



FRIB

Development of Low-Beta Superconducting Cavities for Large Accelerators

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U.S. DEPARTMENT OF
ENERGY

Office of
Science

Outline

- Recent developments of QWR, HWR and spoke-loaded cavities
- ANL: High performance QWR and HWR
- FNAL: High performance single-spoke cavities
- FRIB: Large scale production of cavities and cryomodules with test results per design specifications
- Sub-systems: RF couplers, tuners



Facility for Rare Isotope Beams

U.S. Department of Energy Office of Science
Michigan State University

P.N. Ostroumov, IPAC-18, April 29 - May 4, Vancouver BC, Canada, Slide 2

First low-beta cavity for heavy ion accelerator

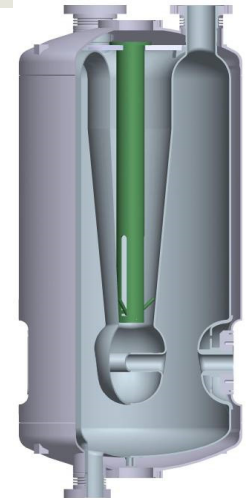
- The three classes of split-ring resonators developed and used at ATLAS (ANL).
 $\beta=0.106$, $\beta=0.15$
 $\beta=0.065$
- On-line since July 1978
- 3-4 MV/m
- Accumulated hours for the lowest beta:
2,100,000, all cavities



Recent QWRs developed at ANL

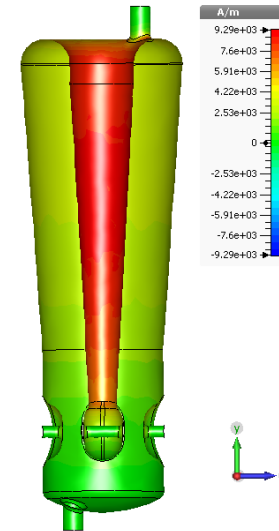
- On-line since 2009
- 7 cavities, average $E_{acc} = 5.4$ MV/m, limited by VCX

Parameter	Value	Units
Frequency	109.125	MHz
Optimal beta, β_{OPT}	0.15	
Effective length, $\beta_{OPT}\lambda$	39.05	cm
E_{PEAK}/E_{ACC}	5.0	
B_{PEAK}/E_{ACC}	9.1	mT/(MV/m)
Geometry factor, G	40	Ω
R_{SH}/Q	547	Ω
Design voltage	2.1	MV
Drift tube face tilt	9	degree
Aperture diameter	30	mm



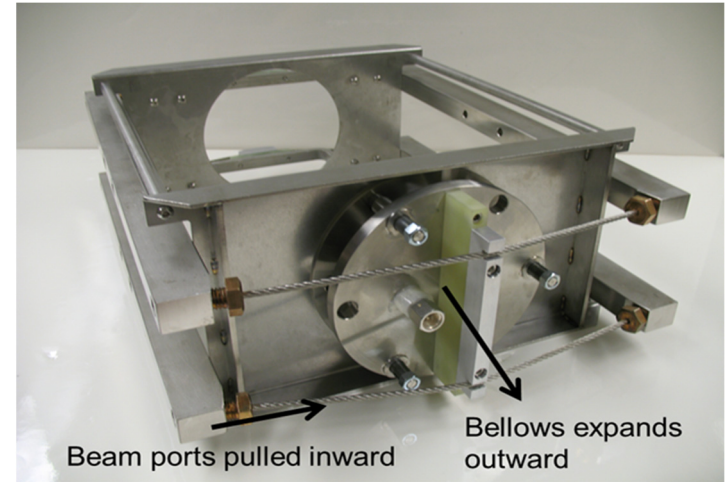
- Double-conical QWR
 - Reduced Bpeak
 - 7 cavities on-line since 2014

Parameter	Value	Units
Frequency	72.725	MHz
Optimal beta, β_{OPT}	0.077	
Effective length, $\beta_{OPT}\lambda$	29.7	cm
E_{PEAK}/E_{ACC}	3.25	
B_{PEAK}/E_{ACC}	4.8	mT/(MV/m)
Geometry factor, G	26.4	Ω
R_{SH}/Q	575	Ω
Design voltage	2.5	MV
Drift tube face tilt	2.5	degree
Aperture diameter	30	mm



Dual window RF adjustable coupler and pneumatic tuner

- Warm and cold windows
- The cold window is cooled LN2 (ATLAS)
- Pneumatic tuner: helium pressure is adjusted 15 to 80 psi



4 K-to-80 K, 7 cm variable bellows

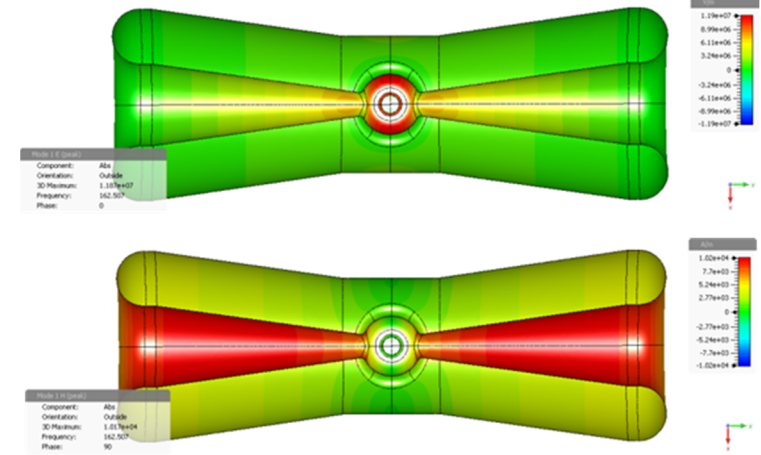


ANL half-wave resonators developed for PIP2

- Highly optimized to reduce peak magnetic field
- 8 cavities are required for the energy range 2 - 10 MeV

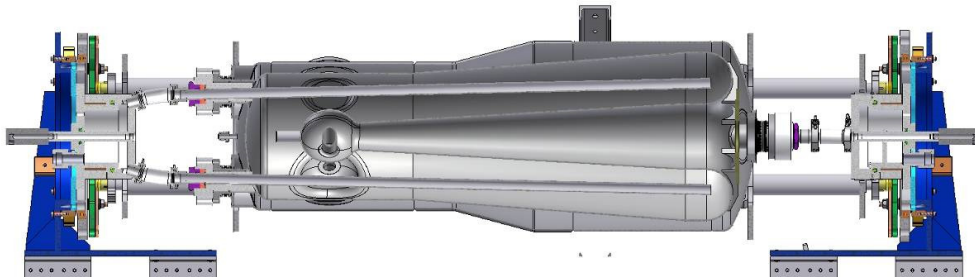


Cavity Type	HWR
Freq. (MHz)	162.5
β	0.112
l_{eff} (cm, $\beta\lambda$)	20.68
E_{pk}/E_{acc}	4.7
B_{pk}/E_{acc} (mT/(MV/m))	5.0
QR_s (Ω)	48.1
$R_{sh}/Q = V^2/P = V^2/\omega_0 U_0$ (Ω)	272

