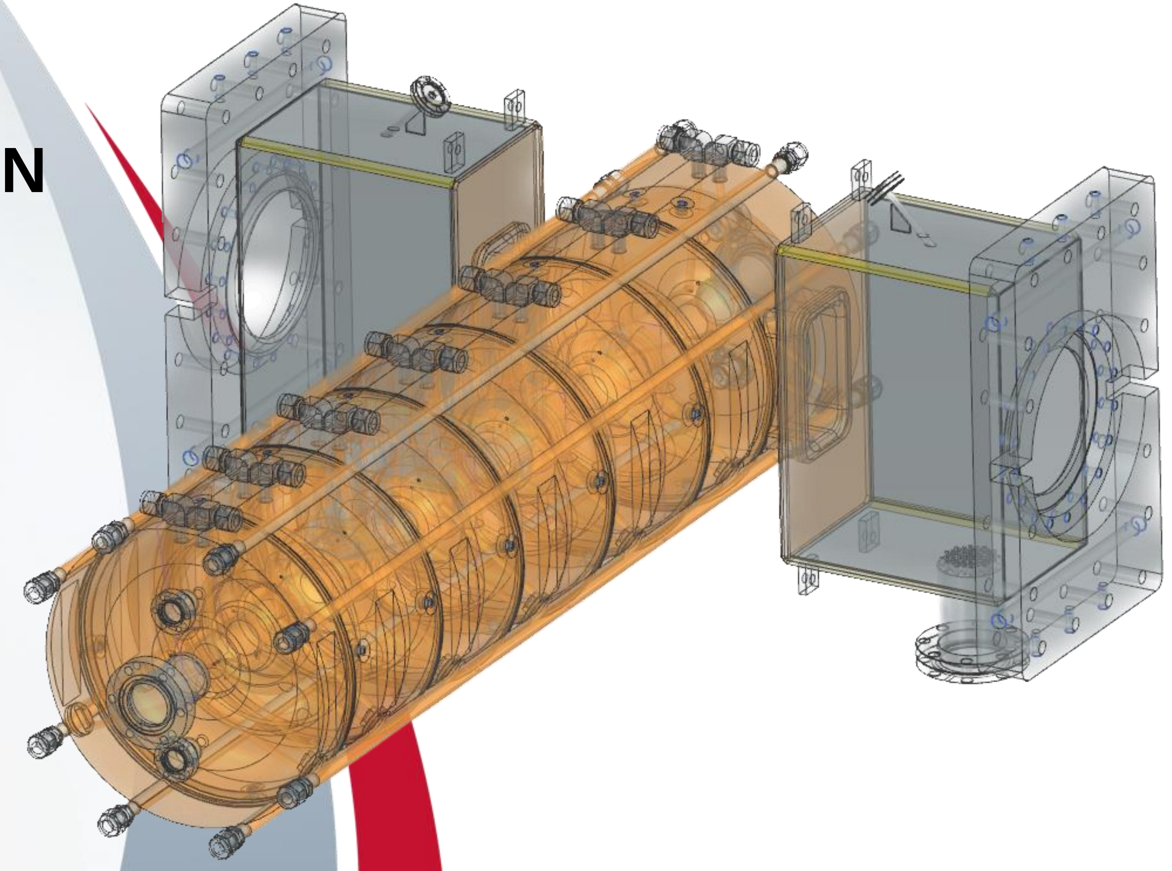
COMPACT AND EFFICIENT CW ELECTRON LINACS FOR INDUSTRIAL AND ENVIRONMENTAL APPLICATIONS

LINAC2026, Korea



8/20/2026

R. A. Rimmer

For the JLab compact accelerator team

Jefferson Lab U.S. DEPARTMENT of ENERGY NNSA National Nuclear Security Administration

Outline

Introduction (JLab, mission)

Applications of compact accelerators

Low energy, high power NCRF linac (NNSA project)

Efficient RF source (Magnetron, ARDAP)

SRF option

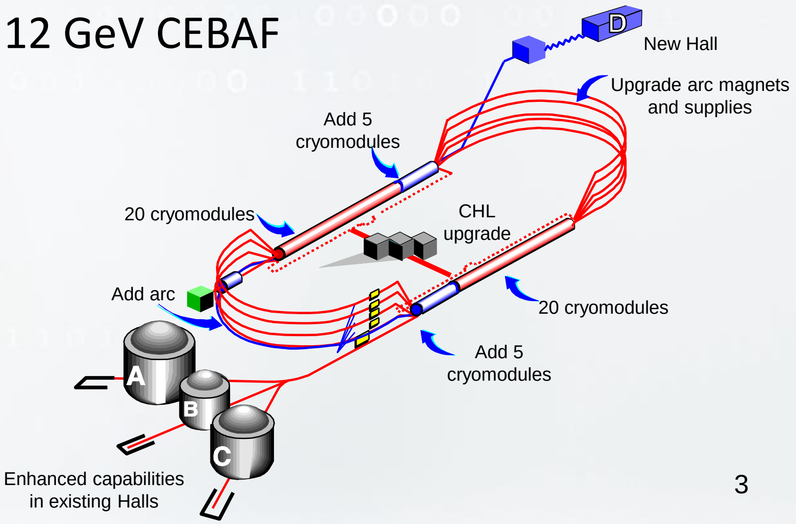
- conduction cooling, Nb3Sn, proof of concept
- 1-cell Stewardship project (Stewardship)
- Multi-cell project (ARDAP)
- Multi-cell project (ACCELERATE)

Summary and future plans

About JLab – Our Mission

Jefferson Lab, a forefront U.S. Department of Energy nuclear physics research facility, provides world-class, unique research capabilities and innovative technologies to serve an international scientific user community. Specifically, the laboratory's **mission** is to:

- deliver discovery-caliber research by exploring the atomic nucleus and its fundamental constituents, including precise tests of their interactions; **CEBAF**
- apply advanced particle accelerator, detector and other technologies to develop new basic research capabilities and to address the challenges of modern society;
- advance knowledge of science and technology through education and public outreach, and;
- provide responsible and effective stewardship of resources.



Applications of low-energy e-beam

Many applications of low-energy e-beam.

