# An Approach to Chemical Free Surface Processing for High Gradient Superconducting RF Cavities

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# FMT Capabilities

- Founded in 1987, FM Technologies, Inc. (FMT) is a technology company with expertise in: charged particle beams, particle accelerators, plasma physics, electron/ion/microwave beam interaction with materials, microwave source development, pulsed power, and integration of these areas
- FMT has several projects approaching the commercial development stage
  - Ceramic/Ceramic & Ceramic/Metal joining for use in high temperature chemical conversion processes
  - Self-Bunching Electron Guns with/without Current Amplification for Accelerators and RF sources
  - Microwave Plasma Torches for various applications

# FMT Facilities/Equipment

- Headquartered in Chantilly, VA, FMT has over 10,000 $ft^2$ of available laboratory space and 8,300 $ft^2$ of available office space
- Offices equipped with advanced multi-core workstations loaded with a variety of sophisticated software codes including:
  - EGUN, ICAP/SPICE, PARMELA, POISSON, SUPERFISH, SolidWorks, FEMM, HFSS, CSIRO, and FlexPDE-3D, FMT proprietary code FMTSEC (a 2 1/2D PIC code with secondary emission), MAGIC3D, CST, and an FMT 3-D relativistic particle pusher
- Laboratory has a full machine shop w/ plasma processing equipment:
  - Small and large (digital) precision lathes with high speed tool post grinder
  - Digital milling machine
  - Grinding and sanding equipment
  - Acetylene, arc and spot welders
  - Cutoff saw
  - Band saw
  - Diamond saws
  - Small (digital) and large precision drill presses
  - Microwave assisted chemical vapor deposition system
  - RF and DC gun sputtering system
  - 2200K brazing/joining furnace

# FMT Facilities/Equipment

- Experimental hardware owned by FMT includes:
  - Pulsed Power Electron Beam and RF sources
    - Electron Beam System (1MV x 40kA x 0.1μs)
    - L-band (0.5 and 5 MW pulsed)
    - S-band (0.8, 1, 2.6 and 13 MW pulsed; 1 and 6 kW CW)
    - X-band (two 0.25 MW pulsed)
    - Broadband Amplifiers (50-2500 MHz, 50-100W CW)
  - MEIJI optical microscope w/ video out (400x, 2.5μm resolution)
  - Fast oscilloscopes
    - Ten 100-400MHz digital scopes
    - One 50GHz sampling scope
  - Particle transport magnetic coils
  - Nine vac-ion pumps, 2-400 L/s
  - Six turbo molecular pumps, 60-400 L/s
  - Various roughing pumps
  - 1.5 MJ Capacitor bank
  - High-power RF components
    - Circulators
    - Isolators
    - Phase/amplitude adjusters
    - 0.1-1 MV pulse modulators
  - Chemicals, labware and glassware
  - Power supplies and other test equipment

# Project

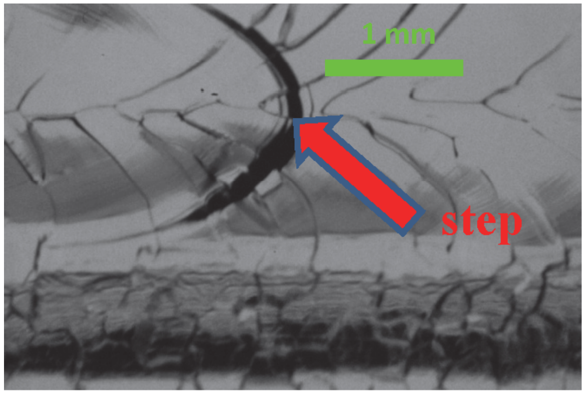
- SRF Cavity chemical treatment is expensive and complex
- After treatment surfaces still have numerous bubbles and pits
- Quench-producing weld defects and contamination result in significant scatter of Nb SRF cavity performance
- High costs and performance scatter are the major manufacturing problems
- FMT proposes to develop an internal electron beam (IEB) system that will perform electron beam melting over the entire interior surface of Nb SRF cavities
- Result is a surface that is smooth, void/bubble free, and free of imperfections
- This may allow manufacturing of the Nb SRF cavities with a reduction in chemical treatment and an increase in cavity high gradient performance
- FMT will design, build and test the new IEB system and process samples/cavities
- Thomas Jefferson Laboratory will measure RF performance of processed samples/cavities

# Seven-Cell Nb SRF Cavity at Thomas Jefferson National Accelerator Facility

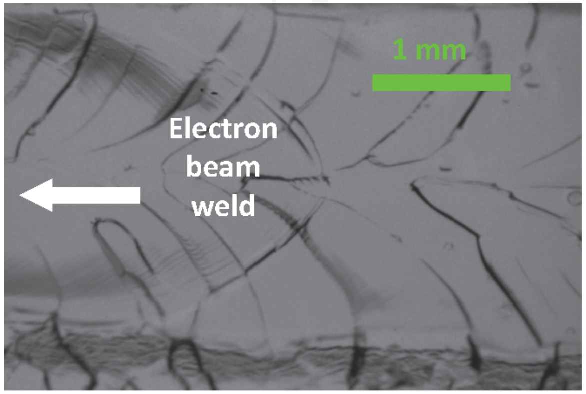
International Linear Collider alone needs 22,000 cavities at $210k (avg.) /cavity = $4.62 Billion

# Typical SRF Cavity Defects

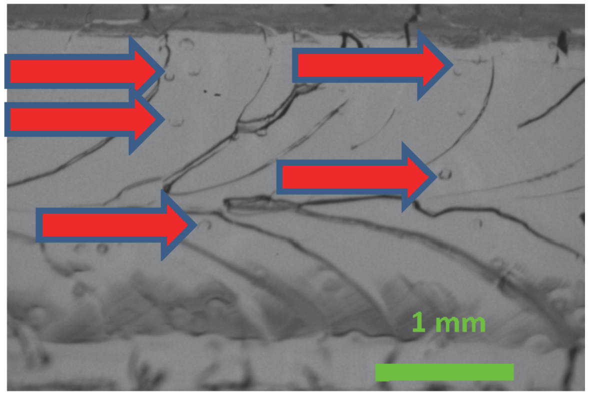
Pictures show typical defects inside Nb SRF cavities around the equator EBW overlaps that remain after chemical treatment:



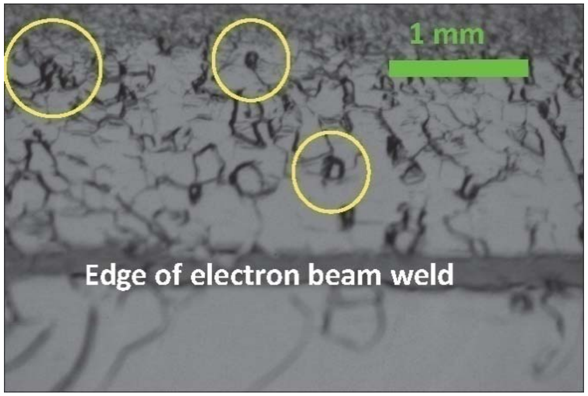

- Irregularity (step) near equator EBW overlap of cell #7 from waveguide




- Two cells have less pronounced features; four cells have no recognizable features




