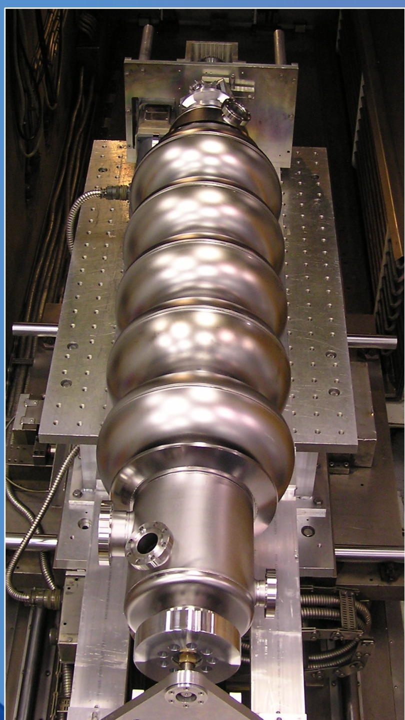
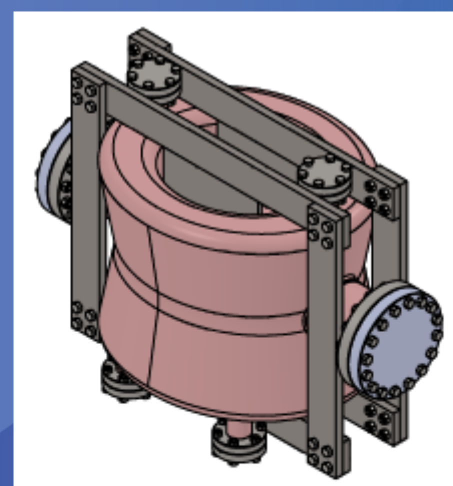
Progress with developing SRF guns and Update on other specialized cavities at BNL



Sergey Belomestnykh

Collider-Accelerator Department, BNL

November 7, 2012



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Acknowledgements

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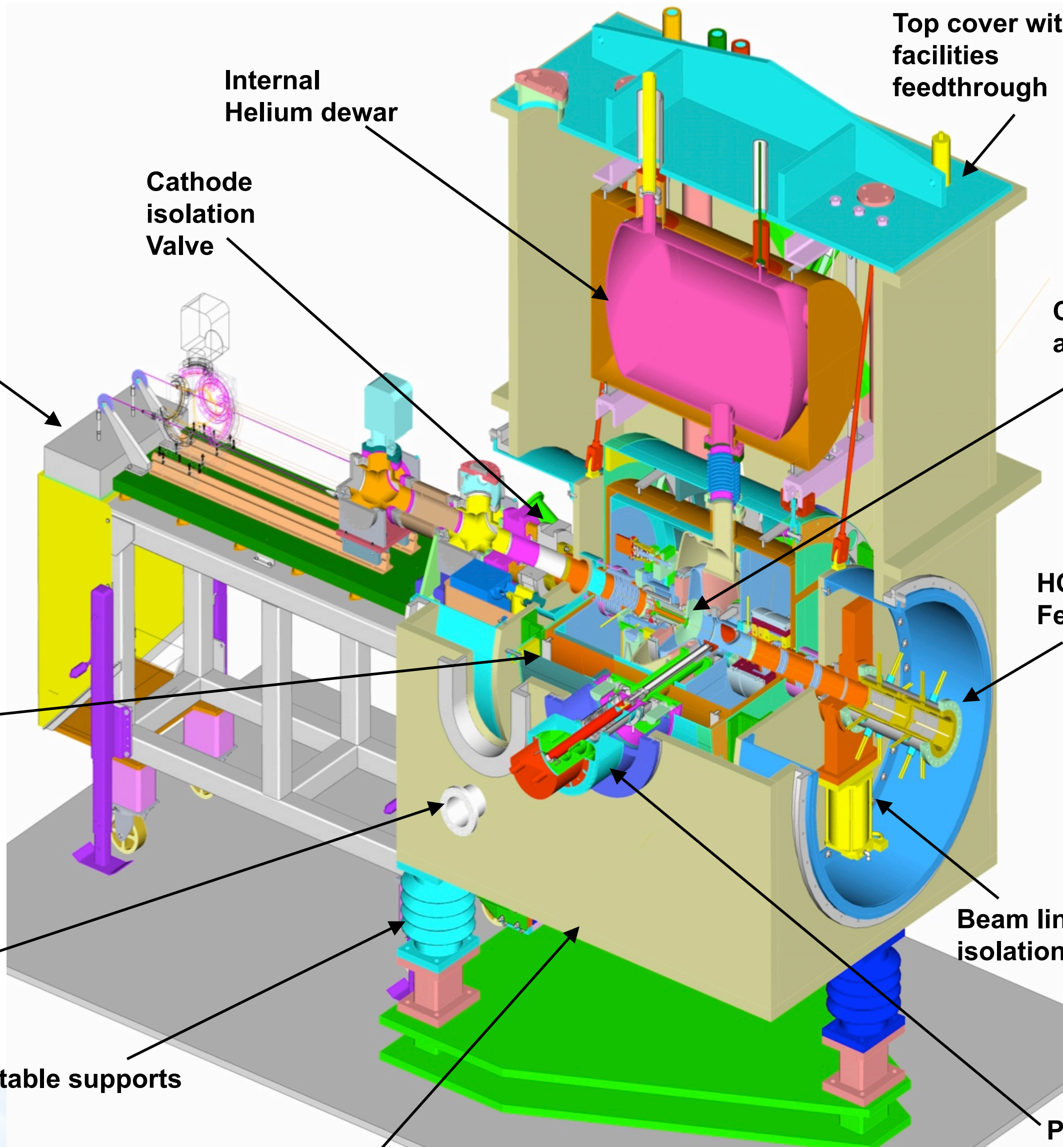
Overview

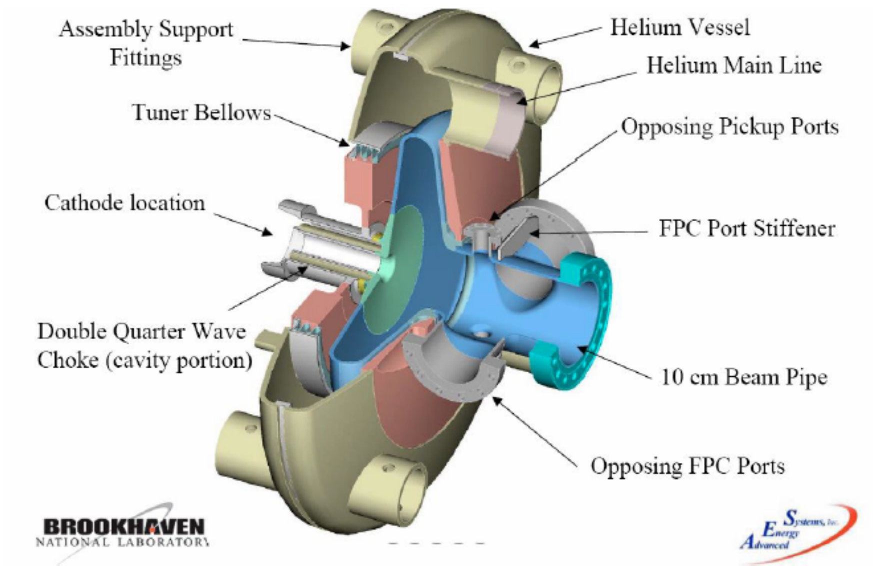
- Two SRF guns are under active development at BNL:
  - The first gun a 704 MHz, ½-cell elliptical SRF guns for R&D ERL. It is designed to produce high average current and high bunch charge electron beams.
  - The second gun is a Quarter-Wave Resonator (QWR) type, operating at 112 MHz. This gun will be used to generate high charge, low repetition rate beam for the Coherent electron Cooling Proof of Principle (CeC PoP) experiment.
- Aside from SRF guns, we develop other specialized cavities:
  - A quarter-wave resonator type 56 MHz storage cavity for RHIC to improve luminosity of ion-ion collisions.
  - A double quarter-wave 400 MHz crab cavity for the LHC Upgrade.
  - A 704 MHz 5-cell cavity (BNL3) for high-current linacs and ERLs.
  - More specialized cavities will be developed for the Low Energy RHIC e-Cooler (LEReC) and future electron-hadron collider eRHIC.

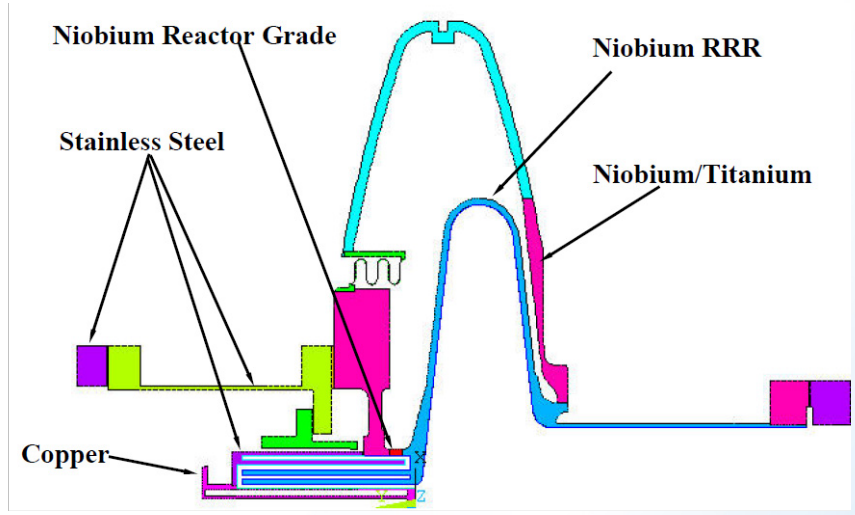
704 MHz SRF gun



- The 704 MHz elliptical half-cell SRF gun will produce an electron beam from a multi-alkali photocathode illuminated by a synchronized green laser with a rep. rate of up to 9 MHz.
- The goal is to demonstrate average beam current of 300 mA and bunch charge of 3.5 nC at 2 MeV.
- Its two Fundamental Power Couplers (FPCs) are capable to deliver 1 MW of RF power to a 500 mA electron beam at an energy gain of 2 MeV.
- HOM damping is provided by an external beamline ferrite load with ceramic break.
- A HTS solenoid is housed inside the cryomodule.

