Chemical Free Surface Processing of 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 simulation and design software 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 & plasma processing equipment:
  - Small and large (digital) precision lathes with high speed tool post grinder
  - 4-axis CNC milling machine
  - 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 3-gun sputtering system
  - 2773K 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
  - Cryo pump
  - 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 Rationale and Approach

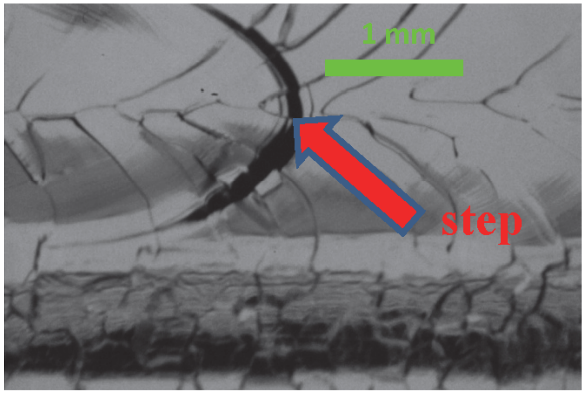
- SRF Cavity chemical treatment is expensive and complex
- After treatment surfaces still have numerous bubbles and pits
- Quench-producing weld defects and contamination result in significant scatter of Nb SRF cavity performance
- High costs and performance scatter are the major manufacturing problems
- FMT is developing 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 without voids, bubbles, or 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

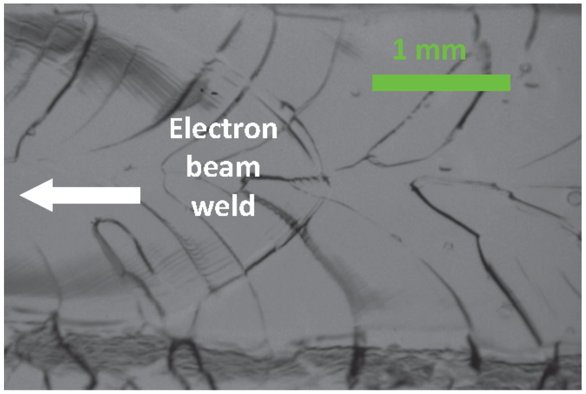
International Linear Collider alone needs 22,000 cavities at $210k (avg.) /cavity = $4.62 Billion

Typical SRF Cavity Defects

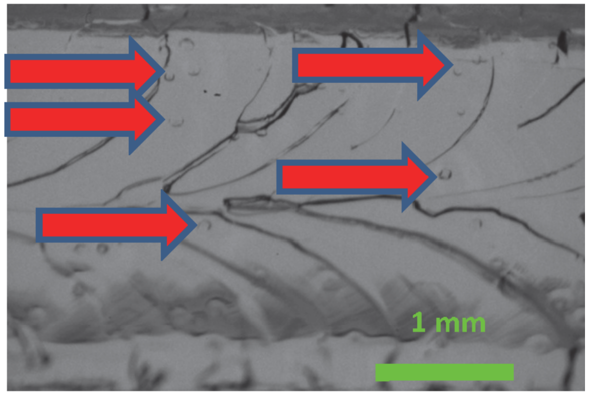
Pictures show typical defects inside Nb SRF cavities around the equator EBW overlaps that remain after chemical treatment:



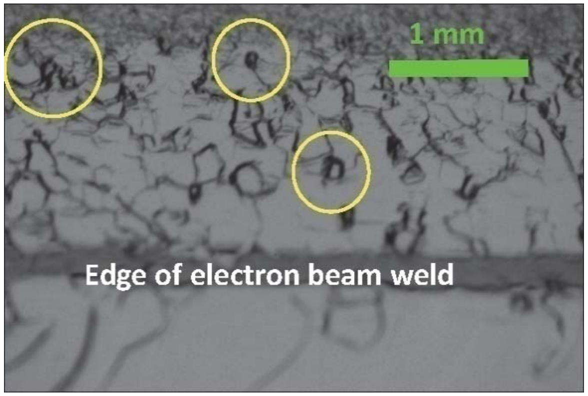
- Irregularity (step) near equator at EBW overlap of cell and waveguide



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



- Many "bubbles" sporadically present inside the weld

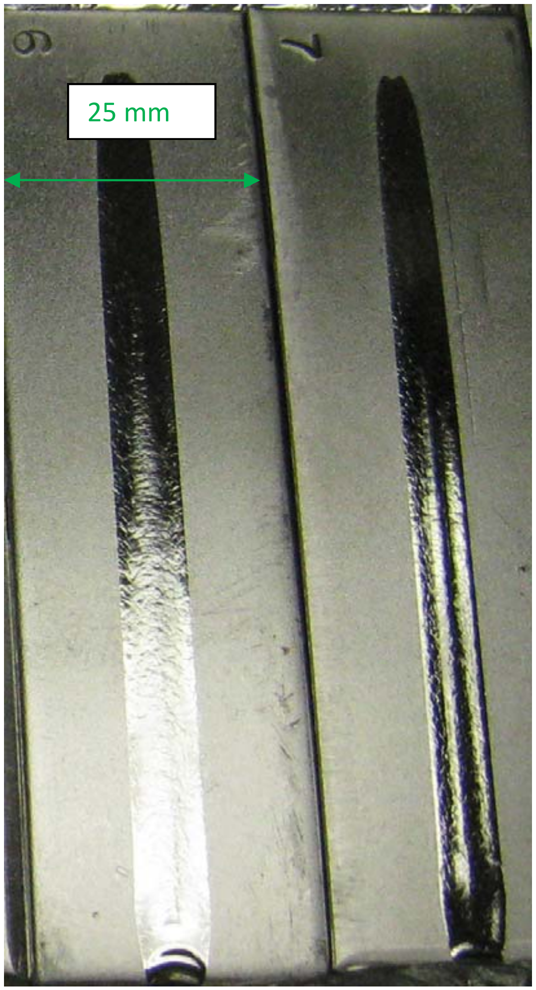


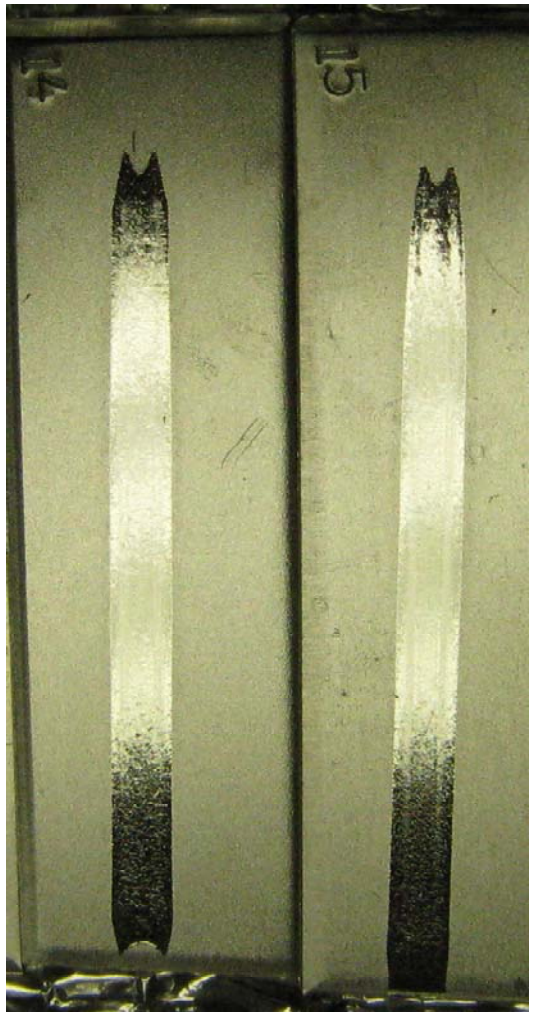
- Many visible "deep pits" in heat affected zone

