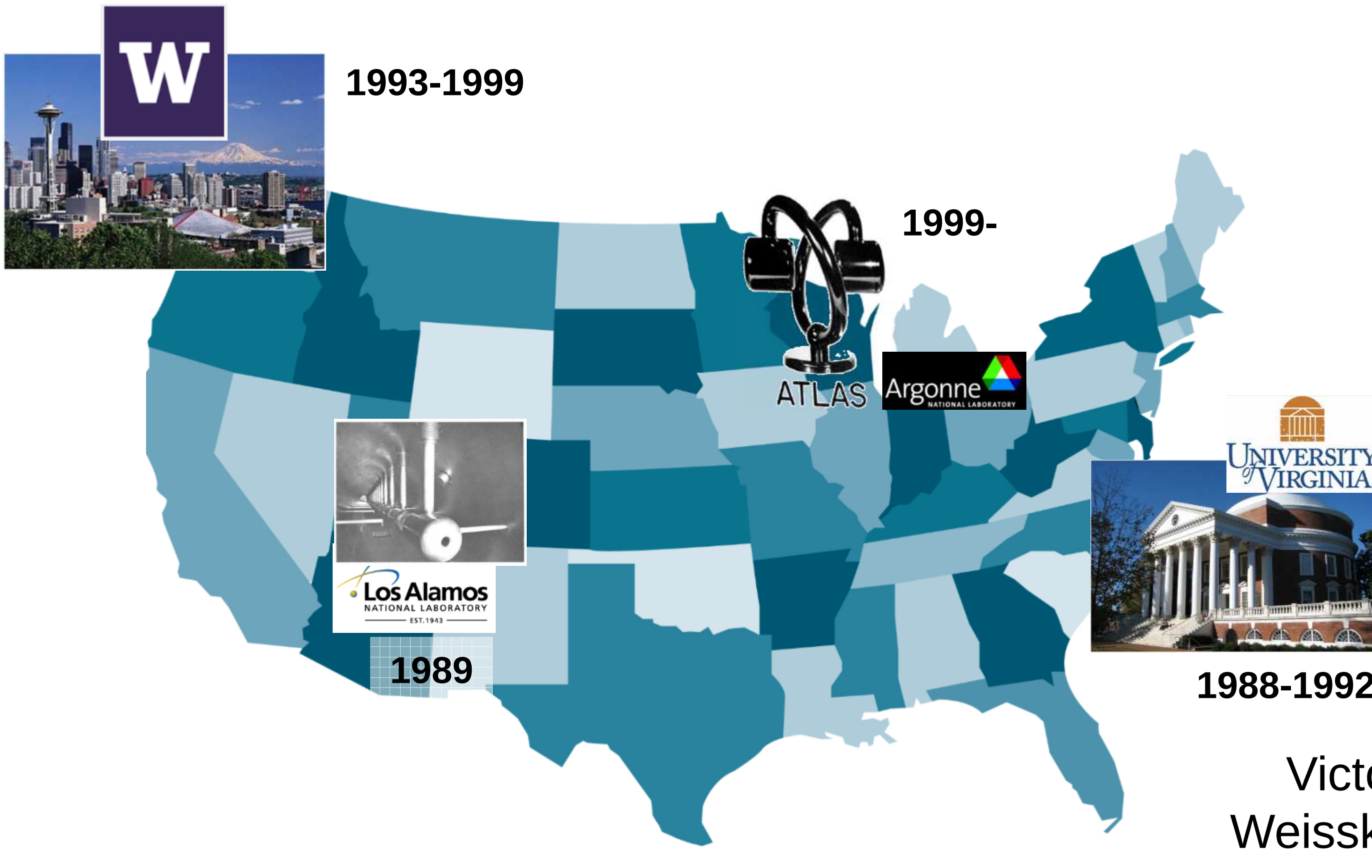
SRF Technology: The Last 15 Years

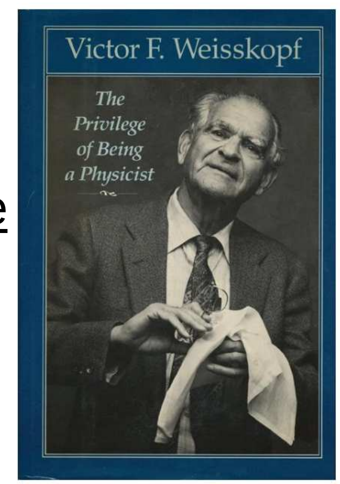
Accelerator Physics and Technology Seminar
Fermilab
January 13, 2015

Speaker: Mike Kelly

A Personal Comment on My Path to SRF Accelerators



Victor Weisskopf, <u>The Privilege of Being a Physicist</u>. (1989) Essays.



Superconducting RF Technology: The Last 15 Years

Superconducting RF technology for accelerators had its beginnings in the 1960's and 70's, when a small number of ***scientists and engineers wagered their reputations and the livelihoods of their laboratories on an unproven technology***. For ion acceleration, the 'killer' application was as an afterburner for a heavy-ion tandem accelerator. The new technology offered efficiency and flexibility that was unmatchable using room temperature structures. The wager paid off. It has been my pleasure to participate in the rapid expansion of the technology over the past 15 years. Widespread interest in large SRF-based accelerators for ion acceleration over the essentially the full velocity range has driven the development of myriad new SRF cavities. A confluence of the efforts on cavities for ion acceleration with those pushing the performance of velocity-of-light structures has benefited performance for the full velocity range. The fruits of these efforts are just beginning to bear. A presentation of the technology ***from the point of view of Argonne's ATLAS*** heavy-ion accelerator illustrates many of these recent technical achievements.

First Work at Argonne on Superconducting Cavities

A. Jaffe (146 P)

Volume 37A, number 2 PHYSICS LETTERS 8 November 1971

100 μm = .004″

A NEW METHOD OF ELECTROPOLISHING NIOBIUM *

H. DIEPERS, O. SCHMIDT, H. MARTENS and F. S. SUN
Research Laboratories Erlangen of Siemens AG, Germany

Received 4 September 1971

By a new method of electropolishing niobium we have obtained very smooth surfaces. In electropolished TE_{011}-cavities with an anodic oxide film a Q-value of 3×10^{10} and a critical magnetic field of 80 mT were obtained in the X-band without any heat-treatment.

There are two ways of producing microscopically smooth and damage-free finishes on niobium, namely by chemical and electrolytic polishing. Mechanical methods can produce smooth finishes, but only with a high concentration of lattice defects and impurities. Where shapes are complicated, chemical polishing has its limitations since the specimens have to be immersed in the solution under defined conditions of solution flow etc. Local disturbance of the solution flow results in etching instead of polishing at such points. In such a case, electropolishing is to be preferred. The potential distribution between the anode and the cathode can generally be adapted to the geometry of the specimen (anode).

A large number of electropolishing solutions are known [1, 2], which would point to the fact that a special method is necessary for a specific geometry or a specific physical state of the niobium. However, the methods employed so far have the disadvantage that etching is observed when removing layer thickness of, for instance, 100 μm. In many cases, however, it is necessary, e.g. for the complete removal of damage

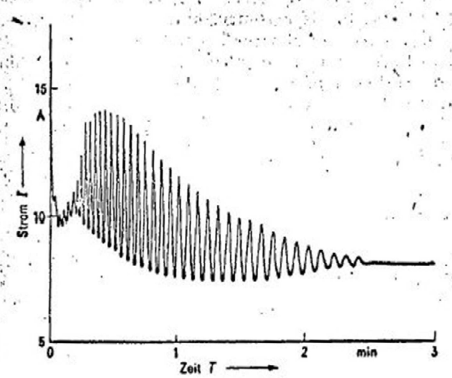
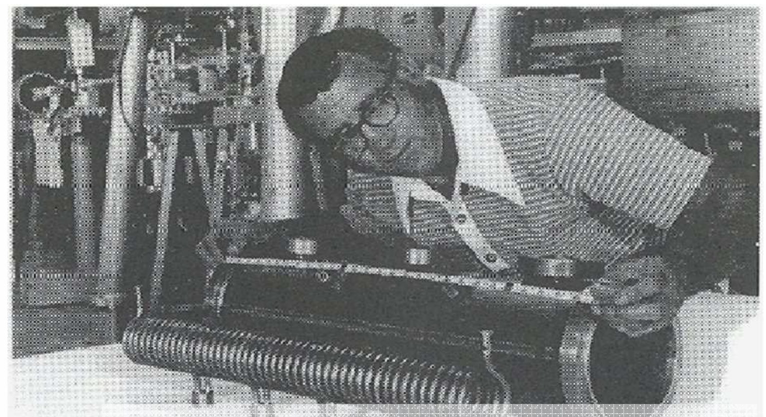


Fig. 1. Electropolishing niobium current oscillations.

in the above-mentioned voltage range. Fig. 1 shows the typical characteristic of this oscillation. The voltage associated with the current oscillations must be controlled at a constant value.

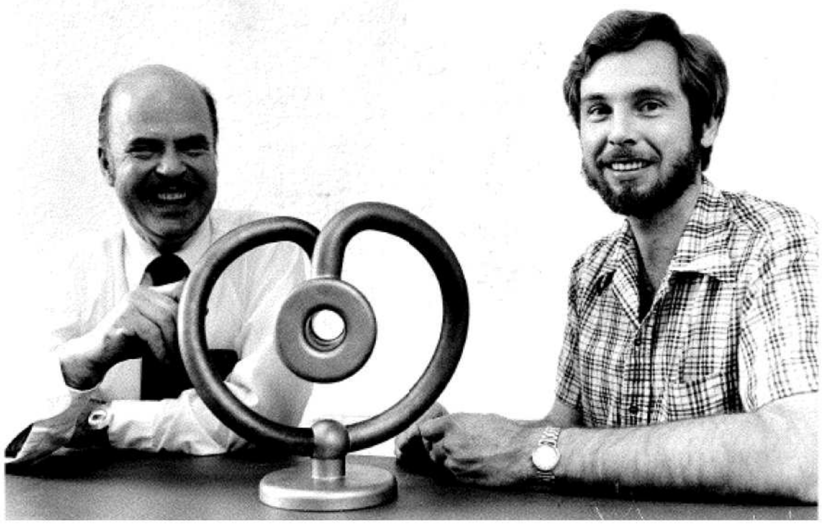
ANL collaboration with Karlsruhe on Electropolishing

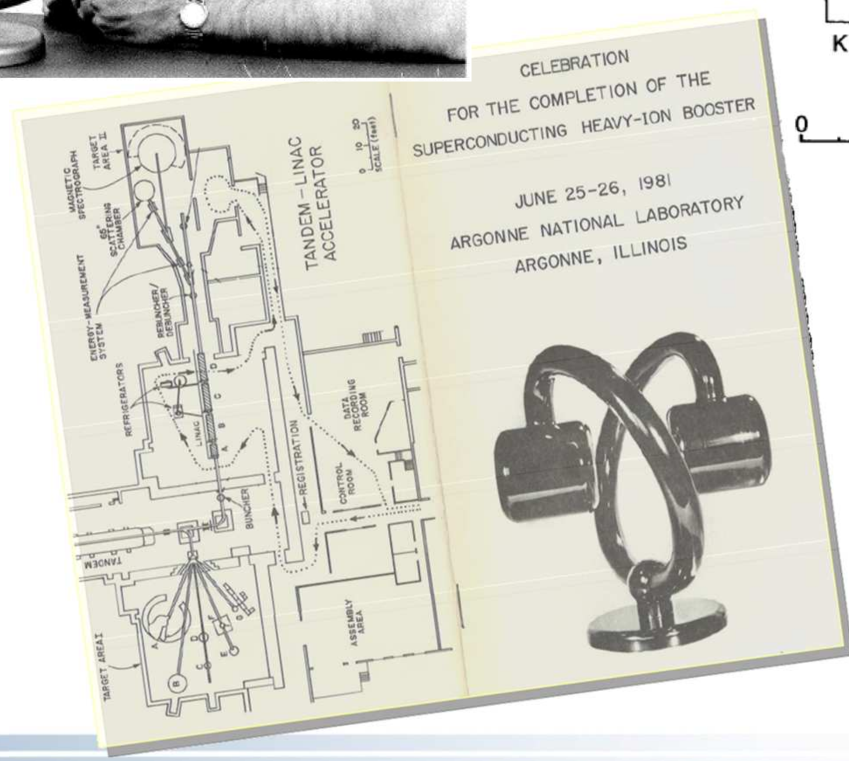


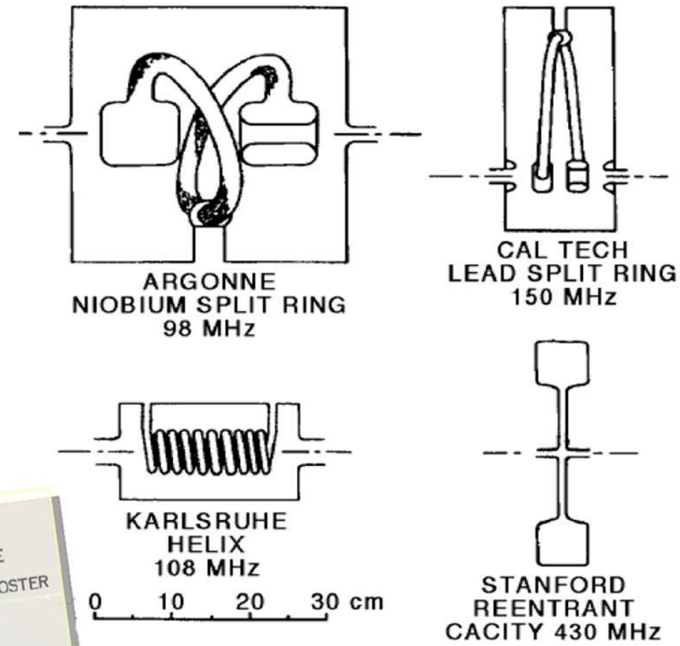
Paul Markovich – ANL chemistry

Helical Nb resonator developed at ANL for a heavy-ion linac.

The Era of the Split-ring Cavity at the ATLAS Heavy-Ion Linac

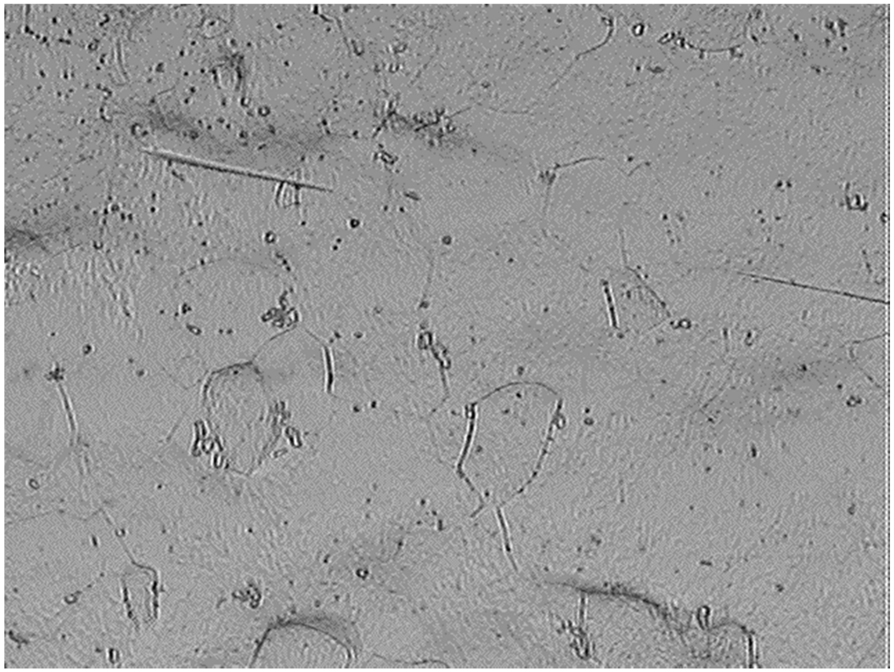


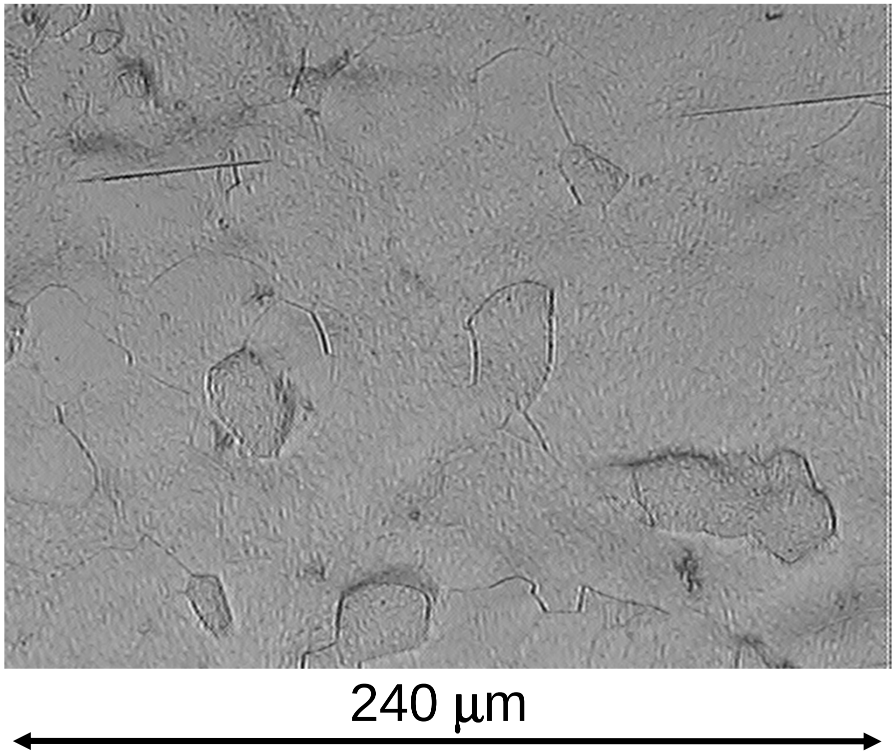




Part I. Development for Rare Isotope Accelerator (RIA, presently FRIB), Spoke Cavities and Electropolishing

I. 15 Years Ago Clean Room High-Pressure Rinsing Was Relatively New. It Had Not Been Used for Low-Beta Cavities



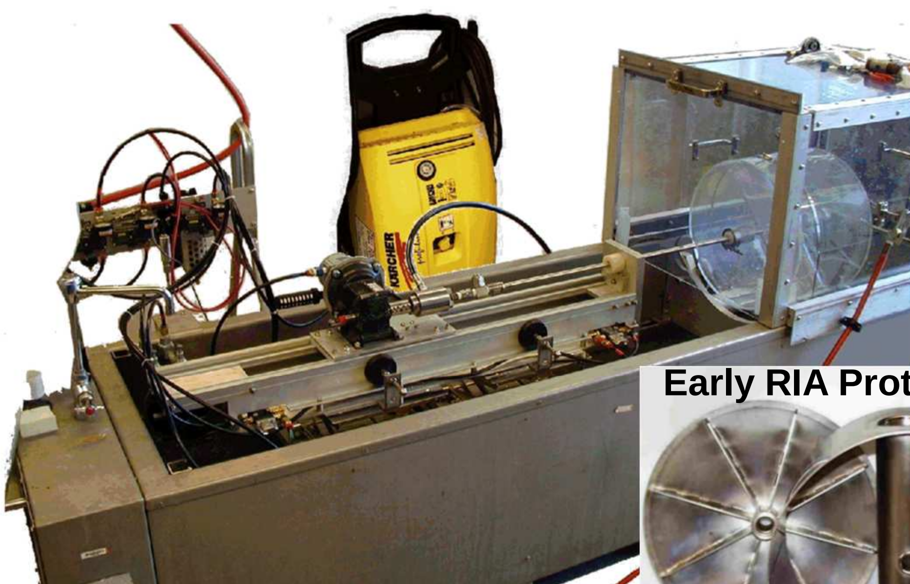


Fine-grained niobium sample

- A high velocity water jet (150 m/s) effectively removed particulates from niobium test samples with no obvious damage
- Practical limit ~ 1 µm

