Development of a Half-Wave Resonator Cryomodule for Ion Beams
(Mostly the Resonators)

Zachary Conway

On Behalf of the ANL Physics Division Linac Development Group

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Acknowledgements

- ANL Personnel:
    - PHY: P. Ostroumov, M. Kelly, S. Gerbick, M. Kedzie, G. Zinkann, S. MacDonald, S.H. Kim and C. Hopper.
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    - Advanced Energy Systems, NY.
    - Adron EDM, WI.
    - Ti Fab, PA.
    - Numerical Precision, IL.
    - M-1 Tool Works, IL.
    - Meyer Tool and Manufacturing, IL.

Introduction – I: FNAL & PIP-II.

- **Fermi National Accelerator Laboratory is working to deliver 1.2 MW of beam power at 120 GeV, with at least 1 MW of beam power available at energies as low as 60 GeV.**
  - **PIP-I has:**
    - **Increased the booster repetition rate from ~ 7 Hz to 15 Hz.**
    - **Doubled the 8 GeV proton flux.**
  - **PIP-II:**
    - **Replace the >40 year old 200 MHz linac.**
    - **Increase the beam power to 1 mA (average).**
    - **Increase the Booster injection energy to 800 MeV (from 400 MeV).**
    - **Ensure an upgrade path to higher duty cycle operation (up to cw).**
- **Replacing the 200 MHz linac requires new technology which has been chosen to be SRF.**
  - **Argonne is supplying the first superconducting accelerator unit in this new machine.**

https://pip2.fnal.gov/files/Users_Meeting_Holmes.pdf

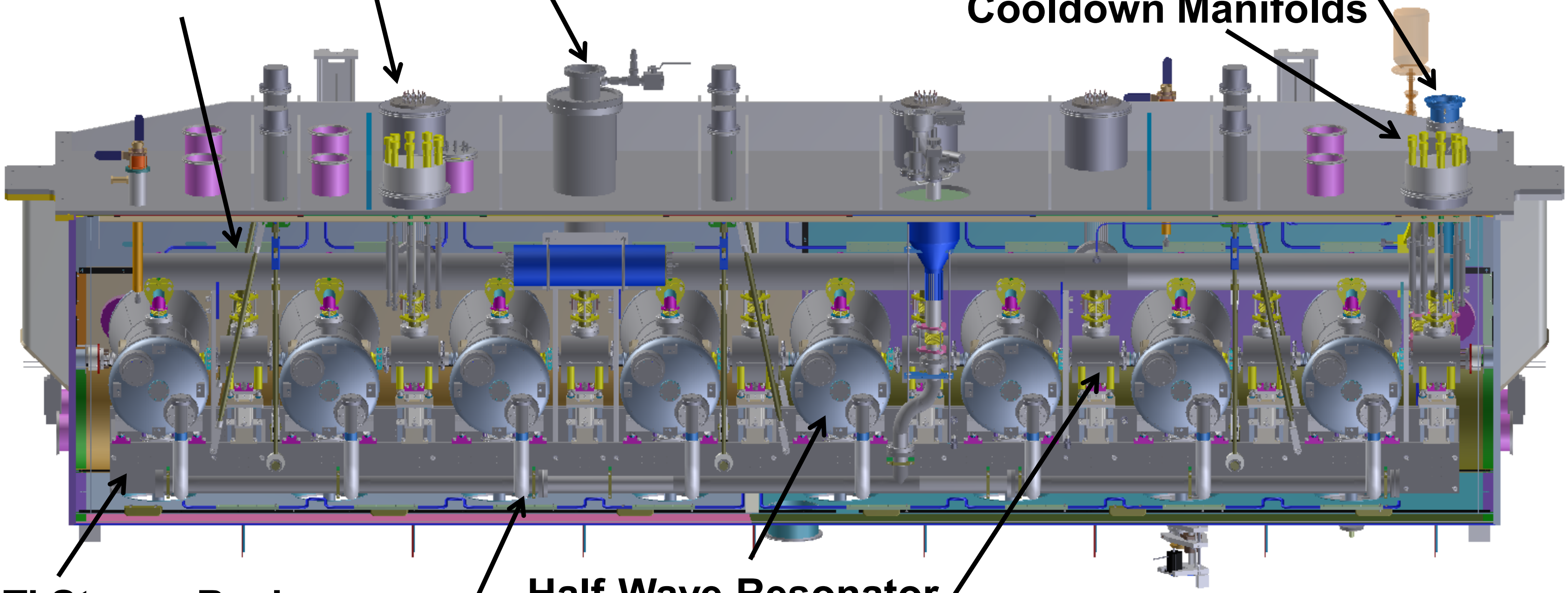
Introduction – II: What is Argonne Doing?

- Building a cryogenic system for the acceleration of H^- ions from 2.1 to 10 MeV for PIP-II @ FNAL.
  - Will contain accelerator cavities and magnets operating at 2 K.
- Will be the first operational 2 K cryomodule for superconducting accelerator cavities with low-beta (beta = v/c < 0.5) structures.
  - Using many techniques developed by velocity-of-light (or close to) accelerators; e.g., elliptical cell cavities.
  - Others are in development too; e.g., IFMIF, MSU-FRIB.
- Design goals for the cryomodule:
  - Operate at 2 K instead of 4 K.
  - Further reduce static cryogenic loads relative to previous low-velocity cavity cryomodules.
  - Comply with DOE, ANL and FNAL safety guidelines for cryogenic, vacuum and pressure vessels.
  - Enable faster more-accurate alignment.

Cryomodule Overview

(Brief)

Half-Wave Resonator Cryomodule



Conduction Cooled Leads (FNAL)

Sub-Atmospheric HTXG Assembly

Helium Relief Port

Helium Manifold

Cooldown Manifolds

Ti Strong-Back

Half-Wave Resonator

Vacuum Manifold

SC Solenoid

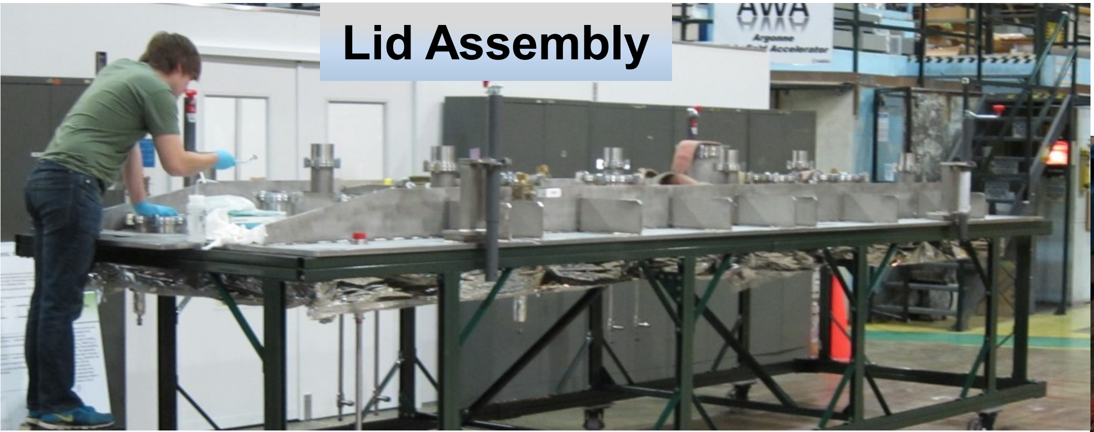
2.2 m X 2.2 m X 6.2 m

Not Labeled/Hard to See:

1) **Couplers.**
2) **BPMs.**
3) **70K HTXG.**
4) **Beam-line gate valves.**

Vacuum Vessel

- The vacuum vessel = Finished.
- Fabricated and Assembled at Meyer Tool.



Lid Assembly

Full Assembly

Lower Vacuum Vessel

Helium Manifold, Vacuum Manifold and Ti Strong-Back Fabrication

- Helium Manifold = Finished.
- Vacuum Manifold = Finished
- Ti Strong-back = Finished.

Vacuum Manifold Part 1

Helium Manifold

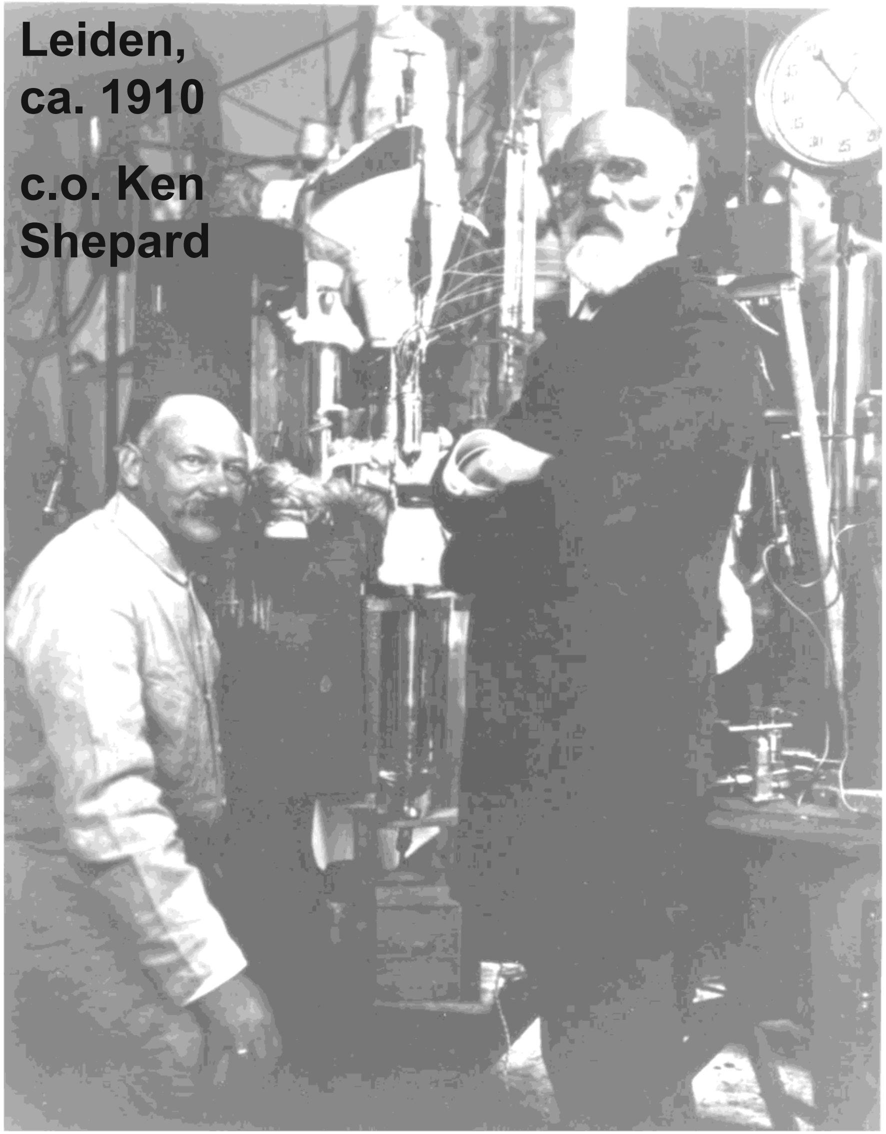
Vacuum Manifold Part 2

Ti Strong-Back

Superconducting Half-Wave Resonators

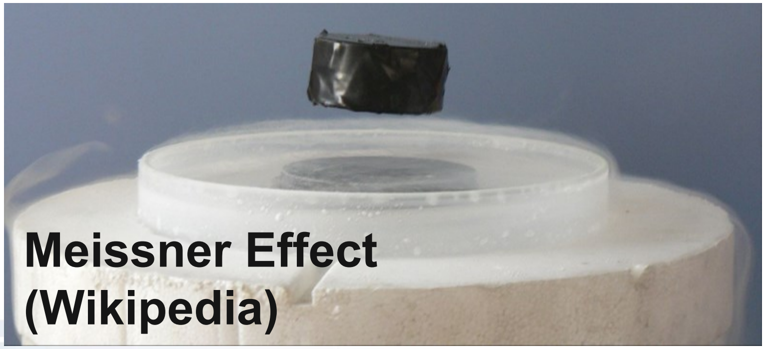
(Not Brief)

Brief History of Superconductivity

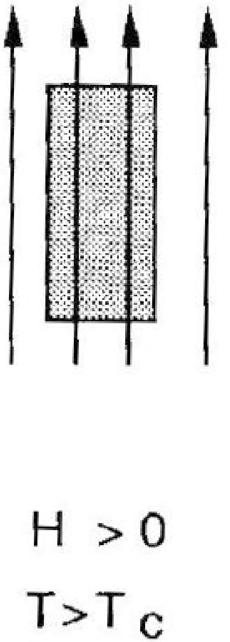

Leiden,
ca. 1910

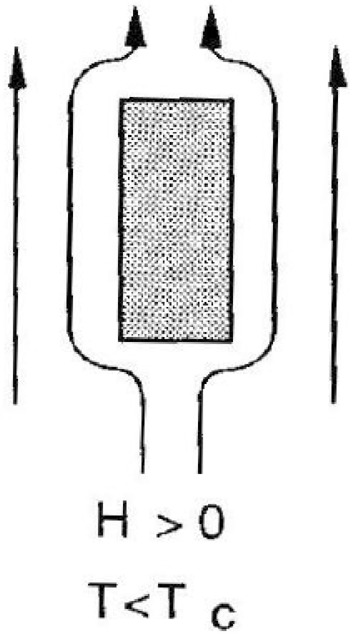
c.o. Ken
Shepard

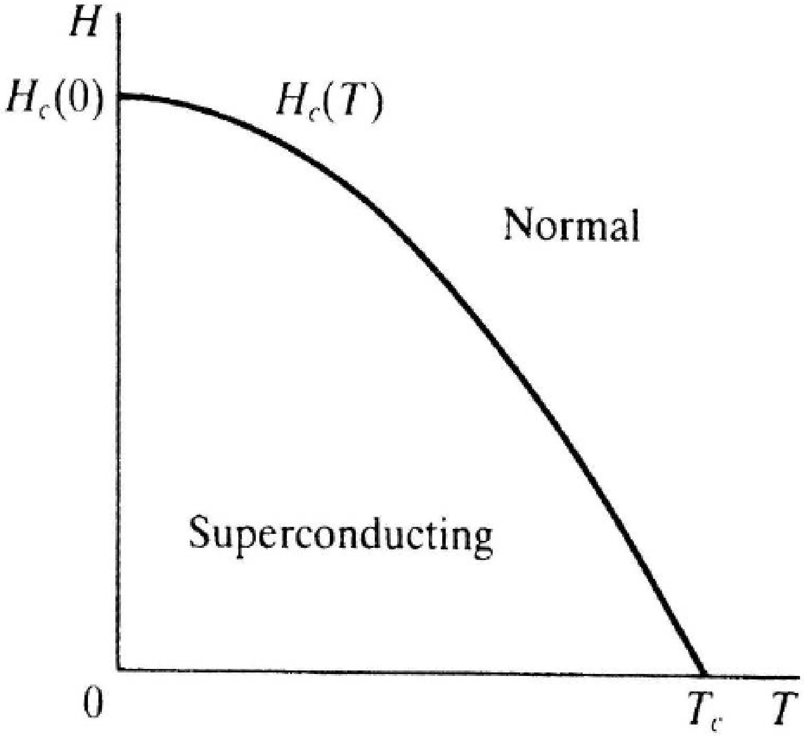
- 1911 – superconductivity discovered by Kamerlingh Onnes (L), van der waals (R).
- 1930's:
  - Magnetic flux expulsion discovered by Meissner and Ochsenfeld
  - London equations (zero momentum state)
- 1950's:
  - Ginsburg-Landau theory developed
  - Pippard: non-local electrodynamics
  - 1957 – Bardeen, Cooper and Schrieffer
- Theoretical understanding opened the way for applications (SC magnets, quantized flux magnetometry, ect.)
- 1964 – A 3 cavity (2856 MHz) 4" Long SRF accelerator operated at SLAC.


