Superconducting Cavity Cryomodules for Heavy-Ion Accelerators @ Argonne

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On Behalf of The Physics Division-Linac Development Group

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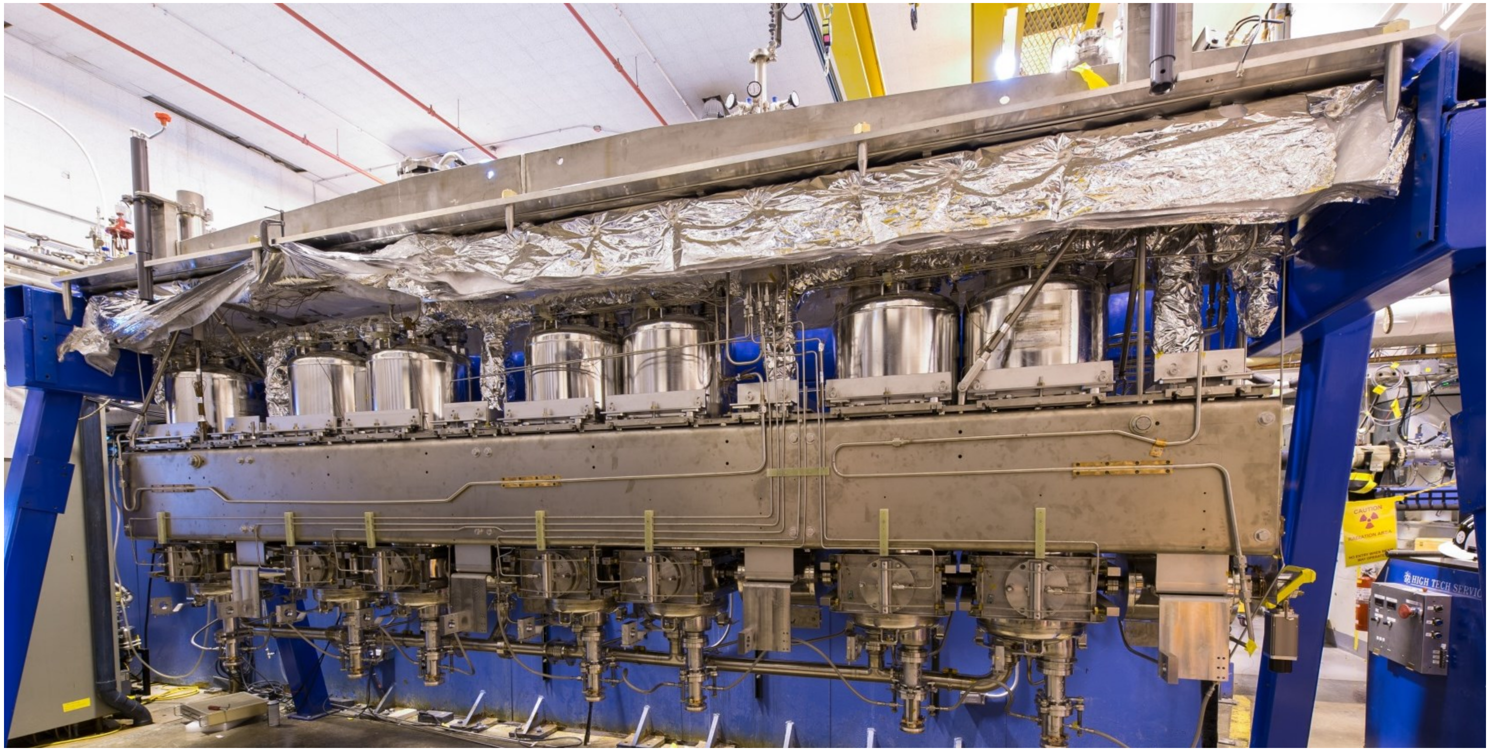
162.5 MHz HWR Cryomodule Magnetic Field Mapping

Presentation Overview

- **Recent History of Heavy-Ion Accelerator Cryomodules at Argonne.**
- **Argonne's Approach for Heavy-Ion Accelerator Cryomodules.**
  - **High Gradient.**
  - **Low Cryogenic Load.**
  - **Passive methods for improving performance.**
  - **Compact.**
  - **Reliability.**
- **Ongoing Work.**
- **Concluding Remarks.**

72.75 MHz QWR Cryomodule Leak Testing

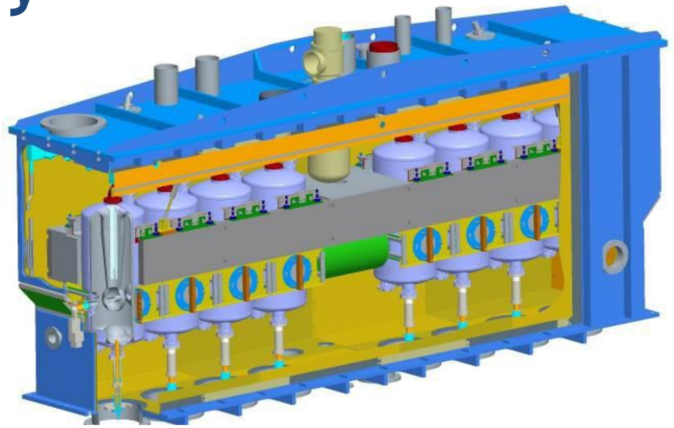
Cryomodule Design



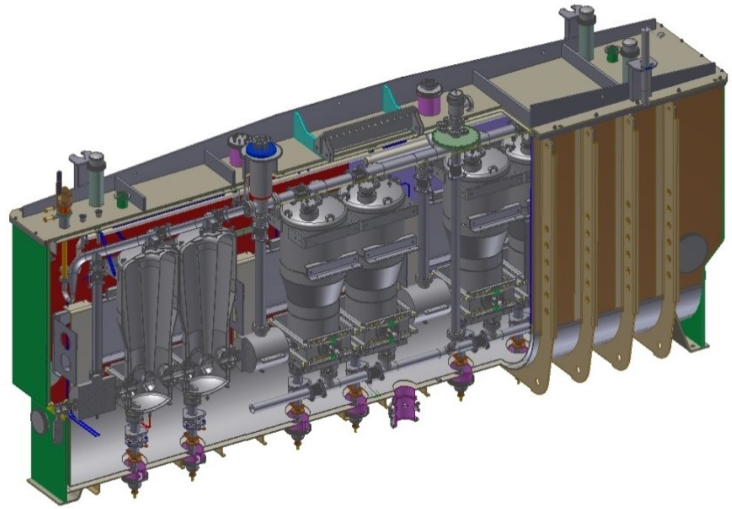
- **Enable and preserve the low-particulate assembly of beam-line components.**
  - **Separate RF cavity and Insulating vacuum systems.**
- **Long cryomodule with high-performance components**
  - **Maximize real-estate gradient.**
  - **Maximize operational reliability.**
  - **Minimize cryogenic loads: static and dynamic.**
- **Compliance with U.S. DOE Pressure Systems Safety Requirements = ASME codes.**

Recent Argonne Cryomodule History

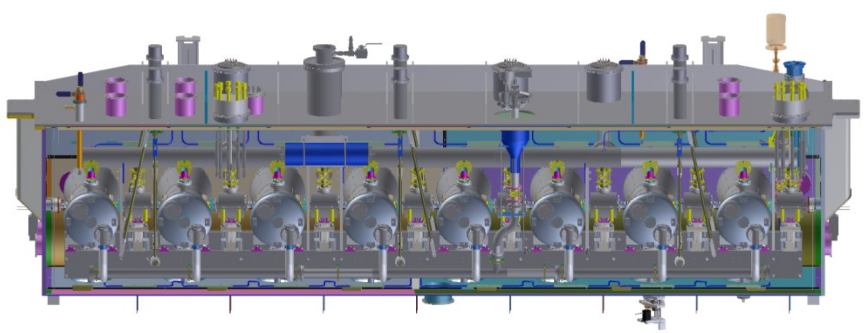
2009
4.5K 7x β = 0.15 QWR and 1x Solenoid
14.5 MV, limited by VCX fast tuners
(21.1 MV would be limit if VCX did not limit cavity performance)
4.6 m long x 2.6 m high x 1.1 m wide



2014
4.5K 7x β = 0.077 QWR and 4x Solenoid
>17.5 MV
5.2 m long x 2.9 m high x 1.1 m wide
Highly optimized cavity design.



On-Going
2K 8x β = 0.11 HWR and 8x Solenoid
>17.5 MV
6.2 m long x 2.2 m high x 2.2 m wide

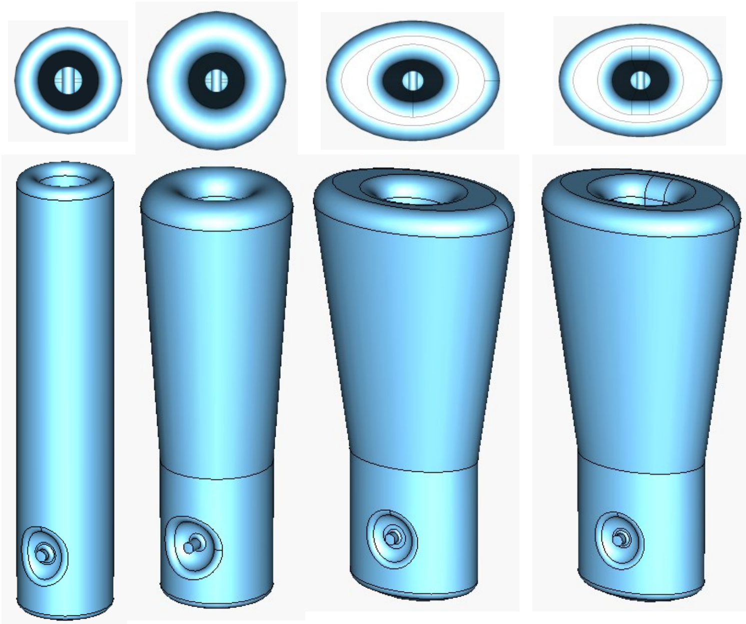


Optimized Components

Optimization of multi-dimensional systems.

