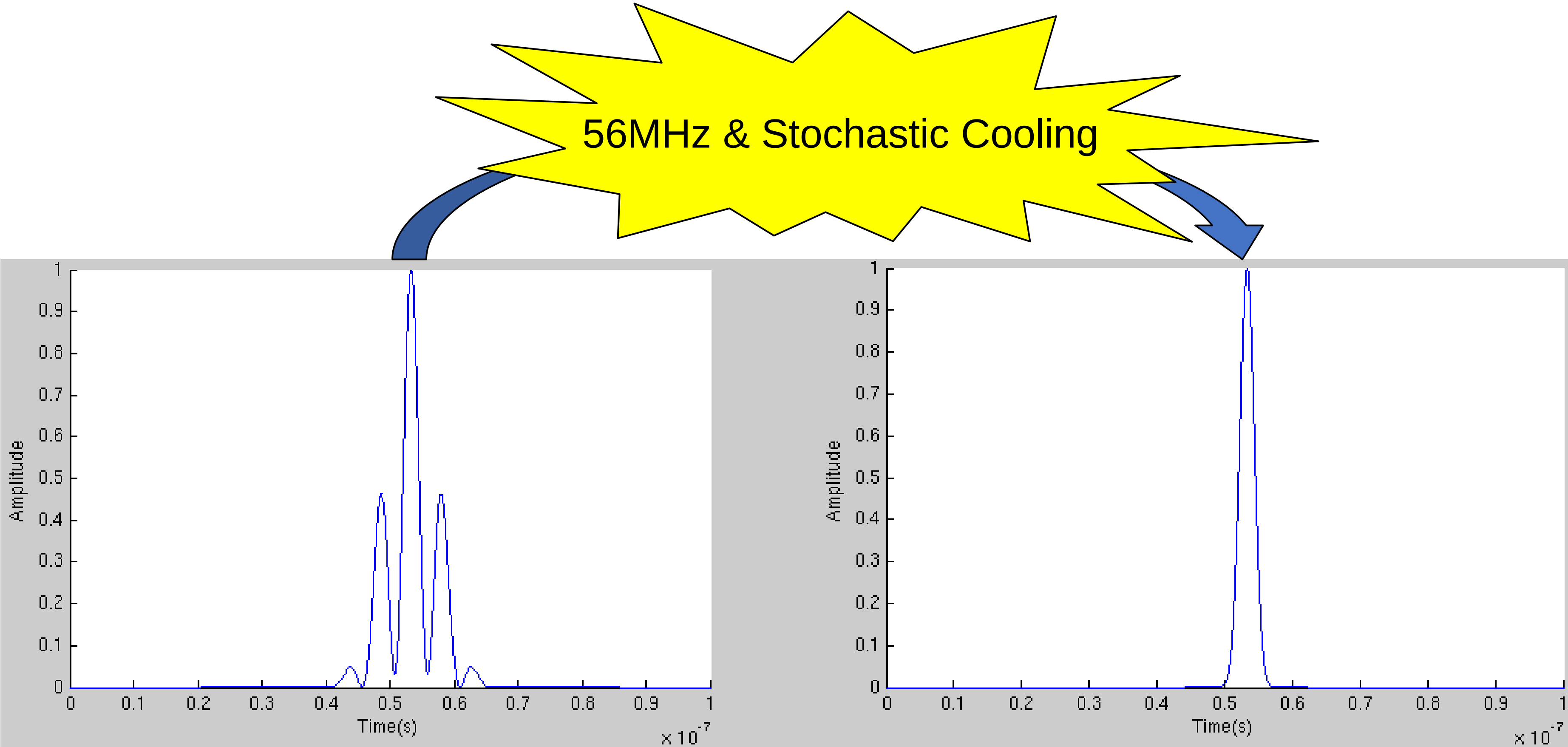
I. Ben-Zvi, Proposal: 56 MHz RHIC SRF Cavity, RHIC Retreat 2007



56 MHz System for RHIC

- RHIC ion beams are accelerated to their collision energy with a 28 MHz RF system.
- At the collision energy RHIC bunches need rebucketing to reduce the bunch length
  - Increases luminosity
  - Reduces the particle loss and energy deposited in the SC magnets.
- The bunches are rotated by temporarily switching the RF phase to the unstable fixed point and then turning on the 197 MHz system to store the shorter bunches.
- The 56 MHz system with stochastic cooling was intended to produce sufficiently short bunches to allow RHIC to operate with direct adiabatic capture by the 197 MHz system

