# Performance of superconducting RF system for the R&D ERL at BNL

*Wencan Xu & Sergey Belomestnykh*

*Collider-Accelerator Department, BNL*

# Acknowledgements

**BNL**: Z. Altinbas, I. Ben-Zvi, S. Belomestnykh, R. Calaga, J. Dai, D. Gassner, H. Hahn, L. Hammons, J. Jamilkowski, D. Kayran, J. Kewisch, N. Loudakis, D. Lederle, V. Litvinenko, G. Mahler, G. McIntyre, C. Pai, D. Pate, D. Phillips, C. Schulheiss, S. Seberg, T. Seda, B. Sheehy, K. Smith, T. Miller, T. Tallerico, R. Than, J. Tuozzolo, D. Weiss, A. Zaltsman, …

**HZB**: A. Burill

**AES**: C. Astefanous, M. Cole, A. Favale, D. Holmes, J. Rathke, T. Schultheiss, …

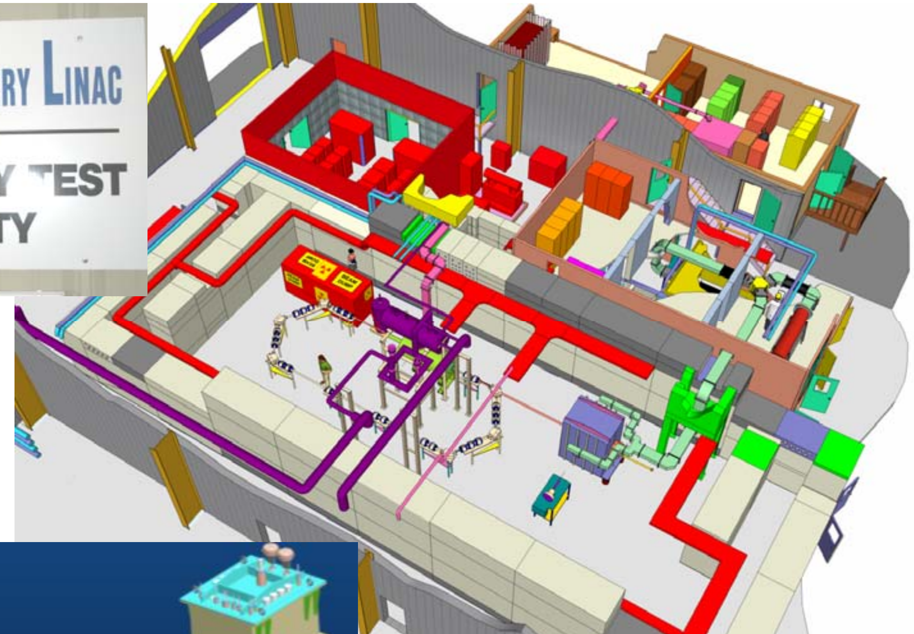
# Outline

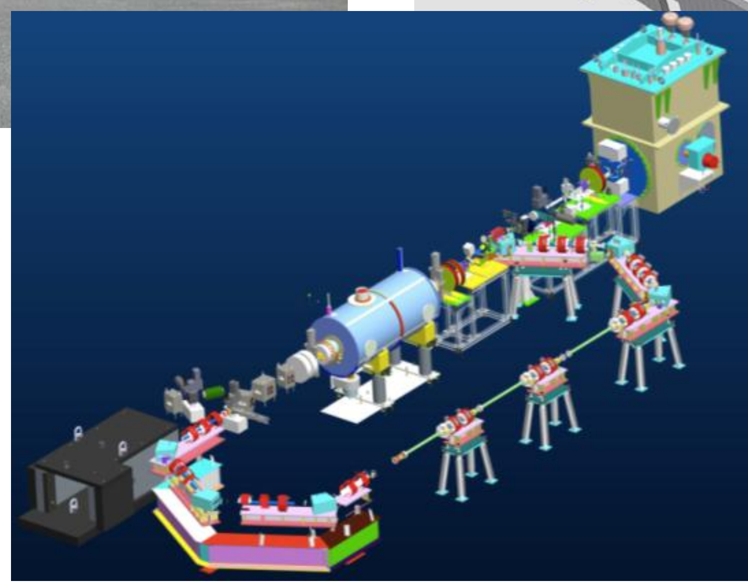
- Introduction of the R&D ERL
- ERL cryogenics
- Digital LLRF
- 5-cell SRF cavity performance
- SRF gun design and assembly
- SRF gun commissioning
- Timeline for the R&D ERL project at BNL

# R&D ERL

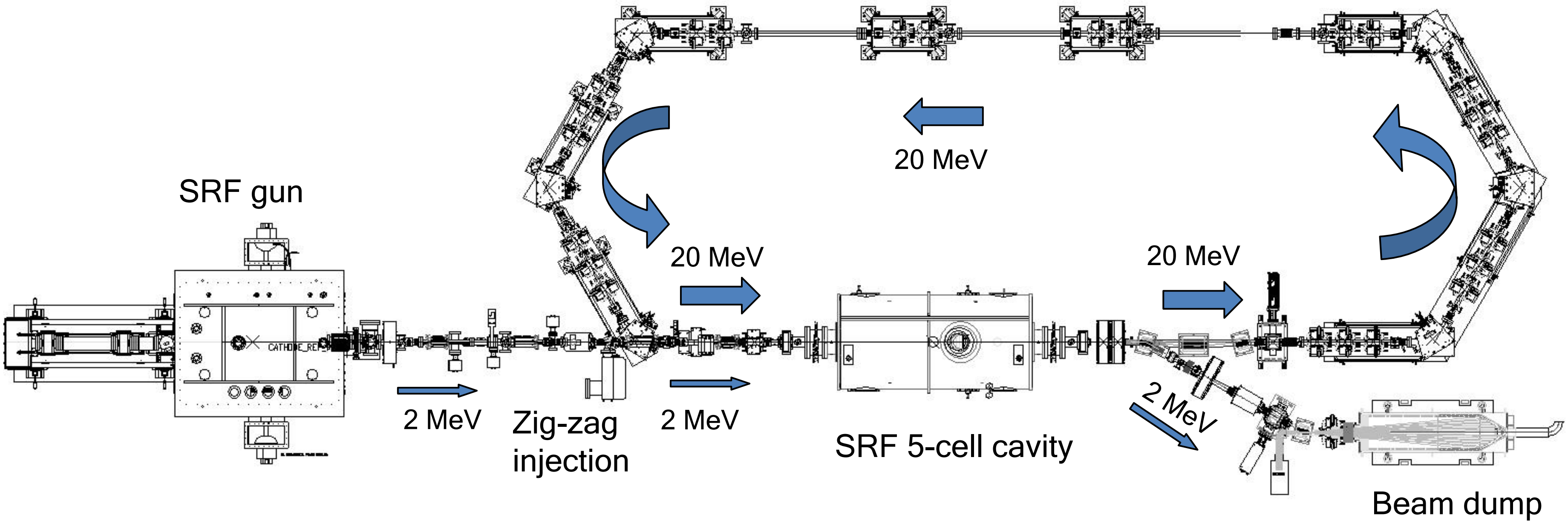

BLDG 912


ENERGY RECOVERY LINAC
AND
SRF CAVITY TEST
FACILITY





# ERL layout and goals




***✓The main goal of BNL R&D ERL project is to serve as a test-bed to demonstrate the main electron beam parameters for future RHIC upgrade projects:***

- ERL-based coherent electron cooling;
- 10-to-20 GeV ERL for lepton-ion collider eRHIC.

***✓Test the key components of a high current ERL based solely on SRF technology***

- SRF photoinjector test with 300 mA: preservation of high-charge, low emittance beam;
- High current 5-cell SRF linac test with HOM absorbers: single turn, 300 mA;
- Stability criteria for CW beam current;
- Attainable ranges of electron beam parameters in an SRF ERL.

# BNL ERLs beam parameters

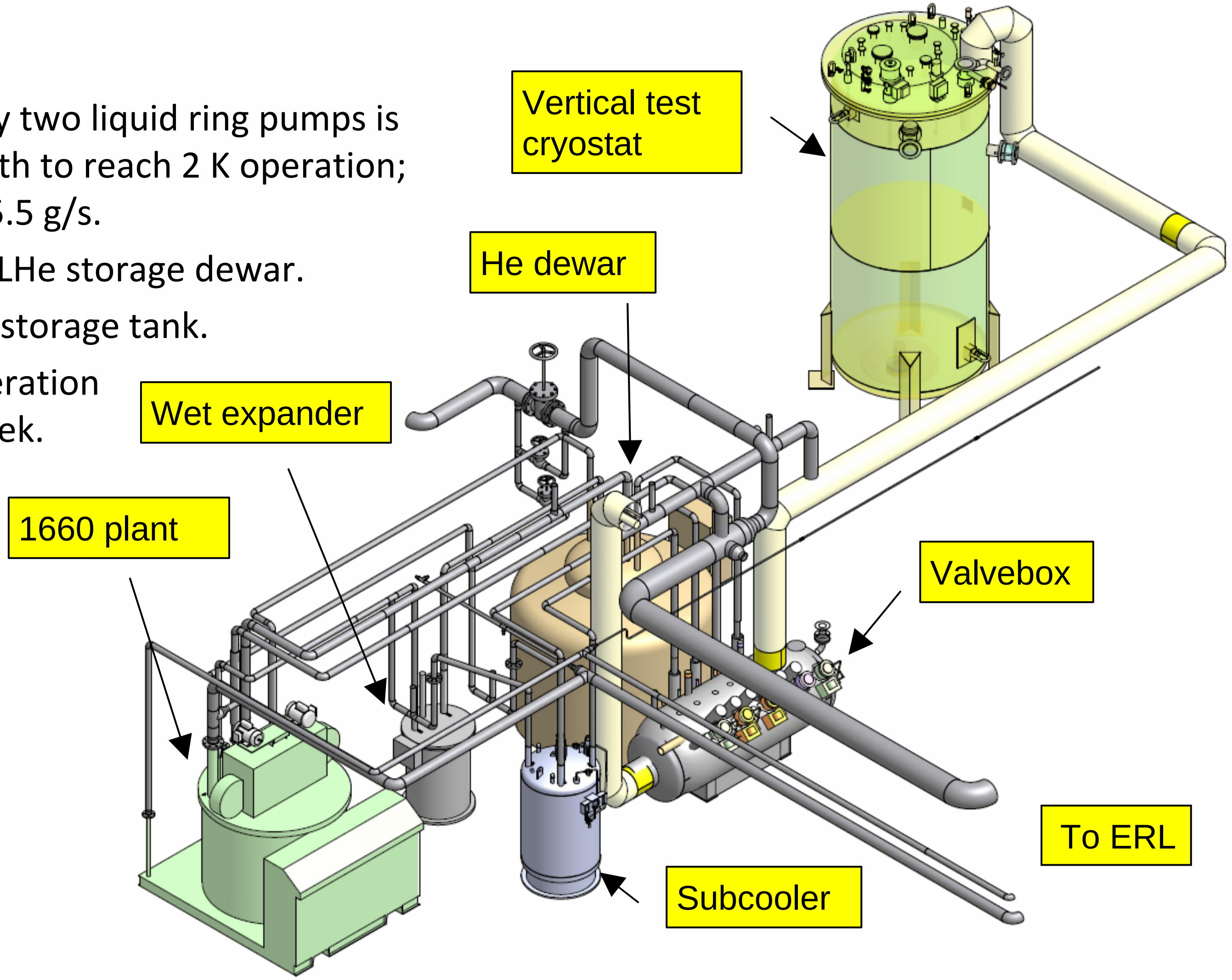
| | R&D ERL design | | | BNL ERL/SRF projects requirements | | |
|---|---|---|---|---|---|---|
| | **Low beam power test** | **High current** | **High charge** | **Proof of Principle of CeC @ 40GeV** | **Low Energy RHIC eCooler** | **eRHIC at 10 GeV** |
| **Charge per bunch, nC** | **0.1** | **0.43** | **5** | **0.5-1** | **3x0.7** | **5.8** |
| Energy maximum/injection, MeV | 20/2.5 | 20/2.5 | 21/3.0 | 21.8 | 0.9-5 | 10000/10 |
| R.m.s. Normalized emittances $\varepsilon_x/\varepsilon_y$, mm*mrad | | 1.4/1.4 | 4.8/5.3 | 5 | 3 | 16-40 |
| R.m.s. Energy spread, $\delta E/E$ | | $3.5\times10^{-3}$ | $1\times10^{-2}$ | $1\times 10^{-3}$ | $5\times10^{-4}$ | $1\times10^{-3}$ |
| R.m.s. Bunch length, ps | 8.5 Gaussian | 18, flat | 31, flat | 1 | 500 | 6.7 |
| Bunch repetition rate, Hz | $10^4$b train | $704\times10^6$ | $9.383\times10^6$ | $78\times10^{3*)}$ | $9.38\times10^6$ | $9.38\times10^6$ |
| **Gun average current, mA** | **0.001** | **300** | **35** | **0.078** | **20** | **50** |
| **Linac average current, mA** | 0.002 | **600** | **70** | **0.078** | **20** | **300** |
| **Dumped beam power, kW** | **0.002** | **600** | **70** | **1.7** | **20-100** | **0.5** |
| Numbers of passes | 1 | 1 | 1 | No recovery | No recovery | 6 |