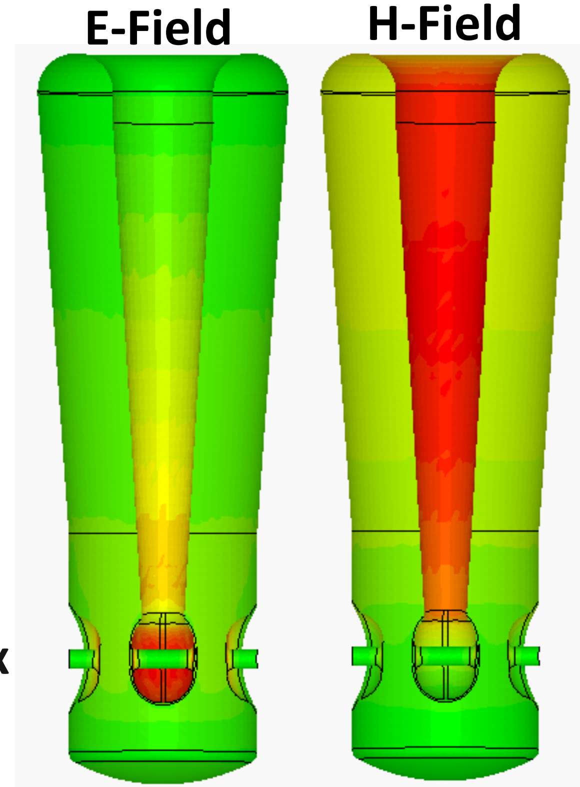
- **Cavities:**
  - RF Performance.
  - Fabrication.
  - Polishing.
  - Cleaning.
  - Assembly.
  - Compliance with relevant safety standards.
- **Solenoids:**
  - Integrate Focusing Solenoids with Return and Steering Coils.
  - Maximize real-estate gradient via magnetic integration.
  - Superconducting and operating at the same temperature as the cavities.
  - No additional magnetic shielding for the solenoids/cavities.
- **Cryomodules:**
  - Long, 4-7 meters.
  - Not much larger than the accelerator components require.

Cavity Optimization - RF Performance

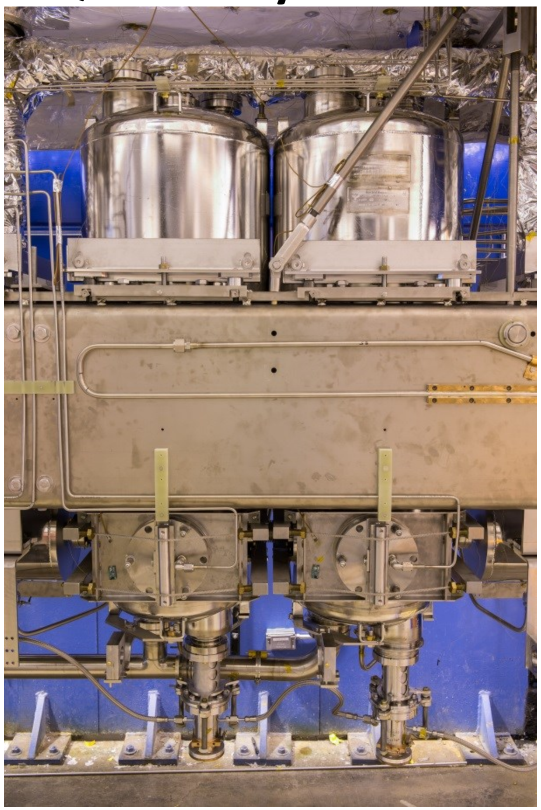


Simple → Complex

Lower Peak Fields



QWR & Cryomodule

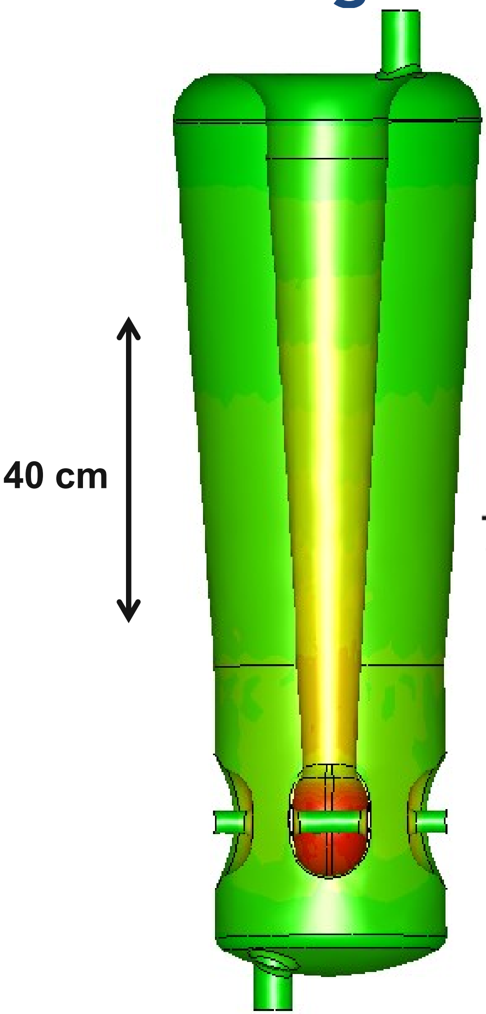


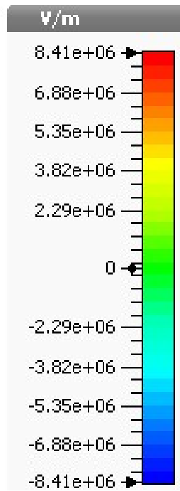
Parameter	Straight Cylinders	Conical	Units
E_{peak}/E_{acc}	5.8	5.0	
B_{peak}/E_{acc}	95	71	Oe/(Mv/m)
$G = R_s \cdot Q$	16.5	25.9	Ω
R_{sh}/Q	509	568	Ω

Use free space which already exists.

Gain the voltage of ~2 cavities without increasing cryomodule length.

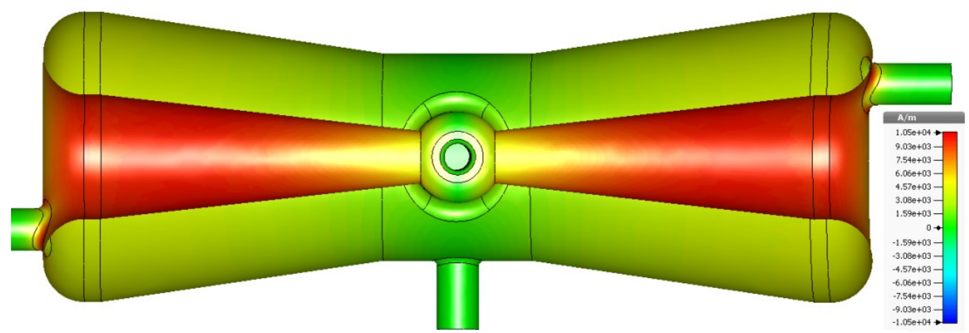
Electromagnetic Design





72.75 MHz, β = 0.077, QWR Surface $\vec{E}$
QWR = Quarter-Wave Resonator

Cavity Type	QWR	HWR
Freq. (MHz)	72.75	162.5
β	0.077	0.112
l_{eff} (cm, βλ)	31.75	20.68
E_{pk}/E_{acc}	5.2	4.7
B_{pk}/E_{acc} (mT/(MV/m))	7.6	5.0
QR_s (Ω)	26.4	48.1
R_{sh}/Q (Ω)	587	272