Meissner Effect
(Wikipedia)

Meissner Effect and the Superconducting Phase Transition







The magnetic field penetrates into the superconductor a distance λ = 39 nm for Niobium to attenuate to 1/e.

The phase transition is second order if there is no applied magnetic field (no latent heat), otherwise the transition is first order.

Pictures from Superconductivity by E.A. Lynton 1964

Penetration Depth - Coherence Length

SC/Normal Conducting Boundary

$\lambda(T) \approx \lambda_0/(1-T^4/T_C^4)^{½}$

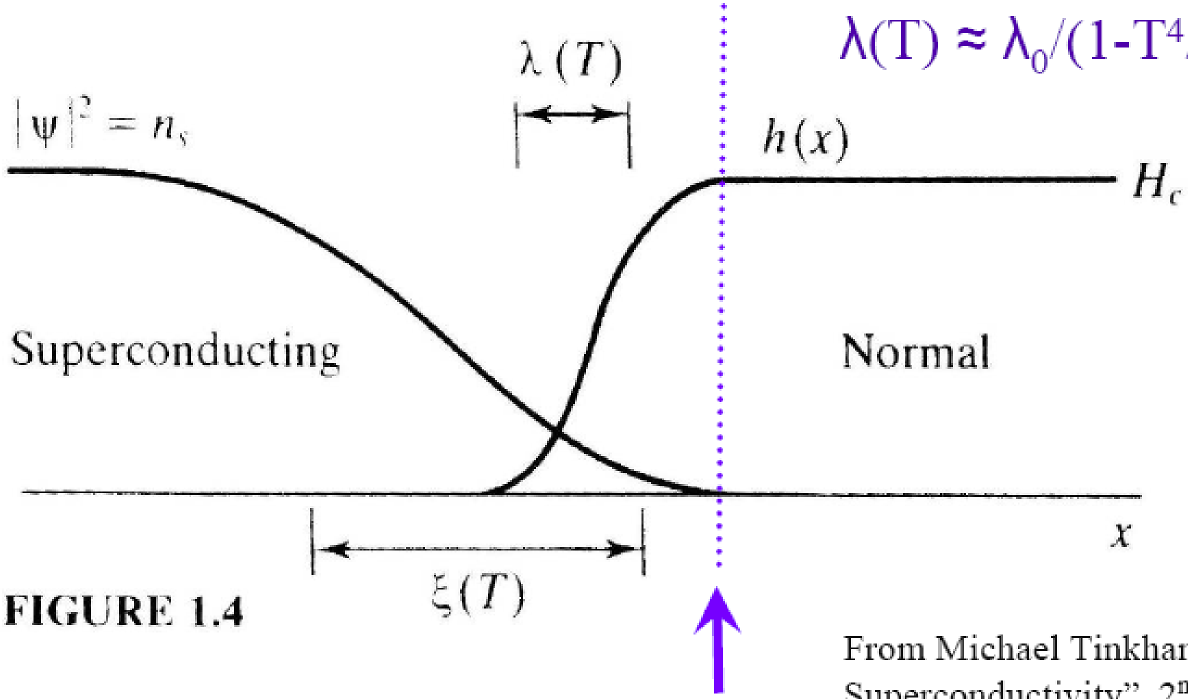


FIGURE 1.4

From Michael Tinkham's "Introduction to Superconductivity", 2nd edition

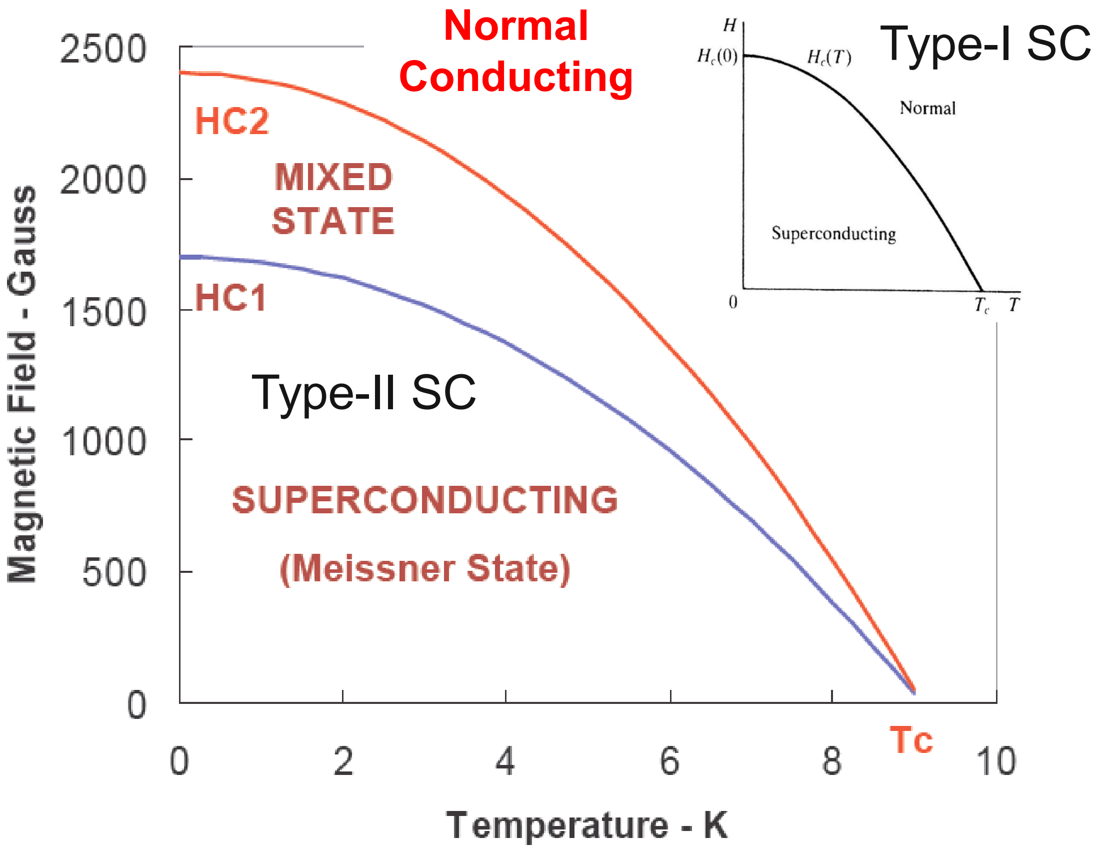
For Nb:
λ_0 = 39 nm
ε_0 = 38 nm
κ = 2

Ginzburg-Landau parameter $\kappa = \lambda/\varepsilon$

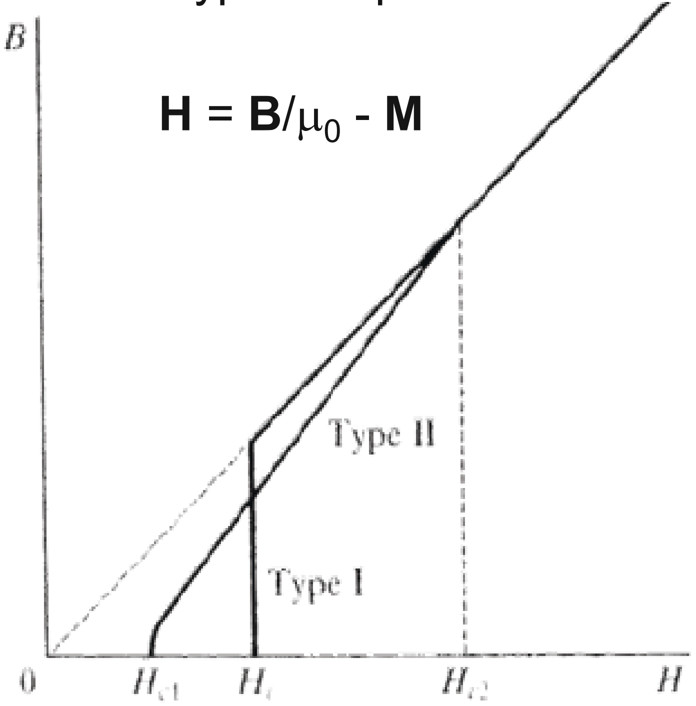
- If $\kappa < 1/\sqrt{2}$, the surface energy is positive (type I SC)
- If $\kappa > 1/\sqrt{2}$, the surface energy is negative (type II SC)

  Magnetic flux breaks into the smallest possible units which are flux-tubes or vortices containing a single quantum of magnetic flux P_0 = h/2e = 2E-15 Webers

Type II Superconductors (The mixed state)



Magnetization curves for type I and type II superconductors



$$\mathbf{H} = \mathbf{B}/\mu_0 - \mathbf{M}$$

Pictures from Superconductivity by E.A. Lynton 1964 (right) and K.W. Shepard (left).

Normal Conductor RF Losses & Anomalous Skin Effect

- RF currents are confined to a surface layer of thickness δ: $\delta = \sqrt{\frac{2}{\mu_0 \omega \sigma}}$
- Giving an effective surface resistance of: $R_s = \frac{1}{\delta\sigma} = \sqrt{\frac{\mu_0 \omega}{2\sigma}}$
- Power loss into the metal surface is: $P = \frac{R_s}{2} \int_S \left|\vec{H}(\vec{x})\right|^2 da$
- Anomalous skin effect at low temperatures:

$$\vec{J}(\vec{x},t) \neq \sigma \vec{E}(\vec{x},t); \vec{J}(\vec{x},t) = \frac{3\sigma}{4\pi l} \int_V \frac{\vec{R}\left(\vec{R} \cdot \vec{E}(\vec{x}',t - \left|\vec{R}\right| / v_F)\right)}{R^4} e^{-R/l} d^3x' \text{ where } \vec{R} = \vec{x}' - \vec{x}$$

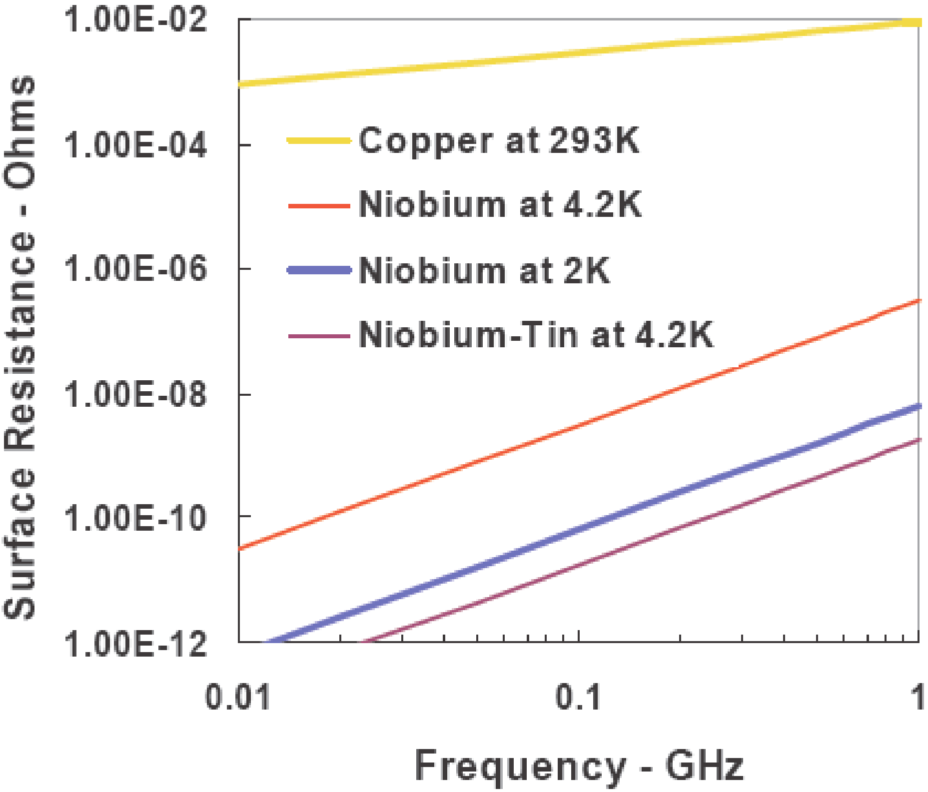
Skin Depth and Surface Resistance at 1.0 GHz			
T		Cu	Nb
293 K	Skin Depth	2.1 μm	6.1 μm
	Surface Resistance	8.2e-3 Ω/m^2	23e-3 Ω/m^2
~30 K	Skin Depth	0.2 μm	1.7 μm
	Surface Resistance	7.9e-4 Ω/m^2	6.3e-3 Ω/m^2

SC Penetration Depth - Skin Depth - Dispersion

- BCS SC surface resistance is lower by 3-5 orders of magnitude.
- Penetration depth does not vary appreciably with frequency (for frequencies much less than the band gap, 100GHz for Nb).
- Maximum SC RF field is $H \leq H_{sh} \approx H_c$.