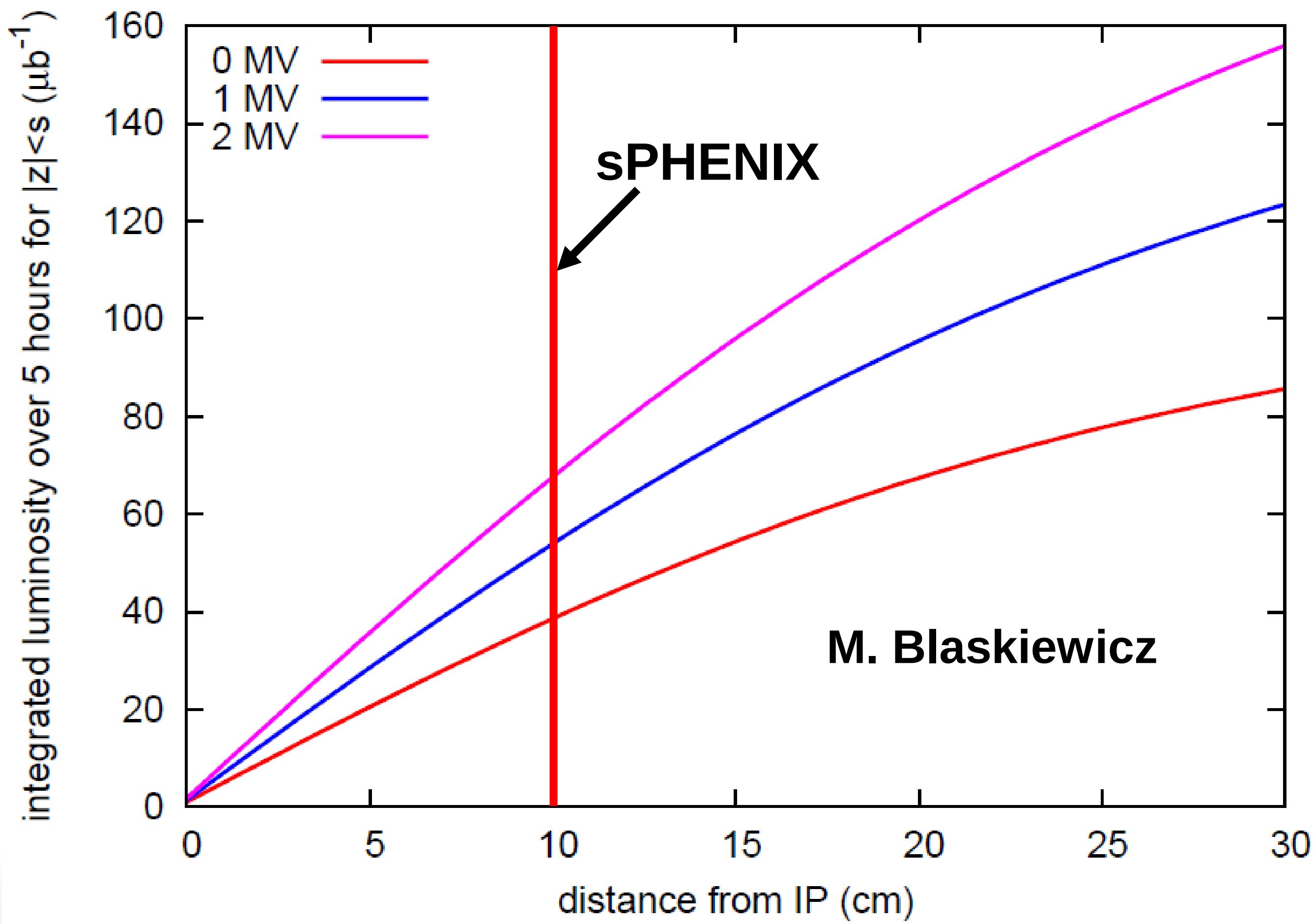
Projected 56 MHz System for RHIC



S. Polizzo, RHIC 2016 MAC

sPHENIX Impact

sPHENIX 2022 Performance with 56 MHz QWR

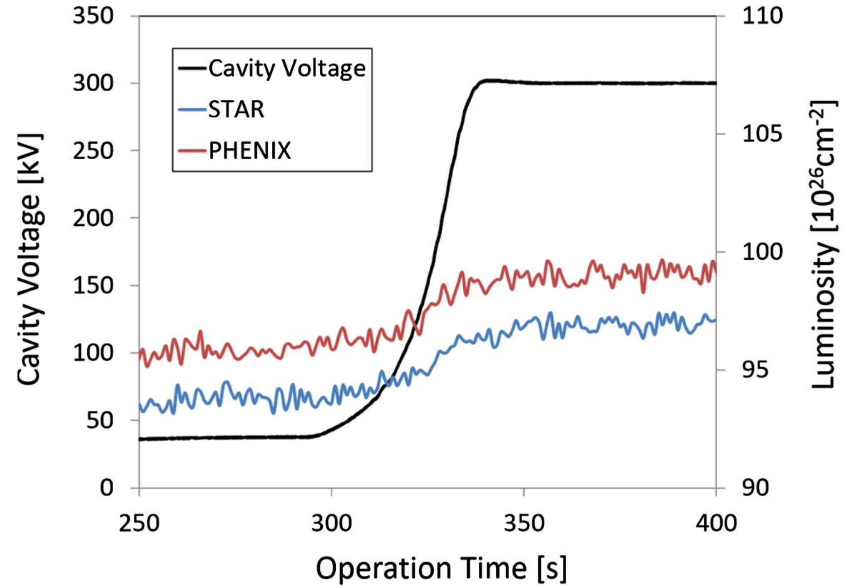


56 MHz Status

56 MHz QWR Performance

- **Superconducting HOM couplers.**
  - **Quench.**
  - **Need for refit.**
  - **HOM coupler removed and other couplers refit for 2016 run.**

2014 RHIC Results

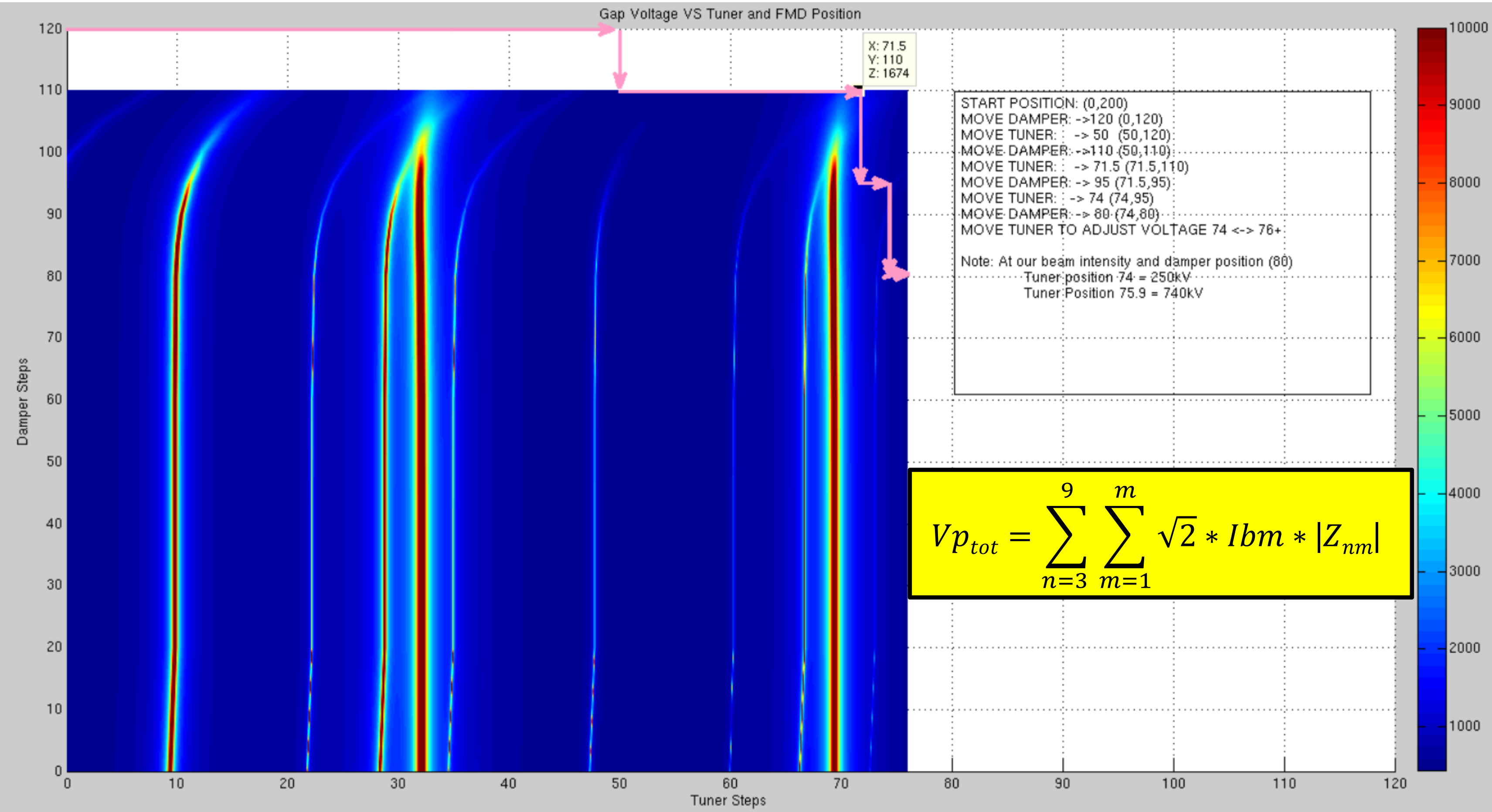


2016 RHIC Results

1MV Normalized System Parameters	Design	Measured (FY16)
Extracted Beam Power	489W	1.8kW
Required FPC Coupling β	79	290
Required Peak Active Tuning Power	250W	2.8kW
Required Active Tuning Range	1.13Hz	22Hz
Mechanical Tuning Range	>24kHz	46kHz
Lorentz Detuning	74Hz	150Hz