- Many "bubbles" sporadically present inside the weld



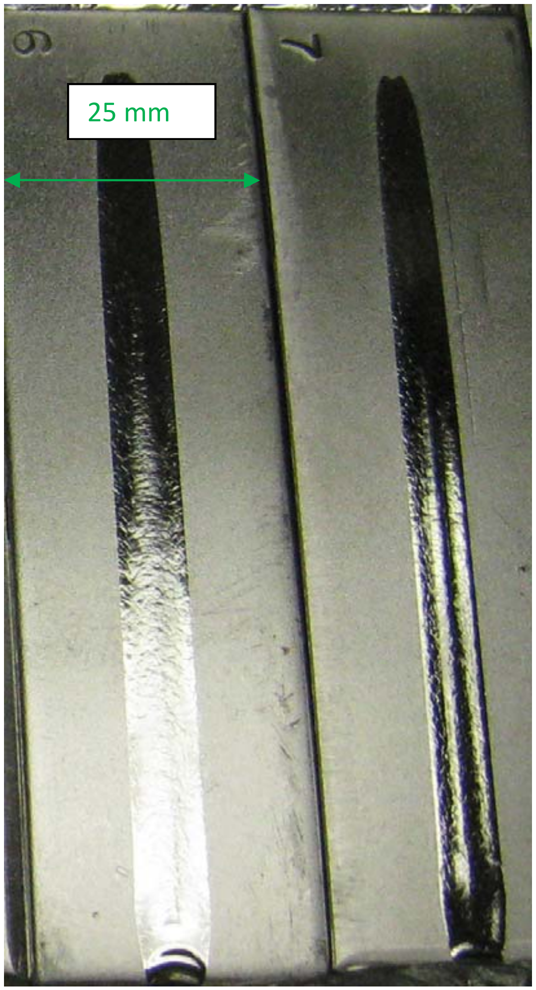

- Many apparent "deep pits" in heat affected zone

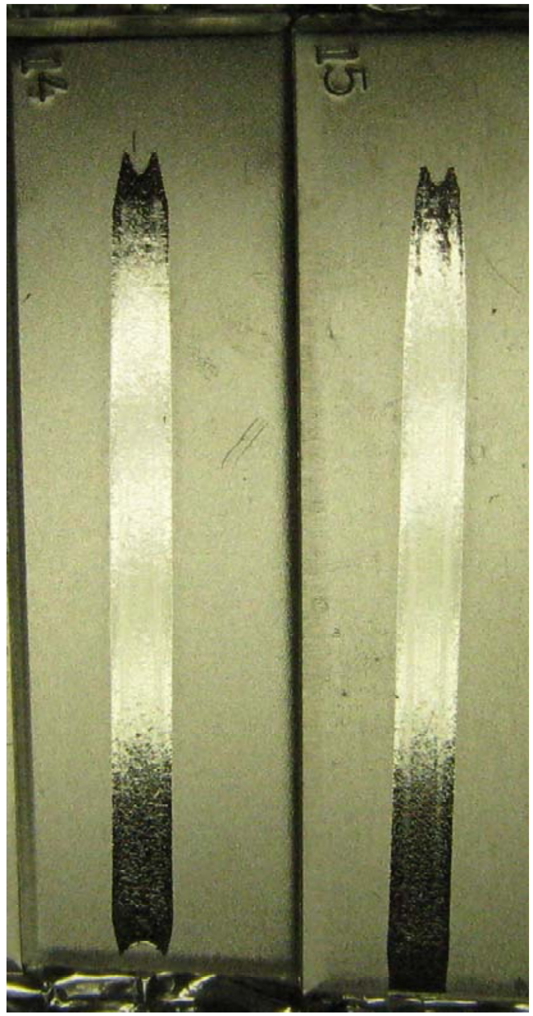
# Study of Beam Processing for Cavities

Objectives:

- Achieve a smooth surface with minimal defects and impurities to reduce quenching
- Achieve a low strain surface to reduce corrosion and absorption of contaminants
- Final goal is to attain reproducible high Q ($>10^{10}$) and high field (~40MV/m) cavities

# Electron Beam Melted Nb Samples Using J-lab SCIAKY Welder



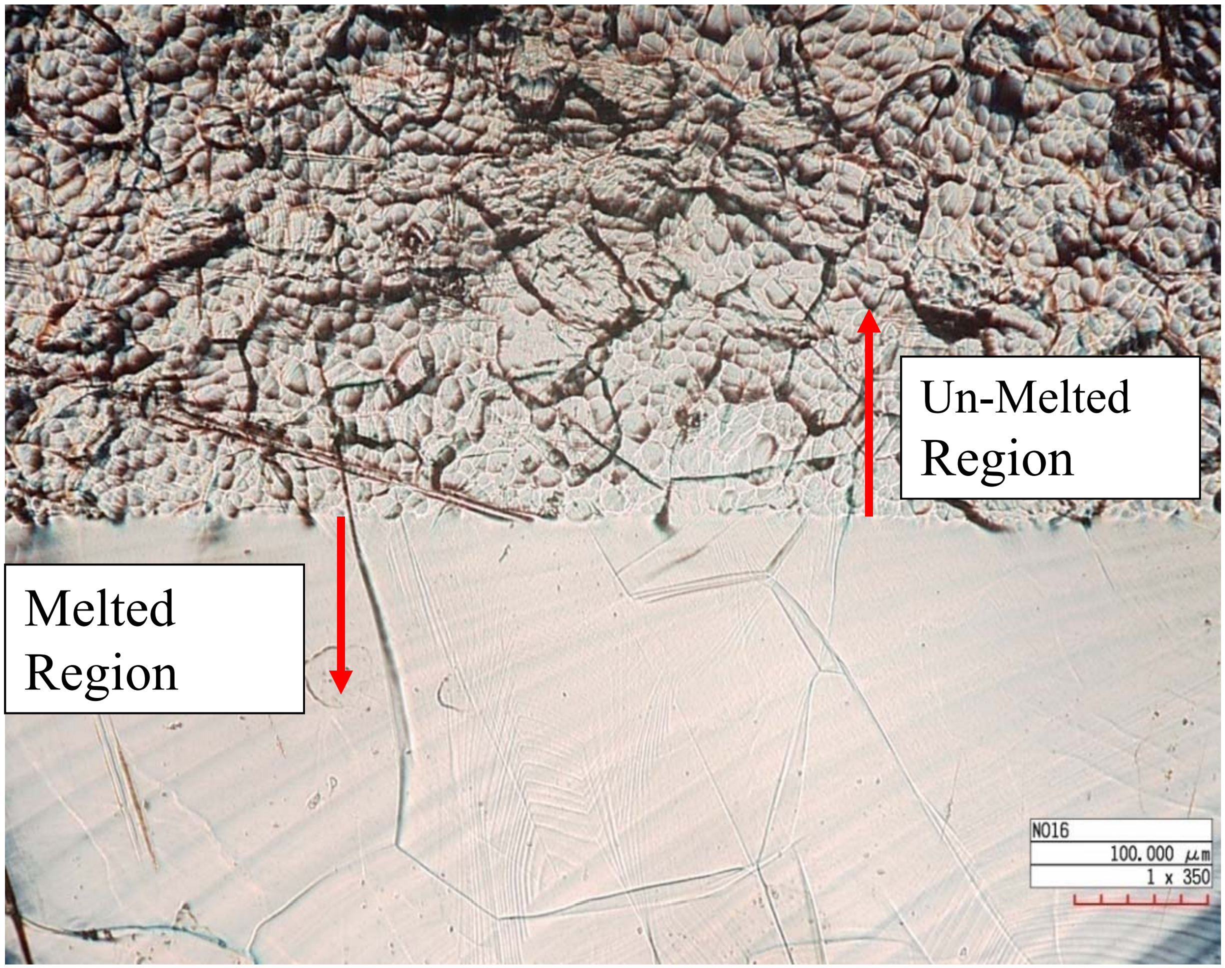

Each single pass melt region is about 6 mm x 74 mm x 0.1-0.2mm deep

A 10 kHz circular to elliptical raster with 0.5-1 mm beam diameter with a particle energy of 50 keV