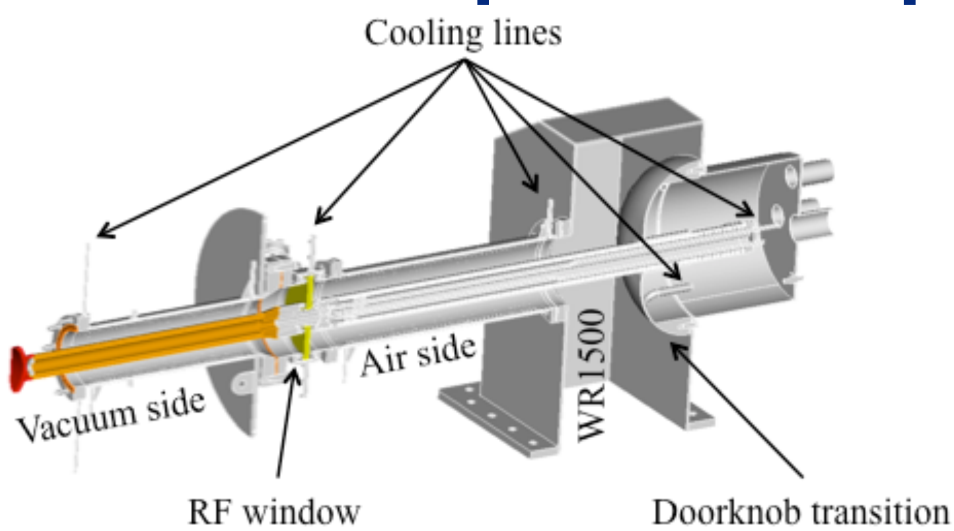
SRF gun cavity

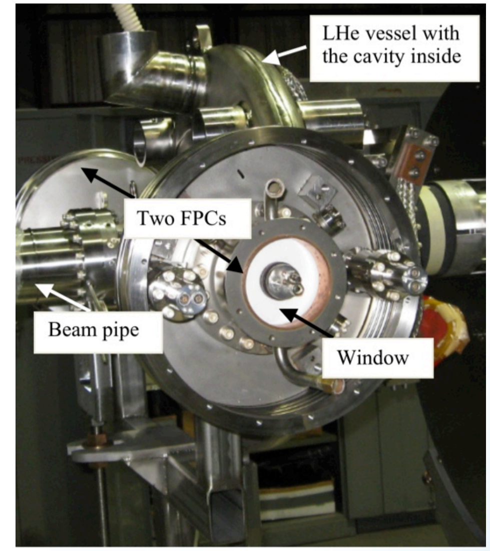




- The gun cavity was designed at BNL and fabricated at AES.
- *R/Q* = 96.2 Ohm.
- $Q_{ext} = 7\times10^4$ (originally 4×10^4).
- The cavity active length is 8.5 cm (0.4 cell).
- It reached 35 MVm during vertical test w/o a cathode.
- At 23.5 MV/m (corresponding to 2 MV) the cavity dynamic loss was less than 7 W.
- The tuning range is 1.2 MHz (1 mm of cavity deformation).
- A folded coaxial choke joint is grooved to prevent multipacting.

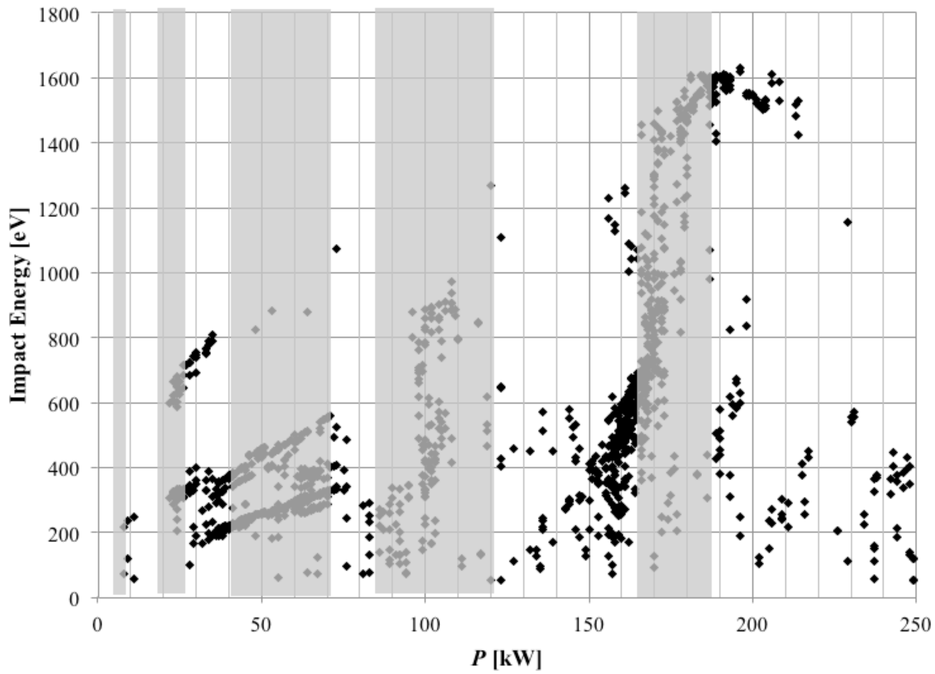
Fundamental power couplers

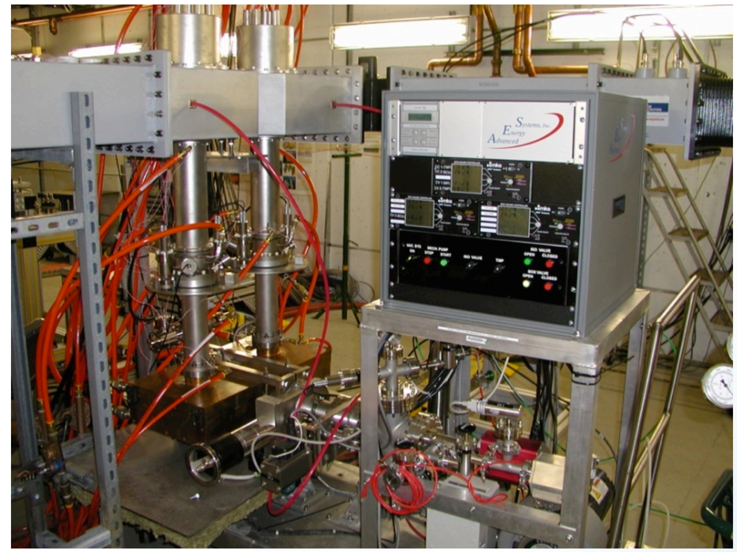




- 500-kW coaxial fundamental power couplers belongs to the family of TRISTAN/KEKB/SNS couplers.
- Two couplers will provide up to 1 MW of RF power to the SRF gun.
- FPC features:
  - Planar berillia window.
  - Inside the cryostat the copper-plated stainless steel outer conductor is cooled by helium gas.
  - Copper inner conductor is cooled by water.
  - Air-side inner and outer conductors are cooled by water.
  - Window assembly has ports for vacuum gauges and arc detectors.
  - Doorknob transition to WR1500.
  - Pringle-shaped tip of the antenna to enhance coupling (similar to that of Cornell ERL injector).
- Designed by AES, manufactured by CPI/Beverly.

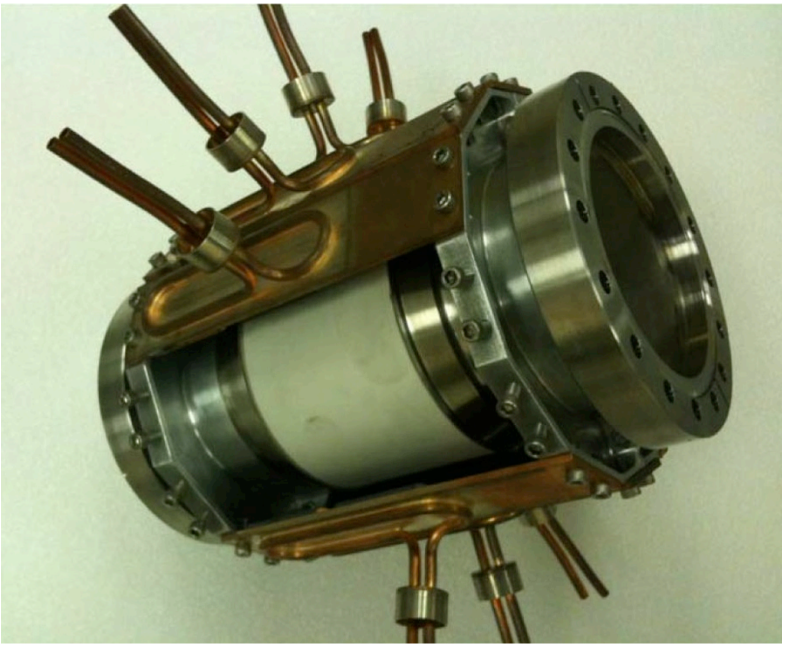
FPC conditioning

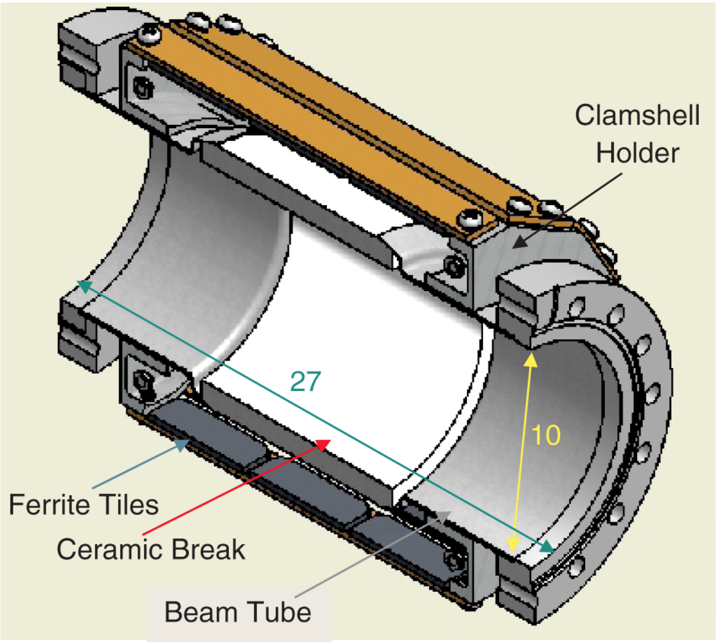




- The FPCs were conditioned in a standing wave mode with full reflection at variable RF phase.
- Maximum power was set to 250 kW in pulse mode (limited by klystron collector) and 125 kW in CW (administrative limit).
- Observed MP barriers were in good agreement with those predicted by simulations with Track3P.
- Simulations results show that most of multipacting occurs in the regular coaxial part of the FPC and only one zone, 40 – 70 kW, is in the RF window area.
- Wencan Xu et al. "Design, simulations, and conditioning of 500 kW fundamental power couplers for a superconducting rf gun," *Phys. Rev. ST Accel. Beams* 15, 072001 (2012)