Q. Wu et al., PRAB 22, 102001
S. Polizzo, RHIC 2016 MAC

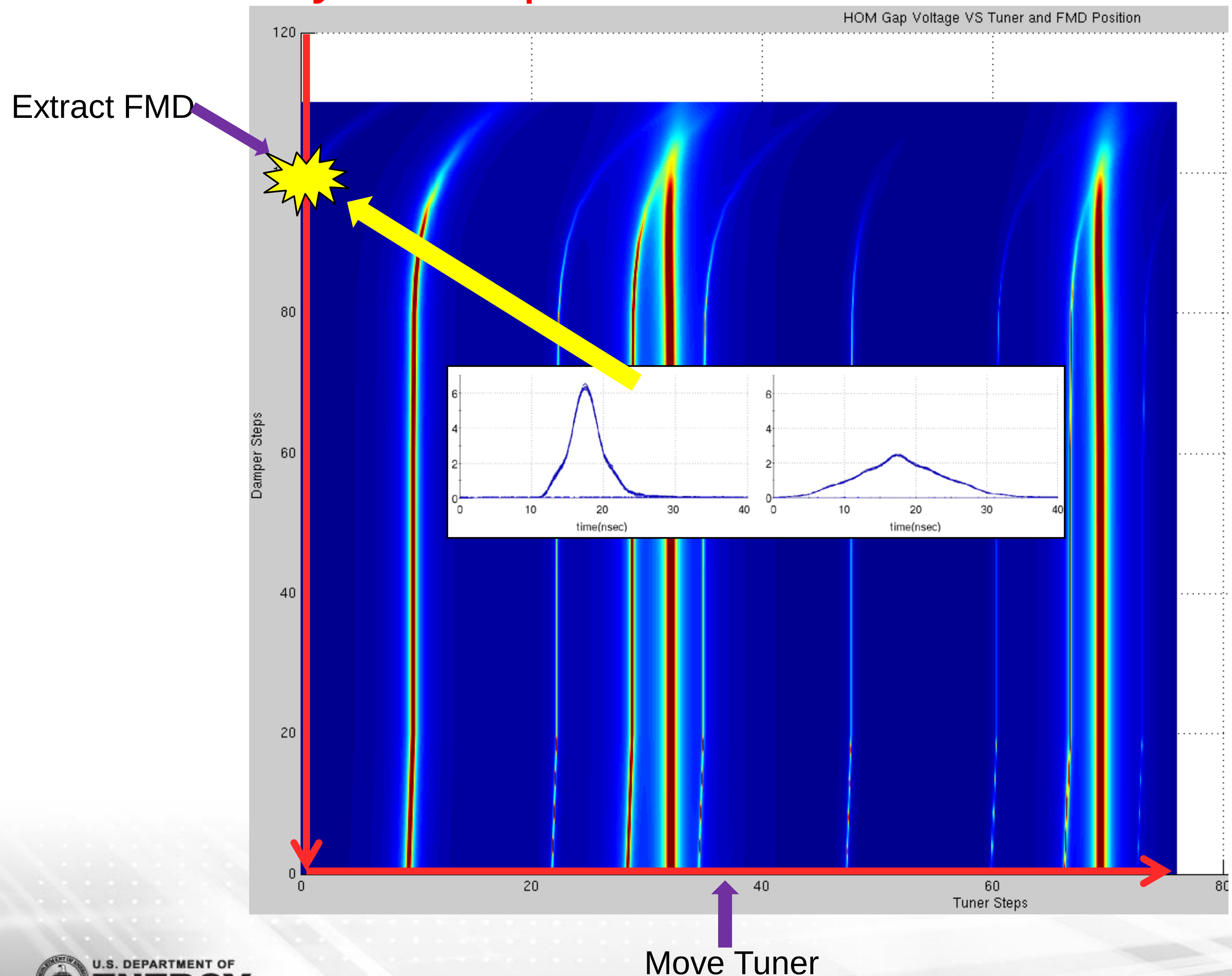
Tuner and FMD Operating in 2016



$$Vp_{tot} = \sum_{n=3}^{9} \sum_{m=1}^{m} \sqrt{2} * Ibm * |Z_{nm}|$$

Tuner and FMD Operating in 2016

- Normal System Operation Path



sPHENIX next.

~30% higher beam current.

S. Polizzo, RHIC 2016 MAC

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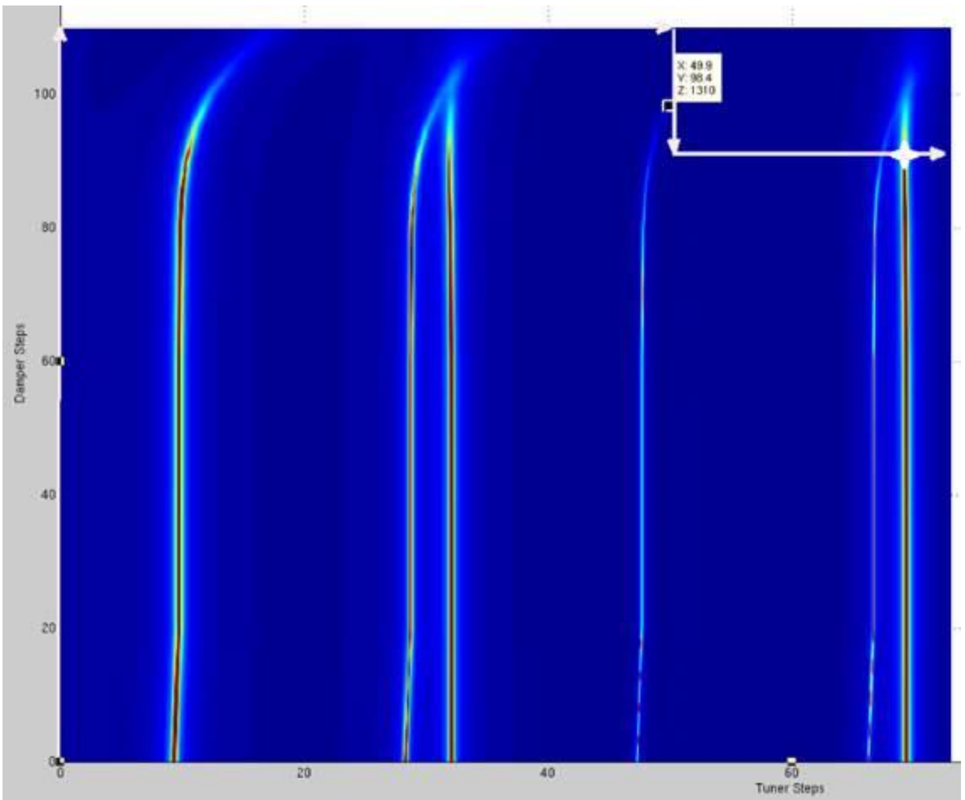
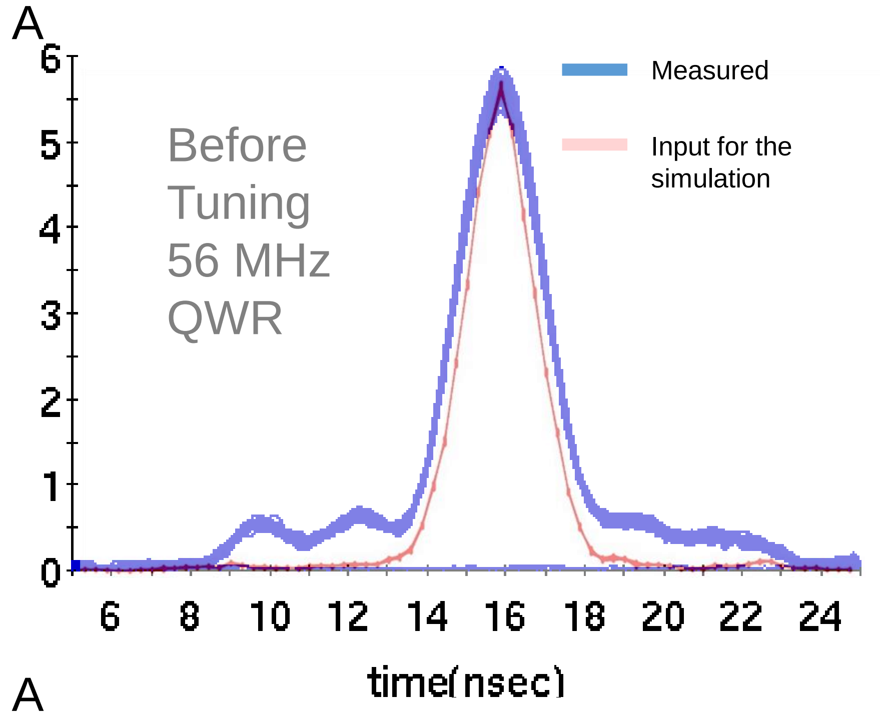
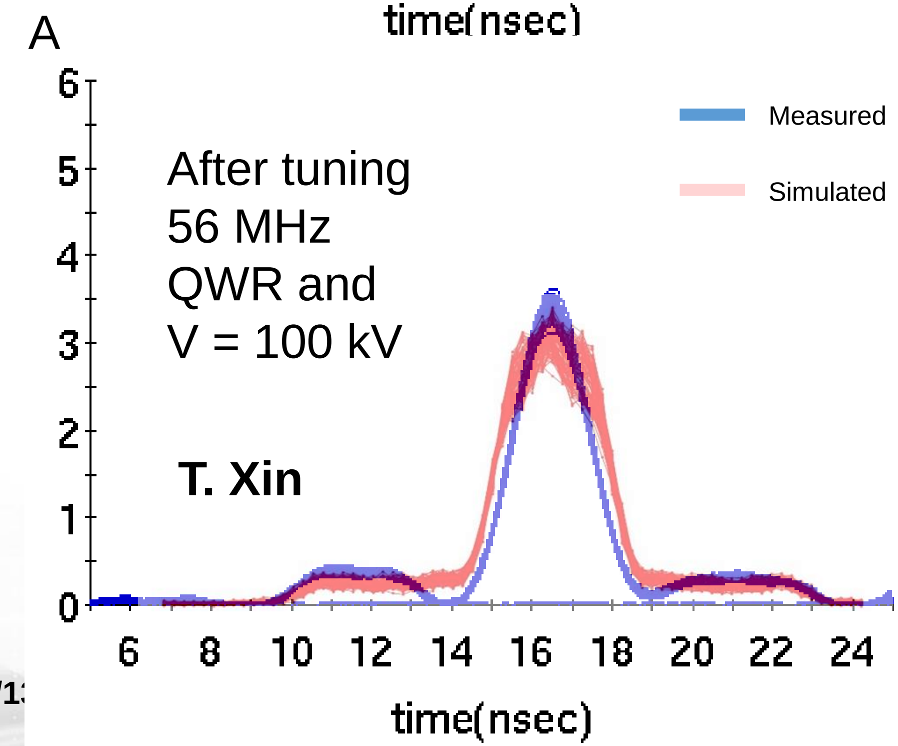
Measurement vs Simulation