Beam current and translation rates varied from 20-250mA and 5-20 in/min

28 plates of Nb with dimensions 3 mm thick x 25.4 mm wide x 88.9 mm long

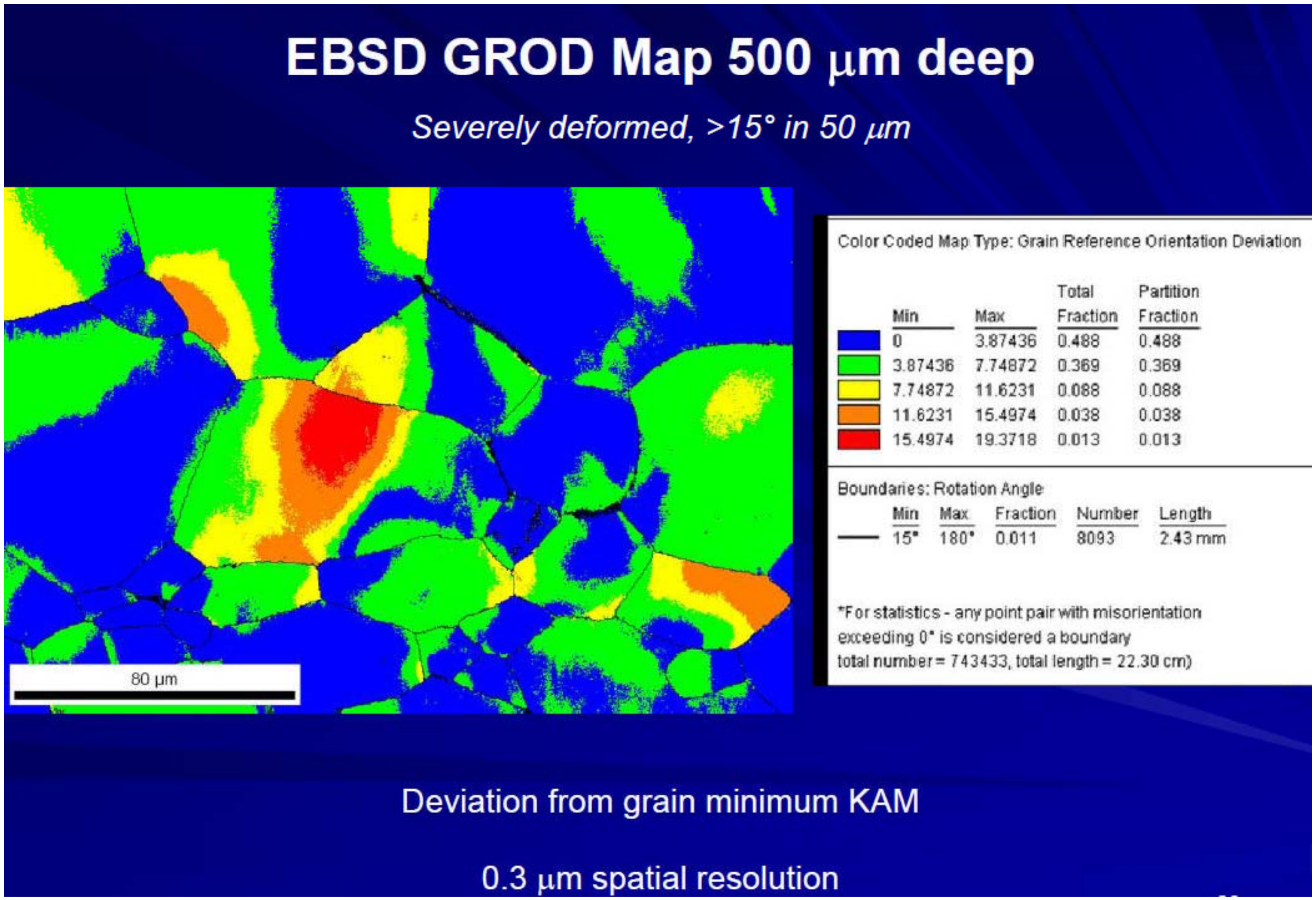
# Magnification of Melt Zone




HIROX digital microscope view of sample #6

Bottom half of image shows the smooth melted region that highlights the grain size of about 300-400 µm, while upper half of image shows the rough un-melted small grain region

# Grain Reference Orientation Deviation (GROD) Map for Deep Drawn Half Cell



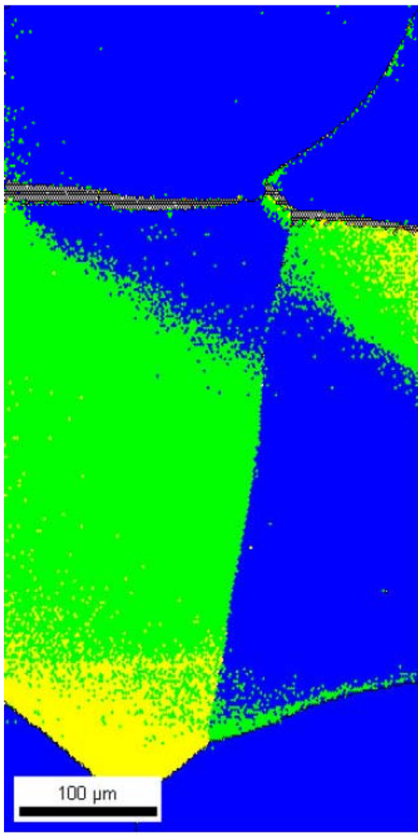

Courtesy of Dr. Roy Crooks of Black Laboratories

The section is taken from 3 mm from the equator

The GROD map shows extreme lattice distortion up to an angular rotation of about 20 degrees

No chemical etching has occurred

# Grain Reference Orientation Deviation (GROD) Map for Nb Flat Sample #7

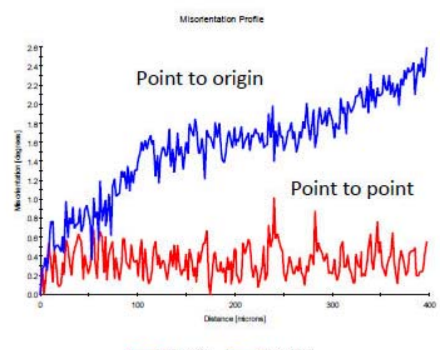



No. 7

GROD

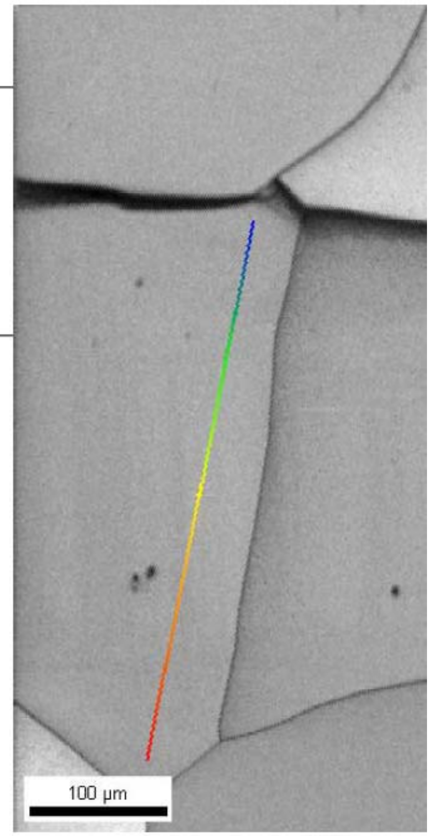
Color Coded Map Type: Grain Reference Orientation Deviation

| | Min | Max | Total Fraction | Partition Fraction |
|---|---|---|---|---|
| Blue | 0 | 1 | 0.602 | 0.602 |
| Green | 1 | 2 | 0.319 | 0.319 |
| Yellow | 2 | 3 | 0.067 | 0.067 |
| Orange | 3 | 4 | 0.000 | 0.000 |
| Red | 4 | 5 | 0.000 | 0.000 |




Misorientation profile within grain, no. 7.

*Note lattice curvature in grain on left*

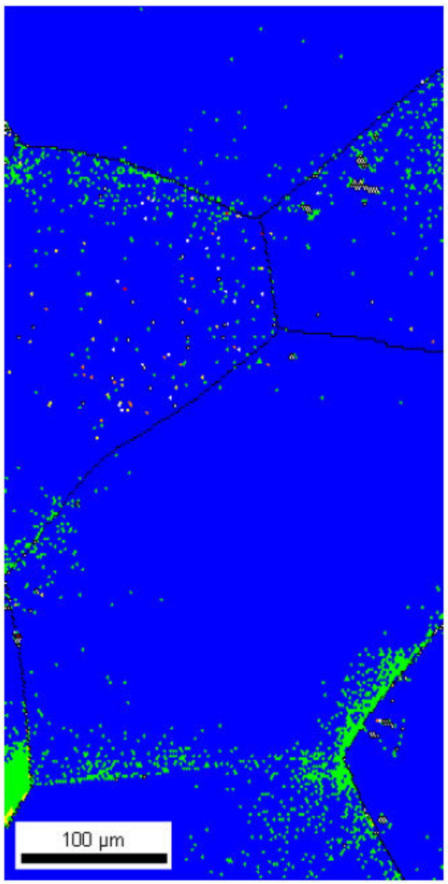



Both samples #6 and #7 show GROD in the range of 0 – 3° over a distance of 100 – 300 µm.

40mA and 10in. /min.

No chemical etching has occurred.

# Grain Reference Orientation Deviation (GROD) Map for Nb Flat Sample #15




No. 15

GROD

Color Coded Map Type: Grain Reference Orientation Deviation

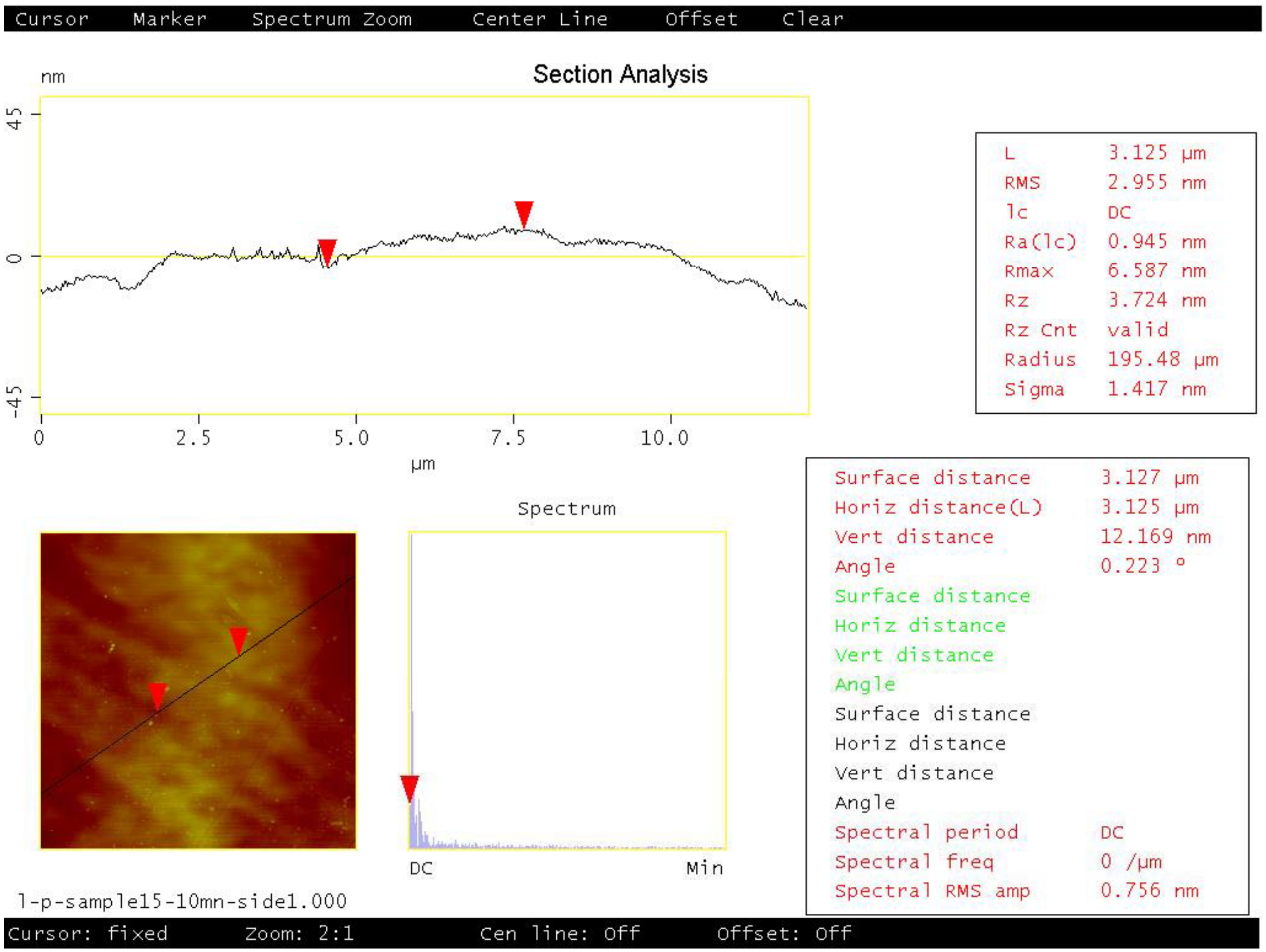
| Min | Max | Total Fraction | Partition Fraction |
|---|---|---|---|
| 0 | 1 | 0.960 | 0.960 |
| 1 | 2 | 0.036 | 0.036 |
| 2 | 3 | 0.001 | 0.001 |
| 3 | 4 | 0.000 | 0.000 |
| 4 | 5 | 0.000 | 0.000 |

