Compact Turn-Key SRF Accelerators

Neil Stilin | Cornell Laboratory for Accelerator-based ScienceS & Education (CLASSE)

International Linear Accelerator Conference (LINAC22)

Liverpool, England

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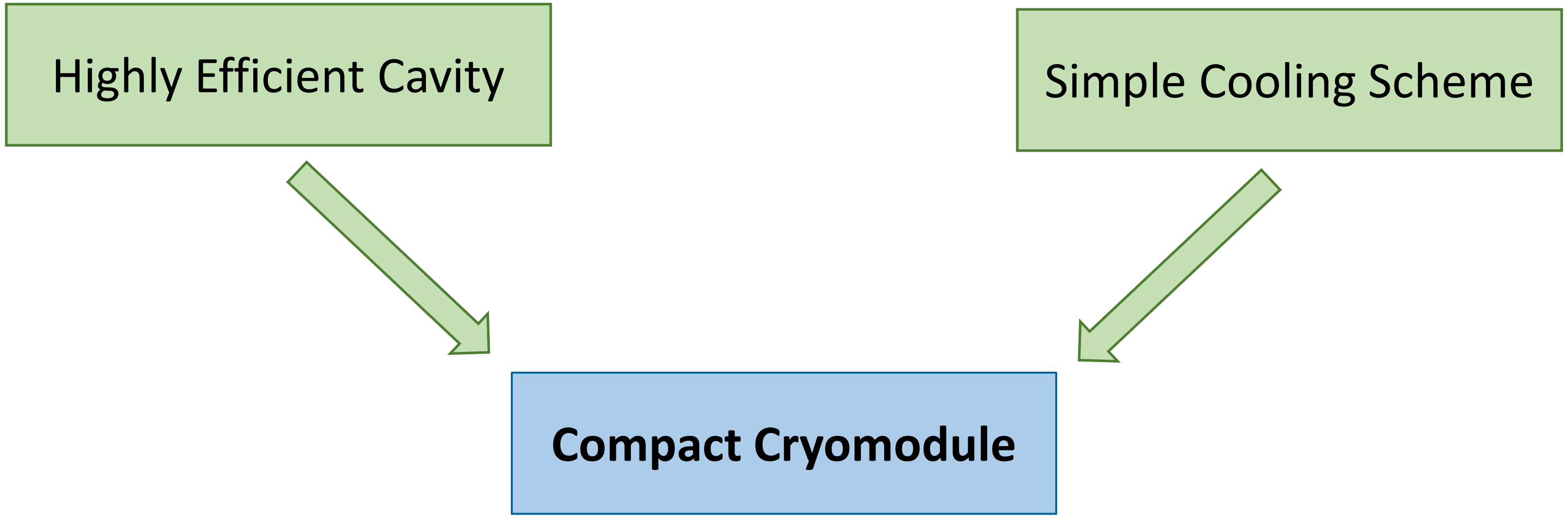
Introduction

1. What **is** a **compact turn-key SRF accelerator**?

(a) Cryomodule only ~ 1-2 meters in length, containing an accelerating SRF cavity

(b) Simplified, non-expert operation

2. What **concepts** make this possible?



Outline

- Ingredients: Nb_3Sn Cavities & Cryocoolers
- Breakthrough: Conduction-cooled SRF Cavities
- Implementation: Compact Cryomodules
- Summary

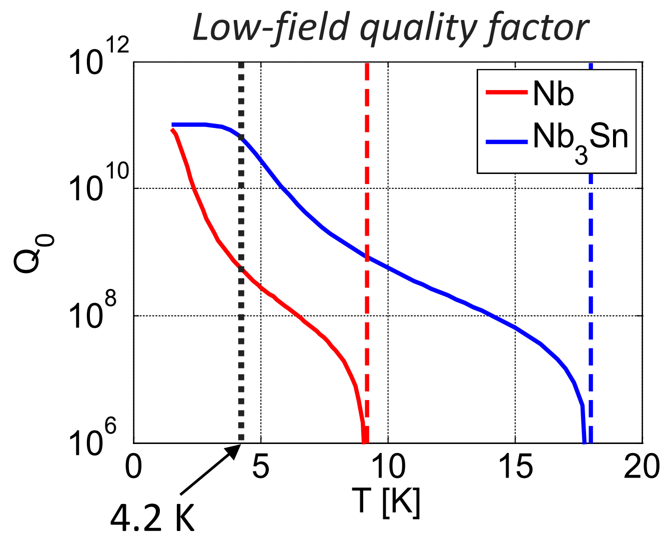
INGREDIENTS

Nb_3Sn Cavities + Cryocoolers

Why Nb_3Sn?