Objectives for Accelerator RF Cavity Processing

- 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 Electron Beam Welder





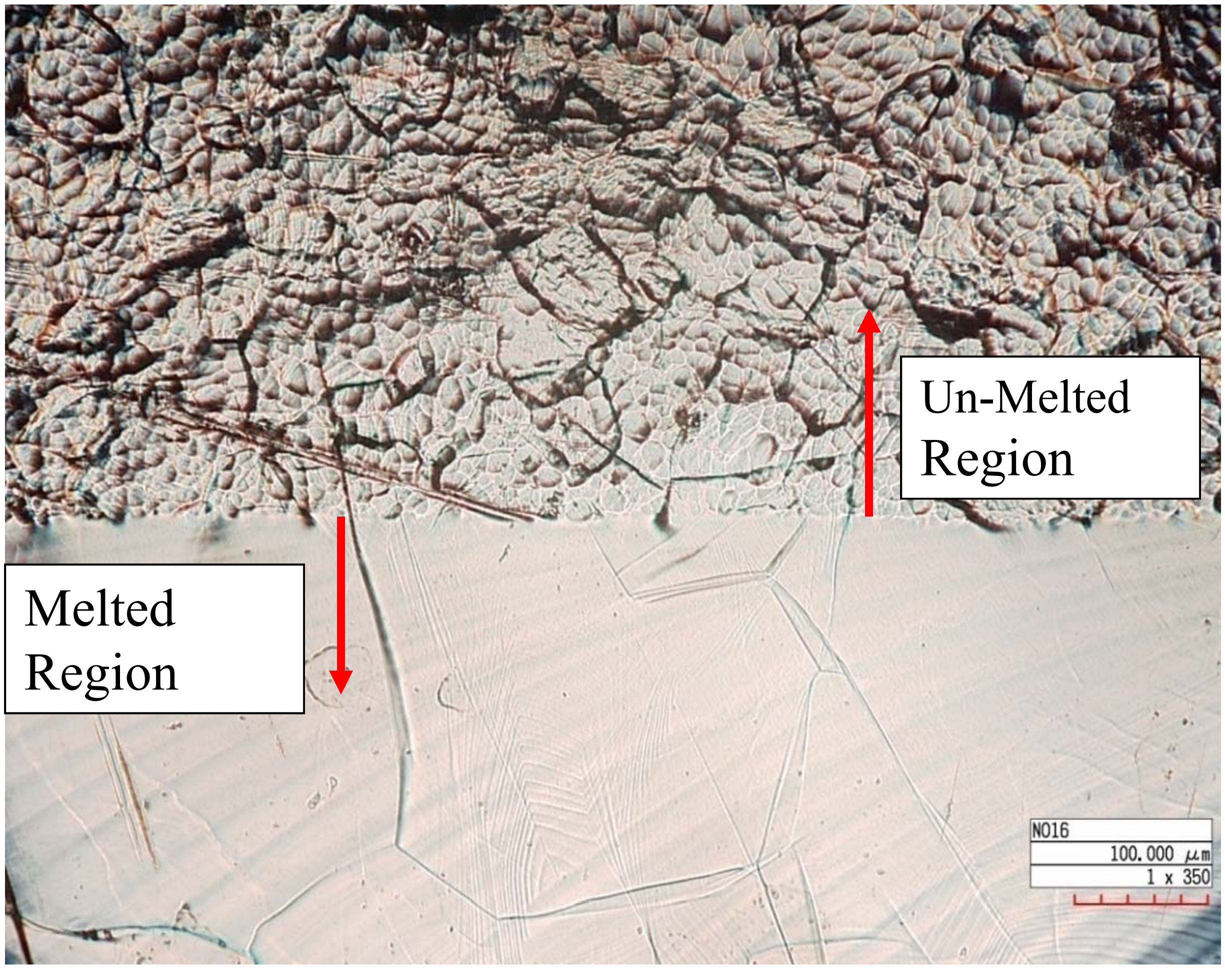
Each single pass melt region is about 6 mm x 74 mm x 0.1-0.2mm deep