Skin Depth and Surface Resistance at 1.0 GHz			
T		Cu	Nb
293 K	Skin Depth	2.1 μm	6.1 μm
	Surface Resistance	8.2e-3 Ω/m^2	23e-3 Ω/m^2
~30 K	Skin Depth	0.2 μm	1.7 μm
	Surface Resistance	7.9e-4 Ω/m^2	6.3e-3 Ω/m^2
4.2 K	Penetration Depth	0.2 μm	0.05 μm
	Surface Resistance	7.9e-4 Ω/m^2	3.2e-7 Ω/m^2
2 K	Penetration Depth	0.2 μm	0.05 μm
	Surface Resistance	7.9e-4 Ω/m^2	6.5e-9 Ω/m^2

RF Surface Resistance vs Frequency (Theory)



$$R_s(NC) = \sqrt{\frac{\mu_0 \omega}{2\sigma}}$$

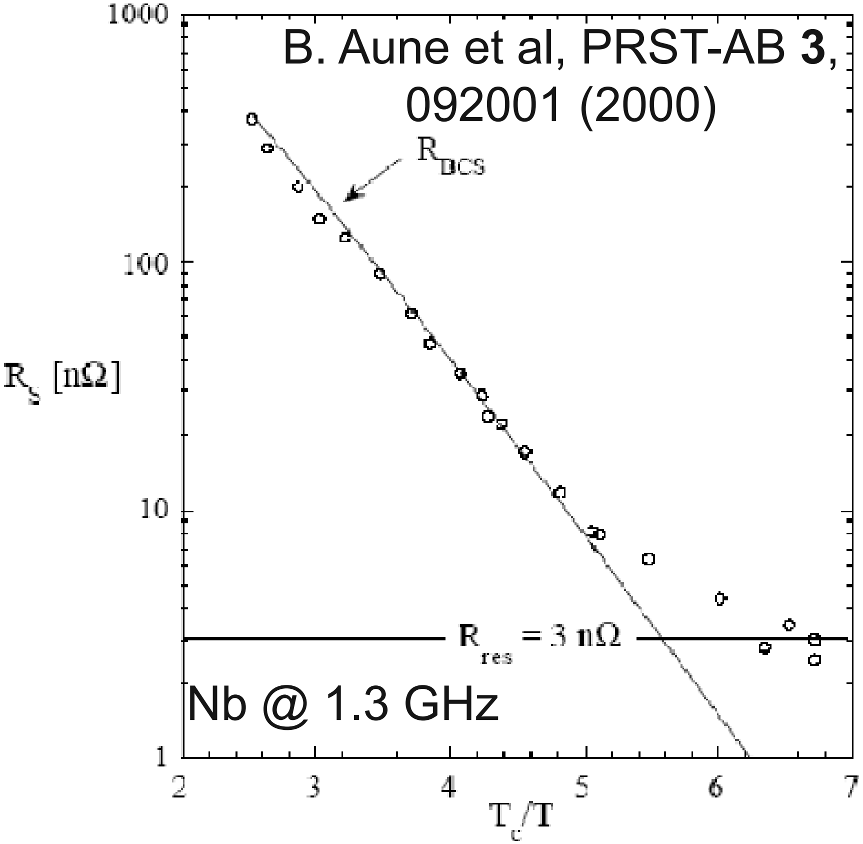
$$R_s(SC) = A(l, \lambda, \xi, \Delta(T)) \cdot \omega^2 \cdot e^{-\Delta(0)/k_b T}$$

RF Surface Resistance and Residual Resistance

$$R_s(SC) = R_{BCS} + R_{residual}$$

$$= A(l,\lambda,\xi,\Delta(T))\cdot\omega^2\cdot e^{-\Delta(0)/k_bT} + R_{residual}$$

- Possible contributions to R_{res}:
  - Surface roughness.
  - Grain boundaries.
  - Normal conducting impurities/precipitates.
    - Hydrogen Q-disease.
    - Low-purity material.
  - Trapped magnetic flux.
  - And on and on and on.
- For high-purity bulk niobium the residual resistance dominates at low temperatures and low-frequencies.



B. Aune et al, PRST-AB **3**, 092001 (2000)

Nb @ 1.3 GHz

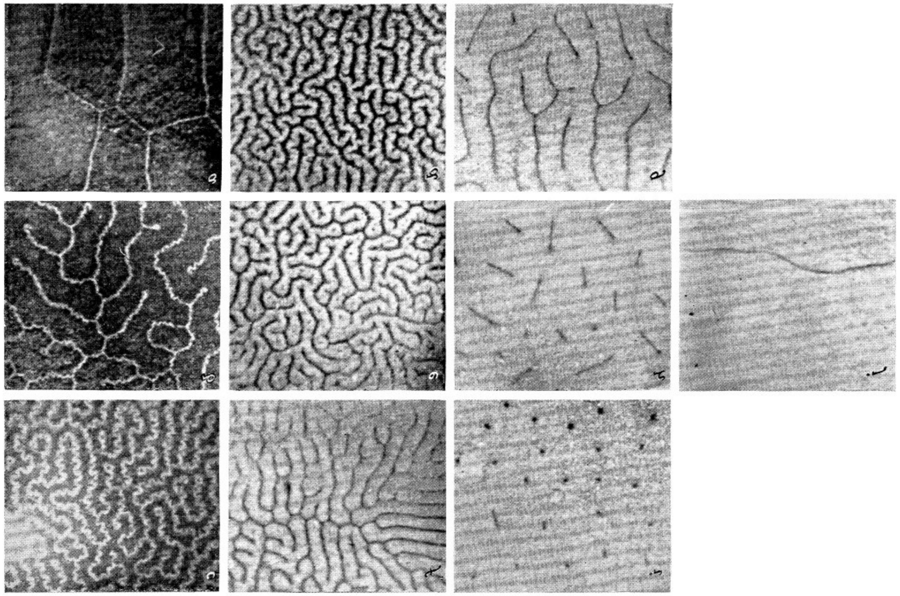
SC Materials - II

- DC Applications (magnets): Type II, mixed state operation.
- AC Applications (RF Resonators): Type I or Type II, Meissner State.

$$H_{c2} = \sqrt{2} * \kappa * H_c$$

- Material examples where high-frequency devices have been made.

* Type I Superconductor
** Extreme Type II



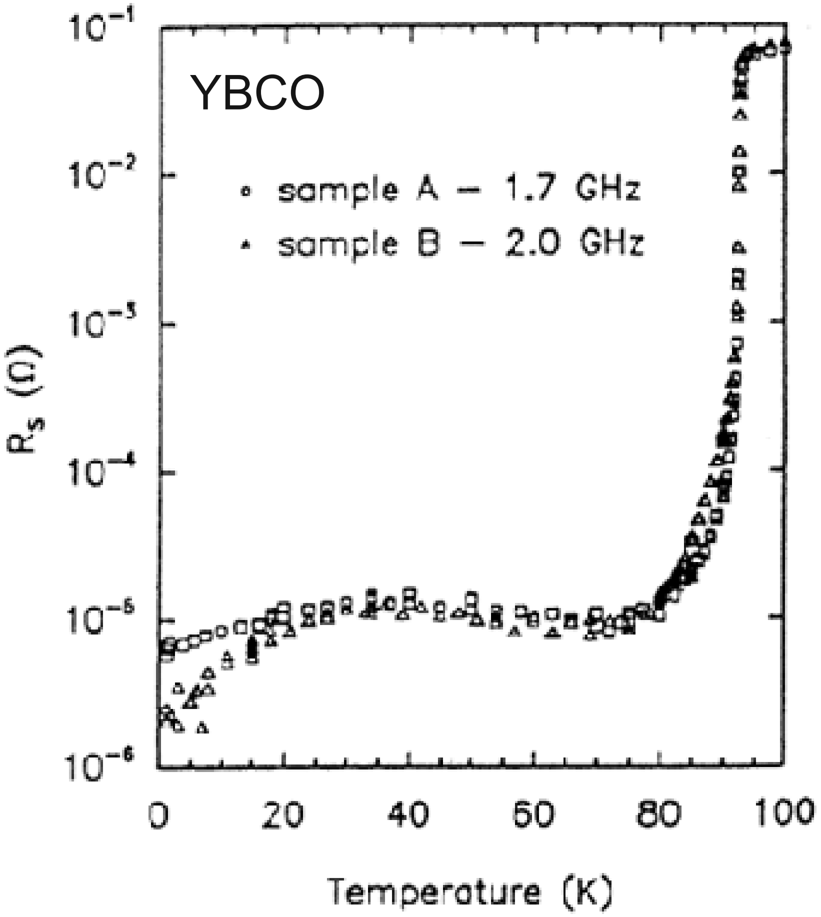
Powder patterns of the SC intermediate state. SC regions are dark. Faber, Pro. Royal Soc. 1958.

Metal	T_C	H_{c1}	H_c	H_{c2}	$\lambda(0)$	$\varepsilon(0)$
Pb	7.2 K	*	803 G	*	37 nm	83 nm
Nb	9.2 K	1700 G	2,000 G	4,000 G	39 nm	38 nm
NbN (Film)	17.3 K	200 G	2,300 G	15,000 G	~400 nm	~3 nm
Nb_3Sn (Film)	18 K	380 G	4000 G	30,000 G	~100 nm	~4 nm
YBCO**	93 K	**	12,000 G	10^6 G**	150, 800 nm	2, 0.4 nm

Numbers above are subject to vigorous debate.

SC Materials - II

- ε ~1 nm or less (<< λ) the cooper pairs are easily disrupted by defects (lattice imperfections, inclusions, grain boundaries, etc.)
- High temperature superconductors often have small ε and corresponding larger R_{res}.
- A partial fix = operate at temperatures much lower that the critical temperature.
- Liquid helium is here to stay and is critical to the future of the field.

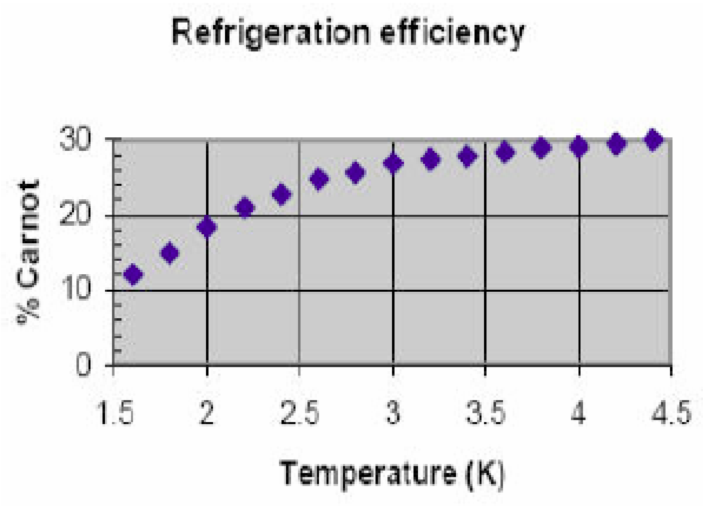


Hein M A 1996 *Studies in High Temperature Superconductors* vol 18 ed A Narlikar (Nova Science Publishers) pp 141–216

Cryogenic Refrigeration Efficiency

	4.2 K	2 K
Carnot Efficiency	1.4%	0.6%
Mechanical Efficiency	30 %	20 %
Required Input Power	240 W per Watt	830 W per Watt

$$\eta_c = \frac{T}{300-T}$$



Schneider, Kneisel, Rode, "Gradient Optimization for SC CW Accelerators," PAC2003

FNAL's Central Helium Liquefier.
Part of their 24 kW 4.5 K helium system.

SC or NC?

Option	SC	NC
Beam Current (mA)	5	5
f_0(MHz)	325	325
Q_0	4 x 10^9	2 x 10^4
R_{sh}/Q_0 (Ω)	108	850
P_{cavity}/L (W/m) @ E_{acc} = 1 MV/m	2.3	59,000
AC Power (kW/m) @ E_{acc} = 1 MV/m	11	128
AC Power (kW/m) @ E_{acc} = 5 MV/m	64	3,000

OR?

Summary So Far

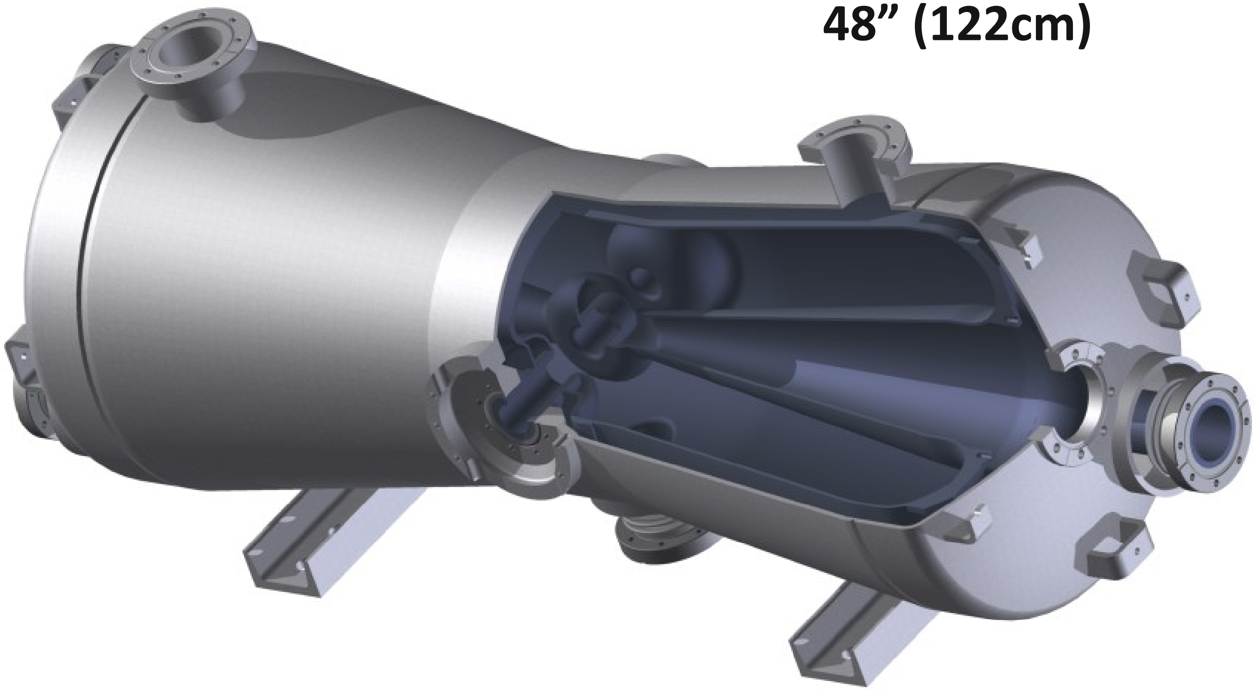
- SC can reduce the RF surface resistance by 3-5 orders of magnitude.

- Given the efficiency of present cryogenic refrigerators, the net wall-plug power savings can be in the range of 30 – 1000.

- Playing the SC game might be worth while...
  - High shunt impedance.
  - Field limits and breakdown.

- SRF cavities are next.