Samples #14 and #15 show less lattice distortion compared to samples #6 and #7 as measured by GROD

0 – 2° with the majority of distortion less than 1° over 100 – 300 μm

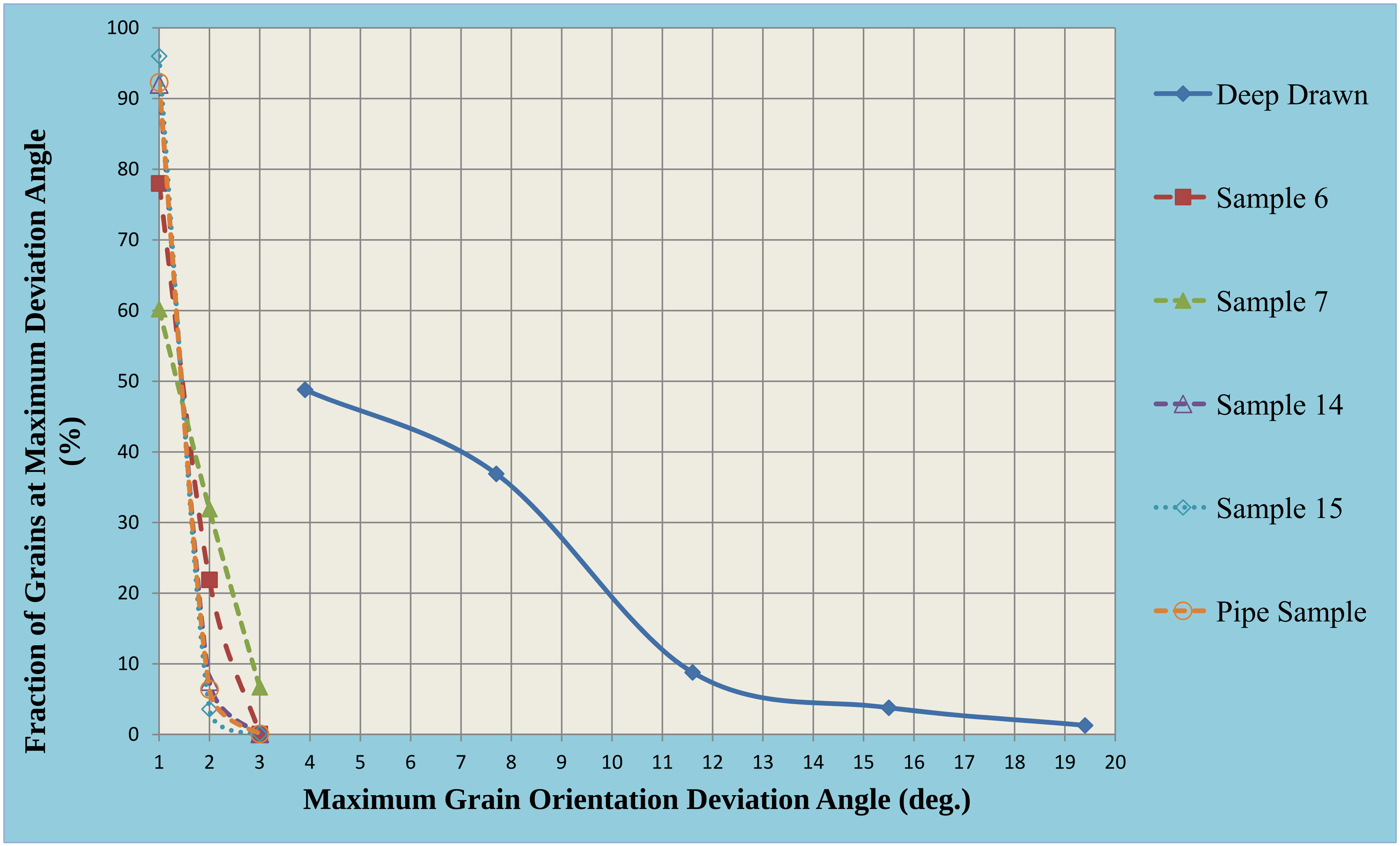
No chemical etching has occurred

# AFM of Sample #15

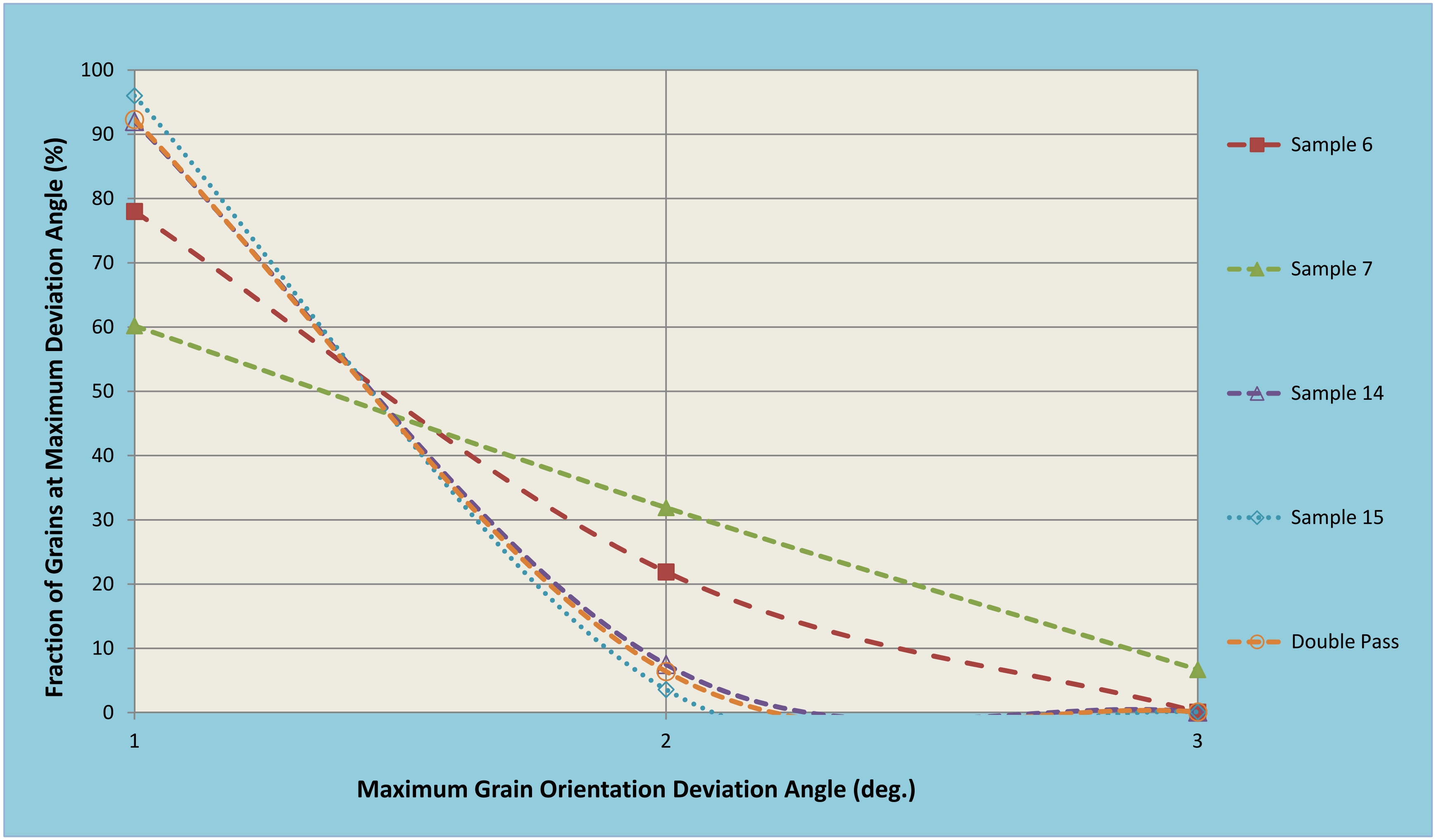



AFM RMS value of less than 3 nm, which is 1/20 of what can be accomplished by electro-polishing and much less than the superconducting layer thickness for Niobium of 42 nm @ 2K