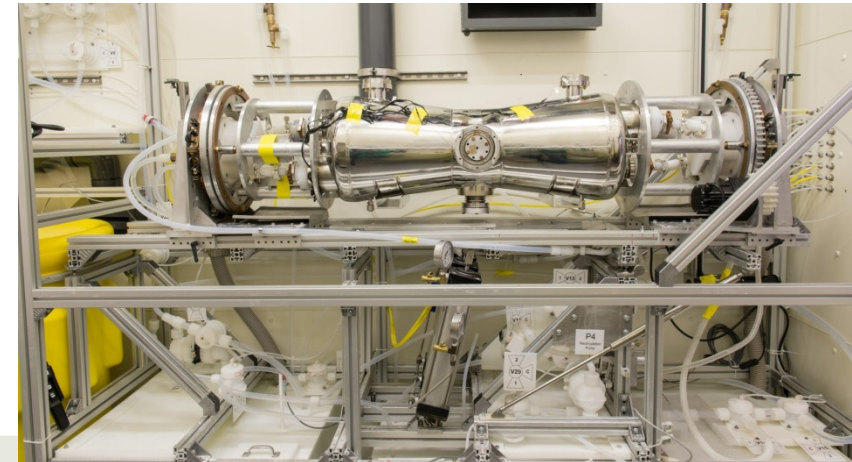
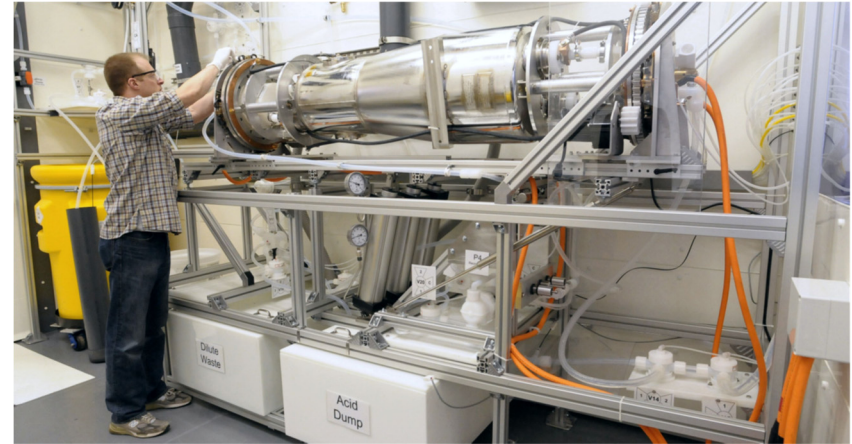
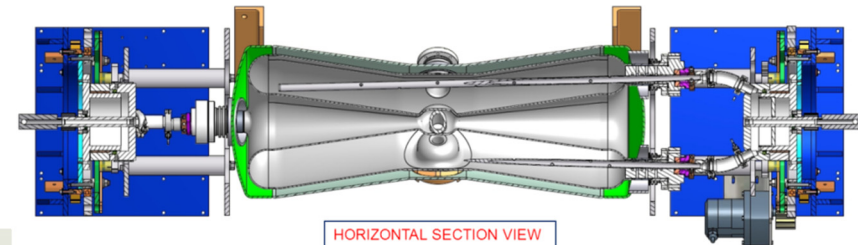
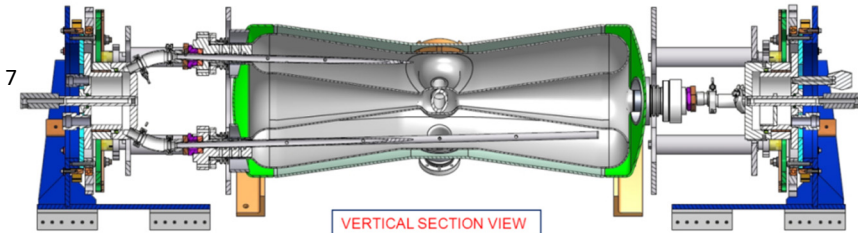


Electropolishing

- Electropolishing is performed after all mechanical work including stainless steel helium vessel has been complete