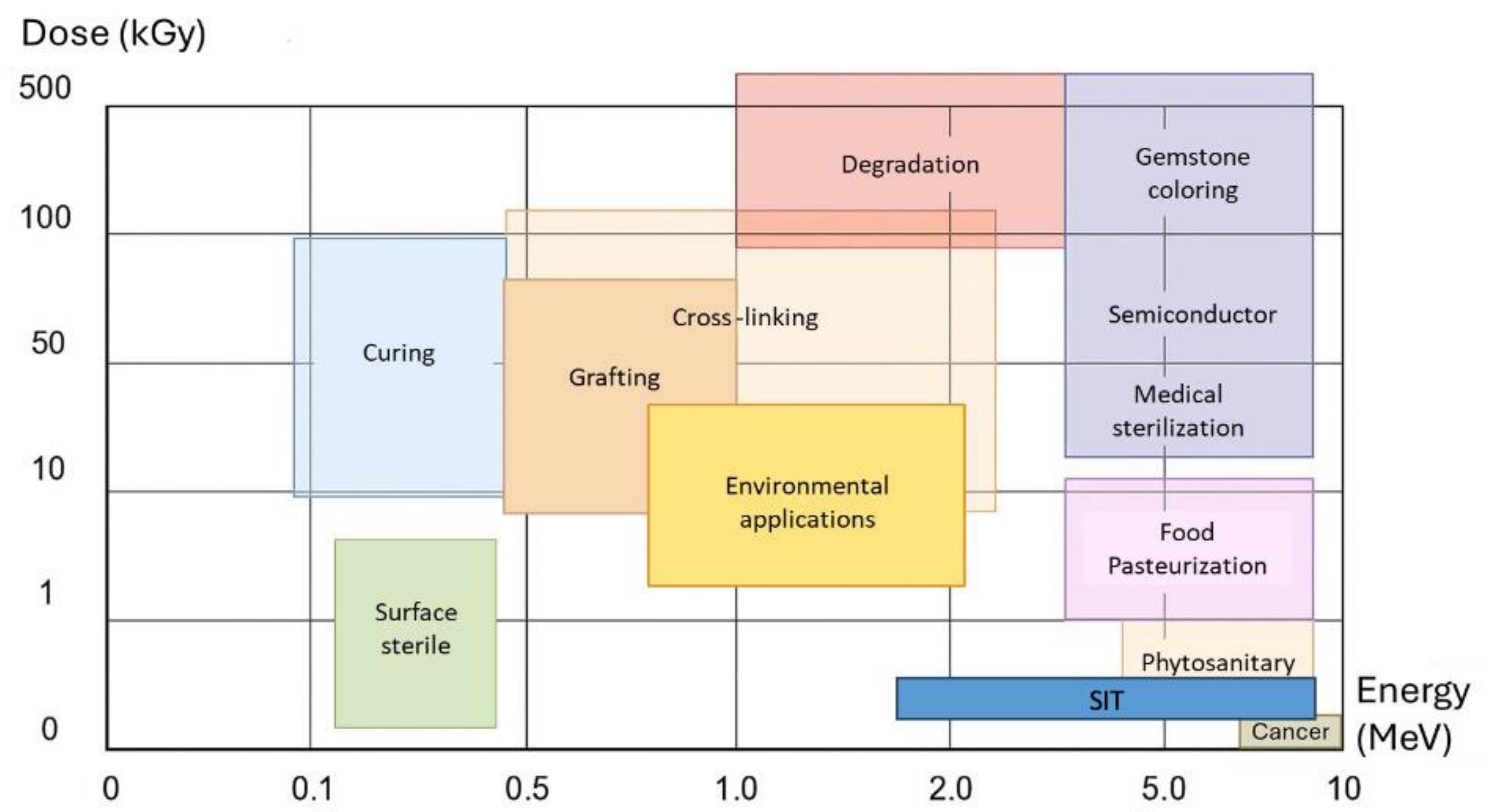
Typical cut-off at ≤10 MeV to avoid activation. *(FDA 21 CFR Part 179)*

Processing of bulk materials, or those requiring high throughput or high dose are often power limited.

E.g. PFAS remediation in soil or wastewater may require 2000 kGy!

Adoption of accelerator sources is sensitive to cost and reliability.

Opportunities for innovation in power, efficiency, capital and operating costs.



(Image from adapted from Ilia Geltser, Medical Device Sterilization Workshop 2023)

N. Ludwig. “Aerial: An irradiation platform for R&D, education and dissemination of the benefits of electron accelerators. Focus on LEEB technology”, IAEA Second International Conference on Accelerators for Research and Innovation, AccConf2026, 22 - 26 June 2026

*Ilia Geltser, Terumo BCT, “Medium-energy, Low-power Needs”, Medical Device Sterilization Workshop 2023: Past, Present, and Future, Sep 20 – 21, 2023

Compact, CW Normal-Conducting LINAC

First developed for the CEBAF injector at 1497 MHz

Scaled to 915 MHz for 1 MeV, 500 kW high current industrial applications (ARDAP)

Graded beta design to match commercial 30 kV electron sources

Small aperture, slot coupled π-mode design for high efficiency

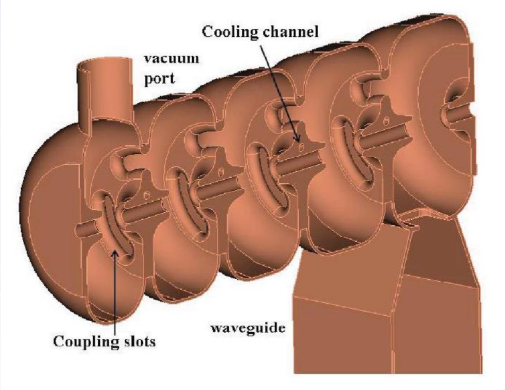
Modest gradient 1 MV/m set by thermal limits

Dual power couplers for high average beam power

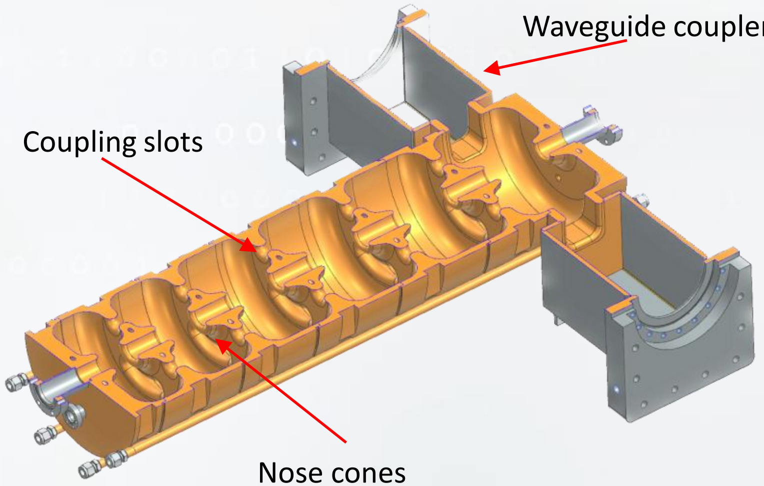
100 kW Prototype funded by NNSA

Thermionic gridded e-gun procured from InnoSys Inc.