# R&D ERL commissioning milestones

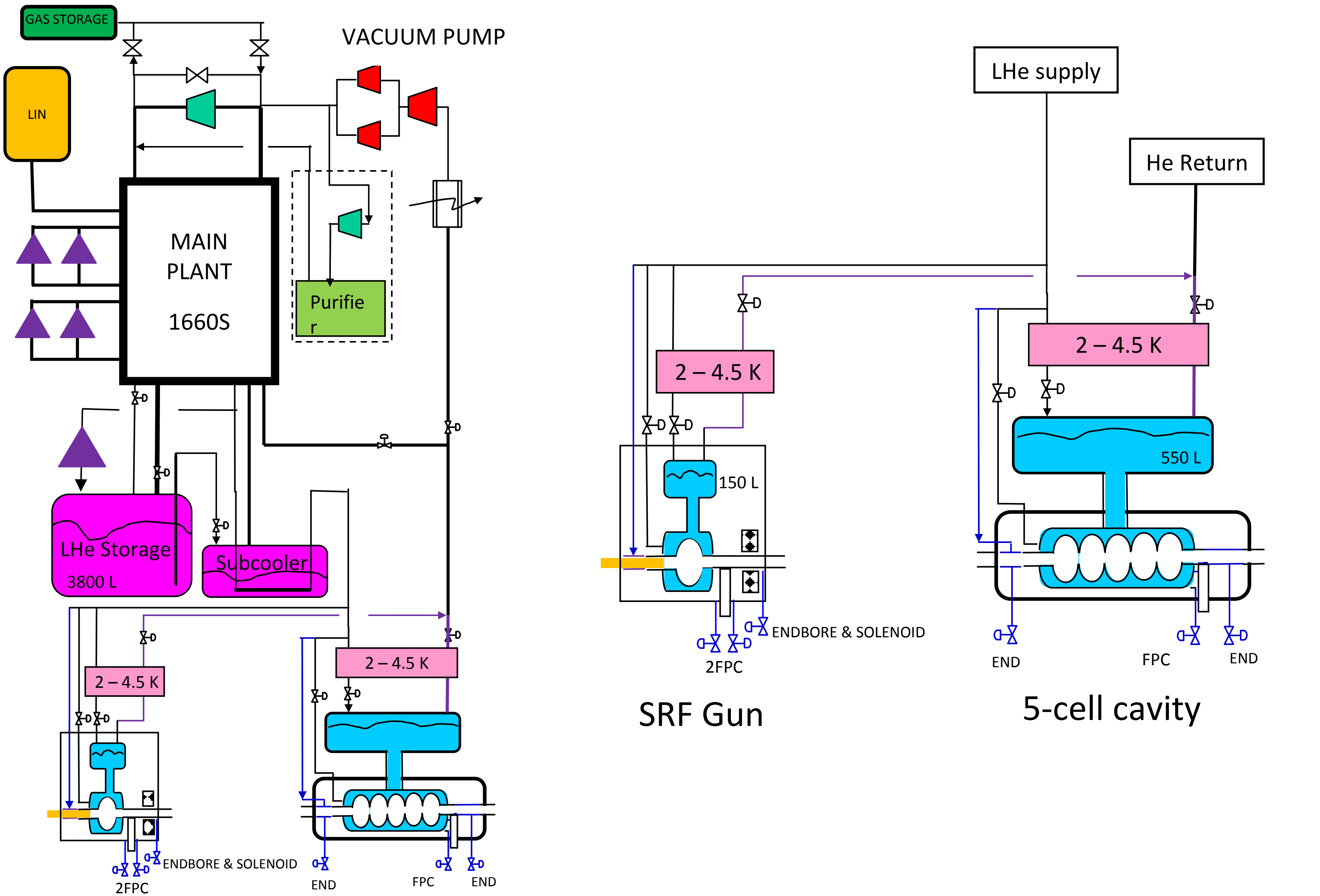
- Commissioning strategy: System by system commissioning of key components.
- Milestones :
  - SRF 5-cell cryomodule cold emission test (complete in 2009)
  - Digital LLRF system commissioning (complete in 2012)
  - 2 K LHe cryogenic system to supply LHe to ERL and SRF VTF (complete in 2012)
  - SRF half-cell gun cold emission test w/o cathode (complete, Nov. 2012 to Mar. 2013)
  - Conditioning of the SRF gun with a copper cathode stalk (Aug. 2013 to present)
  - First beam from the SRF gun with $CsK_2Sb$ photo cathode (Oct./Nov. 2013)
  - Low beam power test into a beam dump (early 2014)
  - ERL beam loop test (end of 2014)
  - ERL at 10 mA
  - Full ERL at 300 mA

# ERL/VTF cryogenic system

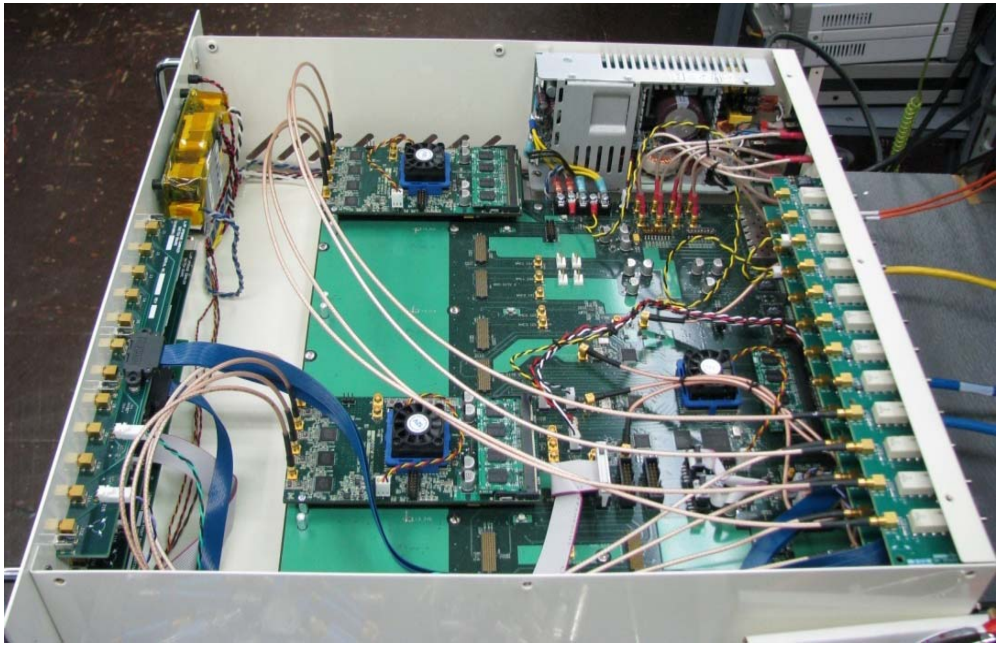
- The cryo plant serves both ERL and SRF Vertical Testing Facility (VTF).
- 300 W 4.5 K refrigerator.
- A Roots blower backed by two liquid ring pumps is used to pump the LHe bath to reach 2 K operation; it is capable of pumping 5.5 g/s.
- 1,000 gallon (3,800 liter) LHe storage dewar.
- 170 m$^3$ warm helium gas storage tank.
- The cryo plant allows operation of ERL 2 to 3 days per week.



# Block diagram of the cryogenic system

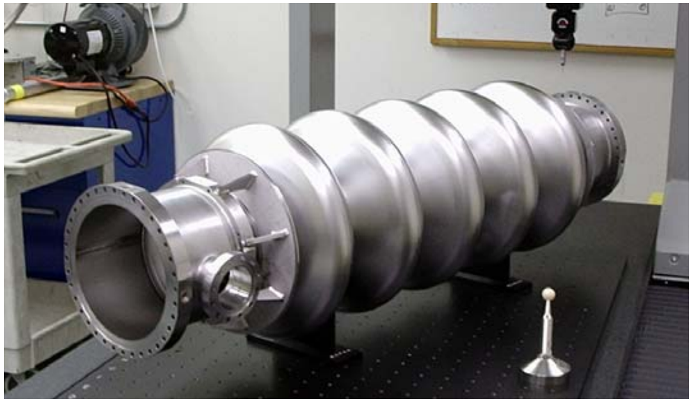


# Digital LLRF

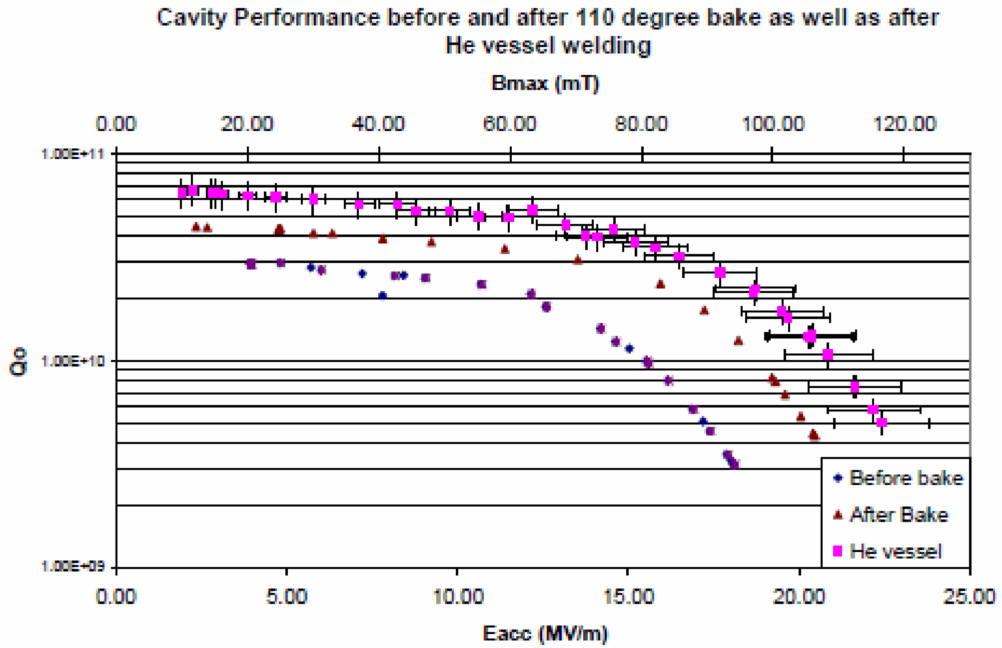
- R&D ERL system is a variant of the recently developed generic digital LLRF Controller, which is being deployed throughout the collider-accelerator complex RHIC (EBIS, linac, AGS, RHIC, …) at BNL.
- IQ feedback loops are implemented. Piezo tuner feedback is under development.
- Systems based on similar technology have already demonstrated 0.01% amplitude and 0.02° phase stability.