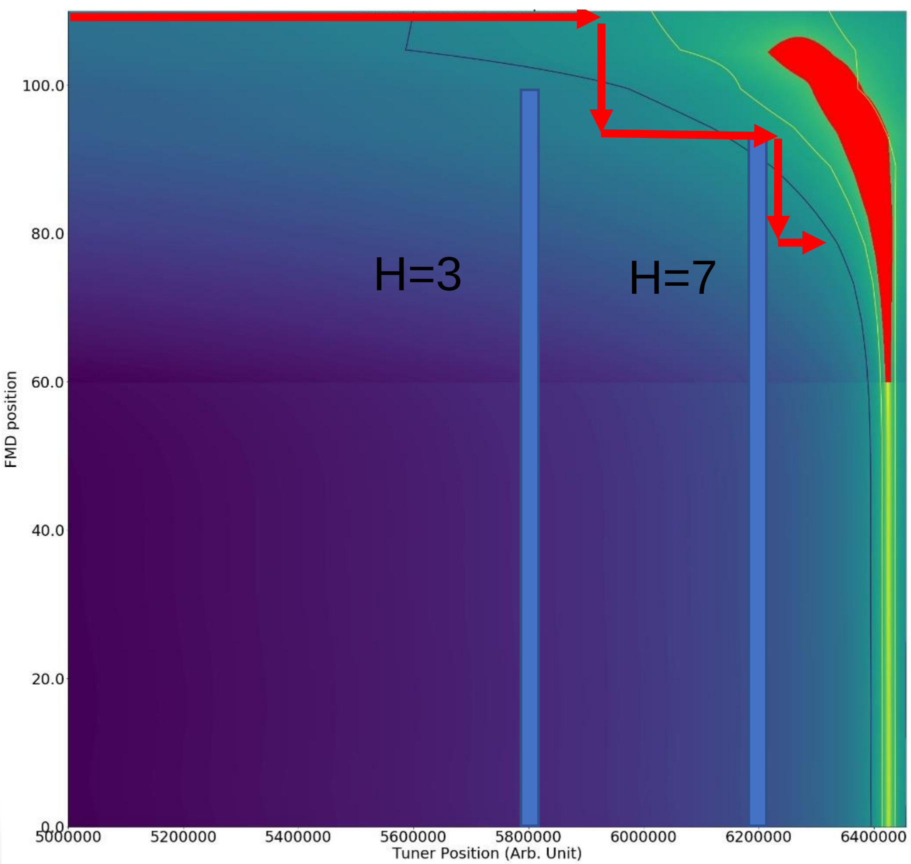




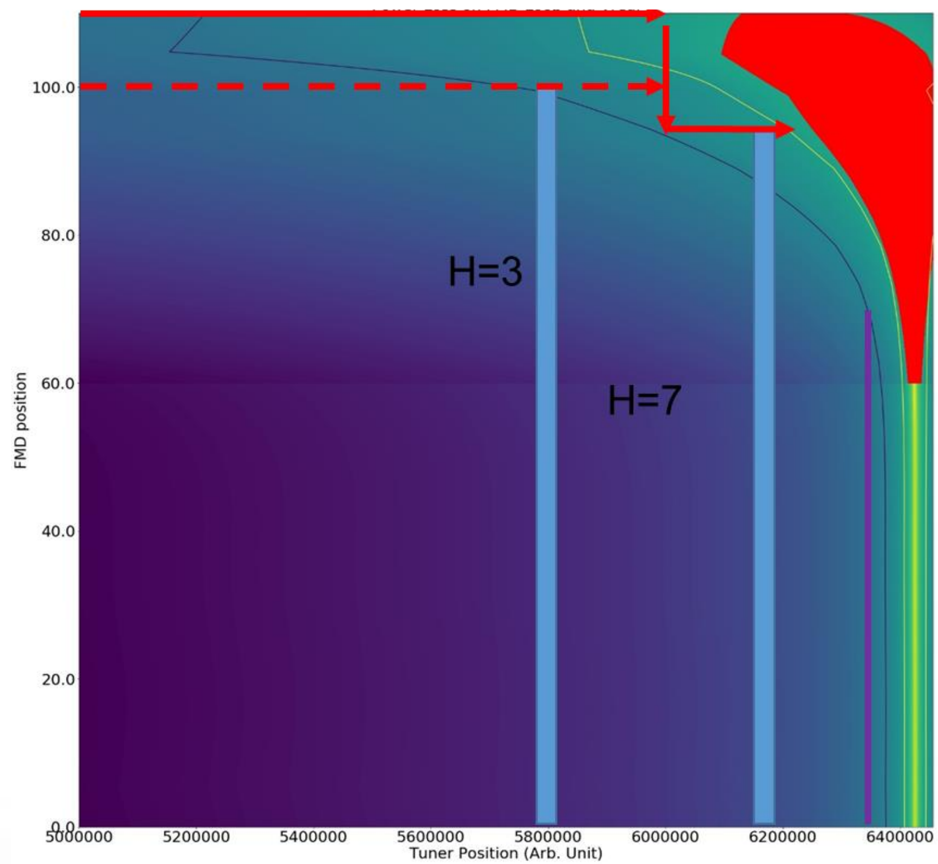


56 MHz Operation: Power Loss on FMD Loop and V_{real}

Simulated Operation During Successful RHIC Run @ 1 MV (Fill 19940)