Magnetron RF power – motivates frequency selection 915 MHz



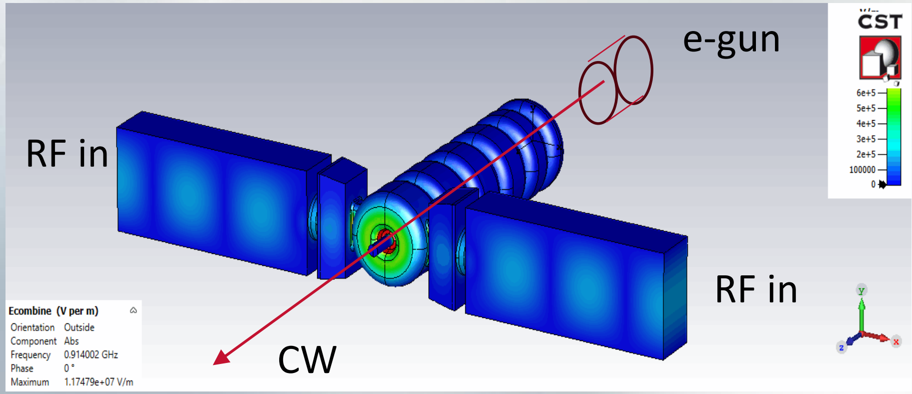
New CEBAF capture cavity

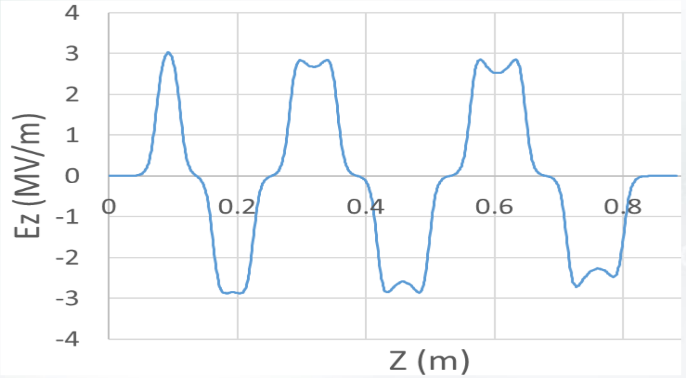


This research was supported by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) and by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

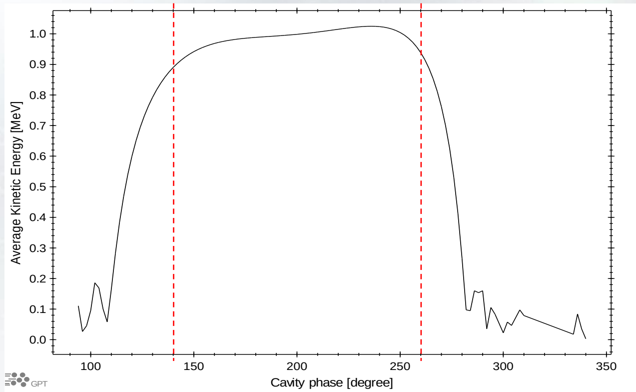
Linac optics

- 30 kV electron gun
- Solenoid focusing
- Graded-beta acceleration
- Coupling set for 100 mA
- >90% beam capture

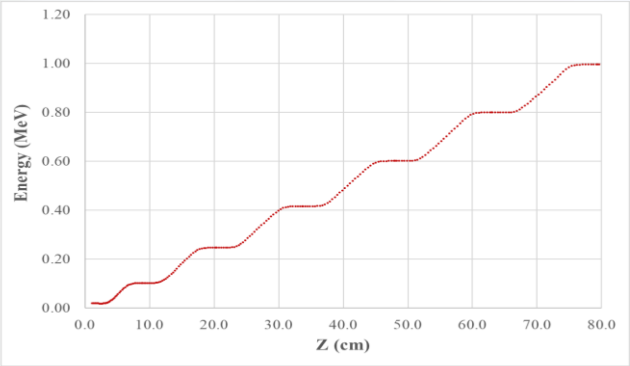




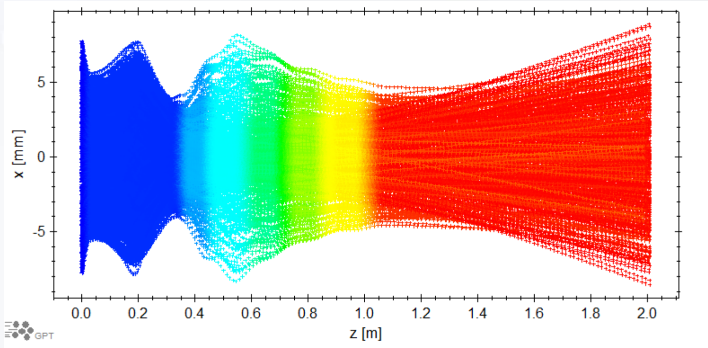
Graded-beta field profile



RF acceptance for 30 kV electrons



Energy profile through the LINAC



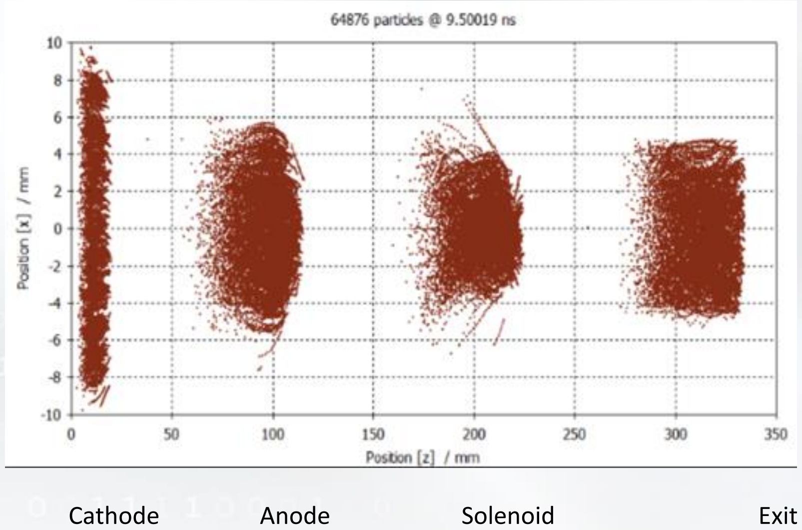
Transverse beam profile from the cathode to the exit of the LINAC

Electron Source

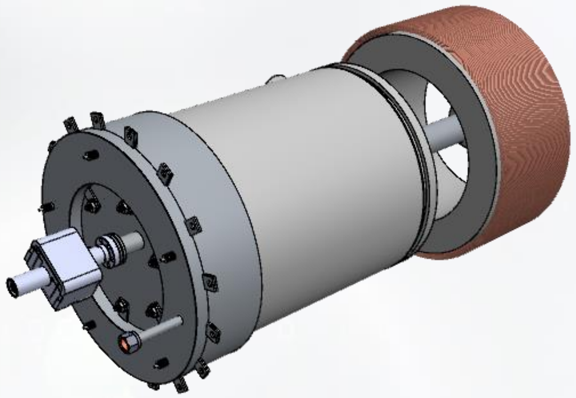
Use a gridded thermionic gun to pre-bunch the beam.