# SRF system: 5-cell SRF cavity

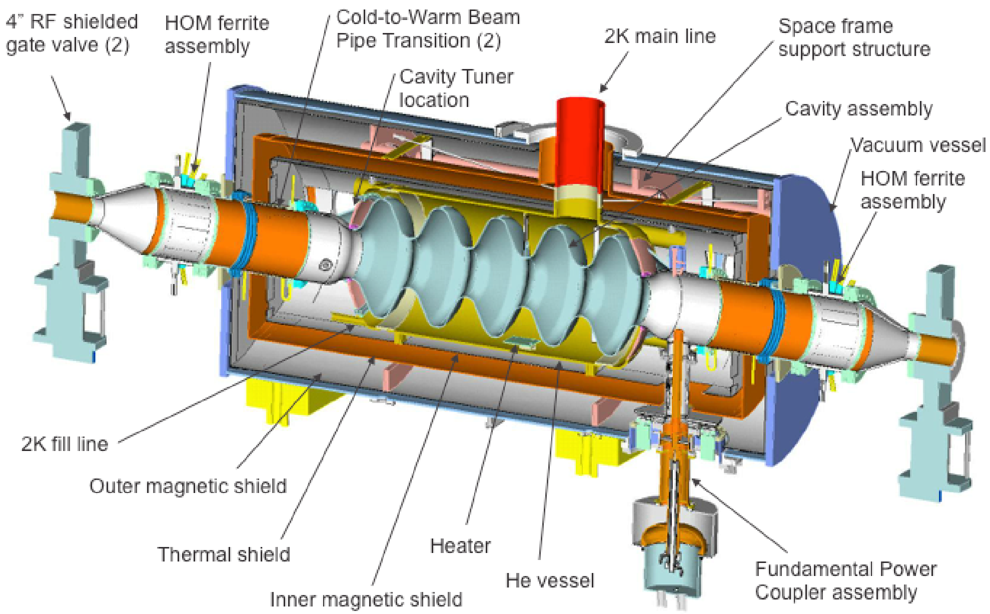


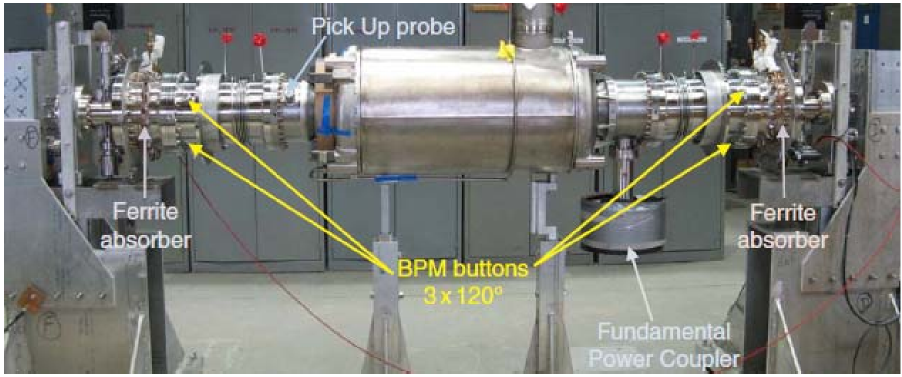
- 5 cell SRF cavity: 17 cm iris, 24 cm beampipe, 703.5 MHz, 20 MV/m @ $Q_0 = 1\ \ 10^{10}$
- Enlarged beam tubes to attenuate the fundamental mode but propagate all the HOMs. The cutoff frequency is at 790 MHz, the first dipole mode is at 810 MHz.

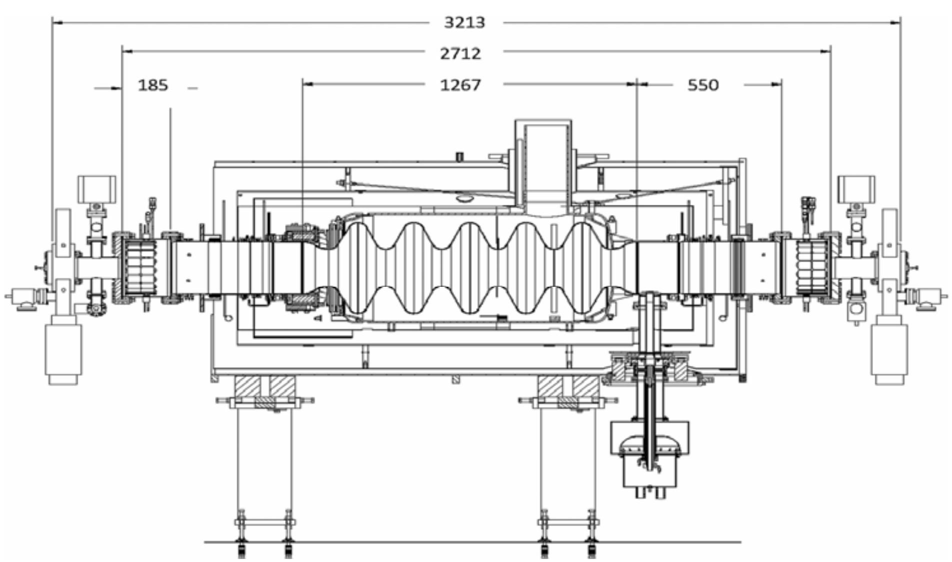
| Parameters | BNL1 |
|---|---|
| Frequency [MHz] | 703.5 |
| No. of cells | 5 |
| Geometry Factor | 225 |
| R/Q [Ohm] | 404 |
| $E_{pk}/E_{acc}$ | 1.97 |
| $B_{pk}/E_{acc}$ [mT/MV/m] | 5.78 |
| Length [cm] | 152 |
| Beam pipe radius [mm] | 120 |



# 5-cell cavity cryomodule



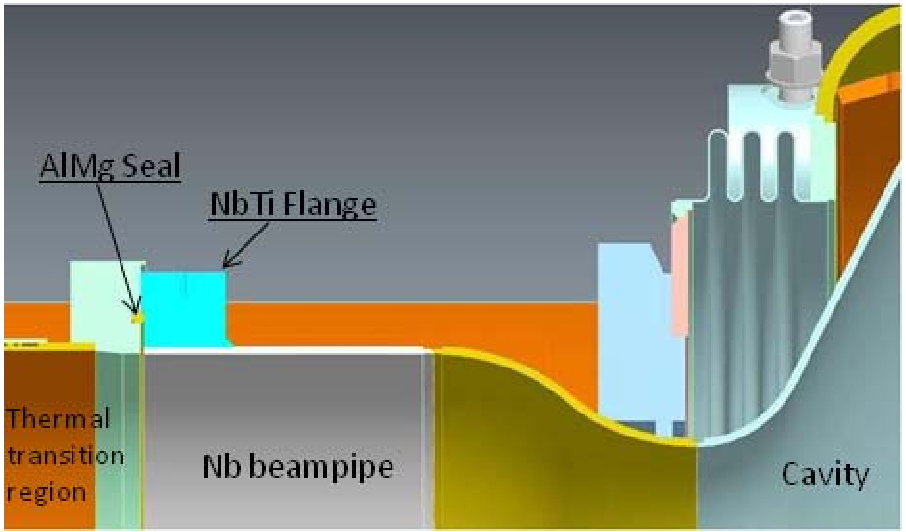



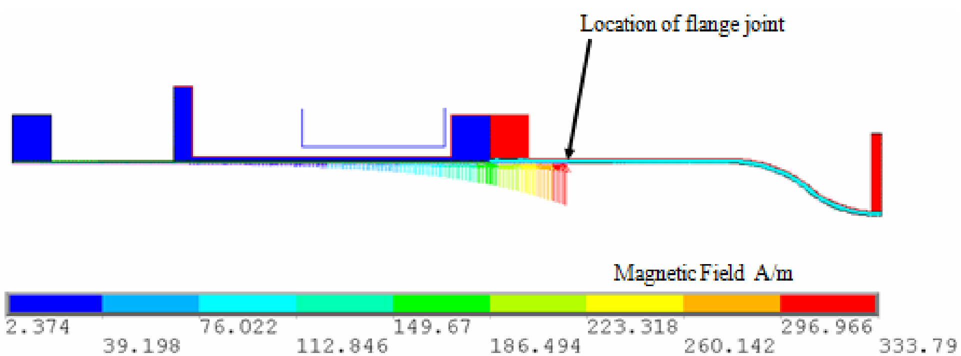



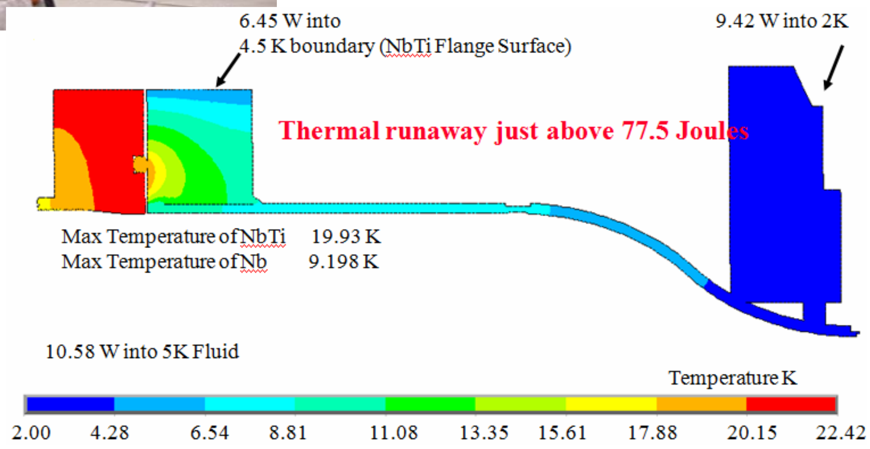

- Room-temperature ferrite HOM damper. HOM measurement at both room temperature and low temperature showed extremely good damping.
- 50 kW CW fundamental power coupler of the SNS type, water cooling on the RF window, no cooling for the inner conductor.
- First horizontal test was in March of 2009. Several more tests were carried out after that ($Q_0 \sim 10^{10}$ at 18 MV/m).
- Mechanical Tuner with 100 kHz tuning range, piezo provides 9 kHz fast tuning.