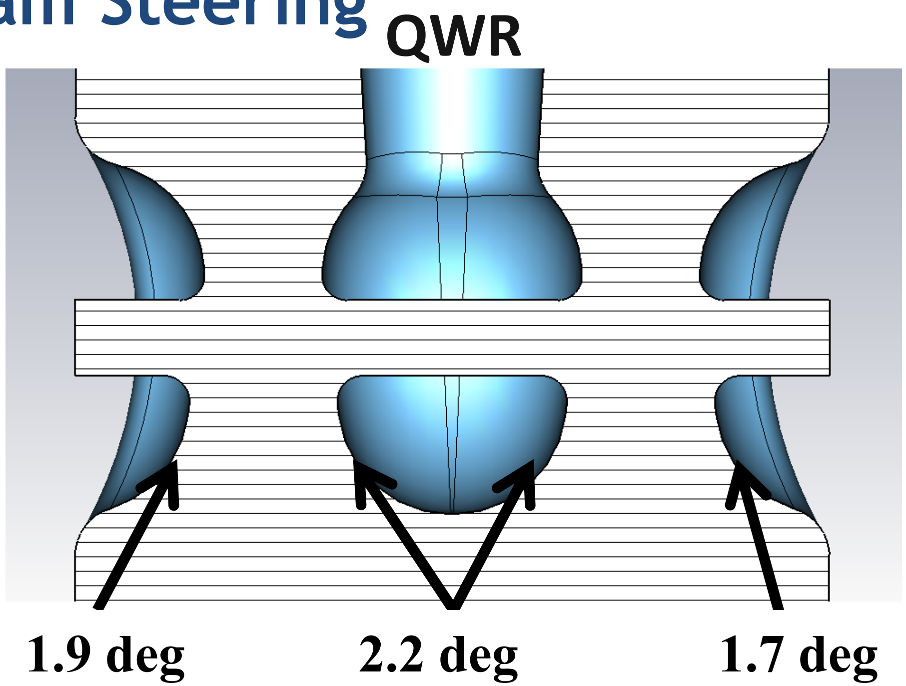


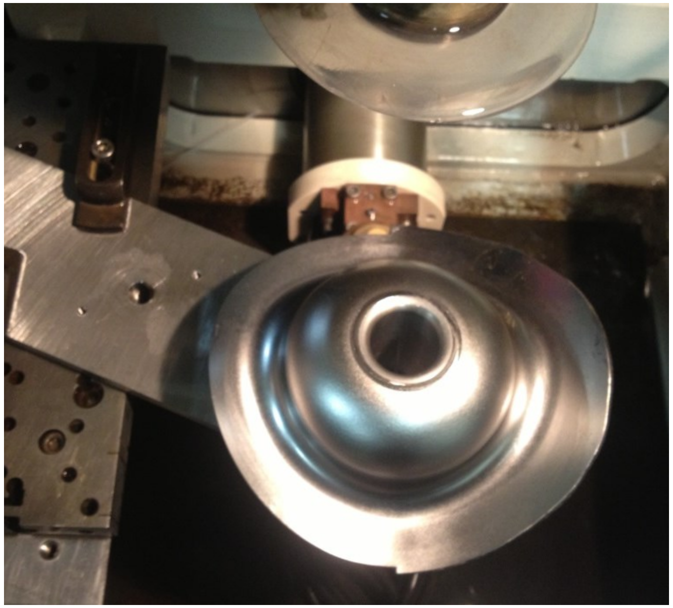
162.5 MHz, β = 0.11, HWR Surface $\vec{B}$
HWR = Half-Wave Resonator

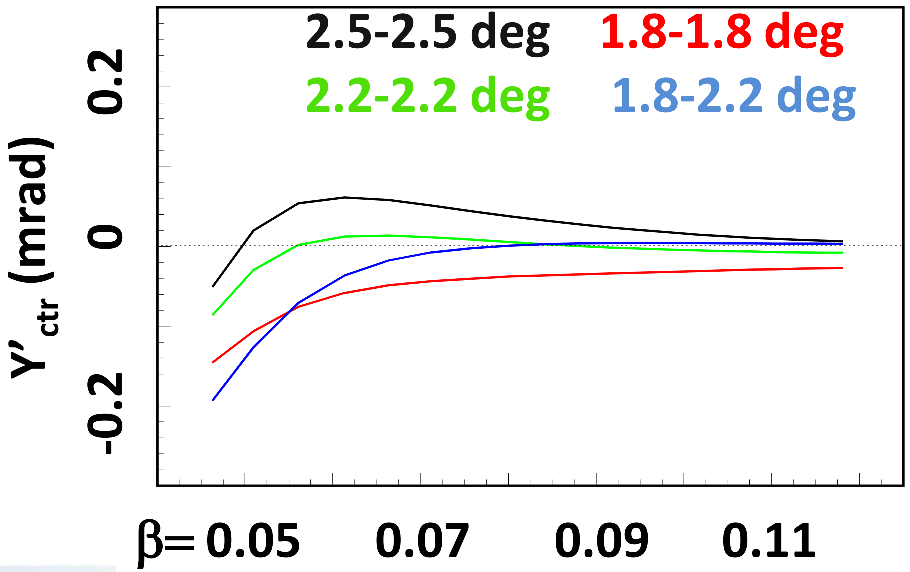
- **Tapered inner/outer conductors increase the performance of these cavities relative to using straight cylinders by 25-35% for B_{peak}/E_{acc}.**
- **First tapered QWRs designed, built, and tested in the world.**
- **RF Design does not stop here.**

Cavity Performance - QWR Beam Steering

- **QWR = Beam Steering due to residual magnetic field.**
- **Leads to emittance growth and subsequent beam loss.**
- **Corrected by deflecting E-field from tilting drift tube faces.**
- **Adding tilt to forming dies.**
- **No Additional Part Cost.**

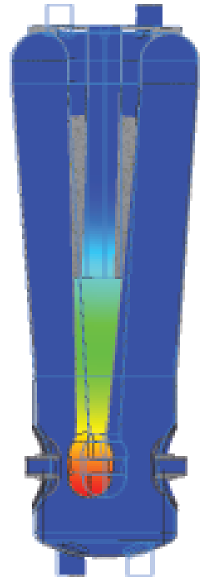


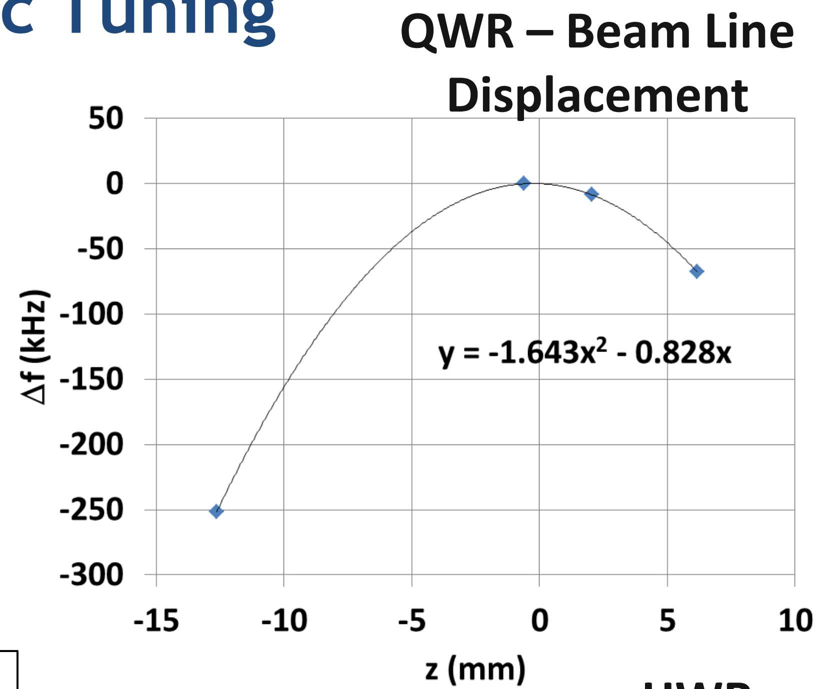


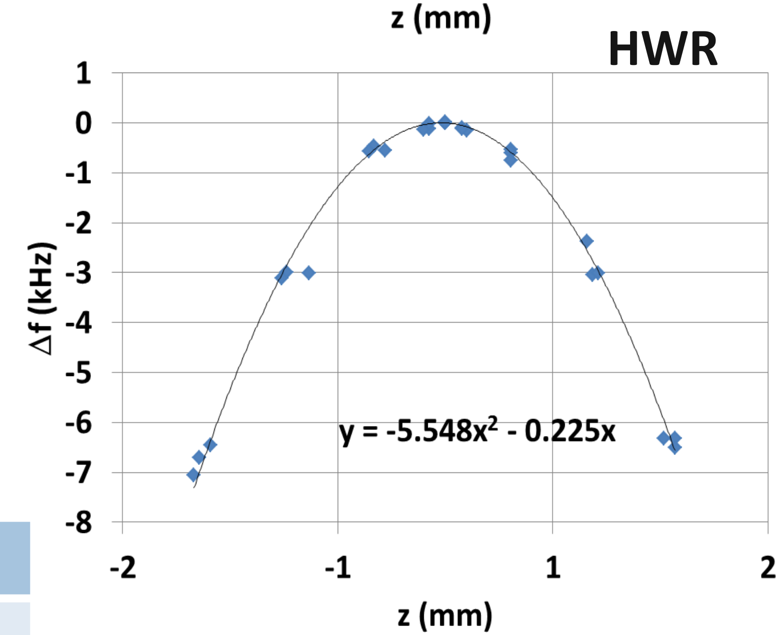


Cavity Performance - Microphonic Tuning

- Electromagnetically center the inner conductor.
  - Reduce microphonic frequency error due to pendulum mode of inner conductor.
- Bend inner conductor to maximize frequency = Passive, low risk and simple to implement.