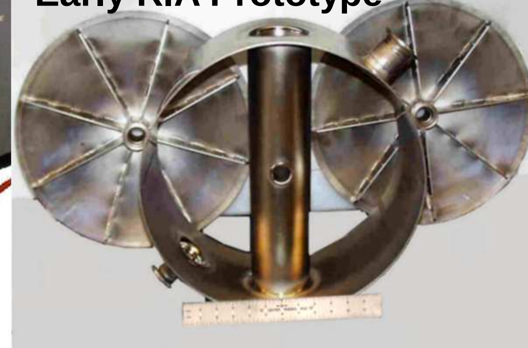
  -adhesion forces scale as particle diameter, mechanical force scales as particle area

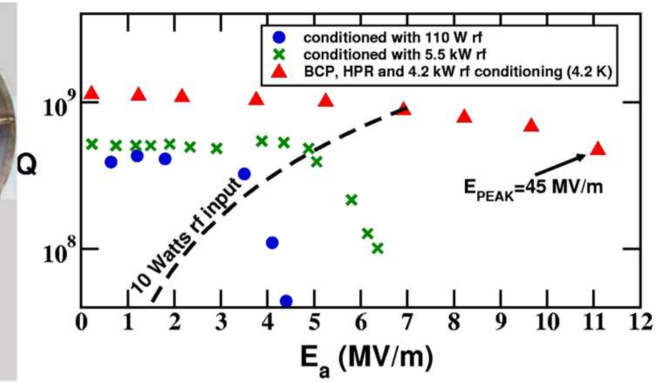
I. First Low-Beta High-Pressure Rinsing Results from 2001



The first clean room high-pressure rinsing system for low-beta cavities was put together at Argonne in 2001 on a budget of just over $10K

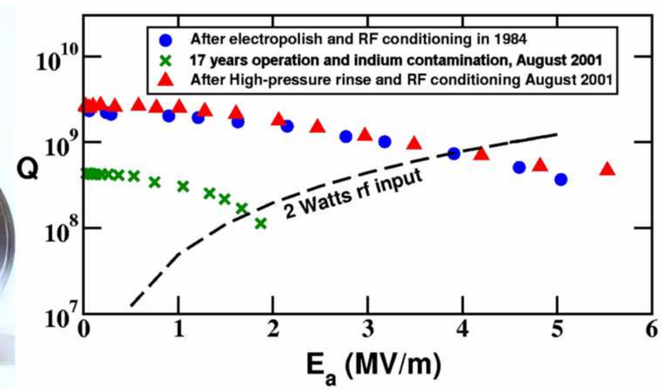
Early RIA Prototype



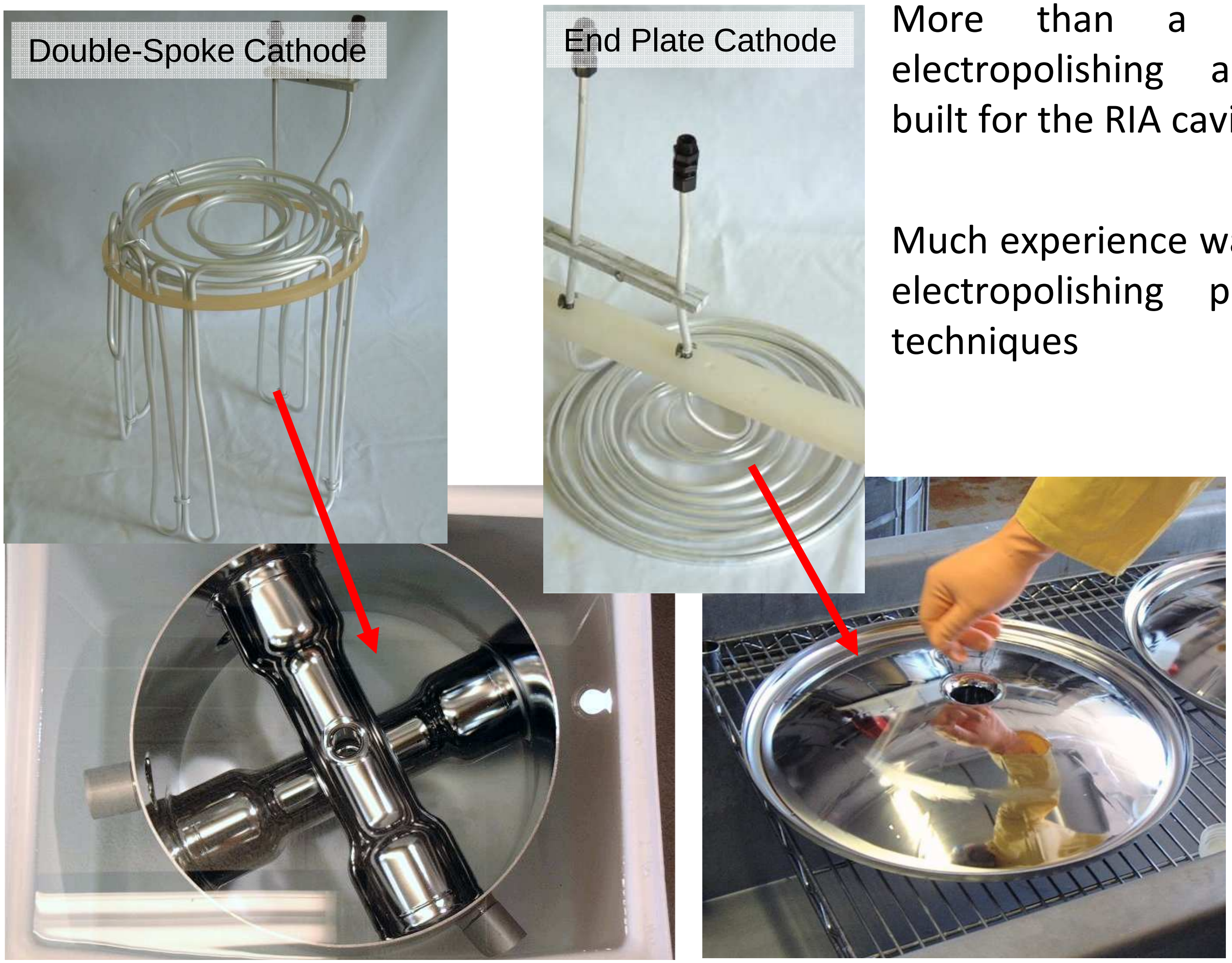


Field performance increases by 2 times or more compared to what could be achieved with rf pulse conditioning

Split-ring from 1984



I. Adaptation of Electropolishing to Complex Geometries

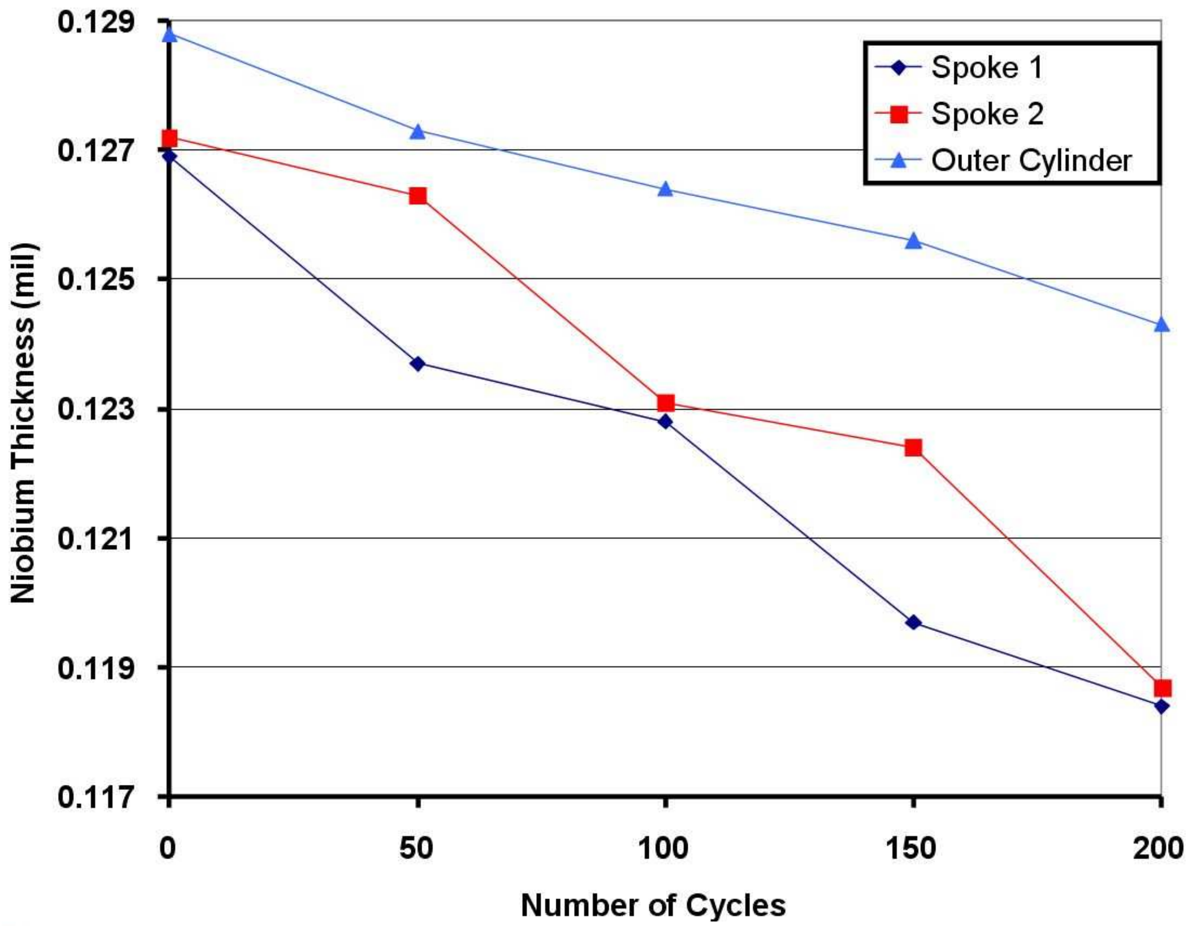


More than a dozen unique electropolishing apparatus were built for the RIA cavities

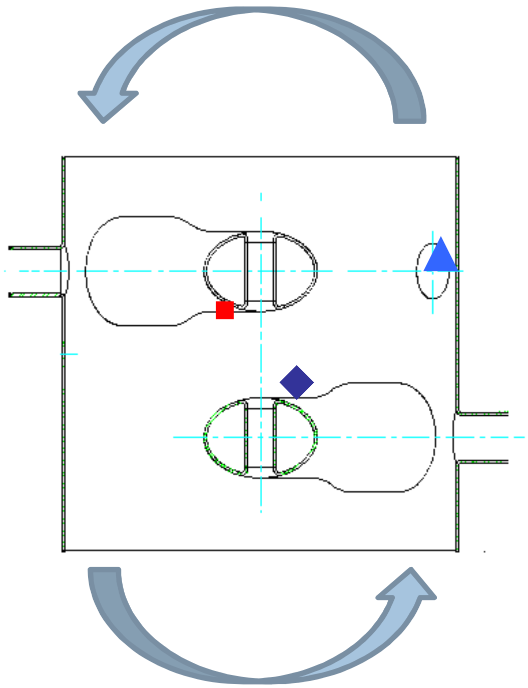
Much experience was gained on the electropolishing parameters and techniques

I. Details of Electropolishing on Real Cavities

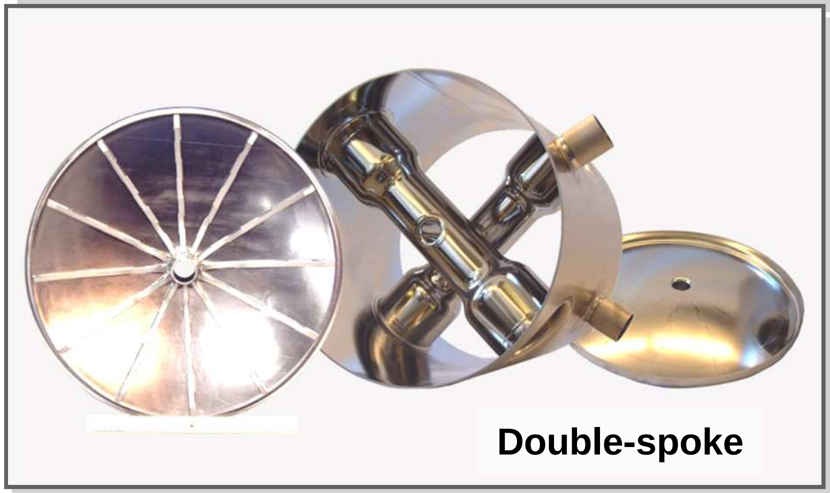
- Cavity surface removal was monitored using an ultrasonic thickness gauge
- The cavity flipped 180 degrees after each set of ‘50 cycles’ (1 cycle = 1 minute)
- Twice the surface removal for downward facing surfaces as for upward facing surfaces
  - The effect comes from the lower density of the reaction products as compared to the bulk electrolyte



Cavity orientation changed after each set of ‘50 cycles’



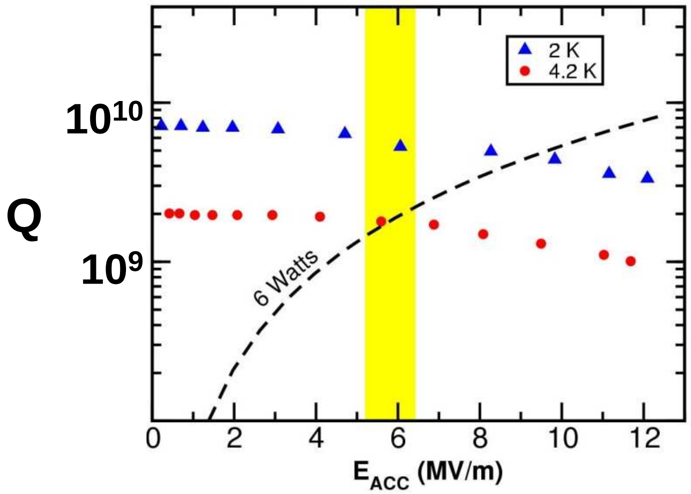
I. Electropolished SRF Cavities for Heavy-Ions with $\beta>0.1$

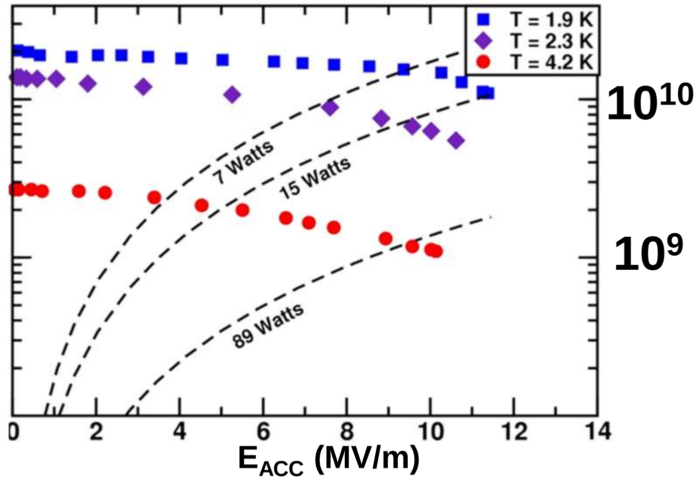


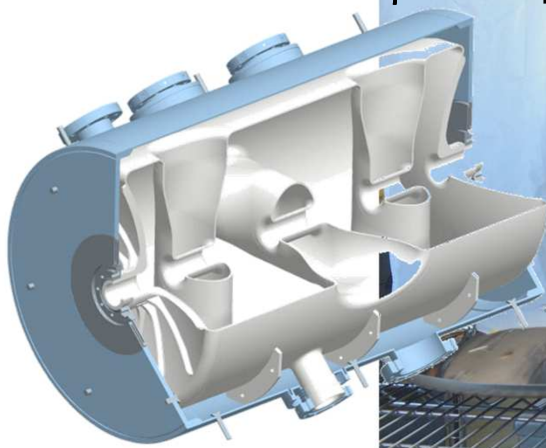
I. Electropolished Triple-Spoke Cavities for β~0.5: (RF surface area ~1.5 m^2)

I. Results for Beta=0.40, and 0.63 Multi-Spoke Cavities

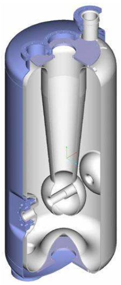
After Hydrogen Degassing, Performance Indicated that Cavities Should be Operated at 2 Kelvin