The HWR discussed here:



162.5 MHz

β = 0.11

Half-Wave Resonator (HWR)

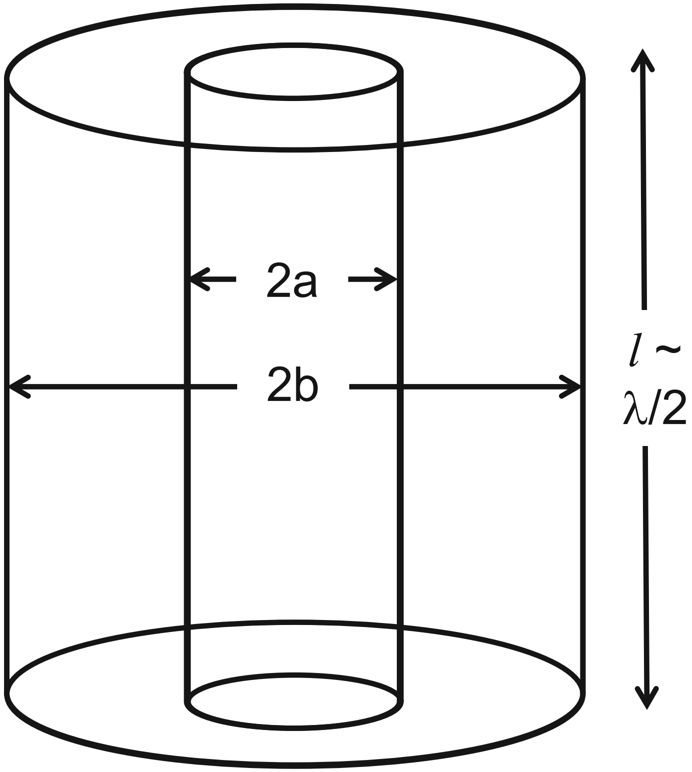
Building 9

1 Extra

Details Next

Resonant Cavity Properties

Half-Wave Resonator



Two Coaxial Cylinders
Shorted on Both Sides.

$$E_r = 2i\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{I_0}{2\pi r}\sin\left(n\frac{\pi z}{l}\right)e^{-i\omega t}$$

$$H_{\emptyset} = \frac{I_0}{\pi r}cos\left(n\frac{\pi z}{l}\right)e^{-i\omega t}$$

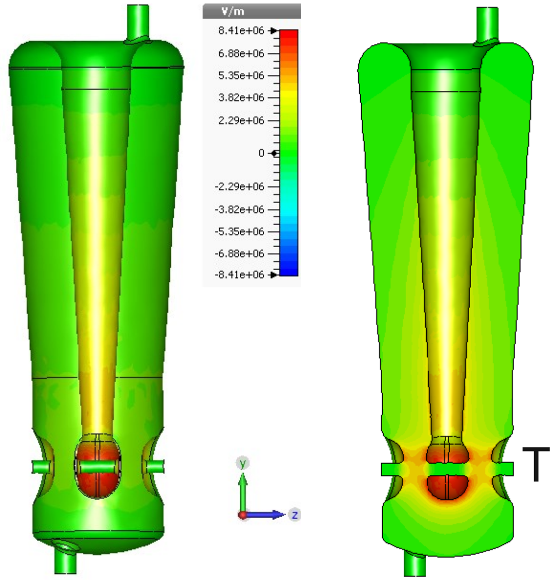
$$U_0 = \frac{\mu_0 l {I_0}^2 ln\left({}^{b}/_{a}\right)}{2\pi}$$

$$G = QR_s = \mu_0\omega_0\frac{\int_V |H|^2 dV}{\int_S |H|^2 dS}$$

$$= p\pi\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{ln\left({}^{b}/_{a}\right)}{l\left(\frac{1}{b}+\frac{1}{a}\right)+4\,ln\left({}^{b}/_{a}\right)}$$

SRF Cavity Fields

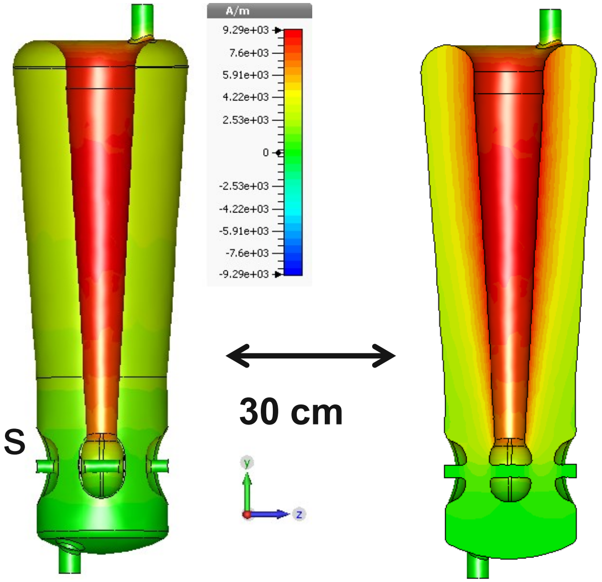
Electric Fields



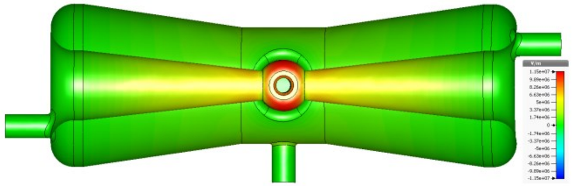
Surface Volume

TEM Fields

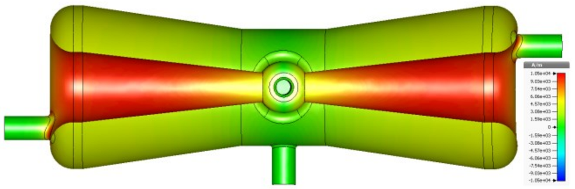
Magnetic Fields



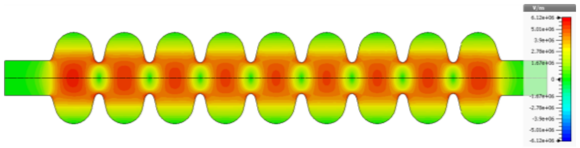
Surface Volume



Surface-E

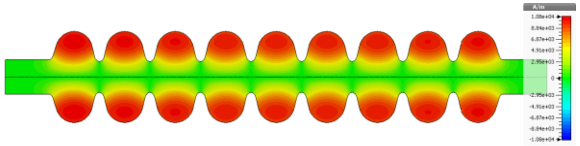


Surface-H



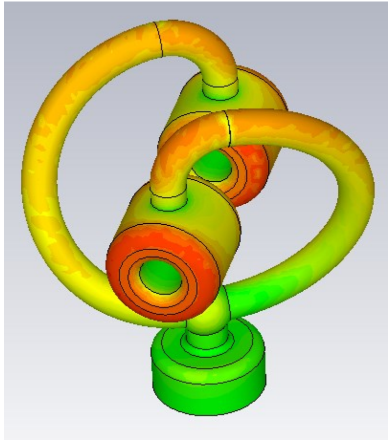
Volume-E

TM$_{010}$

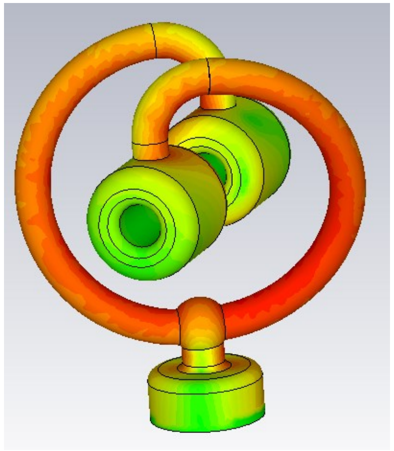


Volume-H

Split-Ring



Surface-E

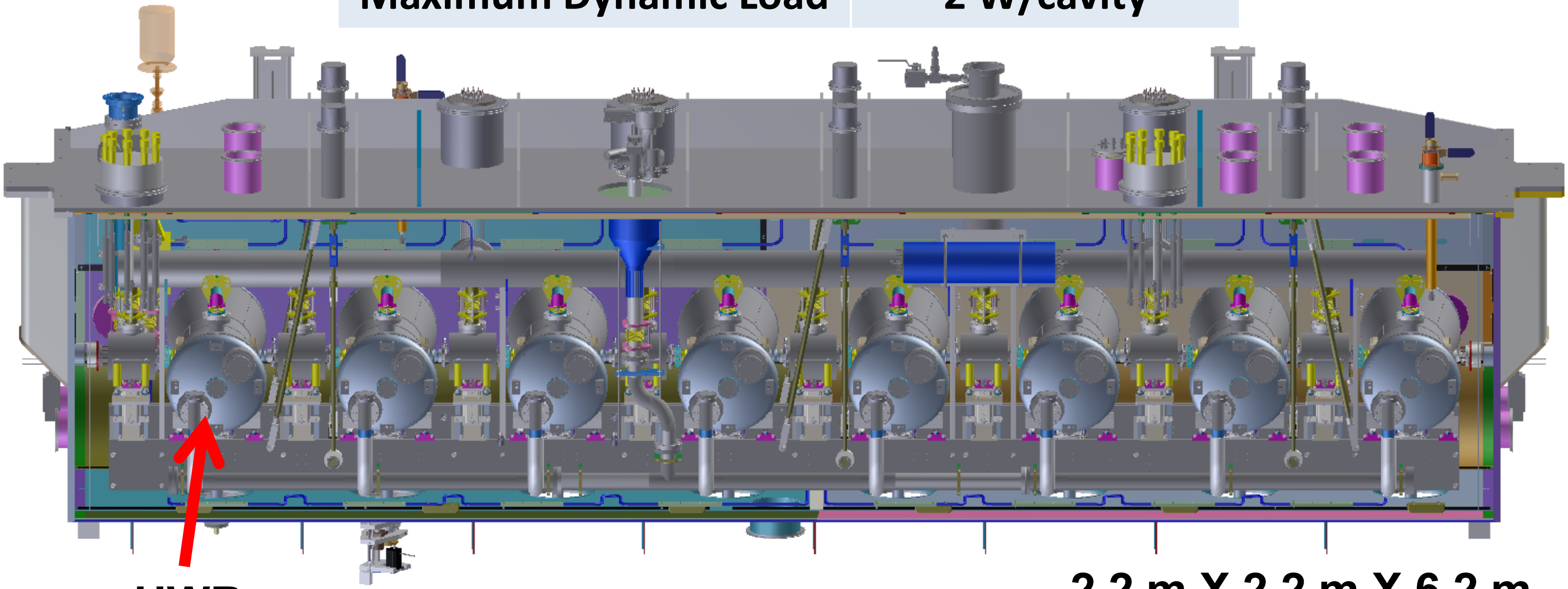


Surface-H

HWR Cryomodule for PIP-II

A new half-wave resonator (HWR) cryomodule for FNAL's PIP-II project.

Half-Wave Resonator	Requirement
Operating Voltage	2 MV/cavity
Operating Temperature	2.0 K
Maximum Dynamic Load	2 W/cavity



2.2 m X 2.2 m X 6.2 m

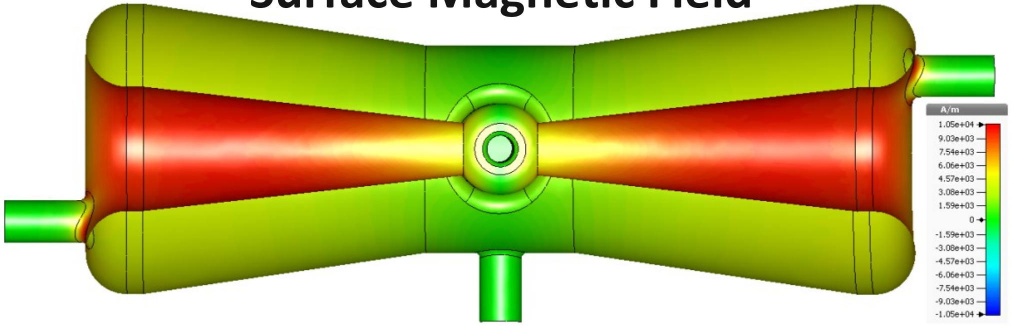
What goes into a half-wave cavity?

- The complex cavity system:
  - Beam physics design.
  - RF Performance.
  - Fabrication.
  - Polishing.
  - Cleaning.
  - Assembly.
  - Safety standards.

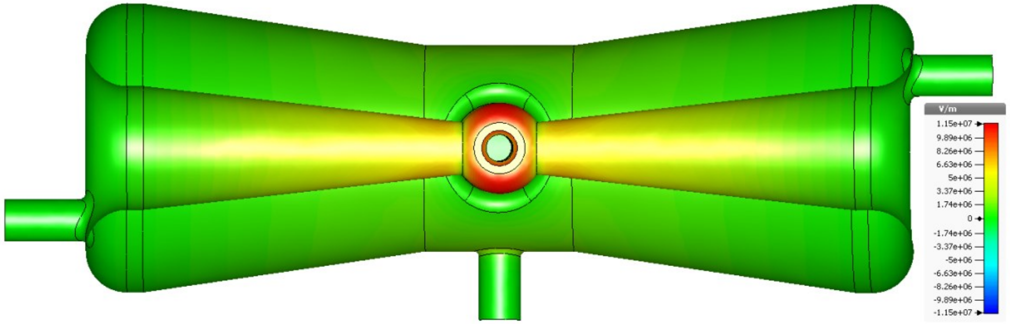
Cavity Type	**HWR**
Freq. (MHz)	**162.5**
β	**0.112**
l_{eff} (cm, $\beta\lambda$)	**20.68**
E_{pk}/E_{acc}	**4.7**
B_{pk}/E_{acc} (mT/(MV/m))	**5.0**
QR_s (Ω)	**48.1**
R_{sh}/Q (Ω)	**272**

- **RF Performance:**
  - **Maximize voltage gain.**
  - **Low cryogenic load.**
  - **Low peak surface fields.**
  - **Design supports fabrication, processing and cleaning.**

Surface Magnetic Field



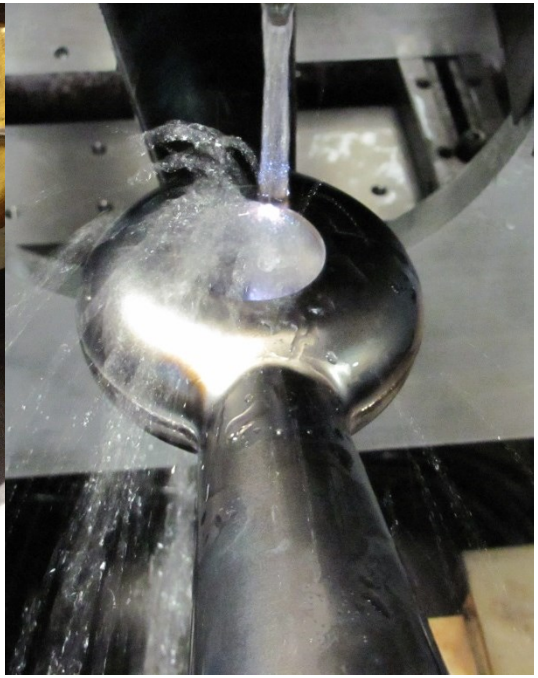
Surface Electric Field



Fabrication

- Cavities are built largely in house with critical vendors.
- ANL does intermediate QA.
- EDM.
- Keyhole EB welding in all high-field regions.
- Significant hand polishing.