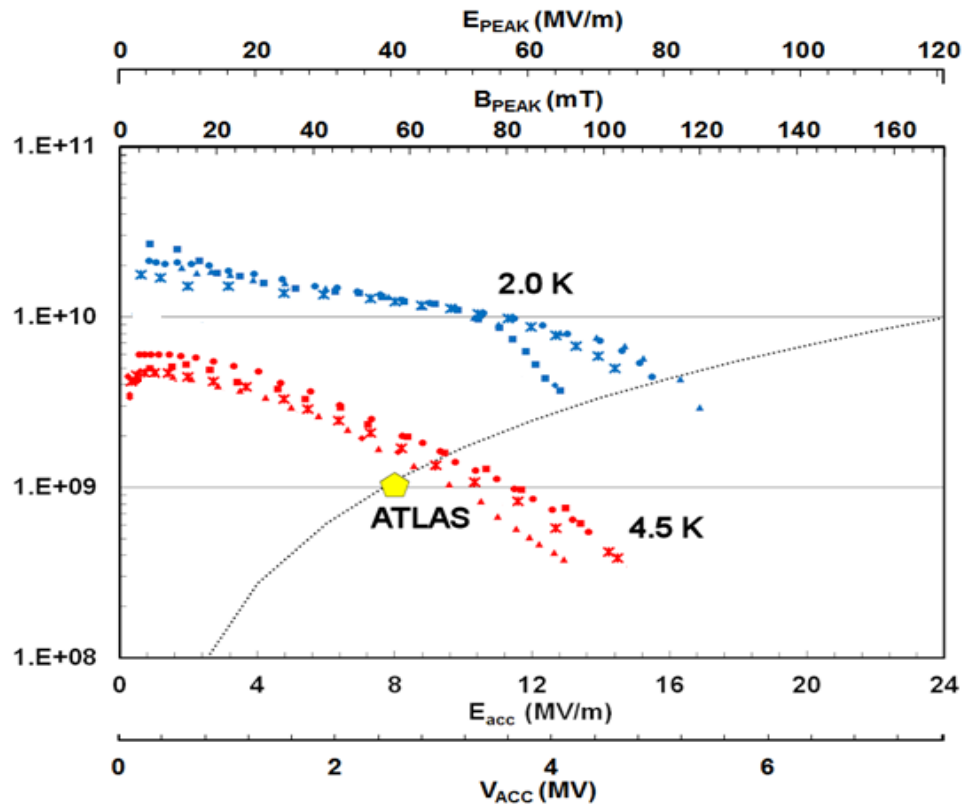


Cathode is parallel to the central conductor. Cooling through the He jacket



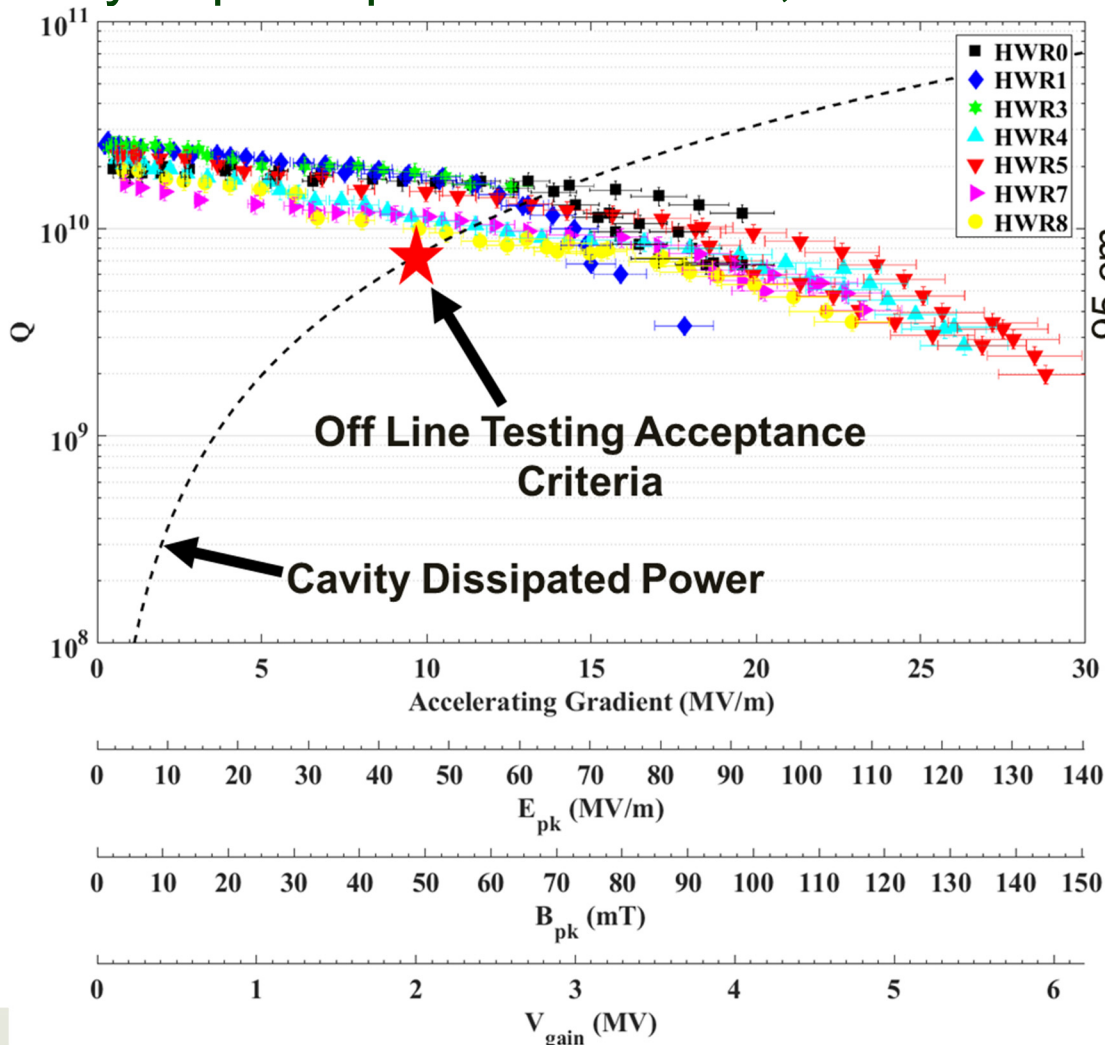
ANL ATLAS intensity upgrade cryomodule

- In operation since 2014
- 8 MV/m

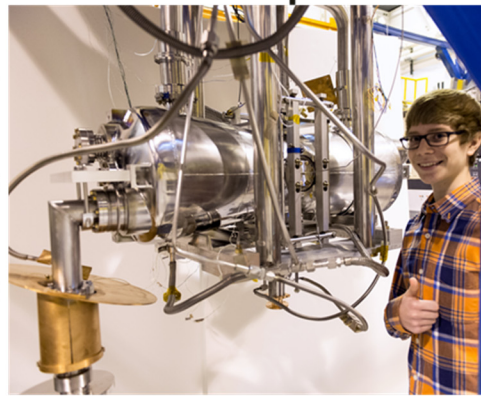


Argonne half-wave resonator performance

- No x-rays up to $E_{peak} \sim 70$ MV/m; Maximum $E_{peak} = 133$ MV/m
- 2K



HWR Test Preparation



Cryomodule with HWRs

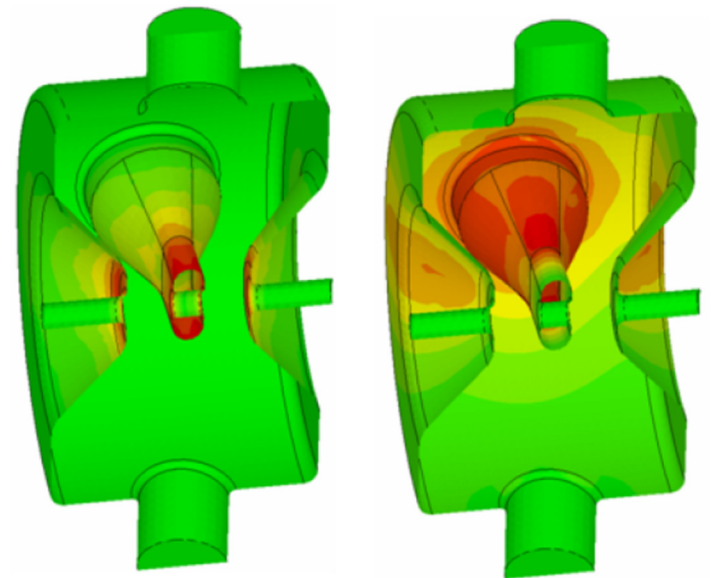
Mock-up assembly

- 8 cavities and 8 solenoids
- Top loaded cryomodule
- Cavities are supported with titanium rails
- Part of the PIP-II



Development of single spoke cavities at FNAL

- FNAL single spokes are highly optimized to reduce field enhancement factors, reduce power consumption and provide accelerating field with reduced multipole components



Cavity Type

SSR1

Freq. (MHz)

325

β

0.21

Accelerating gradient (MV/m)

10

LFD (Hz/(MV/m)²)

3.8

E_{pk}/E_{acc}

2.56

B_{pk}/E_{acc} (mT/(MV/m))

3.87

QR_s (Ω)