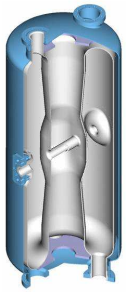




I. Result from 2001-2005: A Practical Set of Superconducting Cavities Spanning the Full Range of Ion Velocities



115 MHz β=0.15 Steering-Corrected QWR



172.5 MHz β=0.26 HWR

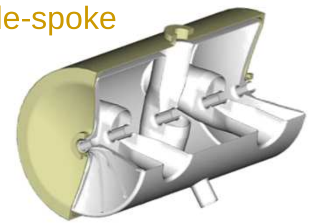
345 MHz β=0.40 Double-spoke

β=0.15 Quarter-Wave

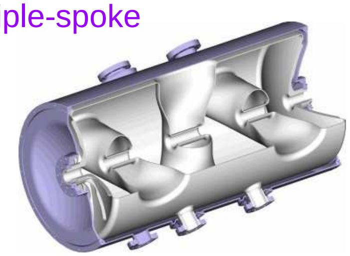
β=0.28 Co-axial Half-Wave

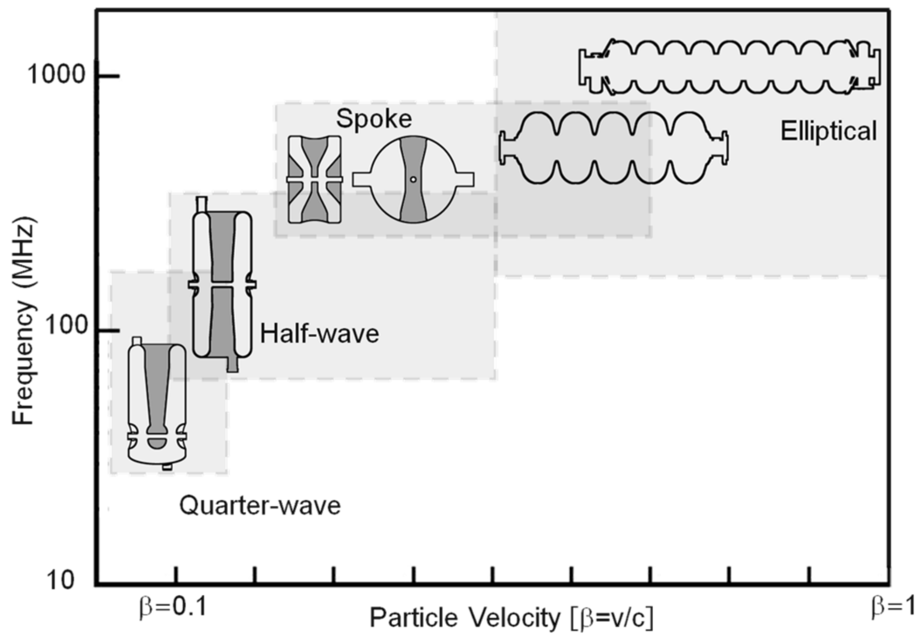
β=0.63 3-spoke

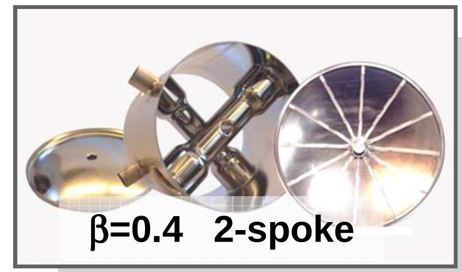
345 MHz β=0.5 Triple-spoke



345 MHz β=0.62 Triple-spoke







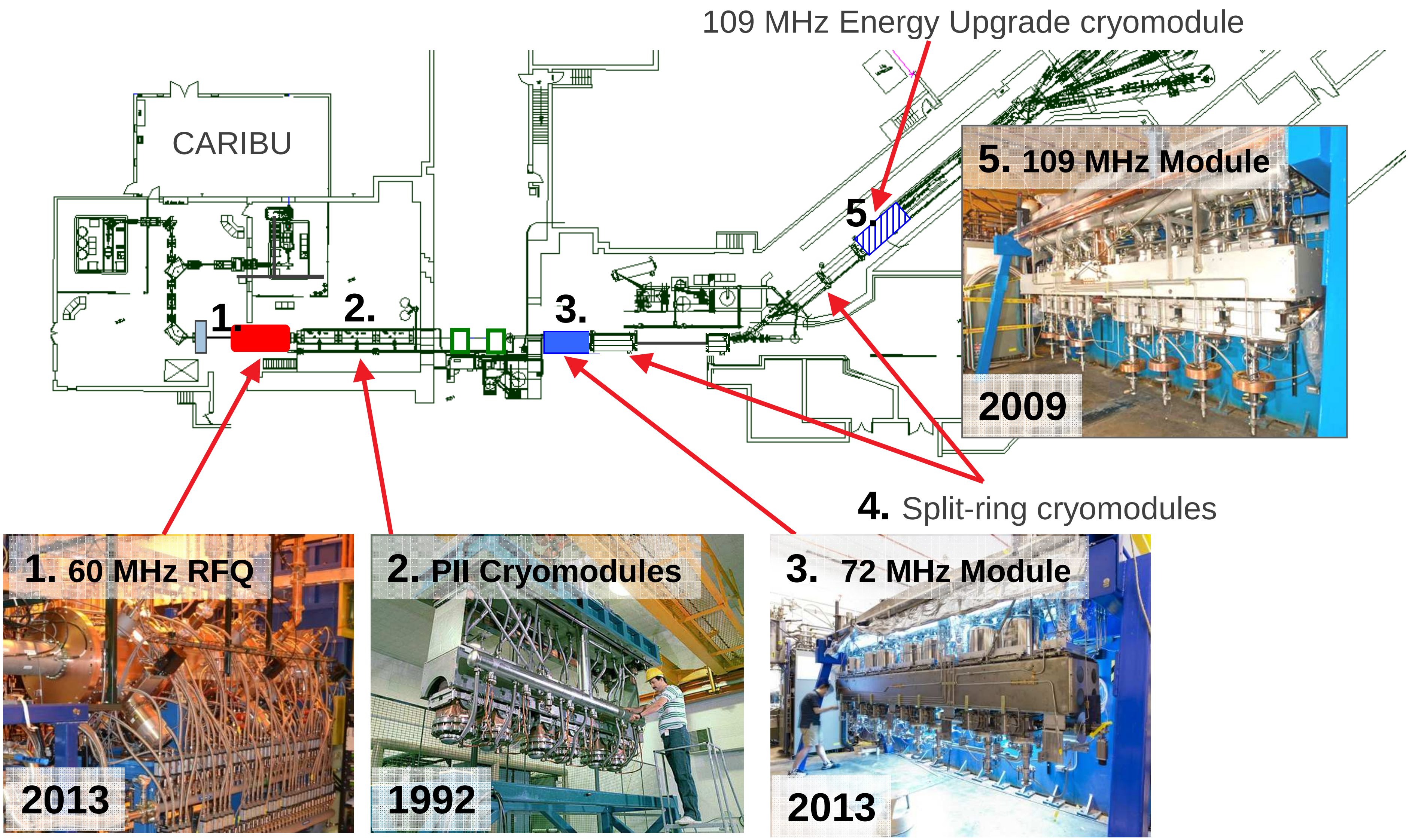
β=0.4 2-spoke

β=0.5 3-spoke

Part II. Overview of ATLAS and Application of Recent SRF Technology

II. The Present ATLAS Accelerator Cryomodules

8 Cryomodules, 47 SC Accelerating Cavities



II. PII Cryomodule During Maintenance – Early 1990's

(PII= Positive Ion Injector)

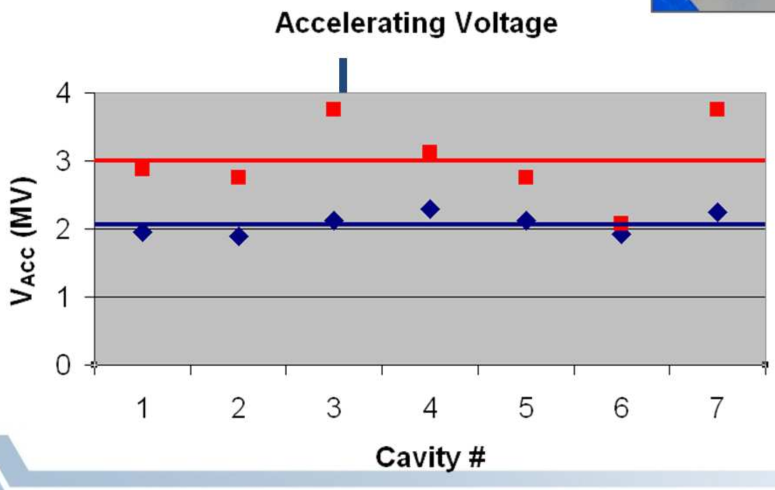
Sub-systems suspended from the lid of a top-loading box cryomodule

This design was popular with the maintenance crew for ATLAS compared to the cylindrical end loading split-rings

This general approach is still used but with the addition of separate cavity and insulating vacuum

II. ATLAS Energy Upgrade Cryomodule (2009)

- A cryomodule of seven β=0.15 quarter-wave cavities at the end of the ATLAS linac
- First ATLAS cryomodule for which the cavity string was assembled and sealed in the clean room
- Established proof-of-principle on important technical questions:
  1. A clean string can be successfully connected to an 'dirty' beamline
  2. Particle migration over time can be mitigated, e.g. cold traps



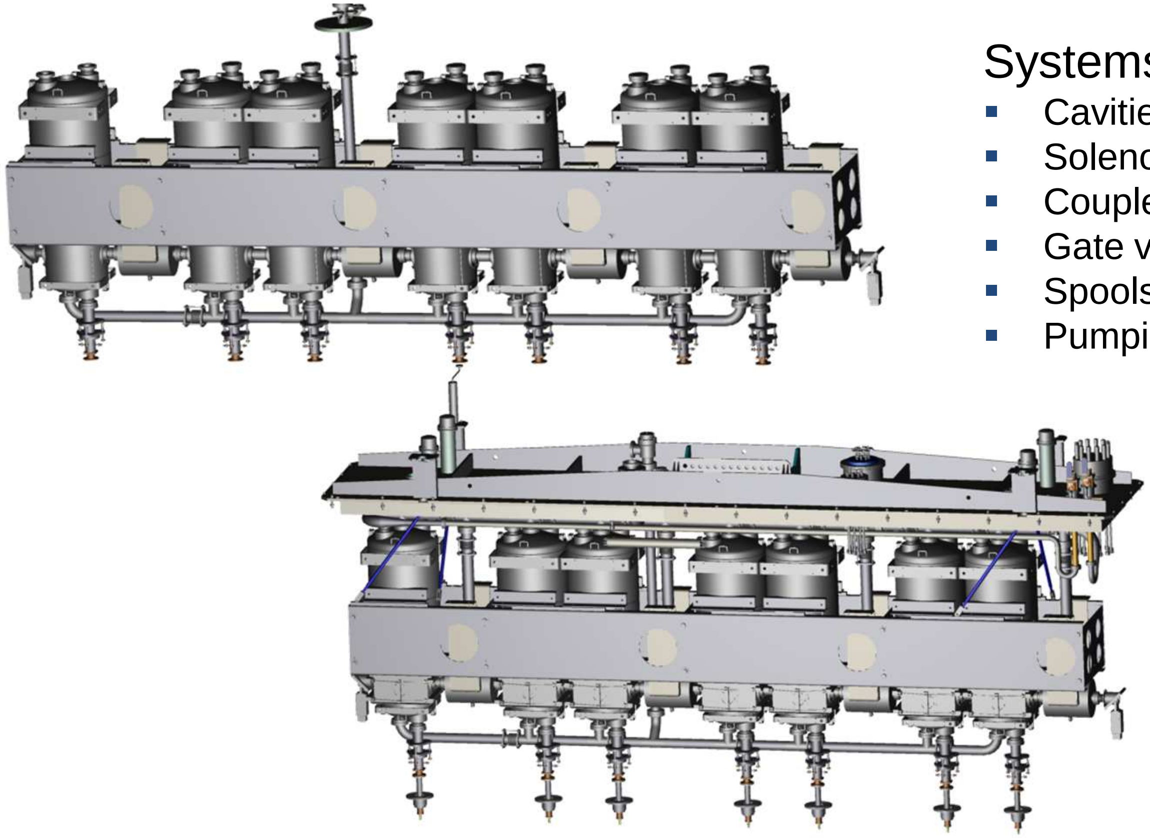
↔ E_{PEAK}=39 MV/m

↔ VCX limit ↔ E_{PEAK}=26 MV/m

(VCX= Voltage Controlled Reactance)

II. ATLAS *Intensity* Upgrade Cryomodule (2013)

Incorporates the best technical ideas from ANL and elsewhere for a 4 Kelvin Cryomodule



Systems assembled in the clean room

- Cavities
- Solenoids
- Coupler cold window
- Gate valves
- Spools
- Pumping manifold

Systems assembled outside the clean room

- Cryomodule and lid
- All cryogenic (He and LN2) plumbing
- Slow tuners, much of coupler
- Shields, MLI
- Diagnostics
- Alignment hardware

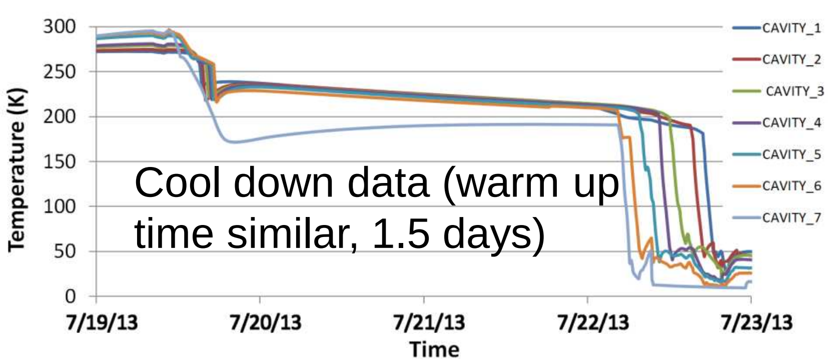
II. Clean Assembly (left) and Hi-bay Work (right) for ATLAS Intensity Upgrade Cryomodule (2013)

Jan. 2013

A well planned and 'minimalist' set of clean assembly hardware (just south side of beamline)

Cryogenics assembly stand on north side of beamline

June 2013

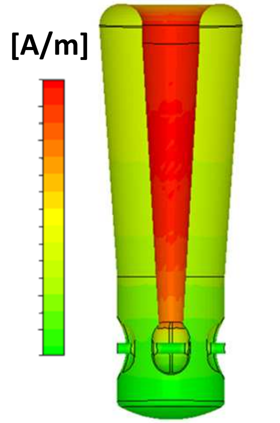


Cool down data (warm up time similar, 1.5 days)

Part III. ANL Approach to Cavities/Cryomodules

- Background on 2-Gap Cavities
- (Select details of) Design
- Technology of Subsystems

III. Superconducting Cavity RF losses, Quality Factor



Surface Magnetic Field

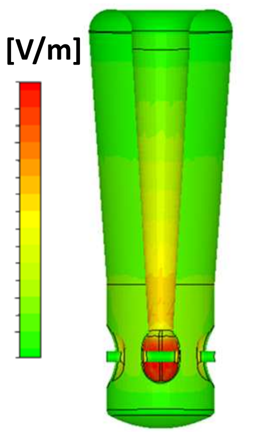
$$P_{IN} = \frac{1}{2} \oint R_S |H|^2 dA \quad \text{[Watts]}$$

Power dissipated in the cavity walls is product of local R_s and square of the (local) magnetic field over the cavity surface

$$R_S = R_{BCS}(T, \omega) + R_{RES} \quad \text{[Ohms]}$$

$$\propto \omega^2 e^{-\frac{\Delta}{k_B T}}$$

Microscopic theory of T, ω-dependent resistance plus everything else



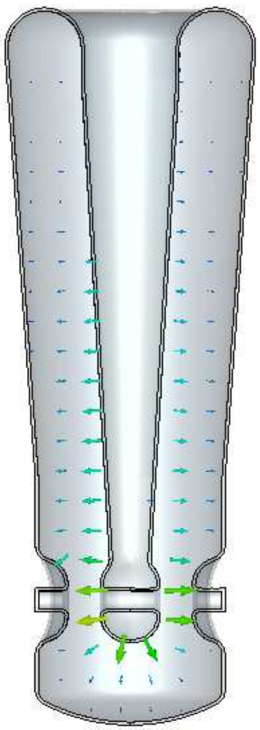
Surface Electric Field

$$Q_o = \frac{U}{\Delta U} = \frac{U_o E_{ACC}^2}{P_{IN}} 2\pi f$$

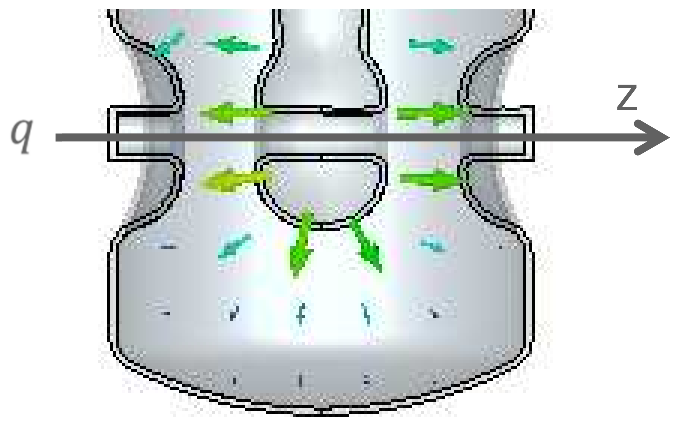
Quality factor as for classical damped oscillator; stored energy divided by fractional energy loss per cycle

III. Charged Particle Acceleration in a 2-gap Accelerating Cavity

Energy gain of a particle, charge q, moving along the z-axis through a sinusoidally varying electric field. φ is the phase of the field as the particle moves through z=0.

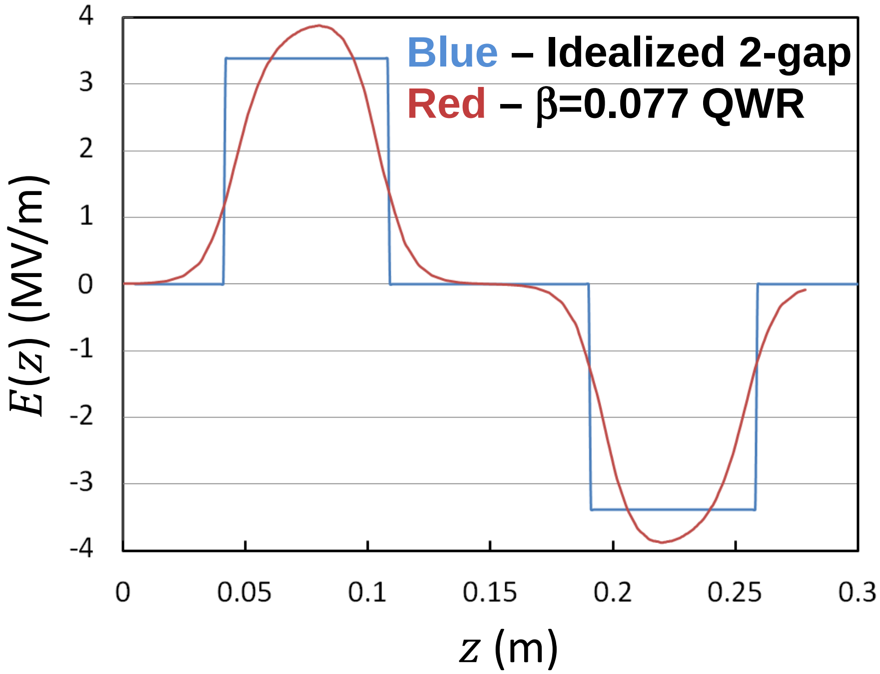


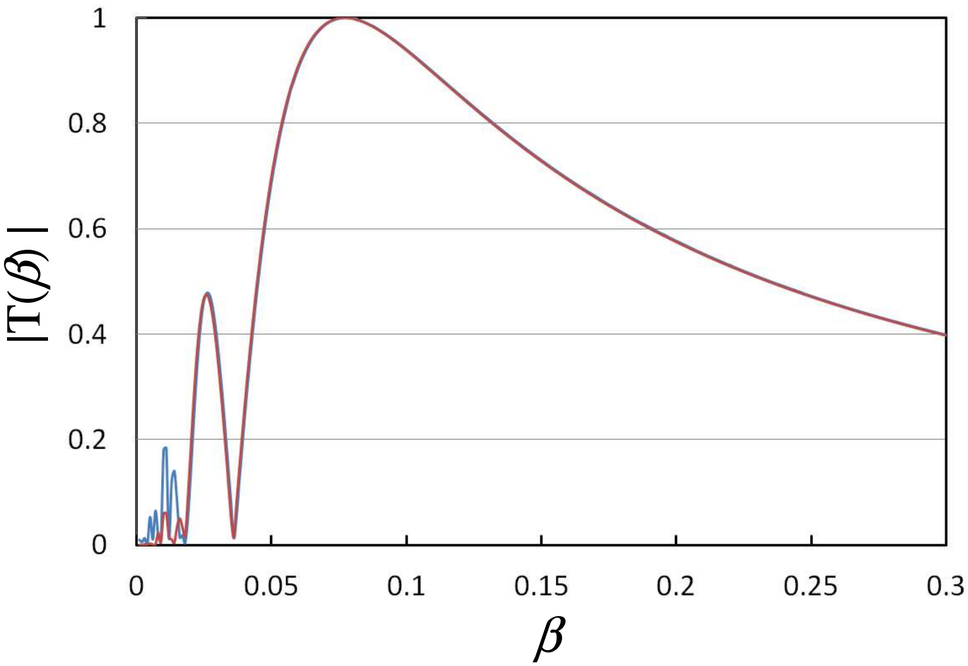
$$\Delta W = q \int_{-\infty}^{+\infty} E(z) \cos(\omega t + \varphi)\, dz$$