Planned Operation For sPHENIX Run @ 2 MV



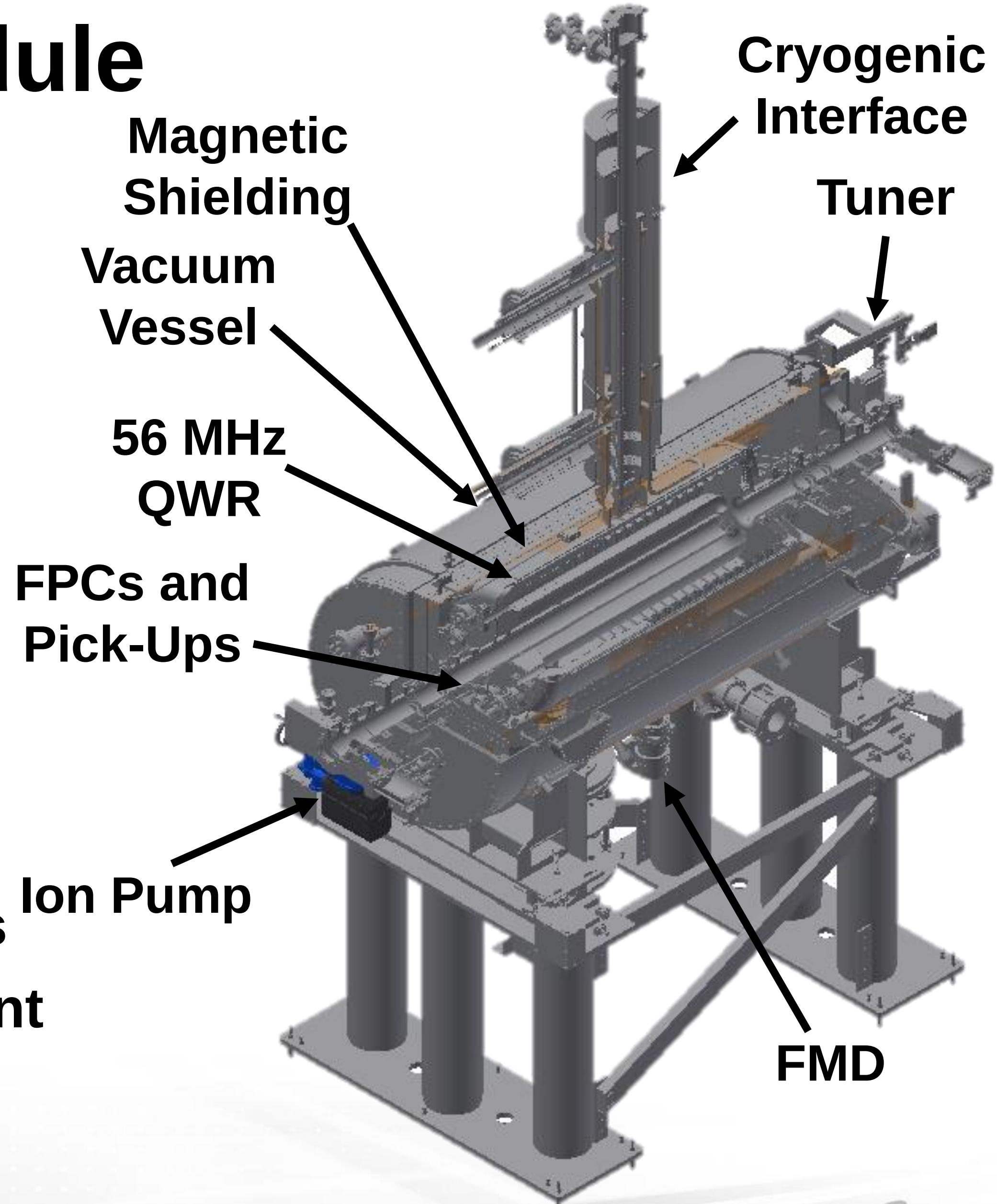
56 MHz Cryomodule

What do we need?

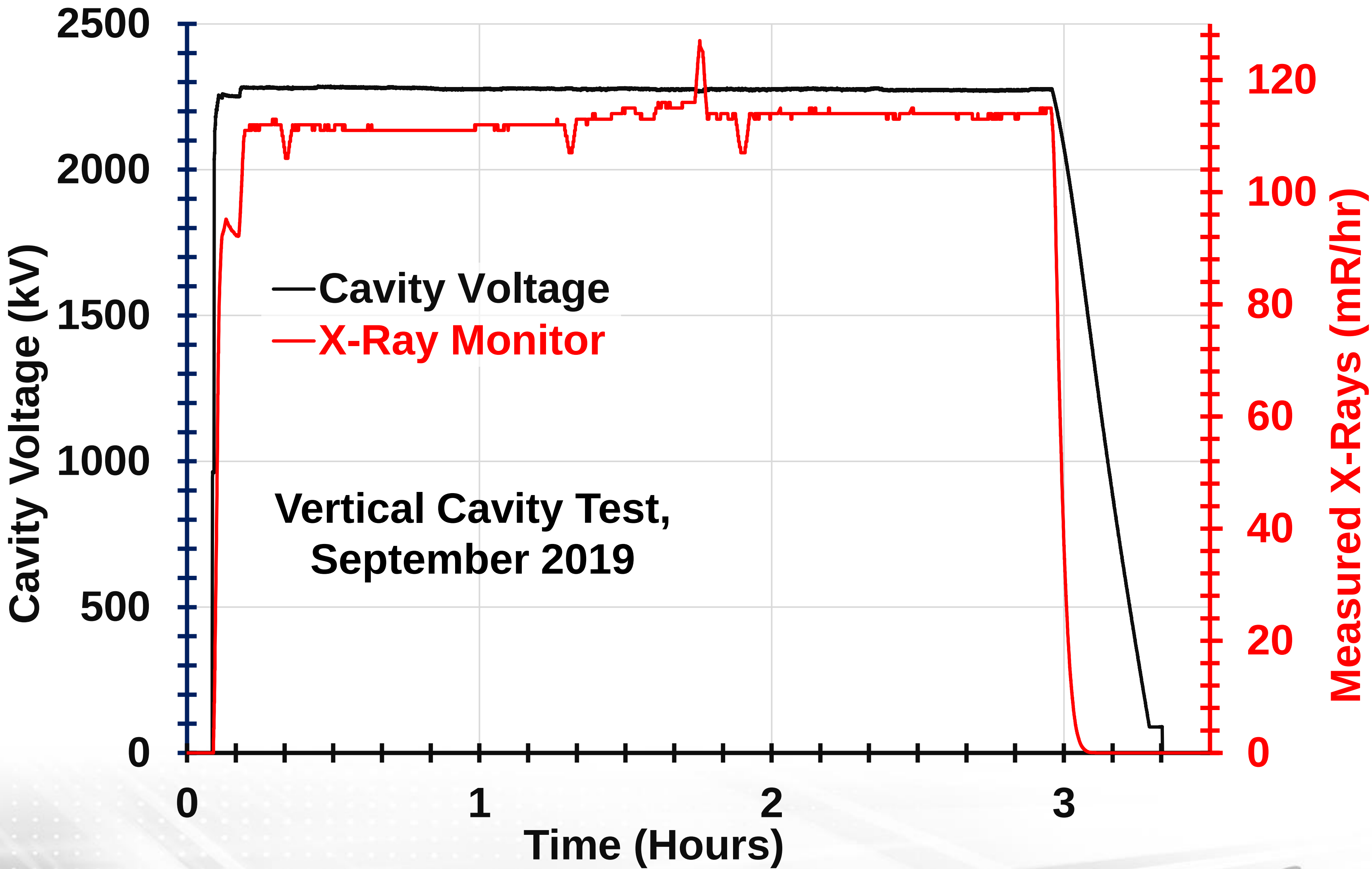
- **Cavity operation > 2 MV**
- **Fundamental Mode Damper (FMD) ~ 90 kW, and HOM Damper**
- **Fundamental Power Couplers (FPCs) ~ 3 kW**

Refit systems:

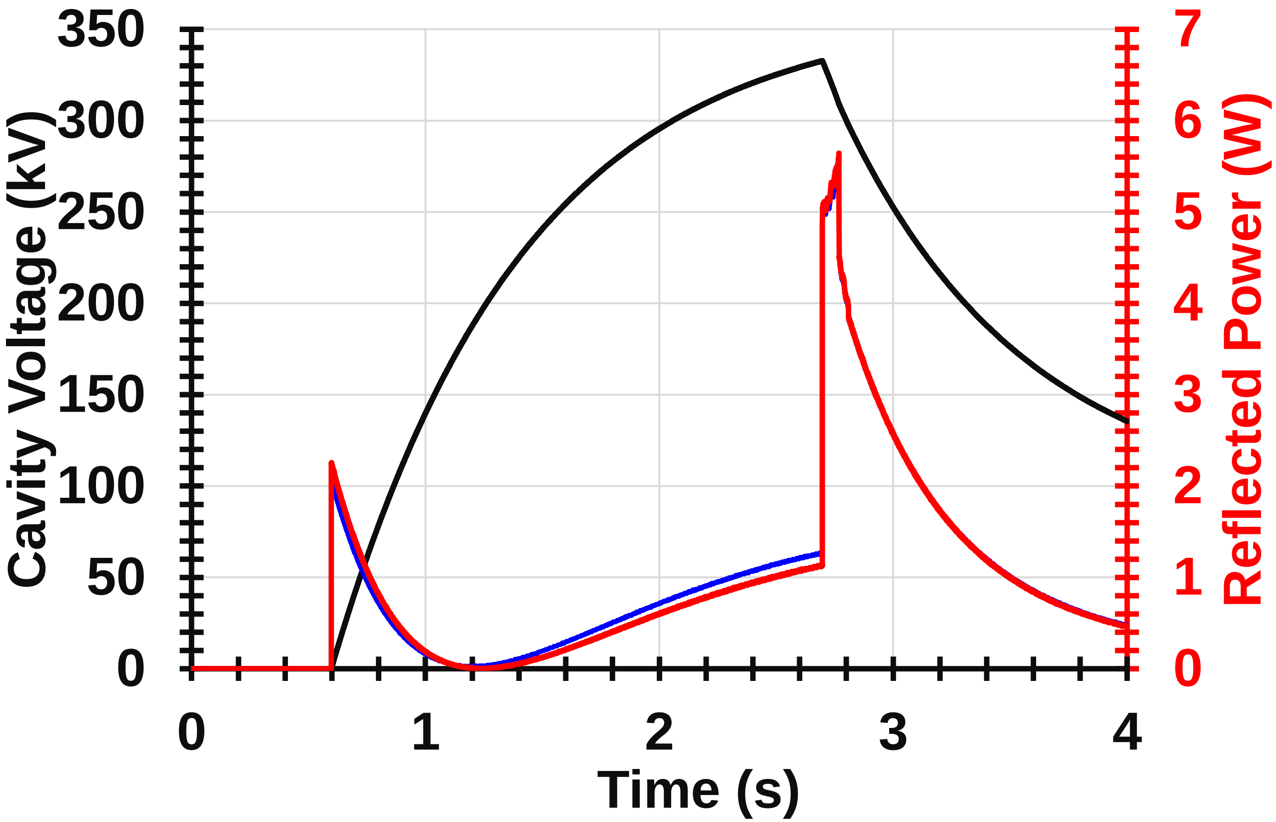
- **Low-Particulate SRF Assembly**
- **Cryo Cooling & μphonics**
- **Adding critical component redundancy**
- **Vacuum Pumping**