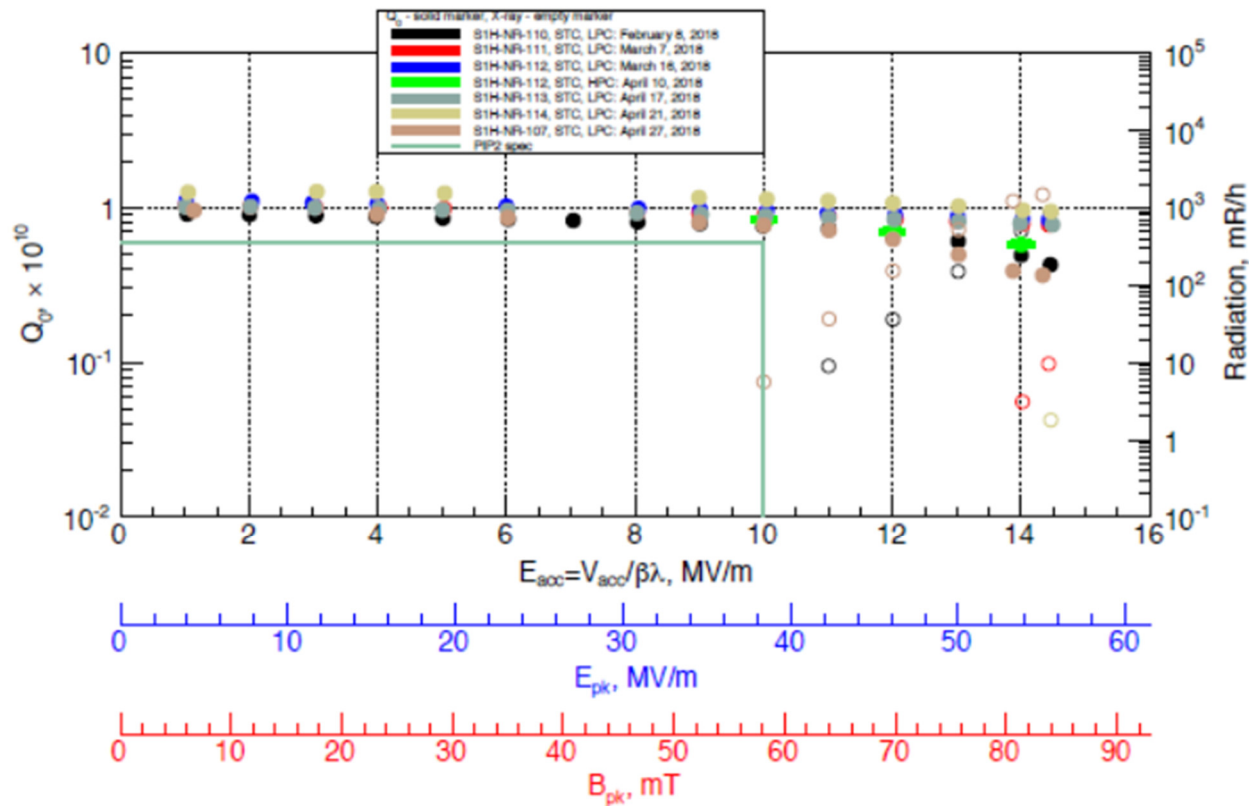
84

$R_{sh}/Q = V^2/P = V^2/\omega_0 U_0$ (Ω)

242

Cold testing of spoke cavities

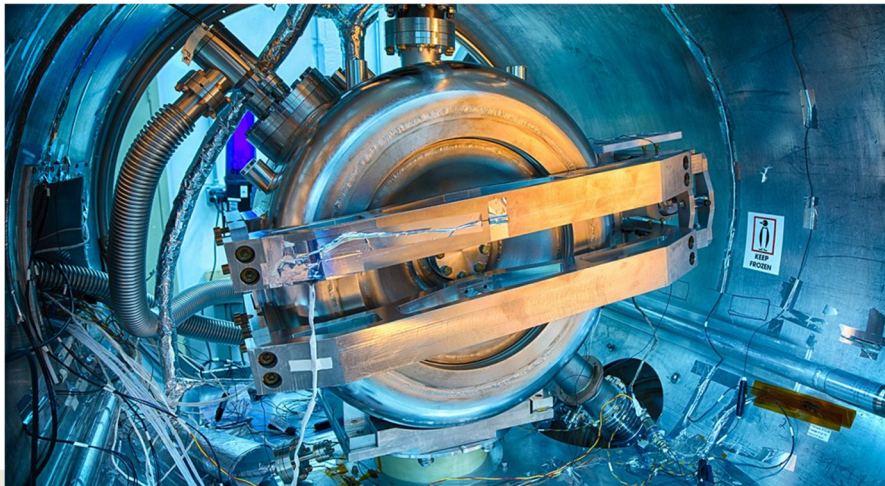
- Due to complicated geometry, the buffer chemical polishing (BCP) has been applied for the surface processing
- Performance of the jacketed cavities is very good



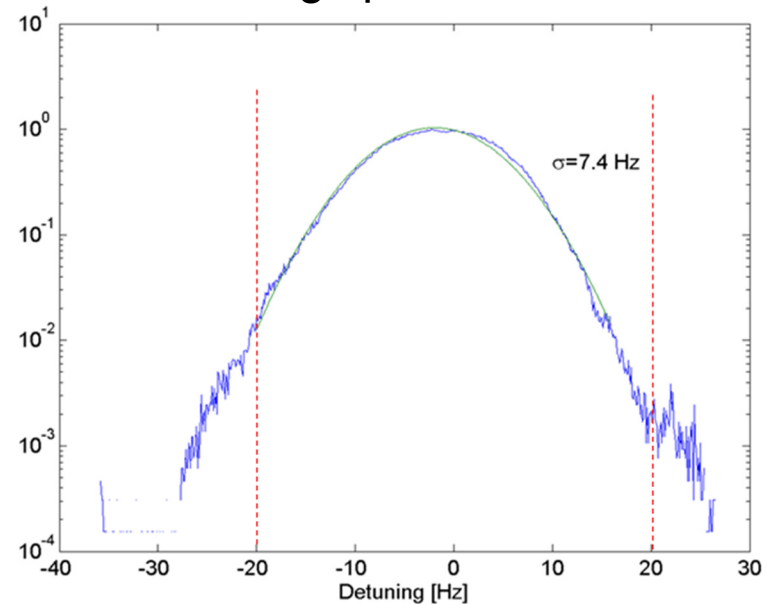
Resonance control for pulsed mode of operation

- The spoke cavities will be operated in pulsed mode in PIP-II
 - 20 Hz, up to 12.5 MV/m, detuning ~ 600 Hz
- High rigidity lever tuner and fast piezo-actuator have been developed
- Feedback and feedforward LFD compensation
- Factor of 2 improvement is required

Spoke cavity in the test cryostat with the tuner installed

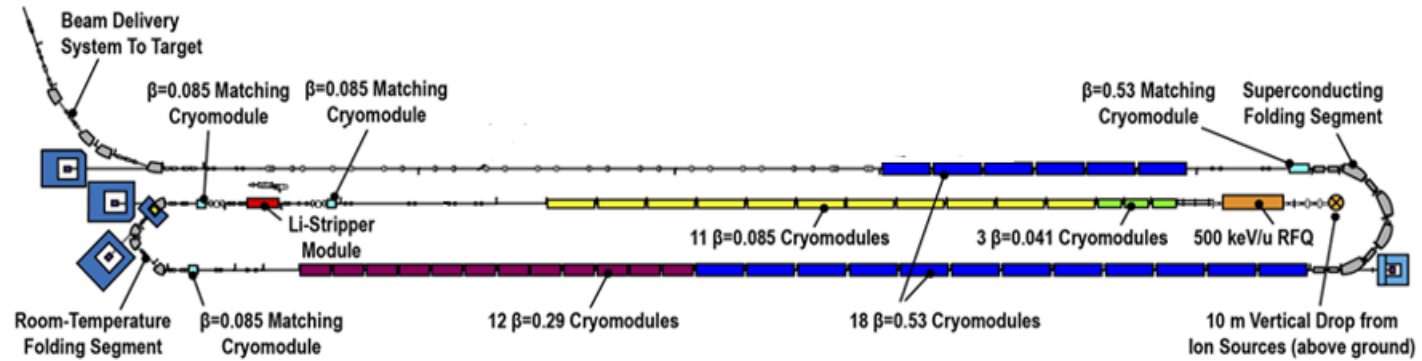
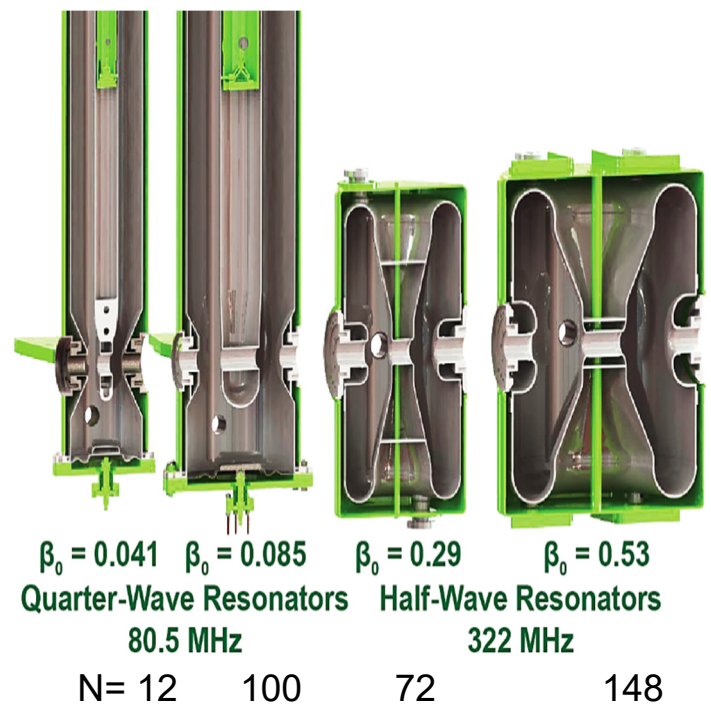