Simulation results:

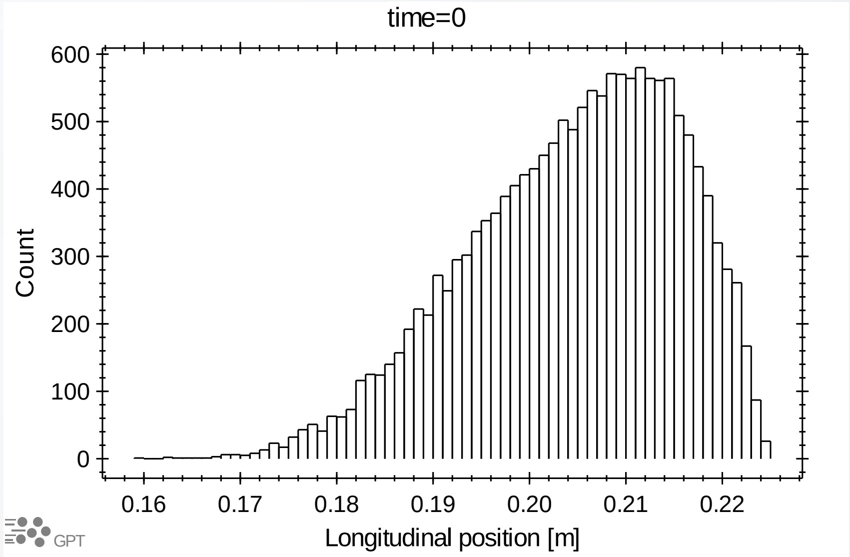
- Peak current about 0.6-0.7A and bunch charge 138 pC
- The DC bias -250V,
- Average current ~**126 mA**
- Cathode grid gap **0.3 mm**



Beam formation in the gun



Electron gun design



Longitudinal bunch profile

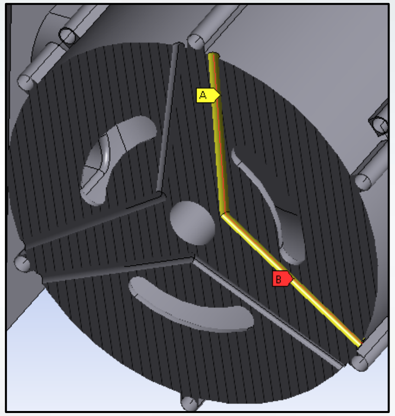
Linac fabrication

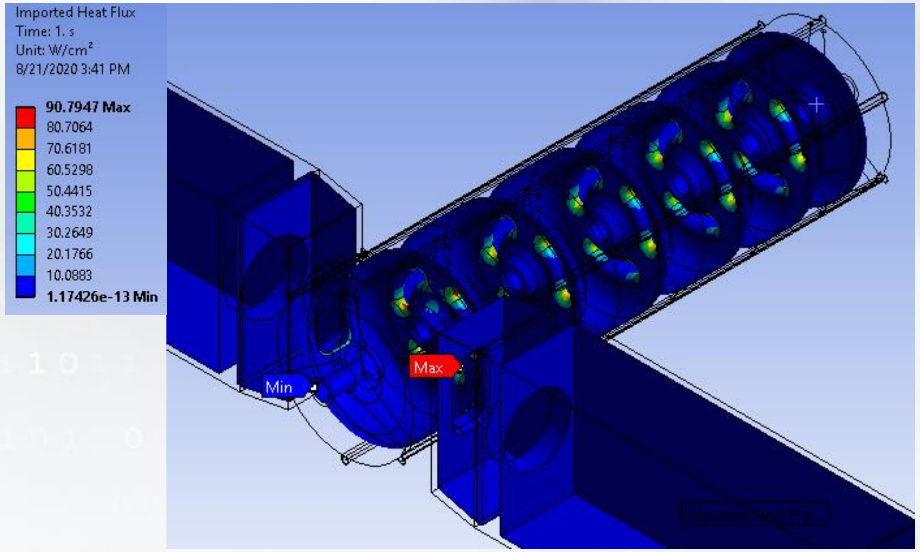
Linac fabrication mostly follows conventional practice:

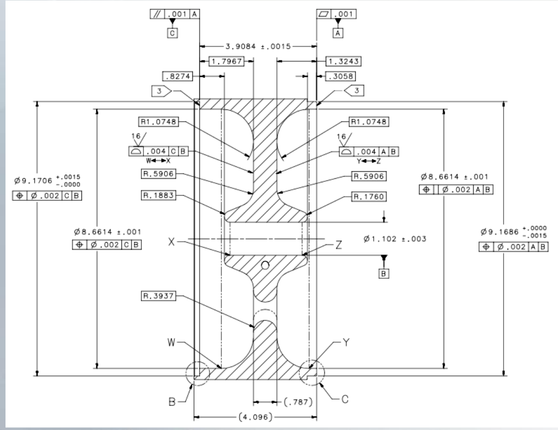
- Machined copper cells
- Stack braze
- Brazed external cooling lines

Unusual features include:

- E-beam welded on waveguides
- Drilled internal cooling passages







Magnetron RF Source

Magnetrons are the cheapest and most efficient RF sources

JLab has an ongoing ARDAP project to combine 4 existing magnetron power sources, each capable of delivering 75kW CW at 915 MHz.

>90% efficiency DC to RF

Injection locking

- noise reduction
- fast modulation

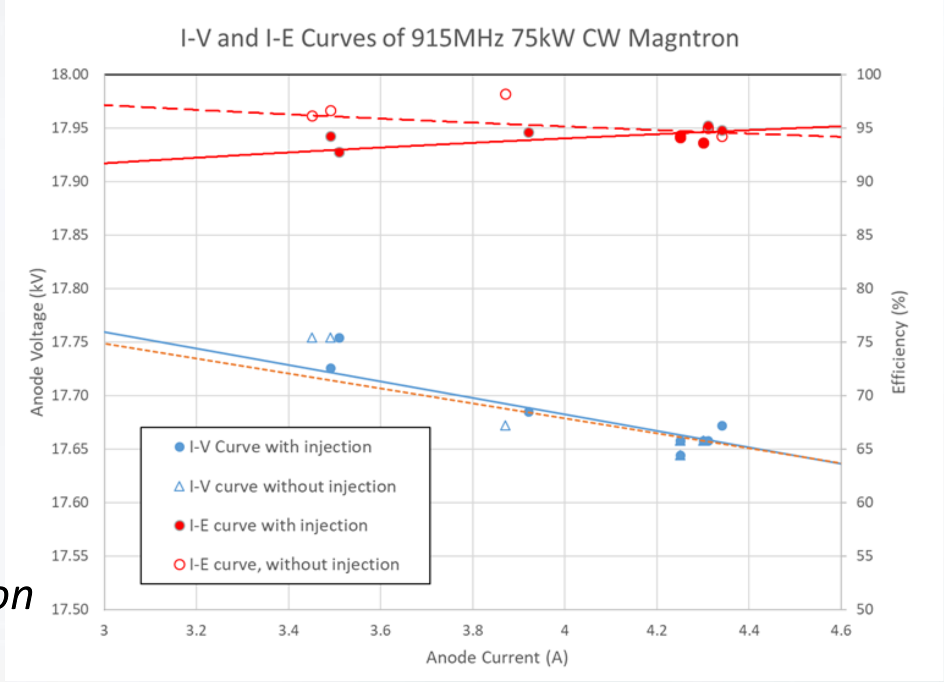
Binary Combining (coming soon)