Cavity Operation > 2 MV?



Cavity Vertical Test - II



Loaded τ_V = 26.58 s

Q_L = 4.7 x 10^9

Residual Surface Resistance ≤ 1.5 nΩ

$$\beta = \frac{1}{2 * \sqrt{\frac{P_f}{P_e^{inst}}} - 1}$$

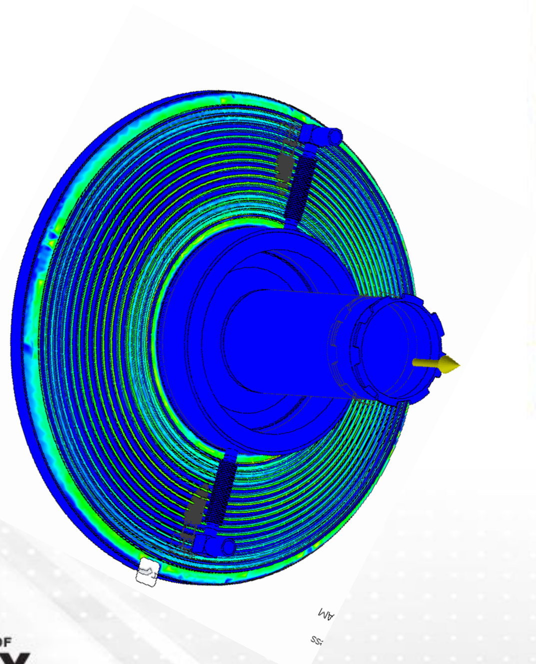
$$Q_0 = (1 + \beta) * Q_L$$

Cryomodule test will have variable coupler and can check this measurement.

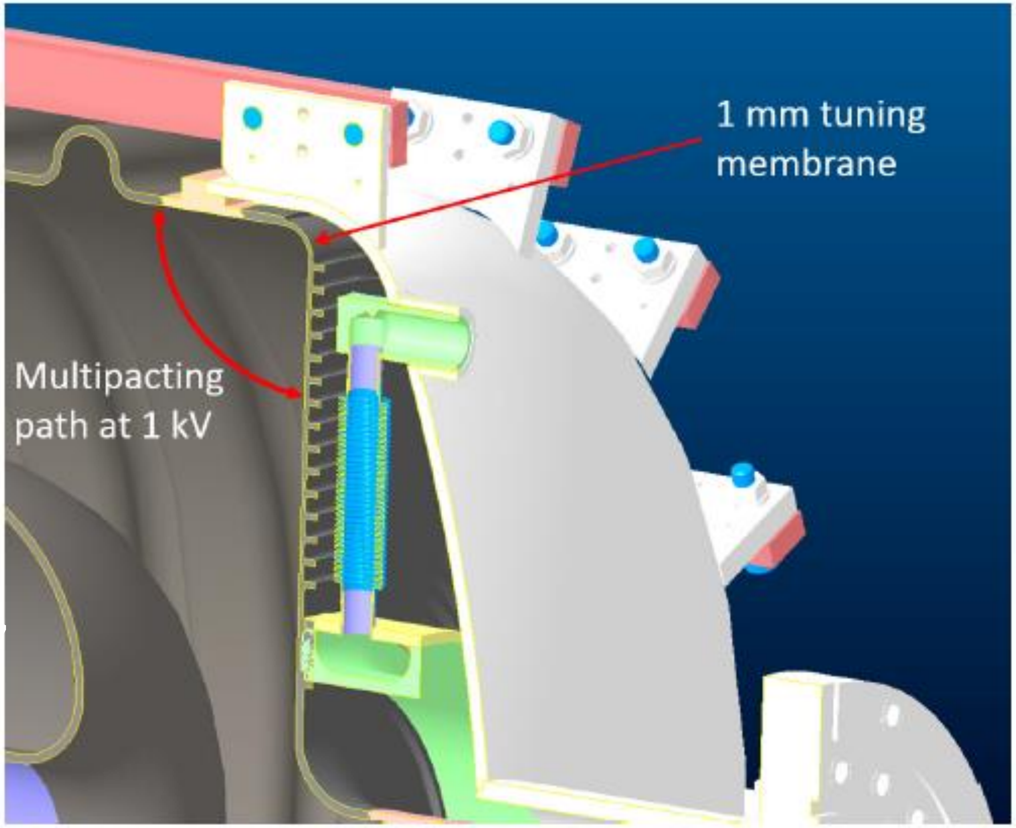
Tuning

- **Niobium cavity tuned by displacing cavity wall.**
- **Tuning range ~46 kHz, at this level the stress in the niobium wall is ~acceptable.**
- **Cap installed to protect end cap from helium system pressure!**

Von Mises Stresses @ 100 lbf, 5 ksi max

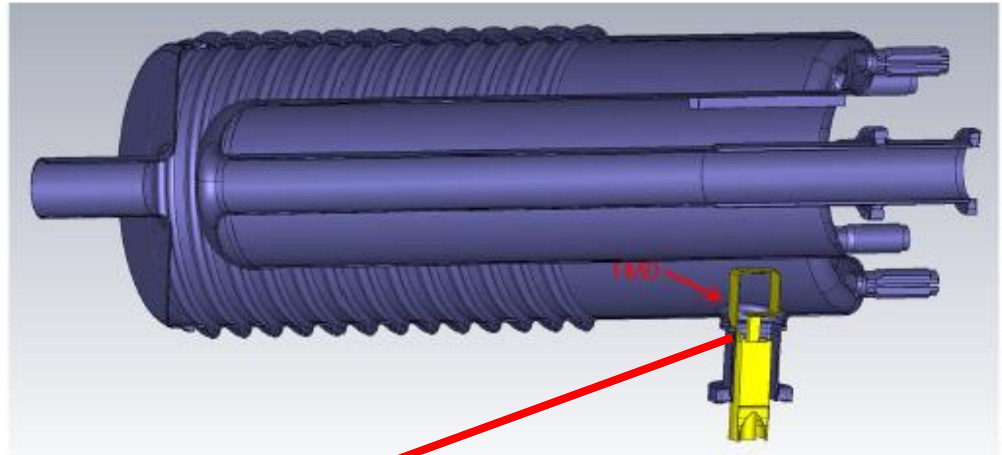


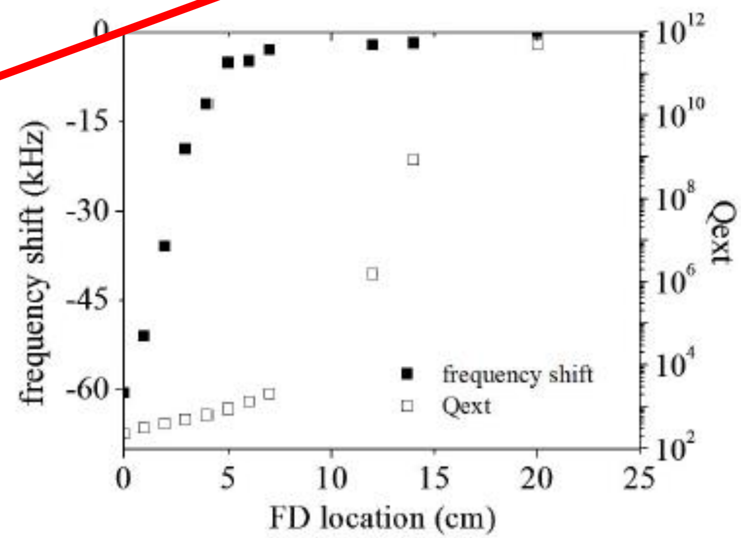
Close Up Section View of QWR Tuning Geometry