Detuning spec is ± 20 Hz



FRIB SRF Cavity Design and FRIB Linac Configuration

Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p/E_{acc}	5.82	5.89	4.22	3.53
B_p/E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
G [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning [Hz/(MV/m) ²]	< 4	< 4	< 4	< 4
Specific Q_0 @VT	1.4E+9	2.0E+9	5.5e+9	9.2E+9
Q_L	6.3E+6	1.9E+6	5.6E+6	9.7E+6



Major contributions to SRF technology at FRIB

- Robust design of QWRs and HWRs suitable for mass production by industry to meet tight schedule
- Innovative cryomodule design: bottom-up assembly
 - Provides high alignment accuracy of cavities and cryomodules
- 2K operation of low-beta cryomodules
 - Previous generation of low-energy heavy ion accelerators operate at 4K
 - Reduced microphonics
 - Enhanced performance of the cavities



Cavity Production in “FRIB SRF Highbay”

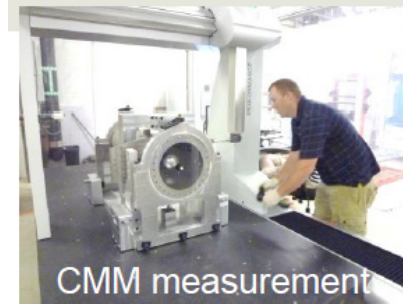
Infrastructure for Mass Production, Fully Functioning Since September 2015

■ Functionalities for Production

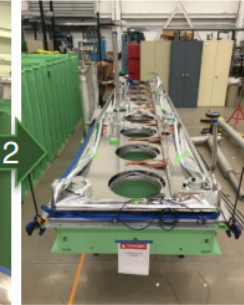
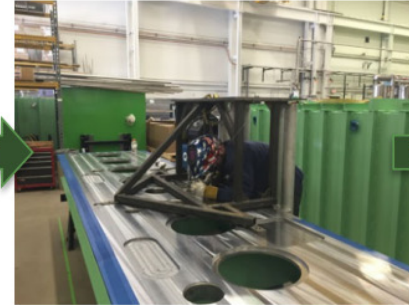
- Acceptance inspection
 - » CMM, Cold shock, Leak check
- Cavity processing and assembly
 - » Large cleanroom
 - Also for clean cavity string assembly
 - » Cavity etching (BCP) system
 - » Robotic high pressure rinsing system
 - » Ultrapure water system
 - » Hydrogen degassing furnace
- RF coupler conditioning

■ Vertical and Cryomodule Tests

- Vertical test
 - » 3 Dewars and 7 cold inserts
- Cryomodule test
 - » 2 test bunkers (one in the other highbay)
- Test capability: 1 cavity/day,
>2 cryomodules/month
- Cryogenic system (Dedicated 900W helium refrigerator, helium purification and 2K system)