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

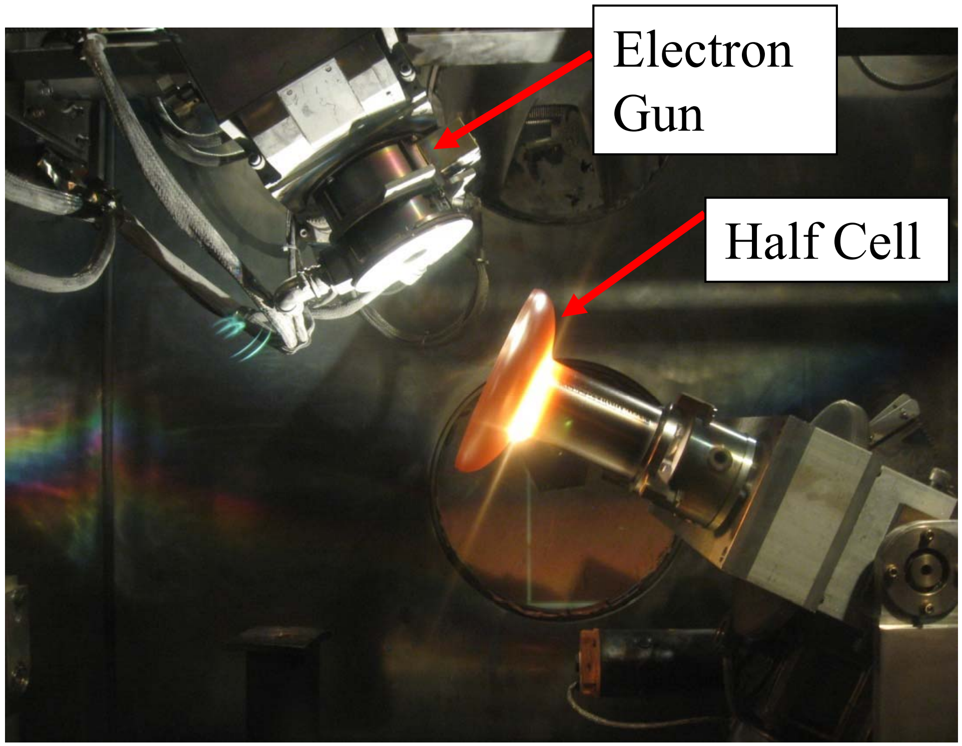
Magnification of Melt Zone



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

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



Finished E-Beam Processed Half-Cell

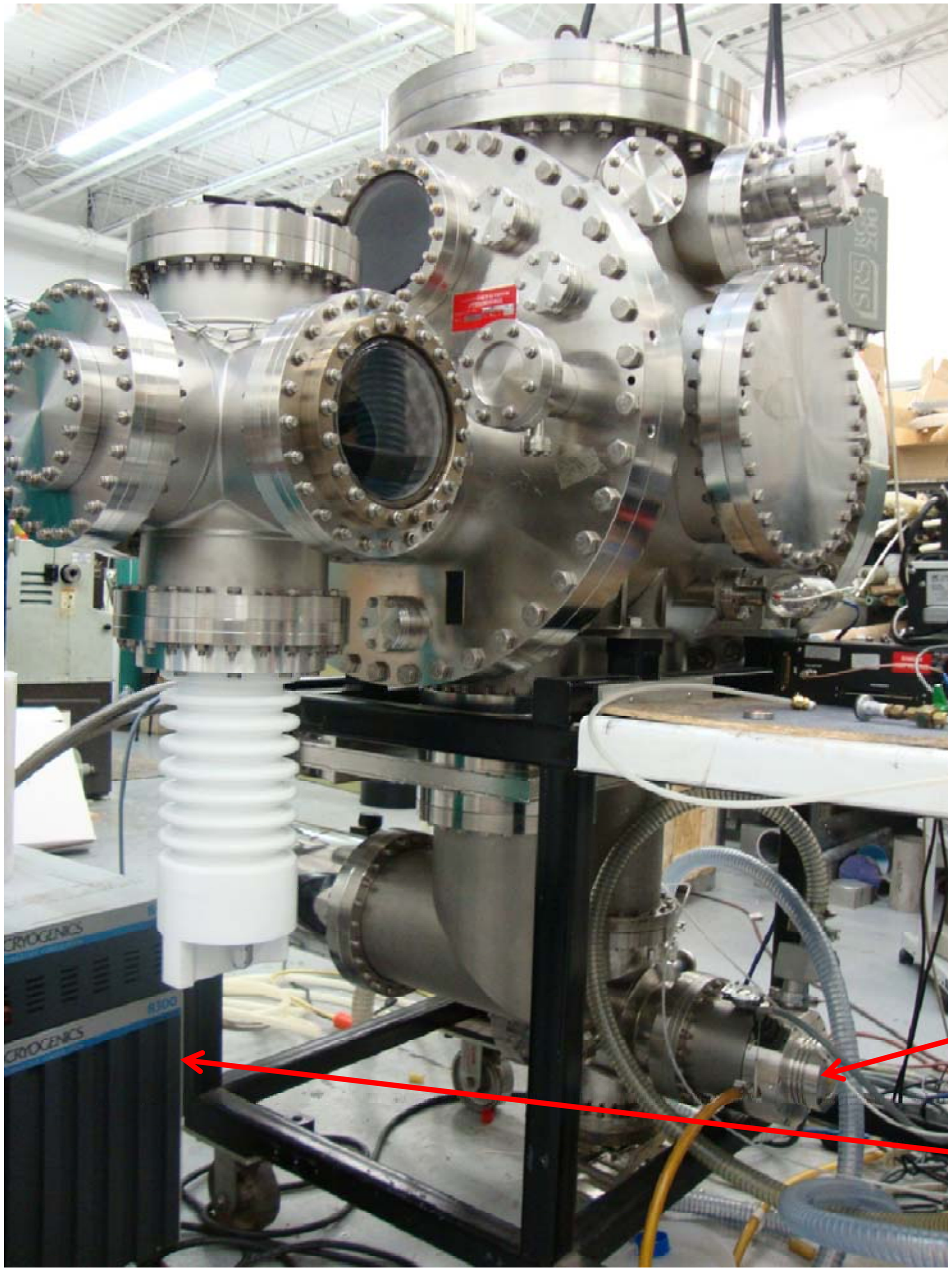
The beam parameters were: 40 mA, 0.5mm diameter beam, travelling at 18 inches per minute, the melting diameter is about 6 mm with a circular pattern at 10 kHz.

Test and Prototype Evolution

Project is proceeding in three development phases:

Initial Test System	Gun Test System	Production Prototype
Isolation Transformer		
High Voltage Power Supply		
Vacuum Chamber and Pumping System		
Anode-Cathode System	Electron Gun	
Water-cooled Target	Rotating Target Mount & FT	Steering Magnetic Field
Graphite Target (No Nb)	Nb strips	Nb SRF Cavity or Cell

Stainless Steel Test Chamber



Chamber reaches $3x10^{-8}$ Torr with test cathode, anode, high current and voltage feedthrus.

Chamber hosted operational high voltage and current tests

Chamber suitable for time dependent magnetic fields with a diffusion time of ~13ms

Turbo-pump

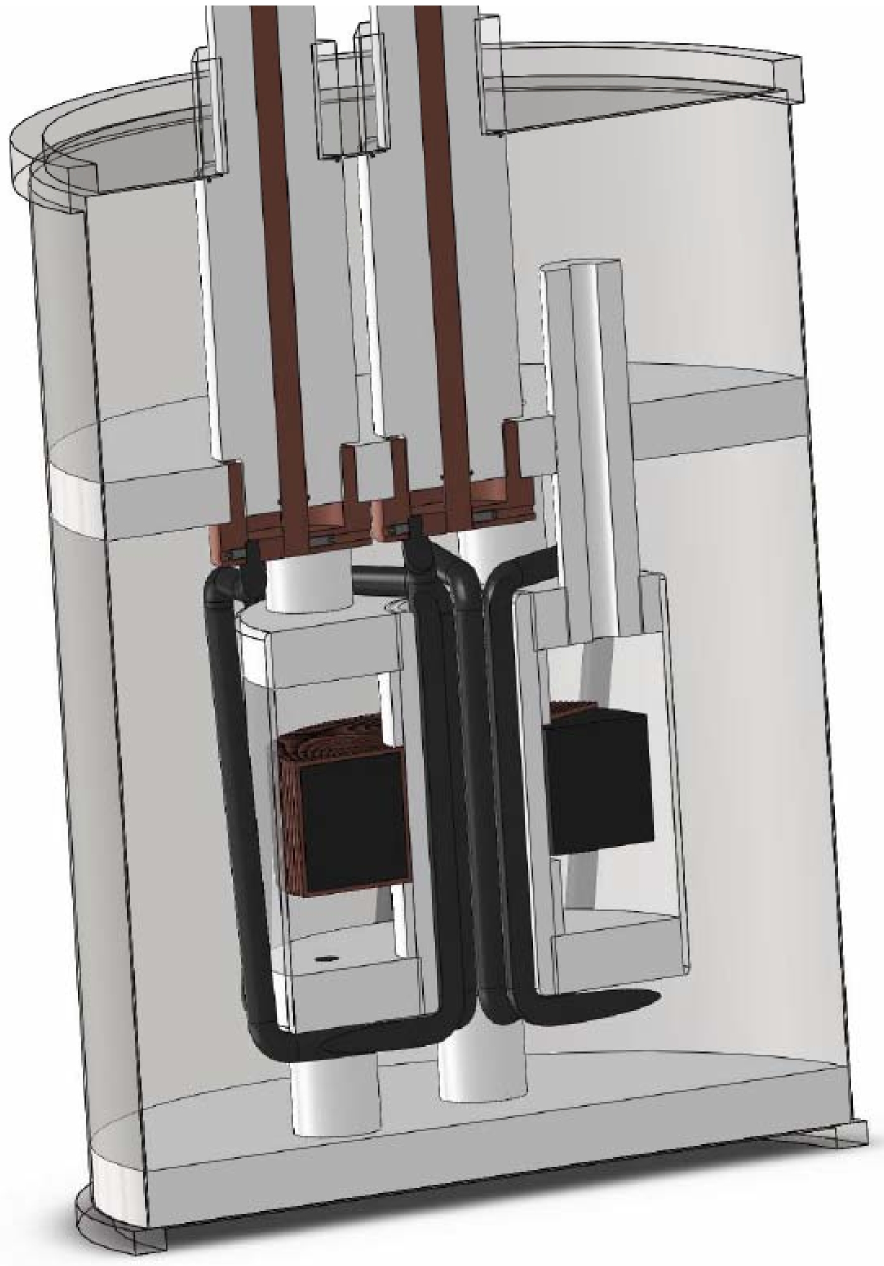
Cryo pump

Isolation Transformer

Purpose: to provide large AC current to heat the filament to provide a copious electron source for acceleration

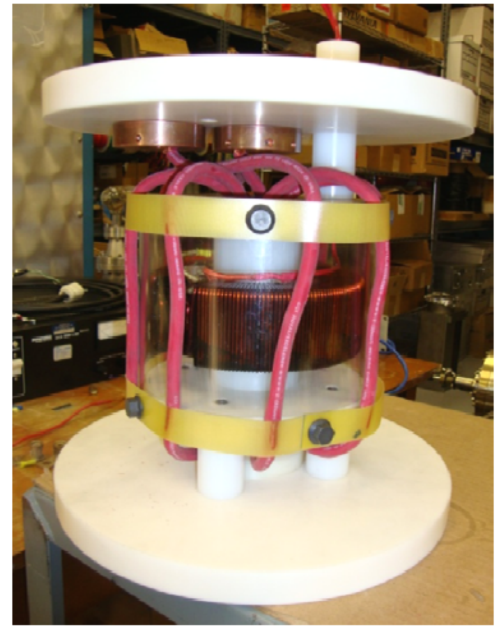
Step-down transformer with primary and secondary coils without common grounding contained in an oil filed tank allowing the secondary to float to high voltage

Isolation (Filament) Transformer Design



- FMT design
- 2.3kVA, 115V RMS input
- 20A primary
- Capable of 430A @ 5.35V w/ 150kV isolation
- Tested to 330A and 100 kV.