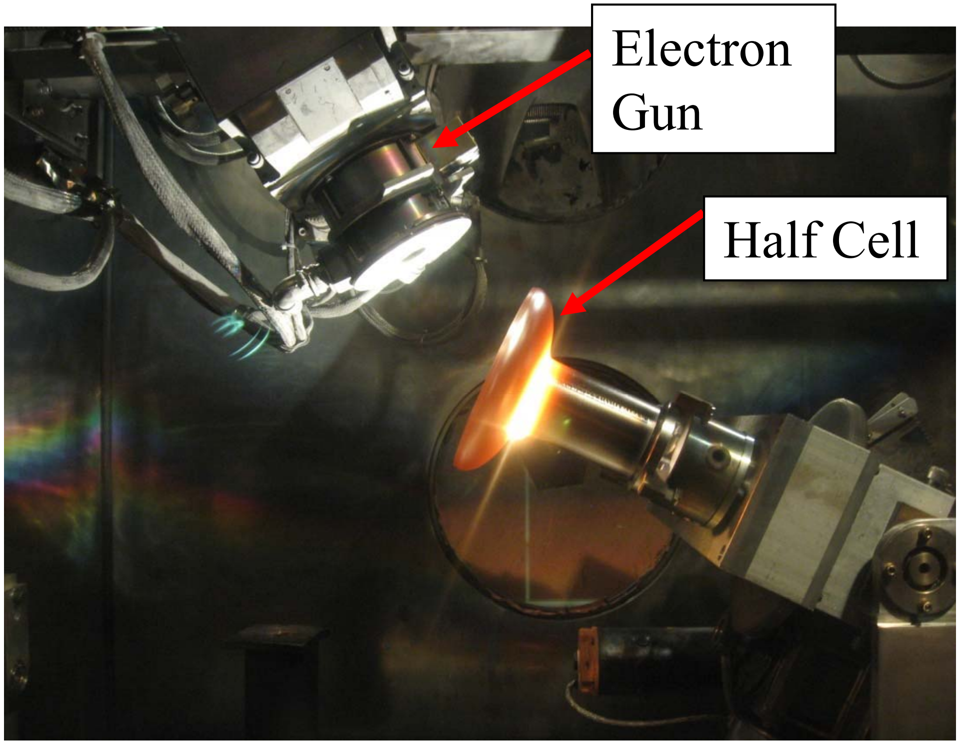
# Comparison Of Grain Deviation For Nb: E-Beam Processed and Deep Drawn



# Comparison of Grain Deviation for Various E-Beam Processed Nb Samples



# Chemical Free Half-Cell Processed in J-lab's SCIAKY E-beam Welder



# Finished E-Beam Processed Half-Cell

The beam parameters were: 40 mA, 0.5mm diameter beam, travelling at 18 inches per minute, the melting diameter is about 6 mm with a circular pattern at 10 kHz.

# Summary of Beam Results for A Smooth-Low Strain Surface

- Both HIROX & AFM suggest that a smoother surface is attained at lower beam energy dose
- EBSD (GROD) maps suggest a lower strain surface is attained at lower beam energy dose
- Desired beam parameters have been determined

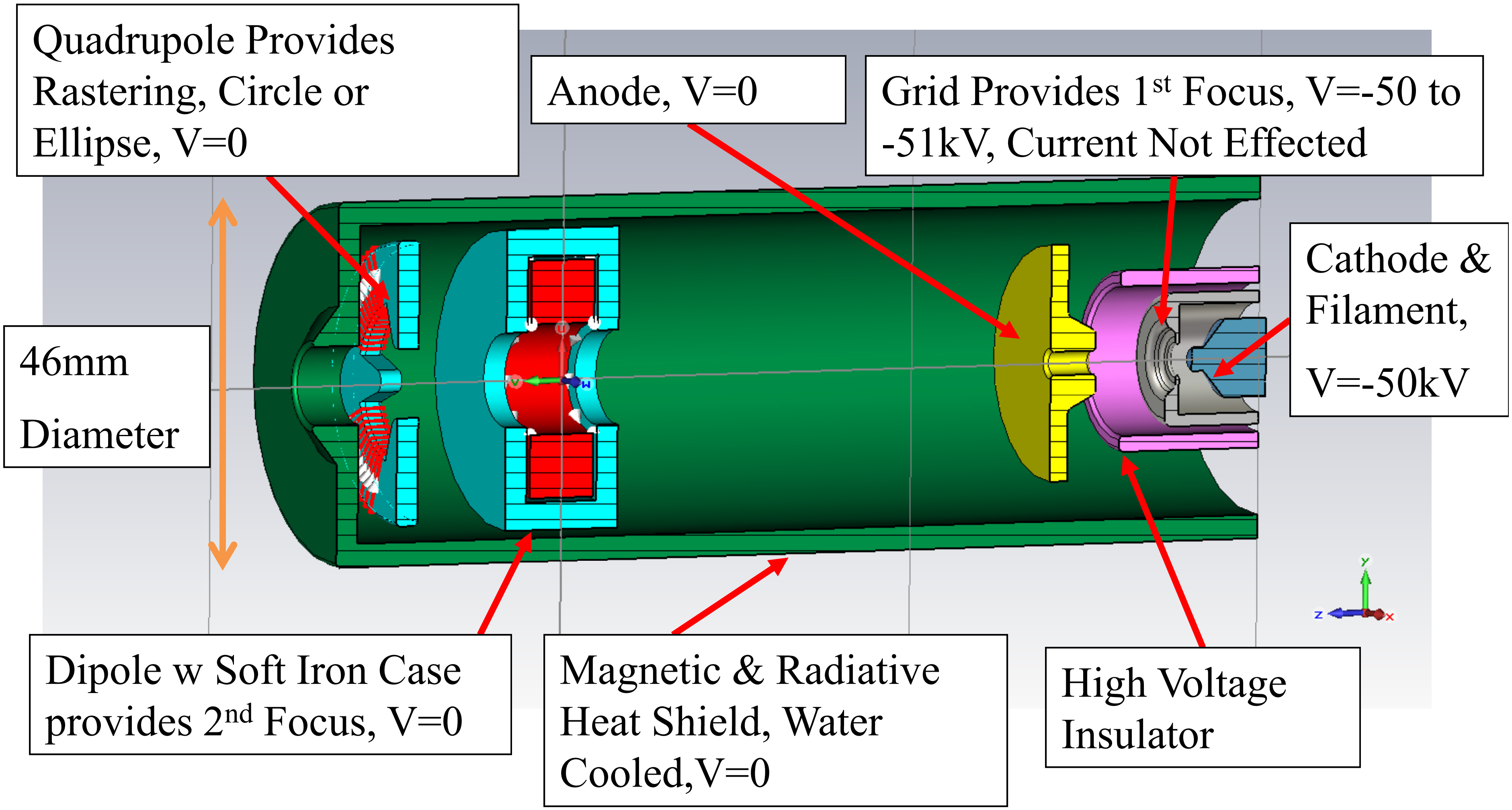
# Electron Gun and Beam Transport Design