Fundamental Mode Damper

- **Niobium cavity tuned by displacing cavity wall.**
- **Tuning range ~46 kHz, at this level the stress in the niobium wall. Cano go farther. See next slide.**
- **Original ~20 kW damper needed upgrading.**

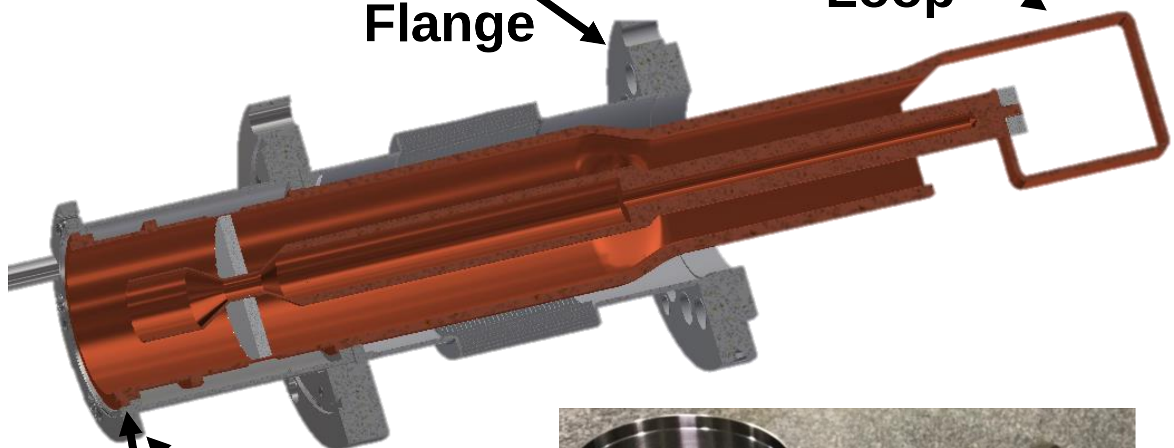




Original FMD Loop

56 MHz FMD

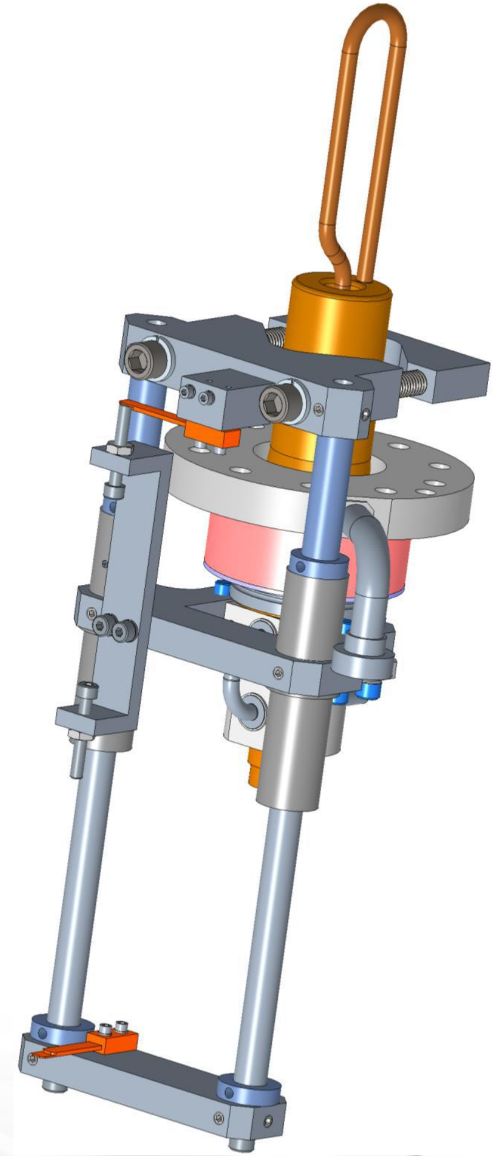
- **Transmission line size increased to maximum allowed by cavity Nb construction.**
  - **1-5/8” → 3-1/8” coax**
  - **Thermal cooling enhanced**
    - **Increased interface areas for thermal transfer.**
    - **Eliminated joints, pressed contacts in the beam volume, and nickel coatings.**
- **Parts in fabrication now and testing is planned for early next calendar year.**