Isolation Transformer Implementation



- Primary coil (from a dismantled variac)
- Secondary coil: 8 turns of #2 welding cable
- Turns ratio ~20
- Immersed in oil for high voltage operation

High Voltage (HV) Power Supply (PS)

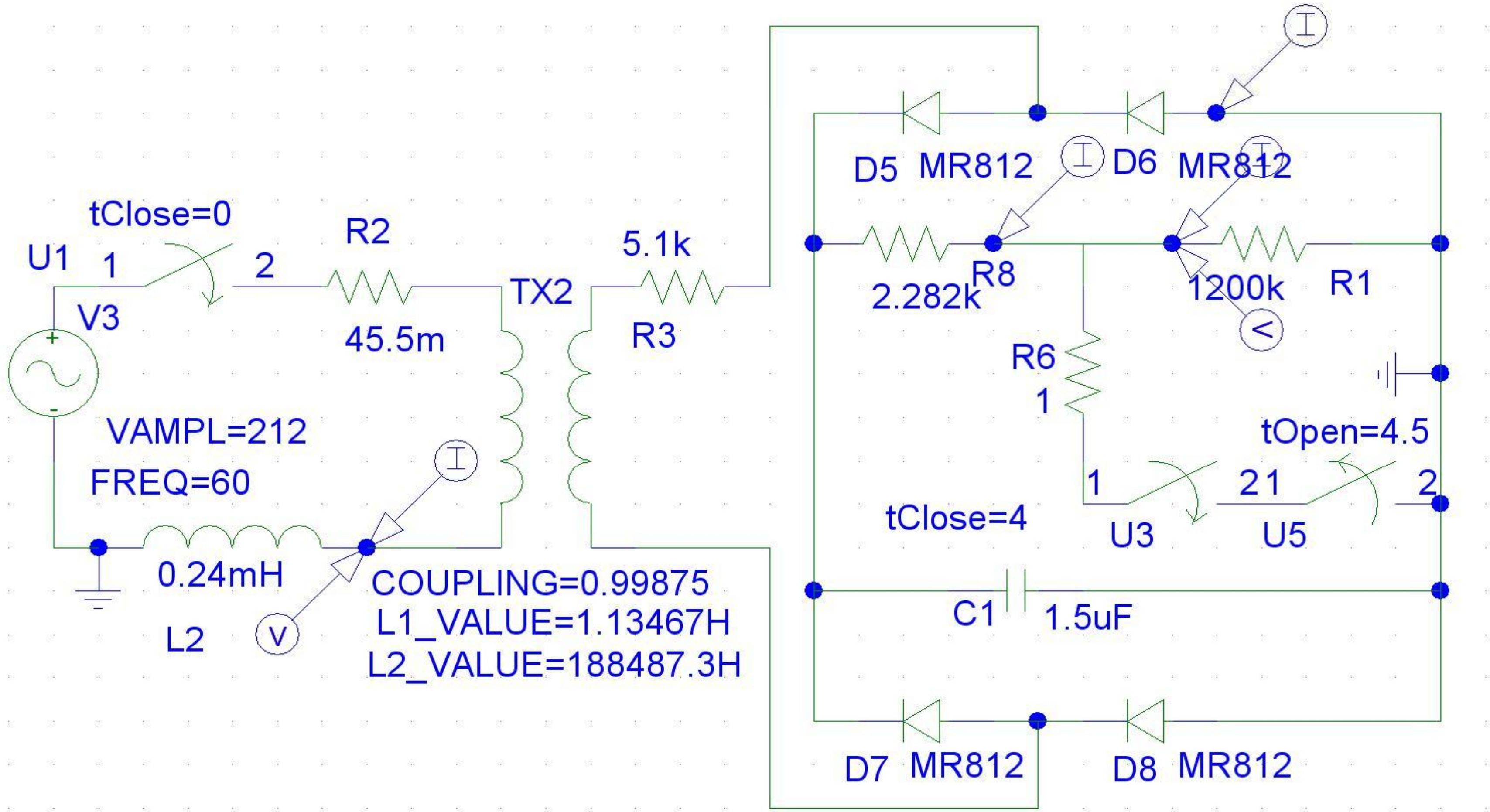
Purpose: to provide a high voltage and power (50 kV, up to15,000 watts) source to accelerate electrons

HV PS consists of:

- Variac
- HV Transformer
- Current Limiting Inductor(s)
- Full Wave Rectifier
- Filtering Capacitor(s)
- Output Resistor(s)
- Plastic Container Oil tank

HV PS must be resilient against short and open circuits suddenly and unexpectedly presented by the load. Circuit simulations aided these design goals.

HV PS Circuit Diagram and Simulations

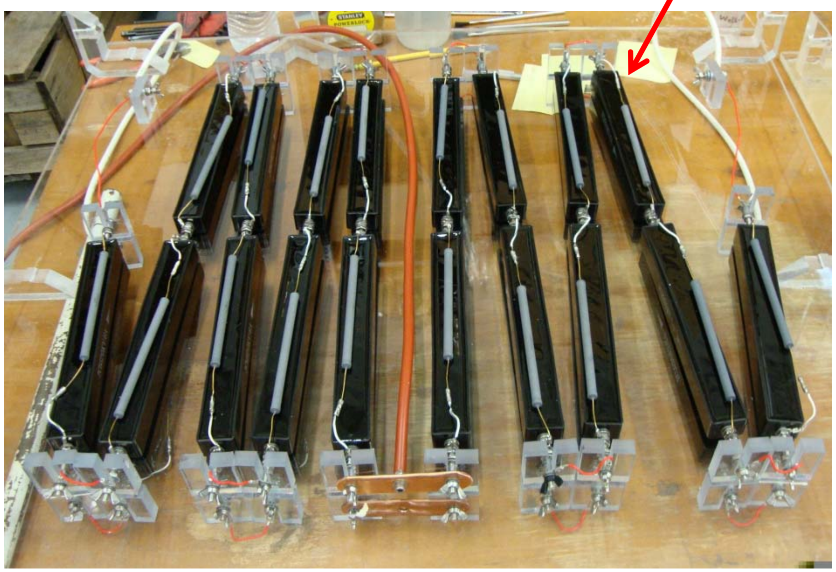


Tested to > 50 kV and > 40 mA.

HV Power Supply Hardware Components

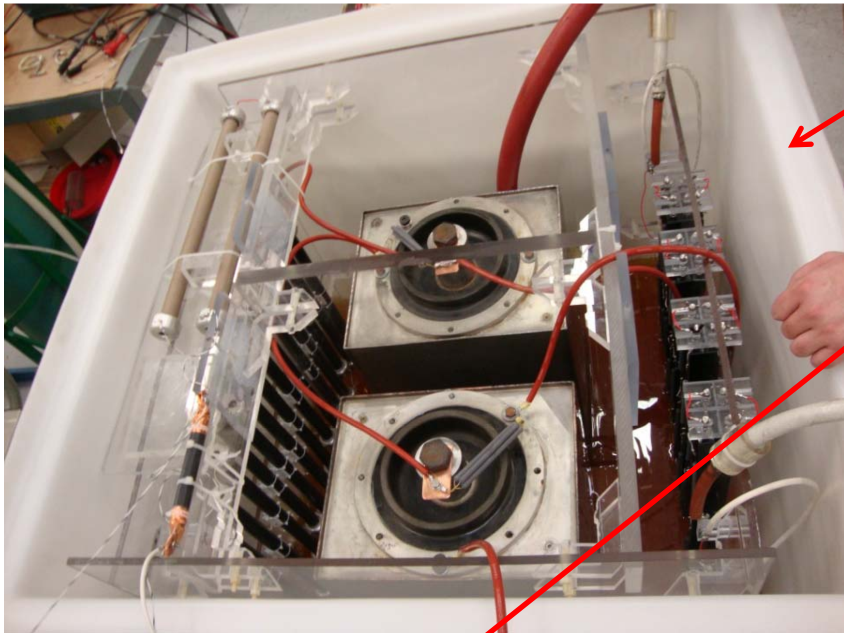
3uF, 60 kV capacitors to be connected in series