- **Nb_3Sn** offers efficient cavity operation at 4.2 K
- **Q_0** comparable to pure **Nb** at 2 K!

Material	λ(nm)	ξ(nm)	κ	T_c(K)	H_{c1}(T)	H_c(T)	H_{sh}(T)
Nb	40	27	1.5	9	0.13	0.21	0.25
Nb_3Sn	111	4.2	26.4	18	0.042	0.5	0.42

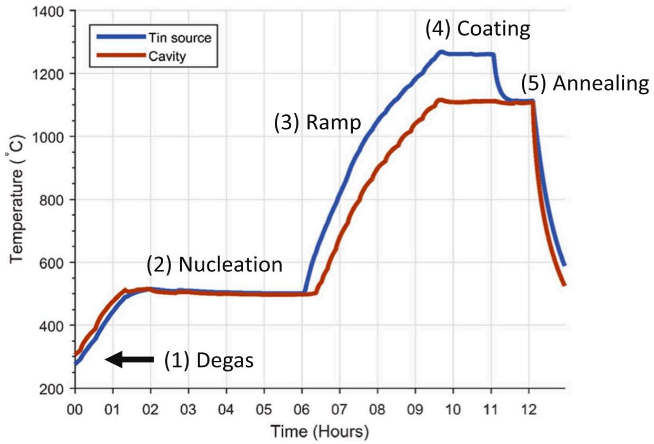


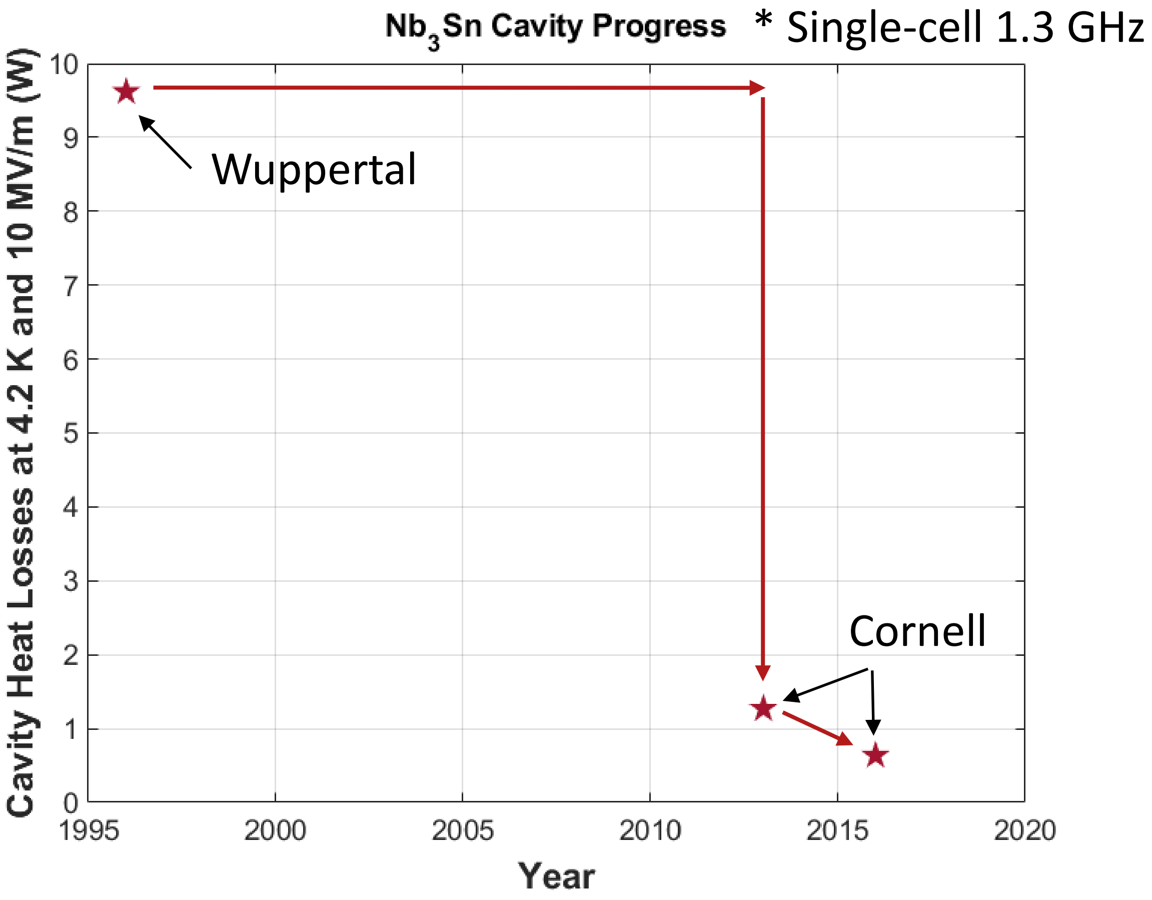
$$R_{BCS} \propto f^2 e^{(-const^* T_C / T)}$$

