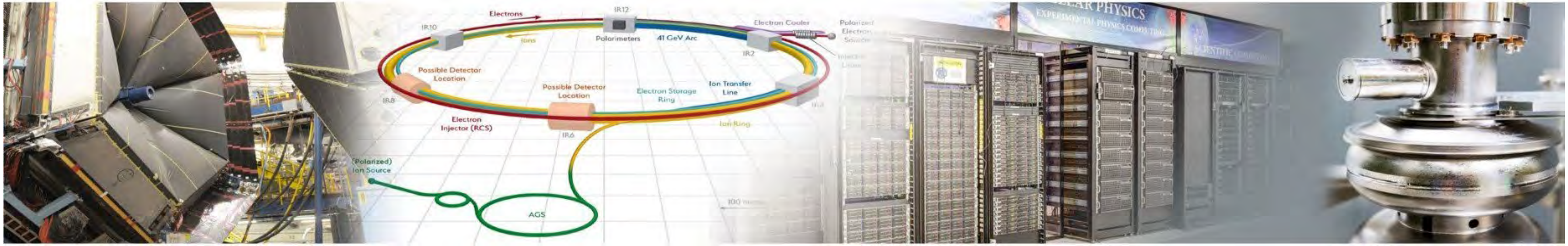
JLab Contributions to the Muon Cooling Demonstrator

Capabilities and possible contributions by Jefferson Lab to the Muon Cooling Demonstrator

Roger Ruber

on behalf of the JLab Teams

Jefferson Lab's Science and Technology Vision



Nuclear Physics at CEBAF

Vibrant nuclear physics research program at **CEBAF with optimal 34 weeks/yr** supporting ~1,900 annual users

MOLLER Project

Future CEBAF Upgrade opportunities complementary to EIC

Theory and computation supporting NP goals

Electron-Ion Collider

Partnering with BNL in the management, design, and construction of the Electron-Ion Collider Project

Leadership in EIC scientific program

Leadership of the Generic EIC–related Detector R&D Program

Computational Science & Technology

High Performance Data Facility
World-leading first-of-its-kind Data-intensive scientific computing facility

Beginning HPDF activities in **partnership** with LBNL

HPDF
High Performance Data Facility

Accelerator Science & Technology

Accelerator component production for DOE construction projects **partnering** across the National Lab complex.

Develop CEBAF upgrade concepts

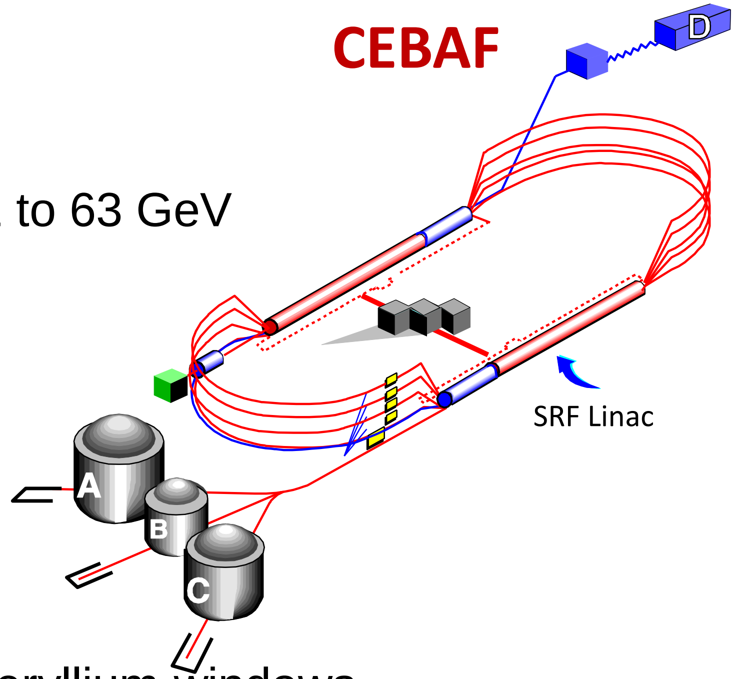
R&D in accelerator, detectors and applications in nuclear imaging and medicine

S&T thrusts are synergistic and mutually supportive

Jefferson Lab

JLab Accelerator Science and Technology Capabilities and Interests

- **Accelerator Science**
  - Beam dynamics
    - "dogbone" recirculating linac (RLA) concept
    - two multi-pass RLA in series to accelerate both μ^+ and μ^- beams from 1 to 63 GeV
  - Beam instrumentation
- **SRF Technology**
  - Material science
  - Thin-film processes, Nb3Sn
  - Structure design and optimization
  - Cavity fabrication and testing
    - fabricated 201.25 MHz normal conducting (NCRF) copper cavity with beryllium windows
      - developed for MICE by US MUCOOL collaboration
  - Cryomodule design, fabrication, and testing
- **RF Technology**
  - High-power RF sources
  - LLRF



CASA: Center for Advanced Studies of Accelerators

23 department members: 19 accelerator physicists, 2 engineers, 2 computer scientists   3 Ph.D. students, 1 Master's student

CEBAF Operations

- Beam planning
- Optics on-call
- Plan and execute CEBAF beam studies
- Accelerator physics/ experiment liaisons
- Collaborate in CEBAF nuclear physics experiments

Accelerator R&D

- CEBAF energy and positron upgrades
- FFA optics design
- Halbach arrays for permanent magnets
- Recirculating linacs (muon dogbone RLA)
- Energy recovery linac expertise

EIC Design

- 3 GeV electron linac
- Energy recovery linac for hadron cooling
- Coherent synchrotron radiation suppression
- Second interaction region design
- Dual-energy storage rings for cooling

Computational Physics

- Large-scale simulation for accelerator design
- Accelerator AI/ML for SRF linac operations
- JSPEC advanced beam cooling/IBS simulation
- Symbolic differential algebra

Diagnostics

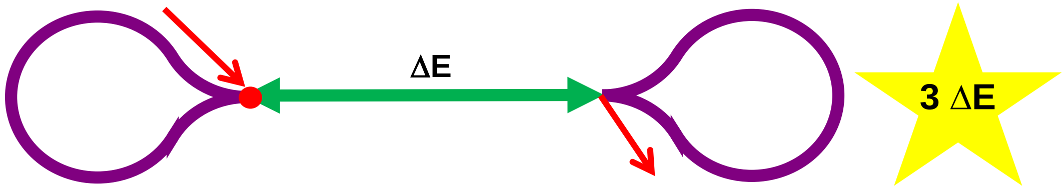
- Optical diagnostics design and fabrication
- Synchrotron light interferometry
- SRF He flow/Q0 monitors
- Boron nitride nanotube scintillators
- Medical imaging

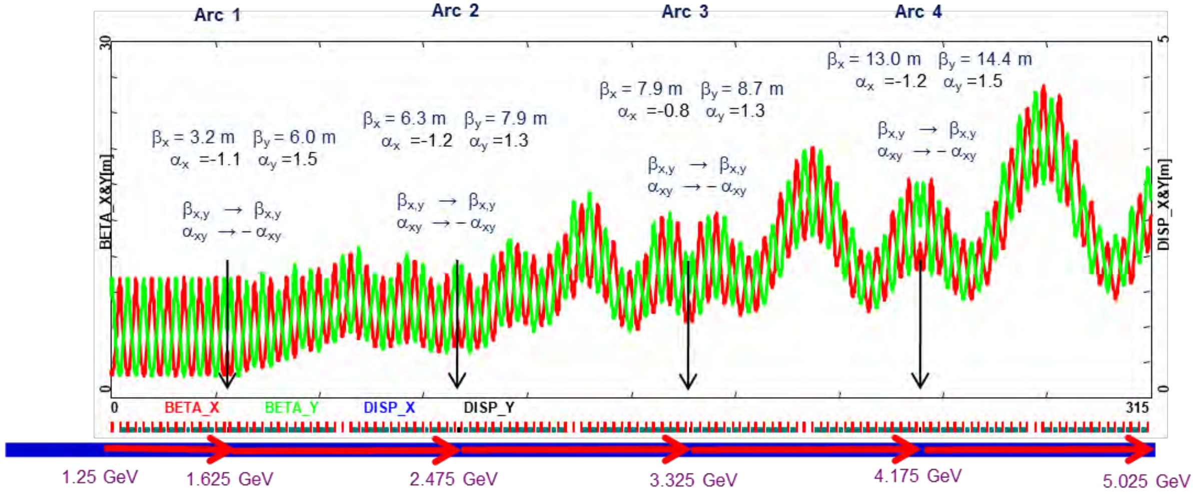
Education and Outreach

- Old Dominion University Jefferson Lab Professorship
- Average 1.5 PhD/year since 2010
- Annually teach graduate accelerator physics at US Particle Accelerator School
- USPAS curriculum committee membership