75 kW + 75 kW = 150 kW

Four-way demo (2027)

300 kW using 75 kW tubes

AMTek Commercial 75 kW CW magnetron supply with JLab modified controls



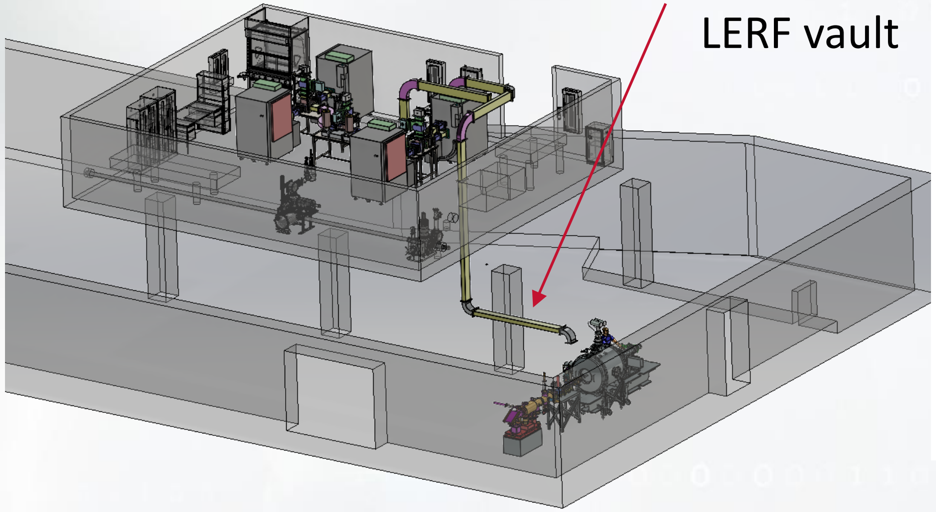
System Integration and Testing

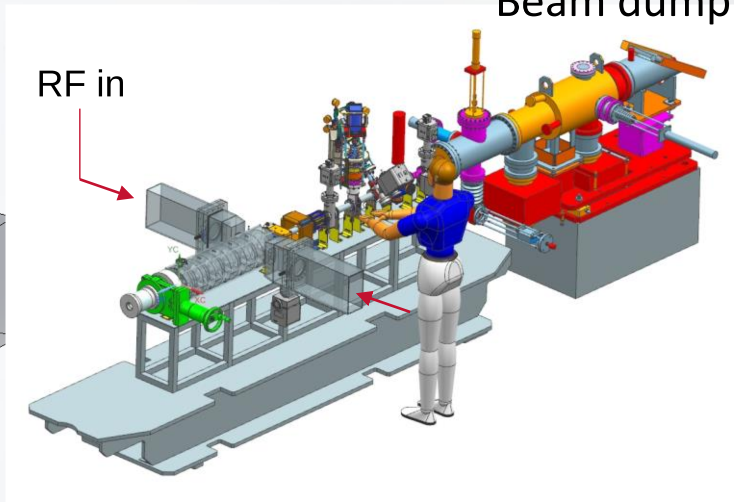
Integration, commissioning, and testing of one full LINAC section with e-gun, magnetron RF, controls and diagnostics.

LERF vault at JLab being prepared for system testing.

Magnetron lab is conveniently above the shielded vault.

JLab Low Energy Recirculation Facility (LERF)





Girder assembly with diagnostics

Future work

- Additional RF sources available at JLab to upgrade to 100 kW.
- Upgrade energy

  Add additional β=1 sections

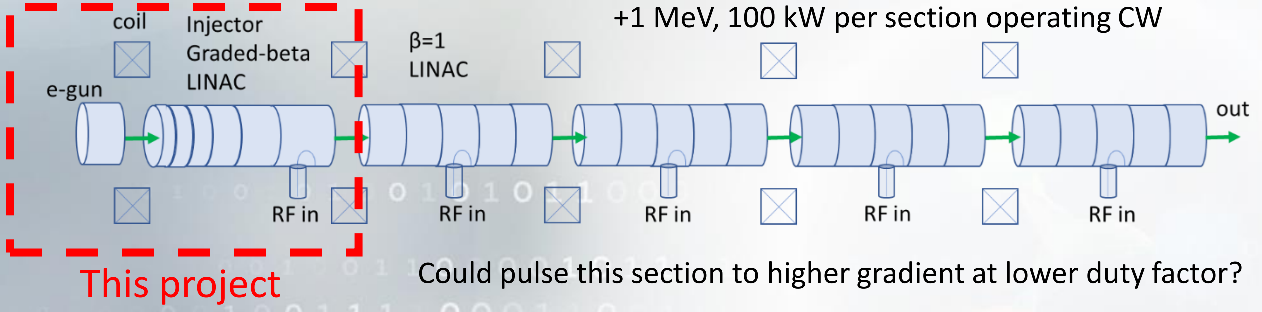
  SRF booster may be available in near future from ARDAP/ACCELERATE programs.
- Could be used for beam tests, target development etc..

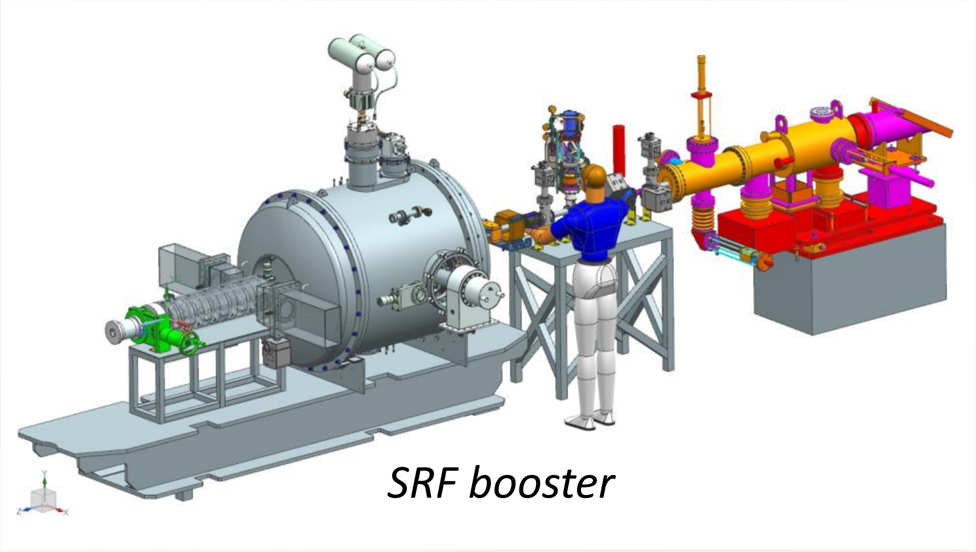
  Sterilization.