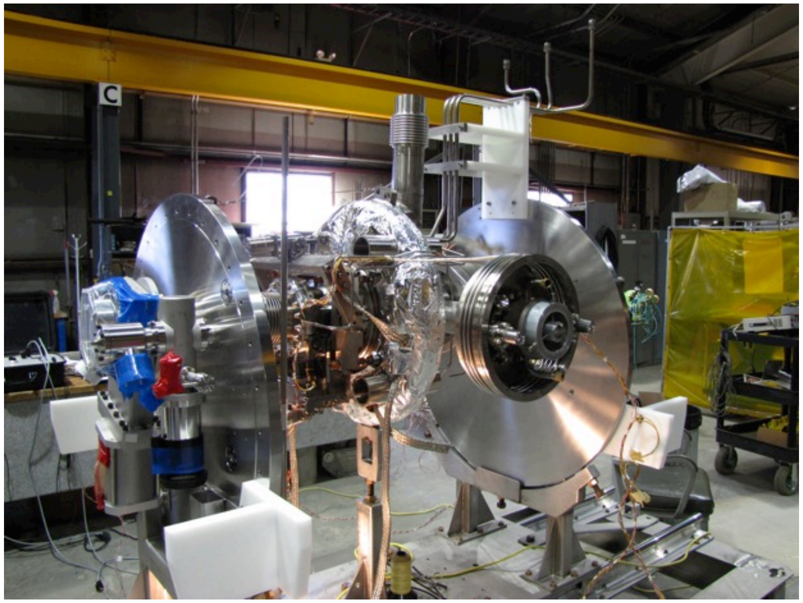
HOM load with ceramic break

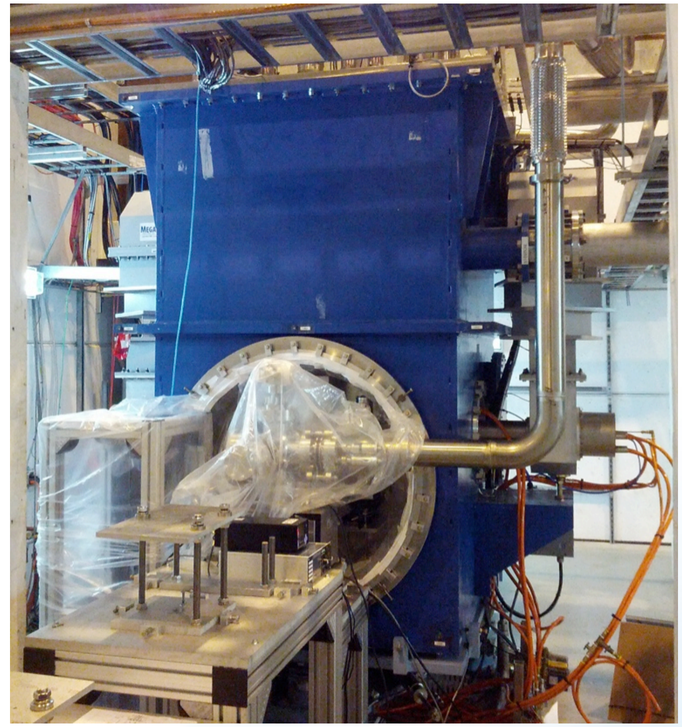


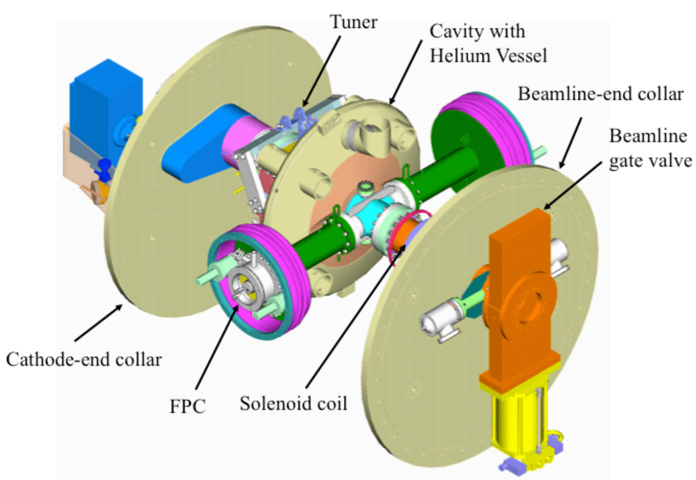


- Ferrite materials are brittle and, if cracked, can contaminate SRF cavities with particles and degrade the cavity's performance.
- A HOM load with ceramic break was proposed as a way to eliminate potential exposure of the SRF gun to ferrite particles. This is a unique, one of a kind design.
- HOM studies indicate that most HOMs will be damped to $Q < 10^5$. Few modes that are below 2.2 GHz (cutoff of the beam pipe) are strongly coupled to FPCs.
- "A Study of Higher-Order Mode Damping in the Superconducting Energy Recovery LINAC at Brookhaven National Laboratory," PhD dissertation of L. Hammons, Stony Brook University, Dec. 2011.

Status of the ERL gun commissioning

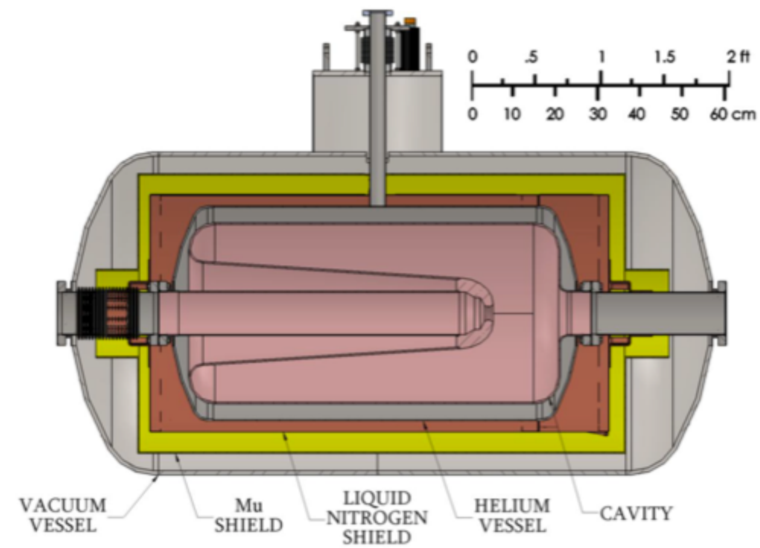






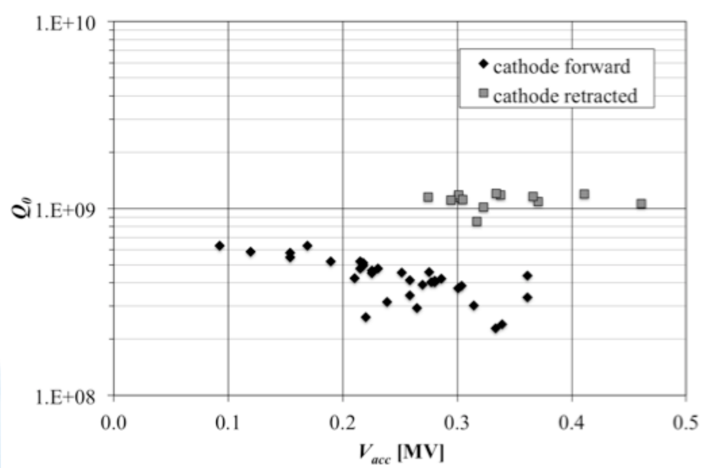
- The gun was assembled at BNL, and currently is installed in the ERL block house.
- A 1 MW klystron, cryogenic system and other ancillary systems are ready.
- The first cooldown to 4.5 K was performed before the hurricane Sandy, then the gun was warmed up to prevent any damage due to power outages.
- It is cold again and ready for testing and commissioning.

Quarter Wave Resonator SRF gun



- Superconducting 112 MHz QWR was developed for electron gun experiments by collaborative efforts of BNL and Niowave, Inc.
- Design, fabrication, chemical etching, cleaning, assembly and the first cold test were done at Niowave as part of DOE SBIR project.
- Why 112 MHz?
  - ✧ Low frequency: long bunches ➔ reduced space charge effect.
  - ✧ Short accelerating gap: accelerating field is almost constant.
  - ✧ Superconducting cavity: suitable for CW, high average current beams.
  - ✧ Cathode does not have to be mechanically connected to SRF structure: flexibility in cathode types.
  - ✧ Simulated emittance of ~3 mm×mrad at 2.7 MeV

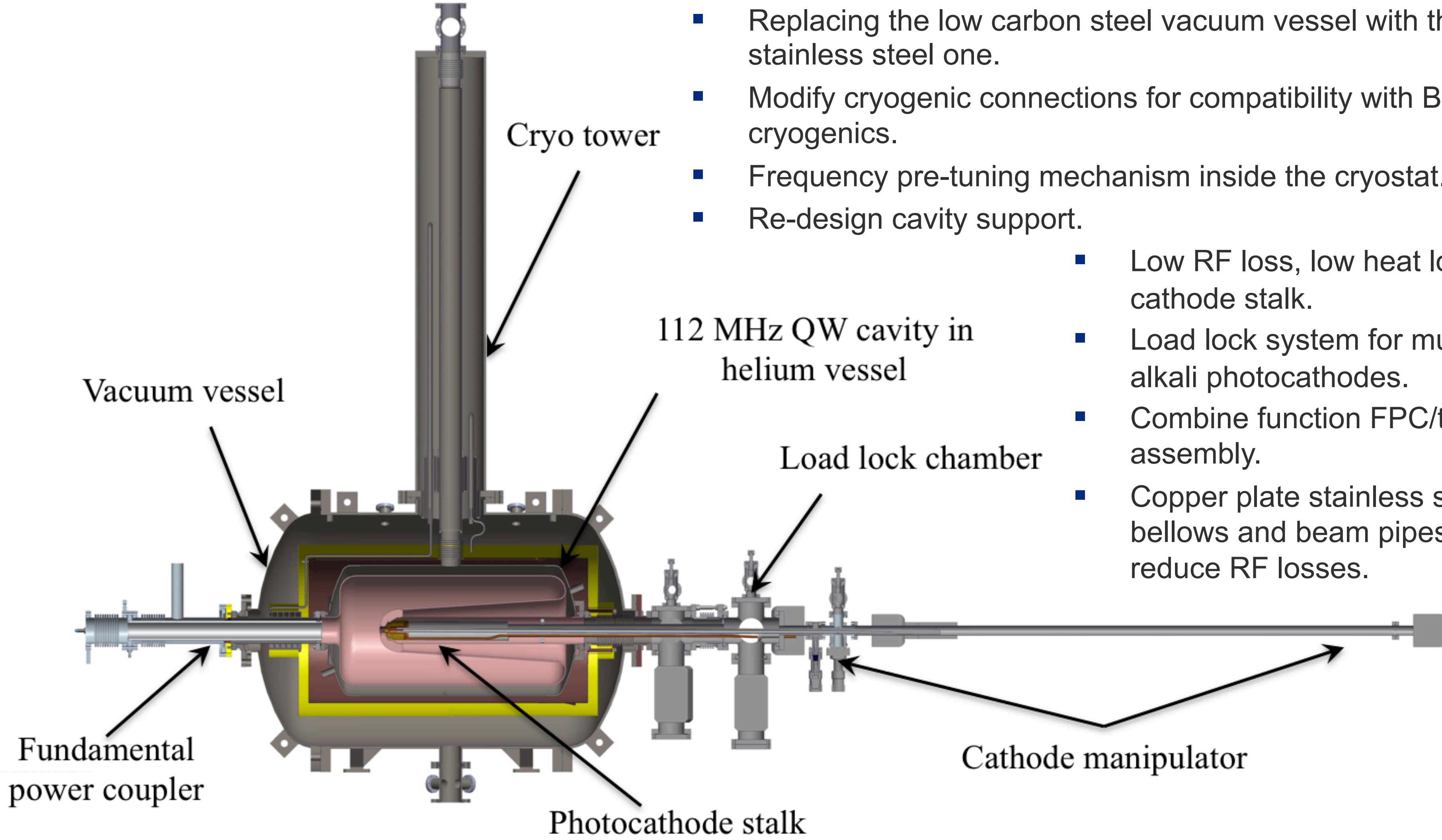
112 MHz SRF gun cold test & plans



- First cold test was successfully performed at Niowave, Inc. in December of 2010.
- Observed multipacting barriers were easy to process.
- Reached about 0.5 MV with Q_0 of 10^9
- Field was limited due to radiation safety requirement of <2 mrem/hr (no dedicated radiation shielding around the cryomodule).
- Measured sensitivity of the cavity resonant frequency to helium bath pressure of 10 Hz/mbar.
- Estimated upper limit for the static heat leak: 7 W.
- This gun is now a baseline option electron gun for the Coherent electron Cooling Proof-of-Principle (CeC PoP) experiment at BNL. The experiment is scheduled for installation in RHIC in 2013.