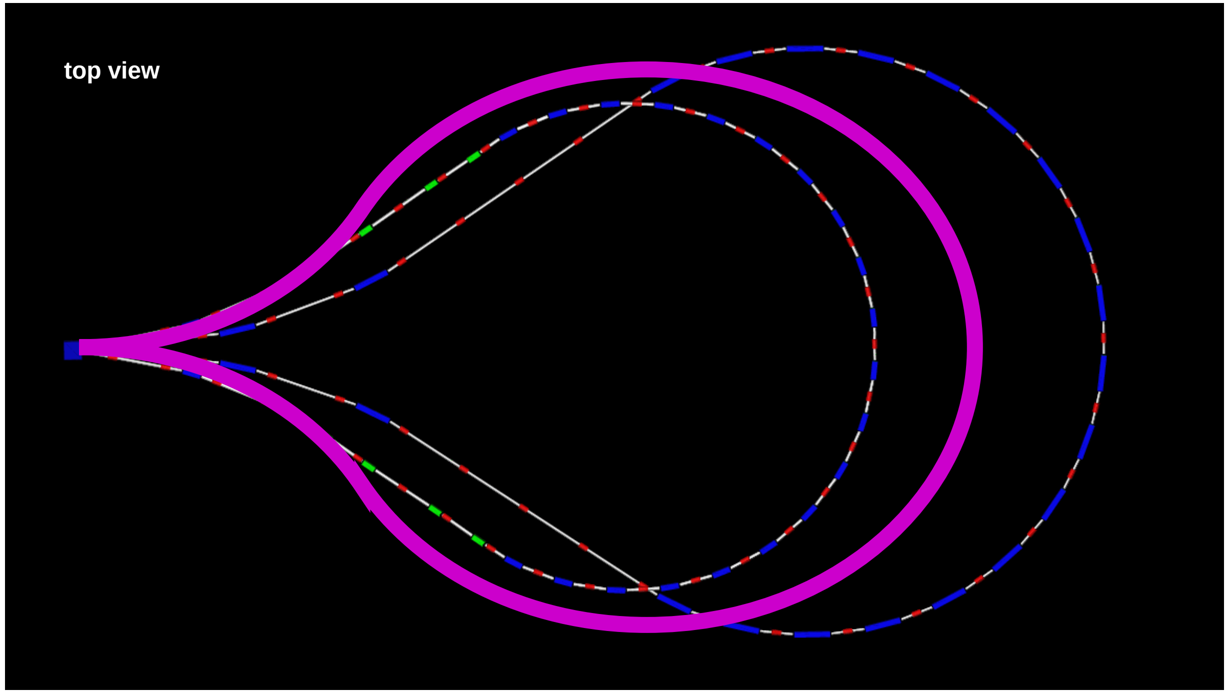
CASA: “Dogbone” Recirculating Linac

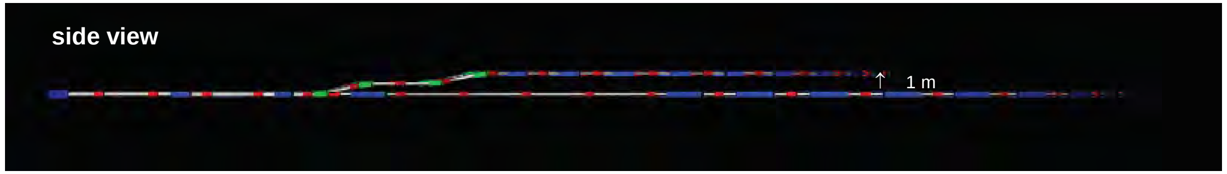
- Traversed in both directions
- Simultaneous acceleration of both charge species
- Extend to multi-pass
  - Two multi-pass RLA in series to accelerate both μ+ and μ- beams from 1 to 63 GeV





Linac optics matched to both arcs for all passes simultaneously.
The arrows indicate arc locations

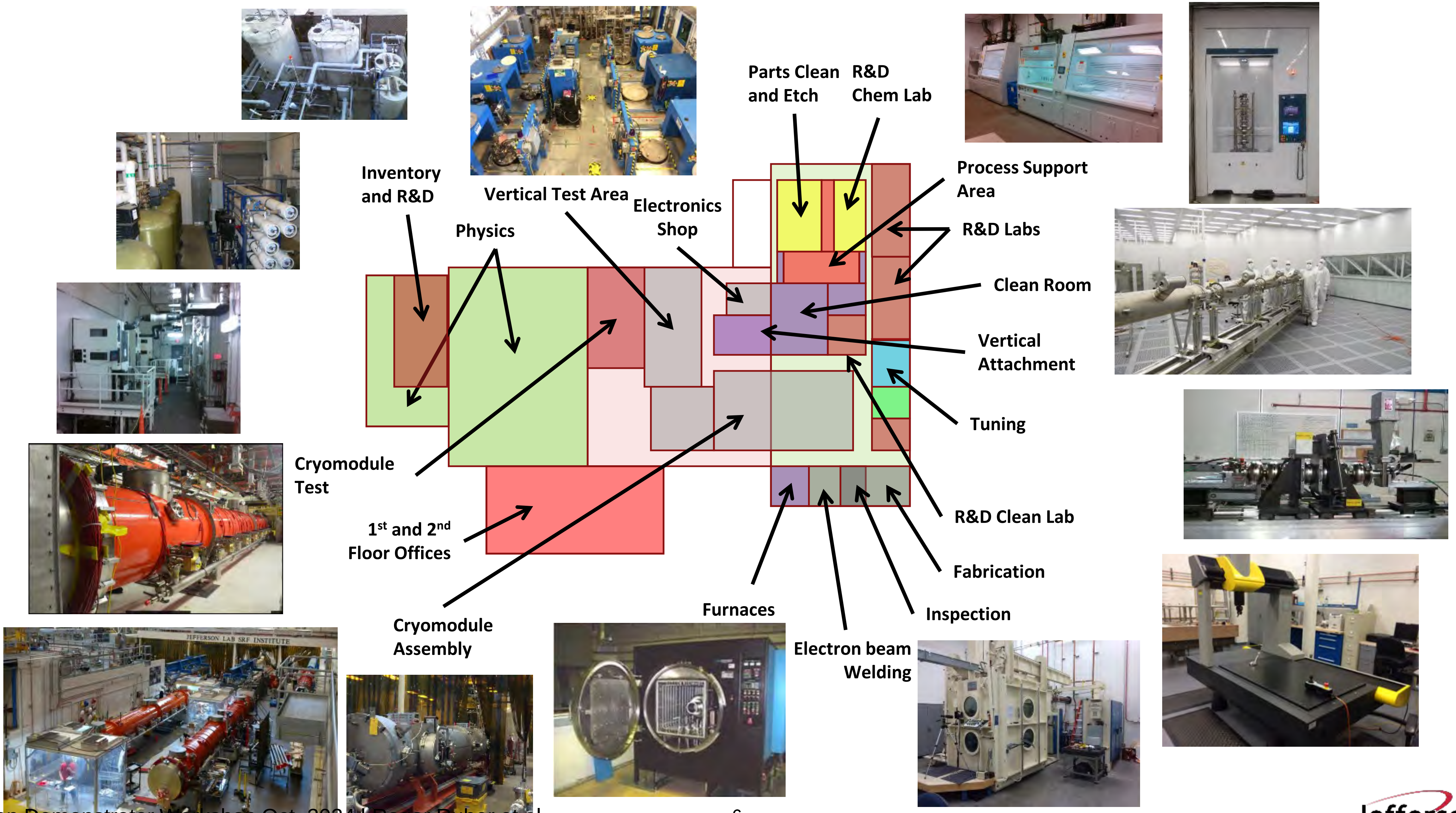




S.A. Bogacz, Nucl. Phys. B (Proc. Suppl.) 149 (2005) 309.
https://doi.org/10.1016/j.nuclphysbps.2005.05.056

S.A. Bogacz et al., PAC 2009, WE6PFP100
https://accelconf.web.cern.ch/PAC2009/papers/we6pfp100.pdf

JLab SRF – All Under One Roof

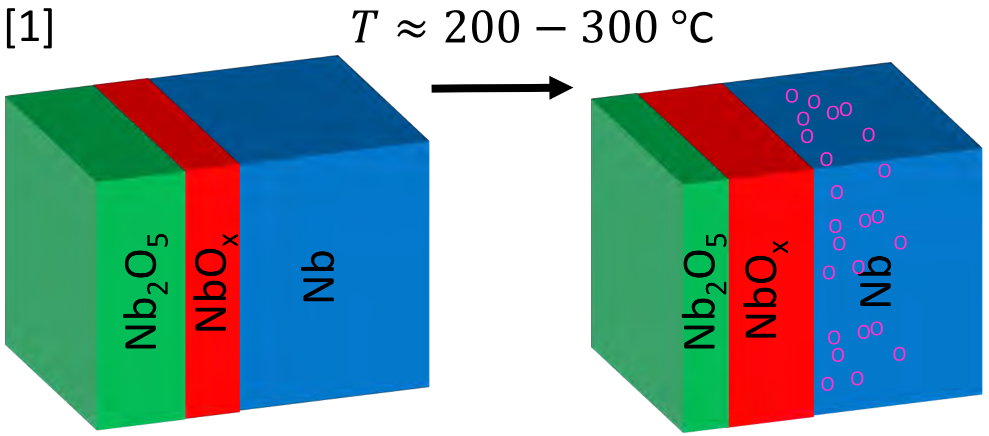


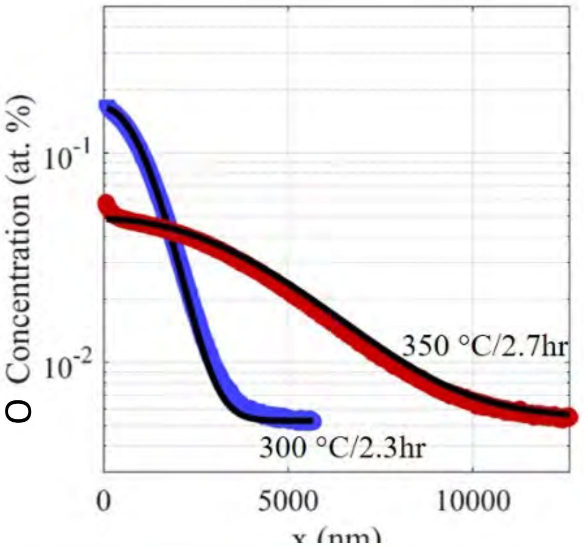
Jefferson Lab

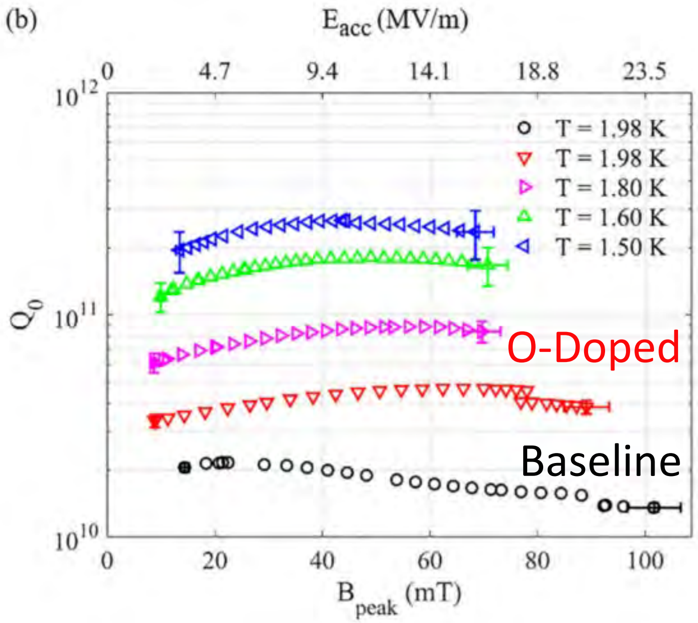
High Q & High Gradient R&D: Oxygen Impurities in Niobium

Native Oxide Dissolution and Oxygen Diffusion

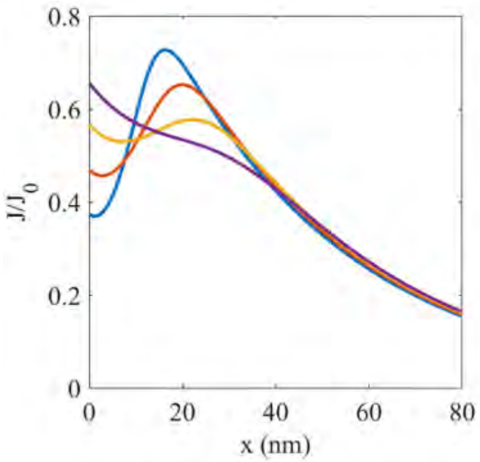
[1]