Higher critical temperature = lower losses and/or higher operating temperature

Nb_3Sn: Brief History

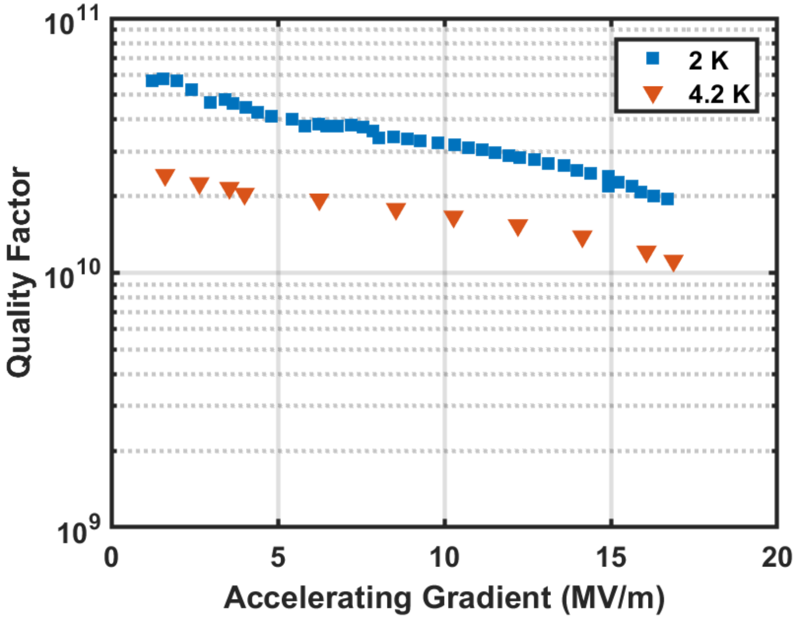
- **4.2 K Q_0** at 10 MV/m has improved significantly
- Early attempts had ~ 2E9 → now ~ 2E10!
- **Heat load** decreased from ~ 10 W to < 1 W!
- Thanks to improved coating methods