  PFAS destruction, GAC/media recovery.

  X-ray modality.

  Any high throughput application.





SRF technology. What is preventing wider adoption?

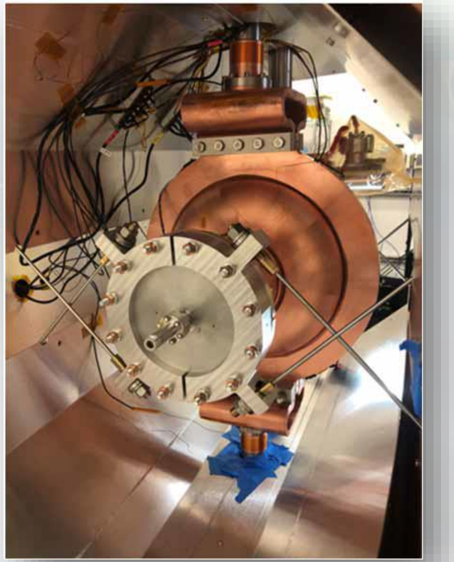
Barriers to adoption

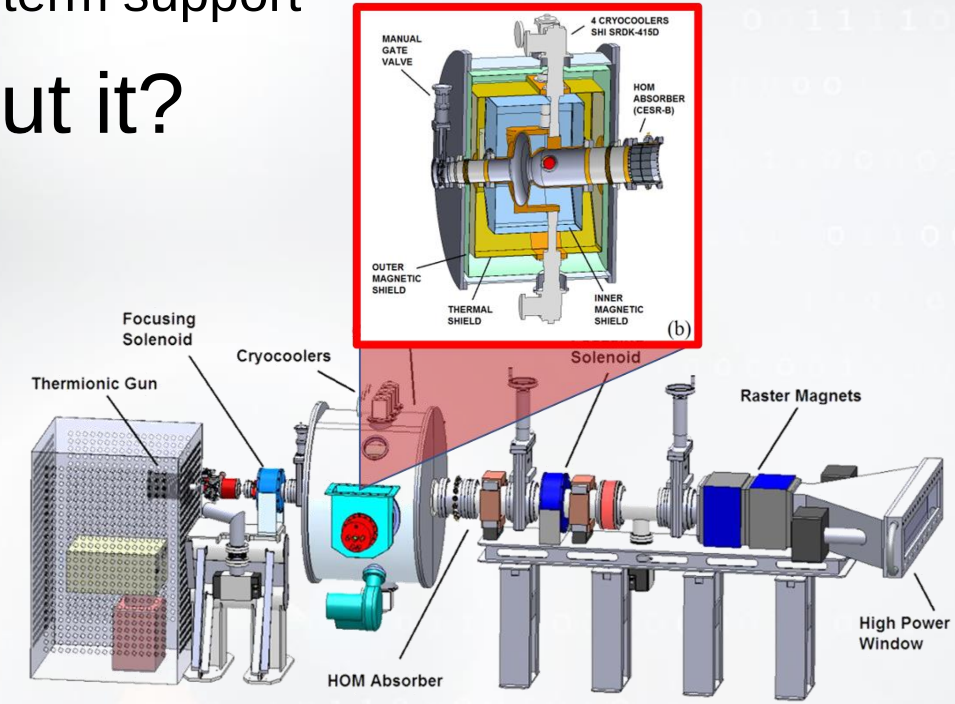
- High capital cost of SRF-based systems, despite efficiency
- Perception of high maintenance, questionable reliability
- Lack of industry base for long term support

What are we doing about it?

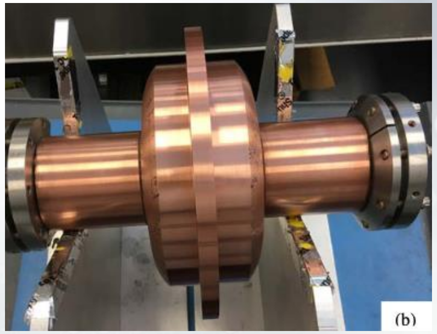
R&D on cost reduction:

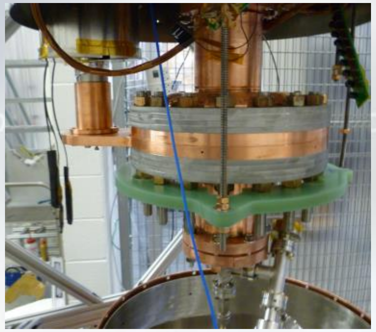
- New materials, e.g. Nb_3Sn
- 4.5K operation
- **Cryocoolers**
- Modular systems
- Outreach to industry





First results from a multi-metallic conduction-cooled SRF single-cell cavity at JLab (2019)





Nb_3Sn thin film grown by vapor diffusion at 1200 °C on ~2.9 mm thick bulk Nb (large grain) 1.495 GHz single cell cavity

Deposit seed layer (~76 μm thick) of Cu on Nb outer surface by cold-spray at CTC, Johnstown, PA

Deposit ≥5 mm thick oxygen-free Cu on seed layer by electroplating at AJ Tuck Co., Brookfield, CT. A 10” diameter, ½” thick ring was also grown at the equator by electroplating.

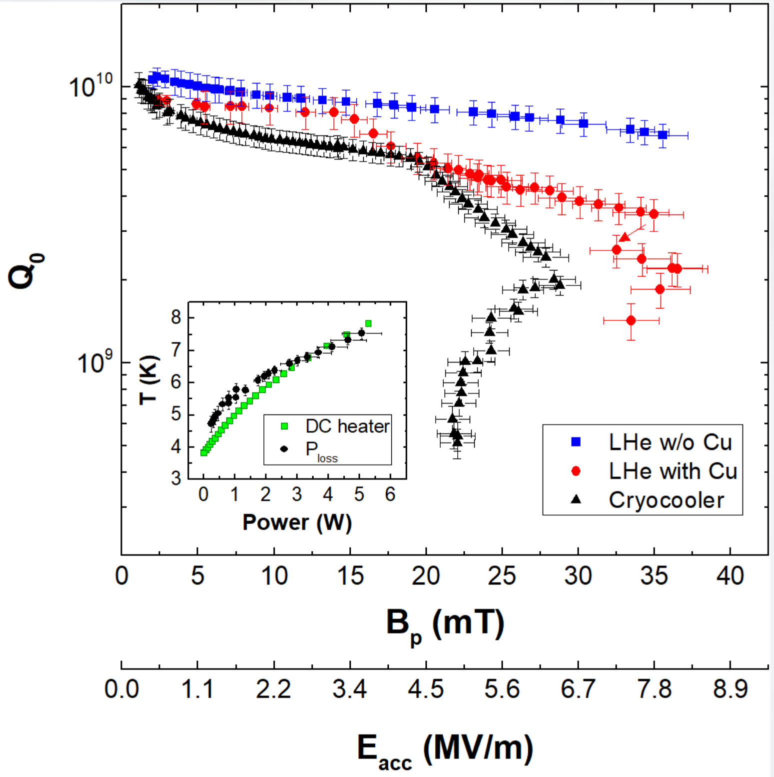
Cavity temperature after cooldown*: ~3.8 K