III. Charged Particle Acceleration: Realistic Field Profile

- Fields in the gaps penetrate into the beam tube aperture in real cavities
- *Velocity acceptance is broad* and insensitive to penetration of fields into the beam aperture





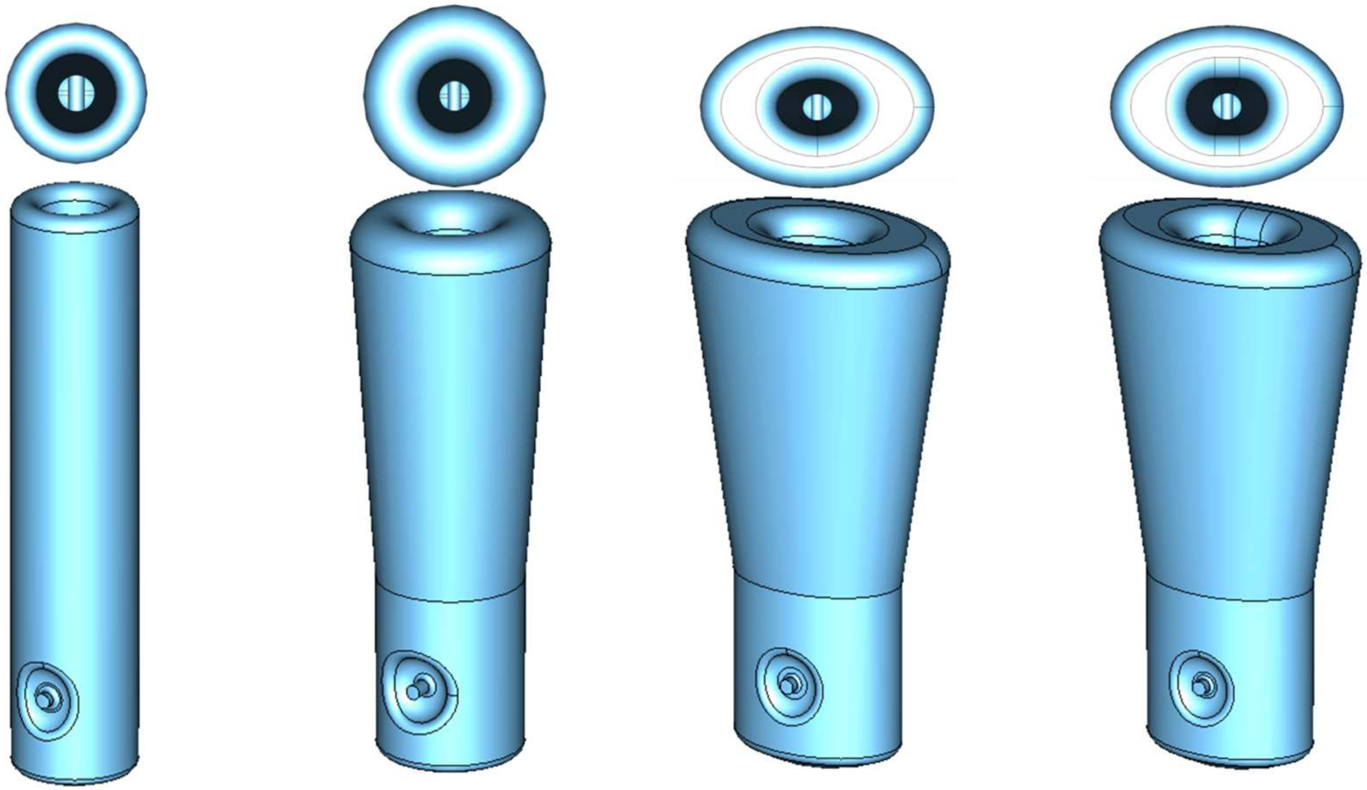
III. 'Figures of Merit' for Cavity Electromagnetic Design

The emphasis or relative importance of the design parameters has evolved (back and forth) over the last 15 years

- E_{PEAK}: Minimize peak surface electric field to reduce field emission (normalized to V_{ACC})
- B_{PEAK}: Minimize peak magnetic field to increase the 'quench' limit (normalized to V_{ACC})
- $R_{SH}/Q = V^2_{ACC}/\omega U$: Maximize R/Q to produce more accelerating voltage (V_{ACC}) for a given stored energy in the cavity (U)
- $G = Q \cdot Rs$: Maximize the geometry factor to increase the cavity effectiveness of providing accelerating voltage (shape alone)

III. QWR EM Design Optimization: Possible Shapes

The effective acceleration could be increased by making use of the space between cavities



Cylinders Conical Elliptical Race-track

Increasing complexity, lower surface fields

III. QWR EM Design Optimization: Possible Shapes

A Tapered Shape With Circular Cross Sections Was Judged to be the Correct Compromise Between Performance and Complexity

Cylindrical

Tapered

EM Design Parameters

Parameter	Cylinder	Tapered	Unit
E-peak*	5.9	5.1	MV/m
B-peak*	10.2	7.6	mT
R/Q	515	575	Ohm
QR_S	16.8	26.4	Ohm

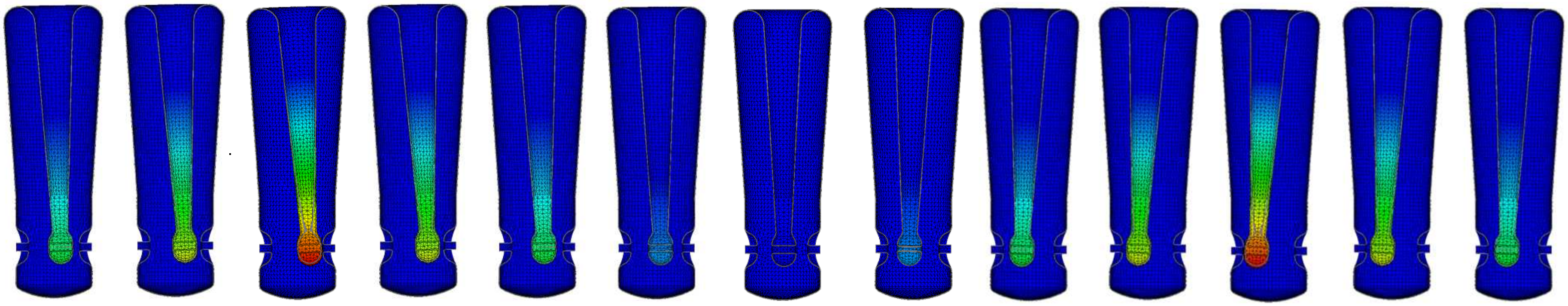
*For E_{ACC}=1 MV/m

$\ell_{EFF} = n \cdot \beta\lambda = 0.32$ m

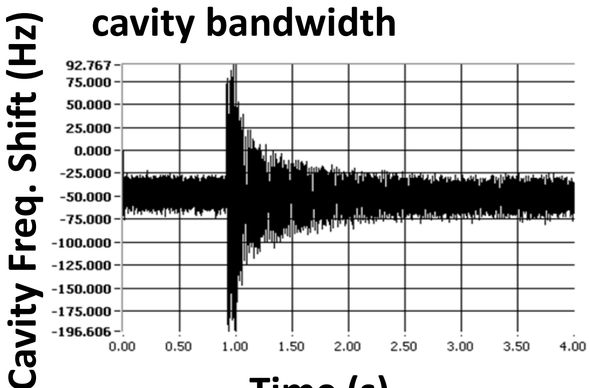
III. Mechanical Vibrations

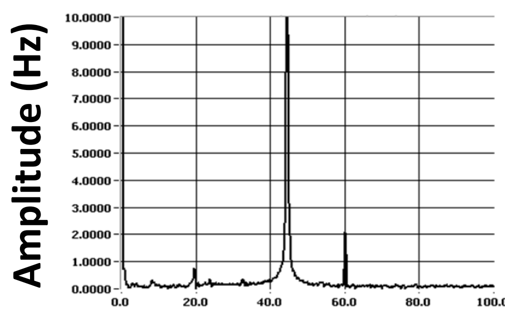
Large thin-walled structures are prone to mechanical vibrations

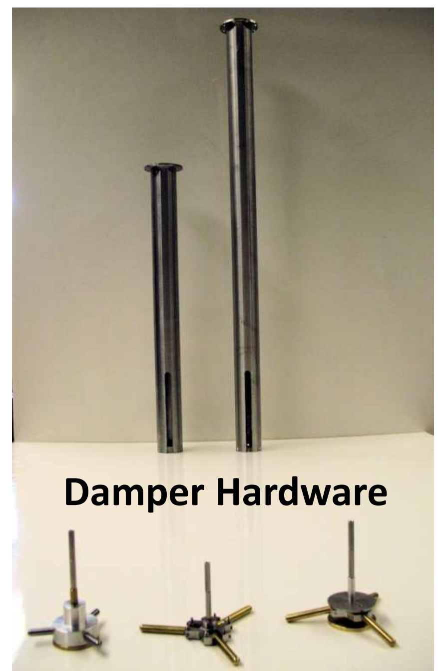
Quarter-wave cavities have a pair of degenerate mechanical eigenmodes, with relatively low frequency, typically ~30-60 Hz



Without damping the amplitude of frequency modulations from external disturbances can be hundreds of times the intrinsic cavity bandwidth





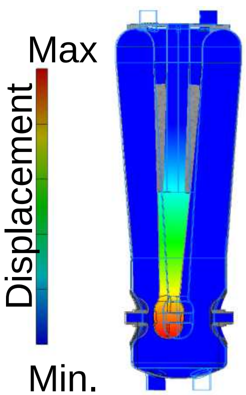


III. Fabrication: Alignment of Central Conductor

The Near Elimination of Resonant Microphonics in Thin-Walled QWR's

Mechanically bending the center conductor to maximize the frequency practically eliminates microphonics due to the 'pendulum mode' (frequency shifts are 2nd order with respect to position)

- Performed for displacements parallel and perpendicular to the beam axis
- No absolute position measurements are needed; only a frequency measurement (network analyzer) and a method to impart displacement



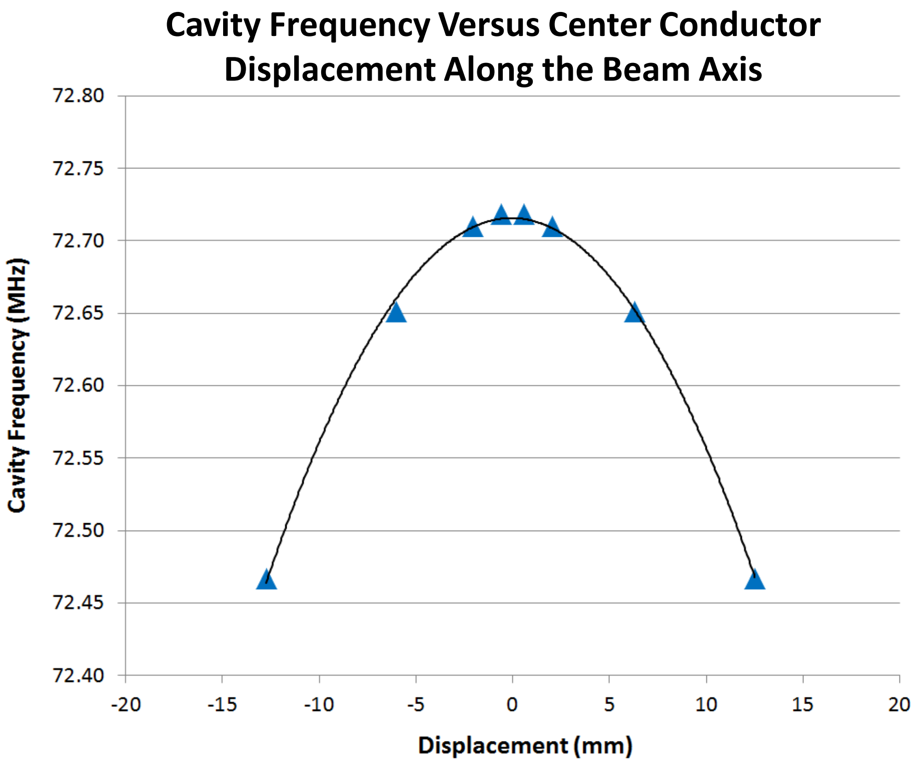
Freq. vs. displacement $f(x) = -1.643x^2 - 0.831x$

Change in Freq. vs. displacement

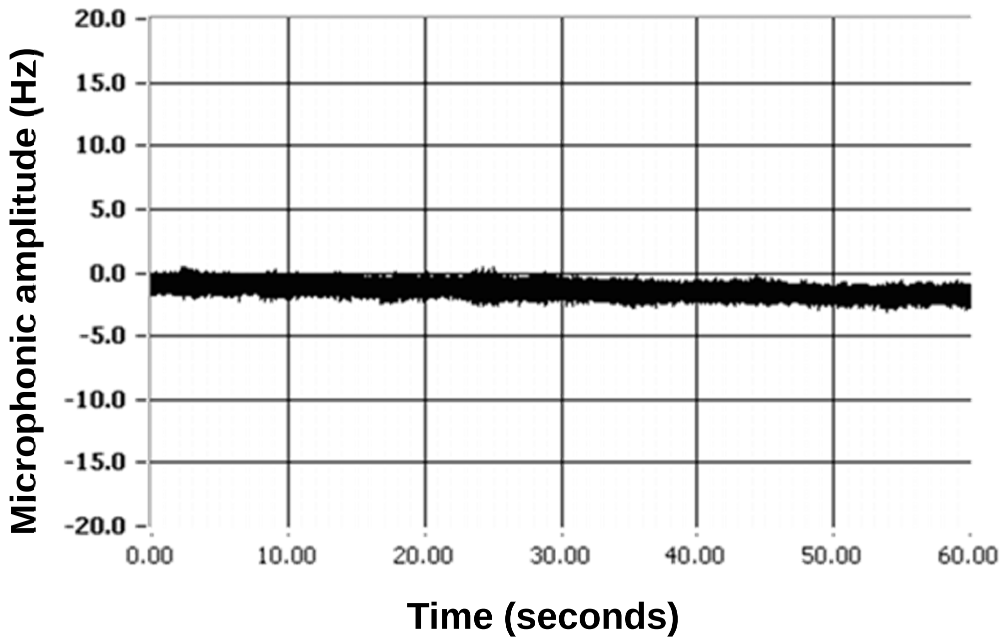
$$\frac{\partial(f)}{\partial x} = -3.286x - 0.831$$

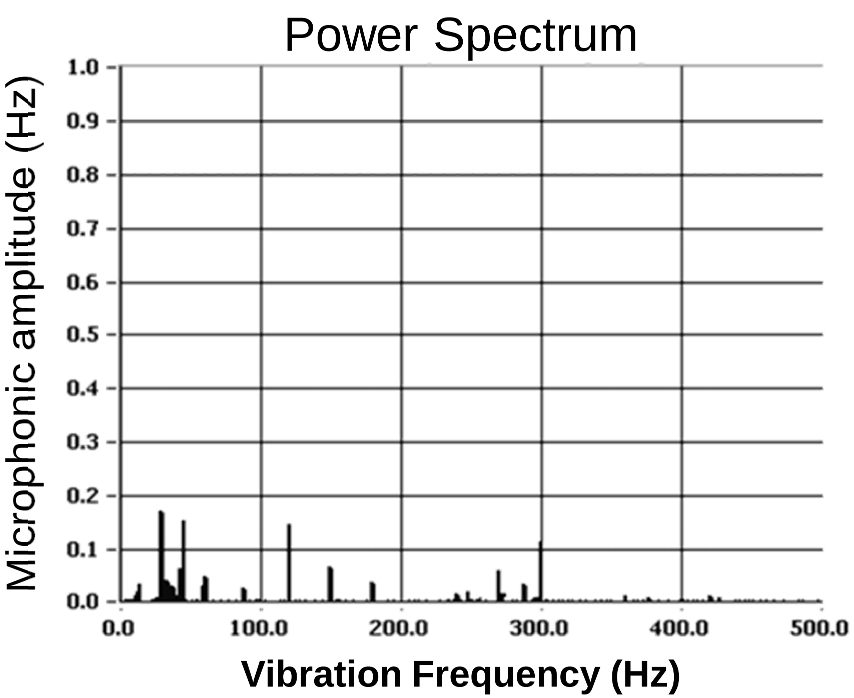
Minimum given by:

$$\frac{\partial(f)}{\partial x} = 0 \qquad x_0 \cong 0.25 \text{ mm}$$



III. Mechanical Design: Great Strides in Reduction of Microphonics in (72 MHz) the Quarter-wave Cavity

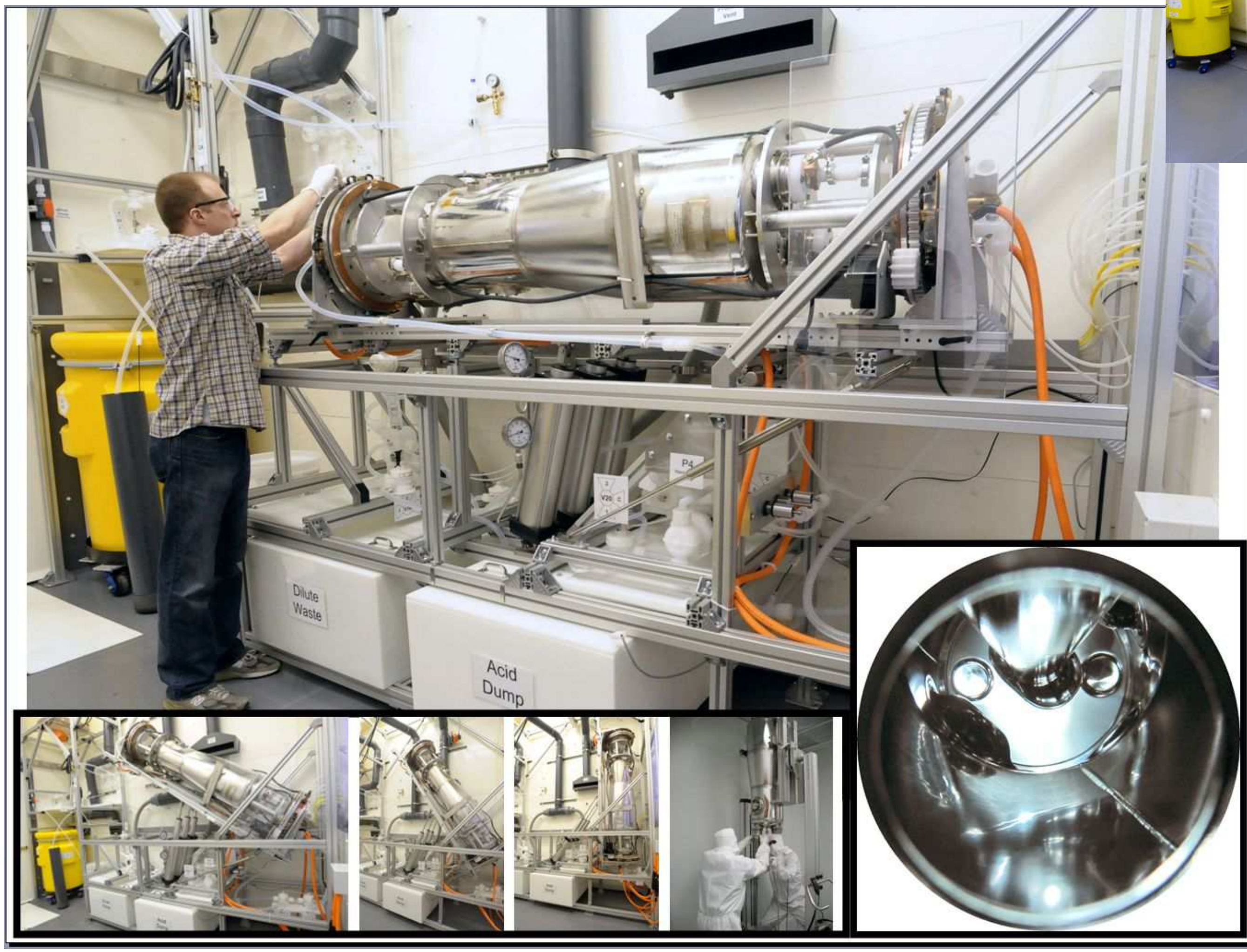




Electrical centering of center conductor together with Δfrequency/Δpressure nearly eliminates the sensitivity to microphonics