- Two Strategies: Ballistic Focusing and Magnetized Beam

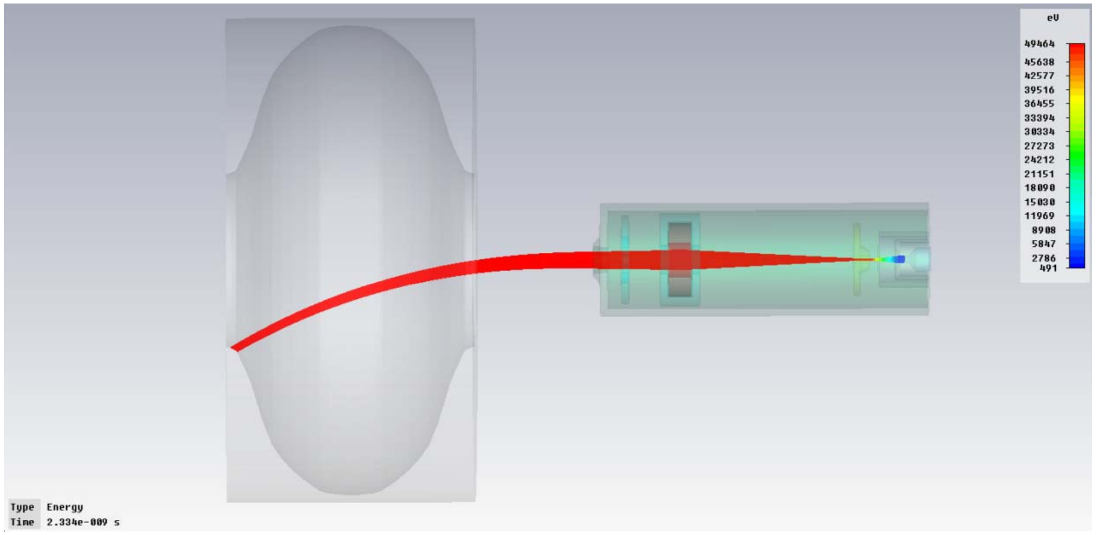
CRITERIA:

- – Can process from iris to equator and circumference
- – Prevent Nb vapor arcing
- – Can tolerate beam induced thermal radiation & filament heat load
- – Electron Gun Characteristics: ~50keV, beam spot 0.5-1mm, gun diameter < cavity iris (<50mm), long focal length (30-100cm) and current control independent of focus

# Ballistic Focusing Gun

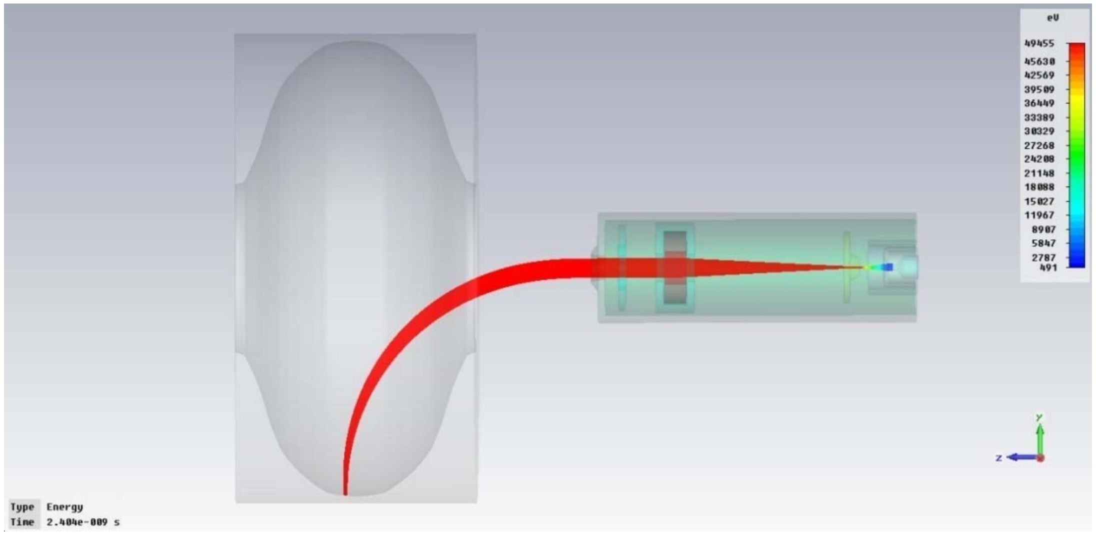


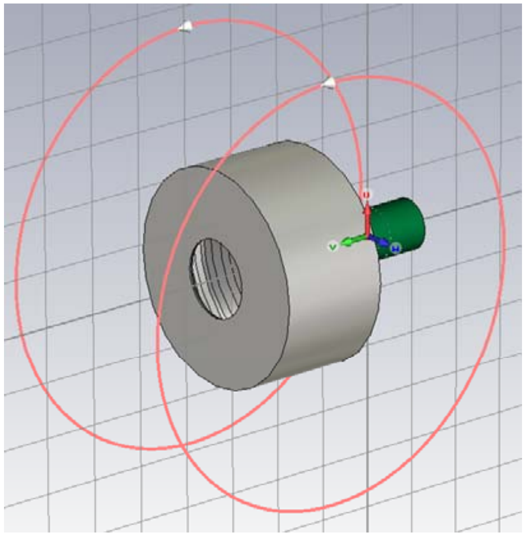
# Ballistic Focusing Gun: Electron Beam Trajectory




Helmholtz coils provide R-Z beam scanning from iris to equator

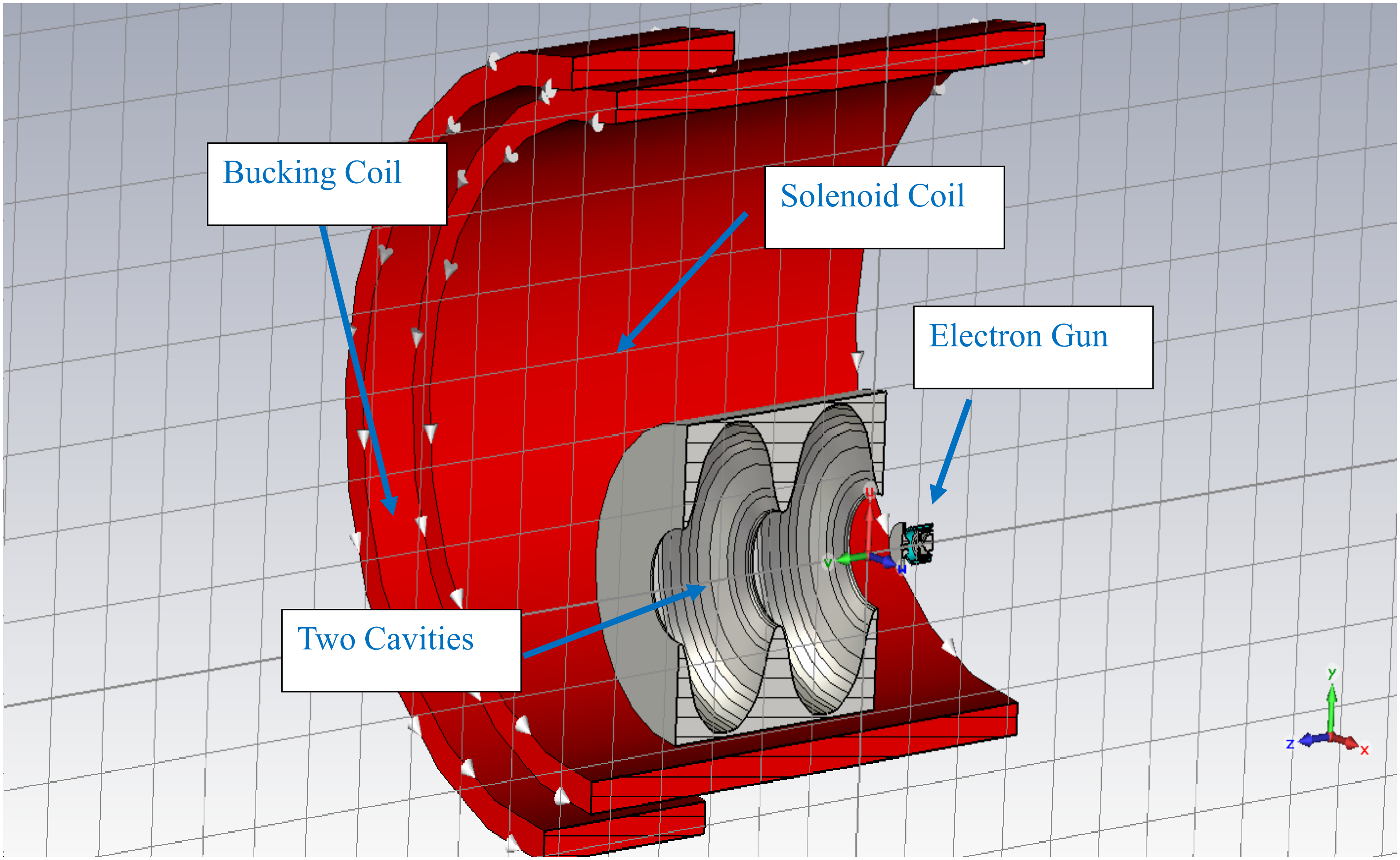
Azimuthal scanning provided by rotating either the cavity or Helmholtz coils or field about the Z-Axis