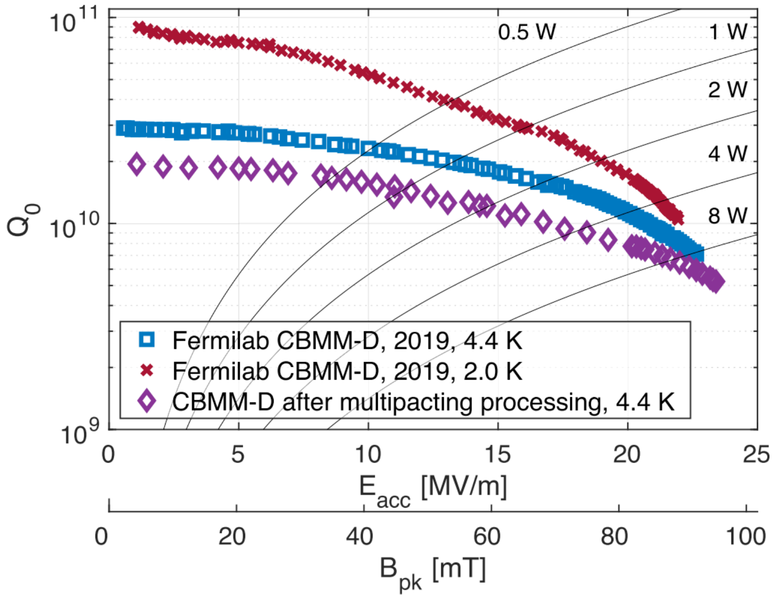
Nb_3Sn State-of-the-Art

Cornell University



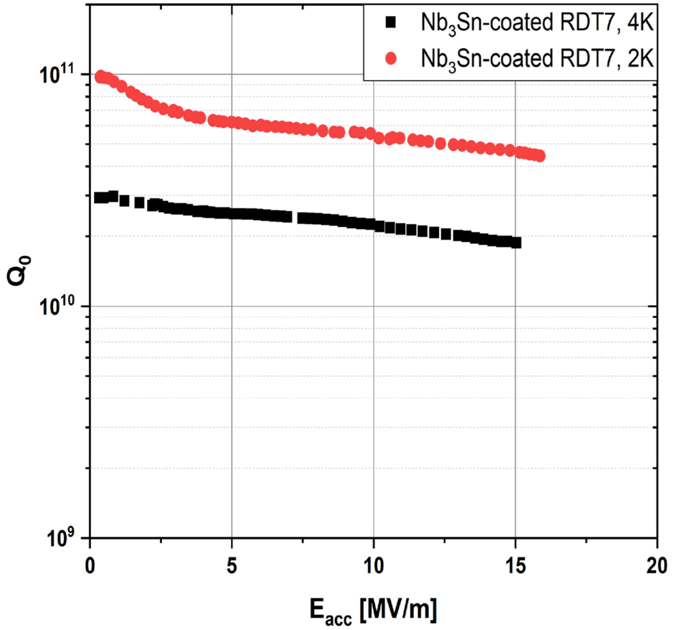
Fermilab

S. Posen, https://doi.org/10.1088/1361-6668/abc7f7



Jefferson Lab

U. Pudasaini, SRF'19

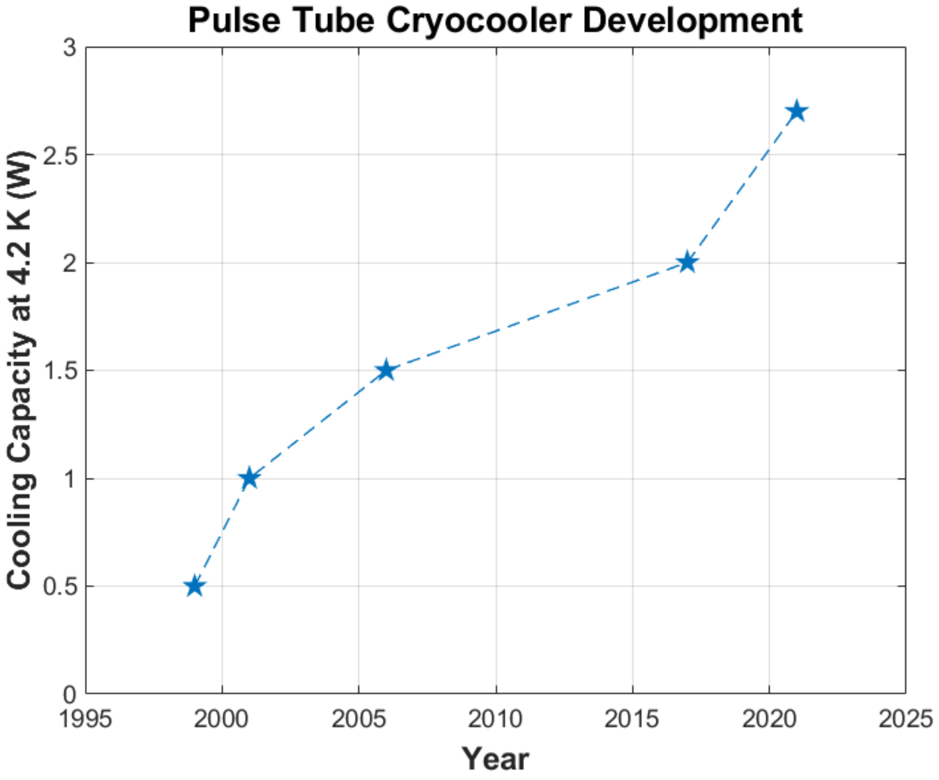


- Nb_3Sn cavities already reach **15+ MV/m** – relevant for small-scale operation
  - Q_0 > 1E10 at 4.2K
- Ongoing research focusing on **increasing E_{acc}**

For in-depth Nb_3Sn discussion: see **N. Verboncoeur's** presentation later this session!