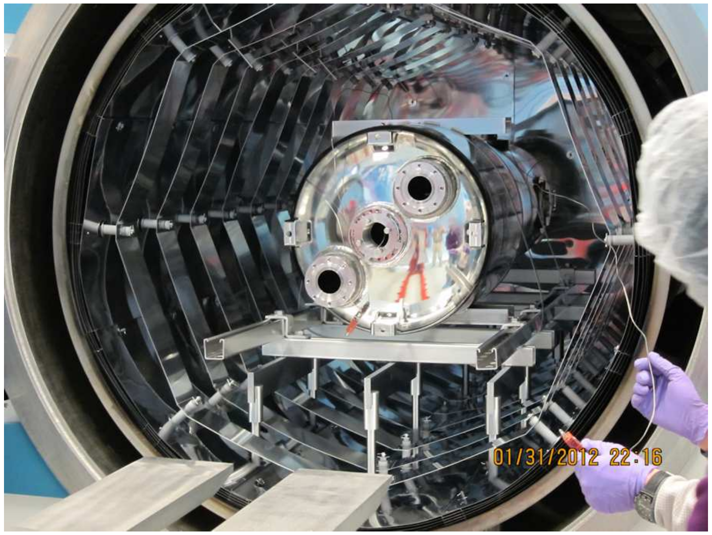
III. Electropolishing System for Low-beta Cavities

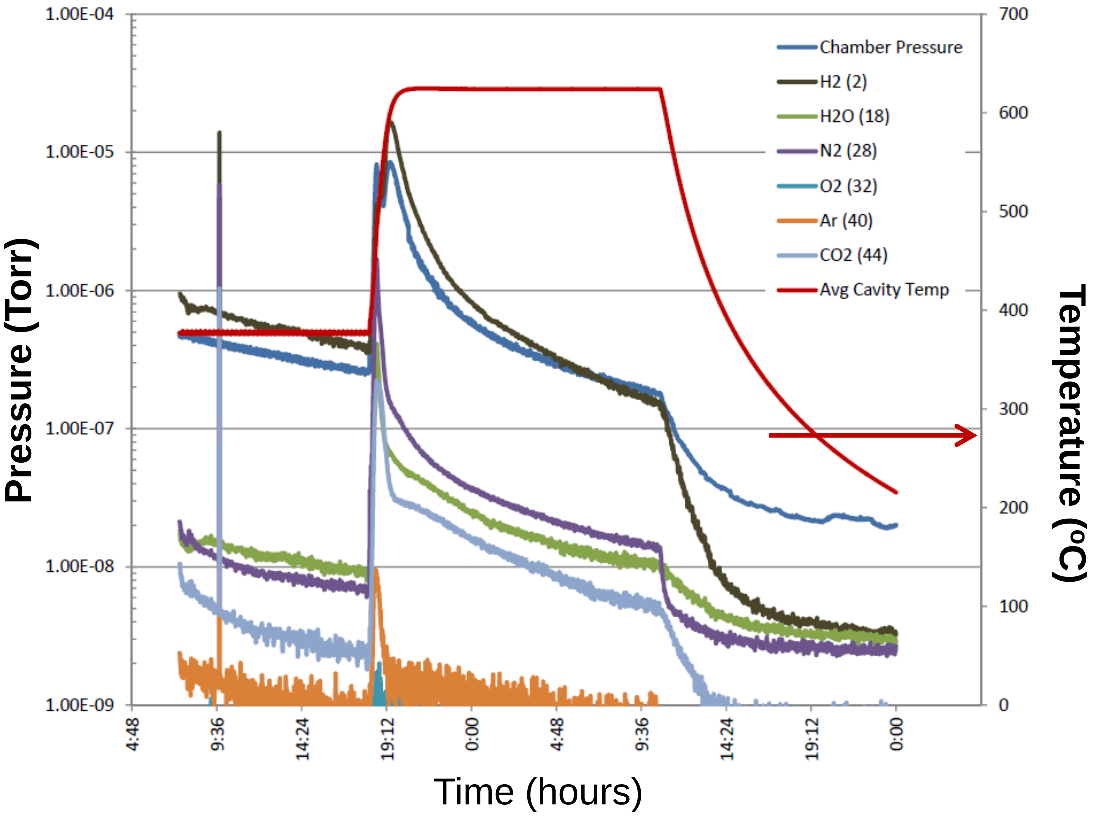
Electropolishing for co-axial TEM-mode structures (quarter-waves, half-waves) is a truly unique ANL capability. It permits reprocessing after all other fabrication is complete



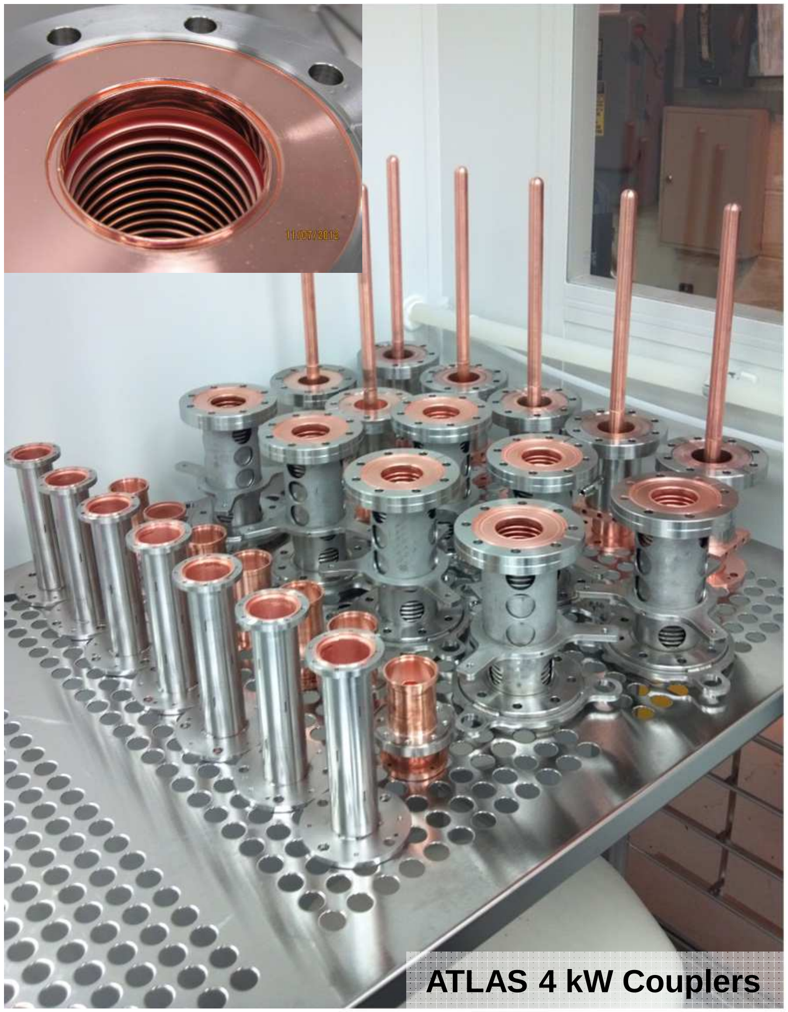
III. Cavities and Maintenance: Hydrogen degassing at 625°C Mitigates the Problem of Dwell in the Hydride Formation Region

Useful even at 4 Kelvin such as during unplanned warm up to 80 Kelvin





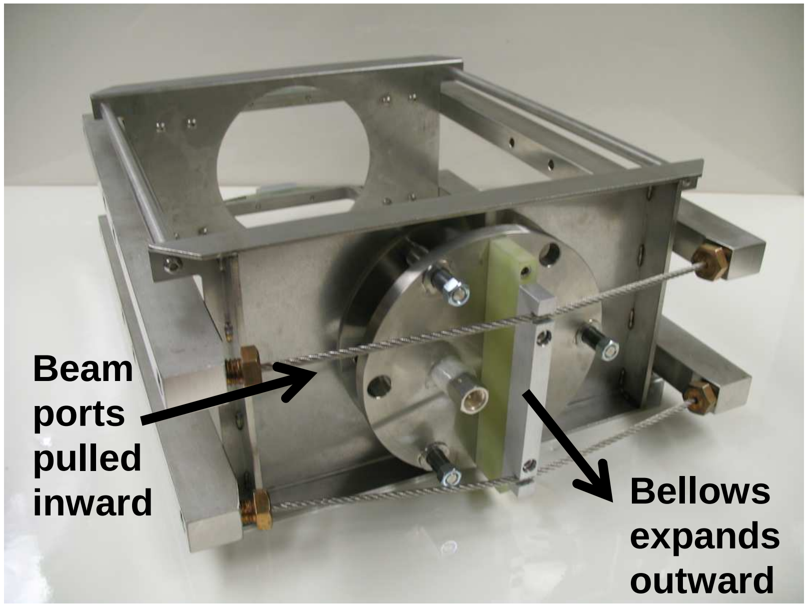
III. Technology of Subcomponents: RF Couplers 4 kW RF Power Couplers

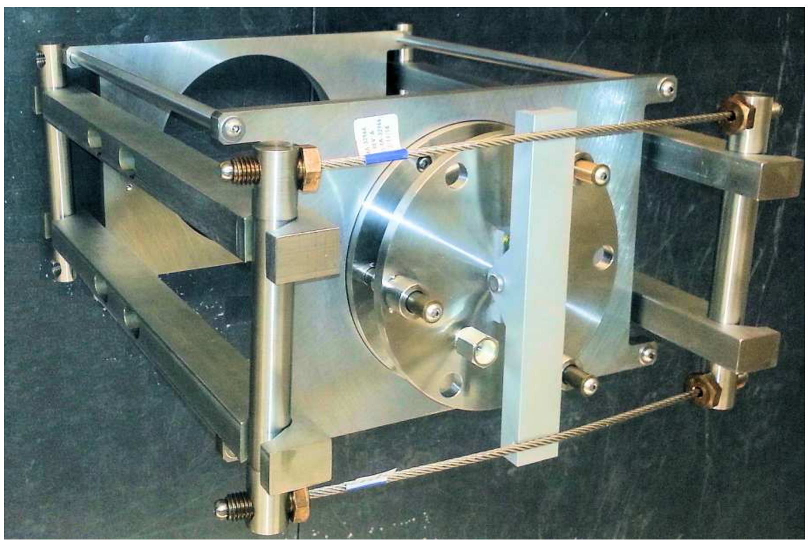

ATLAS 4 kW Couplers


FRIB/ReA3 Couplers for MSU/FRIB

- **Primary concern for long-term operations - 20 microns of copper plating on thermal transitions (Saporito Finishing Co.)**
- **Plating survives high-pressure rinsing and has been stable for 109 MHz QWR couplers since 2009**

III. Technology of Subcomponents: Pneumatic Slow Tuner





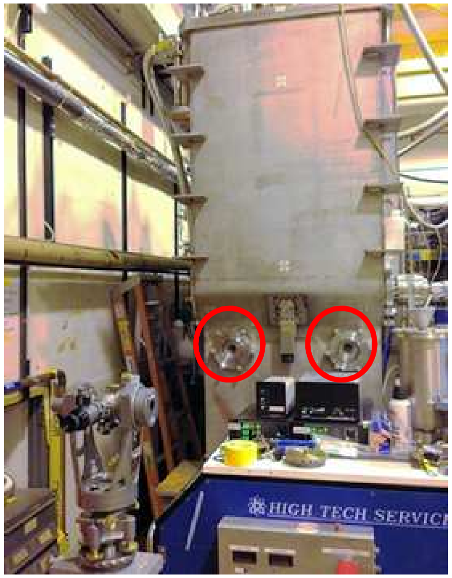
Pneumatic Tuner For PXIE Half-wave Cavity

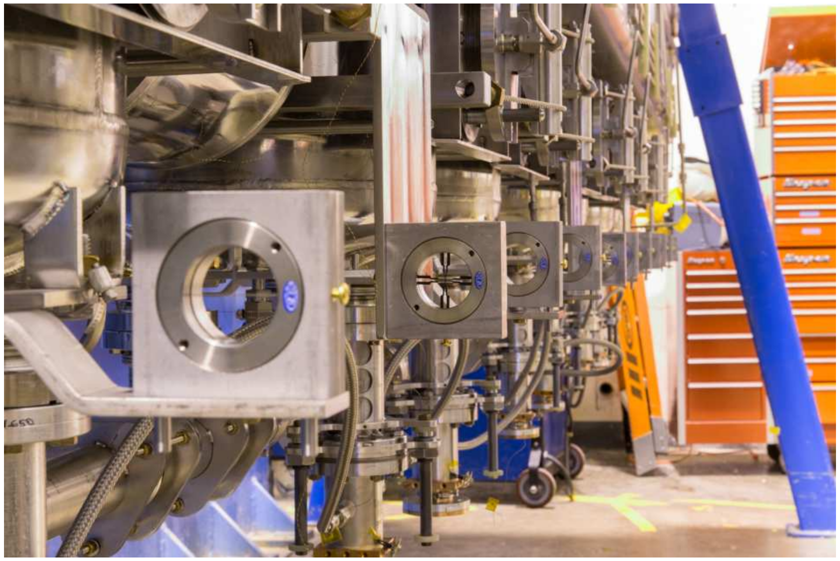
Comments/concerns for long-term operations

- ***No clean work required for maintenance***
- ***Does not induce additional microphonics***
- **Limited number of failure modes due to simplicity**
  - **Overpressure in bellows mitigated by reliefs to prevent overpressure and hard mechanical stops to set upper limit on cavity deformation**
  - **Operation is within elastic limits at all temperatures for 72 MHz cavities. 109 MHz cavities within elastic limits only when cold**
- **A note on good materials for bellows guide assembly:**
  - **Dichronite coated stainless guide bushings**
  - **(Dichronite coated optional) bearing grade bronze guide rods**
  - **These provide low friction and have expansion coefficients that don't produce binding**

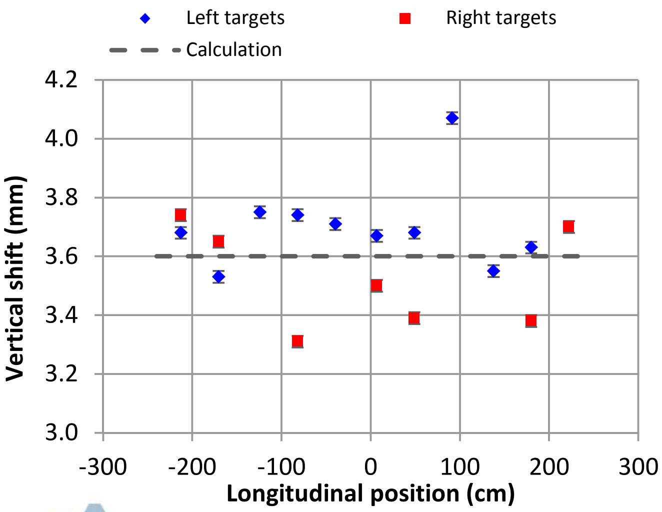
III. Practical Solutions for Cavity and Solenoid Alignment

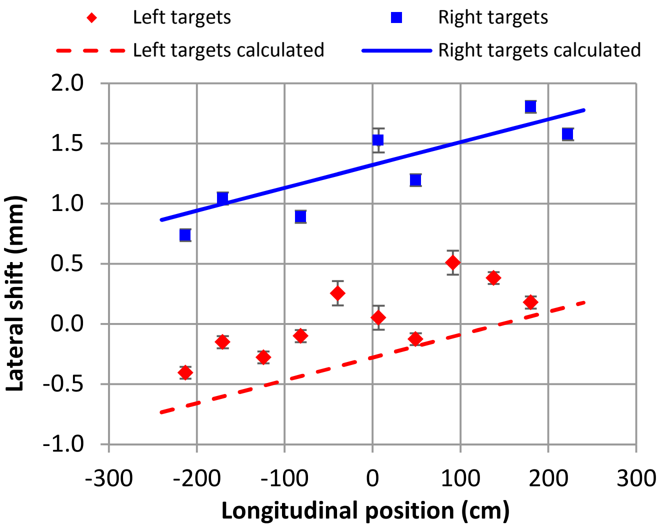
A Solution Based On Three Open Wire Targets Per Element, 4 View Ports, and a Telescope





Vertical and Lateral Shift Data During Cool Down





Final RMS deviation from beam axis after cool down

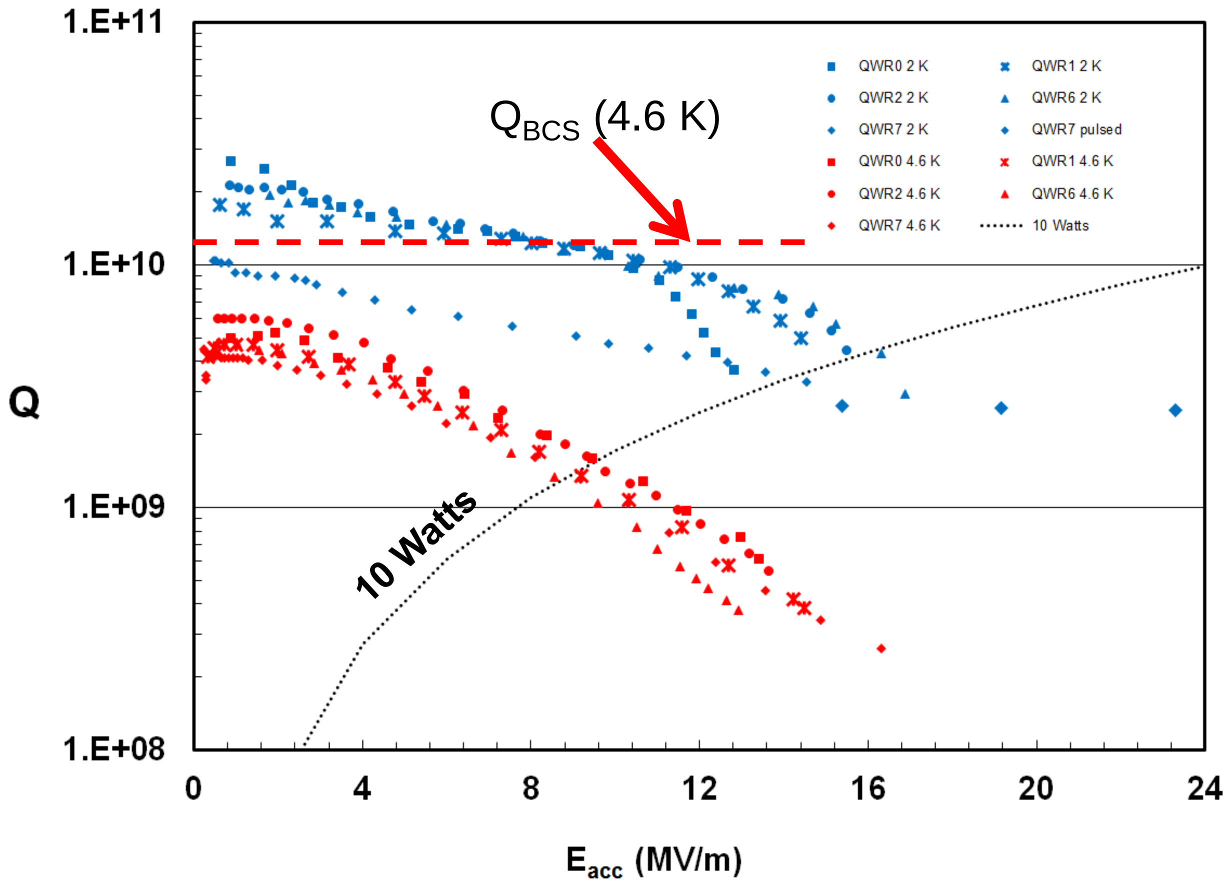
	Solenoids	Cavities
Horizontal	0.12* mm	0.50* mm
Vertical	0.18* mm	0.28* mm

*solenoid values represent accuracy of techniques; cavity alignment was ended when values where 'good enough'

Part IV.