# 5-cell cavity: cold test performance

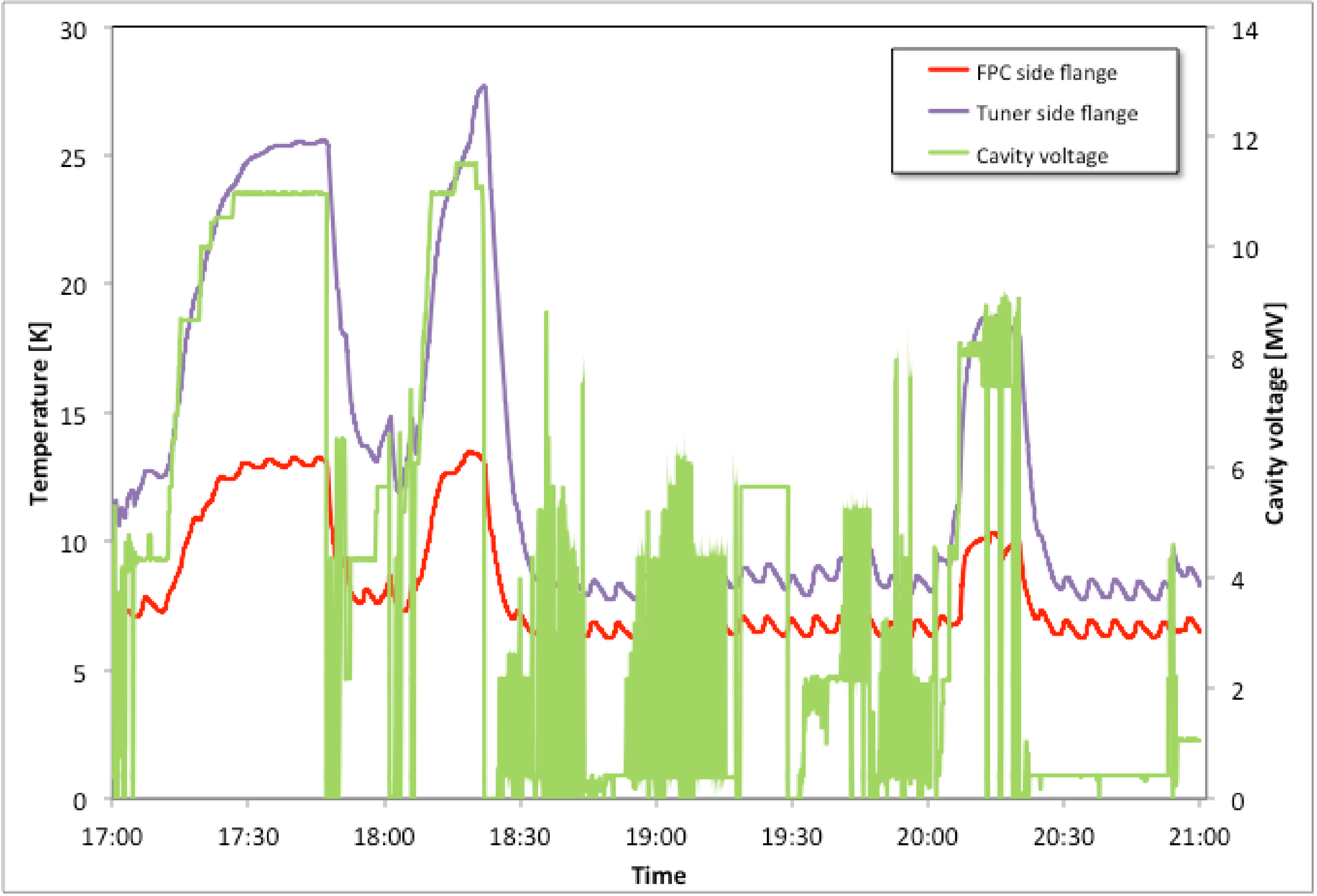
- For ERL prototype, it is necessary to have 15 MV in the cavity, due to beam-dynamics constraints in the beam combiner.
- However, 11.5 MV/m was observed to be the threshold in CW mode, due to the $AlMg_3$ seal located between the NbTi and stainless steel flanges on the beam pipe (on FPC side).
- Quasi-CW operation mode: Test showed that the cavity can safely (thermal stability) run at 18 MV/m with a 6.25% duty factor.



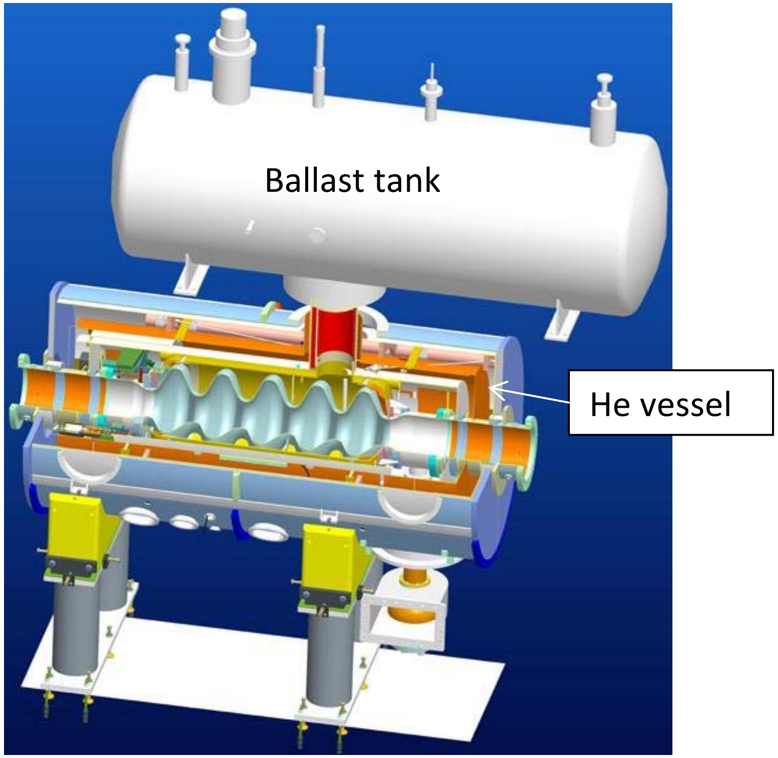



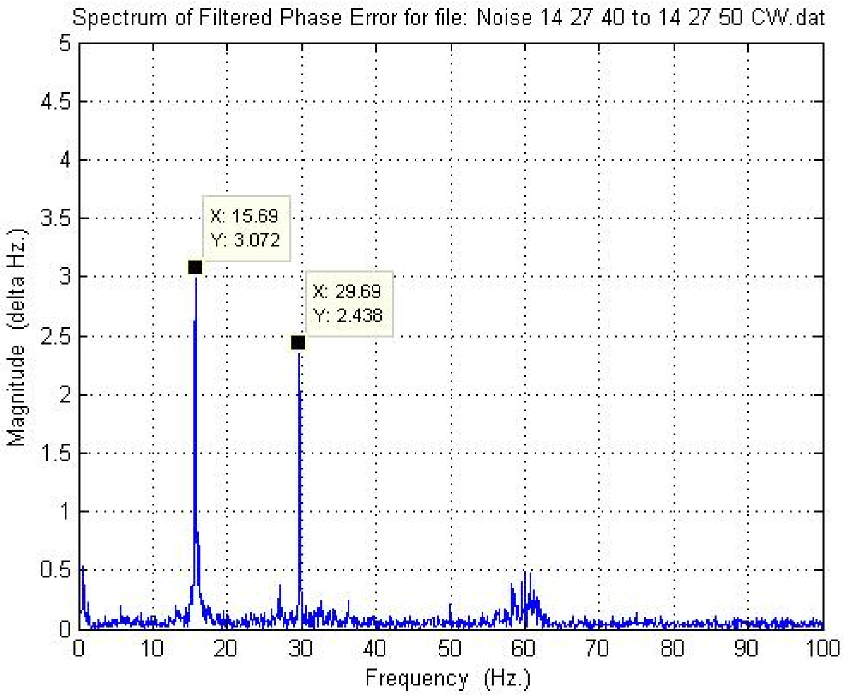



# Cavity voltage and flange temperatures



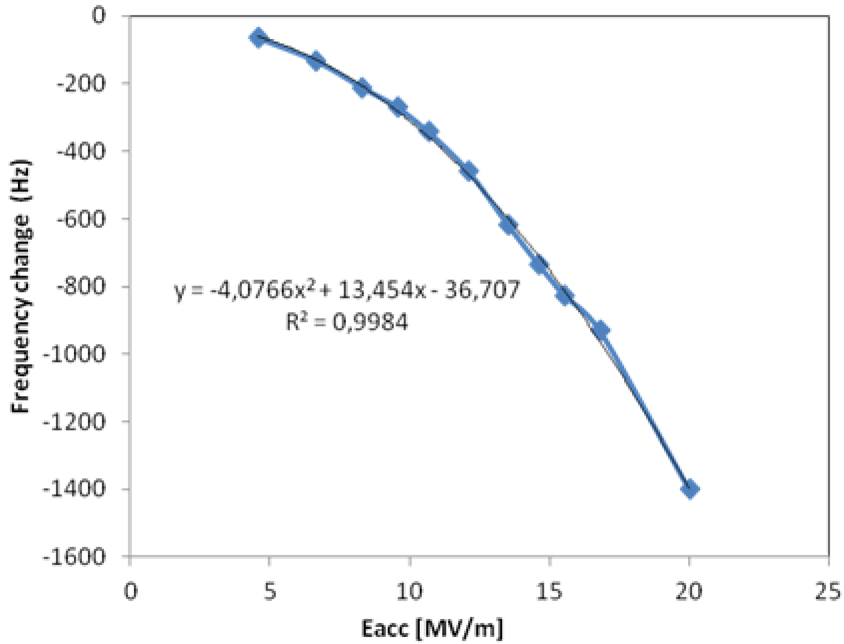
# 5-cell cavity: Microphonics



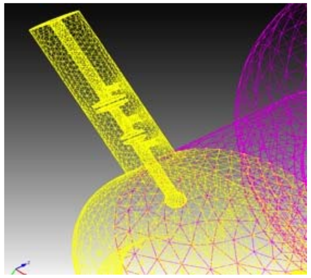

- The '30 Hz' noise originates from the mechanical vibration of the 2 K pump.
- The '16 Hz' microphonics noise was found to shift toward higher frequencies when the LHe level varies from top to bottom of the tube connecting the ballast tank to the cavity helium vessel. When its frequency reaches 30 Hz, there is a strong resonant excitation with a magnitude increase by more than a factor of five.
- This microphonics spectrum line is associated with an acoustical resonance in this line.
- The frequency detuning due to microphonics is comparable to the cavity bandwidth. A three stub tuner has been added to get better control of cavity in the further test. Also, a special feedback utilizing the piezo tuner is under development.