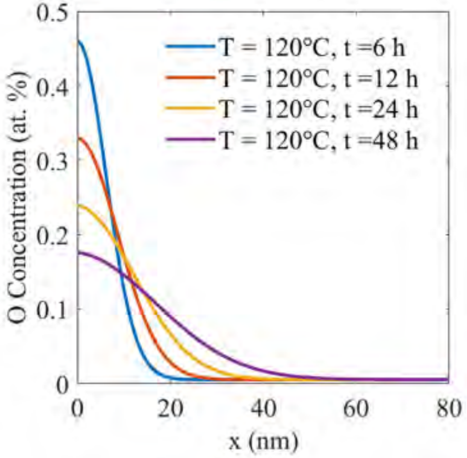


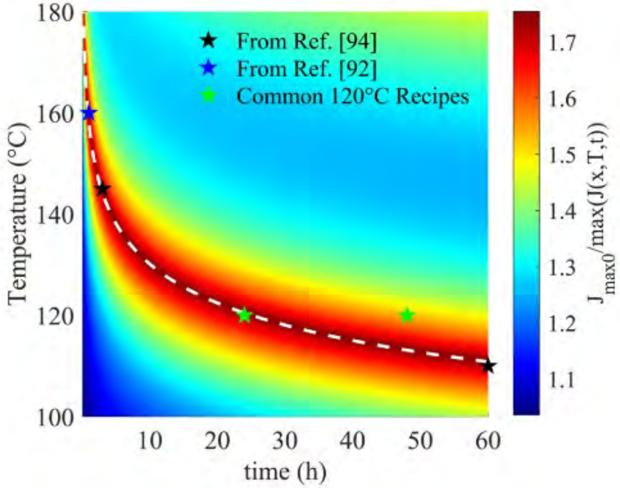




[2]







Exploring the effects of native oxide dissolution process on cavity performance in:

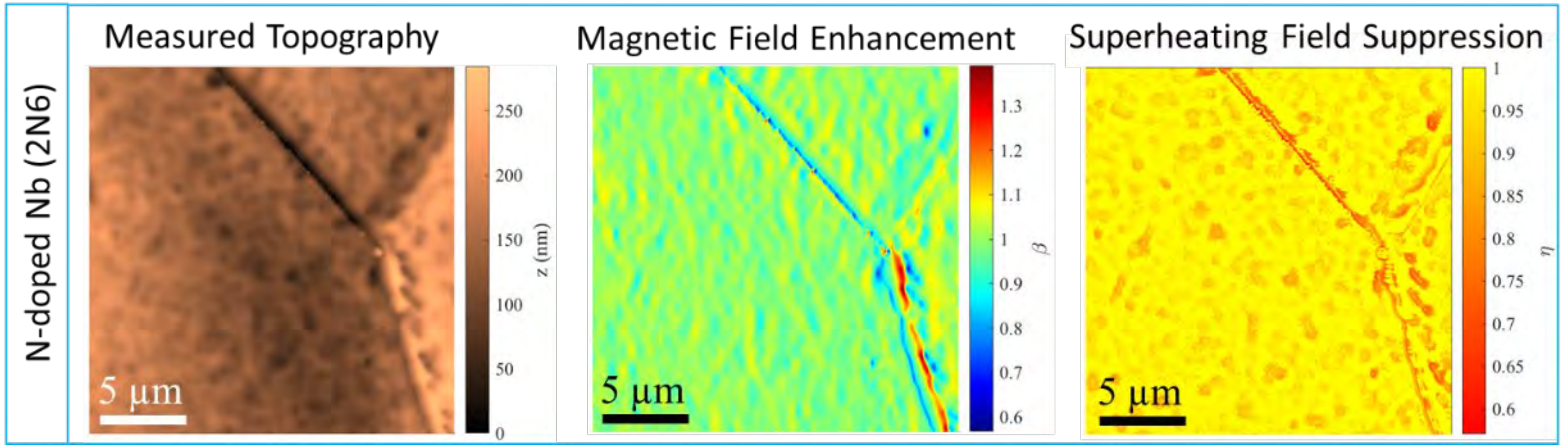
- Case of uniform impurities in the RF layer
- Shallow impurity profile limit which may be related to the effectiveness of the low temperature bake.

[1] Lechner, E. M., et al. *Applied Physics Letters* 119.8 (2021).
[2] Lechner, Eric M., et al. *Journal of Applied Physics* 135.13 (2024).

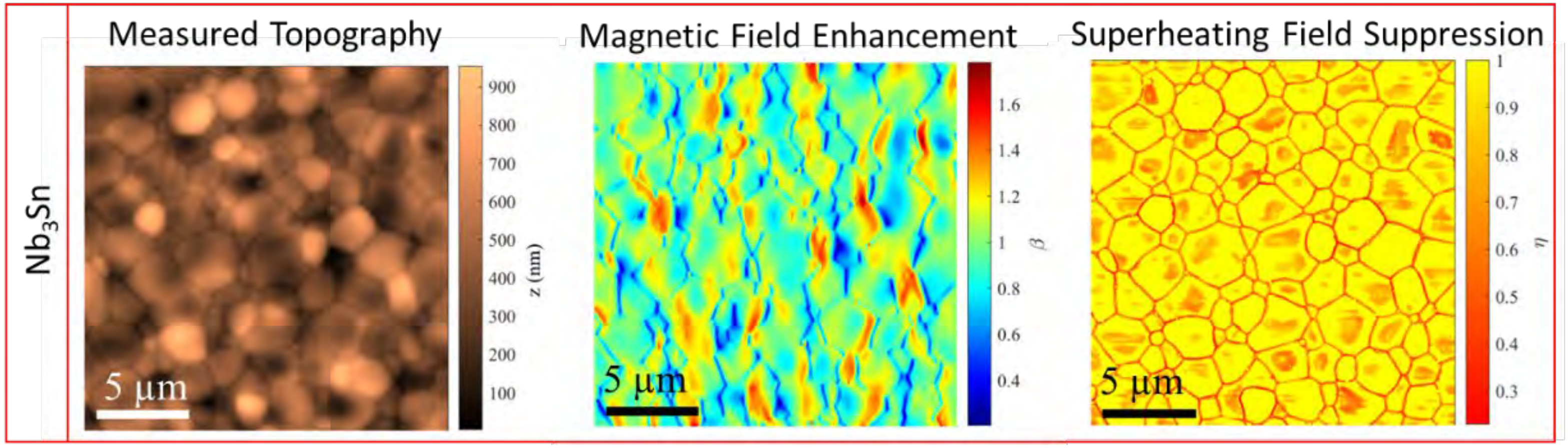
Jefferson Lab

High Q & High Gradient R&D: What Role Does Surface Roughness Play?

[1]



[2]



[1] Lechner, Eric M., et al. *Physical Review Accelerators and Beams* 26.10 (2023): 103101
[2] Lechner, Eric M., et al. *arXiv preprint arXiv:2409.01569* (2024).

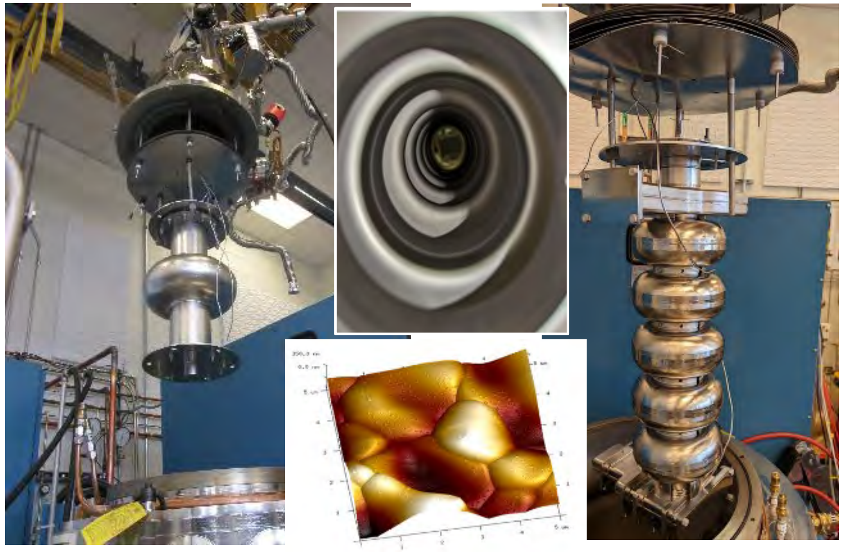
Exploring the effect of surface roughness on Nb and Nb_3Sn and their impact on:

- Magnetic field enhancement
  - Any surface roughness contributes
- Superheating field suppression
  - Grain boundary grooves either via nitride removal during EP or thermal grooving (Nb_3Sn)

How can we optimize the surface treatment, chemical polishing, to enhance these characteristics towards their ideal values and facilitate the largest possible accelerating field?