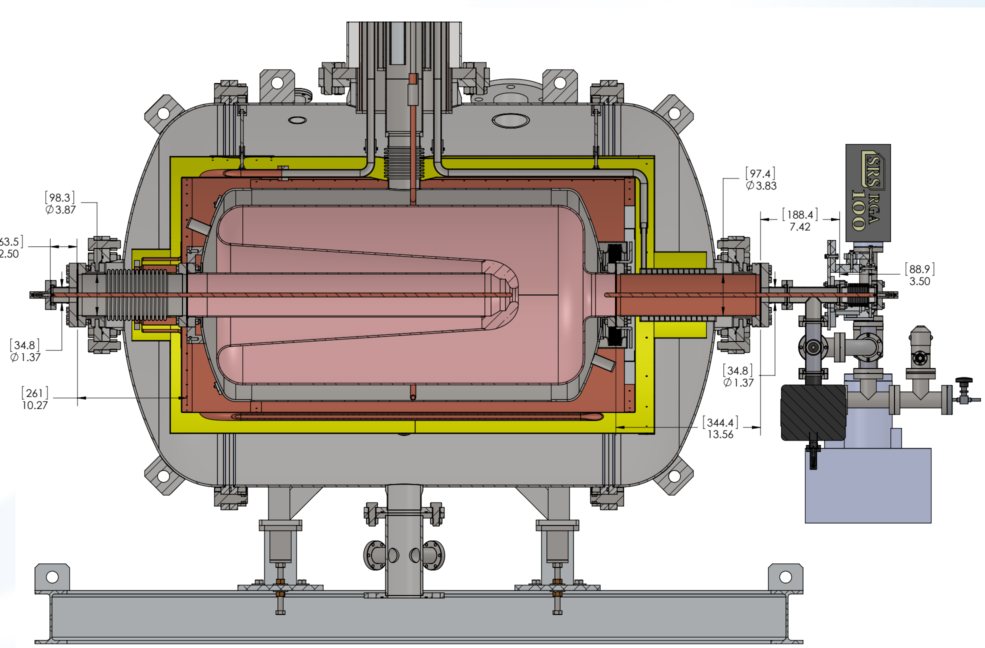
SRF gun upgrades/modifications

- Replacing the low carbon steel vacuum vessel with the stainless steel one.
- Modify cryogenic connections for compatibility with BNL cryogenics.
- Frequency pre-tuning mechanism inside the cryostat.
- Re-design cavity support.
- Low RF loss, low heat load cathode stalk.
- Load lock system for multi-alkali photocathodes.
- Combine function FPC/tuner assembly.
- Copper plate stainless steel bellows and beam pipes to reduce RF losses.

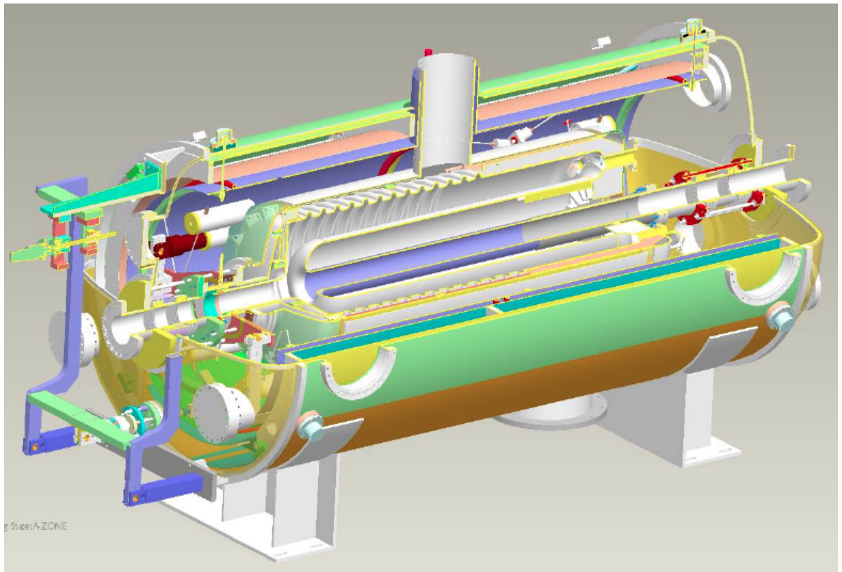


QWR gun upgrade status

- The cathode stalk and load lock system are designed and fabricated.
- The new FPC/fine tuner assembly is designed at BNL and are ordered from Niowave.
- The modification of the SRF gun cryostat is complete, the cryo tower fabrication is in progress at Niowave.
- We plan to perform two tests at Niowave before shipping the gun to BNL.
- The first test, a cryomodule acceptance test (no cathode and FPC/tuner), is scheduled for December of 2012 at Niowave.
- The second test is scheduled for January/February of 2013. During this test we would like to generate a beam with multi-alkali and diamond-amplified photocathodes.

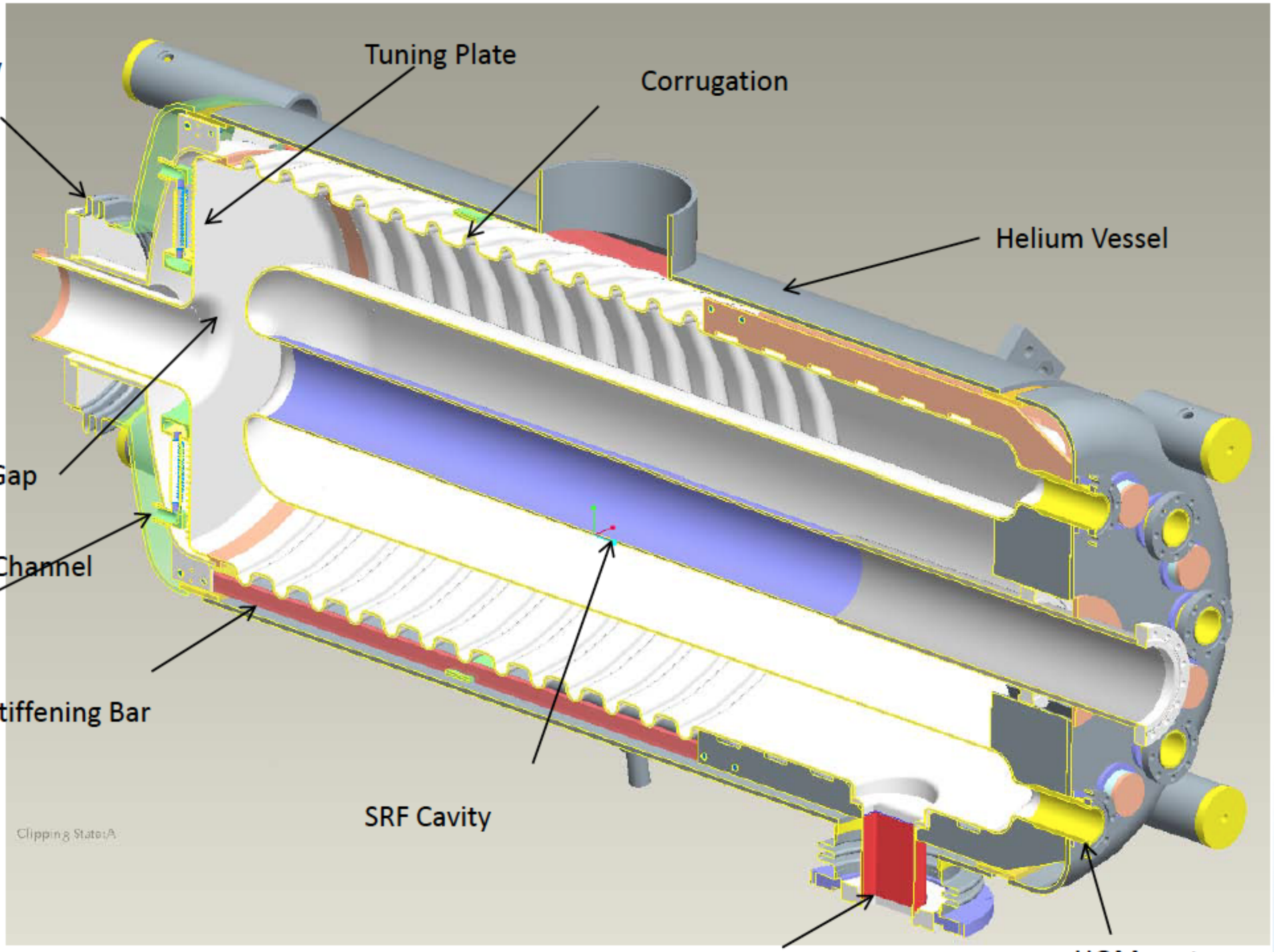


Improving performance of RHIC: 56 MHz QWR



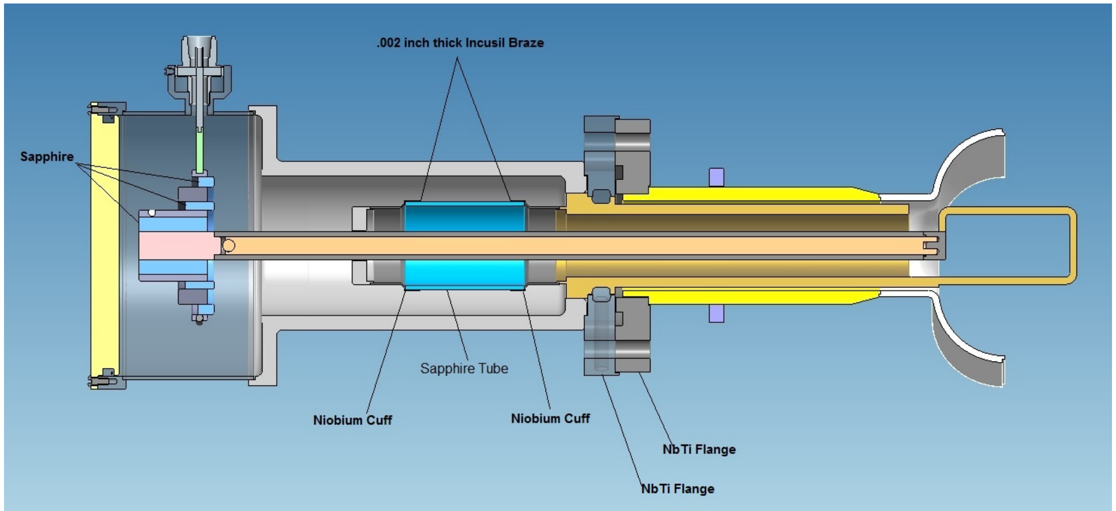
- The purpose of this QWR is to provide a larger RF bucket (5 times larger than that of 197 MHz cavities) for particles, which should result in higher luminosity of RHIC by: direct adiabatic capture from 28 MHz system, better preservation of longitudinal emittance, elimination beam spillage in satellite buckets.
- This is a "storage" cavity: it does not have large tuning range to follow the large frequency change during acceleration from injection energy to energy of experiment and is turned on only after that for re-bucketing. One 56 MHz cavity will serve both RHIC rings. It will be the first superconducting RF system in RHIC.
- It is tuned to 720th harmonic of the RHIC revolution frequency. It is a beam driven cavity. However, there will be a 1 kW RF amplifier. The amplifier will serve to: achieve required amplitude and phase stability and provide conditioning capability.
- The cavity fundamental mode will be detuned and strongly damped during injection and acceleration.
- At the energy of experiment, first the fundamental damper will be withdrawn and then the cavity frequency will be tuned (approaching from below the beam harmonic) to achieve operating voltage of 2.0 MV.
- A piezo tuner will be employed to compensate any fast frequency changes.