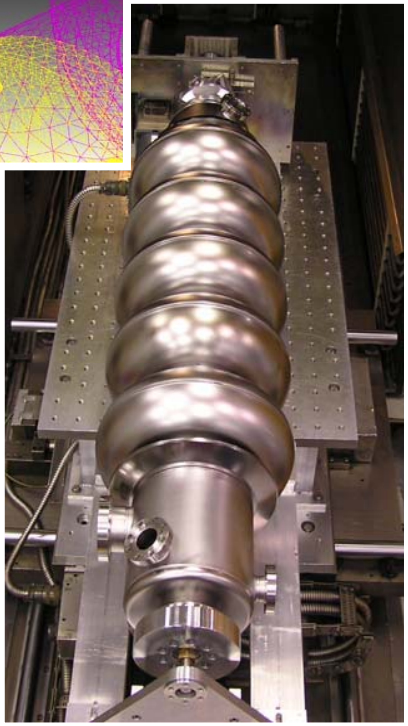
# 5-cell cavity: Lorentz force detuning & field stability



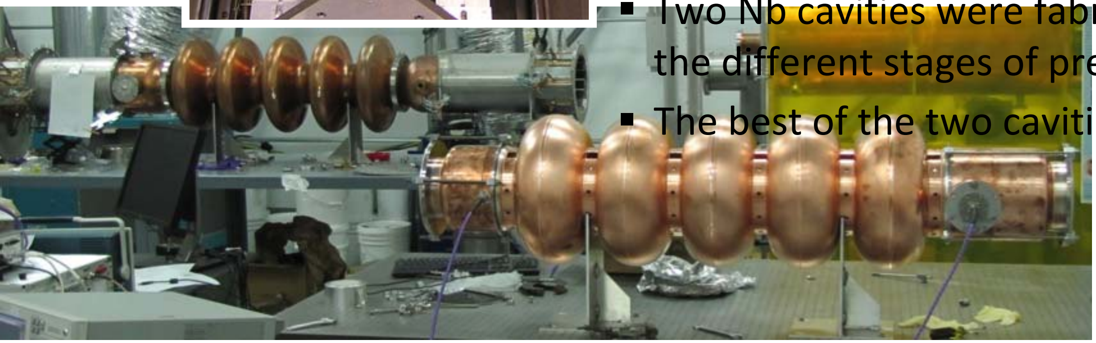

- The Lorentz force detuning factor is measured to be 4 Hz/(MV/m)$^2$.
- Overall, the field stability at 11 MV/m is:
  - o peak-to-peak $\Delta A/A = 1.5\times10^{-3}$, or r.m.s. $\Delta A/A = 2.56\times10^{-4}$;
  - o peak-to-peak $\Delta\phi = 0.43°$ or rms $\Delta\phi = 0.072°$.

# BNL-3 cavity for eRHIC and other projects

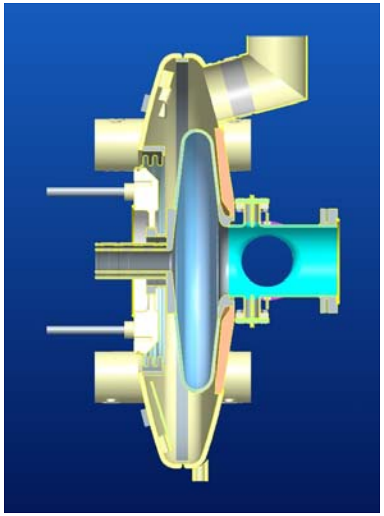


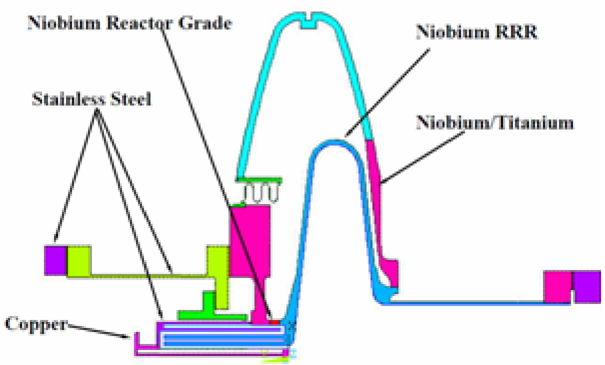


- BNL3 is a 5-cell SRF cavity designed for high-current applications such as eRHIC. eRHIC will have three ERLs based on this cavity. Also, it will be used in the CeC PoP experiment.
- Three antenna-type couplers will be attached to large diameter beam pipes at each end of the cavity and will provide strong HOM damping while maintaining good fill factor for the linac.
- A copper prototype has been fabricated by AES and is used to study HOM damping.
- Two Nb cavities were fabricated: at AES and at Niowave. Both are at the different stages of preparation for vertical testing at our VTF.
- The best of the two cavities will be used at CeC PoP.



# 704 MHz SRF gun system

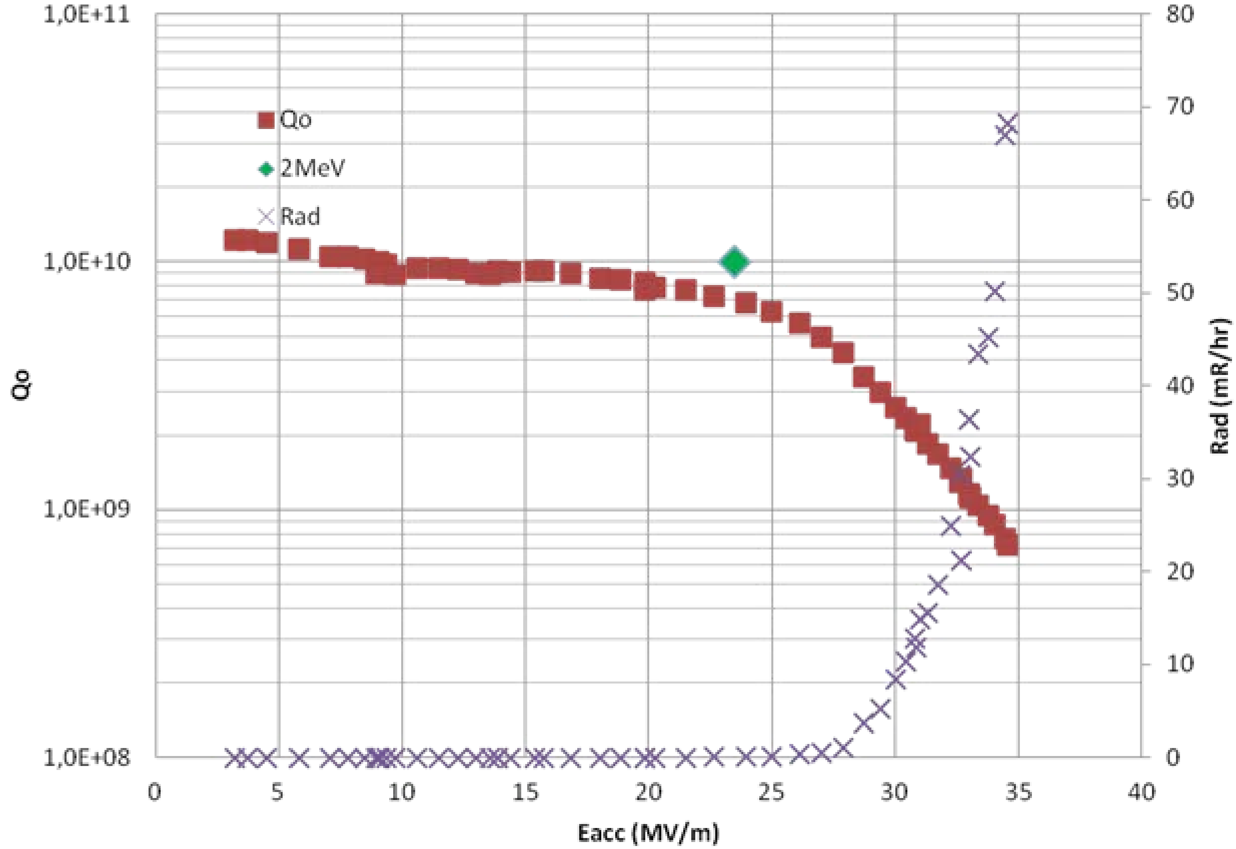





| | |
|---|---|
| RF frequency | 703.5 MHz |
| Cavity active length | 8.5 cm (0.4 cell) |
| Maximum energy gain | 2.5 MeV |
| Maximum field at the cathode | 33.4 MV/m |
| $E_{acc}$ at 2.5 MV | 29.4 MV/m |
| $e^-$ emission RF phase at 2.5 MV | 33.4° |
| Energy gain at 500 mA | 2.0 MeV |
| $e^-$ emission RF phase at 2.0 MV | 29.9° |
| Beam power at 500 mA | 1 MW |
| $R/Q$ | 96.2 Ohm |
| Cavity geometry factor | 112.7 Ohm |
| Cavity $Q_0$ at 2 K | $3\times10^{10}$ |
| 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 |

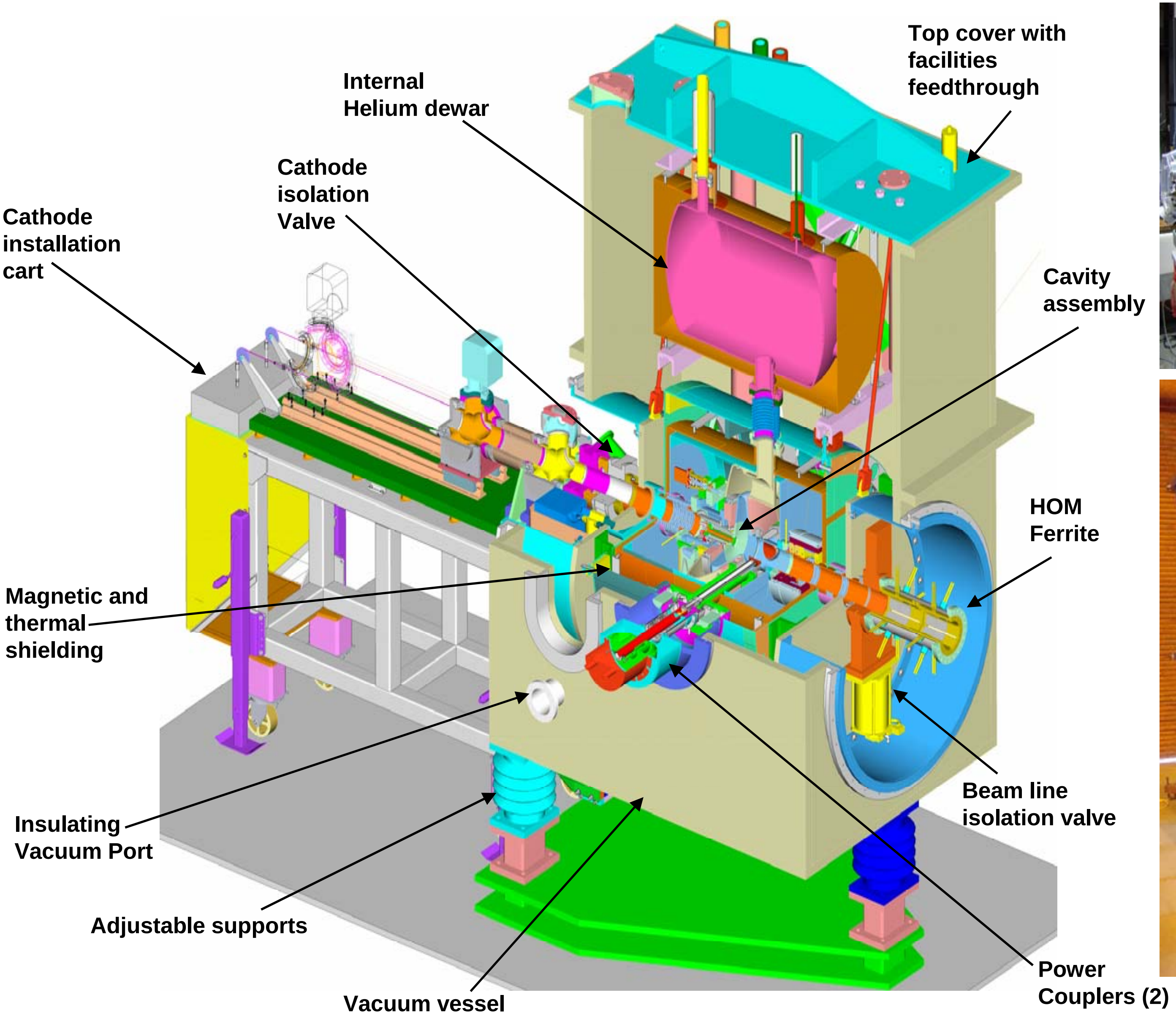
- 704 MHz ½-cell SRF cavity (2.5 MV): Vertical test at JLab in 2009; Cryomodule assembly at BNL.
- Multi-alkali ($CsK_2Sb$) cathode transport and insertion mechanism.
- Room temperature HOM damper: Enlarged beamtube ceramic window + RT ferrite HOM damper.
- Two high power (500 kW) FPCs to transmit 1 MW CW power to the beam conditioned at BNL in 2012.
- Frequency Tuner: 1 MHz range and 1 Hz/step resolution, no piezo fast tuning.
- SRF gun commissioning started in Nov. 2012.
- Quarter wave choke-joint to support the photocathode stalk has triangular grooves for suppression of multipacting.