Cryomodule Assembly



Completed cold mass assembly in clean room

Cold mass assembly transport to cryomodule assembly area

Cold mass ready for baseplate

Start baseplate assembly

Baseplate ready for cold mass



Cold mass on baseplate

Completed cryogenic circuit

Thermal shield installation

Vessel cover installation



Tuner valve manifold installation

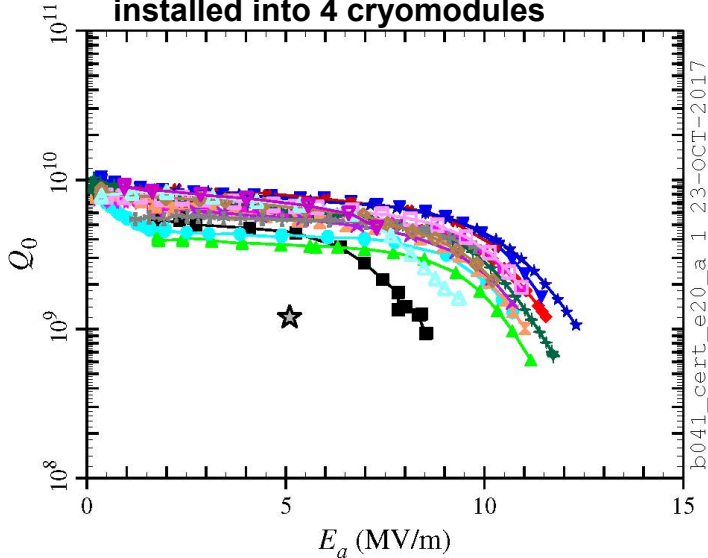
Transport to SRF High Bay

Transport into test bunker

FRIB Cavity Performance in Vertical Test

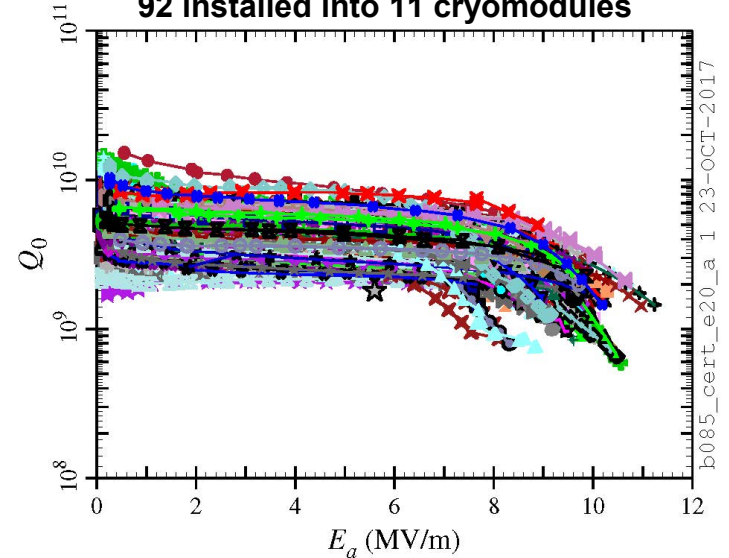
He-jacketed Cavity

16 cavities certified and installed into 4 cryomodules

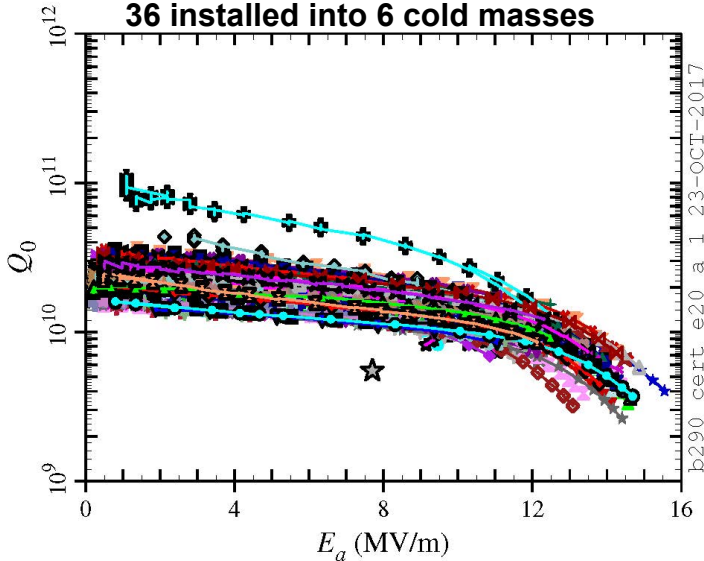


$\beta_0 = 0.041$ $\beta_0 = 0.085$
Quarter-Wave Resonators
80.5 MHz

93 cavities certified and 92 installed into 11 cryomodules

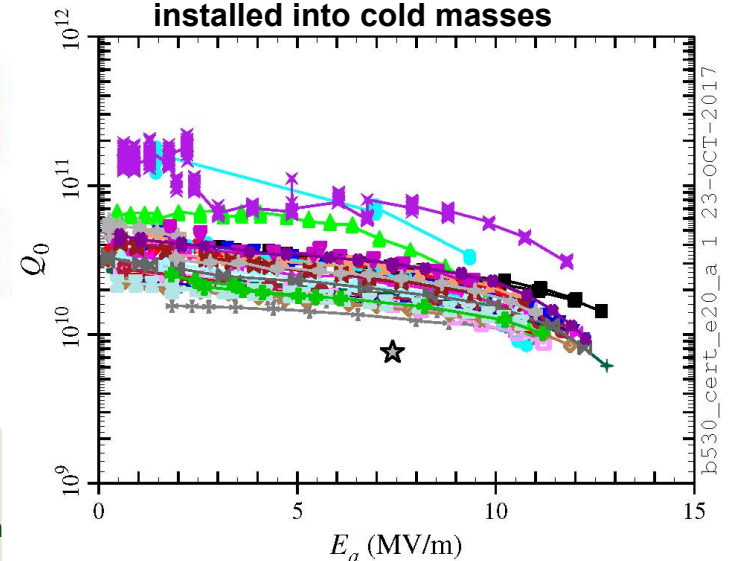


69 cavities certified and 36 installed into 6 cold masses



$\beta_0 = 0.29$ $\beta_0 = 0.53$
Half-Wave Resonators
322 MHz

26 cavities certified and installed into cold masses



Top Beam

Office of Science

P.N. Ostroum

FRIB SRF Cavity Subsystems and Cryomodule

RF Coupler

- 80.5 MHz QWRs: double windows
- 322 MHz HWRs: single window
- Coupling adjusted during assembly but fixed during operation

Frequency Tuners

- Stepper motor tuner for 80.5 MHz QWRs
- Pneumatic tuner for 322 MHz HWRs

Superconducting Solenoid

Local Magnet Shielding

- Magnetic shield wrapping around individual cavity: No global shielding
- Steel vacuum vessel

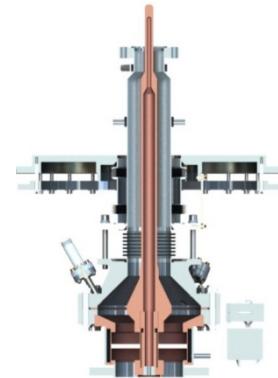
Bottom Loading Cryomodule

- Cold mass string loaded on the base plate
- Cryogenic vessel and piping are supported from the vacuum vessel, mechanically decoupled from the cavities

RF Couplers



80.5 MHz QWRs



322 MHz HWRs

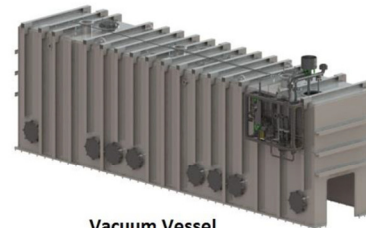
Slow Frequency Tuners



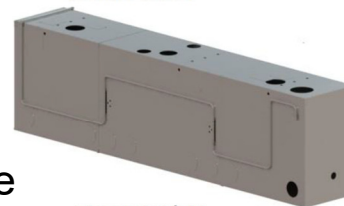
80.5 MHz QWRs



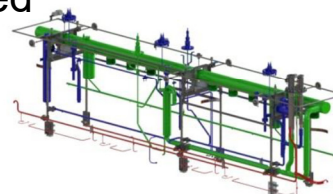
322 MHz HWRs



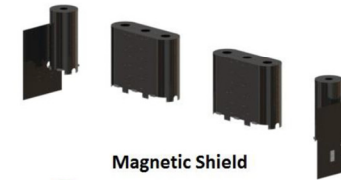
Vacuum Vessel



Thermal Shield



Cryogenic System



Magnetic Shield



Cold Mass



Base Plate



Facility for Rare Isotope
U.S. Department of Energy Office
Michigan State University

FRIB Cavity Performance in Cryomodule

2K Dynamic Load, Field Emission

2K Q_0 in Cryomodule

- Based on helium bath pressure measurement with heater calibration
- Achieved design goal with ample margins
- No substantial degradation from the vertical test results

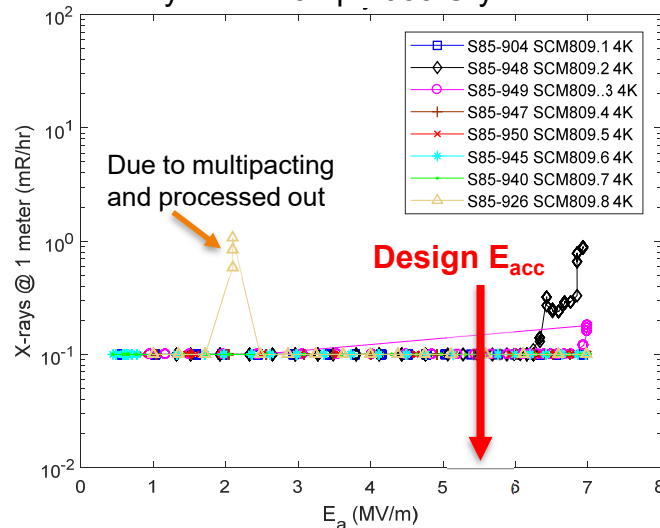
		Q_0 in CM at 2.0 K	
CM Type	CM Tested (as of March 2018)	Spec	Measurement*
041 QWR	4	1.2E+09	2.7E+09
085 QWR	10	1.8E+09	3.3E+09
29 HWR	2	5.5E+09	1.3E+10
53 HWR	2	7.6E+09	1.8E+10