Main features of the 56 MHz cavity

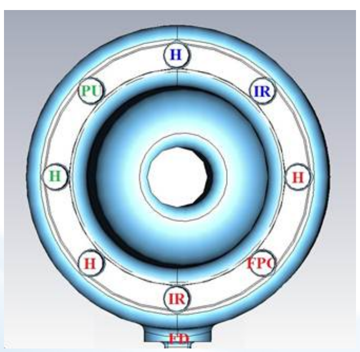


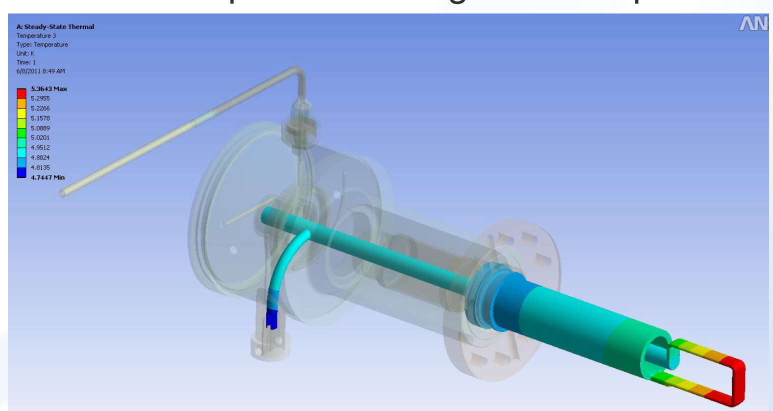
- The cavity is rigid: its first mechanical mode frequency is 98.5 Hz; sensitivity to the helium bath pressure is 0.282 Hz/mbar; Lorentz force detuning is -37 Hz/(MV)^2, or 148 Hz at 2.0 MV.
- The cavity is designed to be multipacting-free.
- High degree of HOM damping is provided by 4 dampers asymmetrically placed at the "short" end of the cavity.
- Fundamental mode Damper (FD) reduces the cavity fundamental mode Q to ~300 during beam injection and acceleration.
- The cavity shape was optimized so that at 2.0 MV we get E_{pk} = 35.3 MV/m, B_{pk} = 83.9 mT, power dissipation < 20 W.
- These numbers are below what was already achieved on SPIRAL2 QWR at 88 MHz: 62 MV/m; 112 mT; 4.5 Hz/mbar; -1.58 Hz/(MV/m)^2, equivalent to 191 Hz at 11 MV/m.

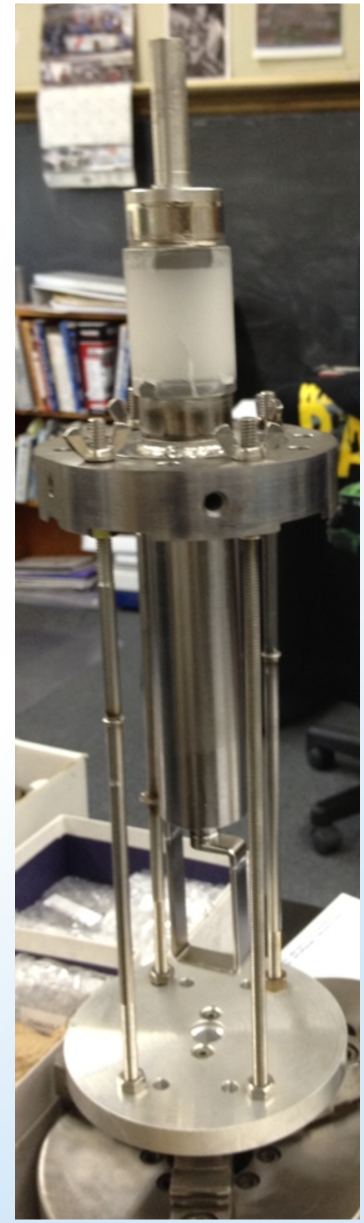
HOM coupler



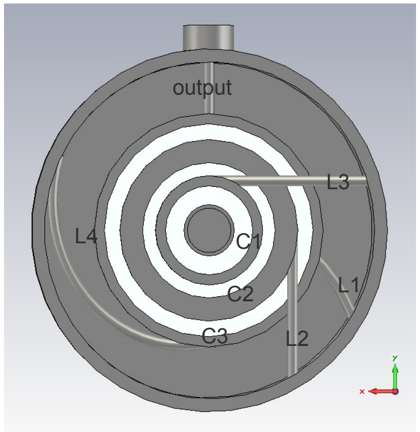
- With optimization to all HOM modes up to 1 GHz, the cavity will have 4 HOM dampers.
- The 4 dampers are inserted in an asymmetric configuration, which ensures all modes can be extracted to a certain degree.
- The NbTi flange will be cooled with helium.
- A high RRR copper rod inside the center conductor improves cooling of the loop.
- The copper rod will be cooled by LHe.

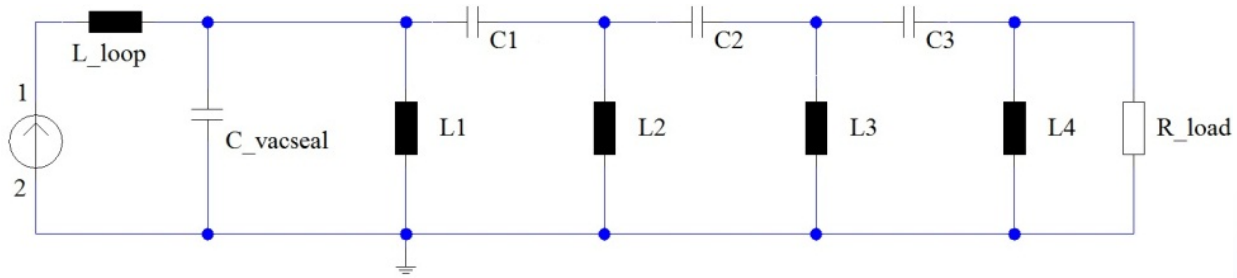


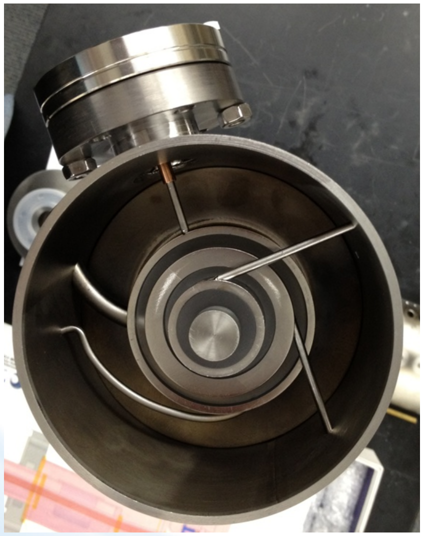




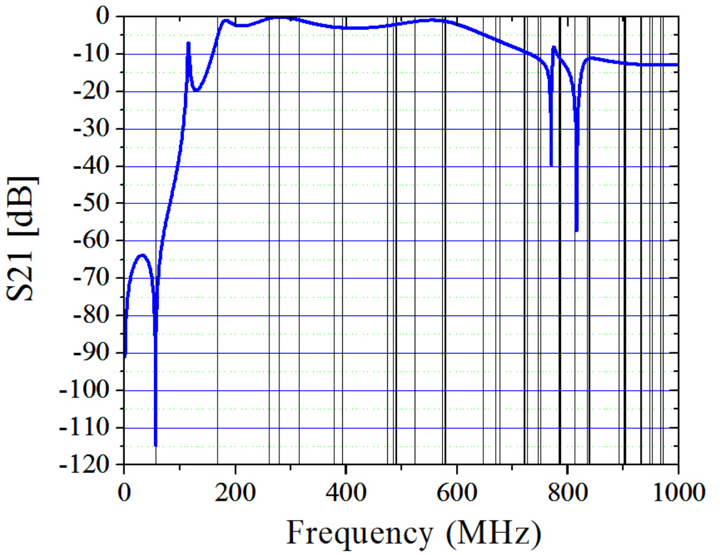
HOM filter







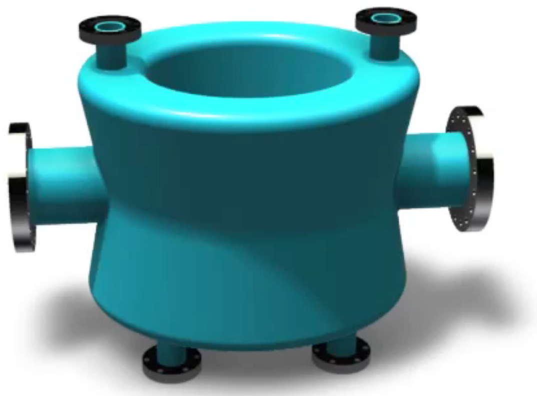
- A Chebyshev-type filter provides -110 dB attenuation at 56.3 MHz, which limits the output power of the fundamental mode to less than 1 mW.
- The total power of the HOM modes excited by the beam in the 56 MHz SRF cavity is ~1.1 W during operation, both rings are included. With the filter installed, the HOM total power output is ~0.33 W/damper.

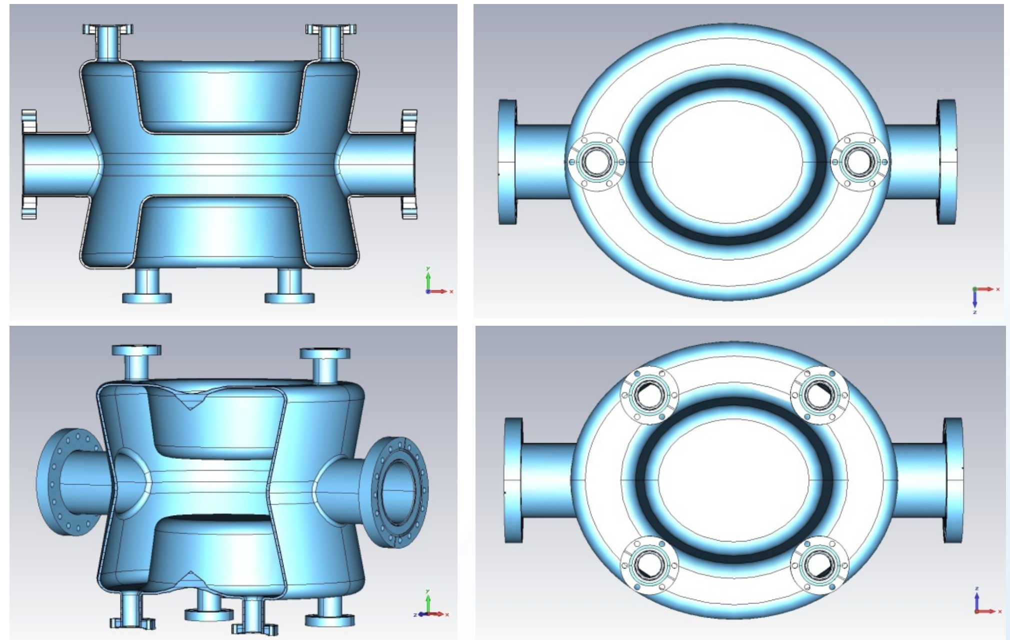


Status of the 56 MHz cavity

- The cavity fabrication, including Ti helium vessel, was recently complete at Niowave.
- Fabrication of other components is in progress.
- The cryomodule is designed to be compliant with the ASME Pressure Vessel Code.
- Bulk BCP was done at the joint BNL/AES BCP and HPR facility. 600°C bake was done at BNL.
- Prior to final BCP and HPR, we are checking and adjusting the tuner operation in a mockup assembly (photo) and fine-tuning the cavity frequency.
- Clean room assembly, VTF and cryomodule tests will be at BNL.
- There will be two VTF tests. The first one is a cavity acceptance test (December 2012). For the second test (January 2013) the cavity will be equipped with a prototype HOM coupler and an IR camera for quench detection.
- A cryomodule acceptance test is scheduled for June of 2013 with the goal is to install the cavity in RHIC for Run-14.