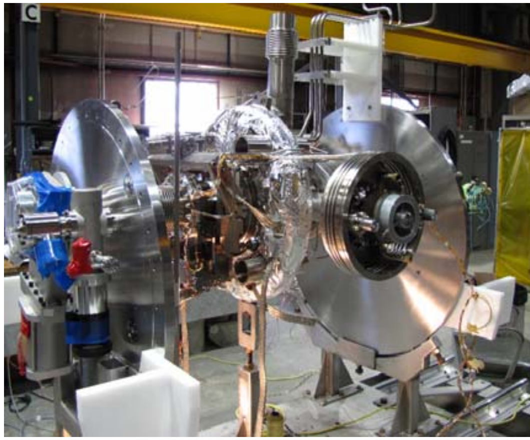
# SRF gun cavity: Vertical test



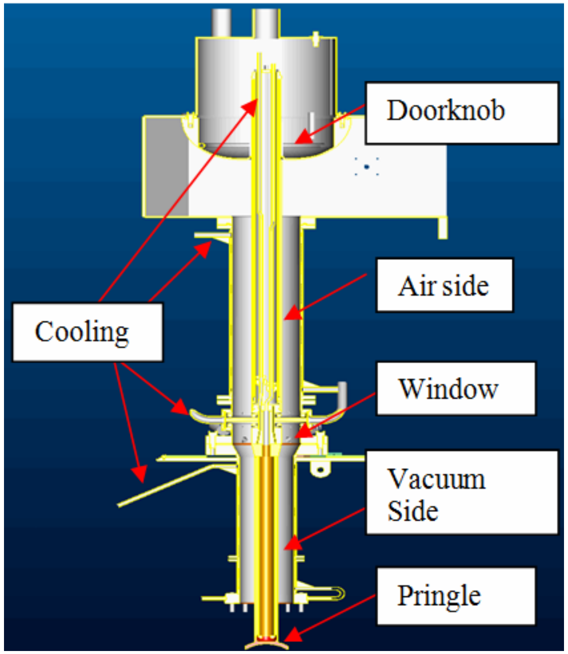

- The cavity was tested vertically at JLab.
- It reached 2 MV (23 MV/m) with $Q_0 \sim 8\times10^9$ without a Nb cathode stalk.
- There was severe mulitpacting in the triangular-grooved choke-joint area with Nb cathode.
- In the SRF gun, the cathode stalk material is copper.

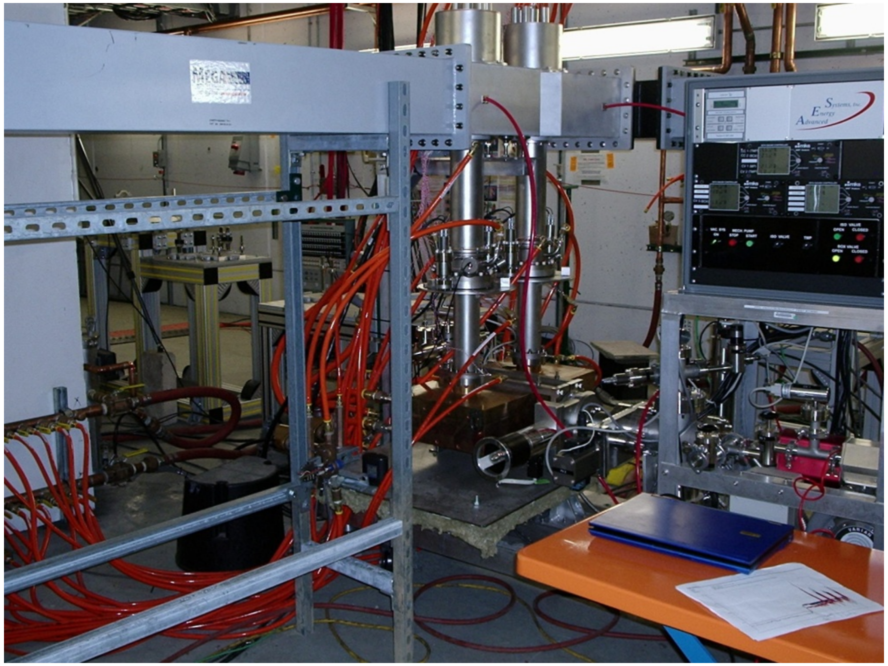
# SRF gun cryomodule



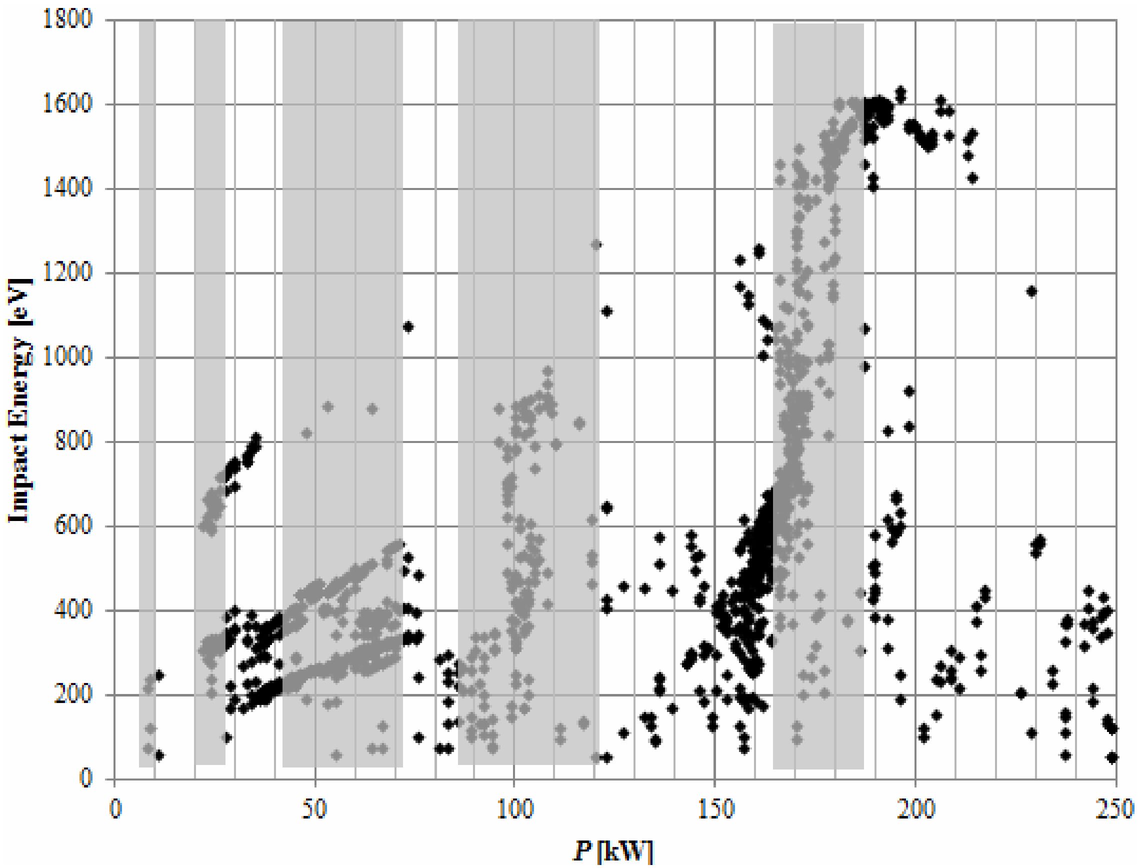
# High power fundamental power coupler

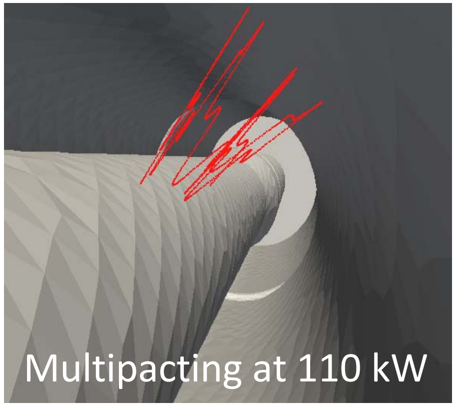


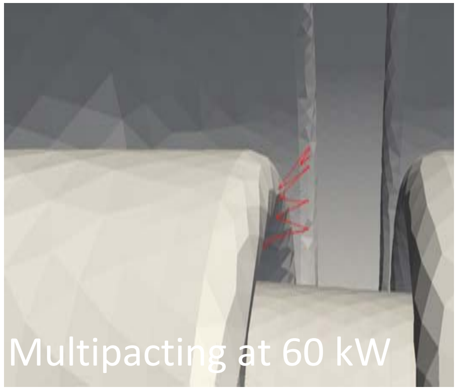



- 1 MW transmitted power was used in design simulations. Water cooling for the BeO window ensures that the temperature rise stays below 0.1°C.
- Pringle tip at the inner conductor lowers the Qext into the range between 40,000 and 70,000.
- Water cooling for the inner conductor and air side; 5 K helium gas cooling at the vacuum side outer conductor.
- Prior to installation of the FPCs, they were conditioned with 1 MW klystron. RF power was limited to 125 kW in CW mode to keep local field levels at standing wave maximum the same as they would be at 500 kW. RF power in pulse mode was up to 250 kW (limited by the klystron collector).