* Average in all the same-type modules

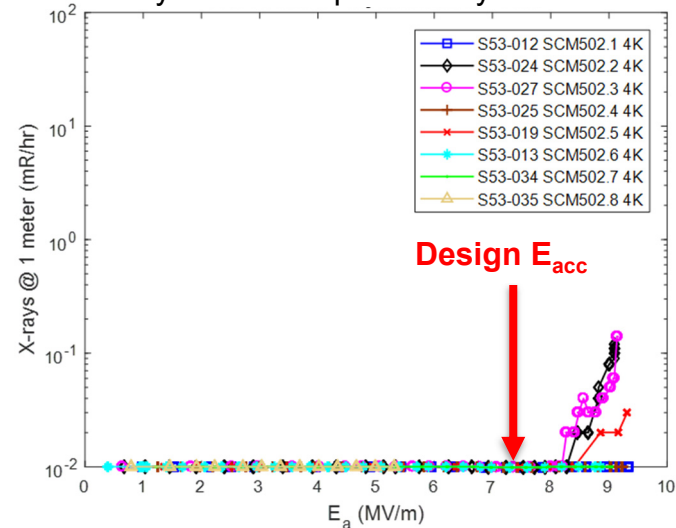
Field Emission in Cryomodule Assembly

- High pressure rinsing (HPR) prior to the vertical tests (VT) but no additional HPR after VT; disassemble, store in a clean bag, and assemble for cavity string
- This technique works for $E_{pk} = \sim 30$ MV/m: in the worst case, X-rays is ~ 1 mR/hr @ 1 meter

X-rays in the 9th $\beta=.085$ Cryomodule



X-rays in the 2nd $\beta=.085$ Cryomodule



Superconducting Solenoids in Cryomodule

■ Solenoid Package

- Solenoid and integrated dipole X and Y coils
- Solenoid field: 8T (both 25cm and 50cm long), Dipole field: 0.032 Tm (25cm) or 0.064Tm (50cm)
- Vendor production completed on January 2017

■ Cold Test at Vendor

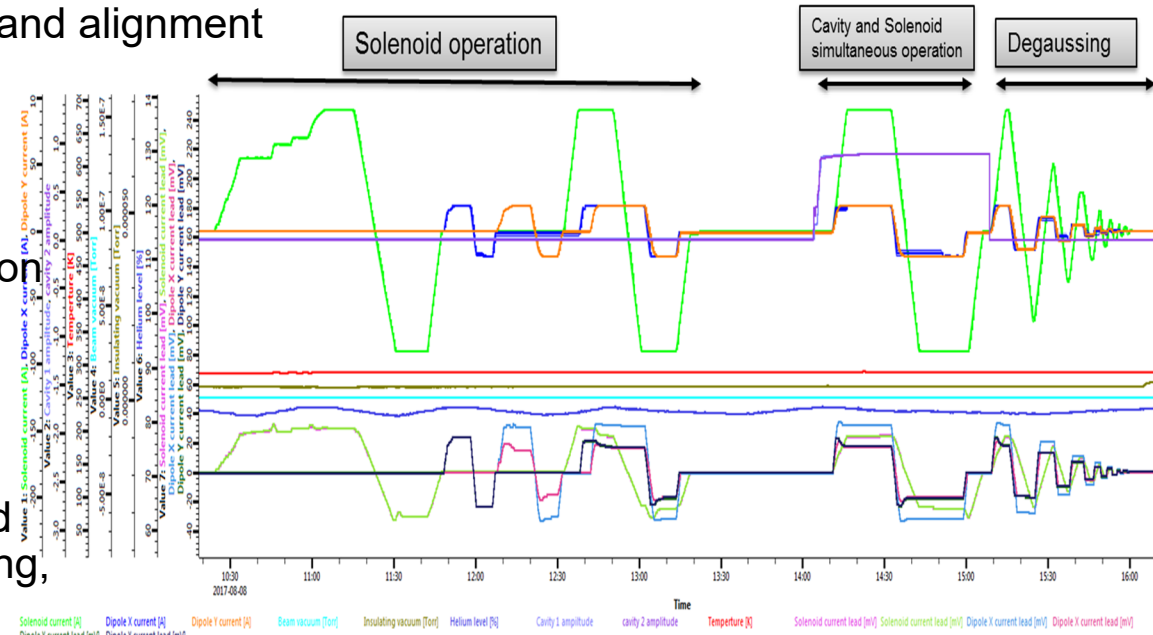
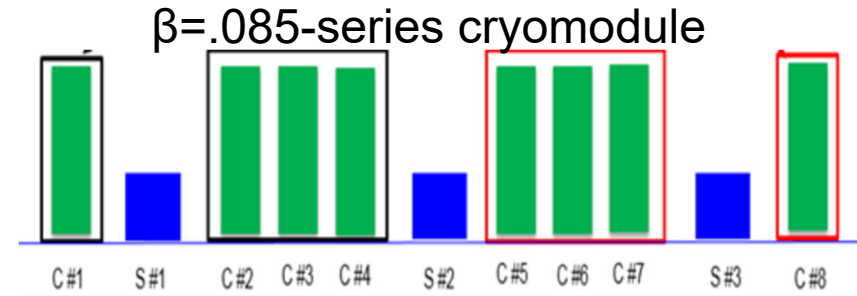
- Measurement of field distribution and alignment

■ Tests in Cryomodule

- Magnet excitation test
- Magnet mutual operation
- Magnets/cavity integrated operation
- Degaussing

■ Confirmed No Impacts on Cavity Performance

- Measured cavity Q was preserved after magnet operation, degaussing, and thermal cycle up to 30 K
- No cases of cavity quench due to solenoid/dipole magnetic field during integrated operation



Coupler Multipacting

RF couplers for 322 MHz HWRs

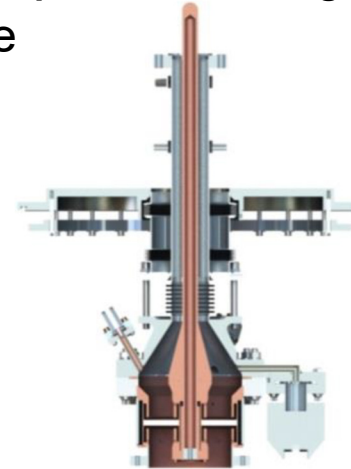
■ Multipacting (MP) in Coupler

- Overheating issue due to MP was resolved with the new production coupler
- Still observing symptom of coupler MP
 - » Vacuum pressure rise, X-rays, cavity quench
 - » MP likely occurs at around cavity entrance and stray electrons are accelerated by cavity field