Modern Cryocoolers

- **New cooling technology** can be used thanks to 4.2 K cavity operation
- Cryocooler concept first proposed in 1960's
- World's first **4.2 K pulse-tube cryocooler** released in 1999
  - Low cooling capacity – only 0.5 W
- State-of-the-art cryocoolers now remove **2+ W at 4.2 K**!
- **Turn-key operation**!



Cryomech.com

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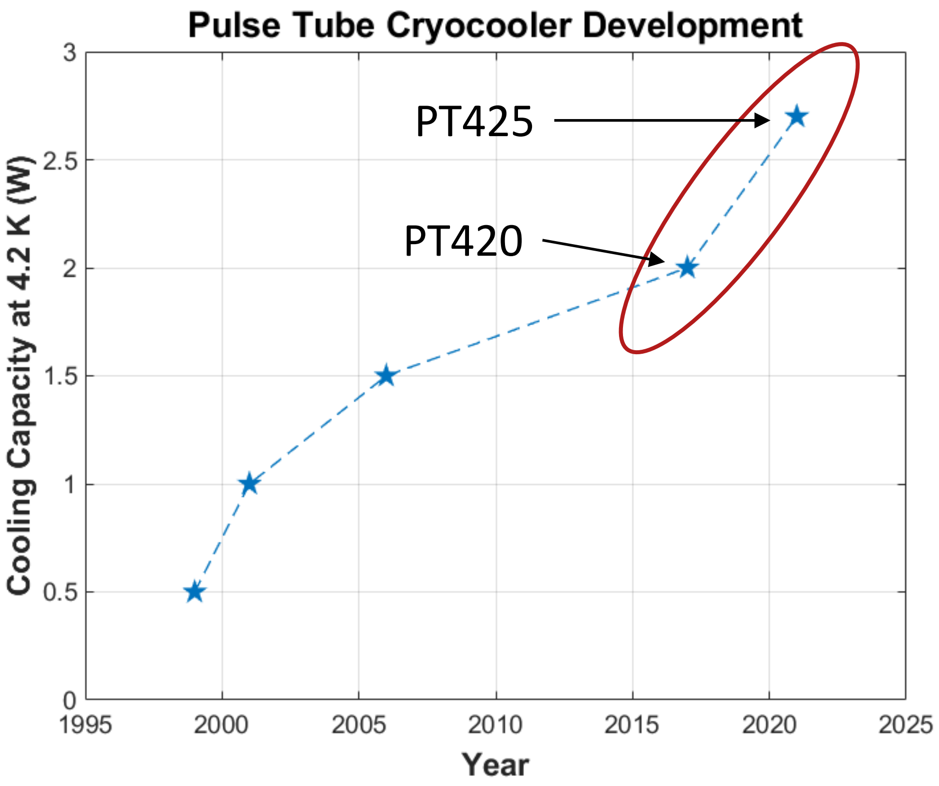
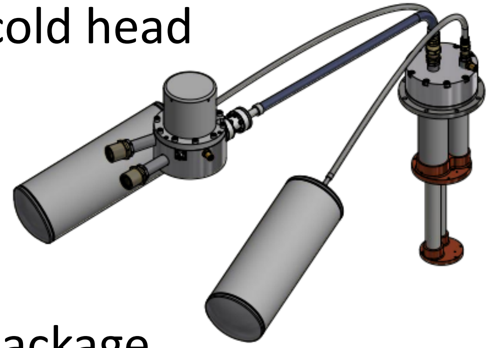
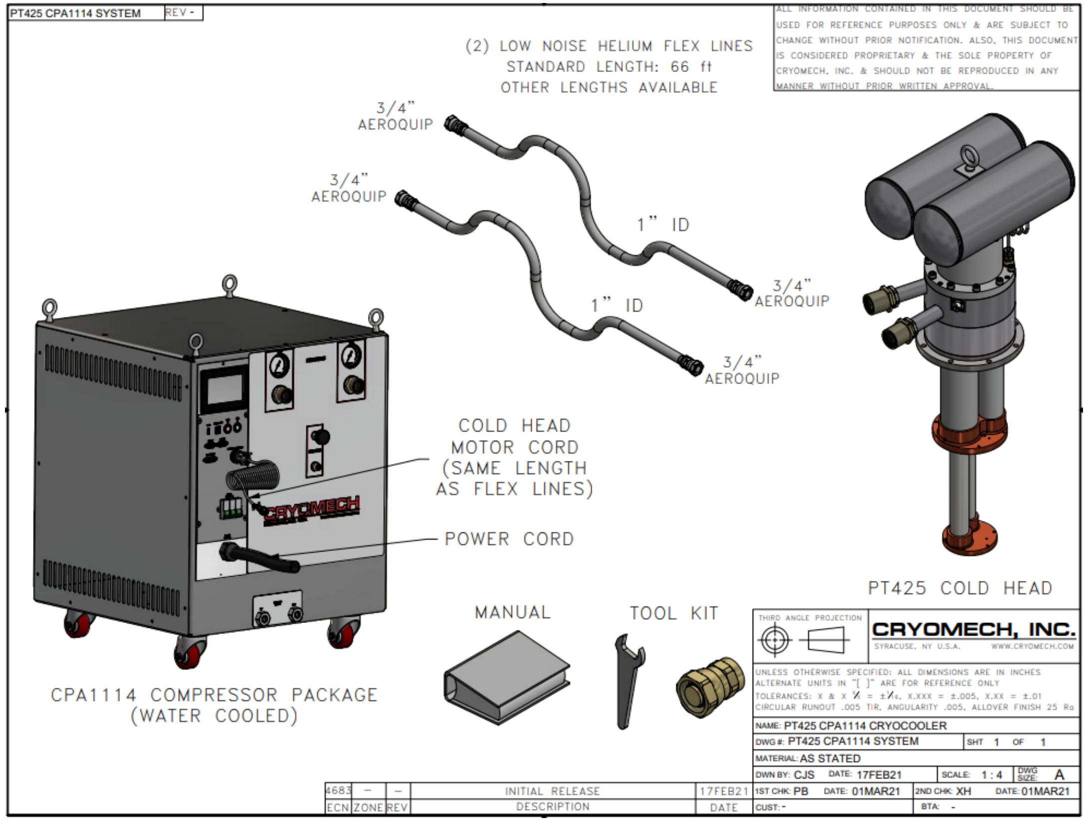