(J.R. Delayen 1987)

QWR f_0 vs. Displacement

$$f_0(z) = -1.643 \cdot z^2 - 0.828 \cdot z$$

Change in Frequency with Displacement

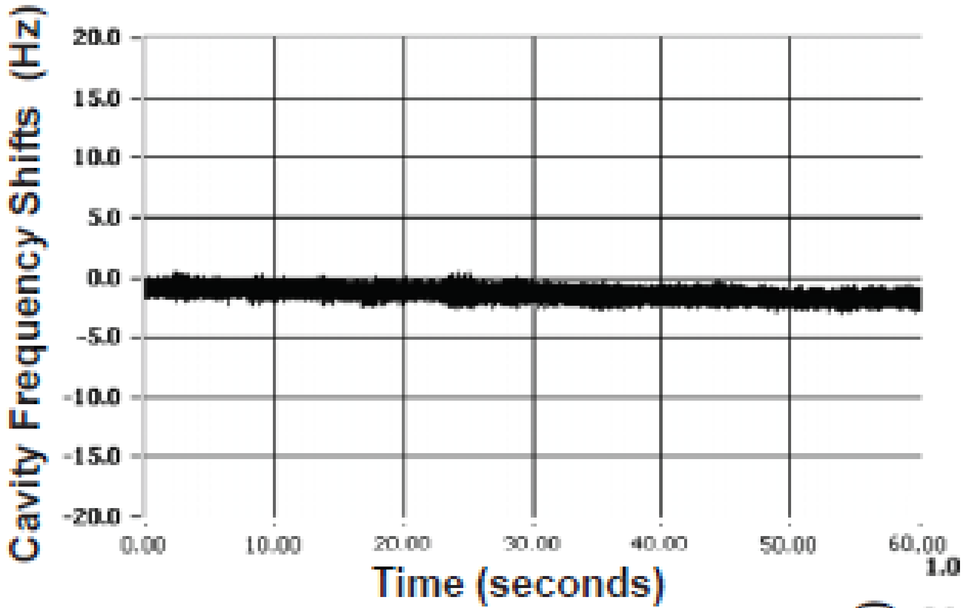
$$\frac{df_0(z)}{dz} = -3.286 \cdot z - 0.828$$

$$\left.\frac{df_0(z)}{dz}\right|_{z=0} = -0.252\, mm$$

For a 1μm$_{p\text{-}p}$ pendulum vibration.

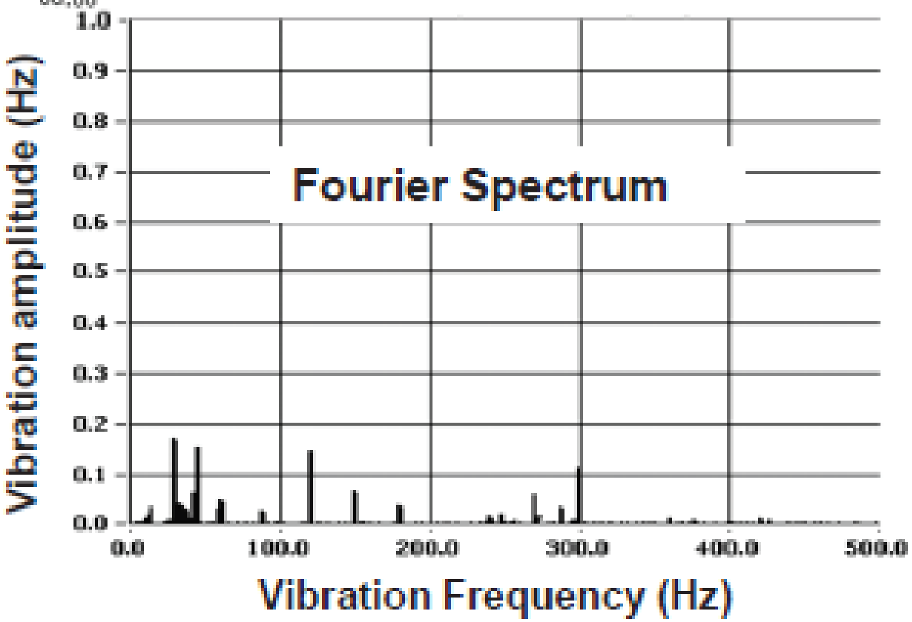
QWR In. Cond. Disp. (mm)	0	0.5
$\Delta f_{p\text{-}p}$ (Hz)	0	3

Cavity Testing – QWR Off-Line Microphonics



After centering observed microphonics span only 5% of planned fast tuning window

Total microphonics from pendulum mode (~50 Hz mechanical frequency) is small

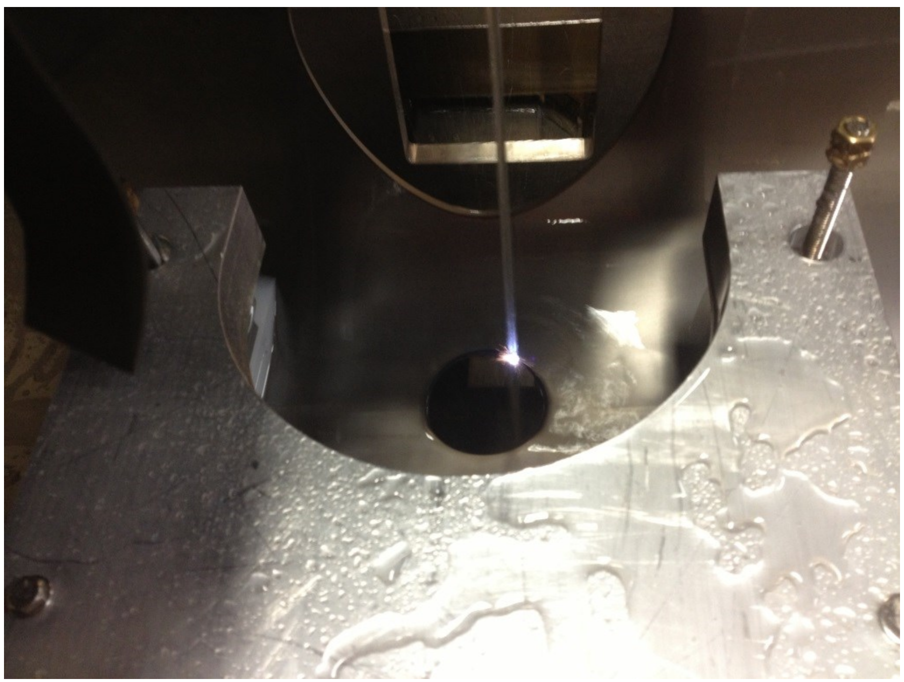


M. Kelly et al., SRF13, Paris, France.

Cavity Fabrication

- Electrostatic Discharge Machining (EDM) = No risk of inclusions.
- Electron Beam Welding in High Field Regions = Keyhole = Less Heat.
- Cavity beam bore cut after all fabrication is finished, including helium jacketing.
- Cavity electropolishing after all fabrication is finished, including helium jacketing and beam bore cut.
- Hydrogen degassing @ FNAL = Reduce Q slope.

EDM of Port Bore

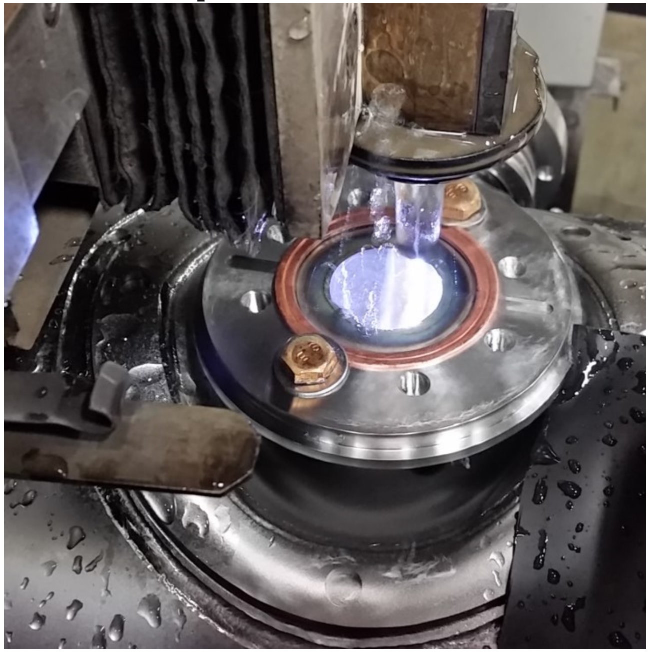


EDM Toroid Trim

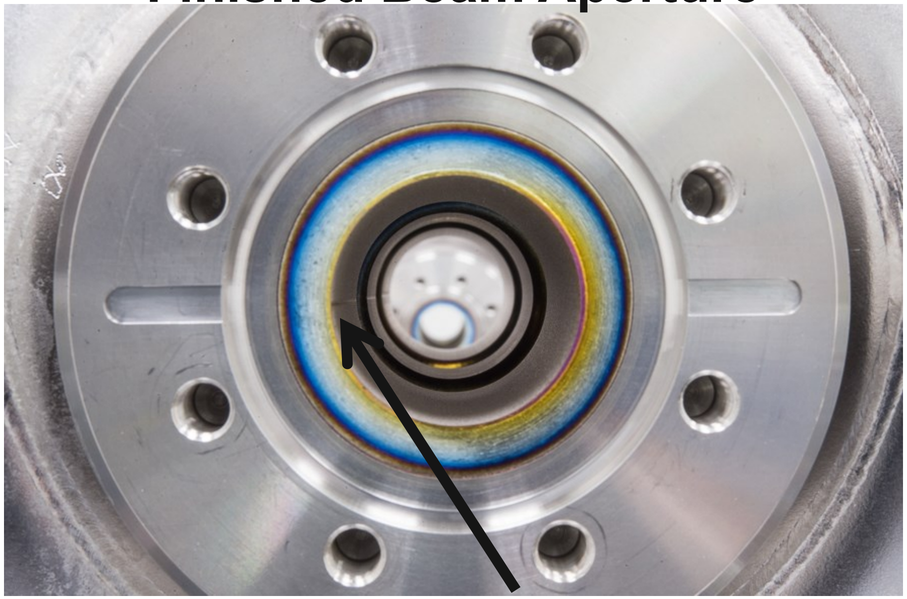
Beam Aperture Alignment

- Design beam aperture = ϕ33.0 mm HWR.
- Wire-EDM bore of the beam aperture gives very accurate results:
  - Aperture diameter tolerance ±0.04 mm.
  - Aperture Pitch and Yaw tolerance <0.1^{0}.
- Wire-EDM is done prior to helium jacketing. This is expected to perturb the Pitch and Yaw alignment by <0.1^{0}.