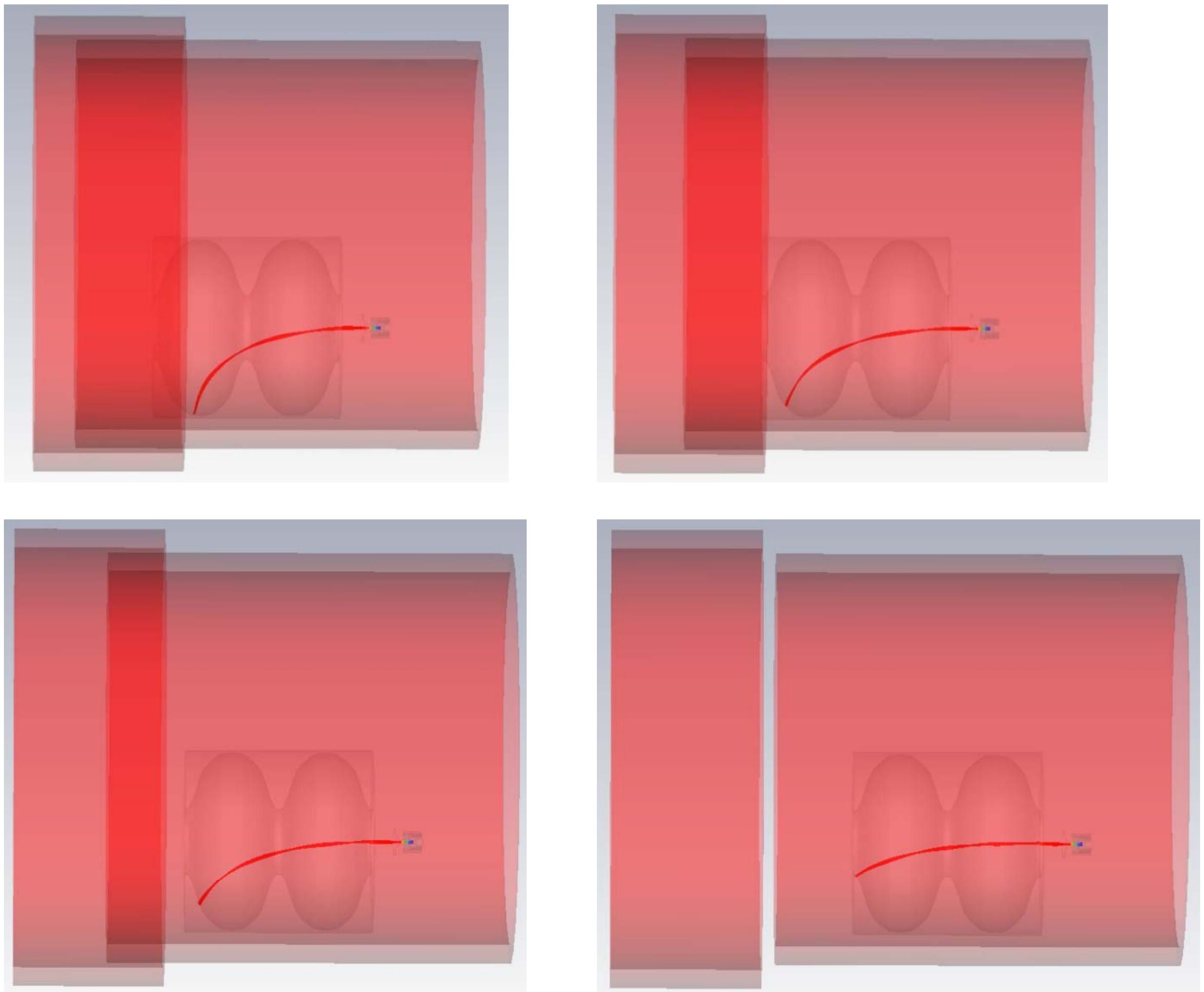



# Magnetized E-Beam Gun

## Simple Gun Design: Only Needs Cathode, Grid & Anode



# Magnetized E-Beam Gun: Electron Beam Trajectory



Bucking coil position/current provides R-Z beam scanning from iris to equator

Azimuthal scanning provided by rotating cavity

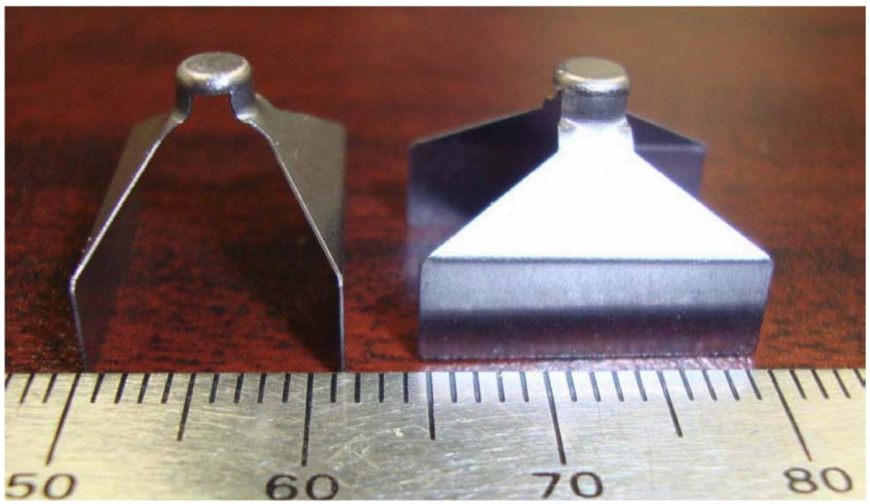
Advantage over ballistic gun of much longer focal length, but more complex magnetics

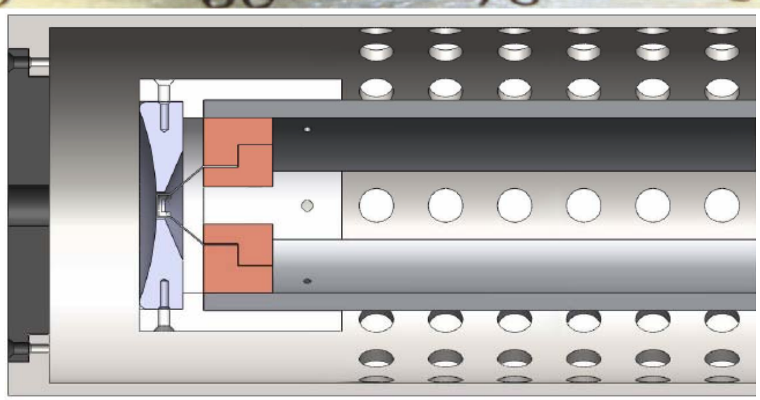
# Ballistic vs. Magnetized Beam

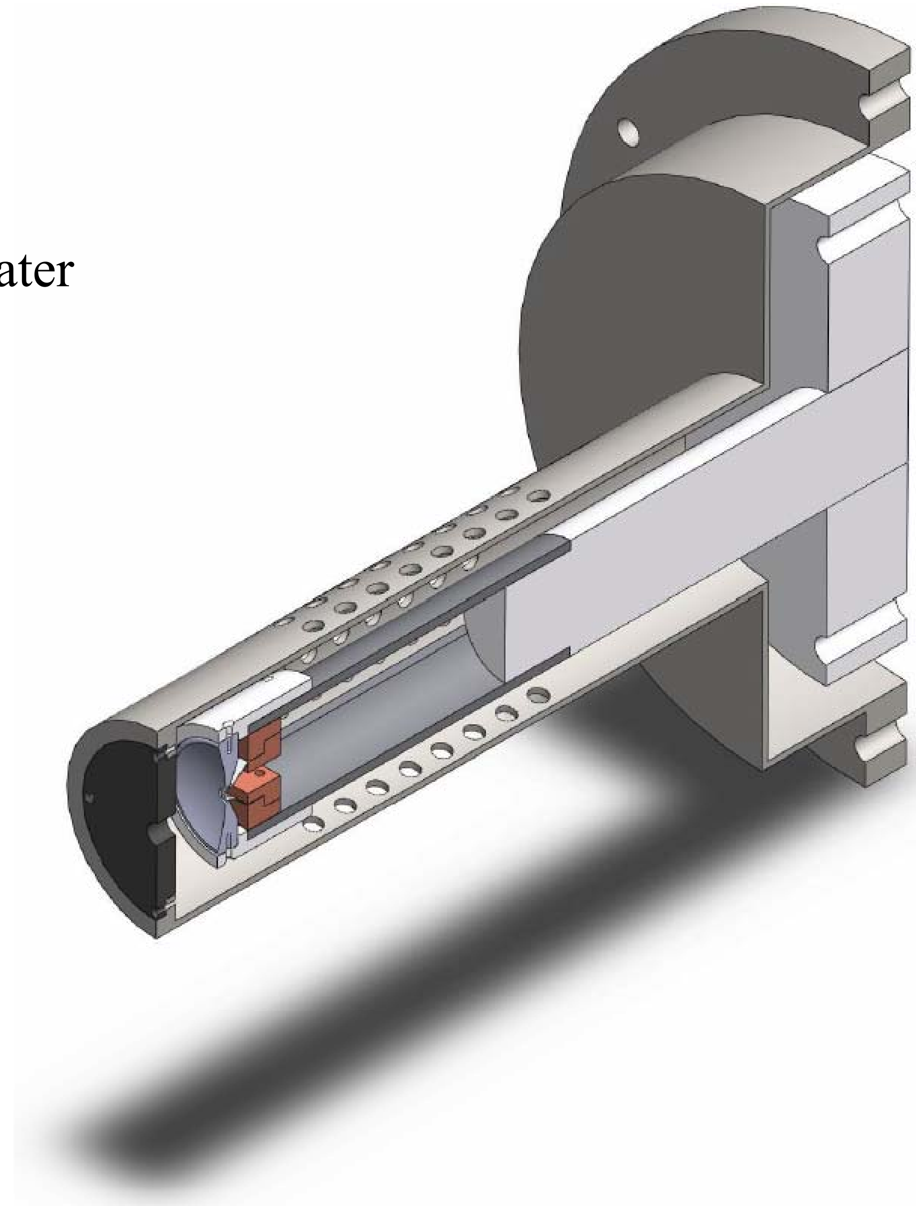
- Ballistic
  - Compact
  - Shorter focal length
  - Slow/uniform melting
  - Complex
  - In-cell processing issues
- Magnetized
  - Simple
  - Long focal length
  - Higher beam power
  - Cannot point focus
  - Requires very large magnets