# Comparison of simulations and test

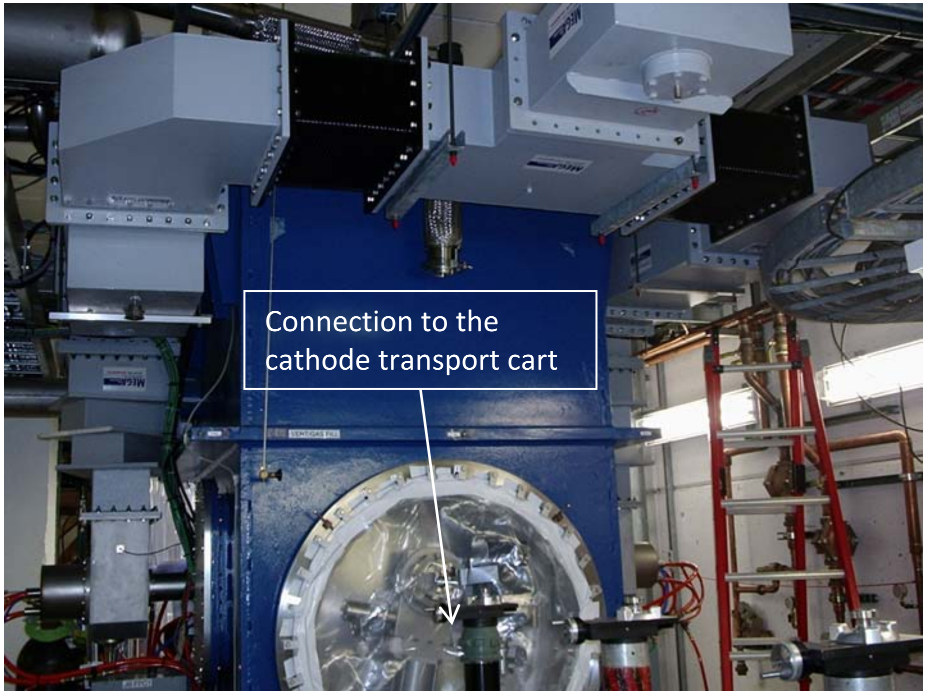



- ACE3P code is used to simulate the electron behavior trajectories, the simulations were carried out for the FPC conditioning setup.
- Simulation shows multipacting will happen at the RF power level about are 8 to 10 kW, 16 to 25 kW, 40 to 70 kW, 85 to 120 kW and about 165 to 185 kW. All these zones were observed in the experiments
- The simulation also shows that multipacting zone is not sensitive to frequency. However, the strength of multipacting changes with frequency.

# SRF gun commissioning




- Prior to assembly into the gun cryomodule, its two FPCs were conditioned off-line in standing wave mode with full reflection at variable RF phase. Maximum power was 250 kW in pulse mode (limited by klystron collector) and 125 kW in CW (administrative limit).
- The gun cryomodule was assembled last year and is installed in the ERL block house. Its 1 MW CW klystron, cryogenic system and other ancillary systems are fully operational.
- The initial commissioning of the gun without a cathode is complete (Nov. 2012 to Mar. 2013) with the gun cavity achieving 2 MV (the original design voltage) and 220 kW of RF power in CW mode. In pulsed mode, with a 0.7 ms pulse duration and 1 Hz repetition rate, the RF power was up to 400 kW.
- The SRF gun is now under commissioning with a copper cathode stalk (from Aug. 2013 to present).
- The test with a real multi-alkali cathode and beam is tentatively scheduled for Oct. - Nov. 2013.
- More details – in tomorrow’s talk.

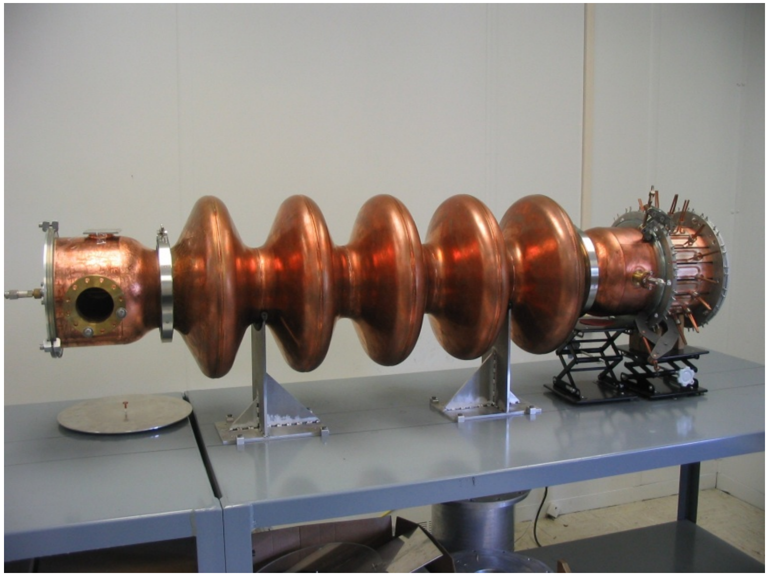
# Summary

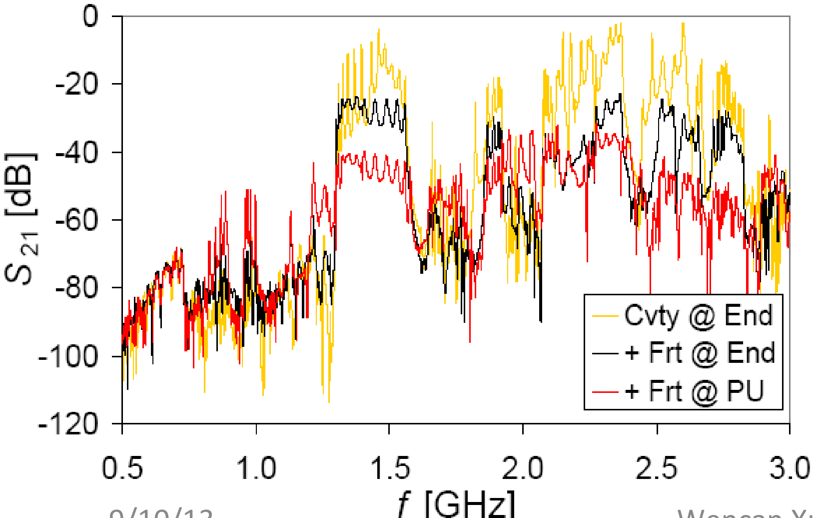
- BNL R&D ERL has been making steady progress in the past 2 years.
- The 5-cell SRF cavity has been successful re-commissioned with the new digital LLRF system and is ready for beam.
- SRF gun cryomodule was assembled and commissioned successfully w/o a cathode up to 2 MV in CW.
- SRF gun commissioning with a copper cathode is in progress
- The first beam from the SRF gun is expected in a few months.

# Backup slides

# 5-cell cavity: HOM damping at RT and 2 K

**RT measurement results**






**Ferrite damper**

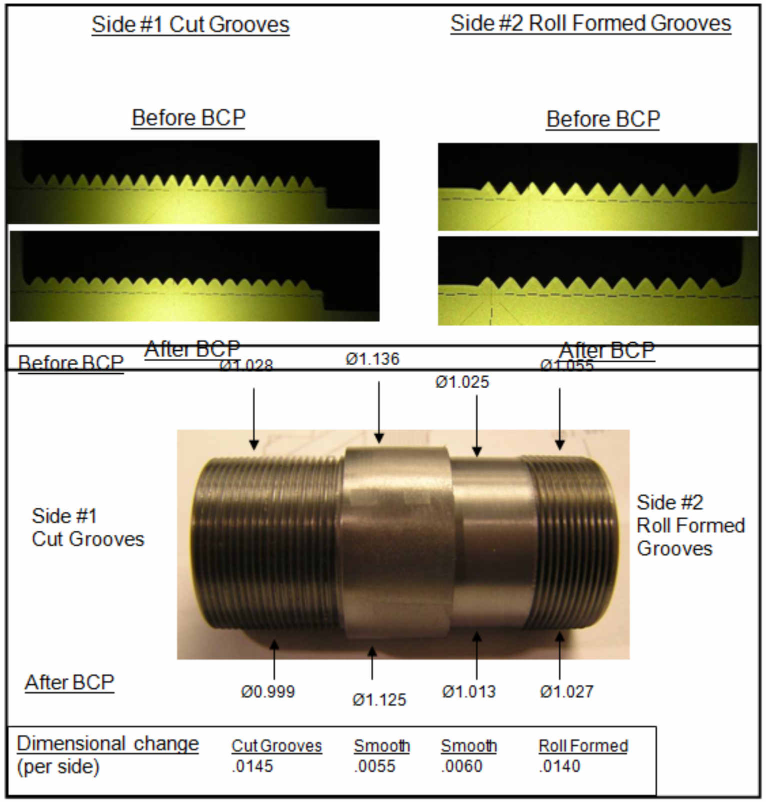
**+**

**large beam tube**

**Works!**

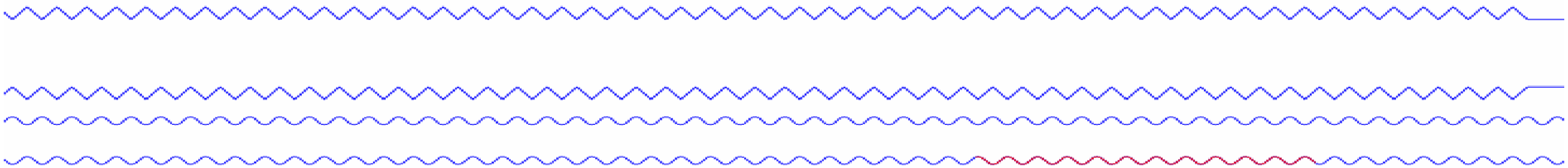
| f [GHz] | BTM 40 K Q | BTM 4 K Q | 1/14/2010 2 K Q |
|---|---|---|---|
| 0.80844 | 900 | 874 | |
| 0.82585 | 370 | 386 | |
| 0.84959 | 130 | 141 | |
| 0.88458 | | 49 | |
| 0.96001 | | 43,500 | |
| 0.96018 | 9,500 | 44,200 | 47,800 |
| 0.96639 | 3350 | 4720 | |
| 0.97829 | 830 | 730 | |
| 0.99561 | 205 | 326 | |
| 1.2233 | | 17,600 | 82,800 |
| 1.2285 | | 3738 | 4300 |
| 1.2341 | | 5,790 | 5,800 |
| 1.2374 | | 17,450 | 17,100 |
| 1.2663 | | 4,900 | 5,700 |
| 1.2797 | | 1,165 | 1,150 |
| 1.2965 | | 1,283 | |
| 1.3024 | | 3,740 | 4,450 |
| 1.3116 | | 2,915 | |
| 1.3211 | | 5,220 | 5,660 |
| 1.3252 | | 474 | |
| 1.4694 | | 172 | |
| 1.6182 | | 280 | |
| 1.6475 | | 244 | |
| 1.6619 | | 307 | |
| 1.6770 | | 665 | |
| 1.6884 | | 860 | |
| 1.6977 | | 850 | |
| 1.7044 | | 1,800 | |
| 1.7297 | | 16,300 | 16,400 |
| 1.8347 | | 1,640 | |
| 1.8384 | | 1,250 | |
| 1.8690 | | 540 | |
| 1.8909 | | 2,430 | |
| 1.8942 | | 4,940 | |
| 1.8949 | | 10,860 | 12,250 |
| 1.8959 | | 2,970 | |
| 1.8976 | | 1,830 | |
| 1.9244 | | 652 | |
| 1.9428 | | 472 | |
| 2.0184 | | 235 | |
| 2.0560 | | 202 | |
| 2.1015 | | 5,550 | 6060 |
| 2.1181 | | 902 | |
| 2.1238 | | 1,450 | |
| 2.2690 | | 250 | |
| 2.2551 | | 3,476 | |
| 2.2675 | | 10,000 | |