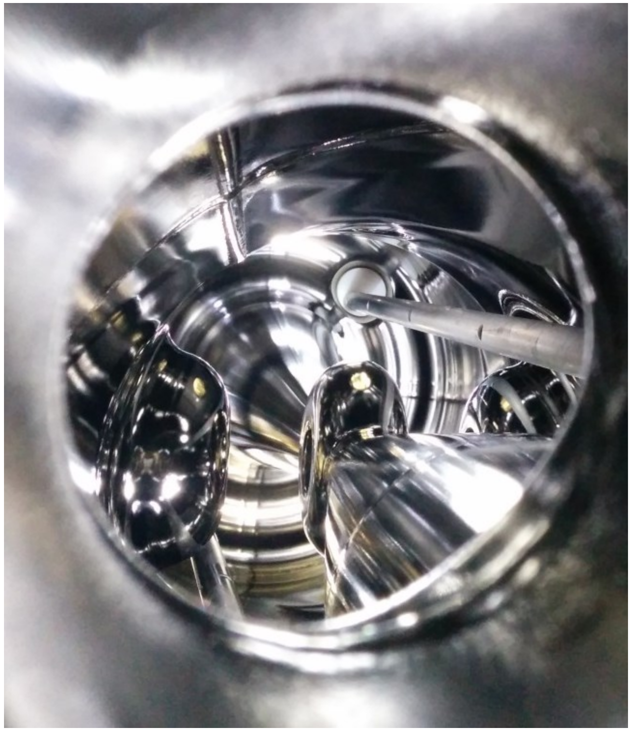
Electrostatic Discharge Machining

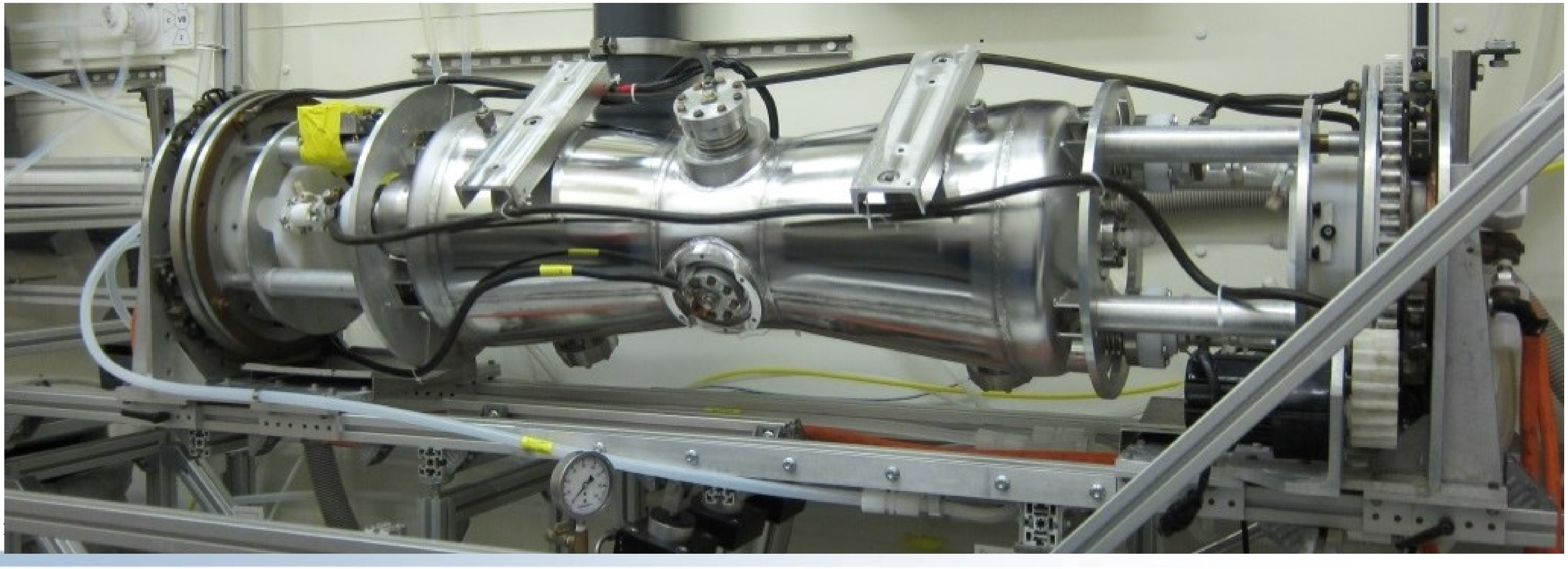


Keyhole Electron Beam Welding in High Field Regions

Cavity Polishing and Processing

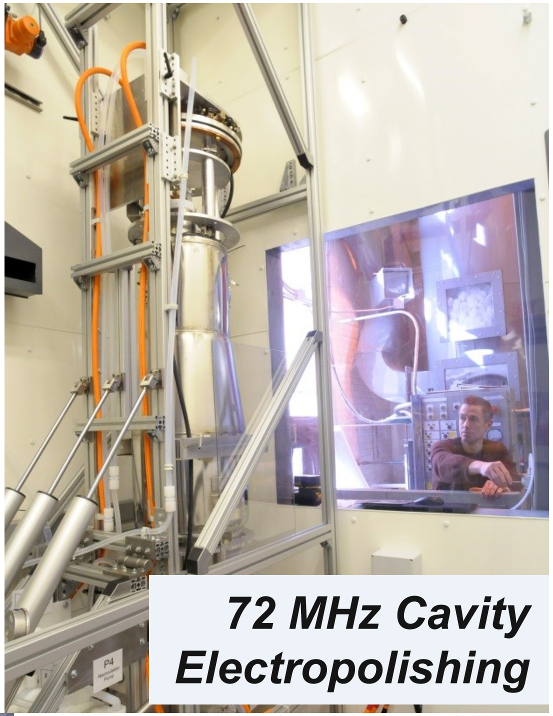
- All polishing is done after fabrication is finished.
- Cooling water flow through space between helium jacket and Nb cavity.
- Unique Argonne Low-Beta Cavity EP Tool.
  - S.M. Gerbick et al, SRF'11.
  - M.P. Kelly et al, SRF'11.
- Successful many times with QWRs:
  - M.P. Kelly et al, SRF'13.





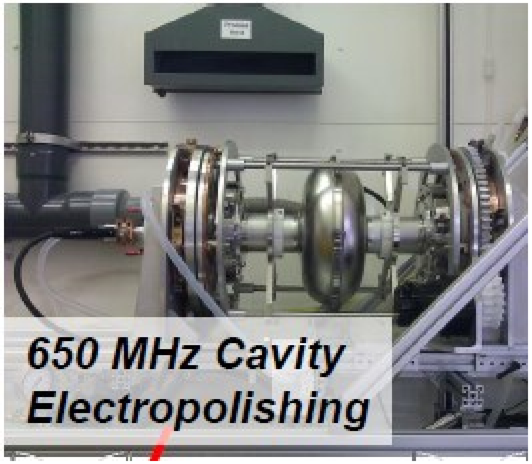
ANL-FNAL Collaboration on SRF

Clean facilities for HPR & Assembly



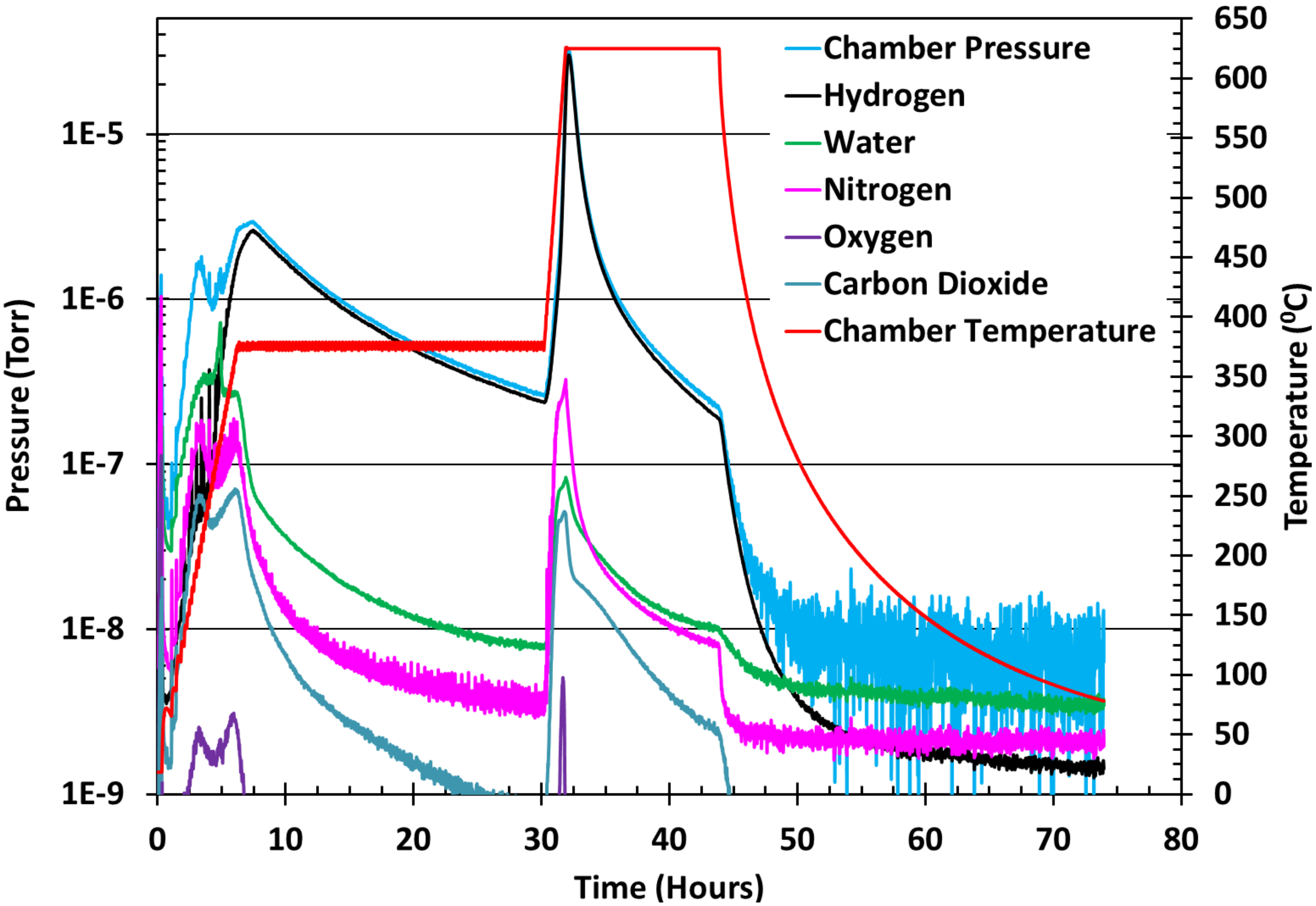
72 MHz Cavity Electropolishing

1.3 GHz Cavity Electropolishing, 325 MHz BCP



650 MHz Cavity Electropolishing

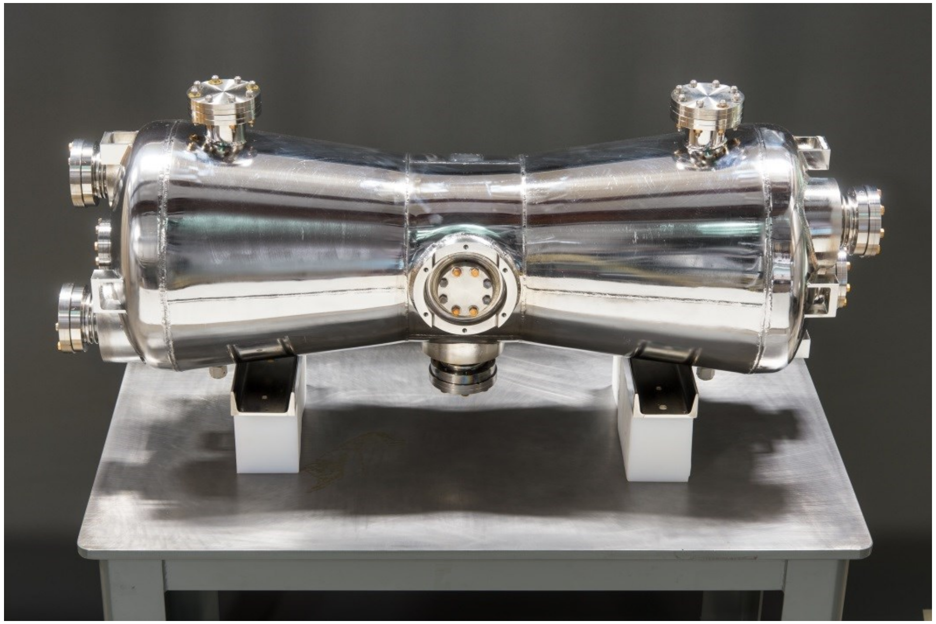
Hydrogen Degassing @ FNAL

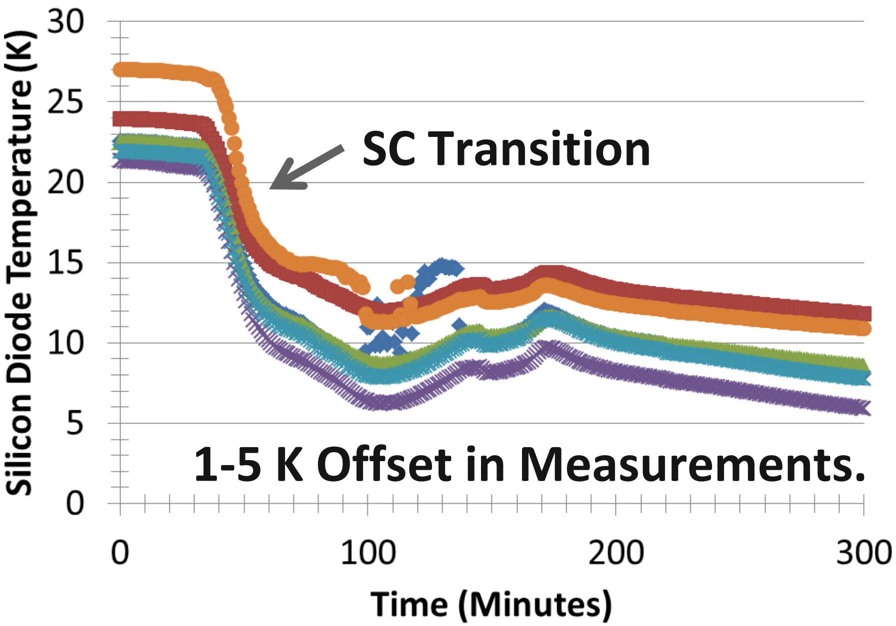


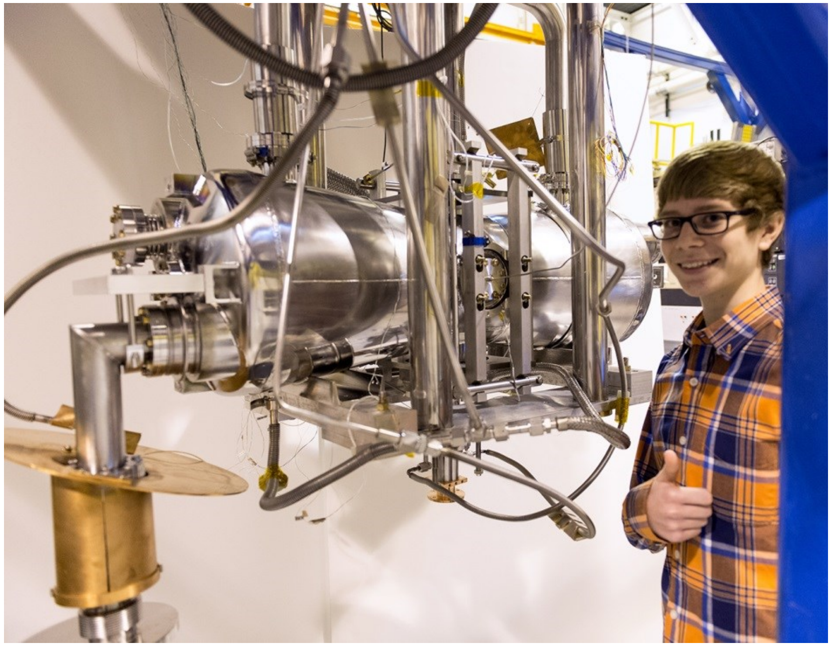
625^{0}C High-Vacuum Bake thanks to M. Merio and A. Rowe (FNAL).