SRF Thin-film Processes and Nb_3Sn Development

Nb_3Sn /Nb by Sn vapor diffusion



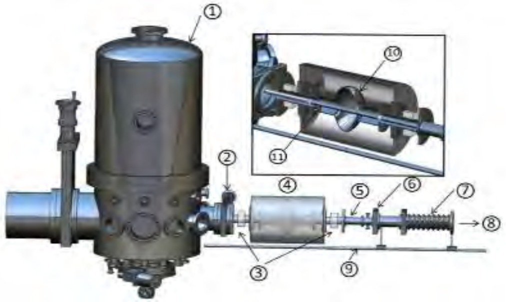
Alternate materials & S-I-S structures

SRF, metamaterials, superconducting logic, qubits

In development

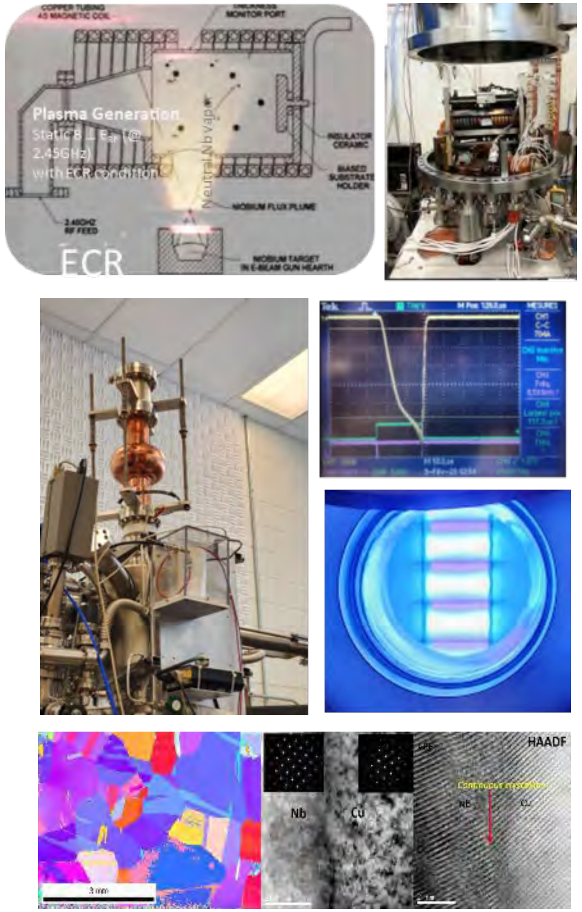
Nb_3Sn/Cu

Nb_3Sn S-I-S



Nb/Cu via ECR & cylindrical HiPIMS

SRF, qubits



SRF Science and Technology Diagnostic Capabilities

Microscopy

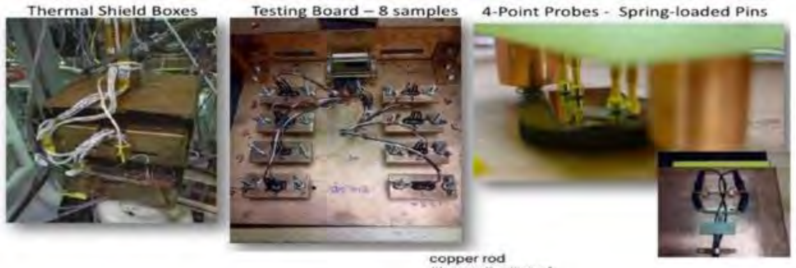
Optical Microscope
Keyence VHX-7000

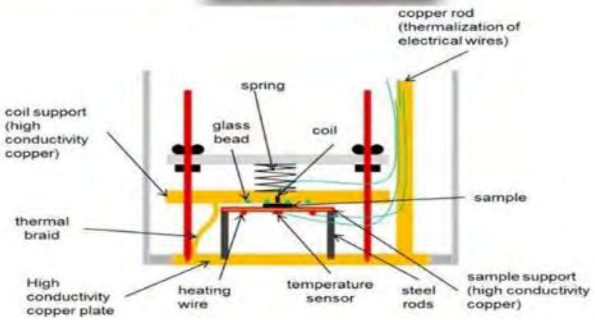
Atomic Force Microscope
Keyence VHX-7000

Optical Microscope
Tescan VEGA3-HMH, LaB_6 w/ EDAX EDS & EBSD

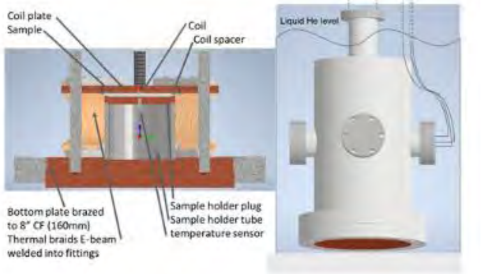
Cryogenic Measurements

Physical Property Measurement system
Quantum Designs, Dynacool 9T



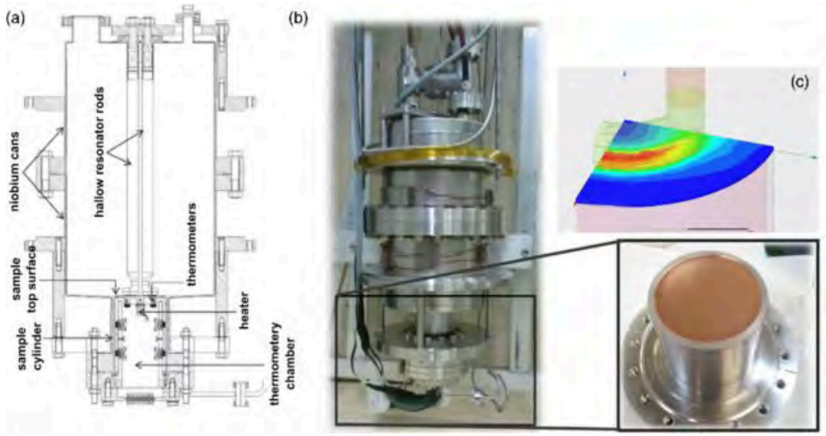


32 sample multiplexed 4-point probe
Custom design



3rd harmonic magnetometer
Custom design

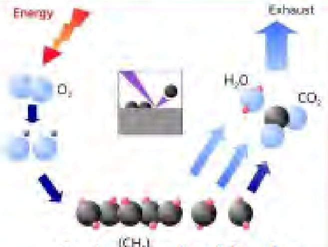
Quadrupole Resonator



In Situ Plasma Processing at JLAB

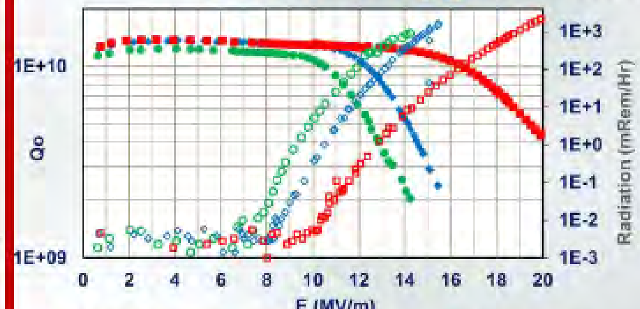
Funding provided by SC Nuclear Physics Program through DOE most recently through SC Lab funding announcement DE-FOA-0002670

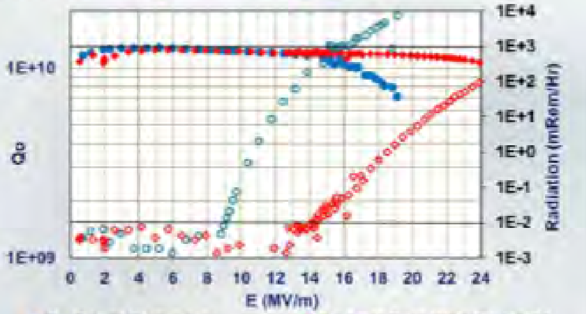
- Program started in 2018 using internal funding.
- Dedicated DOE SC funding since 2020, ending in 2026
- Processed C100 cryomodules in-situ in the CEBAF.
  - 2023 : 2L22, 2L23, 2L24 and 2L25 – in CEBAF
    C100-5 and C100-10R – in Test Lab
  - 2024 : 1L23, 1L24, 1L25, 1L26 and 2L26 (in Oct) – in CEBAF
    C100-8R and C75-03 - in Test Lab



O_2 is cracked in the plasma to atomic oxygen which breaks down the hydrocarbons

Helium/Oxygen better than Argon/Oxygen





RF Out

Process Gas Ar/O_2 or He/O_2

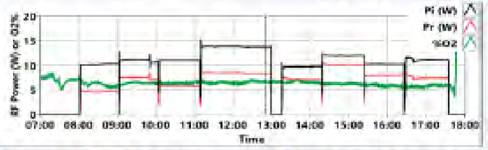
Process Gas With CO_2, CO and H_2O,etc.

RF Into HOM Port

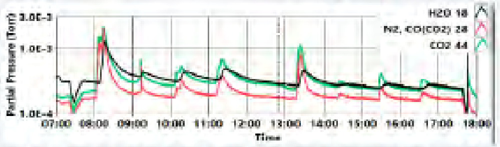
CEBAF C100 cavity with argon-oxygen plasma in each of the 7 cells

Helium-oxygen Plasma

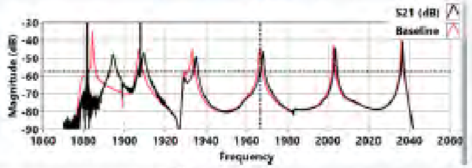
Cavity 7 Cells 7 6/5 4/3 2/1 Cavity 8 7 6/5 4/3 2/1

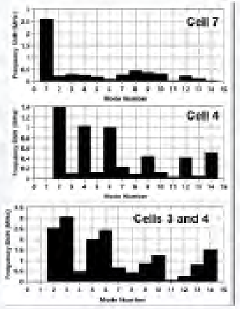


RF Power for 2 cavities and Oxygen percentage ~6 %



Partial pressure of hydrocarbon residuals for all cavities when processing 4 cavities at once



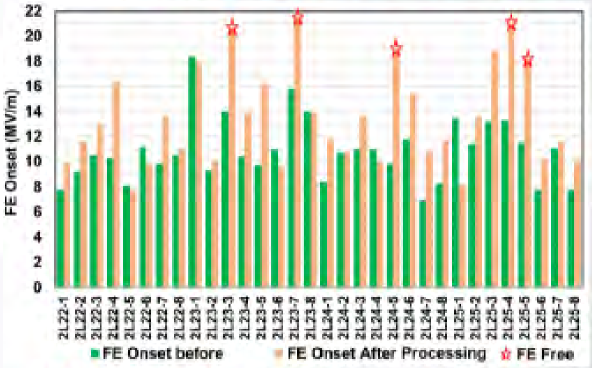


Frequency shift due to change in dielectric constant in cells with plasma.

The frequency shift per mode is presented live while we are processing.

This method allows us to confirm the plasma location without a camera.

In situ cryomodule processing 2023 and 2024



59 MeV or 23% improvement in FE onset

- In 2023, processed 4 cryomodules in situ 2L22 – 2L25.
- Field emission onset was measured before and after processing.
- All cavities had field emission prior to processing.
- 5 cavities were field emission free after processing.
- Five C100 cryomodules in the south linac produced 490 MeV during the last run. The best since 2015 was 435 MeV.

- In 2024, processed 5 C100 cryomodules in situ.
- Processed two cryomodules in test lab prior to installation C75-03 and C100-8R.
- Field emission onset measured before processing and will be remeasured later this fall.

Average improvement in field emission onset was 2.7 MV/m.