Beam Aperture Wire-EDM



Finished Beam Aperture



Wire Start/Stop <0.015 mm deep

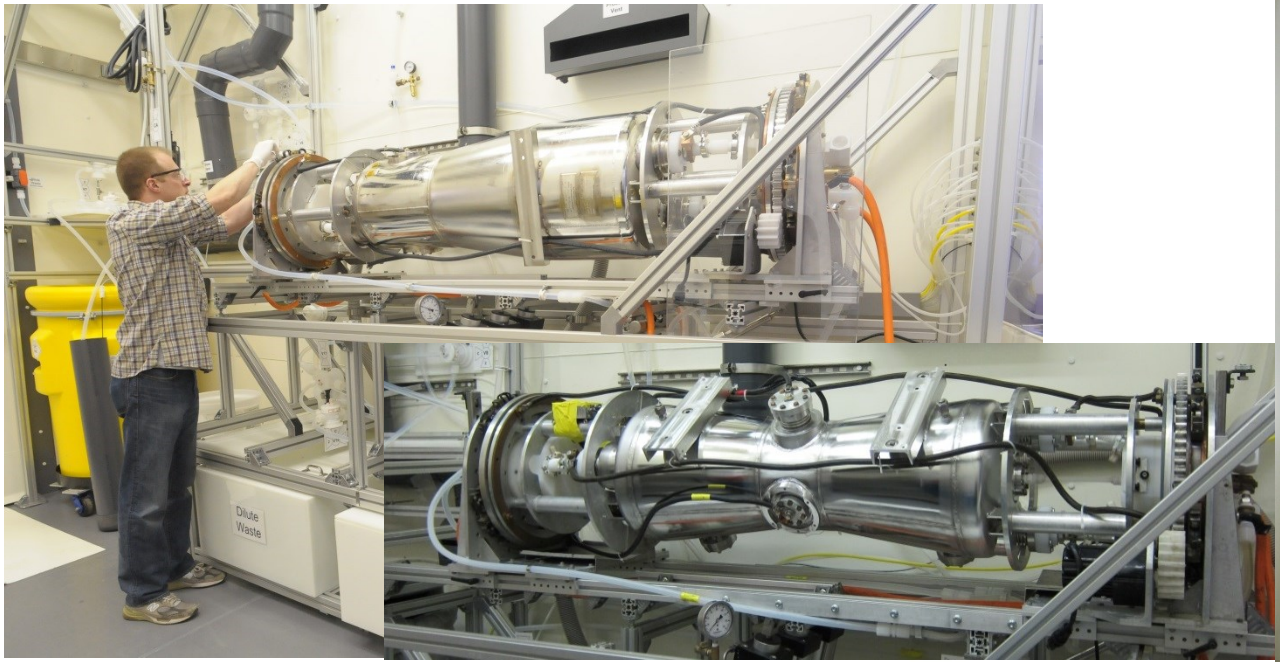
Cut-Away View of Cavity Model

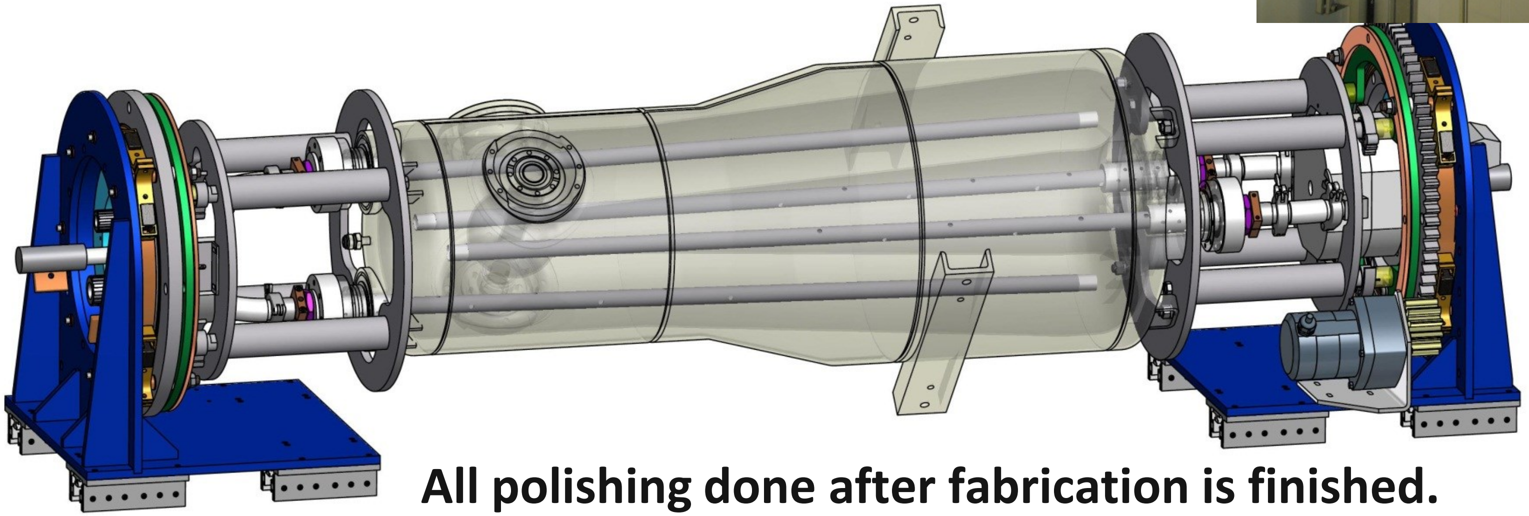
Beam Aperture

40 cm

Cavity Polishing and Cleaning

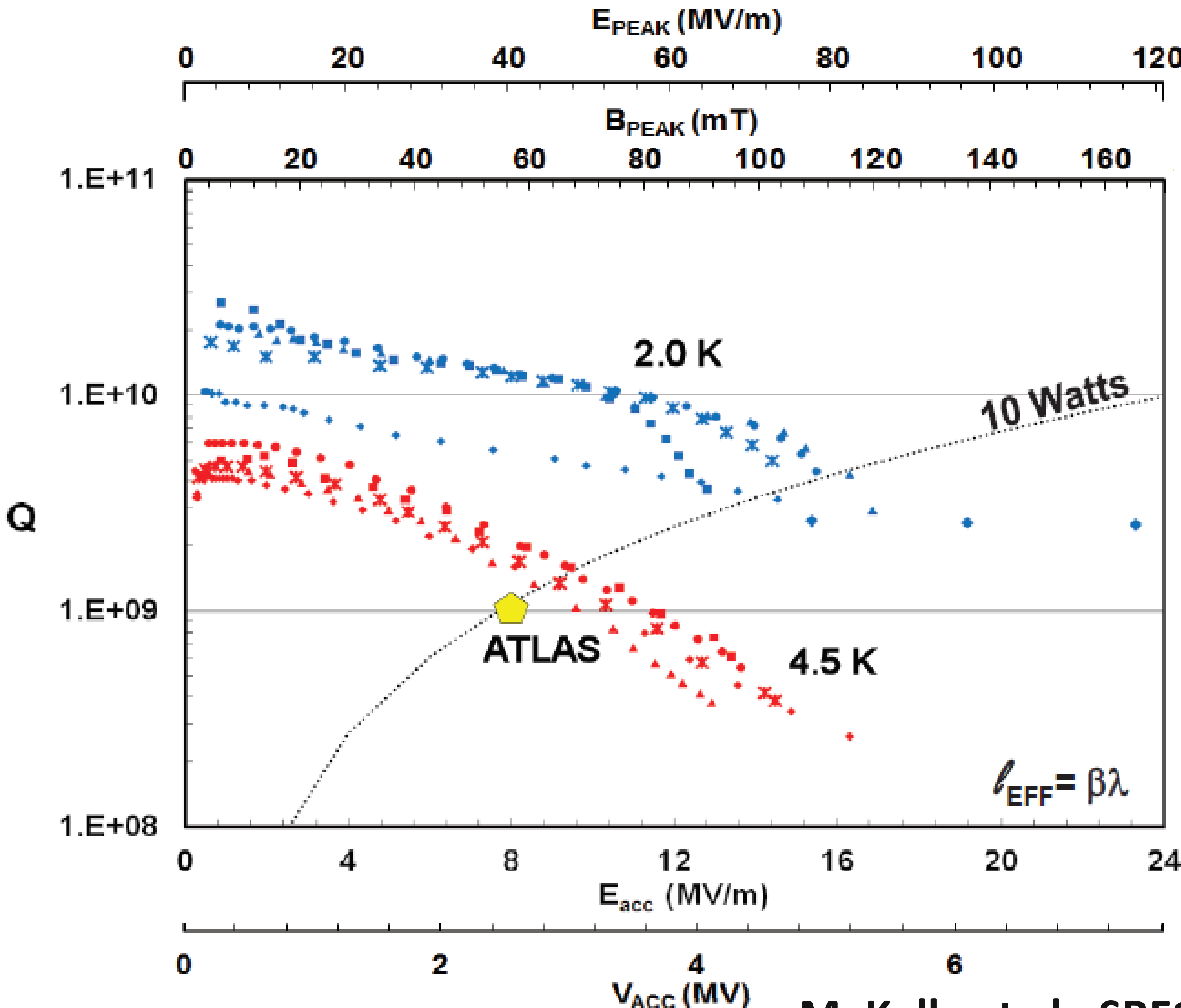
Unique ANL Low-Beta Cavity EP Tool

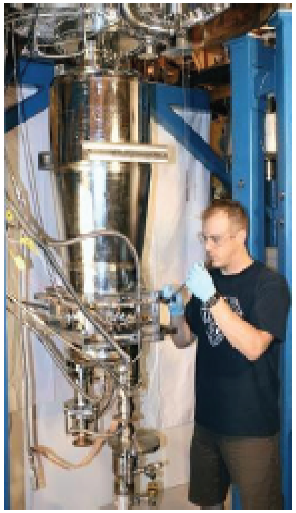




All polishing done after fabrication is finished.