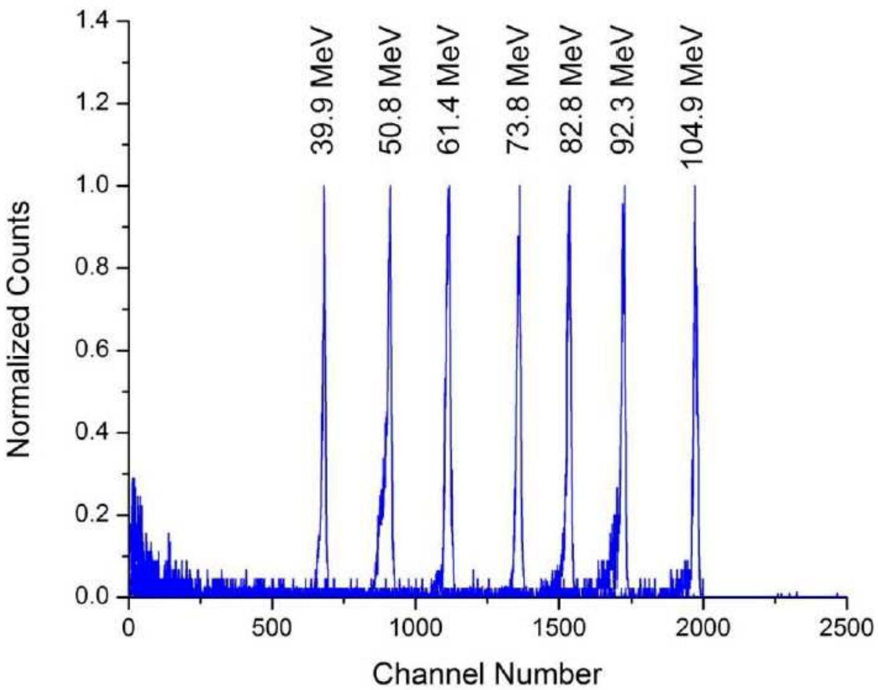
- Recent Test Results
- Context and Impact

IV. Offline Cold Tests for Cavities in the Test Cryostat
Cavity Performance



- The combination of high Q at high fields at 4 Kelvin are easily the highest values achieved to date for this class of cavities
- For the first time performance is such that, even at the low frequency of 72 MHz, cavities would be most efficiently operated at 2 Kelvin

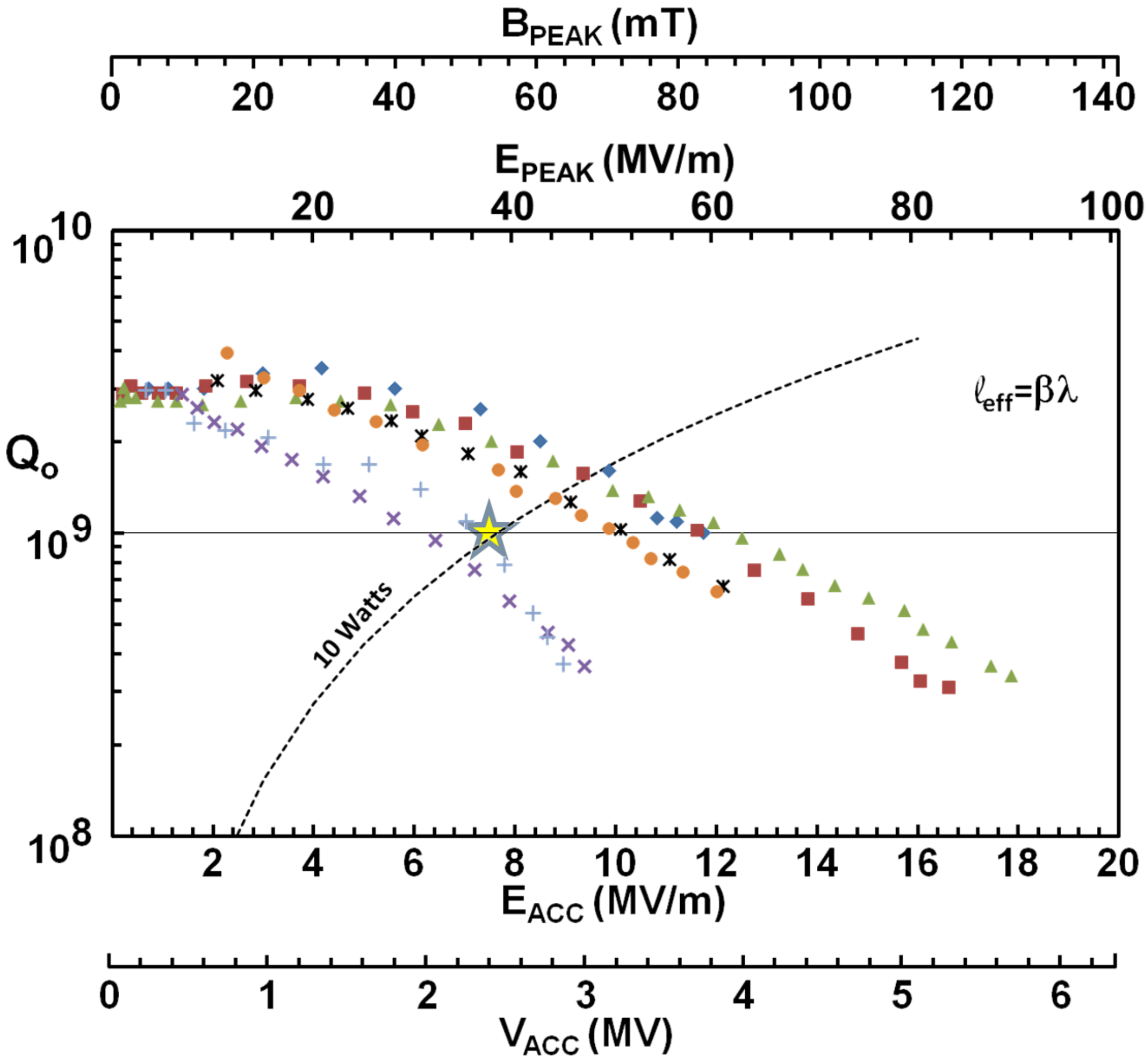
IV. First Beam Delivered by the Intensity Upgrade Cryomodule
(The beam tells the truth)



First beam to experiment
$^{20}Ne^{6+}$ on Feb. 18, 2014 (Ave. Cavity Voltage 2 MV/cavity, Ave. Power per Cavity 1.3 Watts)

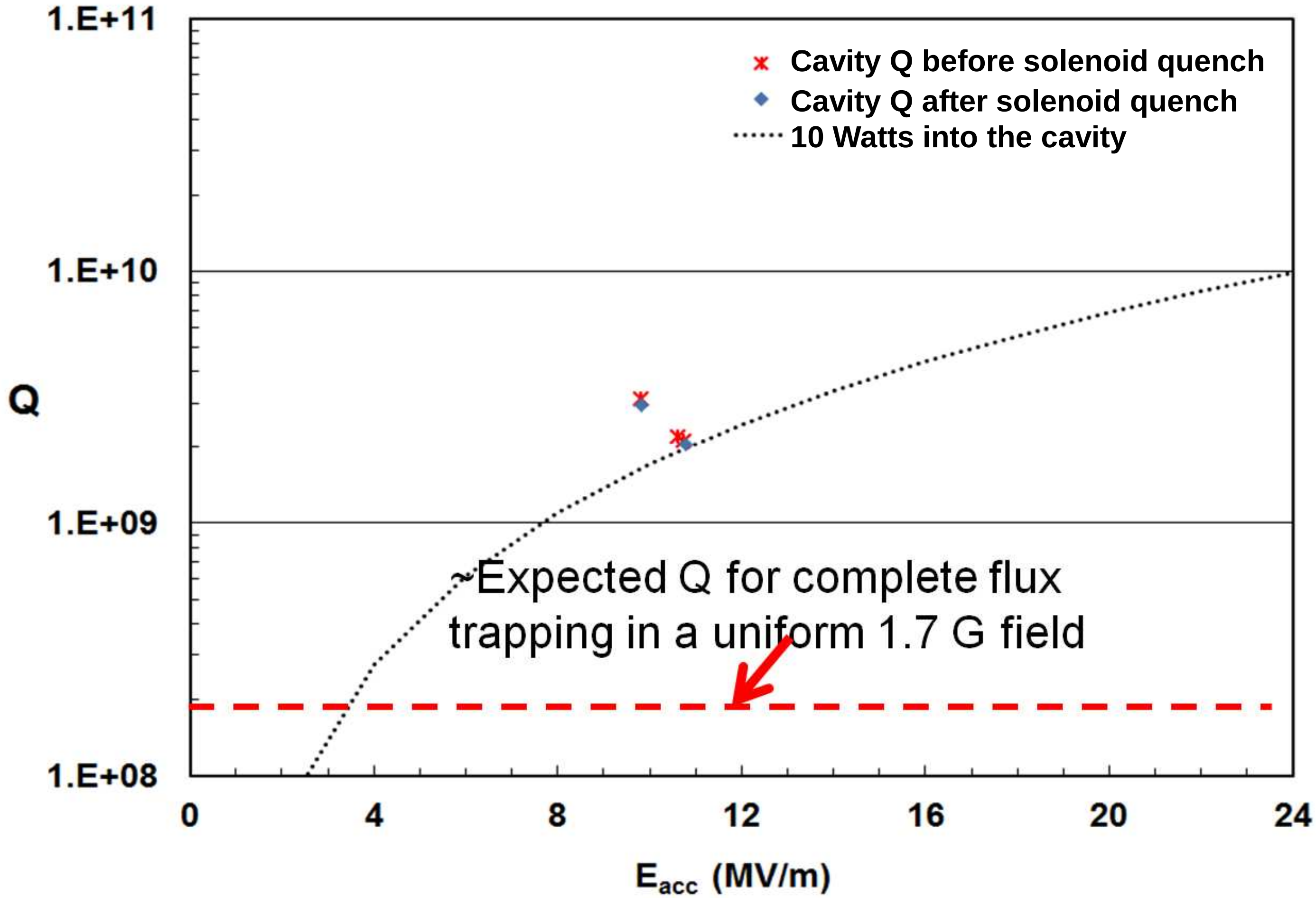
Practically no field emission, E_{ACC}~8 MV/m (E_{PEAK}~45 MV/m), no conditioning/multipacting, far from quench limit in ATLAS operations

IV. Online Cold Test Results for 8 Cavities in the Tunnel



The nominal accelerating gradient, E_{ACC}=7.8 MV/m <-> V_{ACC}=2.5 MV/cavity; the quality factor at that gradient gives a measured refrigerator load of 4.9 Watts/cavity

IV. Test of Quenching the Cavity 7 in the Presence of Magnetic Field from Solenoid

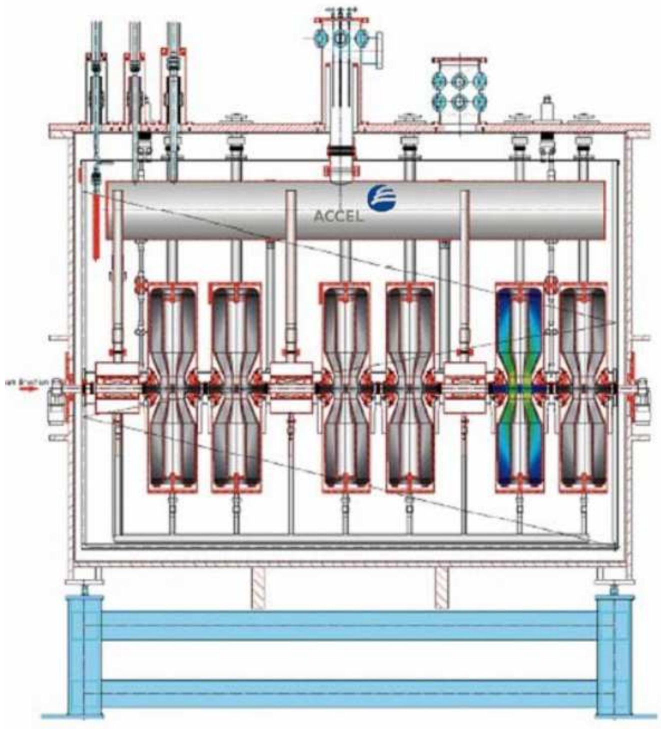


- A solenoid current of 30 A produces 1.7 Gauss at cavity face (along beam axis)
- Inside the cryomodule components are shielded to ~10 mG
- Complete flux trapping would lower Q dramatically; In fact, Q is almost unchanged

IV. Summary of Online Performance for New Cryomodules
Bringing all systems together in a working system is not easy

	Beta=0.077	Beta=0.15	Comment
Number of Cavities	7	7	
Number of Solenoids	4	1	
Operating Temperature	4.5 K	4.5 K	
Voltage per Cavity in Cryomodule	2.5 (4.1) MV	2.0 (3.0) MV	Cavity limit in parentheses
Performance Limiting System	?	VCX fast tuner	
E_{PEAK} in Cryomodule	40 (70) MV/m	26 (39) MV/m	Cavity limit in parentheses
B_{PEAK} in Cryomodule	57 (100) mT	47 (69) mT	Cavity limit in parentheses
Power to Helium/Cavity	5 W @2.5 MV	8 W @ 2 MV	

IV. Context and Impact: SARAF Proton/Deuteron Accelerator



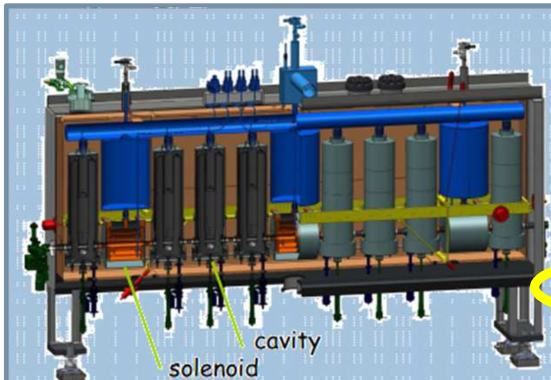
HWR Parameters	
Frequency	176 MHz
Geom. β	0.09
$L_{acc}=\beta\lambda$	0.15 m
E_{acc}	5.5 MV/m
ΔV	830 kV
$Q_0@E_{acc}$	$>4.7\times10^8$
Q_{ext} Loaded BW	$\sim1.3\times10^6$ ~130 Hz

Cavity	Acceleration (voltage (kV	Phase (deg)	Energy (MeV)
HWR 1	212	-95	1.5
HWR 2	552	30	1.86
HWR 3	646	-25	2.36
HWR 4	493	-10	2.81
HWR 5	552	-10	3.31
HWR 6	544	-20	3.82

IV. Context and Impact: MSU Re-Accelerator (ReA3)

In operation since 2011

Type	λ/4
Optimum β	0.041
Frequency	80.5 MHz
E_{peak}	16.5 MV/m
V_{acc}	0.445 MV
B_{peak}	29 mT



Type	λ/4
Optimum β	0.085
Frequency	80.5MHz
E_{peak}	20 MV/m
V_{acc}	1.08 MV
B_{peak}	47.4 mT

Planned performance for 2014

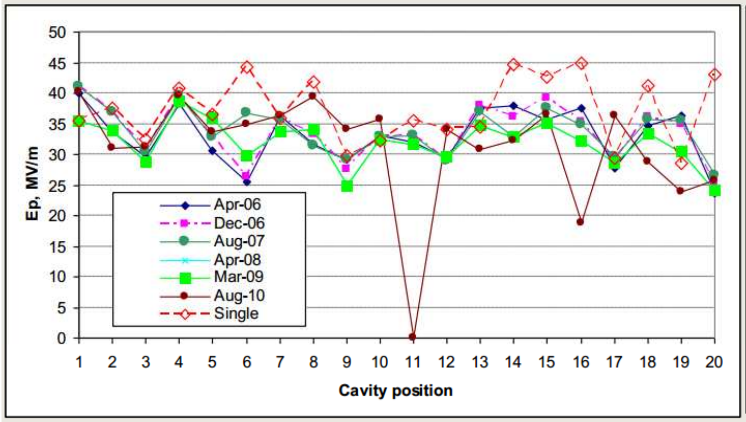
IV. Context and Impact: ISAC-II Heavy-ion Linac, 6 Cryomodules