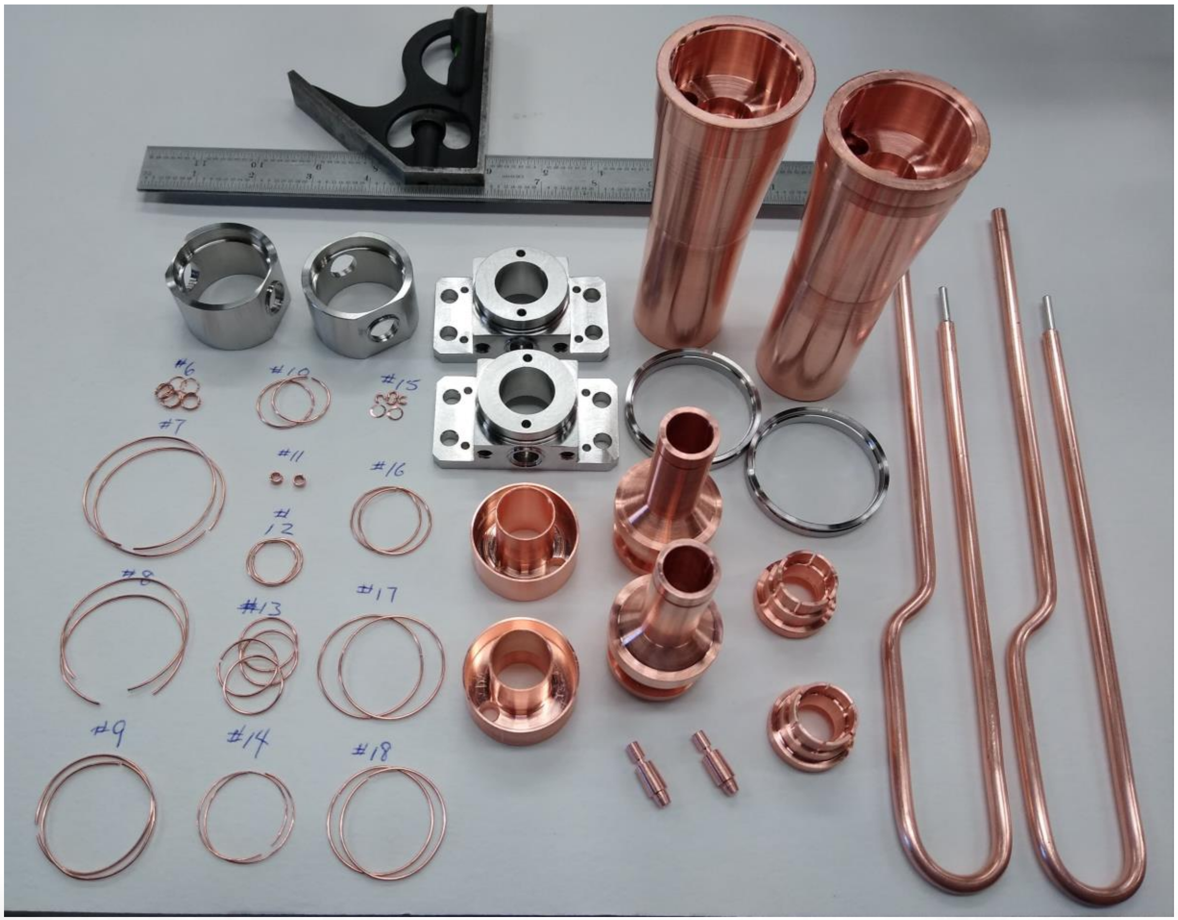
Loop Bending Test

Fundamental Power Couplers

FPC Model



FPC Parts



D. Holmes

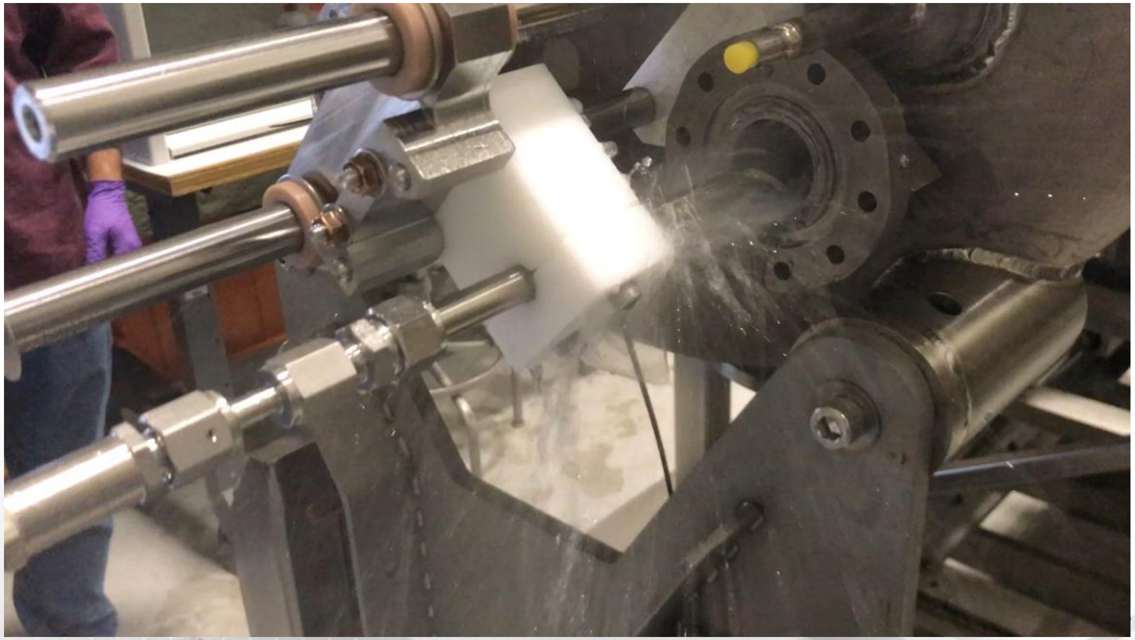
SRF Cleaning

- **Previous cleaning of 56 MHZ QWR to be improved:**
  - **Surface areas not covered by HPR.**
  - **Sub-assembly cleaning/installation.**
- **Moving toward low-particulate cleaning and assembly of entire cavity system.**

Tuner Installation

FMD HPR

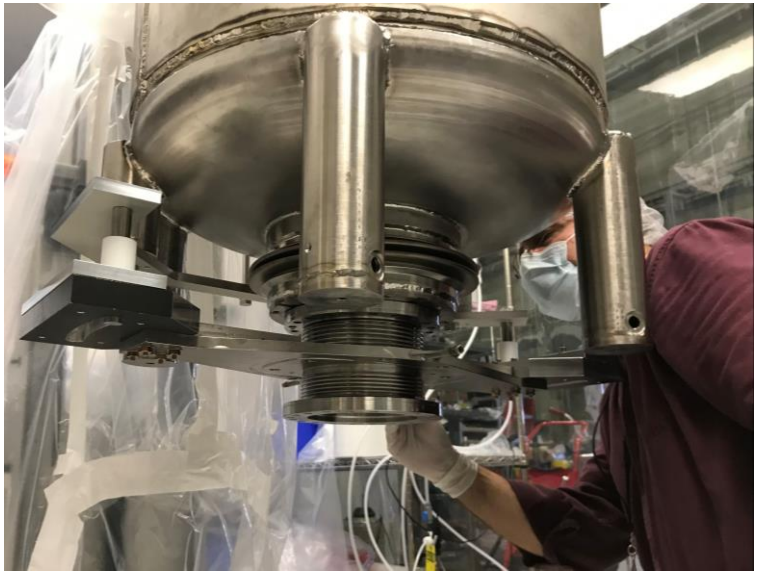
Port HPR



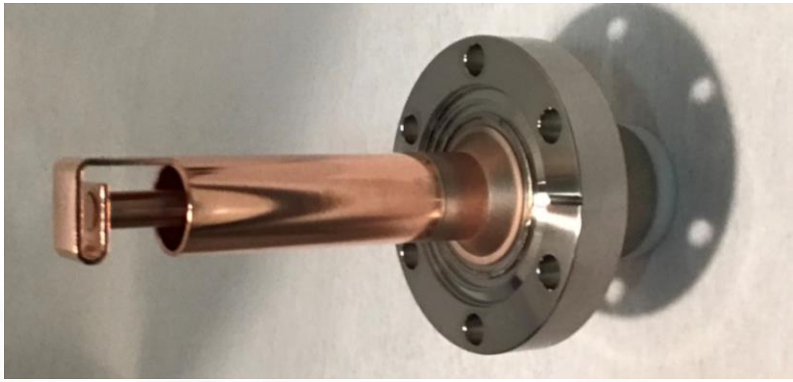
56 MHz QWR Schedule & Challenges

- To finish the 56 MHz QWR cryomodule:
  - Fabricate 2 fundamental power couplers, fundamental mode damper and other components. (Q1-Q2 FY2021)
  - Repair and reclaim SRF clean room after floor buckling. (Finished Q4FY2020).
  - Recover SRF high pressure water system for SRF cavity processing. (Q2FY2021)
  - Finish 56 MHz QWR SRF beam-line clean assembly. (Early Q3FY2021)
  - Finish 56 MHz QWR cryomodule assembly. (Q3FY2021).
  - Offline test 56 MHz QWR cryomodule in old ERL Test Cave. (Q4FY2021)
- Major tasks:
  - Finish fabrication and testing of fundamental power couplers.
  - Finish fabrication and testing of fundamental mode damper
  - Restart low-particulate cleaning operations.

New Tooling for Assembly of Tuner



New Pick-Up Probe



Fundamental Mode Dampers

- HSR bunch lengths and energies change between EIC runs:
  - Bunch lengths vary from 6.0 to 13.0 cm_{rms}.
  - Energy from 41 to 275 GeV.
  - The HSR 5-cell cavity the pass band extends from 576 to 591 MHz.
  - You cannot prevent the harmonics of the beam revolution frequency from exciting high-impedance modes in the 5-cell passband.
    - Undamped passband mode Q ~ 1e9 and R/Q ~1mΩ, yields 1 MΩ impedance, which for a 1 A hadron beam gives 1 MW of RF power extraction!
- HSR SRF crab cavities which are turned on after store energy reached.
- Only 1 current SRF system with a fundamental mode damper.
  - Discussed here.

Future Work

- Fundamental mode dampers are demonstrated in RHIC operation.
- Power handling on par with pulsed high-power couplers: 120 kW for 1-2 minutes.
  - May need a superconducting coupler to operate in EIC.
- Plan on having finished offline test results for the 56 MHz RHIC system in January 2022. Installation in RHIC July 2022 for sPHENIX campaign.
- EIC has a very real need for FMDs in the HSR 5-cell cavities and crab cavity. Cannot tune our solution.
- Demonstration in 2022 is key to future proposals for EIC R&D.

Acknowledgments

RF Group: K. Mernick, S. Polizzo, F. Severino, K. Smith, Q. Wu, B. Xiao, T. Xin, W. Xu & A. Zaltsman

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Cryo Group: V. Soria, T. Tallerico, N. Nilsson, P. Orfin & R. Than

Mechanical: D. Holmes & M. Grau