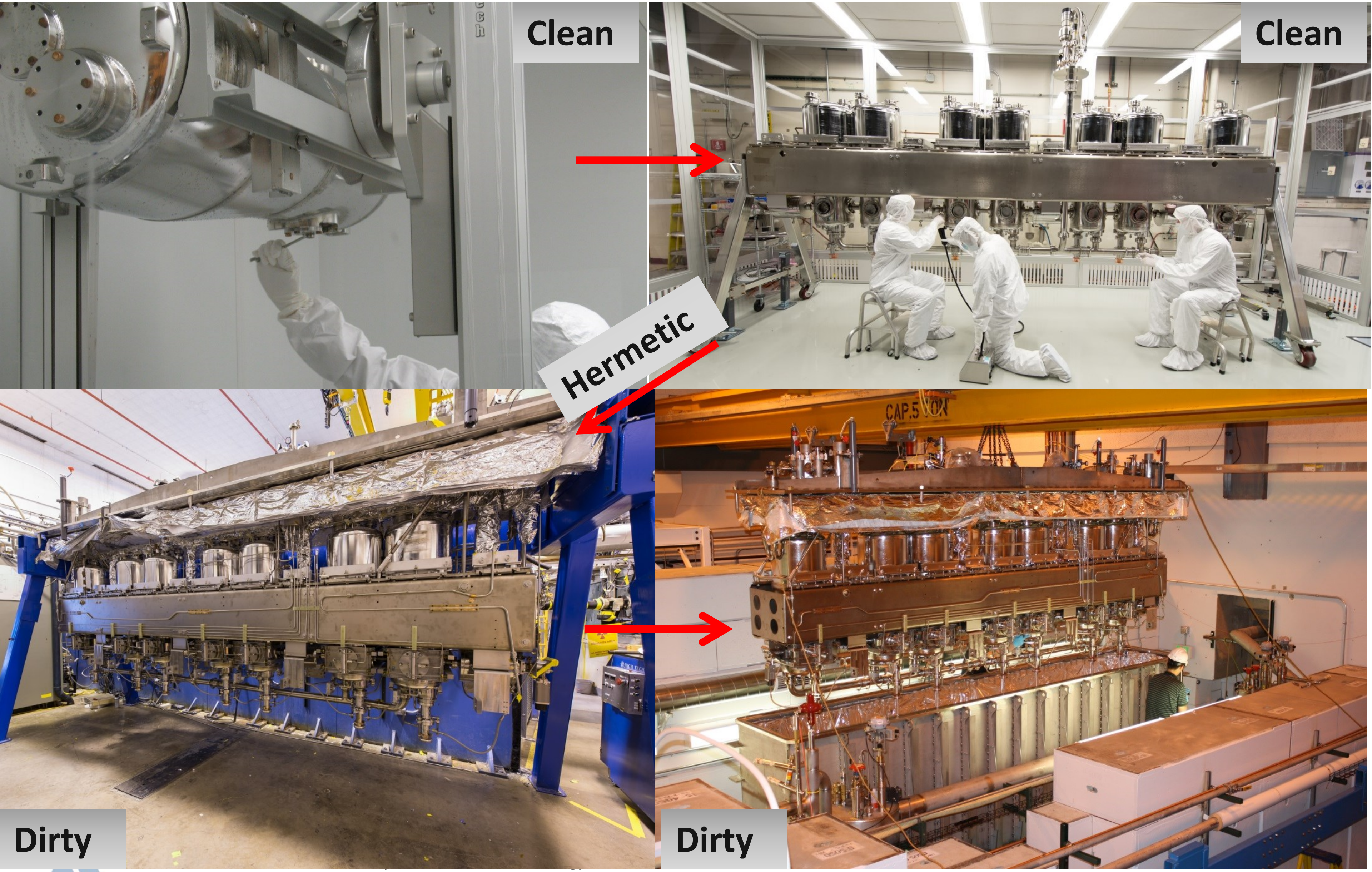
Cavity Testing – 4 of 8 QWR Off-Line Testing