# Prototype Gun Design

- SCIAKY tantalum filament
- 67A @ 1.4V
- Passively cooled
- Improved filament design to come later





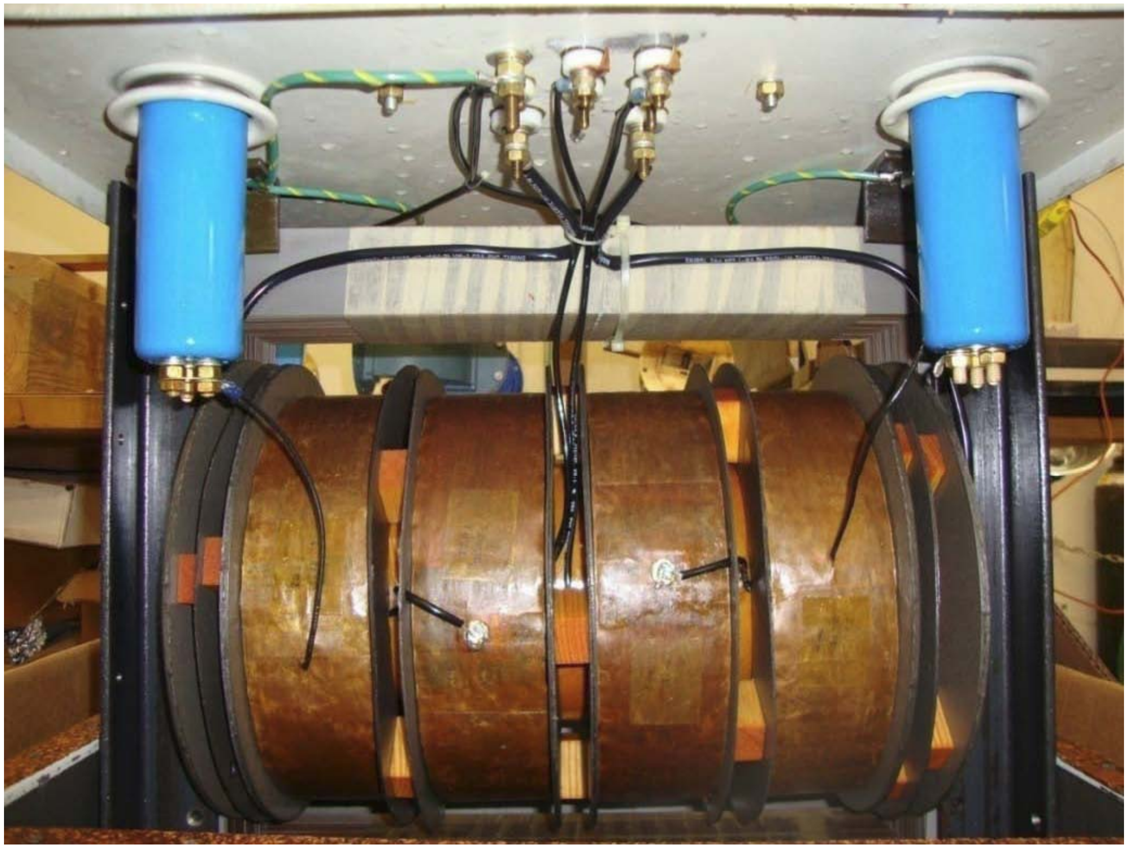
# Stainless Steel Test Chamber

Chamber reaches $10^{-8}$ Torr in ~2hr with turbo and cryo-pumps

Chamber ready for gun installation and high voltage

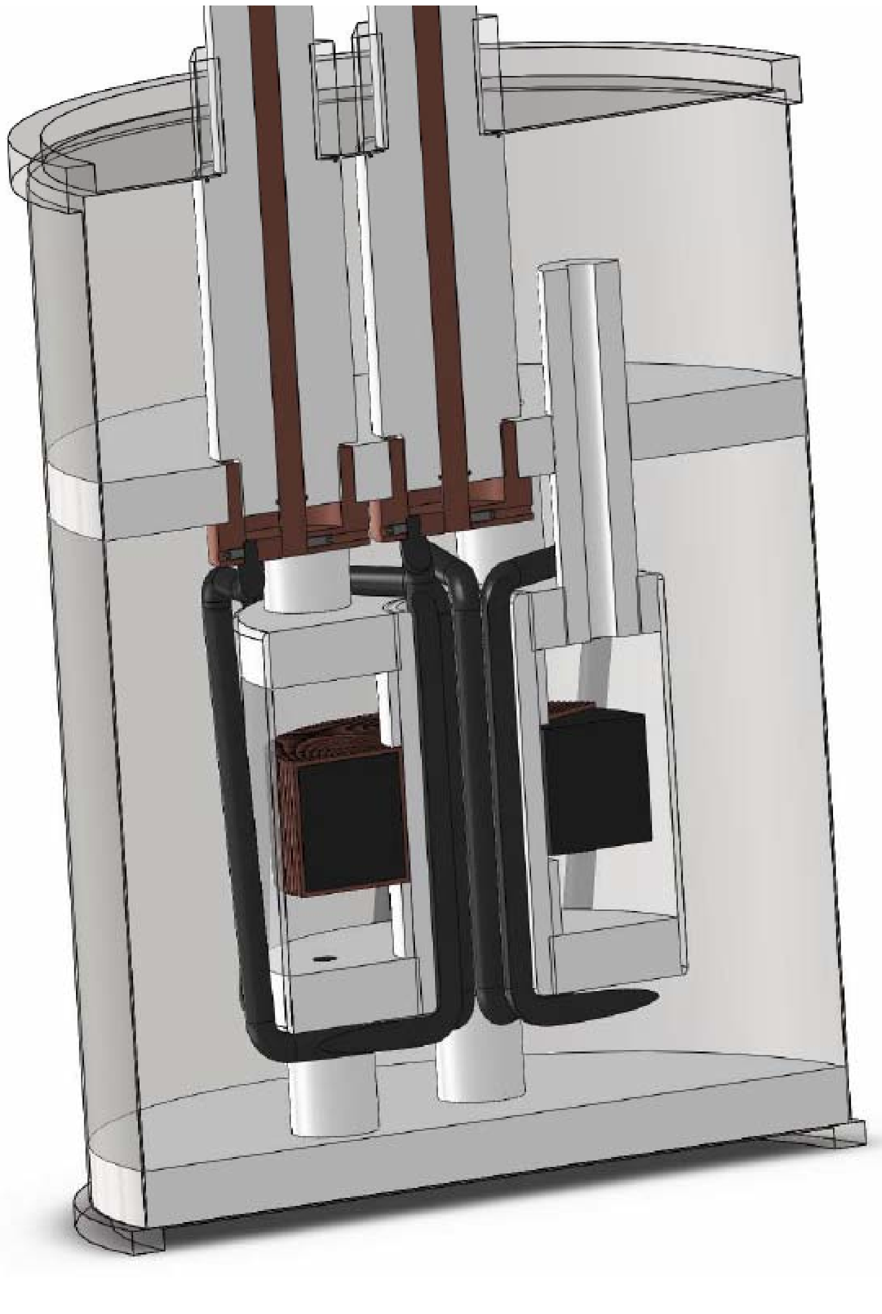
Chamber suitable for time dependent magnetic fields: magnetic diffusion time ~13ms

# High Voltage Transformer



- "E" core transformer
- 15kVA, 220V RMS input
- Four secondary windings
- 2+2 configuration gives 230mA @ 65kV

# Filament Transformer



- FMT design
- 2.3kVA, 115V RMS input
- 20A primary
- Capable of 430A @ 5.35V w/ 150kV isolation

# Summary and Status

- Beam parameters have been determined that give a smooth low strain surface using a conventional rastered beam
- Two gun designs examined (ballistic & magnetized beams) to meet the requirements with and without rastering for both internal and external gun operation
- Stainless steel vacuum chamber, suitable for time dependent magnetic fields, ready for high voltage and e-gun
- High voltage power supply and filament transformer ready for e-gun
- Prototype gun designed and ready for fabrication
- Next step will be to surface melt Nb flat strips with new e-gun