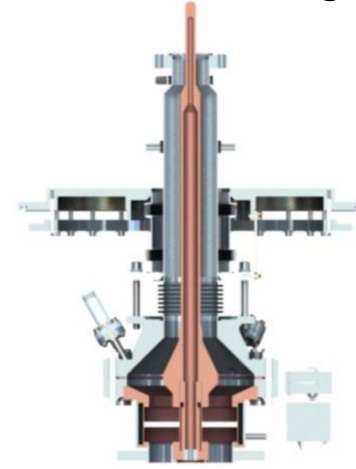
■ DC Bias on Coupler Inner Conductor

- Bias tee based on quarter-wave stub to apply -1 kV to the inner conductor
- Coupler MP is suppressed in any modes relevant to operation

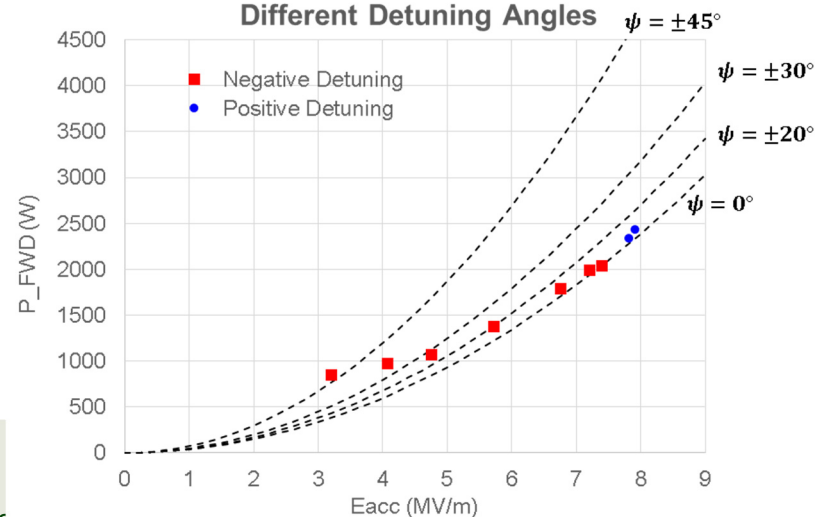
Preproduction Design



Production Design



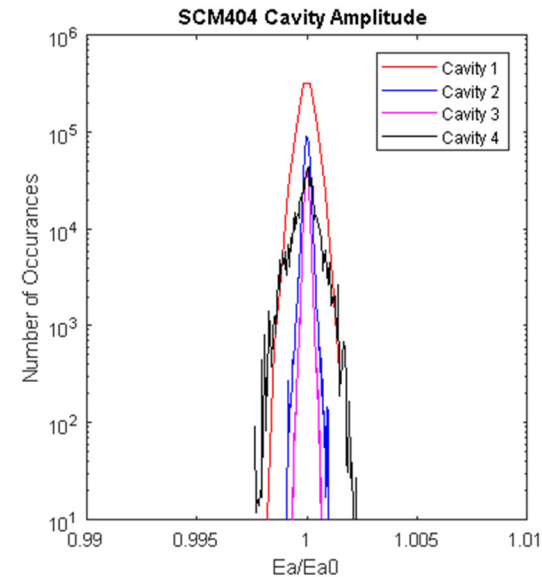
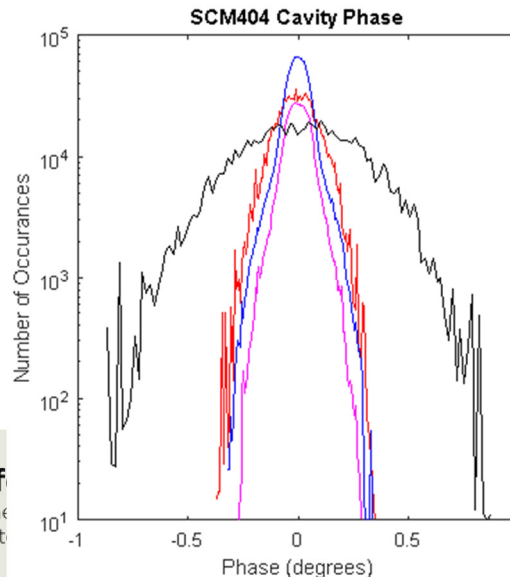
MP Onset Voltage and P_FWD at Different Detuning Angles



Cavity Phase Stability in Cryomodule Test

- Criteria for Acceptance in Cryomodule Test regarding Phase Lock
 - Specifications: cavity voltage phase jitters $< 2^\circ_{pk-pk}$, amplitude jitters $< 2\%_{pk-pk}$
 - Lock the cavity phase to a reference clock for 1 hour at 4.3 K; done for every cavity
 - Amplitude is also locked (necessary to suppress LFD effects) and the tuners are adjusted to compensate slow frequency drifts
- Performance
 - All cavities which have been tested in cryomodules so far satisfy this criteria
 - » Two $\beta=.041$ QWRs in the spare cryomodule (SCM404) initially suffered from microphonics
 - They were OK when the external vibration is at off-resonance of the cavity mechanical mode: demonstrated in the test bunker
 - Will do more study on effects of vibration from the real cryogenic system in the FRIB linac

- Cavity 1 and 4: locked for 4 hours, Cavity 2 and 3: for 2 hours
- Cavity 3: tested at 5.8 MV/m, The others: at 5.1 MV/m



Cold Mass Production Status

On Track for Completion by June 2019

- Total 33 cold masses completed
- 5 completed cold masses stored in the clean room and ready for cryomodule assembly
- All $\beta=0.29$ coldmass are completed ahead of schedule
- ANL (WFO) continues to be a very helpful partner



Storage of completed HWR cold masses in clean room



#6 $\beta=0.53$ HWR coldmass assembly on-going



Last $\beta=0.29$ HWR coldmass assembled

Cryomodule Production Status, End of April 2018

Type	Coldmass completed	Cryomodule assembled	Cryomodule bunker tested	Cryomodule placed in tunnel	Cryomodule needed (T + P)
0.041QWR	4	4	4	3	3 +1
0.085QWR	11	11	11	10	11+1
0.085 Matching	1	1	1	1	1 +1
0.29HWR	12	6	4	3	12
0.53HWR	5	2	2	2	18
0.53 Matching	0				1
Total	33 complete (+1 ongoing)	24 complete (+5 ongoing)	22 complete (+2 ongoing)	19	46 + 3

Cryomodules in the Tunnel

- LS1 cryomodule production is finished
- Module production rate is steady at one per month in the past 12 month
- LS2, LS3 installation is ongoing in the tunnel
- On track to complete all cryomodule assembly work by end of 2019



LS1 Cryomodules in tunnel

Summary

- Technology of TEM-class low-beta SC cavities is well established in several laboratories
 - Cavities provide 6-8 MV/m accelerating gradients in routine operation
 - R&D cavities produce 2x higher gradients without X-rays
- ANL demonstrated high performance of QWR and HWR
- FNAL demonstrated high performance of single-spoke cavities
- FRIB demonstrates that production of large quantity low-beta cavities and cryomodules can follow original schedule and stay within budget
- FRIB SRF status:
 - Cold mass assembly of 3 types of cryomodules is complete
 - 19 (out of 46) cryomodules are in the tunnel
 - Assembly and installation of all 46 cryomodules will be completed in 2019
 - Beam commissioning through the first 3 cryomodules will take place this summer

Acknowledgments

- Many thanks to my colleagues for their contribution to this presentation
 - Zack Conway (ANL)
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 - Alexander Sukhanov (FNAL)
 - Ting Xu (FRIB/MSU)
 - Slava Yakovlev (FNAL)