Full wave rectifier made from 36 20-kV diodes
100 Mohm resistors in parallel to equalize voltage across diodes



14 163-ohm resistors in series on PS output

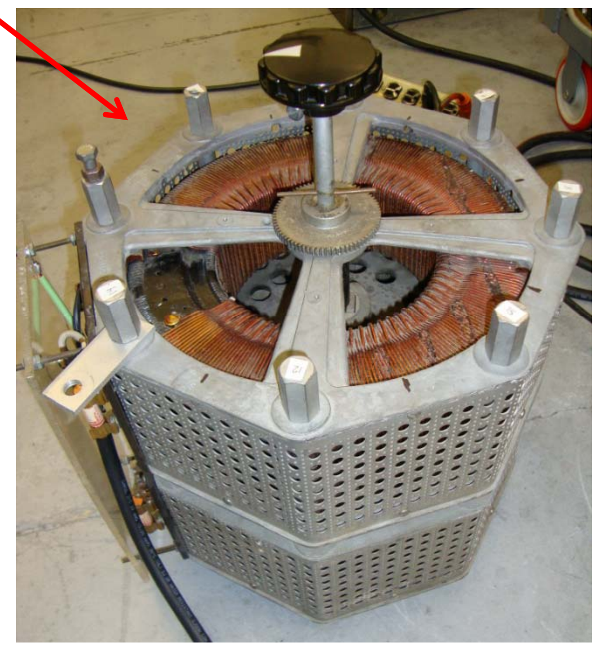
HV Power Supply Hardware Components (cont.)



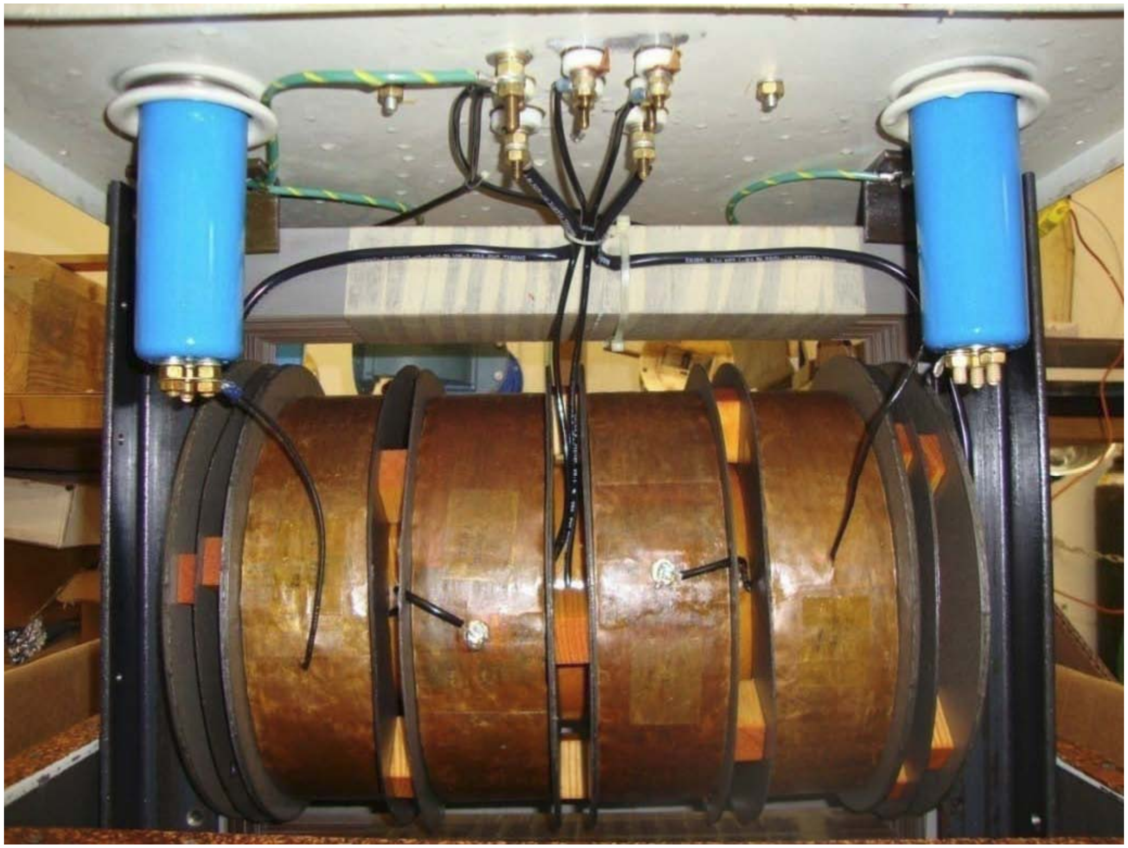
Tank with rectifier, resistors, capacitors, and dummy load installed; oil being added

Inductors wired in parallel with each other and in series with transformer

Variac providing HV PS voltage control



High Voltage Transformer



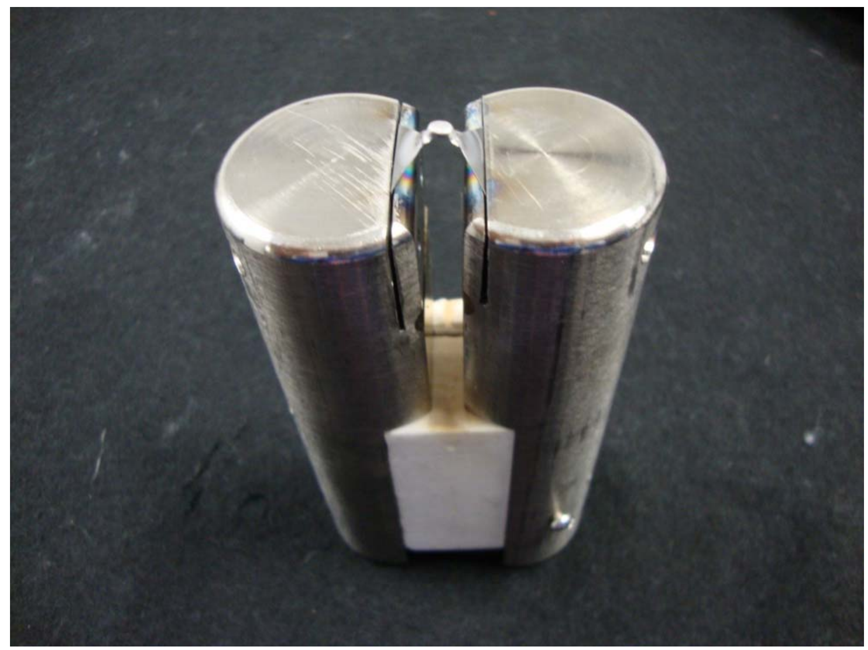
- “E” core transformer
- 15kVA, 220V RMS input
- Four configurable secondary windings
- 2+2 configuration gives 230mA @ 65kV

Cathode/Anode Diode Assembly

Its purpose is to test beam generation at operational power within the chamber.