Jefferson Lab

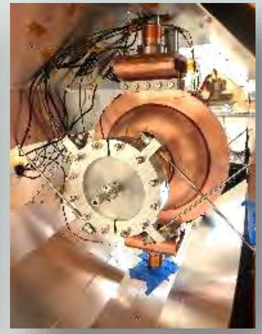
Compact SRF for Industrial & Environmental Applications

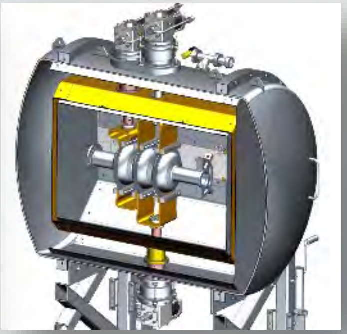
- Nb & liq. helium → Nb_3Sn & cryocooler(s)

↪ compact, conduction-cooled SRF for irradiation applications

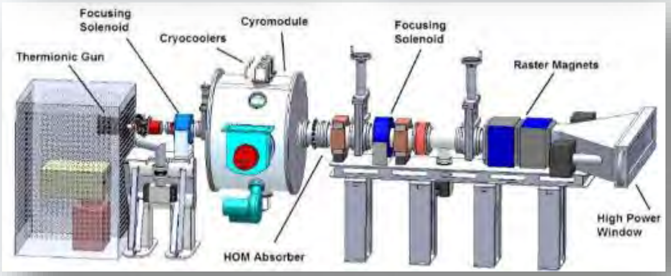
GENERAL ATOMICS

- hardware studies

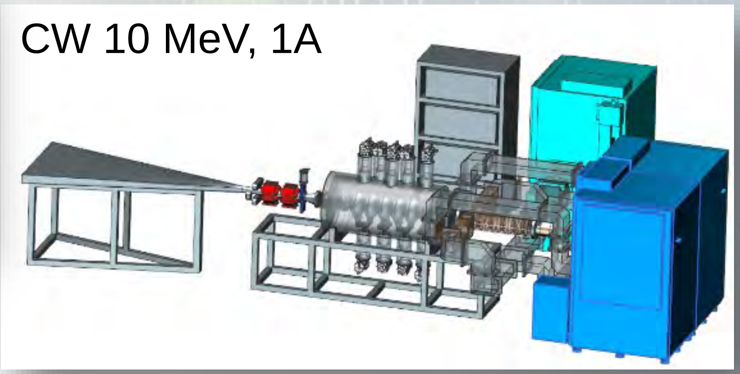




- design efforts



CW 1 MeV, 1A



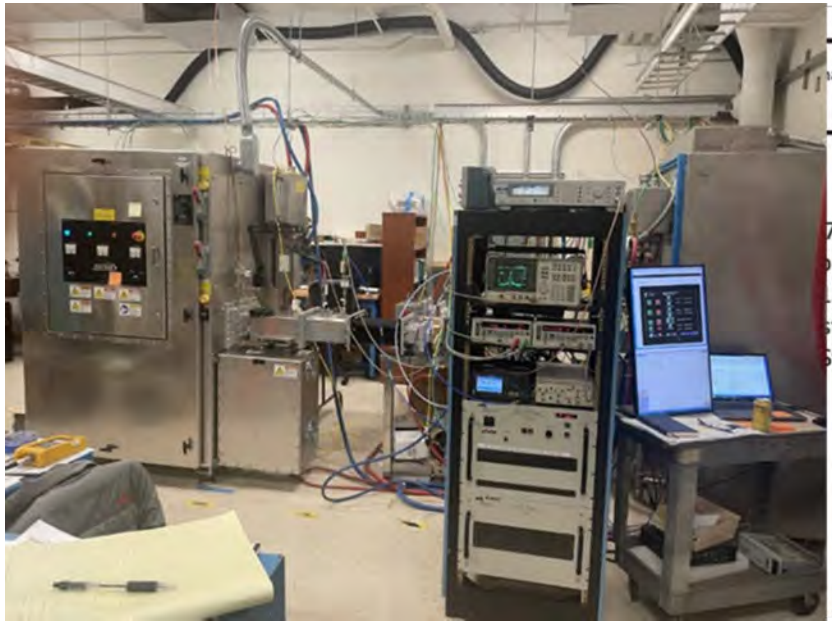
- application/customer discovery

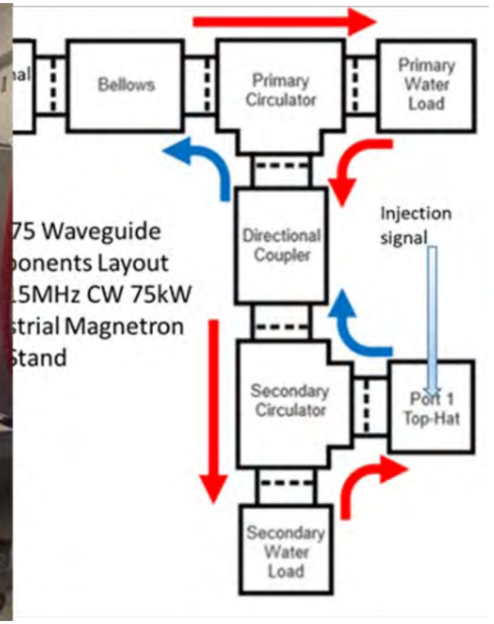
environmental ↔ industrial

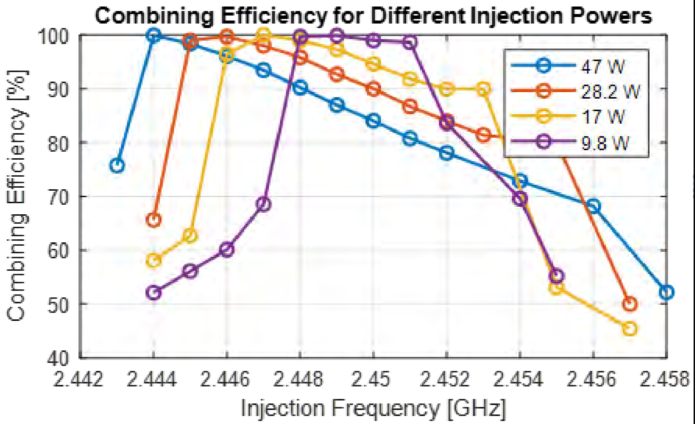
HRSD

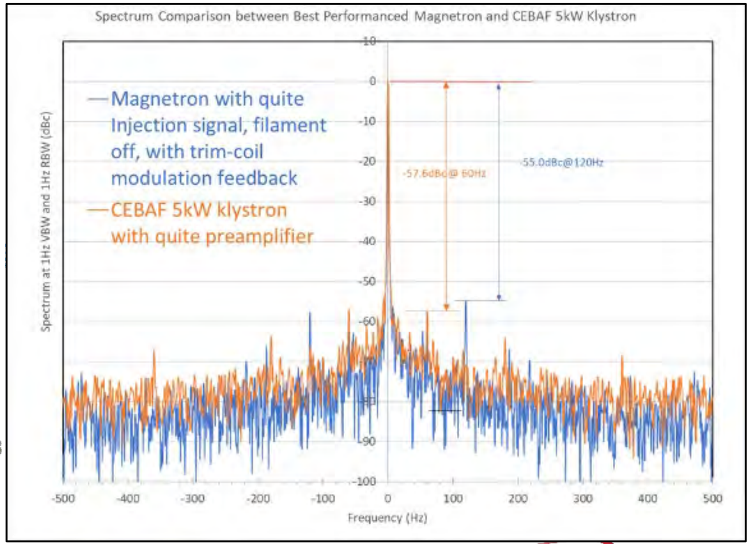
Magnetron R&D for High-efficiency Low-cost CW RF Source

- High (>90%) AC to RF power efficiency
- Low (<$2/W) capital cost
- Demonstrated injection phase lock performance
- Magic-tee power combining demonstration 4X1.2kW @ 2.45GHz at GA
- 4x75kW @ 915MHz power combining demonstration at JLab
- Smart and low-cost switching power supplies for SRF application



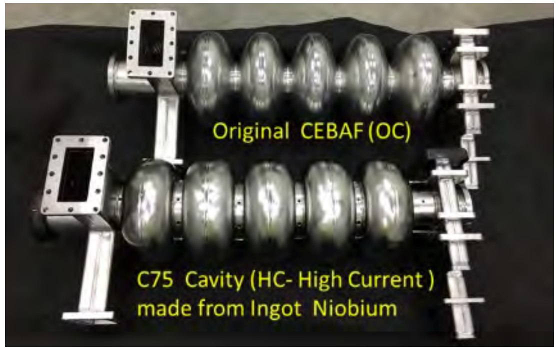




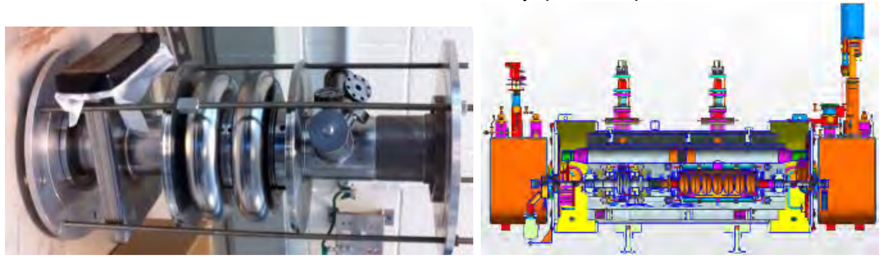


A Sampling of Cavity R&D

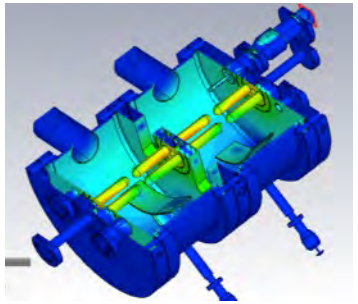
For CEBAF



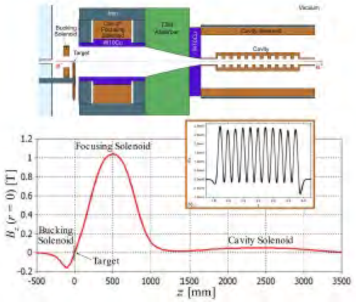
HC 5-cell 1.5 GHz C75 Cavity (CEBAF)



Beta-matched 2-cell for new injector



CEBAF 750 MHz separator



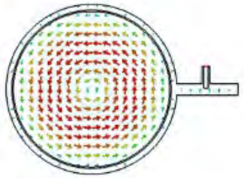
Positron source target design for 22GeV Ce⁺BAF

For EIC

197 MHz Crab Cavity

951 MHz prototype

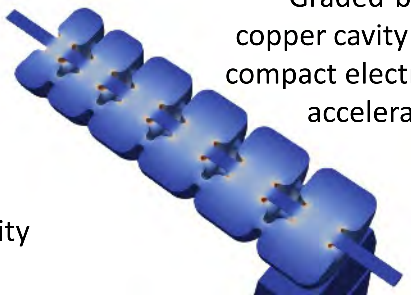
Harmonic kicker



magnetization cavity

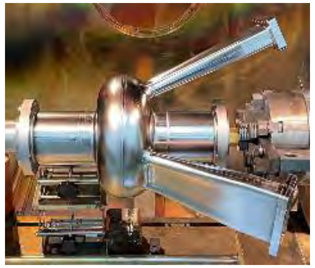
For Projects and R&D

5-cell 802 MHz ERL main linac cavity (PERLE/Orsay & LHeC/CERN)