Remote cold head



Cryomech PT 425 standard package

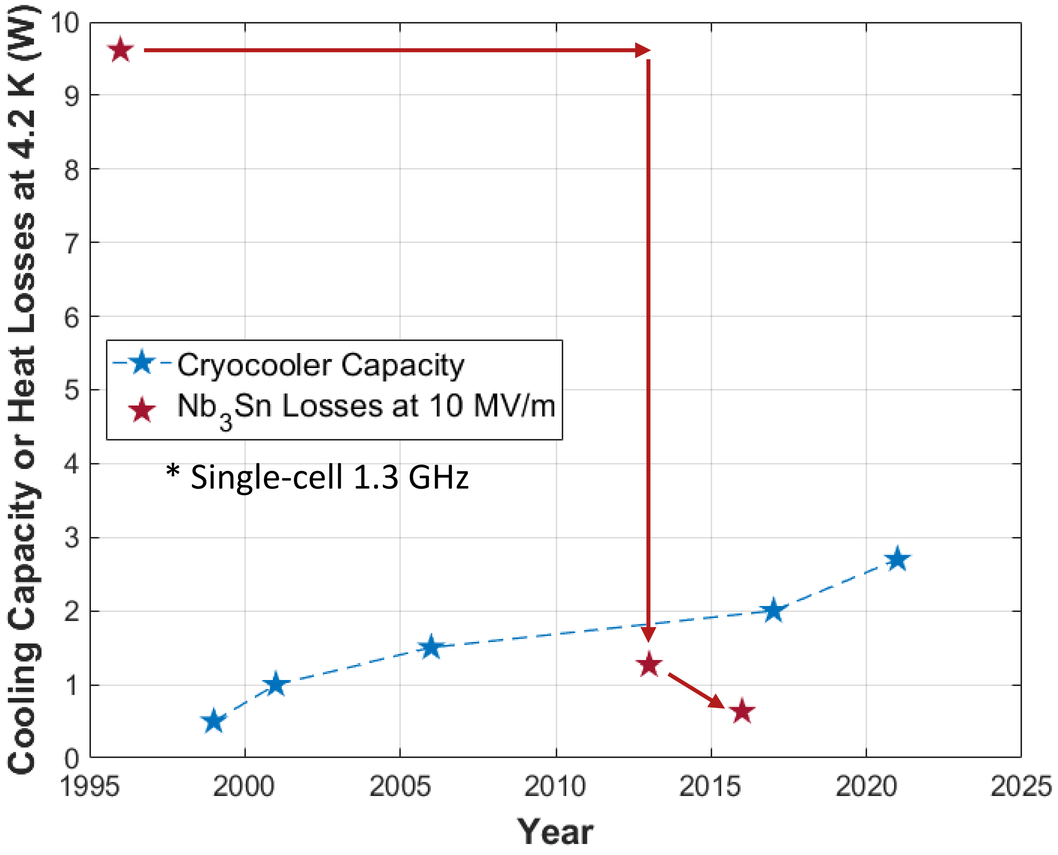