Cathode assembly is comprised of:

- Tantalum filament (Sciaky)
- Two Titanium mount/feeds
- Macor insulating block
- Aluminum feed-thru rods



Water-Cooled Target Assembly

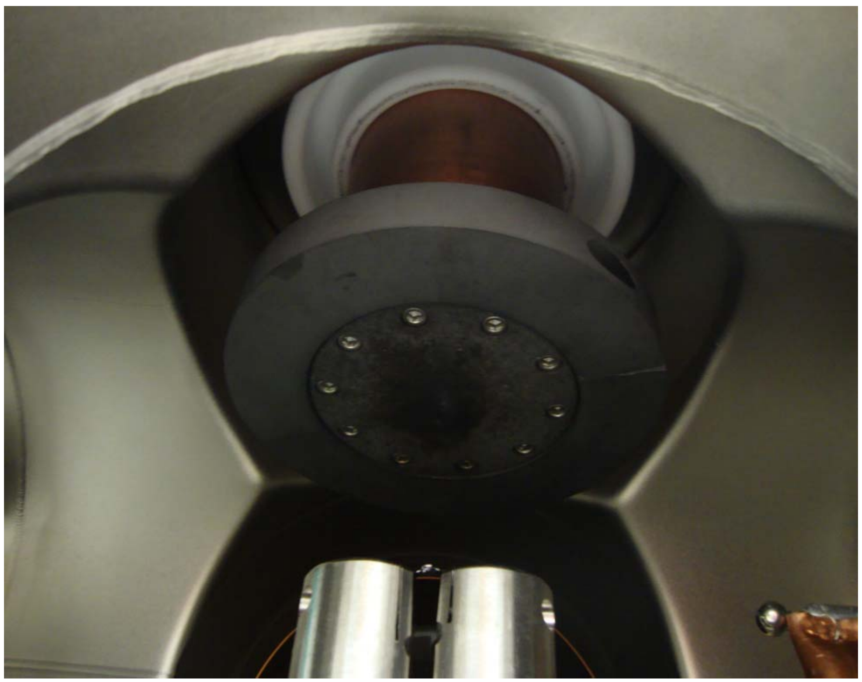
Comprised of:

- Graphite Target
- Teflon Bushing
- Water-cooled Cu Heat Exchanger
- Shunt Resistor to measure current