Graded-beta copper cavity for compact electron accelerator

HiLumi-LHC 400 MHz RFD Crab Cavity



High-Current SRF Cavity With On-Cell Waveguide Dampers

1.5 GHz ERL twin-axis cavity

Cavity Fabrication and Testing

- Extensive capabilities for fabrication, processing and testing of SRF structures
- Machining, e-beam welding, brazing, heat treatment, EP and HF chemistry, thin-film coating

Jefferson Lab

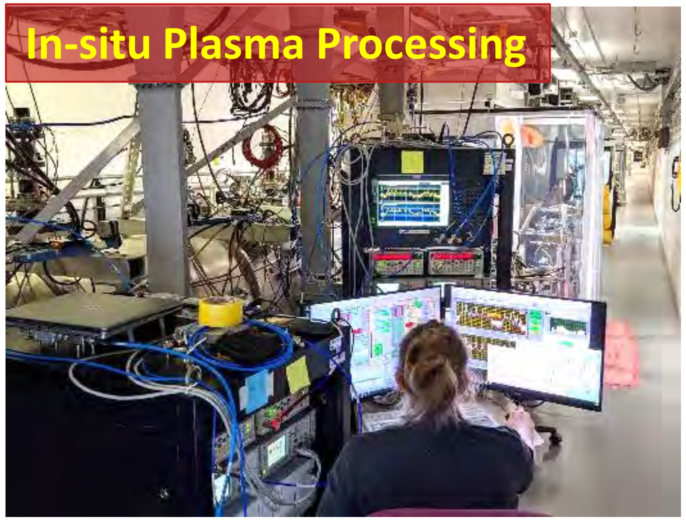
Cryomodule Fabrication and Testing


SNS Cavity String


C75-04 Final Assembly


Cryomodule Test Facility


C100-05R Final Assembly

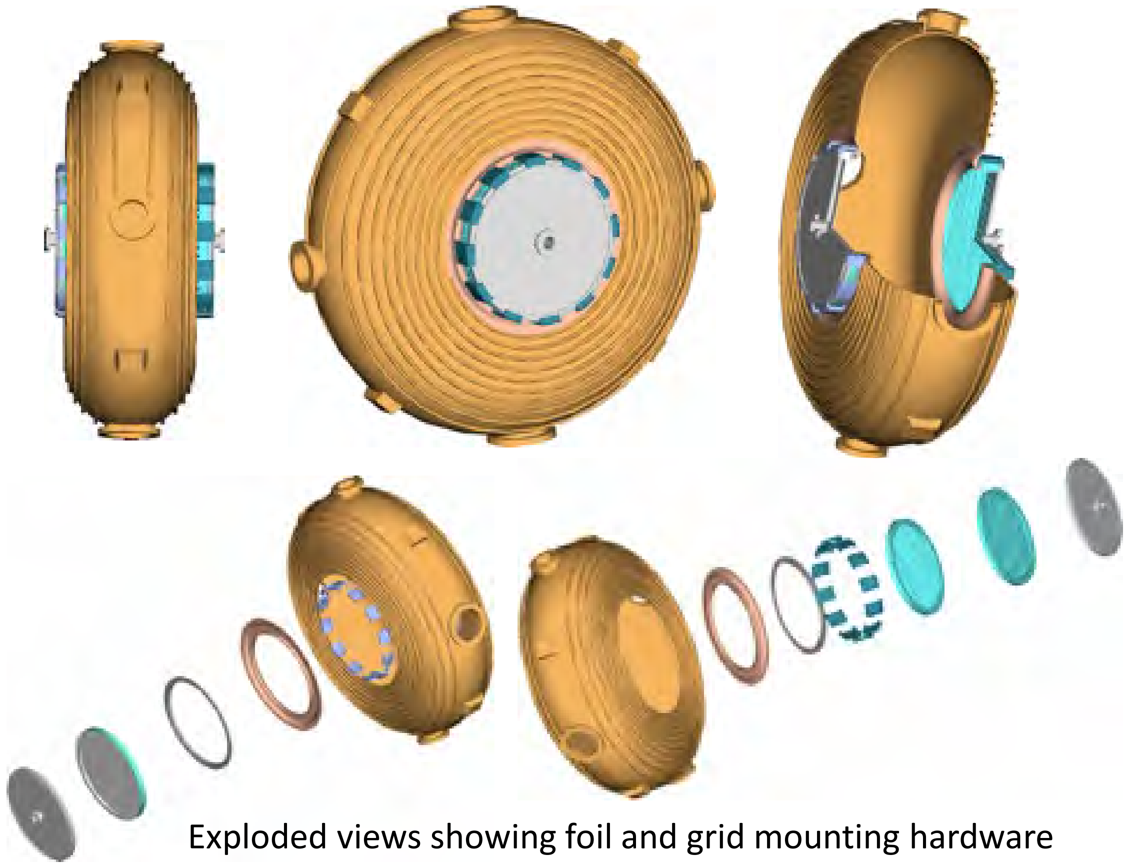

In-situ Plasma Processing


SNS CM-07 in Vacuum Vessel

LCSL-J1.3-23 cold mass into vacuum vessel

Fabrication of a 201.25 MHz Cavity for MICE

- Fabricated 201.25 MHz normal conducting (NCRF) copper cavity
  - with beryllium windows
  - developed for MICE by US MUCOOL collaboration



Exploded views showing foil and grid mounting hardware

First 200 MHz cavity welded and EP'd by Jlab.
Assembled in clean room

R.A. Rimmer et al., PAC 2005, TPPT029
https://accelconf.web.cern.ch/p05/PAPERS/TPPT029.PDF

Jefferson Lab

JLab SRF – ISO Certification

intertek
Total Quality. Assured.

CERTIFICATE OF REGISTRATION

This is to certify that the management system of:

JSA/Jefferson Lab, SRF Operations

Main Site: 12000 Jefferson Ave,
Newport News, Virginia, 23606, United States

has been registered by Intertek as conforming to the requirements of:

ISO 9001:2015

The management system is applicable to:

The production, delivery, improvement, and maintenance of superconducting radio-frequency systems in collaboration with the Department of Energy, Jefferson Lab, and the global SRF community.

Certificate Number:
0148897

Initial Certification Date:
11 May 2023

Date of Certification Decision:
11 May 2023

Issuing Date:
11 May 2023

Valid Until:
10 May 2026

ISO 9001:2015 CERTIFICATION intertek — ANAB ANSI National Accreditation Board ACCREDITED ISO/IEC 17021-1 MANAGEMENT SYSTEMS CERTIFICATION BODY

Calin Moldovean
President, Business Assurance

Intertek Testing Services NA, Inc. 900 Chelmsford Street, Lowell MA 01851, USA

Page 1 of 1

JLab Contribution Possibilities

- **Beam Dynamics**
  - Beam dynamics simulations
    - beam dynamics study of “dogbone” accelerator for muons;
    - incorporation of a single FFA arc replacing multiple standard droplet arcs.
- **RF Structure Technology**
  - NCRF cavity development for muon cooling demonstration (incl. “cold” copper);
  - SRF cavity development for high current, high gradient, high Q;
    - development of alternative materials and thin films;
    - recirculation of beam-cavity interaction in SRF cryomodule analysis,
      - fast RCS beam dynamics with cavity tuning, HOM damping, and BBU effect analysis;
  - Breakdown rate study, including cryo-cooling,
    - investigate copper doped silver or copper plating technique for improved cryo-cooling;
  - Alternative materials to beryllium windows.
- **RF Power Technology**
  - RF high-power development;
  - LLRF development;
- **Education**
  - Training the next generation scientists and engineers;

BACKUP SLIDES

Material Science, Thin-film Processes and Nb_3Sn


Vertical Coating System

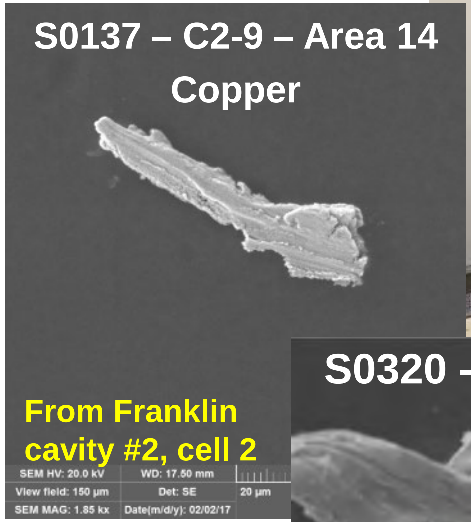

3.9 GHz


Two Nb_3Sn Cavity Cryomodule

Surface and Particulate Analysis

- Examination using SEM with elemental analysis
- Feedback for process improvement