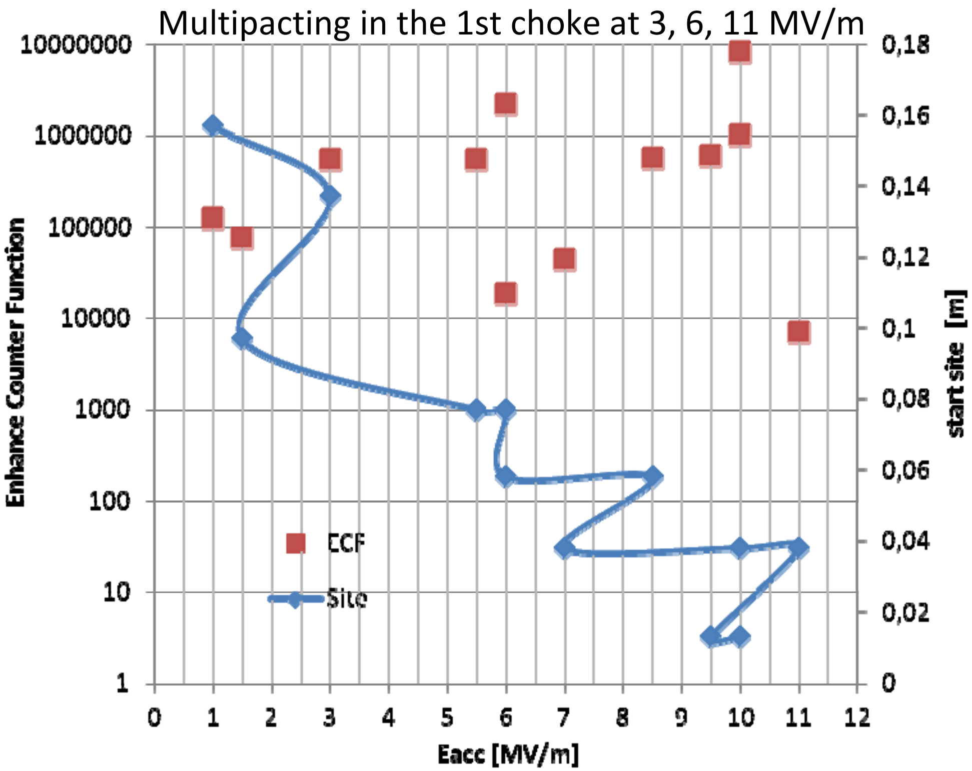
# Reason for multipacting

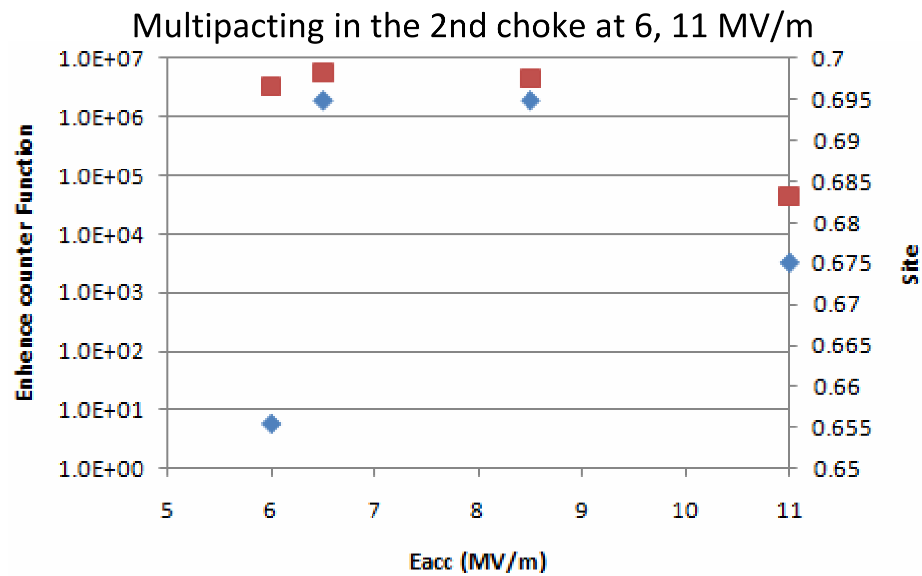



- BCP etching distorts the groove geometry: the valleys became rounded.
- Simulations with rounded grooves (0.2 mm rounding radius) found MP barriers at 3 MV/m, 6 MV/m, and 11 MV/m.
- Studies indicate that roll formed grooves sustain BCP better than cut grooves.
- We have devised a special experiment 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 zones



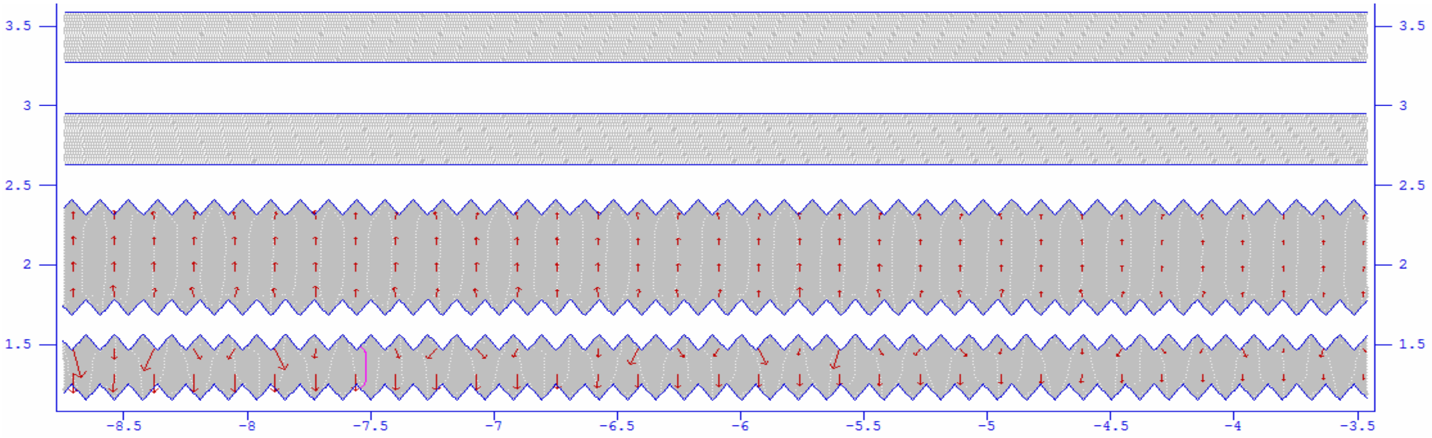


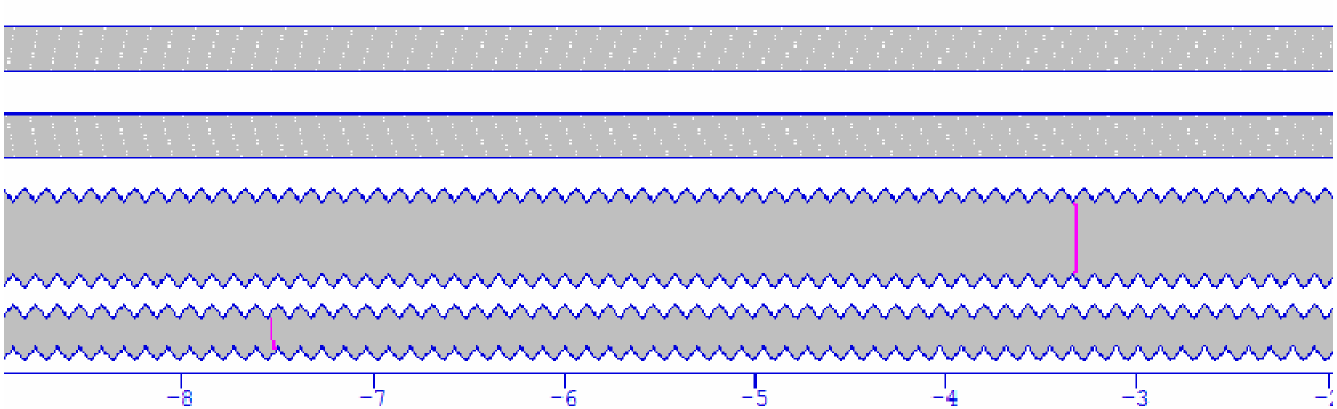

The higher the gradient, the closer location of multipacting to the cathode surface, which is reasonable as the electric field is stronger when it is further from the cathode surface.

# Simulation results

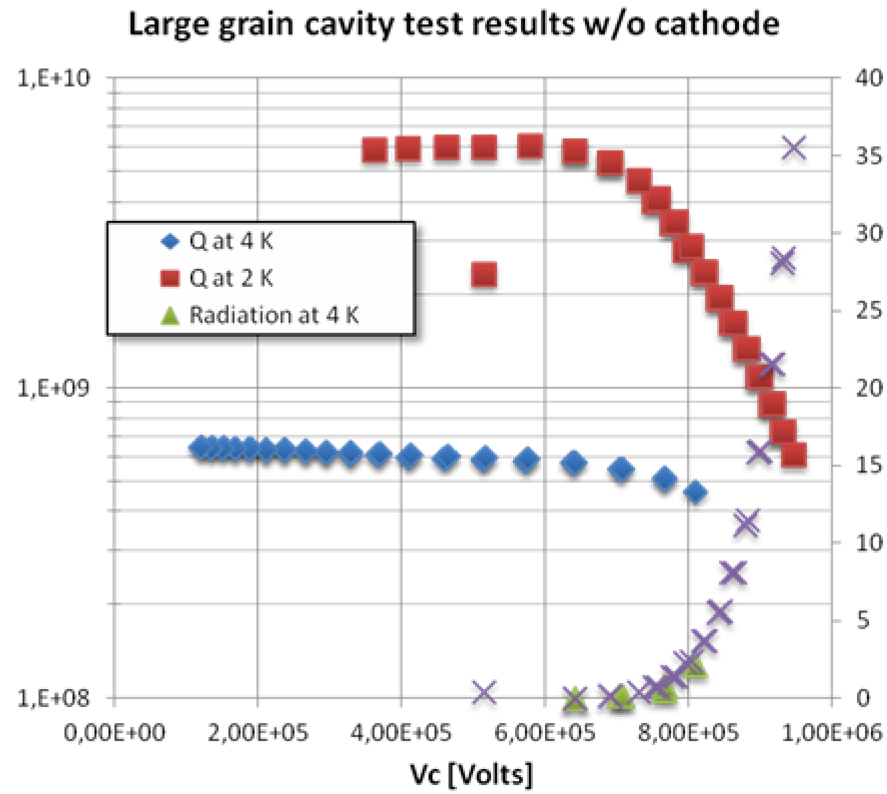
- Case 1: Ideal triangular groove → No MP




- Case 2: Ideal triangular groove + misalignment → No MP



# Large grain cavity test to study MP in the grooves




- Although there is MP in the vertical test due to the low power limit to condition the MP, we continue to assemble the cavity into the cryomodule and will use 1MW klystron to test
- In the meantime, we use a spare large grain cavity to study MP.