IV. Context and Impact: ISAC-II Heavy-ion Linac

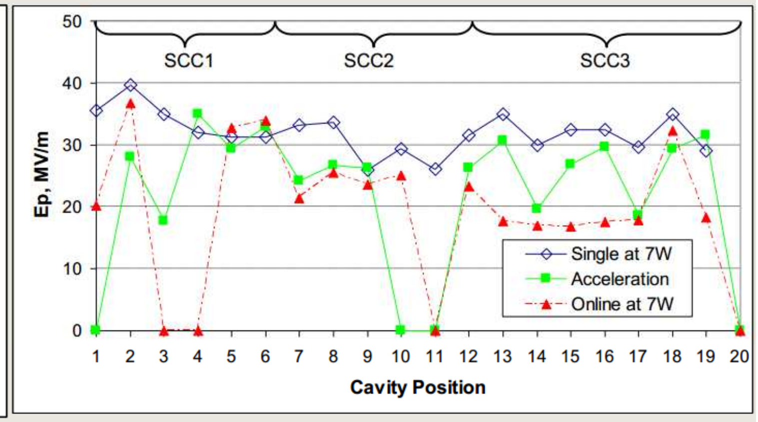
TRIUMF

Online Performance

Phase-I



Phase-II

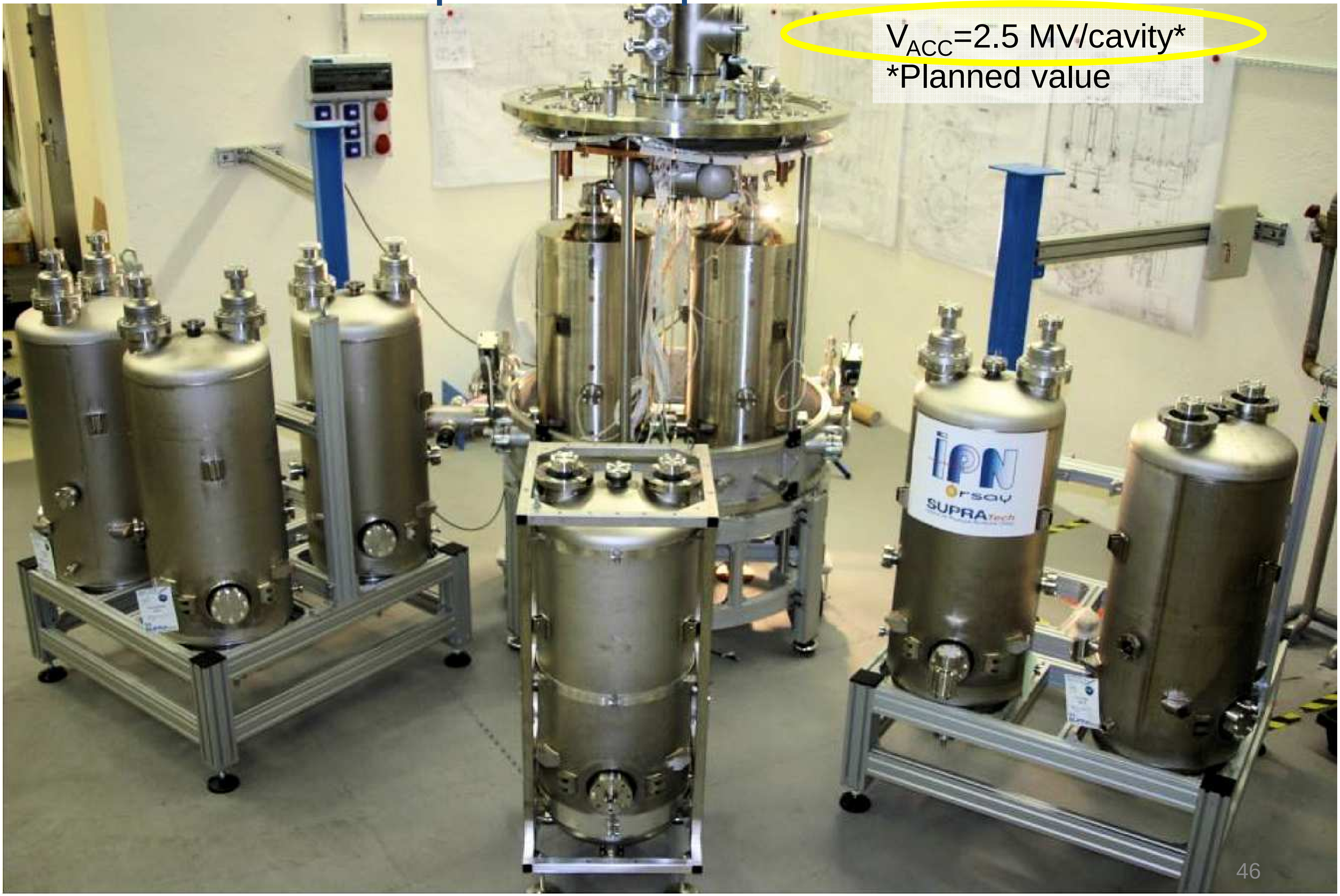


Test	Metric	PHASE I (MV/m)	PHASE II (MV/m)
Single Cavity	<Ep> @ 7W	37	32
Installed	<Ep> @ 7W	33	26
Acceleration	Stable <Ep>	30-32	27

Peak field Ep=5*Ea, Bp=10*Ea, Acceleration voltage Va=Ea*0.18

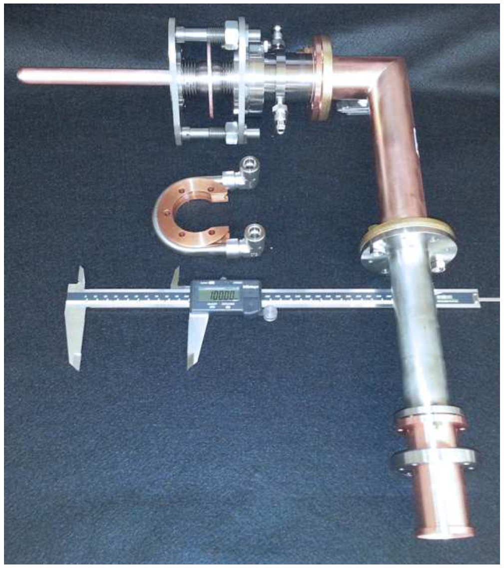
Ave V_{ACC} for operational cavities is 1.05 MV

IV. Context and Impact: Ganil/Spiral-2 Proton/Deuteron Linac



IV. Accelerator Development for FRIB ($1M)

Argonne Work for Others with MSU: January 2015 – September 2017



FRIB RF Coupler for MSU/FRIB

ANL Half-wave Pneumatic Tuner

Deliverable 1 – Engineering support through modeling and design reviews

- **FRIB quarter-wave production coupler thermal models**
- **Coupler mechanical and thermal design review**
- **Fabrication drawing review**

Deliverable 2 – ANL-style pneumatic slow tuner for:

- **β=0.29 HWR**
- **β=0.53 HWR**

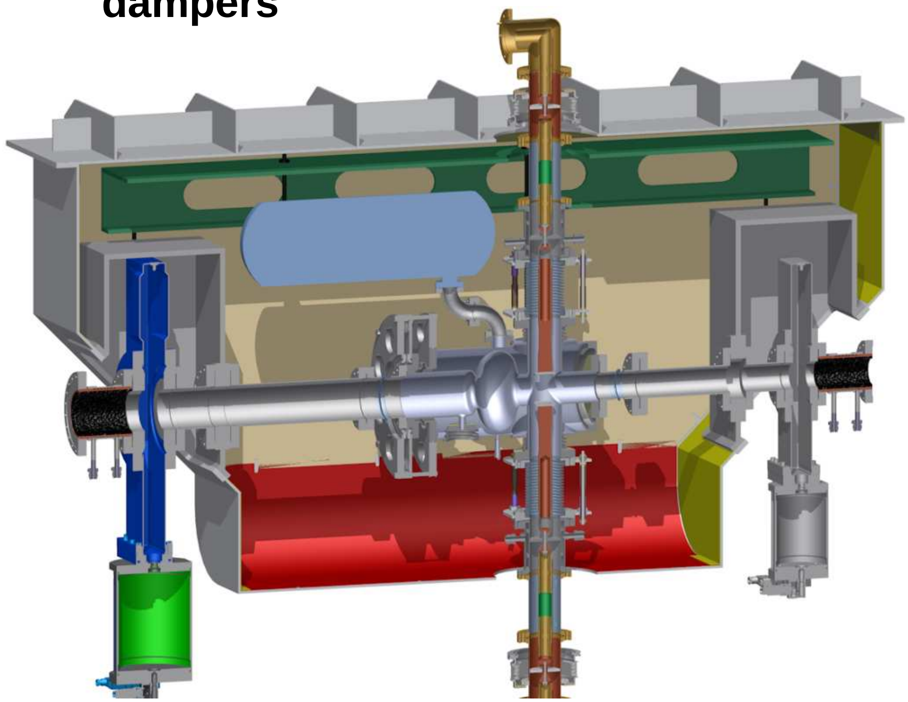
Deliverable 3 – Validation of cryomodule sub-systems by cold testing in ANL test cryostats

- **β=0.29 HWR pre-production pneumatic tuner**
- **Development and testing of a pre-production coupler for β=0.041 QWR**
- **Integrated testing of β=0.041 QWR with a production coupler and tuner**
- **Integrated testing of a HWR with production coupler and tuner**
- **Development and/or testing of a prototype multi-pacting free coupler for HWR cavities**

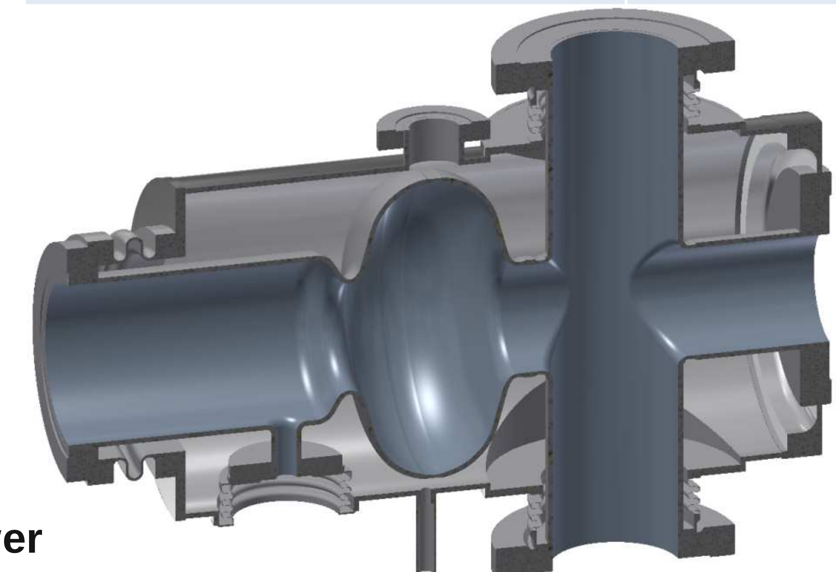
IV. Bunch Lengthening for the APS MBA Upgrade ($4.8M)
A Single Superconducting Cavity Will Be Used to Increase the Beam Lifetime

- New 4th harmonic 1408 MHz elliptical cell cavity
- A pair of 20 kW high power couplers
- Room temperature higher-order mode dampers

Parameter	Value
Cavity Freq. (MHz)	1408
Relative Touchek Lifetime	4.1
Cavity Voltage (MV)	0.9
Ep at 0.9 MV, MV/m	17
Bp at 0.9 MV, mT	35



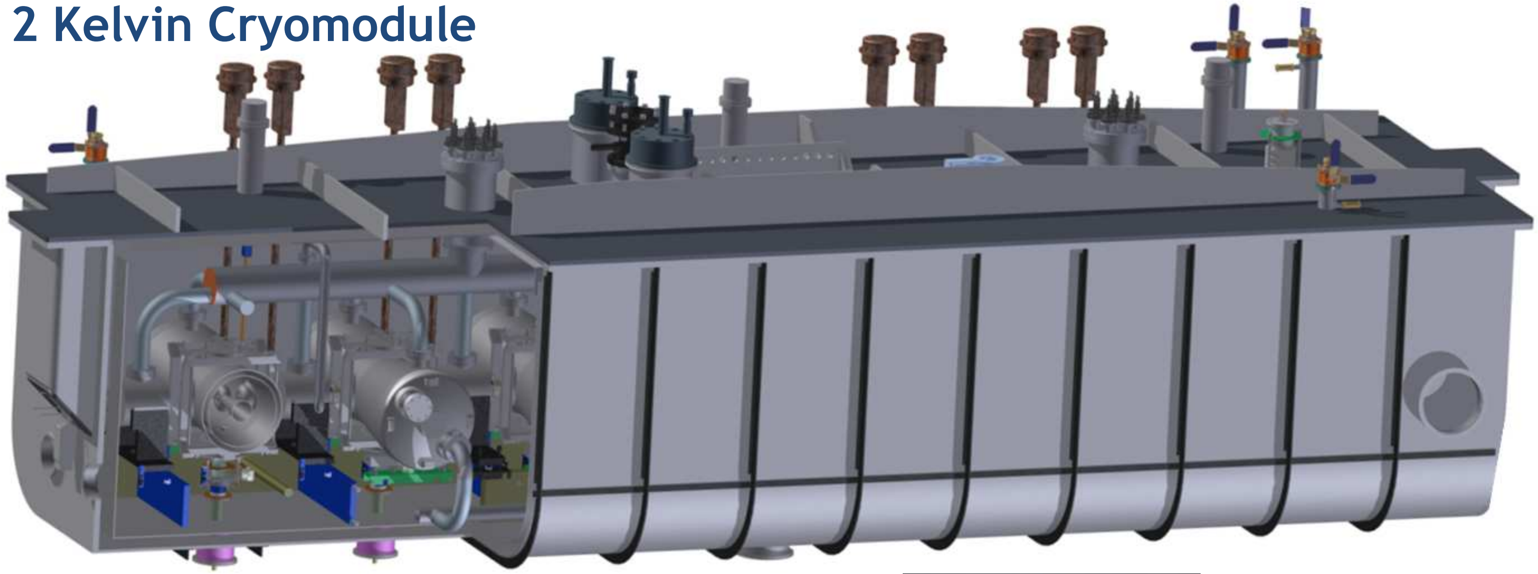
2-meter cryomodule with cavity (center), power couplers (vertical) and HOM dampers (ends of beamline)



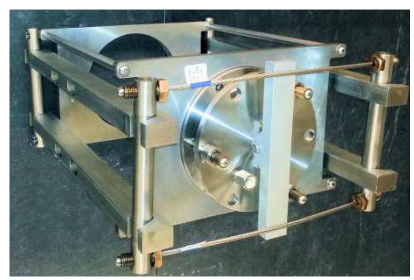
Half-section of the 1.4 GHz cavity

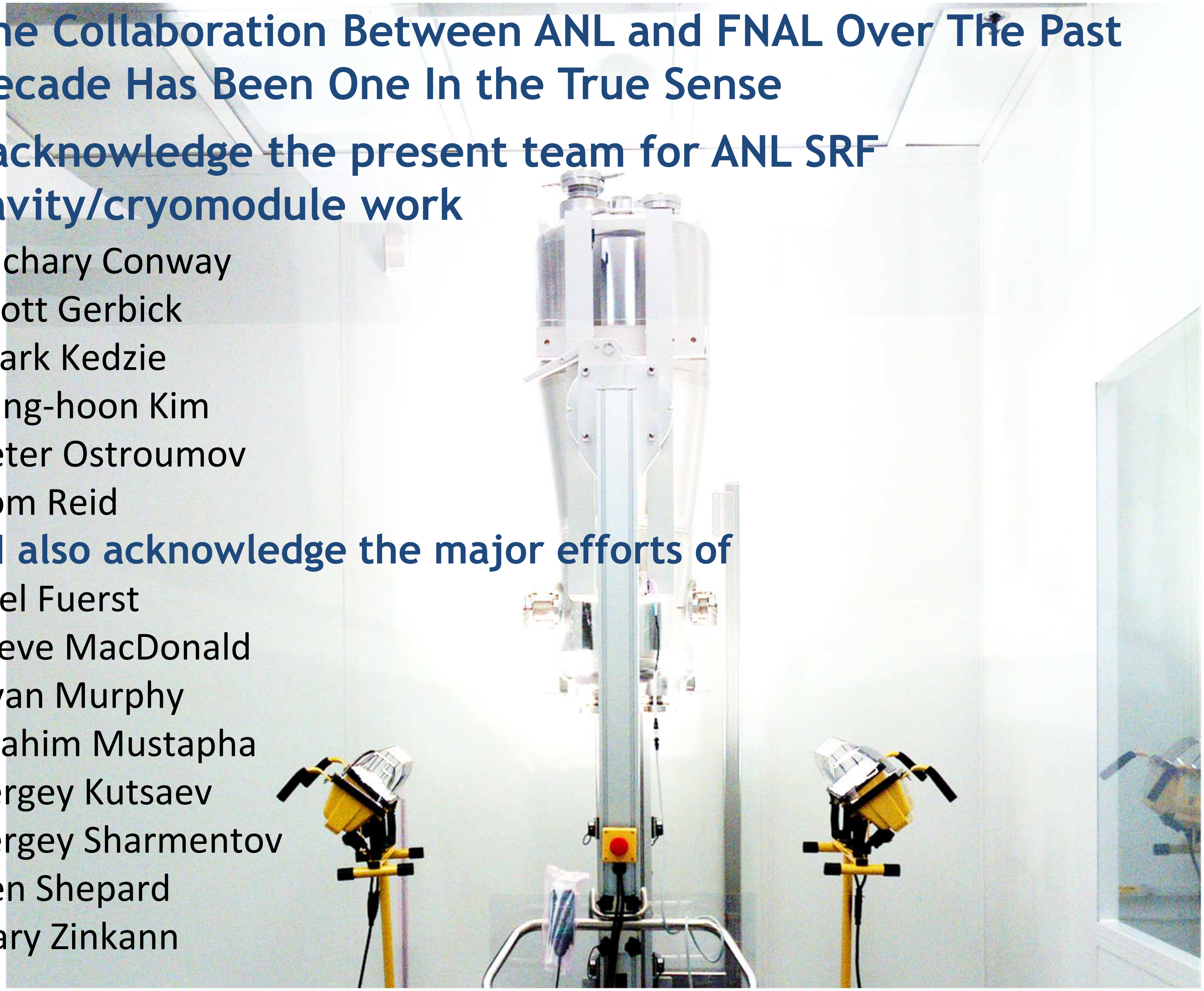
IV. Context and Impact: Accelerator Development for PIP-II

PXIE 2 Kelvin Cryomodule



- 6-meter 2 Kelvin SRF cryomodule
  - Intended for a 5 mA proton beam from 2.1 to 10 MeV
  - Eight 162.5 MHz β=0.11 half-wave cavities
  - Eight SC solenoids with integral steering coils
  - 10 kW capable power couplers
- New concerns:
  - Sub-atmospheric operations
  - Increased sensitivity to Q-degradation
- Field performance is demonstrated in two prototype cavities





The Collaboration Between ANL and FNAL Over The Past Decade Has Been One In the True Sense

I acknowledge the present team for ANL SRF cavity/cryomodule work

Zachary Conway
Scott Gerbick
Mark Kedzie
Sang-hoon Kim
Peter Ostroumov
Tom Reid

…I also acknowledge the major efforts of

Joel Fuerst
Steve MacDonald
Ryan Murphy
Brahim Mustapha
Sergey Kutsaev
Sergey Sharmentov
Ken Shepard
Gary Zinkann

Additional Slides

II. Charged Particle Acceleration: Constant Velocity Approximation

If the particle does not change its velocity substantially:

z(t)= $\beta c t$

(Valid except for very low beta cavities running at high gradient)

$$\Delta W = q \int_{-\infty}^{+\infty} E(z) \left(\cos\left(\frac{\omega z}{\beta c}\right) \cos\varphi - \sin\left(\frac{\omega z}{\beta c}\right) \sin\varphi\right) \, dz$$

$$\Delta W = q \, \cos\varphi \int_{-\infty}^{+\infty} E(z) \cos\left(\frac{\omega z}{\beta c}\right) dz$$

(For the case where E(z) symmetric with respect to the cavity center)

II. Charged Particle Acceleration: Transit Time Factor, Velocity Acceptance and Energy Gain

$$\Theta = \frac{\int_{-\infty}^{+\infty} E(z)\cos\left(\frac{\omega z}{\beta_0 c}\right) dz}{\int_{-\infty}^{+\infty} |E(z)| dz}$$

Reduction in energy gain due to time varying e-field, "Transit time factor"

$$\mathrm{T}(\beta) = \frac{\int_{-\infty}^{+\infty} E(z)\cos\left(\frac{\omega z}{\beta c}\right) dz}{\int_{-\infty}^{+\infty} E(z)\cos\left(\frac{\omega z}{\beta_0 c}\right) dz}$$