Examples

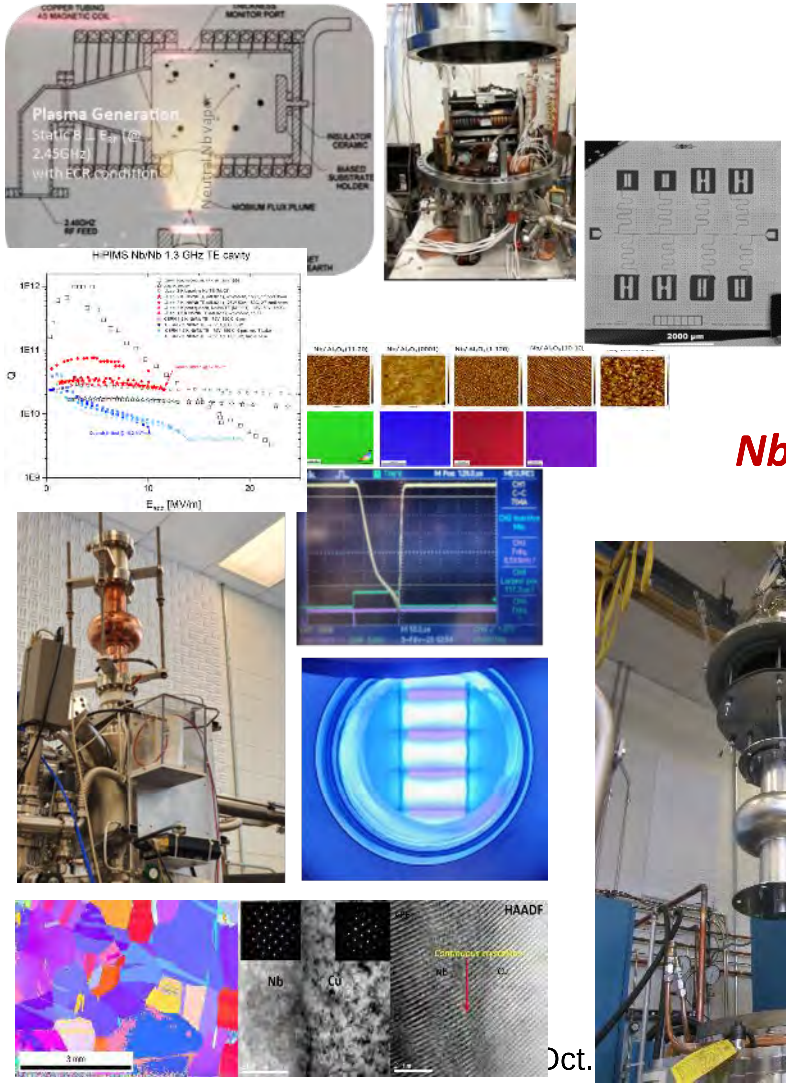


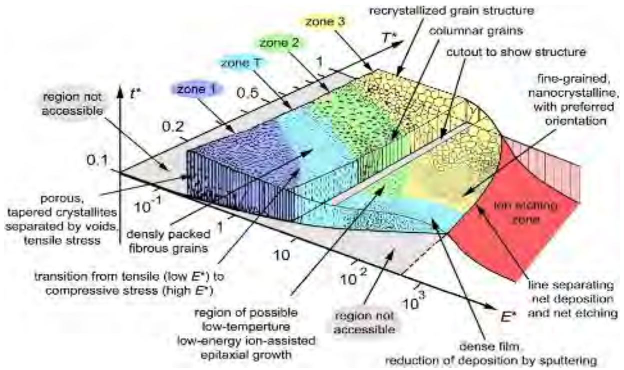
SRF Thin Film Capabilities

High Quality Superconducting Films for Accelerators and Synergistic Applications

Nb/Cu via ECR & cylindrical HiPIMS

SRF, qubits





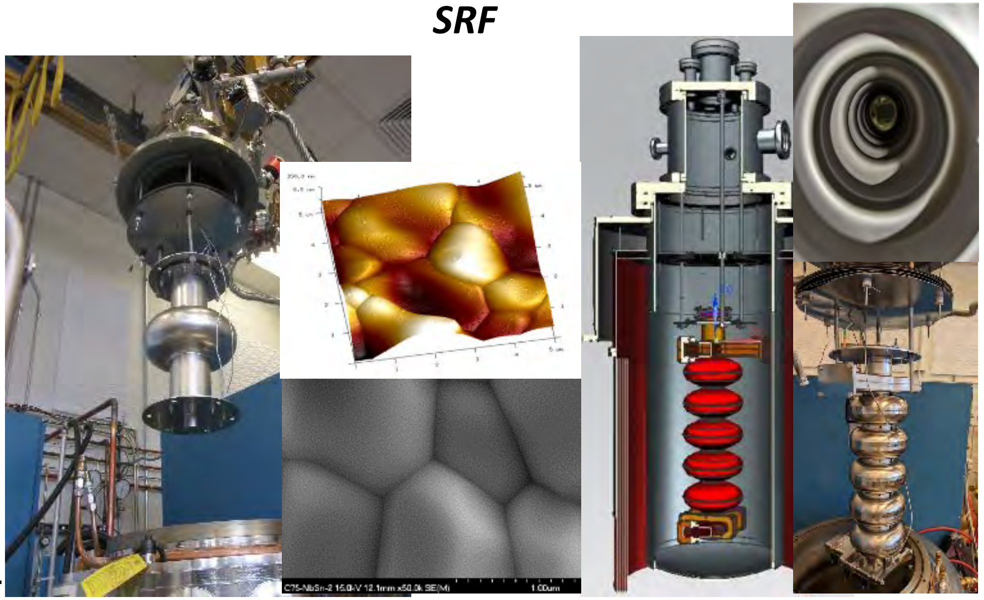
A. Anders, Thin Solid Films ***518*** *(2010) 4087*

Alternate materials & S-I-S structures

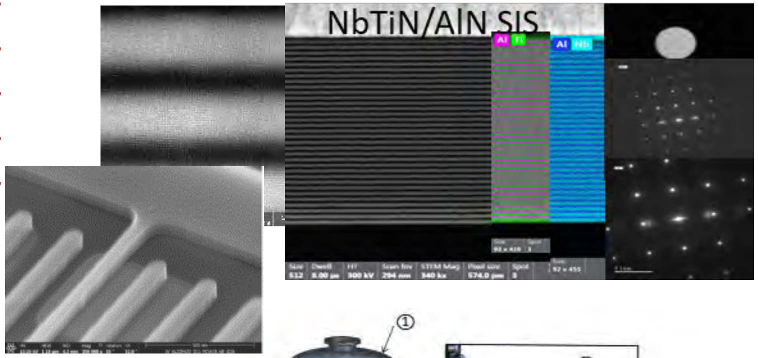
SRF, metamaterials, superconducting logic, qubits

Nb_3Sn /Nb by Sn vapor diffusion

SRF

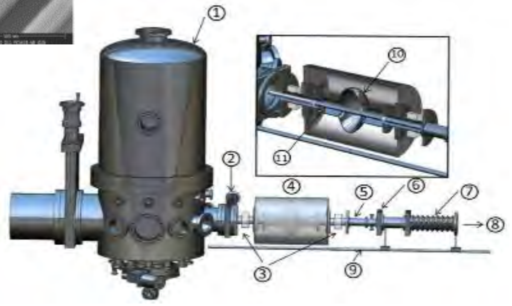


DC-MS
RF-MS
HiPIMS
Re-DCMS
Re- HiPIMS



In development

Nb_3Sn/Cu
Nb_3Sn S-I-S

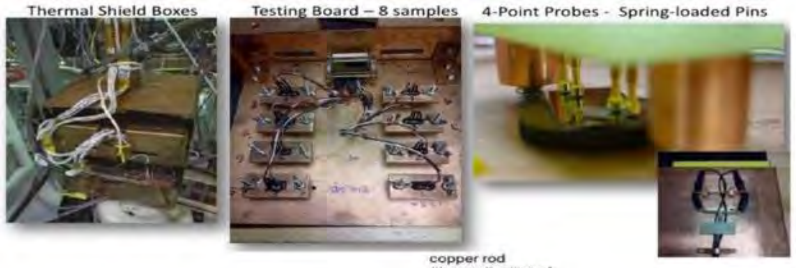


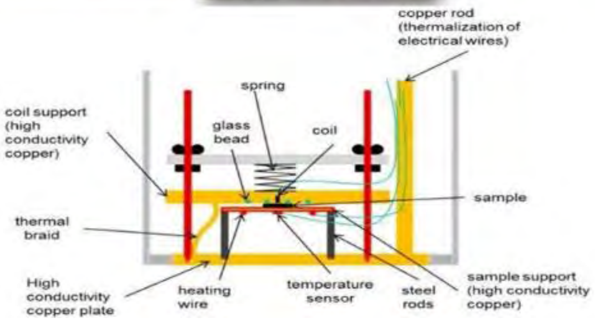
SRF Science and Technology Capabilities

Microscopy

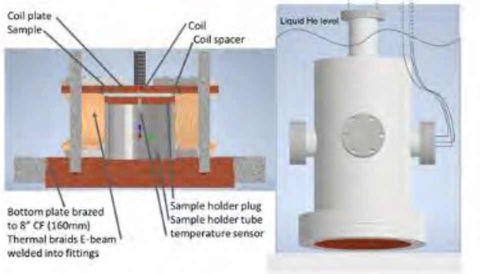
Cryogenic Measurements

Physical Property Measurement system
Quantum Designs, Dynacool 9T



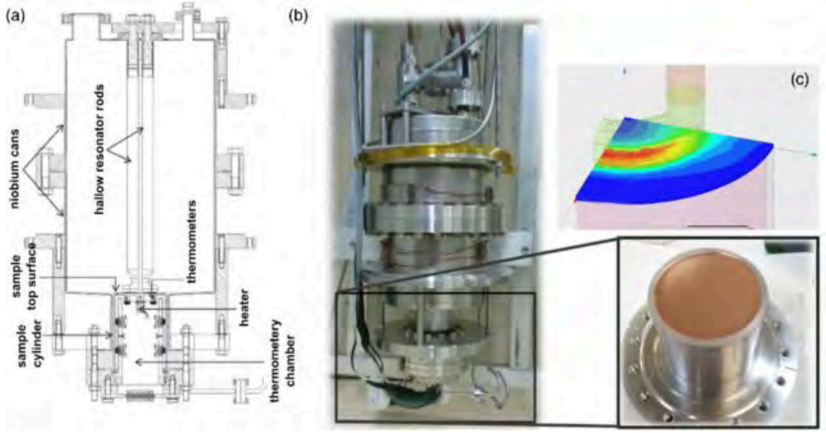


32 sample multiplexed 4-point probe
Custom design



3rd harmonic magnetometer
Custom design

Quadrupole Resonator



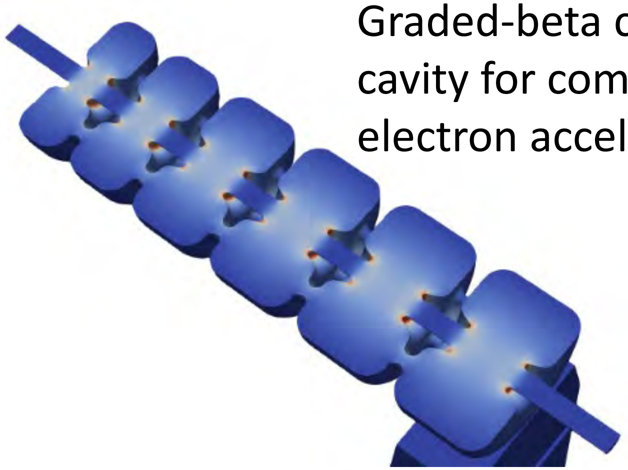
SRF Scientific &Technological Ongoing Developments

- Nb/Cu Development : Q~ 4e10, 25 MV/m @ 2K
  - Energetic Condensation with ECR & HiPIMS
- Nb3Sn films on Nb, on Cu: 1st operation with beam , 4 K operation, industrial accelerators…
  - Sn vapor deposition, Magnetron sputtering and HiPIMS, CVD (at collaborator), exploratory electroplating
- Alternate superconductors & SIS Development: 4 K operation
  - Magnetron sputtering and HiPIMS
- Coating for Ancillaries Development: HiPIMS Cu coated bellows/waveguides
- Synergistic Applications : Metamaterials, Superconducting Digital Logic & Quantum Devices and Sensors