T-gradient at 18 K: ~0.09 K/cm. Max residual B at 18 K: ~14 mG

Bp ~ 29 mT (Eacc ~ 6.5 MV/m)

Amplitude of microphonics: 13.8 Hz pk-to-pk

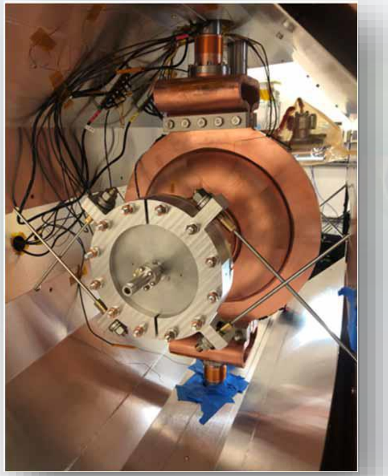
The cavity was thermally stable during a 1 h operation at Pdiss = 5 W even with anomalous losses (Q0 ~ 5e8 at 22 mT)



19th Int. Conf. on RF Superconductivity SRF2019, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP050

*Sumitomo RDE-418D4 cryocooler

1-cell conduction-cooled horizontal cryostat



3-year collaboration among JLab, J. Rathke, T. Schultheiss, General Atomics

Funded by DOE-ARDAP (Accelerator Stewardship)

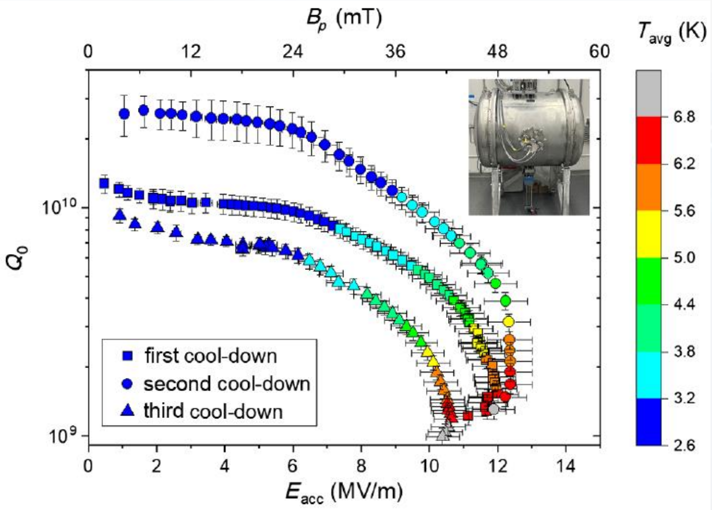
1 MeV, 1 A CW electron beam linac at 915 MHz Designed for use in wastewater and flue-gas treatment

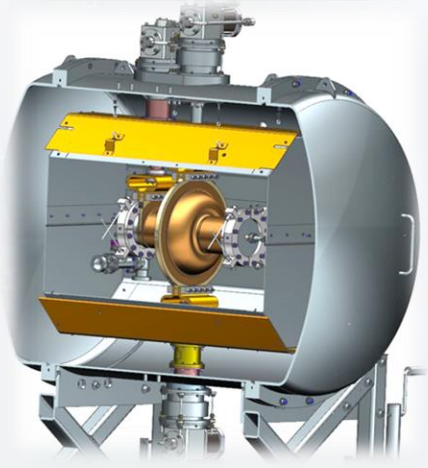
Multi-metallic Cu/Nb/Nb_3Sn 952 MHz single-cell cavity cooled by 3 cryocoolers at GA (no FPC, no beam)

Achieved B_p=50 mT surface field

Stable operation with 18.5 W of RF heat load at ~6 K

23 Hz pk-pk microphonics detuning





G. Ciovati et al., "Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators", Phys. Rev. Accel. Beams, vol. 26, 044701, 2023. doi:10.1103/PhysRevAccelBeams.26.044701

2-cell conduction-cooled horizontal cryostat

3-year collaboration among JLab, J. Rathke, T. Schultheiss, General Atomics and RadiaBeam

Funded by DOE-HEP (ARDAP) and DOE-NP (Accelerate)

915 MHz 2-cell cavity (Roark) with low-loss FPC (RadiaBeam)

Two cryocoolers (Sumitomo GM, 2 W at 4 K and Bluefors PT, 5 W at 4K)

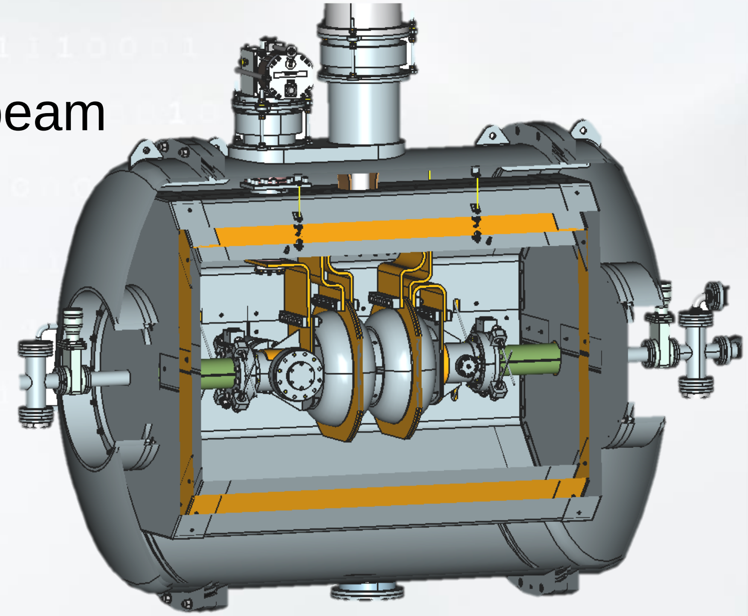
To be tested at GA in 2028 with the goal of achieving E_{acc} = 6 MV/m, no beam

Magnetron to be used as RF source

Capability to provide 20 kW beam power

Parameters of the 915 MHz 2-Cell Cavity

f	915 MHz
R/Q	264 Ω
G	275 Ω
E_p/E_{acc}	2.17
H_p/E_{acc}	3.69 mT/MV/m



G. Ciovati *et al*., "RF and mechanical design of a 915 MHz SRF cavity for conduction-cooled cryomodules", in Proc. LINAC'24, Chicago, IL, USA, Aug. 2024, pp. 732-735. doi:10.18429/JACoW-LINAC2024-THPB046
S. Thielk *et al*., "Design of a 25 kW fundamental power coupler for conduction cooled Nb_3Sn industrial linac", in Proc. LINAC'24, Chicago, IL, USA, Aug. 2024, pp. 526-529. doi:10.18429/JACoW-LINAC2024-TUPB100