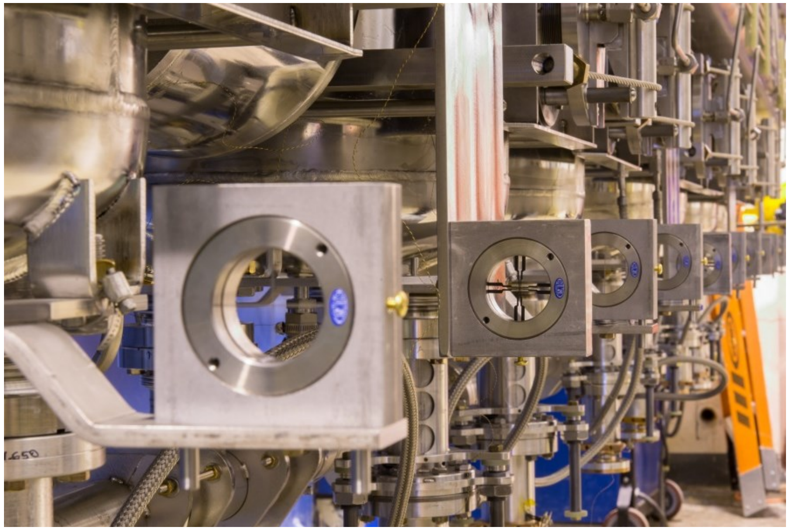


M. Kelly et al., SRF13, Paris, France.

Cryomodule Assembly – Maximizing Cavity Performance

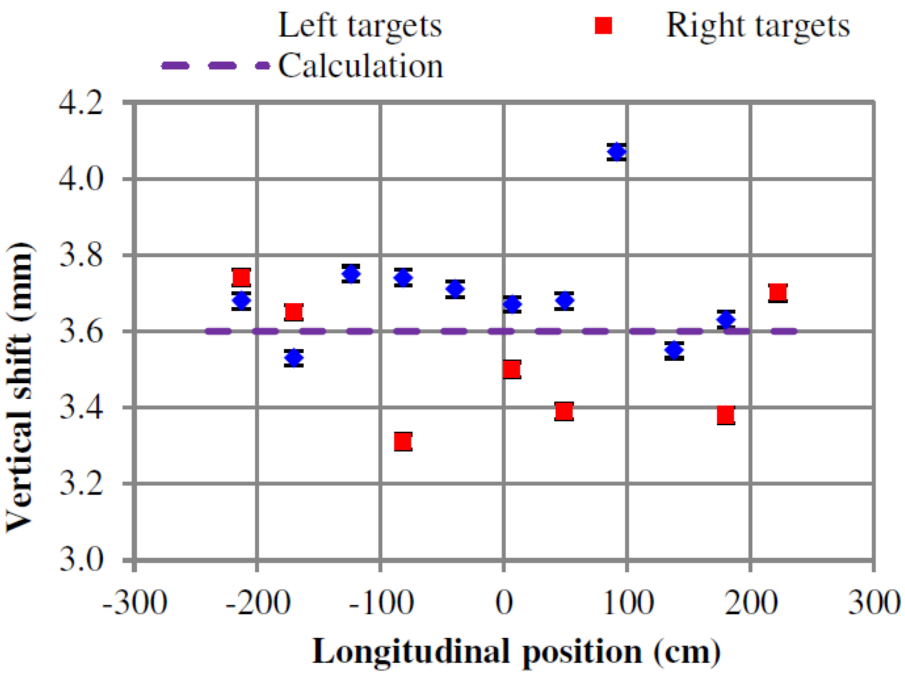


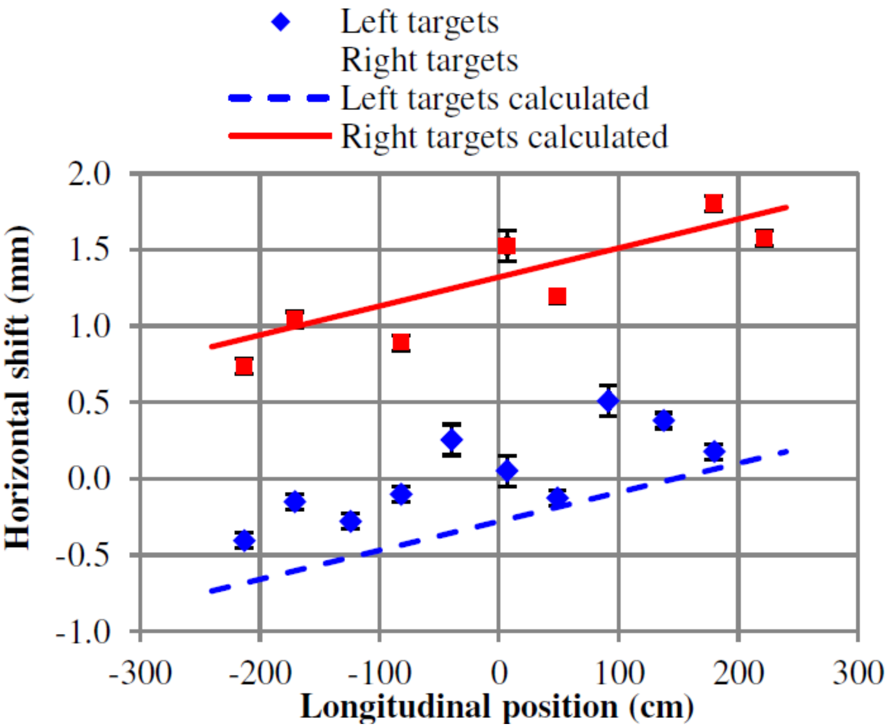
Cryomodule Assembly - Alignment



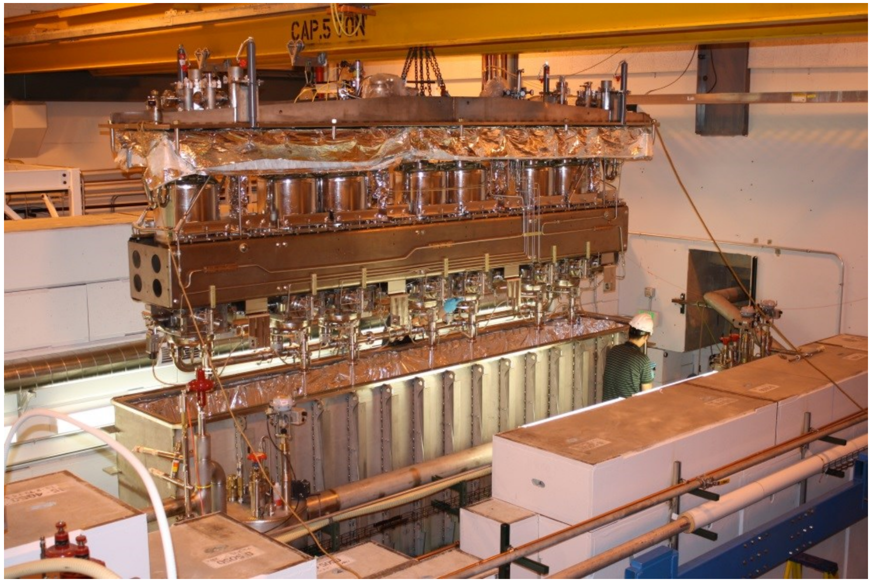
Final Alignment Errors

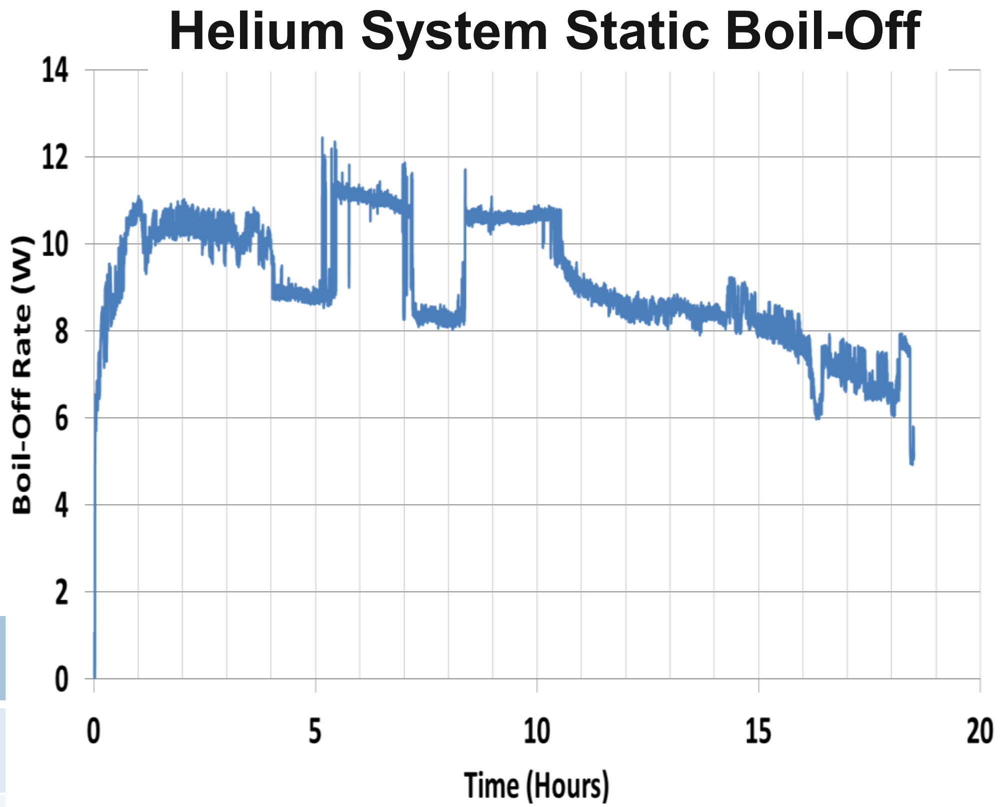
Direction	Solenoid	Cavity
Horizontal	0.12 mm RMS	0.50 mm RMS
Vertical	0.18 mm RMS	0.28 mm RMS





Cavity Testing - QWR On-Line Performance





Load	Measured Value
Liquid Helium	12 W (Static)
Liquid Nitrogen	160 W (Static)

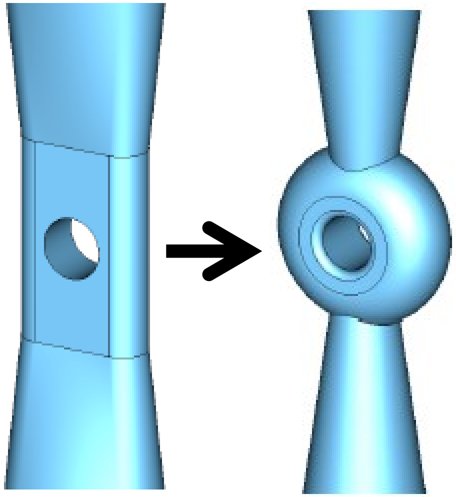
Dynamic Load for 2.5 MV Operation	Measured Value
Single Cavity Dynamic Load (Measured Off-line 4x)	5 – 8 W (Dynamic)
Measured Cryomodule Dynamic Load	33 W (Dynamic)

Cavity Performance - HWR Quadrupole Asymmetry

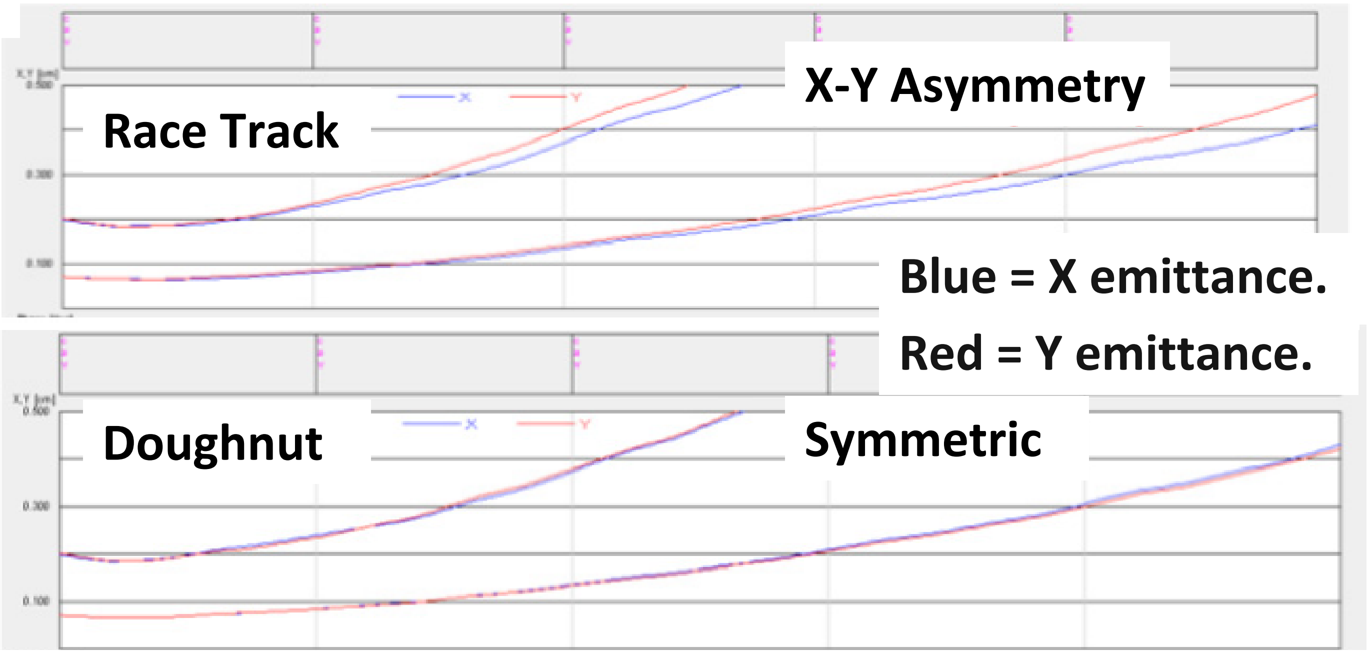
- HWR = Quadrupole field X-Y asymmetry.
- Corrected by symmetrizing center conductor around beam aperture.
- Again solution made in shaping forming dies. = No Additional Part Cost.