Double quarter wave crab cavity (DQWCC)

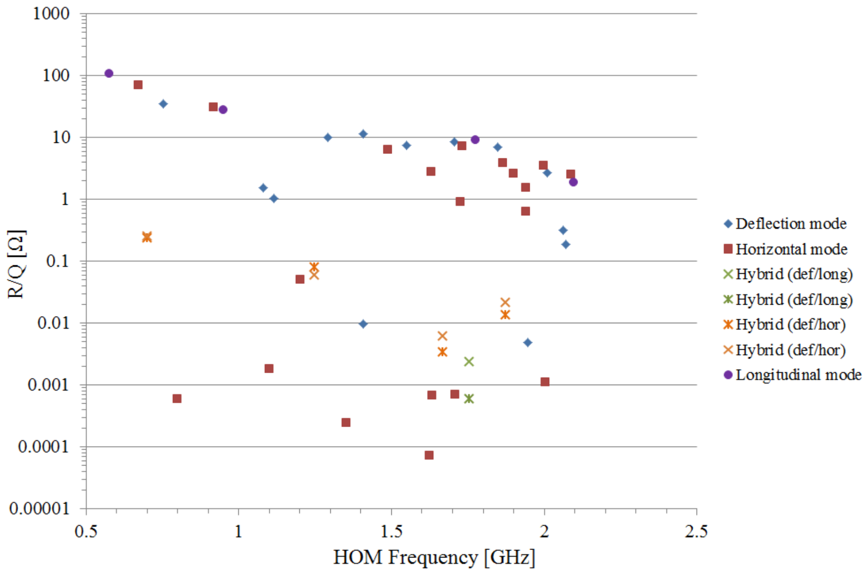


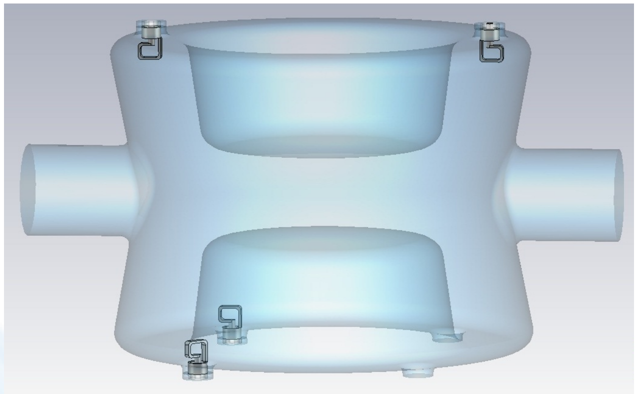


- Double quarter-wave resonator: Compact design at low frequencies; No Lower Order Modes and Same Order Modes, nearest Higher Order Mode is well separated from the fundamental mode ➔ easier damping than in other designs; Very little parasitic acceleration (1.6 kV).
- 6 RF ports: 4 for HOM damping, 1 for FPC, and 1 for pickup.
- The cavity is developed as part of LARP and satisfies very strict space constrains near the LHC IPs.
- Similar cavities are considered for eRHIC.

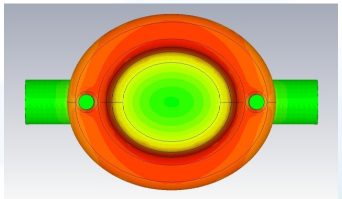
Crabbing (fund.) mode	1st HOM	Cavity length	Cavity width	Beam pipe diameter	Deflecting voltage
400 MHz	579 MHz	38.4 cm	14.2 cm	8.4 cm	3 MV

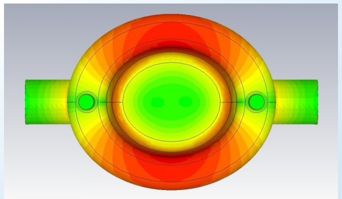
HOM damping

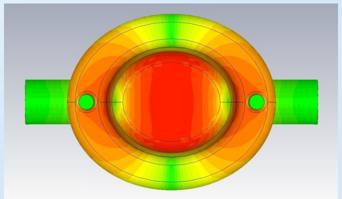




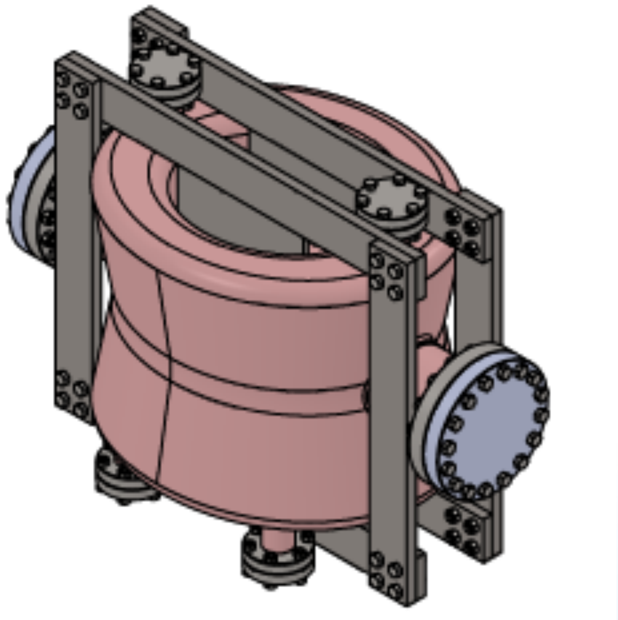
HOM frequency [GHz]	Mode Config.	R/Q [Ohm]	Qext
0.579	Longitudinal	108	1130
0.671	Horizontal	70.5	2340
0.700	Hybrid (y, z)	0.24/0.25	1140
0.752	Deflection	34.9	1750
0.800	Horizontal	6.02e-4	3160
0.917	Horizontal	30.9	2050
0.949	Longitudinal	28.1	3180
1.080	Deflection	1.54	1240
1.102	Horizontal	1.84e-3	1380
1.114	Deflection	1.06	1380
1.202	Horizontal	5.07e-2	7880
1.247	Hybrid (y, z)	8.0e-2/6.0e-2	1730
1.291	Deflection	10.0	926





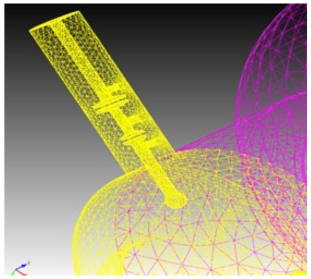


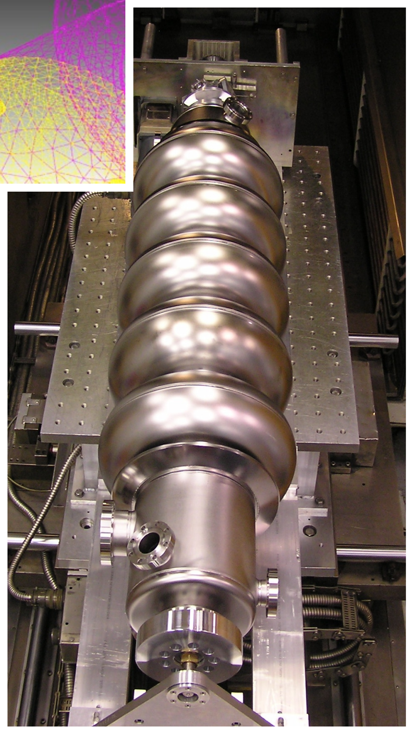
DQWCC prototype status



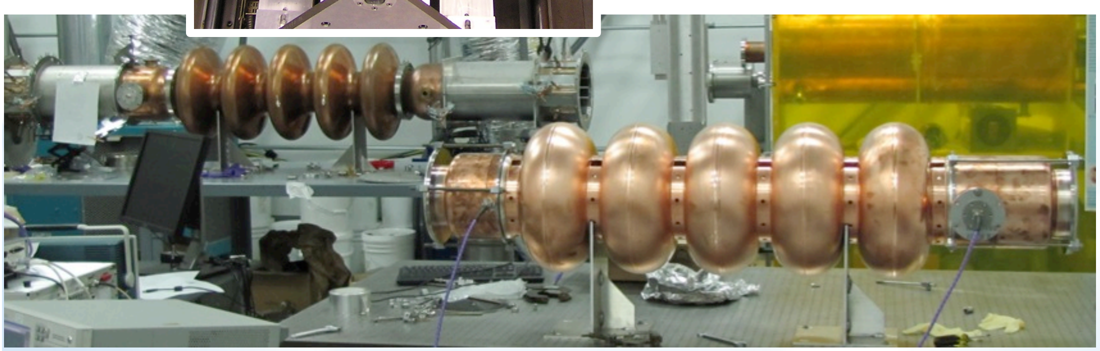
- Fabrication of a prototype cavity has started at Niowave.
- The cavity will be made of 4-mm thick Nb.
- There will be special stiffeners welded to the cavity as there is no helium vessel on the prototype.
- In the future a helium vessel will stiffen the cavity.
- VTF tests – early 2013.
- Design of HOM couplers, FPC, tuner is in progress.

704 MHz BNL3 cavity for high-current linacs





- We used our experience with BNL1 cavity (installed in R&D ERL) to design and optimize a new cavity, BNL3, for high-current applications such as eRHIC, SPL, ESS. The cavity was developed with funding provided via BNL/Stony Broo University Ceneter for Accelerator Science and Education (CASE).
- *R/Q×G* of this cavity is 1.58 times better than of BNL1 cavity.
- eRHIC will have three ERLs employing elliptical 5-cell BNL3 cavities.
- Three antenna-type couplers will be attached to large diameter beam pipes at each end of the cavity and will provide strong HOM damping while maintaining good fill factor for the linac.
- The cavity RF design is complete. A copper prototype has been fabricated by AES and is used to study HOM damping.



- Fabrication of the first niobium cavity is complete and the cavity is being prepared for BCP at AES. The first VTF testing – early 2013.
- A second cavity and a cryomodule are on order from Niowave to be used in CeC PoP experiment.