10 MeV Compact Accelerator Concept

4-year design collaboration among JLab, J. Rathke, T. Schultheiss, General Atomics

Funded by DOE-ARDAP (Accelerator Stewardship)

Designed for all irradiation applications (7-7.5 MeV for X-ray generation)

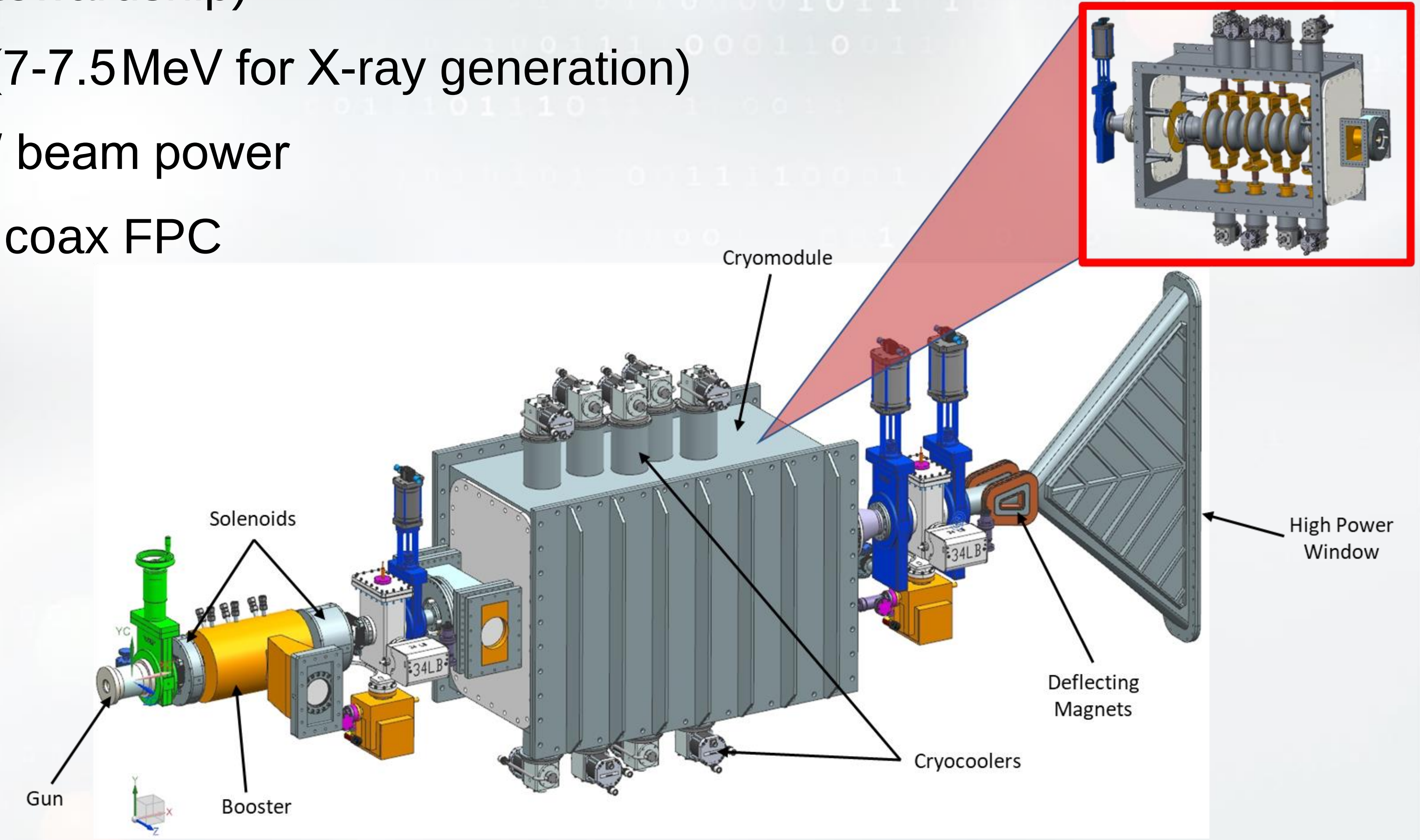
10 MeV, 100 mA electron beam ↔ 1 MW beam power

CM has total of 9 cryocoolers, beamline coax FPC

normal cond. booster → 600 keV
(similar to 1 MV structure)

Design Parameters for the 915 MHz Five-Cell Cavity

f	**915.032 MHz**
l	81.9 cm
R/Q	607.1 Ω
G	275.3 Ω
$Ep/Eacc$	2.145
$Hp/Eacc$	4.235 mT/MV/m



ON THE WAY TO A 10 MeV, CONDUCTION-COOLED COMPACT SRF ACCELERATOR, J. Vennekate et. al, 21th Int. Conf. RF Supercond. SRF2023, Grand Rapids, MI, USA JACoW Publishing. ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi: 10.18429/JACoW-SRF2023-TUPTB033

Summary and future work

- Growing interest in compact accelerators for industrial, environmental applications
- NCRF technology can serve many needs
- CW operation can deliver higher power
- Magnetrons offer low-cost, scalable RF power
- SRF offers improvements in efficiency, size
- Further R&D needed
  - Improved PVD & CVD for Nb_3Sn
  - Beam delivery systems including X-ray modality
  - Operational demonstrations with beam
  - Proof of Reliability
  - Critical applications
  - Cost reduction

QUESTIONS?

What are better SRF Materials?

T_c [K]	ρ_n [μΩcm]	Δ [meV]	$H_c(0)$ [T]	$H_{sh}(0)$ [T]	$H_{c1}(0)$ [T]	λ(0) [nm]	Material
9.25	0.1	1.45	~ 0.2	~ 0.24	~ 0.17	40	Nb
17.2	70	2.6	~ 0.23	~ 0.19	~ 0.02	~ 200	NbN
17.5	35	3.0	~ 0.28	~ 0.24	~ 0.03	~ 151	NbTiN
18.3	5	3.1	~ 0.54	~ 0.45	~ 0.05	~ 85	Nb_3Sn
40	2	2.3/7.1	~ 0.43	~ 0.27	~ 0.03	~ 140	MgB_2

- s-wave superconductor
- large energy gap
- high H_{Sh}
- low normal conducting resistivity

Material	Nb	Nb_3Sn
T_c [K]	9.25	18.3
ρ_n [μΩcm]	0.1	~ 5
$H_{sh}(0)$ [T]	0.24	~ 0.45
Δ [meV]	1.45	~ 3.1
Q^{BCS} @ 2K	$\sim 5 \cdot 10^{10}$	$\sim 5 \cdot 10^{14}$
Q^{BCS} @ 4K	$\sim 5 \cdot 10^{8}$	$\sim 5 \cdot 10^{10}$
E_{acc} [MV/m]	~ 50	~ 100