Cryomech.com

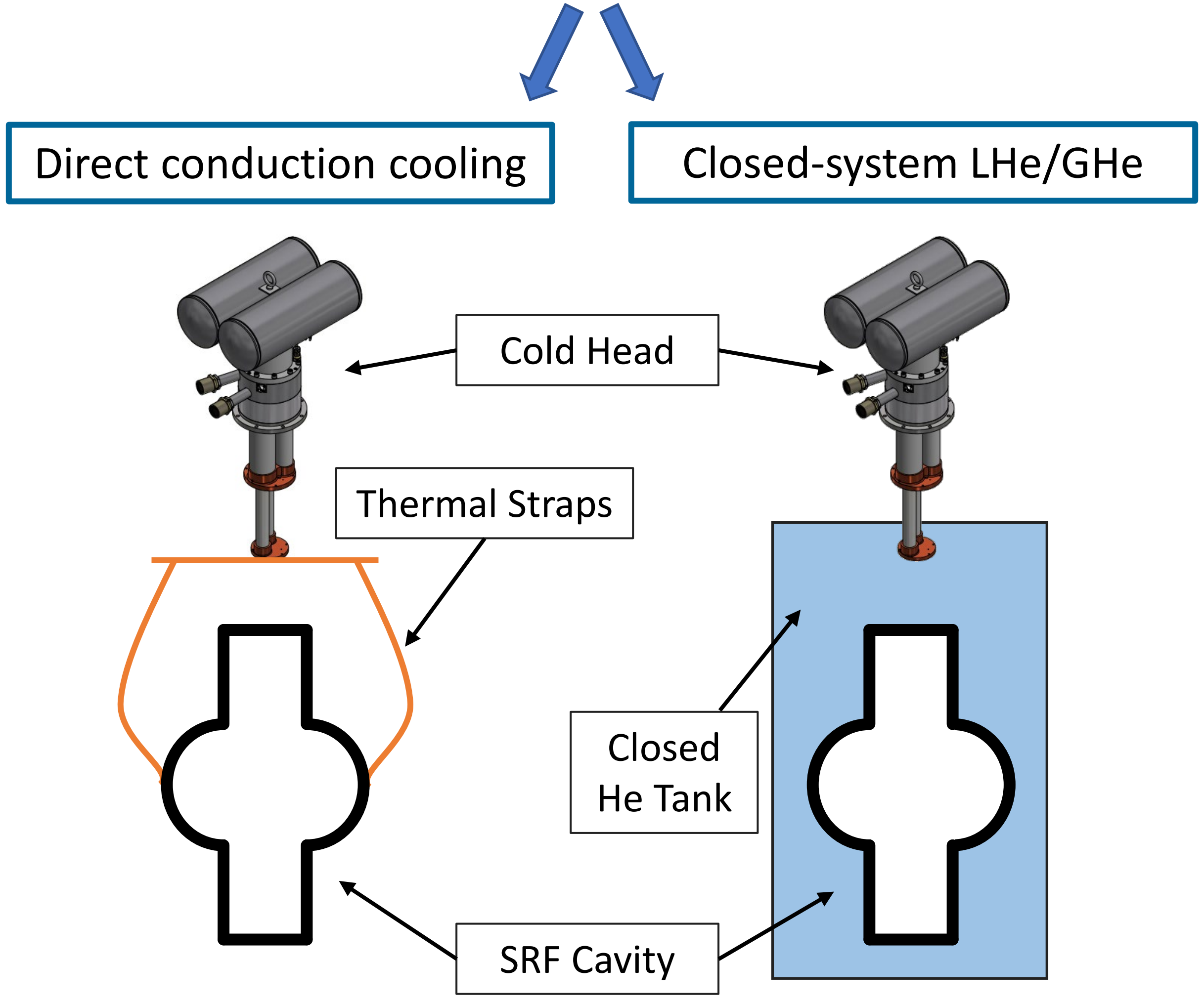
BREAKTHROUGH
Conduction-cooled SRF Cavities