Summary

- BNL has a diverse program of developing SRF guns and other specialized cavities. All of them are related either to improving performance of RHIC or to developing future electron-hadron collider eRHIC.
- Two SRF guns (704 MHz and 112 MHz) are assembled in the cryomodules and their testing will be commenced soon:
  - The guns are designed to generate high charge bunches (up to 5 nC) from multi-alkali photocathodes.
  - The 704 MHz ½-cell gun is capable to support an average beam current up to 500 mA in the R&D ERL.
  - The QWR-type 112 MHz gun will provide a low rep rate, high bunch charge beam for CeC PoP experiment. Also, it will be used for experiments with a diamond-amplified photocathode.
- The specialized cavities address challenges of different kind:
  - 56 MHz QWR-type storage cavity will provide a large longitudinal potential well to long hadron bunches in RHIC.
  - 400 MHz DQWCC, with its compact design, will enable a crab crossing scheme in the LHC Upgrade. Similar cavities are planned for eRHIC.
  - 704 MHz 5-cell BNL3 cavity will be equipped with a strong HOM damping, sufficient for high-current linacs and ERLs, while not compromising real-estate gradients too much.

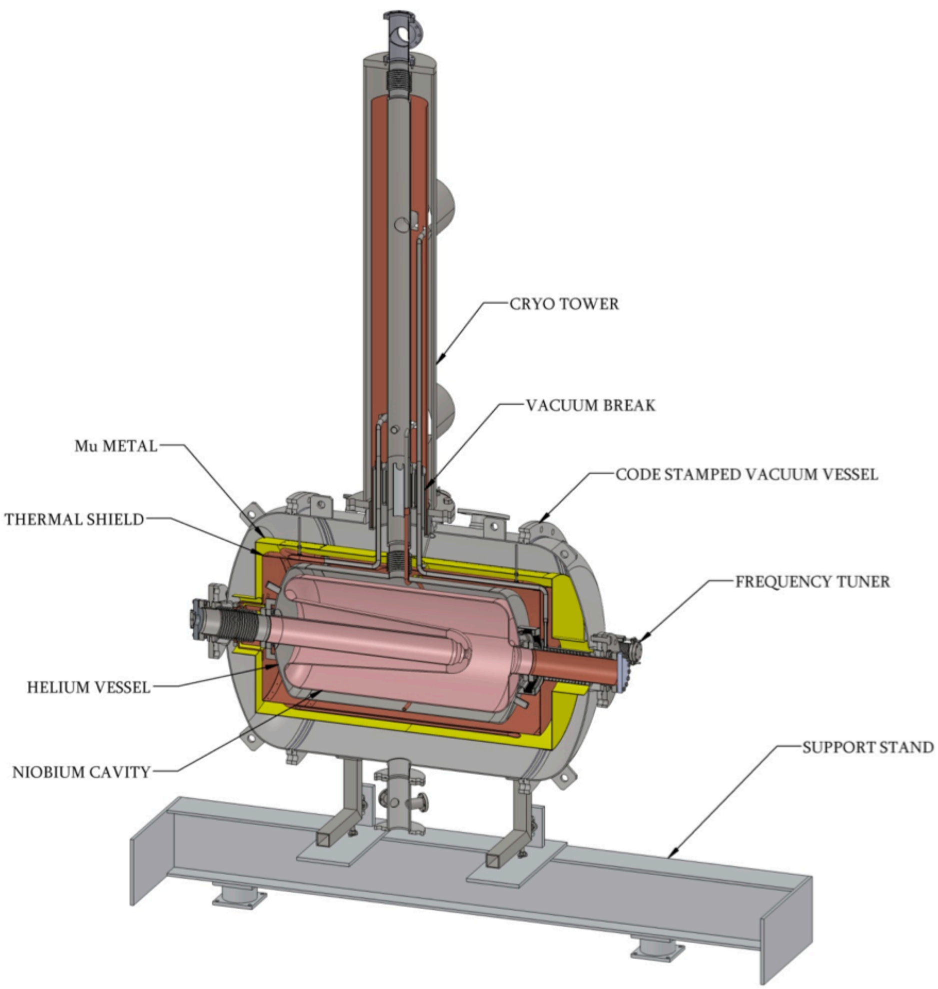
Thank you!

Backup slides

704 MHz SRF gun parameters

RF frequency	703.5 MHz
Cavity active length	8.5 cm (0.4 cell)
Maximum energy gain	2.5 MeV
Maximum field at the cathode	33.4 MV/m
E_{acc} at 2.5 MV	29.4 MV/m
e^- emission RF phase at 2.5 MV	33.4º
Energy gain at 500 mA	2.0 MeV
e^- emission RF phase at 2.0 MV	29.9º
Beam power at 500 mA	1 MW
R/Q	96.2 Ohm
Cavity geometry factor	112.7 Ohm
Cavity Q_0 at 2 K	3×10^{10}
Cavity operating temperature	2 K
Cavity RF losses (2 K) at 2.0 MV	1.4 W
Cathode operating temperature	80 K
Copper cathode RF losses (80 K) at 2.0 MV	226 W

QWR SRF gun parameters



Parameter	QWR SRF gun
Frequency [MHz]	113.04
Aperture (beam tube) [cm]	10
Cavity diameter [cm]	42
Cavity length [cm]	110
V_{acc} per cavity, max [MV]	2.0
Peak electric field [MV/m]	38.2
Peak magnetic field [mT]	72.8
Field at the cathode [MV/m]	14.5
R/Q [Ohm]	126
Geometry factor [Ohm]	38.2
RF power loss at 4.5 K [W]	12.3
RF power loss at RT in cathode stalk [W]	62.3
Beam power [W]	156
RF power per cavity [kW]	2

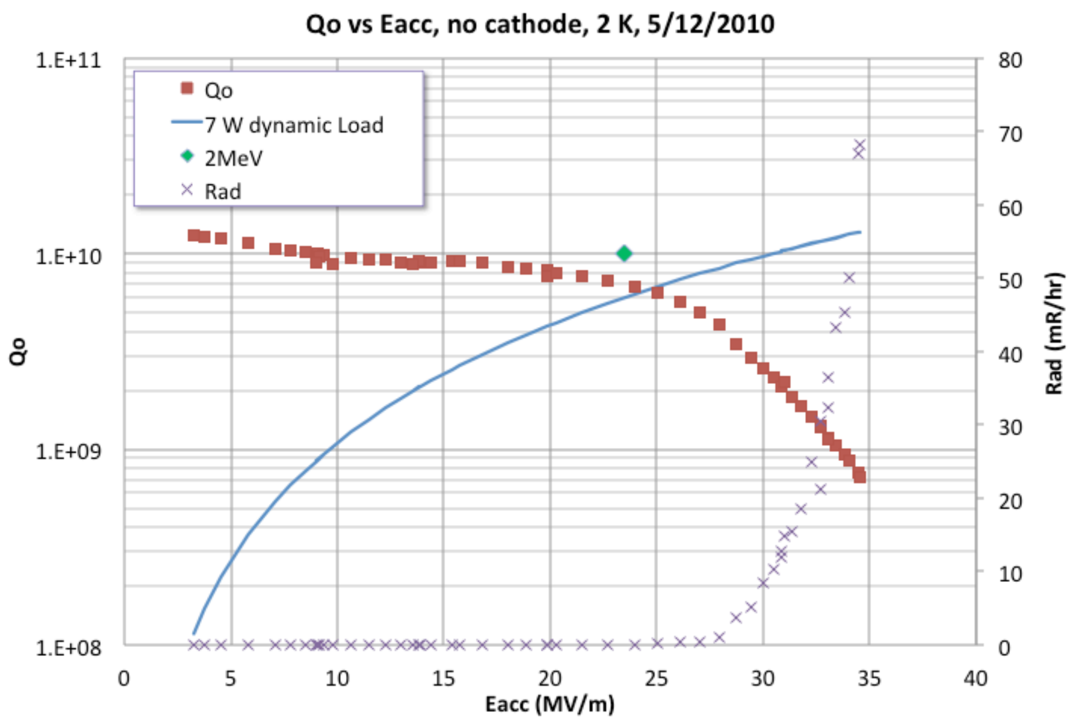
Parameters of BNL1 and BNL3 cavities

Parameter	BNL1	BNL3
Frequency [MHz]	703.5	703.8
No. of cells	5	5
Geometry Factor	225	283
R/Q [Ohm]	404.0	506.3
E_{pk}/E_{acc}	1.97	2.46
B_{pk}/E_{acc} [mT/MV/m]	5.78	4.26
Length [cm]	152	158
Beam pipe radius [mm]	120	110

DQWCC parameters

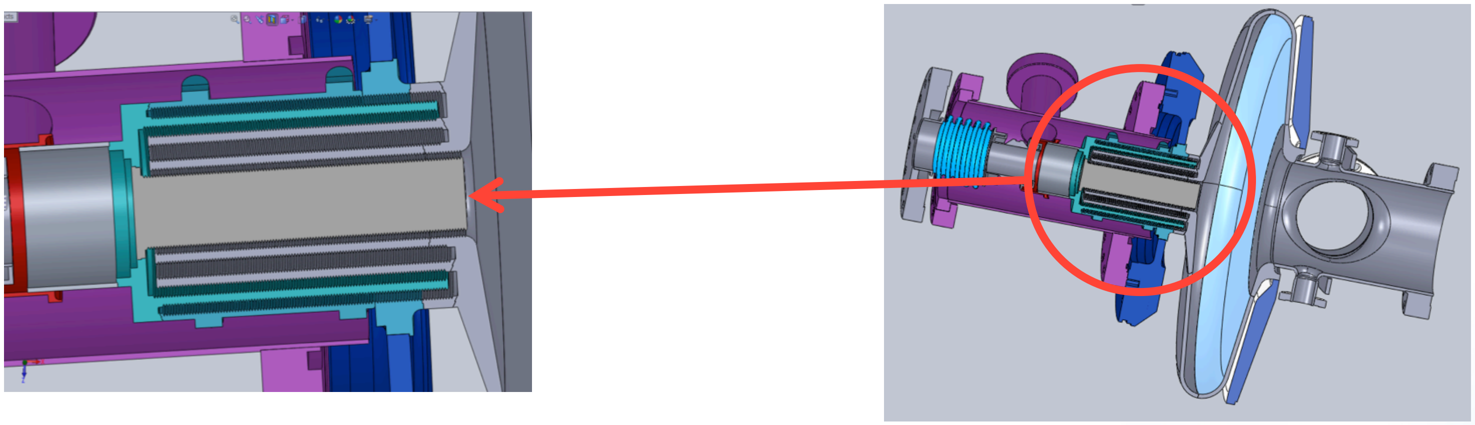
Parameter	DQWCC
Fundamental Mode Frequency	400 MHz
Nearest Mode Frequency	579 MHz
Vertical Deflection Voltage	3 MV
Rt/Q (Fund. Mode)	400 Ohm
Epeak	44 MV/m
Bpeak	60 mT
Energy Content	12 J

SRF gun cavity processing and testing



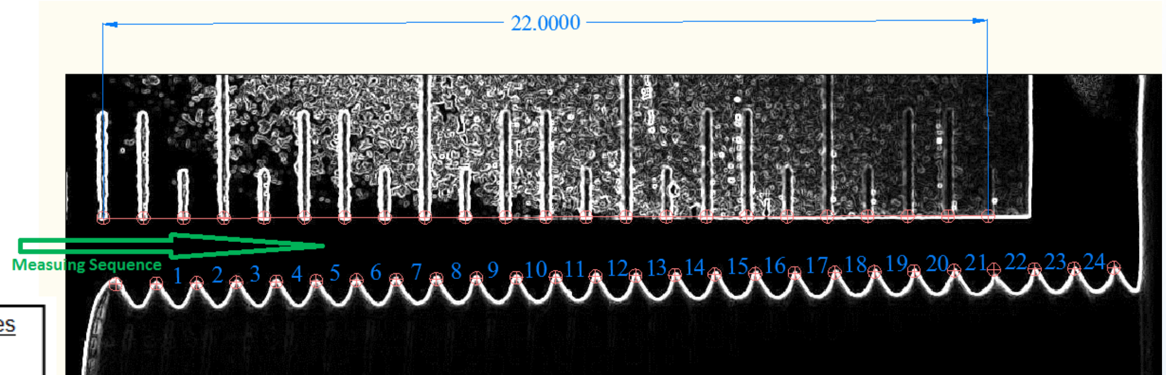
- The gun cavity underwent the following processing at JLab: ~120 um BCP, HPR, 60-hrs bake at 200°C (to reduce SEY of Nb as opposed to standard 24-hrs bake at 120°C).
- After that the cavity was tested in a vertical cryostat several times.
- Tests without the cathode stalk were good.
- At 23.5 MV/m (corresponding to 2 MV) the cavity dynamic loss was less than 7 W.
- FE started at >25 MV/m.