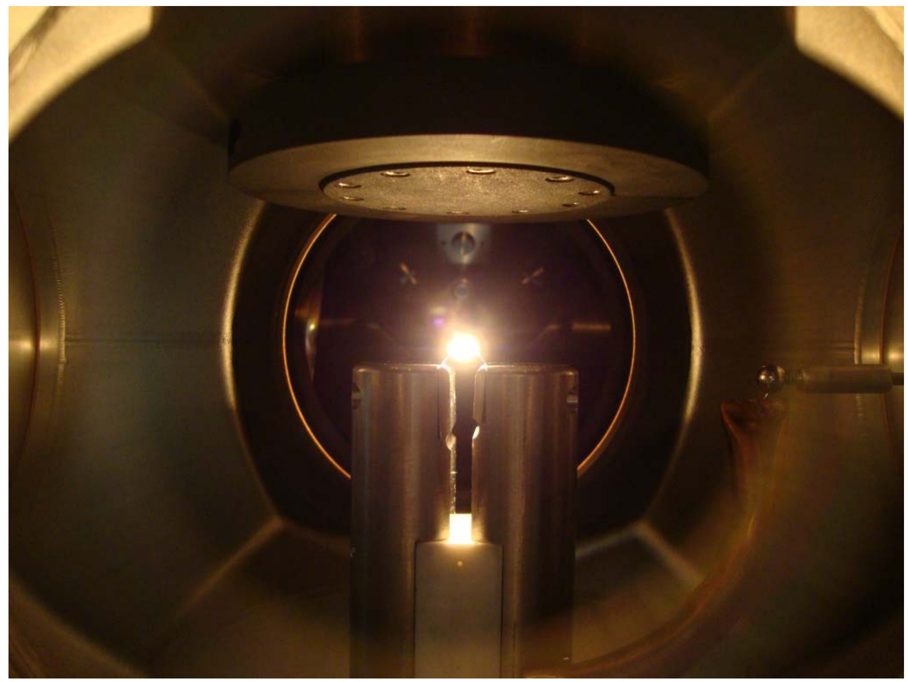
Cathode/Anode Diode Assembly

Anode, Cathode, Filament, and Target in Chamber

Looking up inside and toward target



Filament in operation



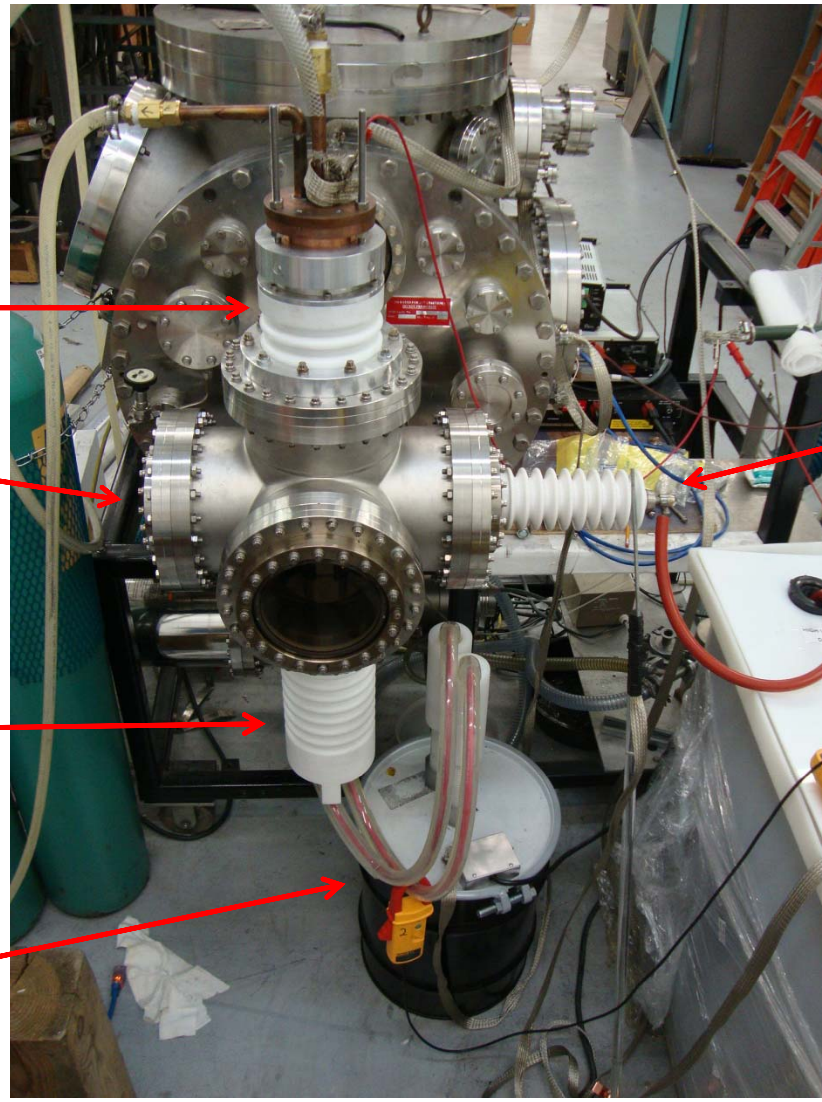
Cathode-Anode System Test Setup

Target Assembly

Test Chamber

Filament Current
Bushing Feed Thru

Isolation
Transformer



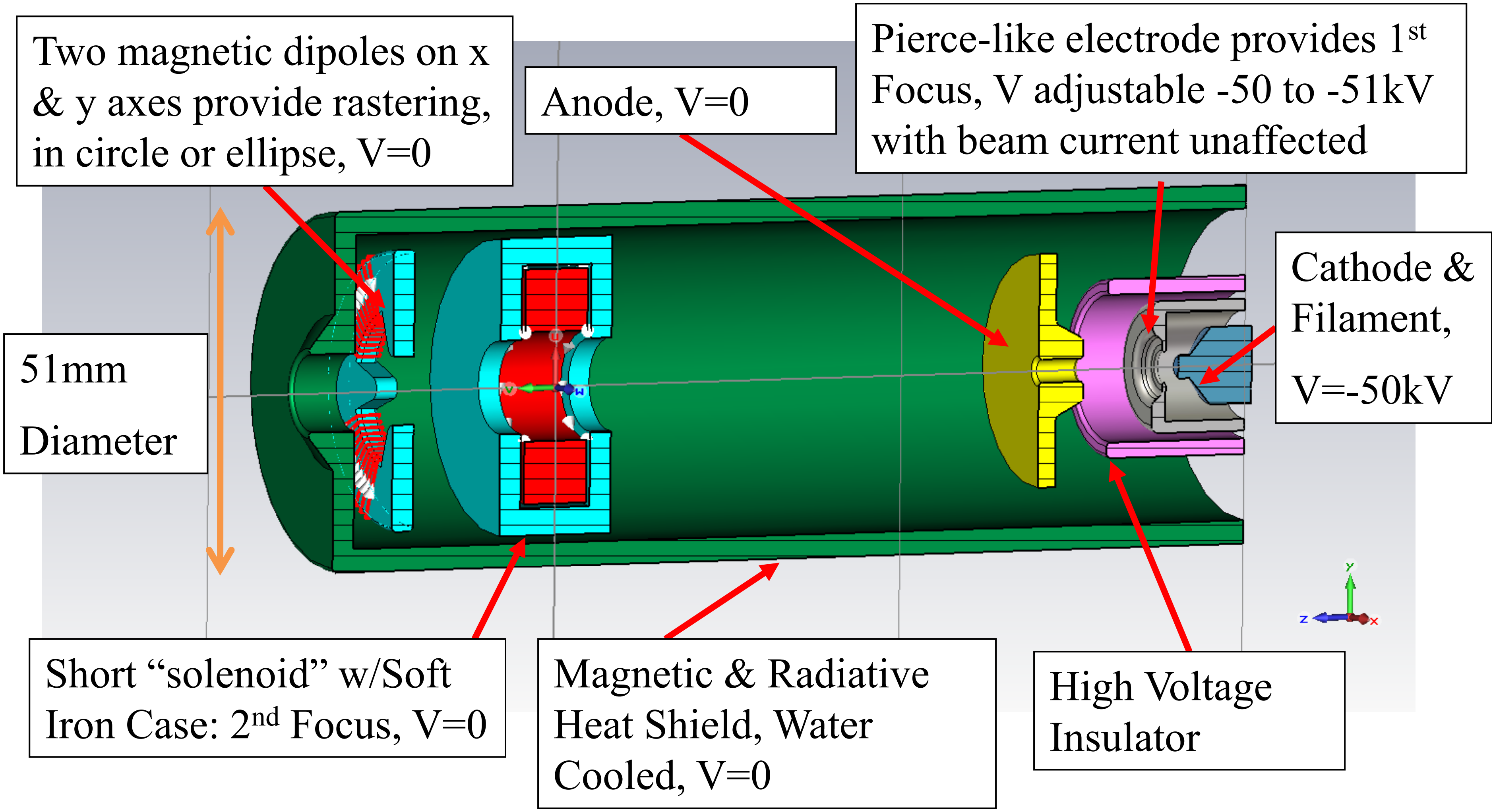
HV Bushing
and Feed Thru

HV Power Supply
and connecting cable

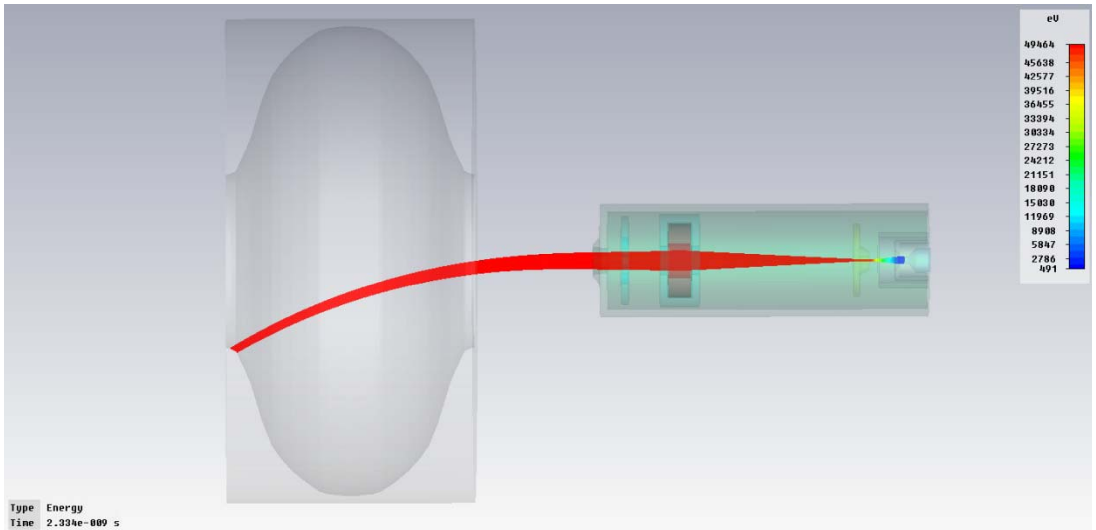
Electron Gun and Ballistic Beam Transport Design Considerations

- Process from cell iris to equator and circumference
- Prevent Nb vapor arcing
- Tolerate beam induced thermal radiation & filament heat load
- Electron Gun Characteristics:
  - ~50 keV energy, up to 250 mA of current
  - beam spot 0.5-1mm
  - 10 kHz rastering capability
  - gun diameter < cavity iris (~65 mm)
  - long focal length (30-100 cm)
  - current control independent of focus

Ballistic Focusing Gun

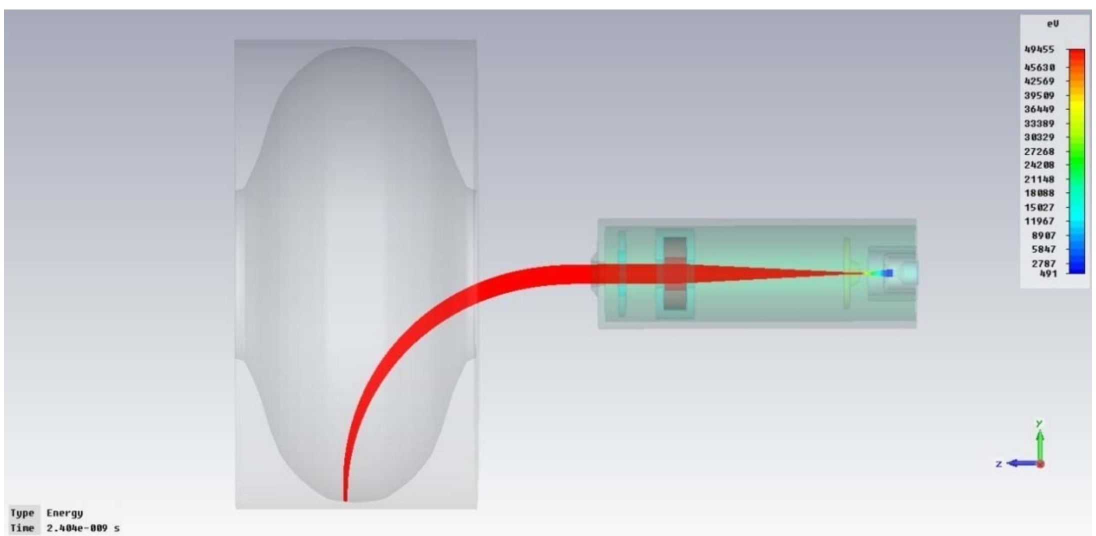


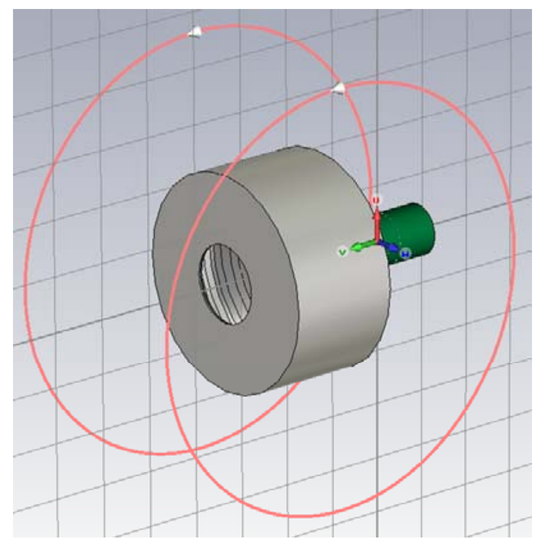
Ballistic Focusing Gun:
Electron Beam Trajectory