Cold Test & Cooldown

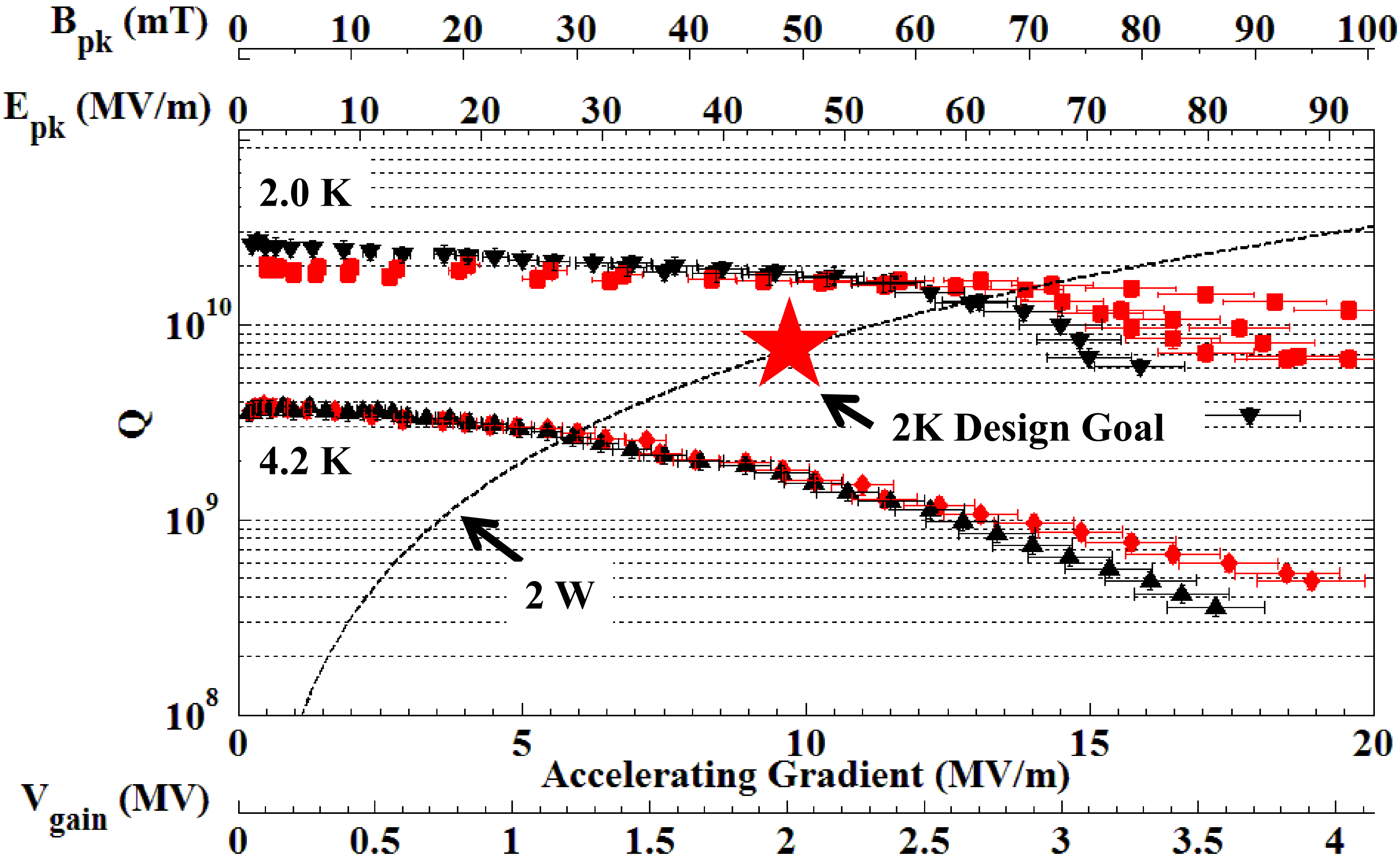
- Cavity hung beneath a large helium reservoir.
- Silicon diodes are used for temperature measurement.
- Cavity cooled to 4 K with dewars.
  - Rapid cooling 165 – 50 K.
- Entire bath pumped to 2.0 K.



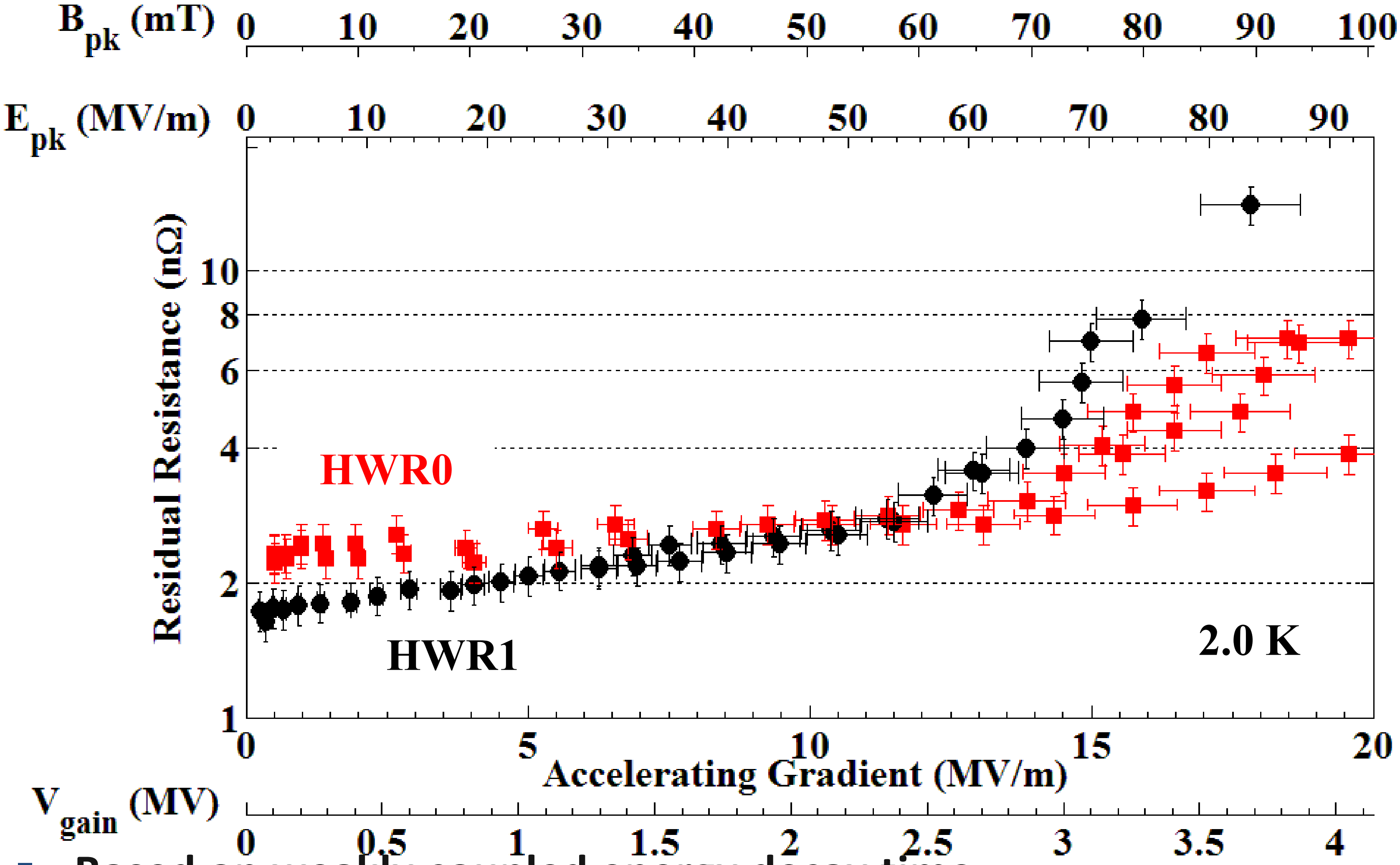




162.5 MHz HWR Q Curves



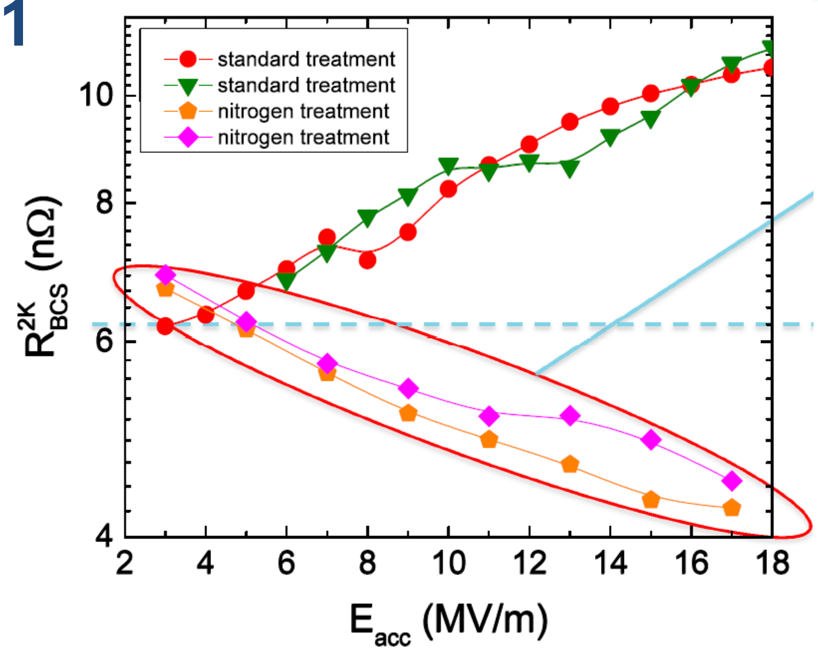
162.5 MHz Residual Resistance

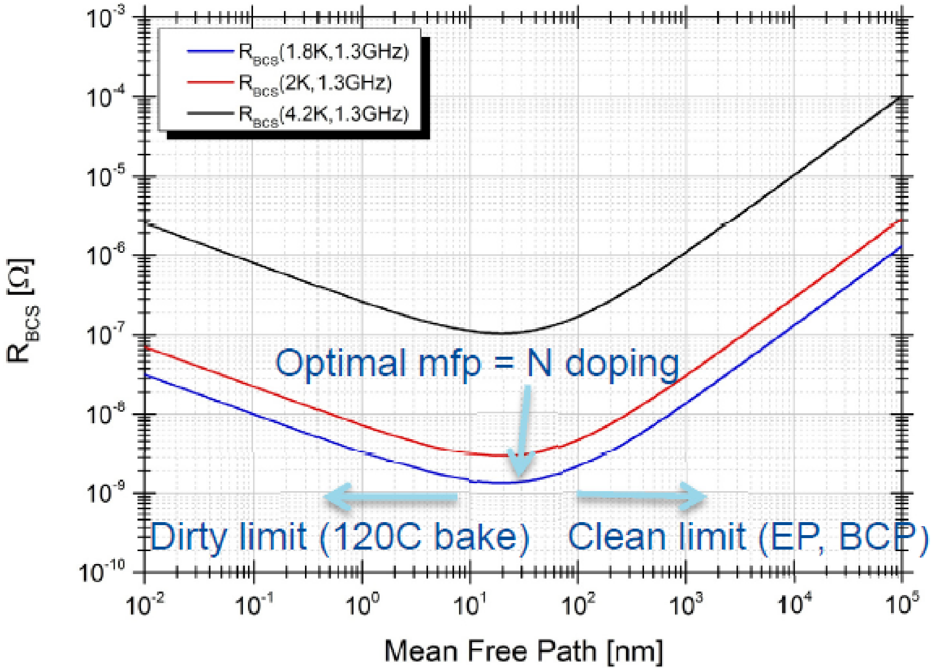


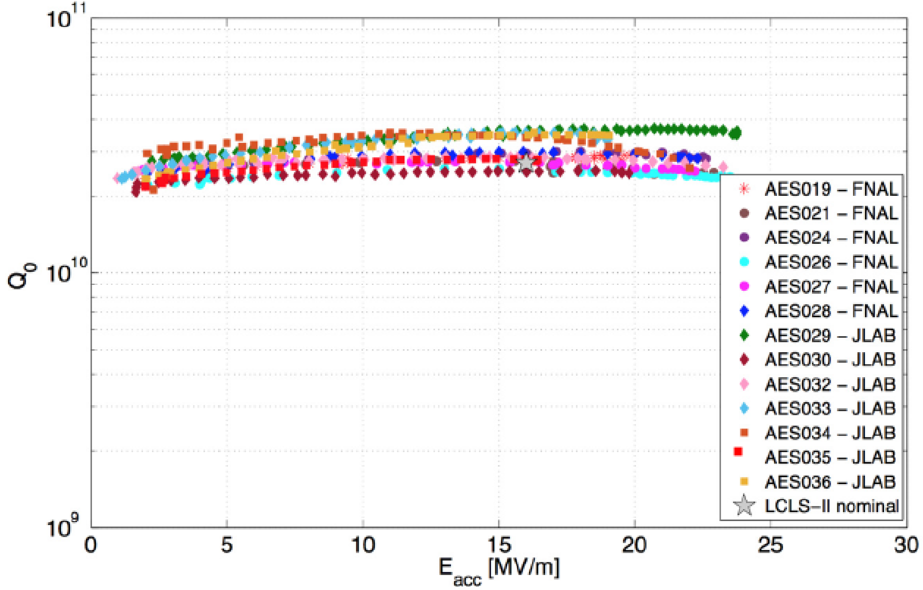
- Based on weakly coupled energy decay time.
- Ambient magnetic field 0-40 mG mostly aligned with the axis of the cavity. Fluxgate magnetometers used for this measurement.