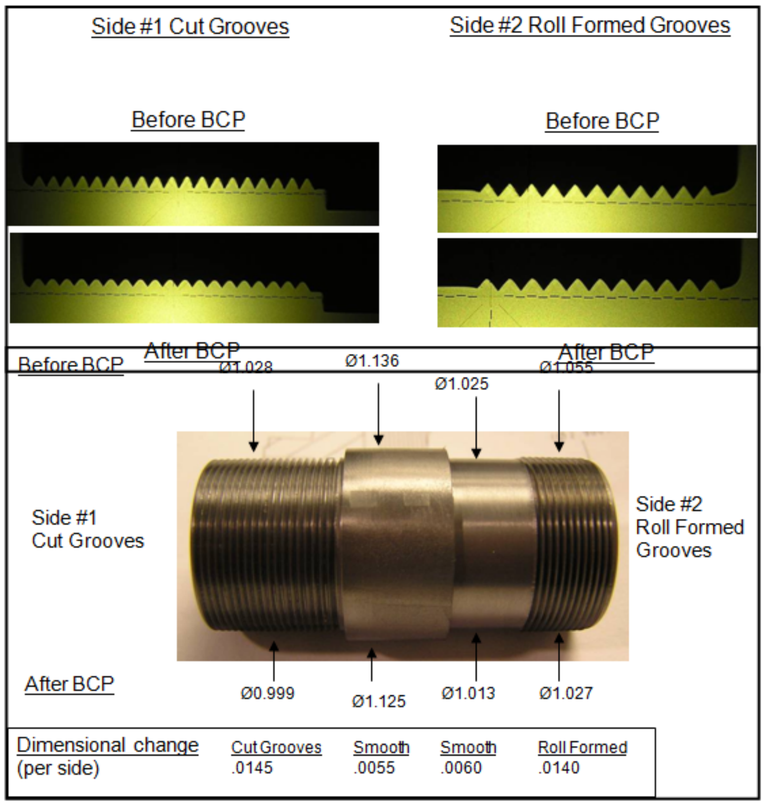
MP in the grooved choke joint



- Tests with the stalk (made of high RRR Nb) suffered from multipacting (MP) in the choke joint region and were limited to ~3 MV/m.
- Baking helped to increase the field to ~6 MV/m, where another barrier prevented further progress.
- It was not possible to overcome MP due to available RF power at JLab's VTF.
- MP simulations were performed using FishPact. No MP was found with ideal triangular grooves.
- However, due to BCP etching, the groove valleys became rounded.
- Simulations with rounded grooves (0.2 mm rounding radius) found MP barriers at 3 MV/m, 6 MV/m, and 11 MV/m. Studies indicate that roll formed grooves sustain BCP better than cut grooves. Thermal analysis, incorporating heat load due to MP, was performed. The results indicate that 3 MV/m barrier should be the most difficult to overcome.
- As we were able to process this barrier during vertical tests, and we will use a copper cathode insert with freshly formed grooves in the cryomodule, it was decide to proceed with the cryomodule assembly.

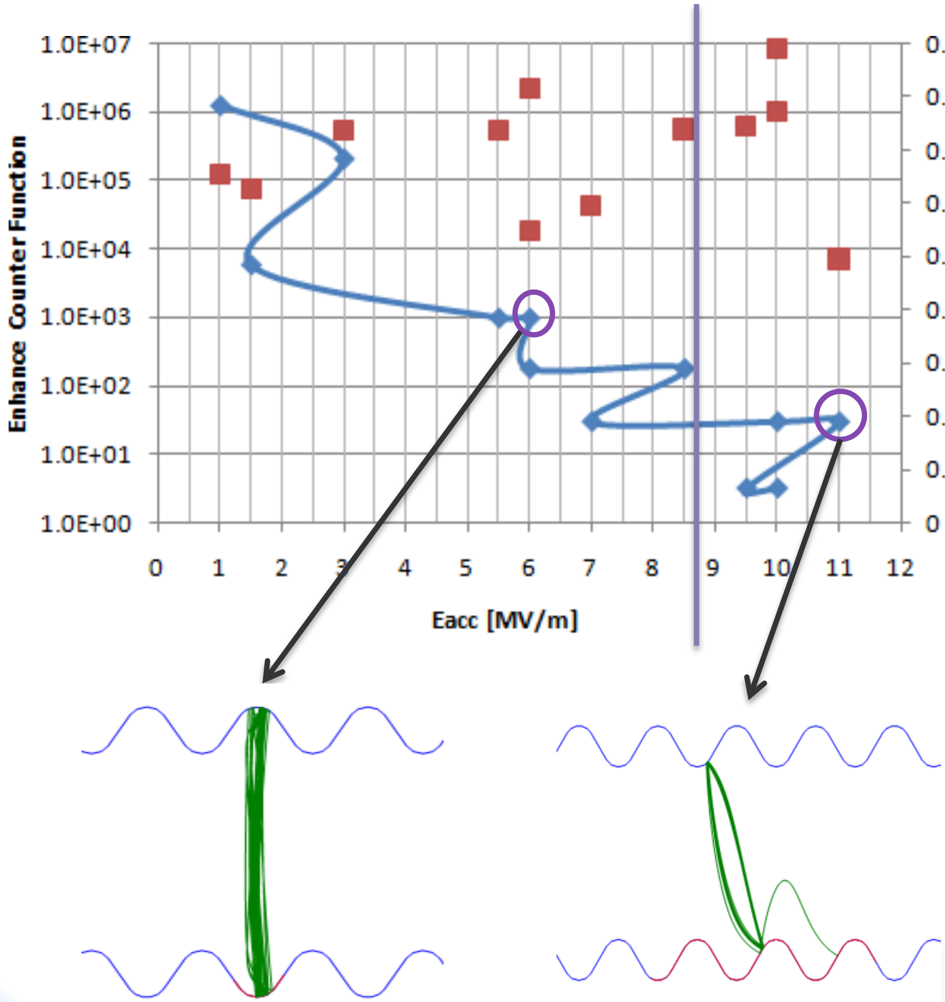
Rounding of the grooves after BCP

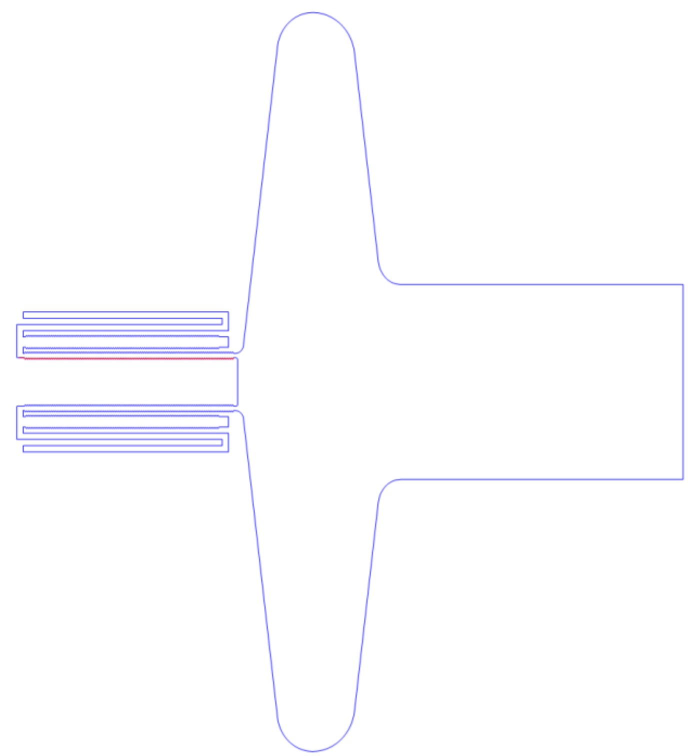




- Due to BCP etching, the groove valleys became rounded.
- Simulations with rounded grooves (0.2 mm rounding radius) found MP barriers at 3 MV/m, 6 MV/m, and 11 MV/m.
- Studies indicate that roll formed grooves sustain BCP better than cut grooves.
- We have devised a special experiment to further study conditioning of MP in the choke joint. A spare (large-grain) gun cavity in the vertical test dewar will be used.

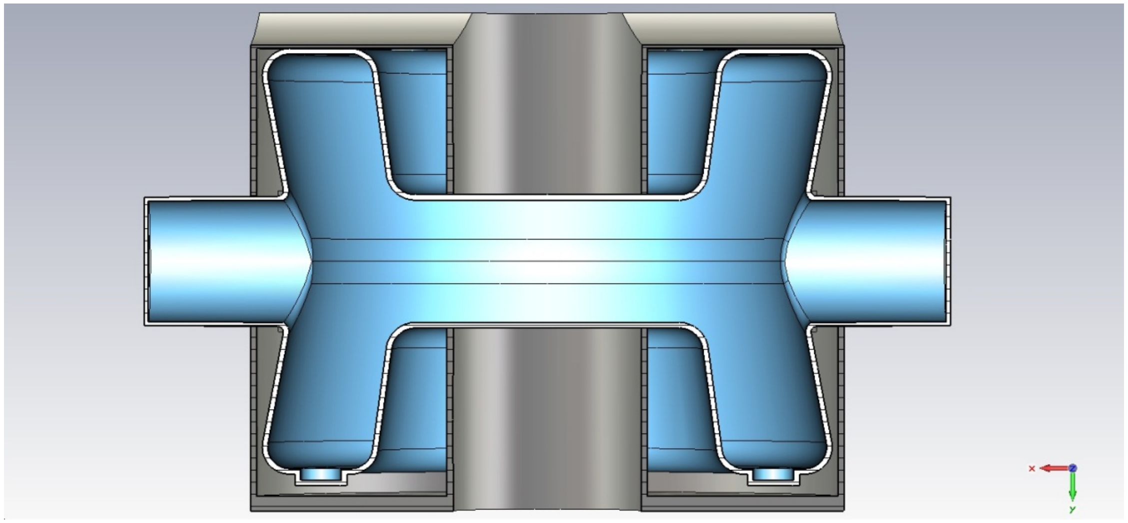
MP simulations of BCP-treated choke joint





Wencan Xu et al. “Multipacting in a Grooved Choke Joint at SRF Gun for BNL ERL Prototype,” *Proceedings of 2011 Particle Accelerator Conference*, TUP059

DQWCC helium vessel



- Preliminary design of the helium vessel
- The vessel will play a role in stiffening the cavity
- Clearance for other beam lines in the vicinity.
- Simple machining and welding
- Compact design which saves LHe