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

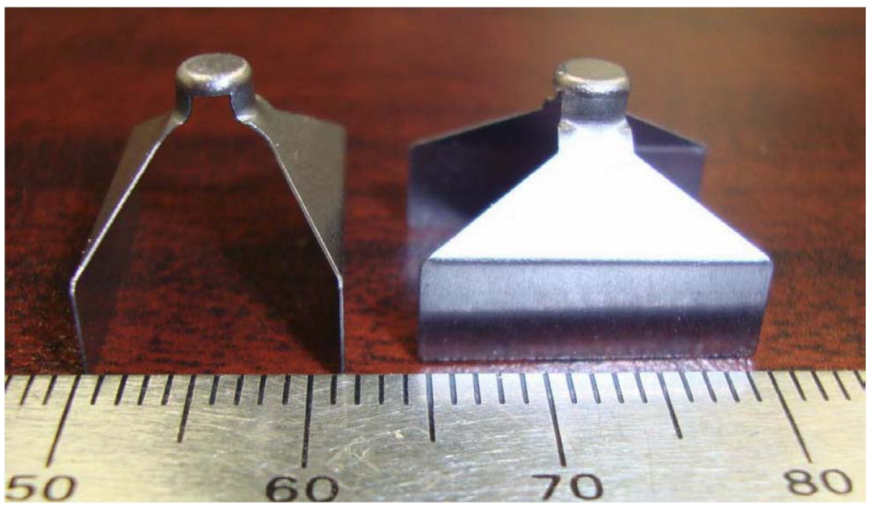
Azimuthal scanning provided by rotating the cavity about the Z axis in a fixed field provided by Helmholtz coils.

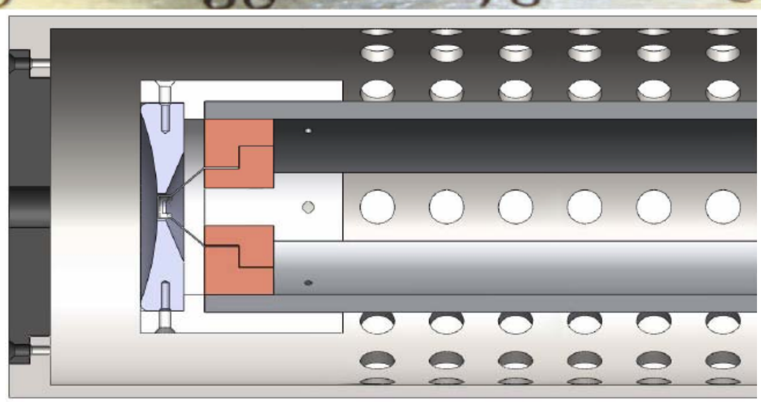


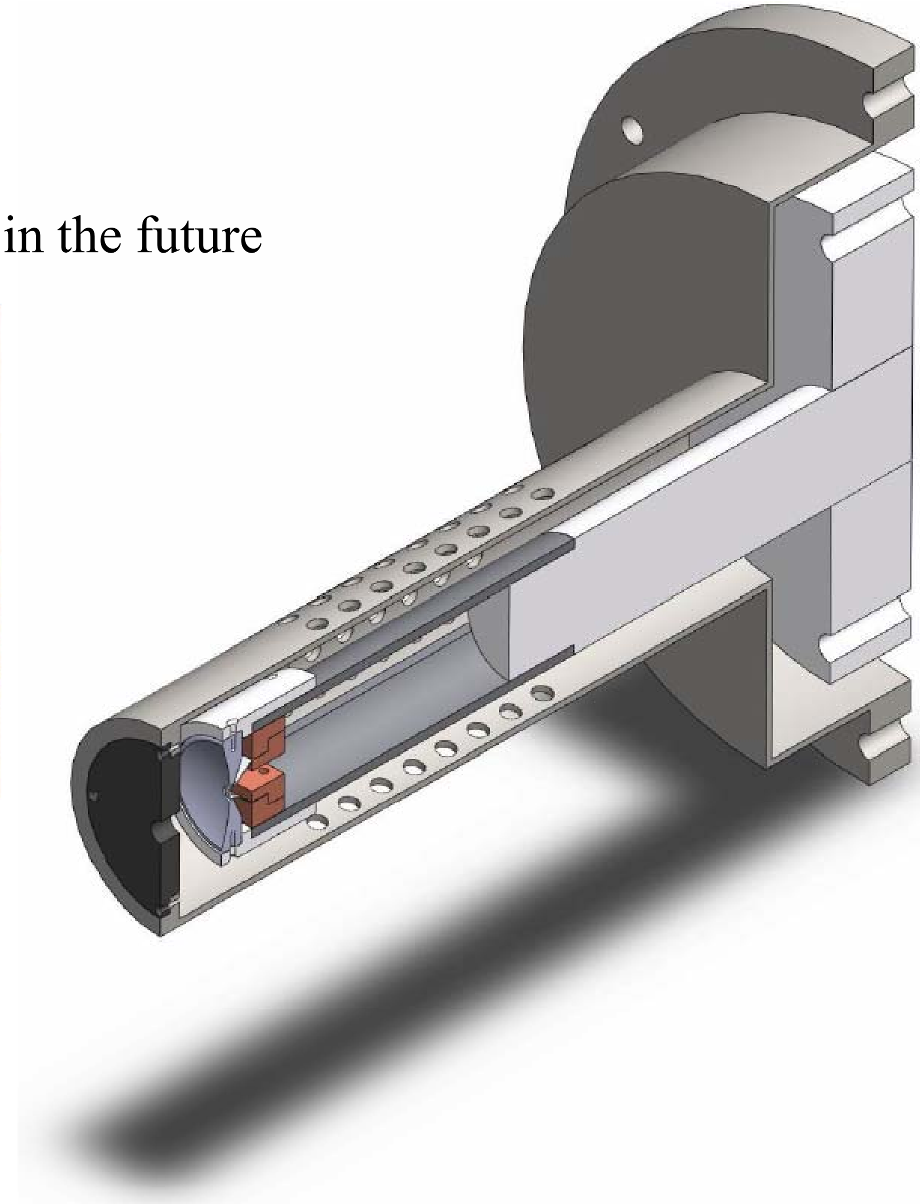


Prototype Gun Design

- SCIAKY Tantalum filament
- Rated at 67A @ 1.4V
- Passively cooled
- Improved filament design expected in the future







Summary and Status

- Beam parameters have been determined from real world tests that produce a smooth low strain Nb surface using a conventional rastered electron beam
- A step-down, Isolation Transformer was designed and built to provide the filament current and heating to provide sufficient thermal emission in the electron gun
- Stainless steel vacuum chamber hosted electron beam tests using HV supply, Isolation Transformer, custom anode and cathode at operational voltage and current
- HV power supply (up to 50 kV and up to 250 mA) has been constructed and tested
- We are pursuing a compact electron gun design that produces a rastering ballistic beam to meet the previously determined energy, current, and beam size requirements to process Nb accelerator cell surface
- A rotating target with mounting points for Nb strips and necessary x-ray shielding has been designed to fit into the existing vacuum chamber
- Follow-on goals: gun design and fabrication, gun driven melting of Nb strips, design and fabrication of Helmholtz coils, and processing of a sample accelerator cell