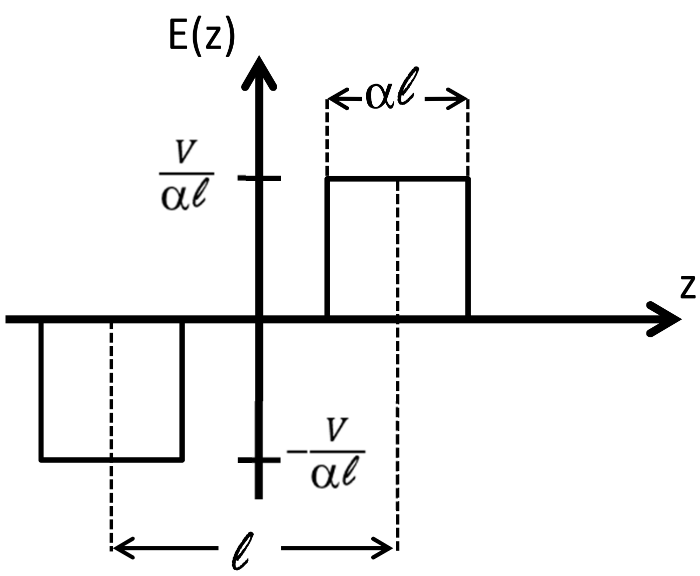
Reduction in energy gain due to non-optimal velocity, "Velocity acceptance factor"

$$\Delta W_0 = \Theta \int_{-\infty}^{+\infty} |E(z)| dz$$

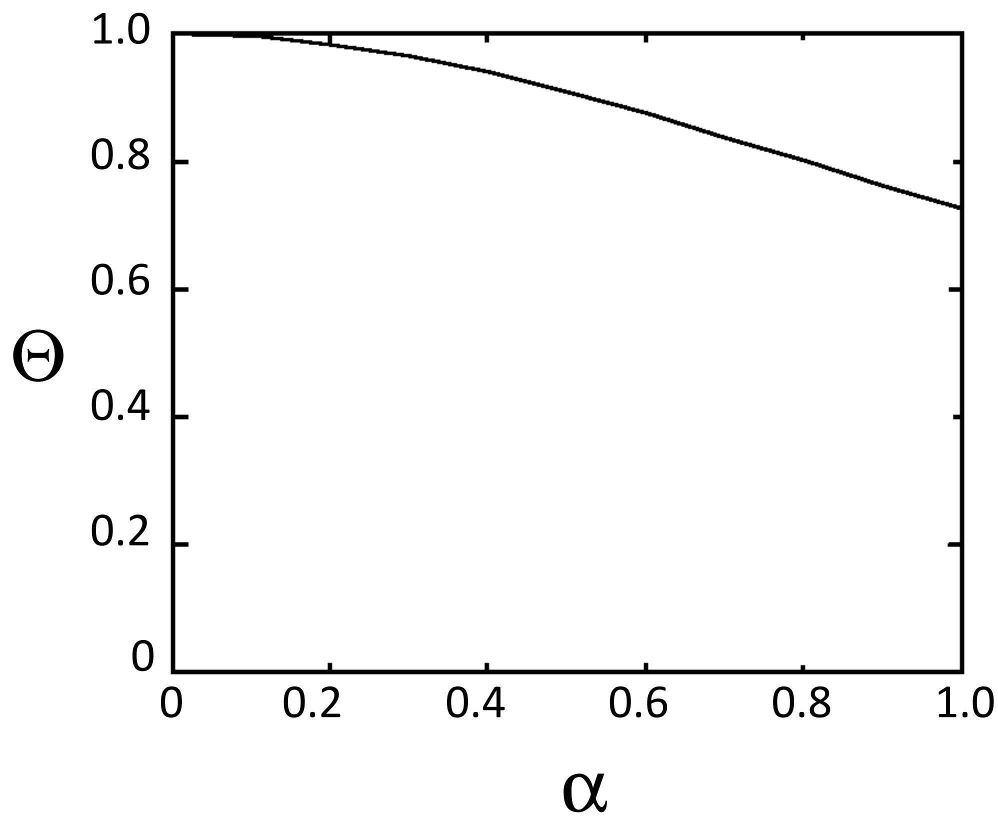
Energy gain by a synchronous particle (φ=0) of unity charge (q=1) and $\beta=\beta_0$

$$\boldsymbol{\Delta W = q \cos\varphi\ \Delta W_0\ \mathrm{T}(\beta)}$$

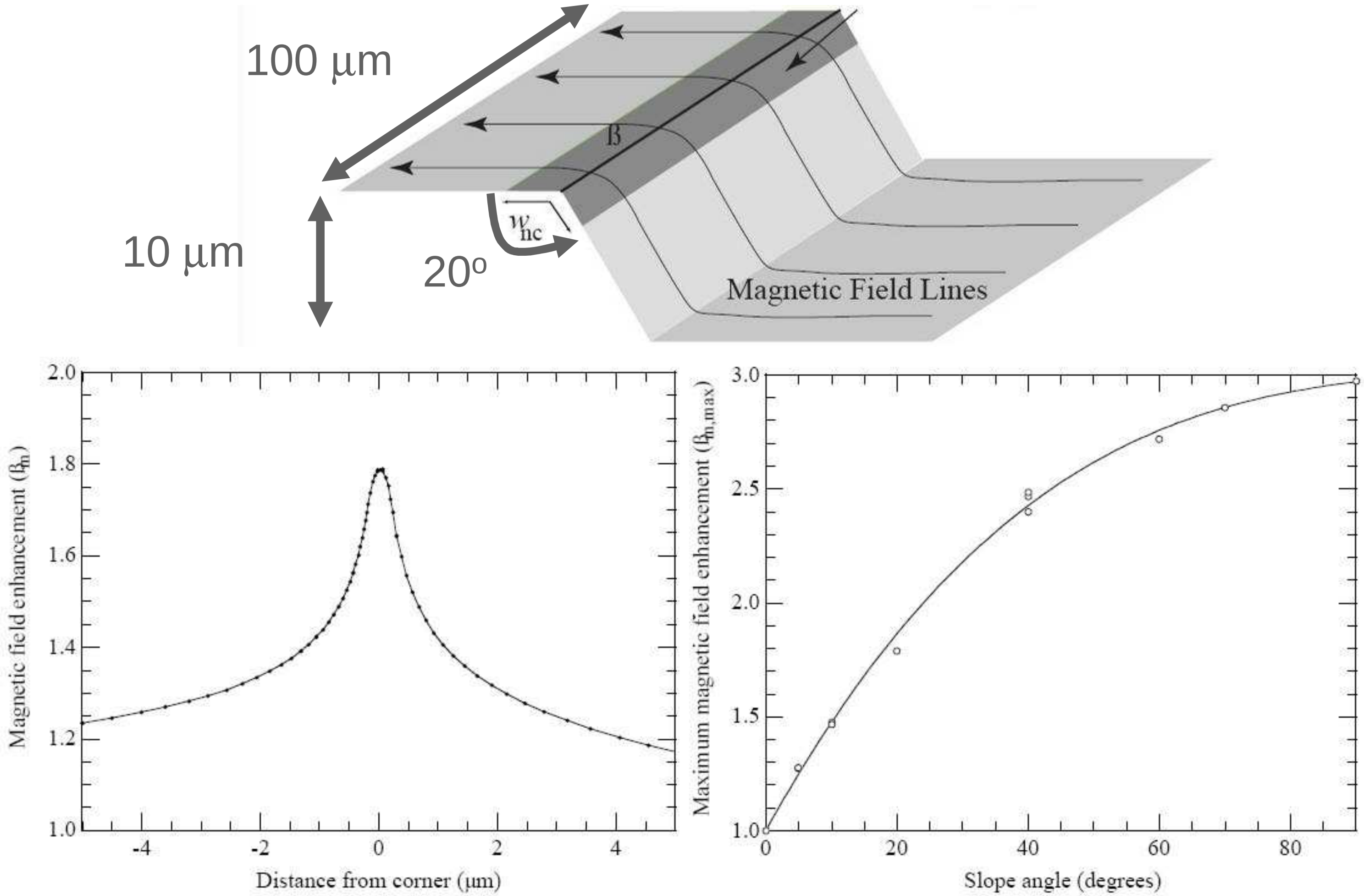
II. Charged Particle Acceleration: Transit Time Factor, the Reduction in Energy Gain Due To Time Varying Field



Idealized electric field profile in a 2-gap accelerating cavity

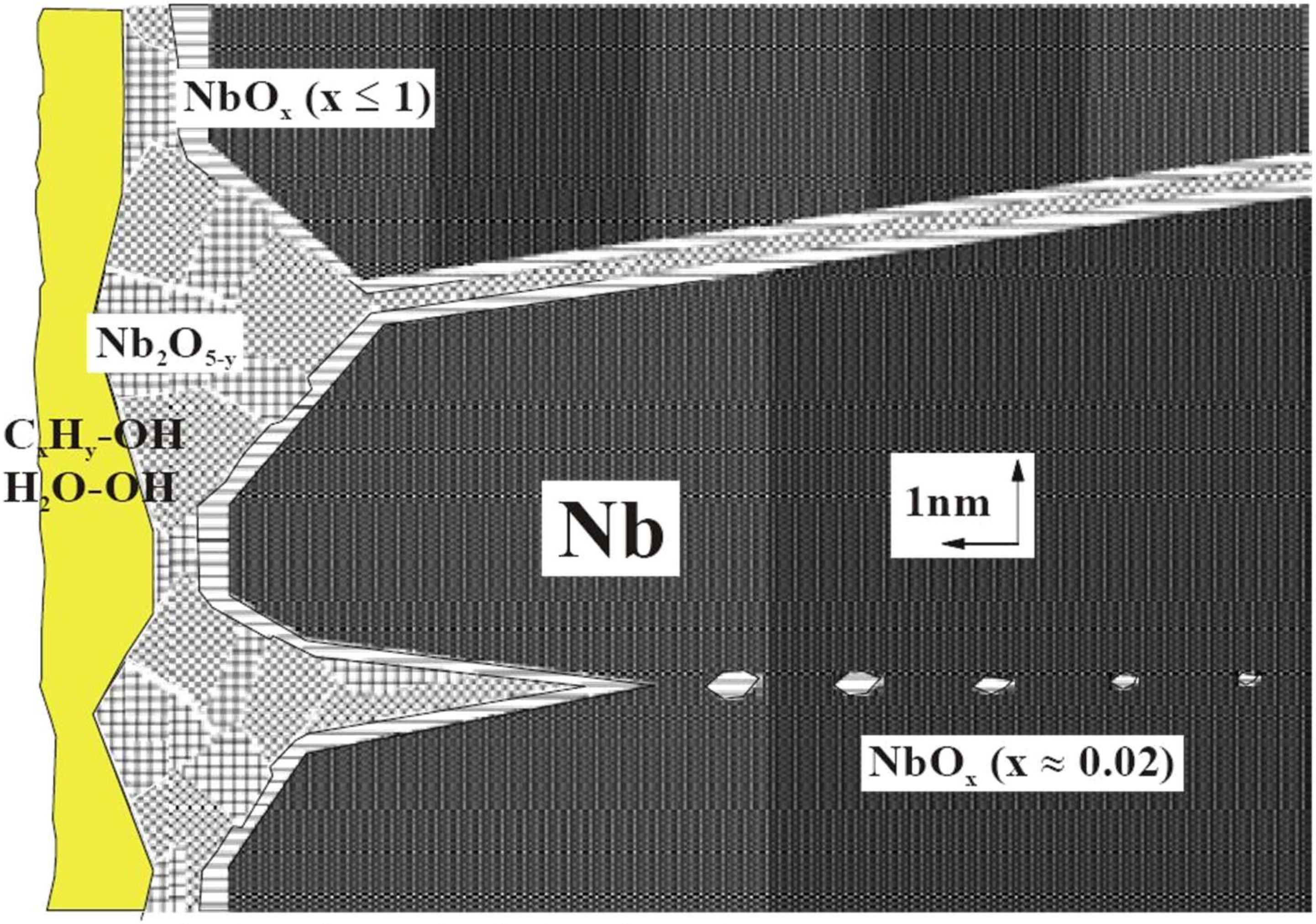


II. RF Surface: Surface Roughness



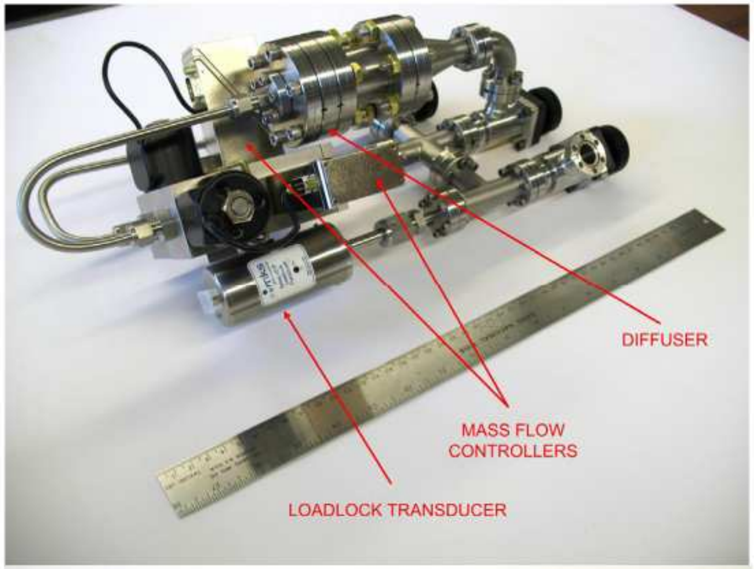
- Surface magnetic fields are enhanced when current runs along a (grain boundary) step
- Thermally stable regions of enhanced losses lead to a lowering of observed Q
- Reasonably low surface roughness is a necessary condition for achieving high Q

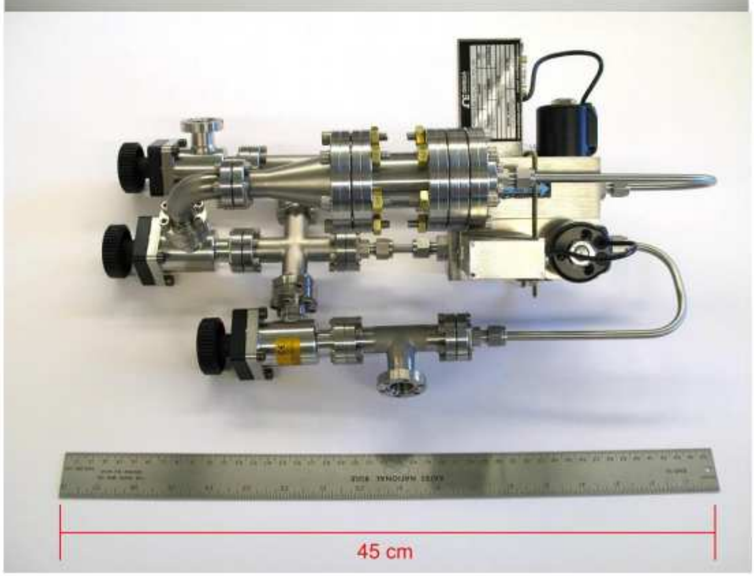
II. RF Surface: (Simplified) Niobium Surface



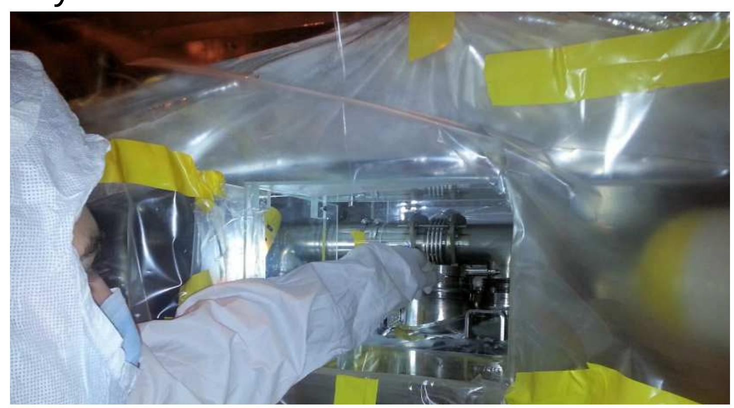
- Water, hydrocarbons adsorbed to the surface
- Several nm of Nb_2O_5 reforms rapidly even for low partial pressures of O_2
- Metallic NbO_x clusters

III. Pumping and Venting for SRF Cavities and Cryomodules



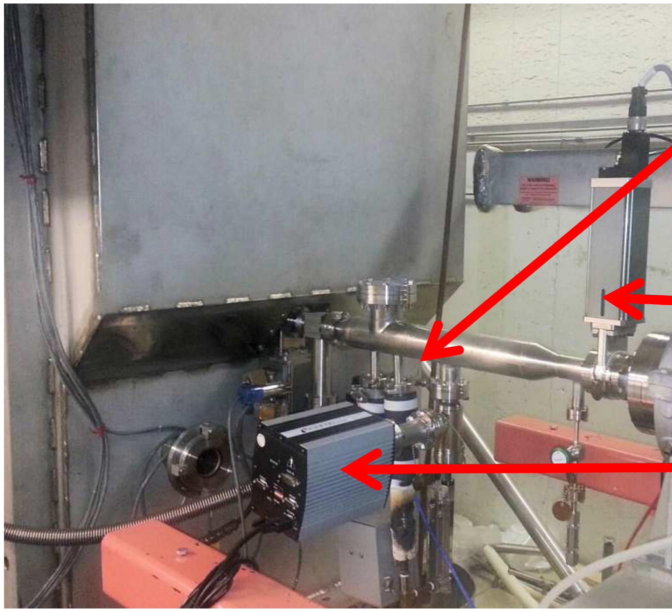


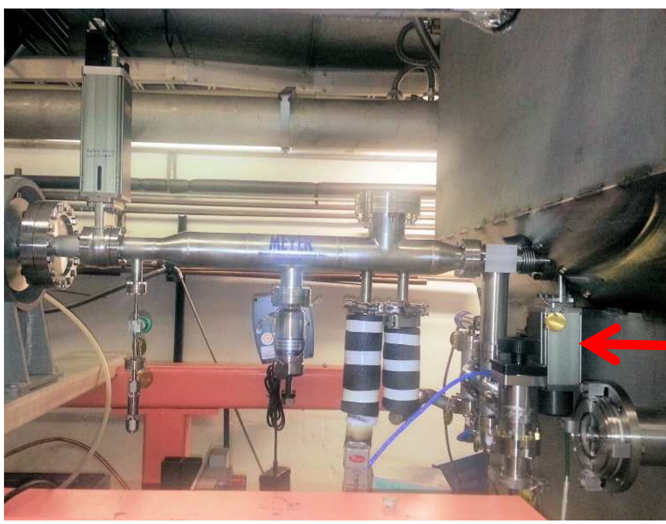
- Cryomodules are pumped down or back filled at a constant rate of 50 mbar-l/s (8 hours for the 72 MHz cryomodule)
- Flow is controlled using a pair of mass flow controllers, one each for pumping and backfilling
- Air filtered using a ‘0.003 μm’ diffuser
- ‘Loadlock’ transducer used to adjust crymodule to a pressure 1-2 Torr above atmosphere just before opening clean cavity system



All 7 RF pickups replaced in Nov. 2013 in a local ‘clean room’ after venting

III. Issue of Maintaining the Clean Vacuum Space





- 80 Kelvin ~1/2 meter long liquid nitrogen cooled cold traps installed at the entrance and exit for clean cryomodules
- Volatiles, water, particulates adsorb to the surface of a 2.5” cm diameter copper tube
- Gate valves at the entrance and exit of the cryomodule are interlocked to cold trap ion gauges
- A fast acting valve (~10 mS) will isolate experimental areas from the accelerator in the event of a vacuum accident