Today’s State of the Art for $\beta = 1$

- What is state of the art?
- Velocity of light 1.3 GHz elliptical cell resonators.
  - Nitrogen doping.
  - New materials, Nb_3Sn @ Cornell. Not discussed here.
  - Cooldown speed.
  - Bulk niobium’s hydrogen/nitrogen content.







A. Grassellino, SRF15, presentation MOBA06
A. Grassellino et al, SC. Sci. Tech. **26** 102001 (2013)
A. Romanenko et al, Appl. Phys. Lett. **102** 252603 (2013)

Cavity Summary

- **Highly optimized cavities.**
  - RF Performance improved by increase volume over which the magnetic energy is distributed.
  - Including fabrication and processing.
- Constantly working to improve cavity fabrication and processing.
- High peak fields achieved.
  - Peak Electric > 70 MV/m.
  - **Peak Magnetic Field no fundamental limit observed.**
- Low residual resistance:
  - **Low field 1.7 - 2.3 nΩ.**
  - Full range 1.7 – 8 nΩ.
  - @ operating voltage of 2 MV/cavity 2.3 – 2.7 nΩ.
    - < 1 W into helium bath for E_{pk} = 45 MV/m and B_{pk} = 48 mT.

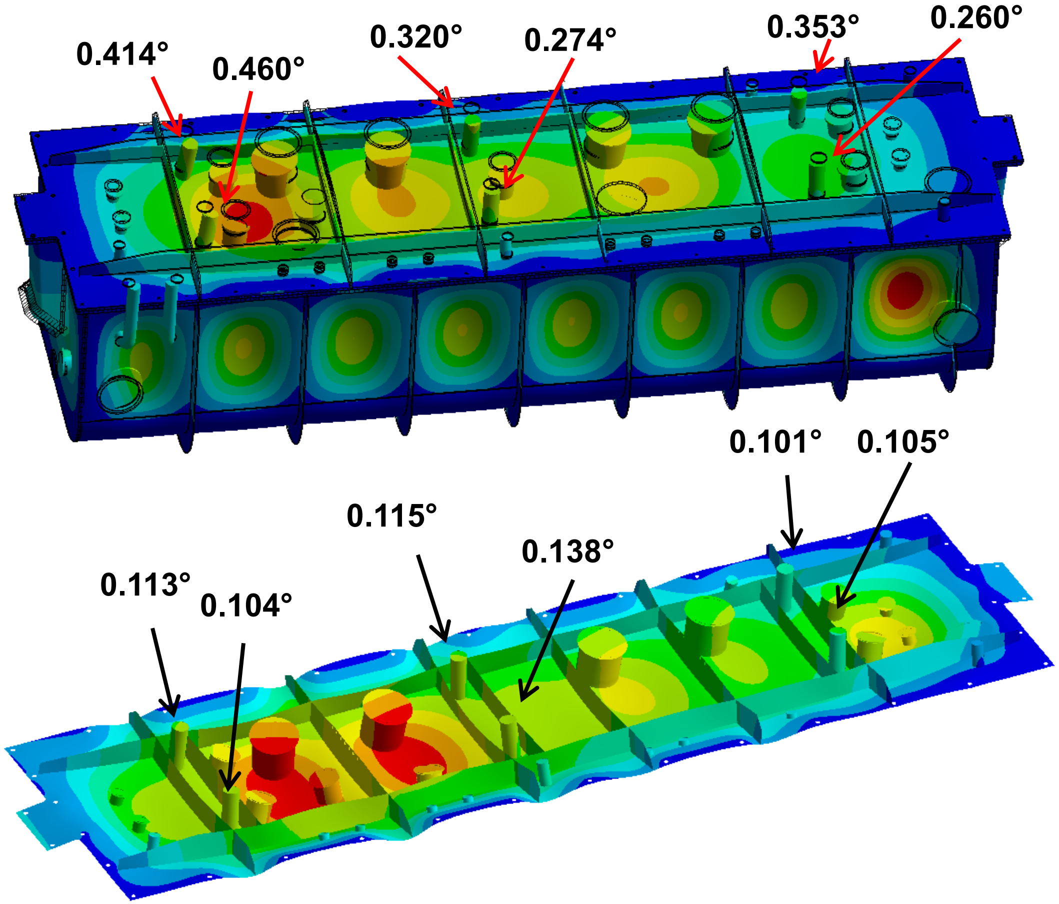
Where are we going with the cryomodule?

- Everything designed to meet relevant safety codes.
  - Cavities: Niobium not a code allowable material. Use “industry standard” material properties and follow ASME BPVC.
  - Solenoids: Jacket = ASME U-stamped.
  - Cryomodule = vacuum vessel. ASME BPVC analysis rules followed no code stampl.
  - All internal cryomodule plumbing = ASME B31.3, the process piping code.
- Next a brief review of all of this.

Design: Cavities and Cryomodules

- Design must protect against:
  - Plastic Collapse.
  - Local Failure.
  - Buckling.
  - Failure with Cyclic Loading.
- Design must also:
  - Maintain alignment.
  - Not break penetrations.
- Not discussing solenoids. They receive an ASME U-stamp.

Port Deflection Initial and Final

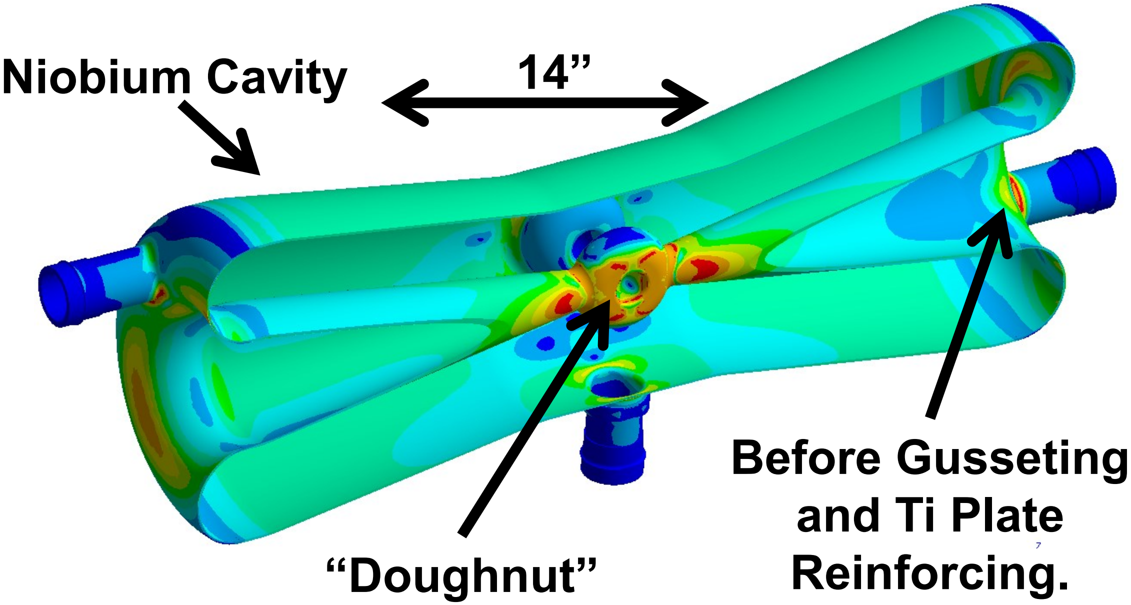


20^{0}C Material Properties

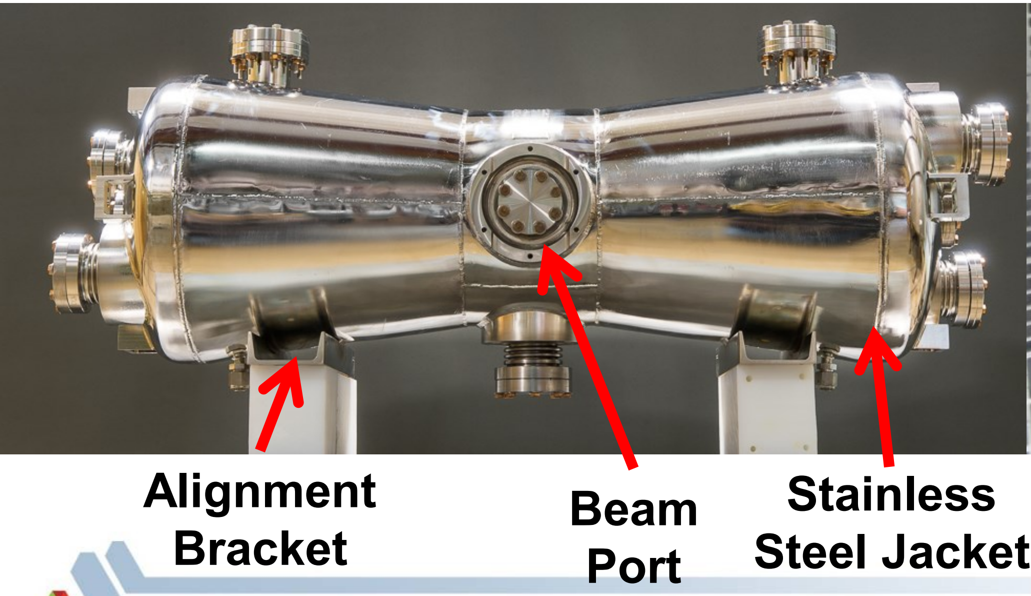
Material	Young's Modulus (ksi)	Poisson's Ratio	Density (lbs/in^3)	Maximum Allowable Stress (ksi)
304 Stainless Steel	29,000	0.270	0.286	20.0
Niobium	15,200	0.396	0.310	5.5

Vessel Design: Cavities

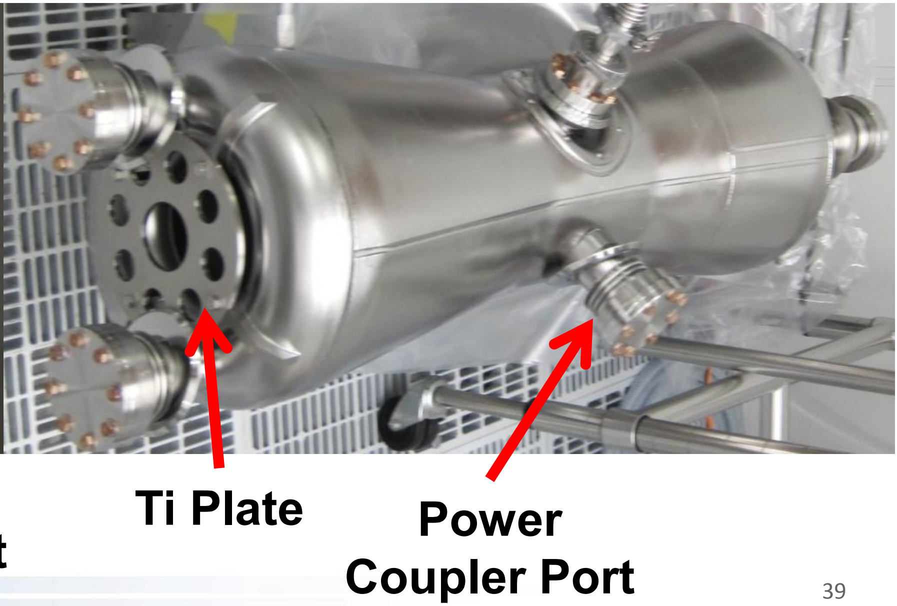
- Design Loads:
  - 2 bar @ R.T.
  - 4 bar @ 2 K.
- Used the rules in the ASME BPVC. No code stamp.
- Used material properties for Nb in compliance with "industry standards".



Finished Cavity

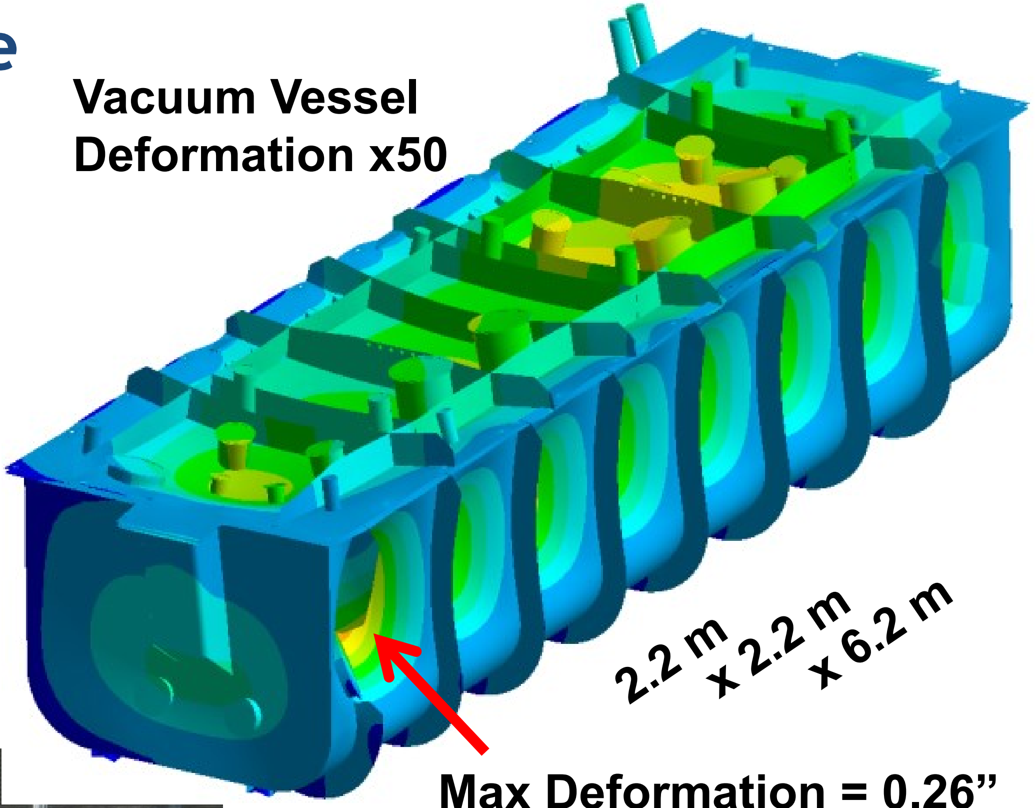


Bare Niobium Cavity



Vessel Design: Cryomodule

- Vacuum Vessel @ 14.7 psiv.
- Used ASME BPVC code to demonstrate protect against:
  - Plastic Collapse (Limit-Load).
  - Local Failure.
  - Buckling.
  - Ratcheting and Cyclic Loading.
- Very safe vacuum vessel.