R&D Capabilities in SRF Systems' Group

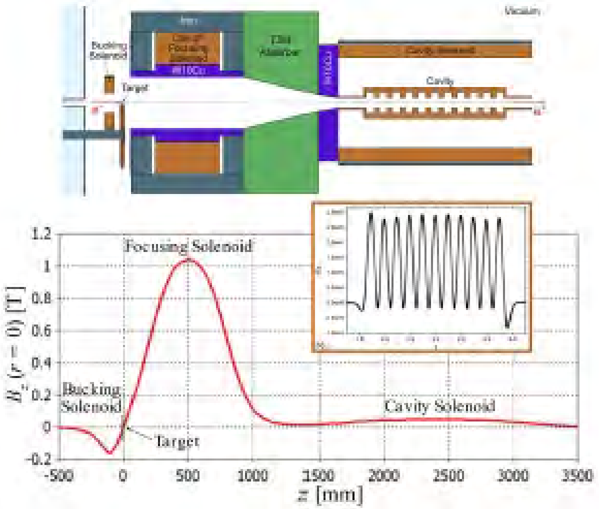
Experiences and capabilities that could be useful and collaborated in muon collider acceleration, target, cooling studies at Fermi Lab

- Graded-beta copper cavity design for electron and positron sources at JLab
  - ✓ rapid and efficient acceleration of non-relativistic charged particles
  - ✓ Large radius positron capture cavity and matching solenoid design
  - ✓ RF, thermal and beam loading design capabilities
- Positron beam dynamics matching and capturing design with high-field solenoid and optimization analysis for beam loss and emission reductions
  - ✓ RF cavity design, power coupler, thermal, beam-cavity interaction simulation and integration to beam dynamics analysis
  - ✓ RSF/RF cavity designs including RF window designs for cooling channel and power coupling
- Recirculating of beam-cavity interaction in SRF cryomodule analysis
  - ✓ Fast RCS beam dynamics with cavity tuning, HOM damping, and BBU effect analysis



Graded-beta copper cavity for compact electron accelerator

Positron copper capture cavity

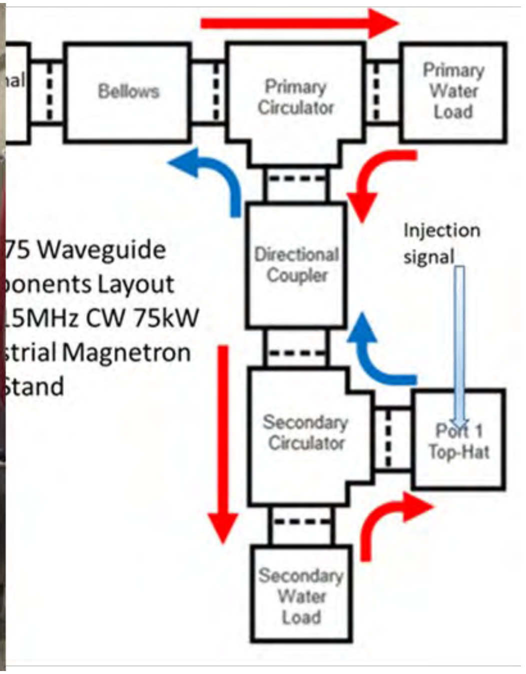


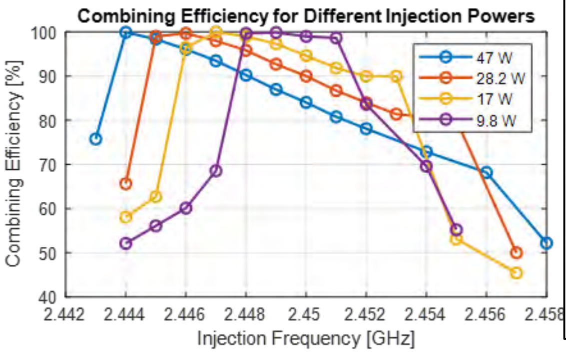
Positron source targetry design for Ce^{+}BAF 22GeV at JLab

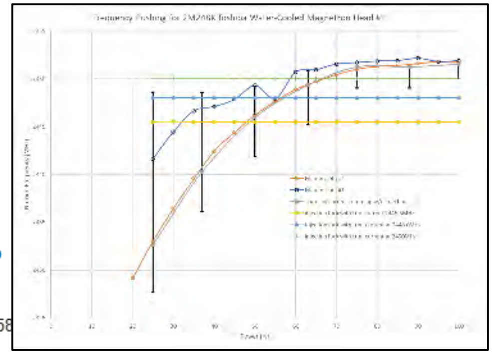
Magnetron R&D for high-efficiency CW RF sources for Industrial NP/HEP/BES accelerators

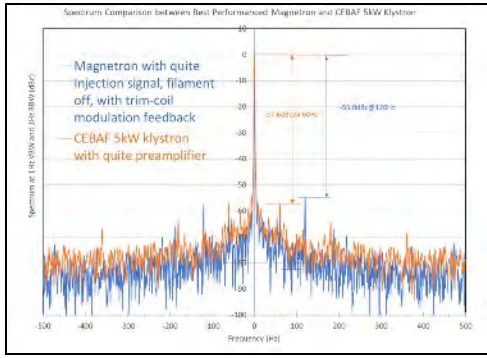
High efficiency, low cost CW type magnetron can be used for muon targetry capturing/ cooling channel demonstration experiment

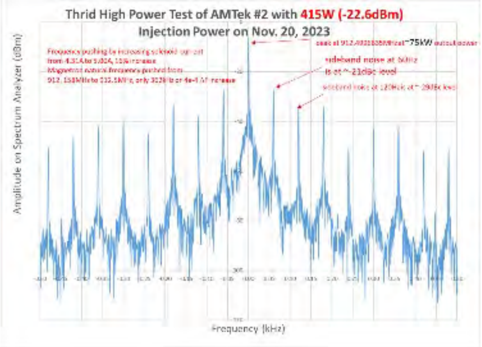
- High (>90%) AC to RF power efficiency
- Low (<$2/W) capital cost
- Demonstrated injection phase lock performance
- Magic-tee power combining demonstration 4X1.2kW @ 2.45GHz at GA
- 4×75kW @ 915MHz power combining demonstration at JLab
- Smart and low-cost switching power supplies for SRF application

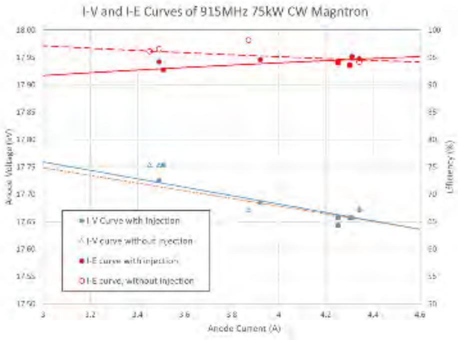




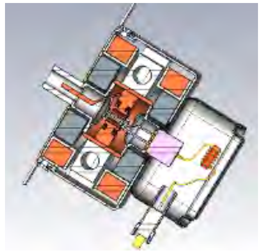








- Magnetron modification with trimming magnetic field feedback
- Injection phase lock
- Anode current modulation
- Achieved S/N performance closed to the klystron used at CEBAF
- Delivering characterized magnetron heads to GA for power combining experiment



EIC Electron Storage Ring SRF Cavity Cryomodule Assembly Design

Design, prototype and fabrication
niobium, copper cavity and beam line components for high current EIC collider rings

- Capabilities of SRF/RF cavity design, prototype and fabrication for high current linac, storage ring and high gradient accelerator cavities
- Design for stringent requirement of HOM damping, short-range wake minimizing for high charge high current beams
- Engineering design fundamental and HOM couplers including Beam line absorbers, bellows and tuners

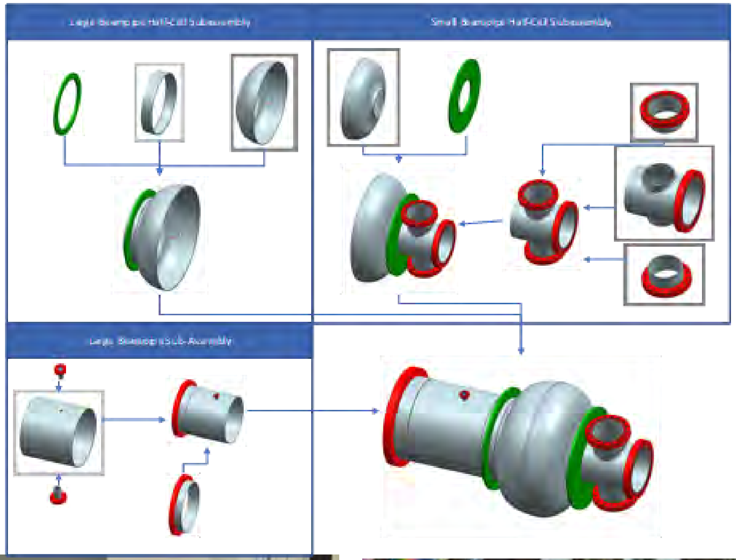
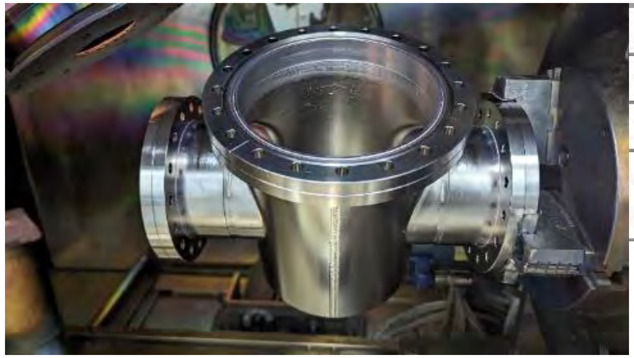


Figure 1: ESR cavity string.

Table 2: Basic Parameters of the ESR Cavity Designs

R/Q (Circ. Def) (Ω)	38
Epk/Eacc	2.01
Bpk/Eacc (mT/(MV/m))	4.87
G (Ω)	307
FPC tip penetration (Qext ~2E5)	9 mm
Approximate total length (gate valve to gate valve)	2.8 m



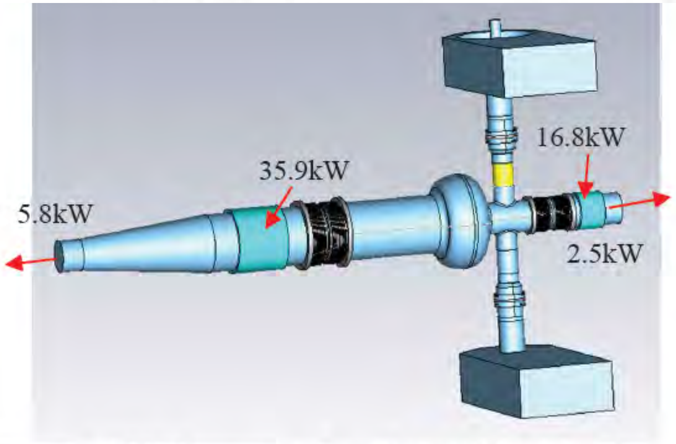


Figure 4: HOM loss power flow, 7 mm 27.6 nC bunches, 2.5 A average current, R 75mm beampipe design.