HWR Center Conductor Halves

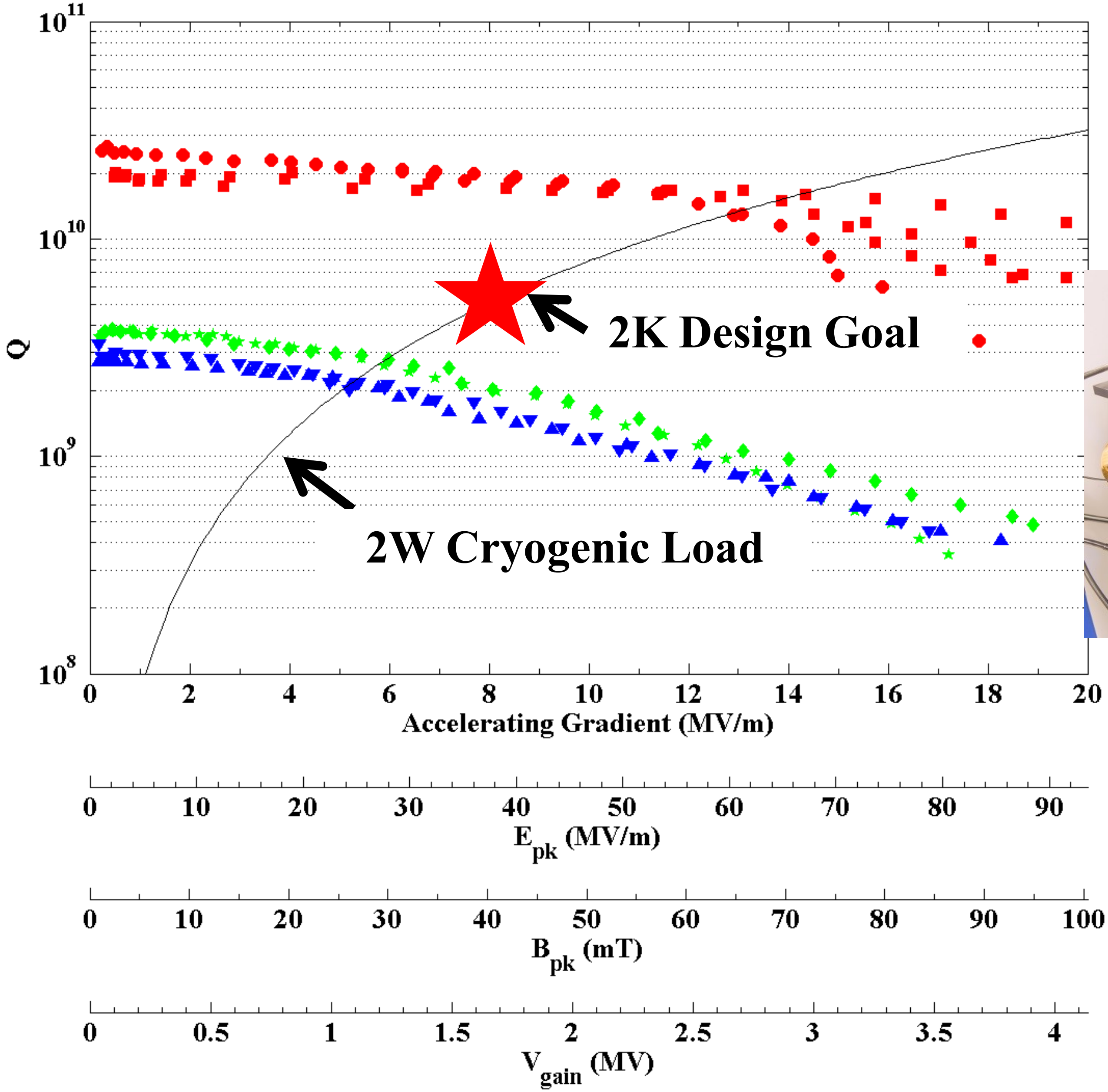
Race Track   Doughnut

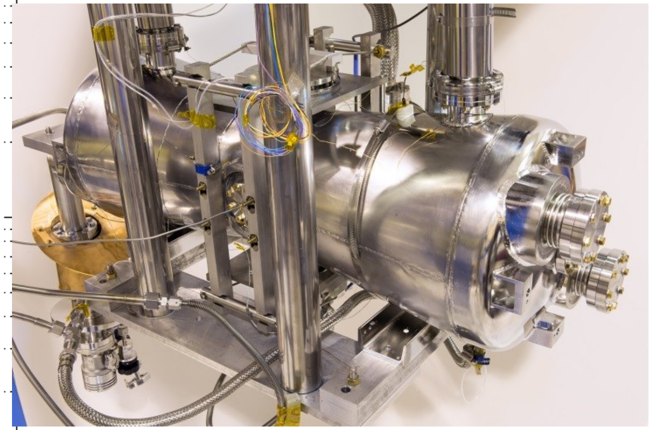


Race Track (Top) and Doughnut (Bottom) Asymmetry



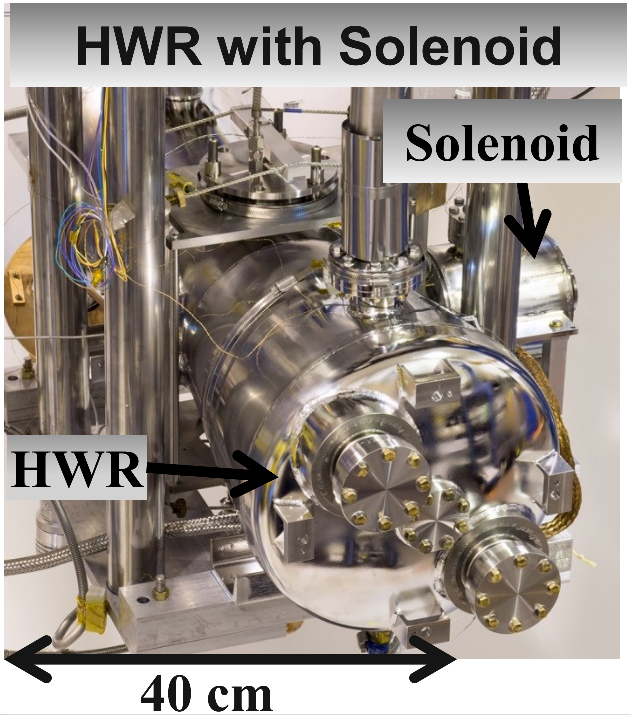
Cavity Testing – HWR Off-Line

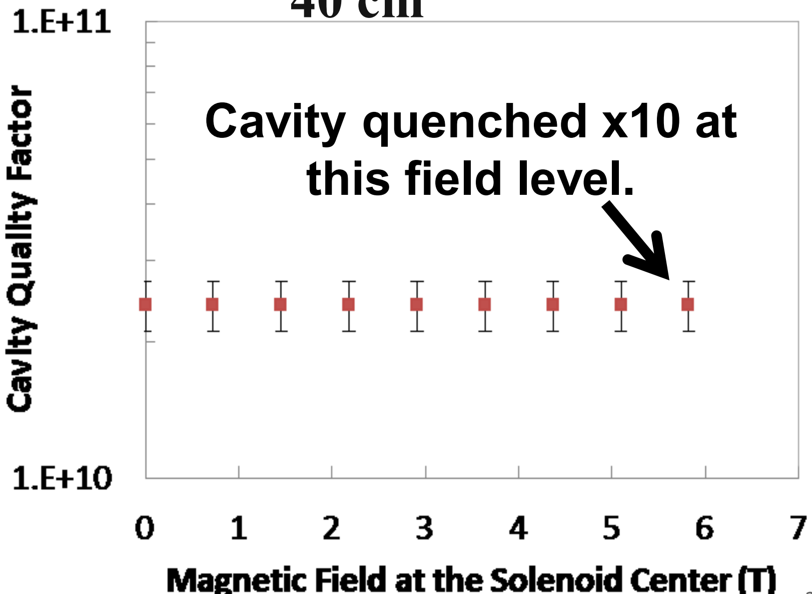




HWR Magnetic Field Sensitivity

- To decrease the accelerator lattice length we have integrated x-y steering coils into the focusing solenoid package.
- Important design issue:
  - Minimize stray field @ the RF cavity to prevent performance degradation due to trapped magnetic flux.
- Measured RF surface resistance with a sensitivity of ±0.1 nOhm before and after each quench of the cavity.
- The cavity was quenched with the solenoid and the steering coils energized.
- No quantifiable change to the cavity RF surface resistance.





Concluding Remarks

- **Highly optimized cavities and solenoids.**
  - **RF Performance improved by increase volume over which the magnetic energy is distributed.**
  - **Minimal to no sensitivity to helium pressure fluctuations or pendulum motion of inner conductors.**
  - **Many passive design features with little risk:**
    - **Beam Steering.**
    - **Inner conductor electromagnetic centering.**
- **Improved cavity fabrication and processing.**
- **High real-estate gradients achieved and improving, > 3.3 MV/m @ β = 0.077.**
  - **Low cryogenic loads for high real-estate gradient, 33 W dynamic and 12 W static to 4.5K for 7 cavities and 4 solenoids over 5.2 meters.**
- **Working on next cryomodule, our first for 2K. Initial results promising for >2 MV/cavity operation with low dynamic loading (<1 W per cavity).**