Vacuum Vessel Deformation x50

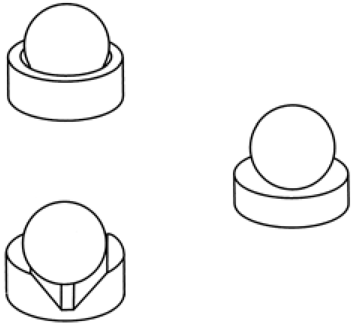
Max Deformation = 0.26”

- Magnetic shielding lines the inner surface of the vacuum vessel.
- 70 K thermal shield inboard of magnetic shield.
  - 32 layers MLI outside.
  - 16 layers MLI inside.

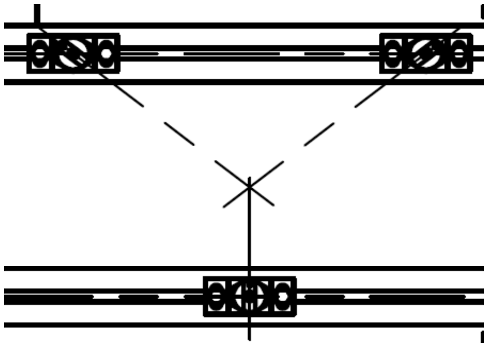
Alignment – 1: Thermal Contraction & Kinematics

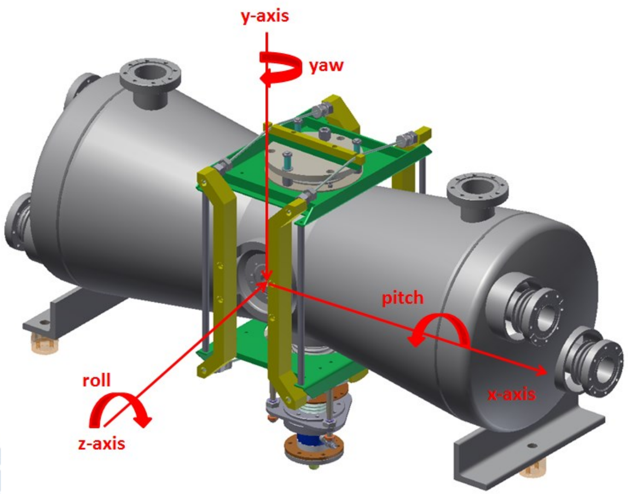
- Need to align solenoids to ±250 μm_{rms} and $\pm 0.1^0$ in pitch, yaw and roll relative to the beam axis.
- Transverse shift ~ negligible.
  - We have changed from a Kelvin to a Maxwell planar kinematic coupling.
    - Maxwell geometry can be designed to be thermally invariant.
    - Kelvin geometry shifts toward fixed point.
- Vertical Shift = 650 μm up.
  - Hanger Contraction = + 1,640 μm up.
  - Alignment System contraction = -990 μm up.
  - Possible to zero.

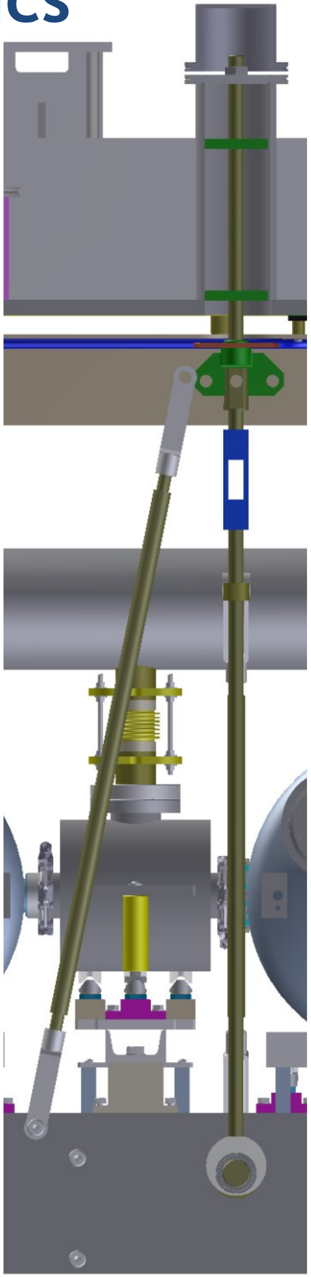
Kelvin



Maxwell







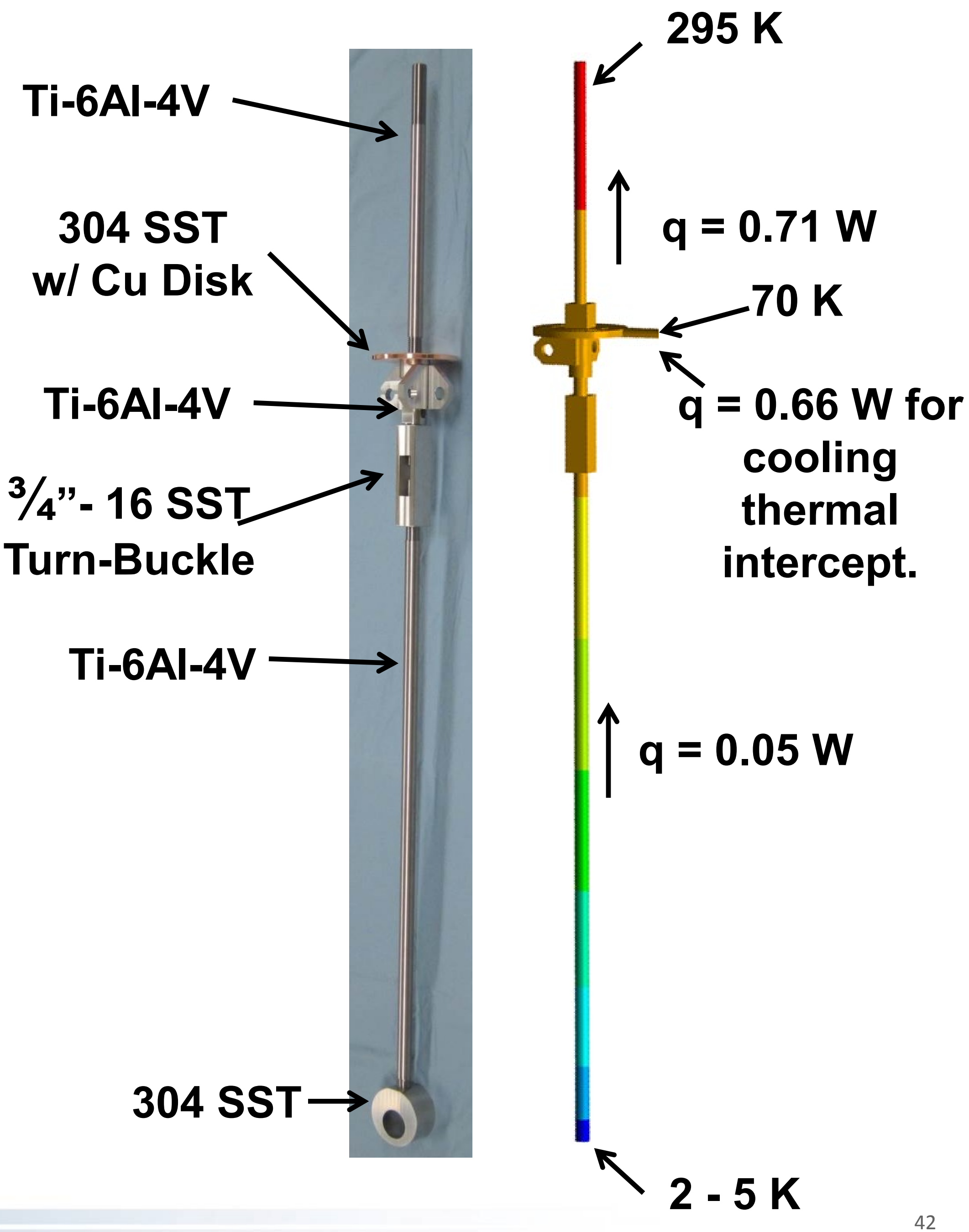
“Design of three-grove kinematic couplings,” A.H. Slocum, Precision Engineering **14**, Pg. 67 (1992).

“Optimal design techniques for kinematic couplings,” Precision Engineering **25**, Pg. 114 (2001).

Cold-Mass Hangers

- Hangers have to:
  - Support the 4 ton cold-mass.
  - Allow for adjustment and alignment of the cold-mass.
  - Thermally isolate the ~2 K cold-mass from room temperature.

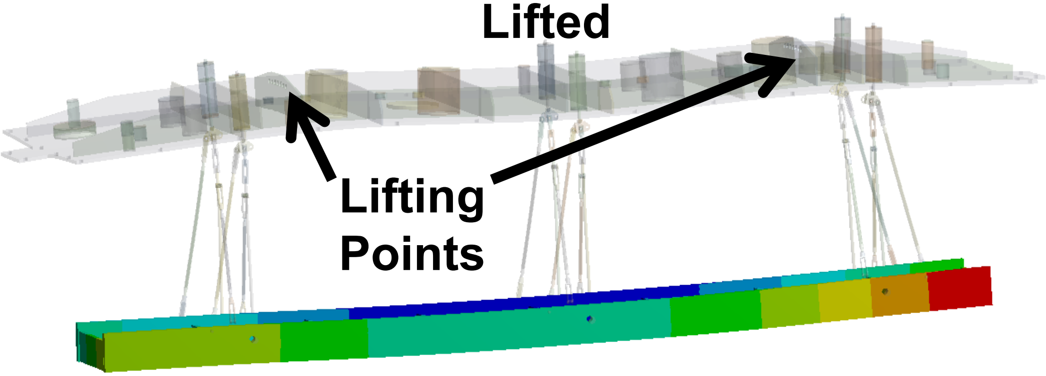
- We take advantage of:
  - Low thermal conductivity materials.
  - Relatively high thermal contact resistance for grease- and lubrication-free connections.



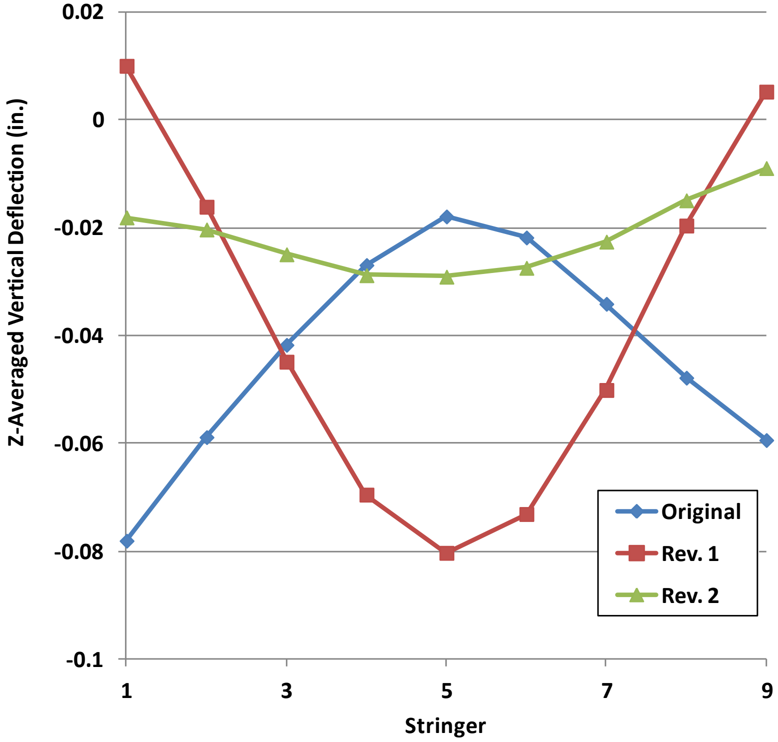
Alignment – 2: Ti Strong-Back

- When lid is on the box the loaded strong-back rails are flat and parallel within 0.005”.
- Lifting may perturb the alignment.
- Reduced lifting disturbance via design.

Model of Lid/Strong-Back being Lifted



Lifting Analysis Design Evolution



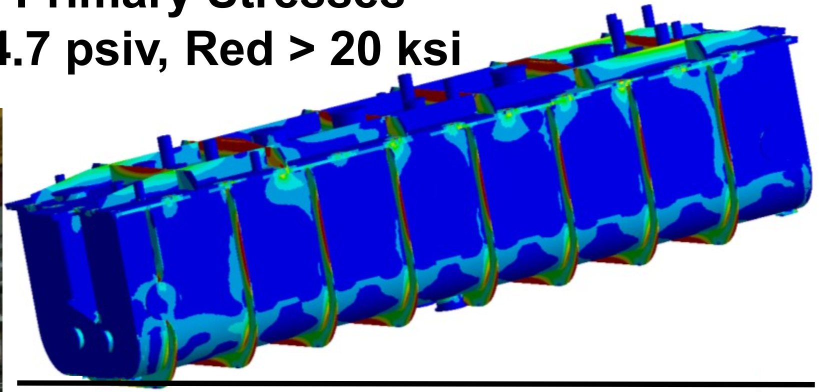
Strong-Back

Summary

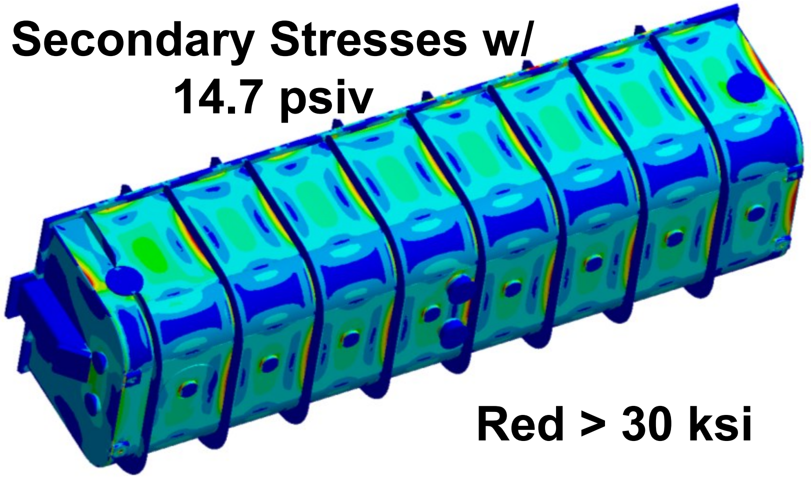
- The half-wave cavities perform well.
- Almost ready to start assembling the cryomodule.
- Everything designed to meet relevant safety standards.
- This is a work in progress and this is an exciting time.

Delivery of Cryomodule @ ANL

Primary Stresses
14.7 psiv, Red > 20 ksi



Secondary Stresses w/
14.7 psiv



Red > 30 ksi