A New Frontier

Cryocooler-based cooling is now possible!



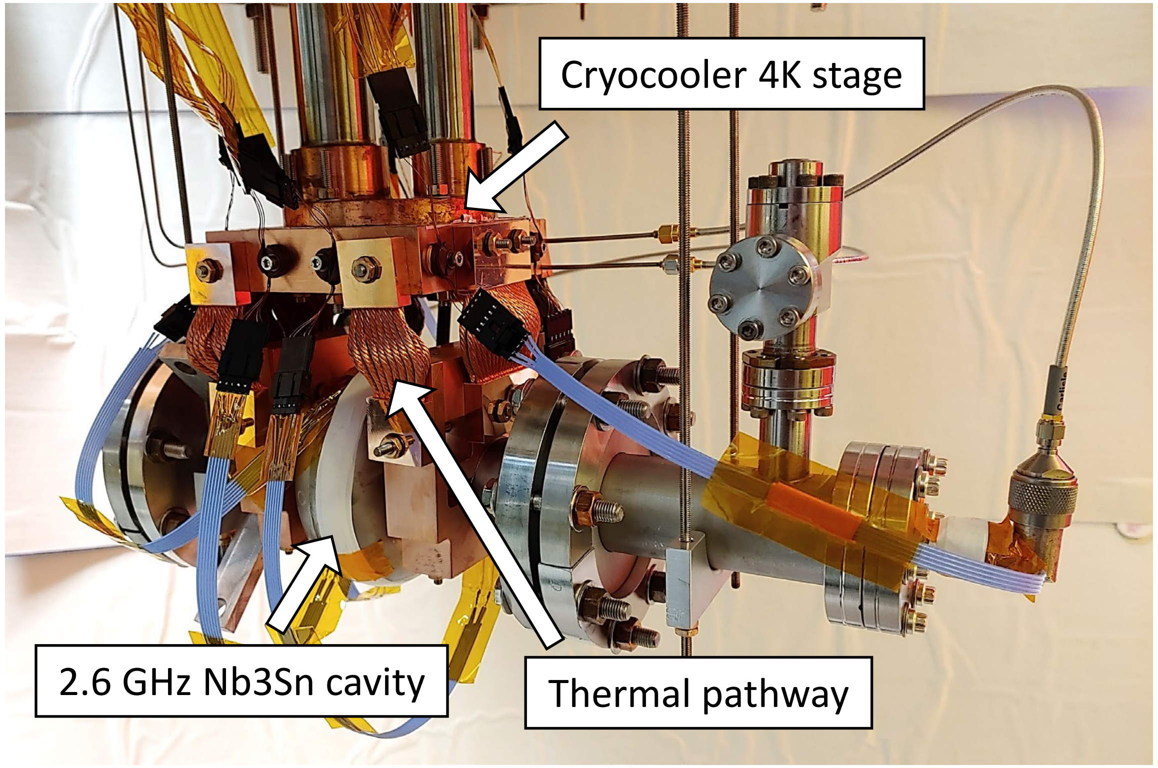
New **cooling schemes** for SRF cavities

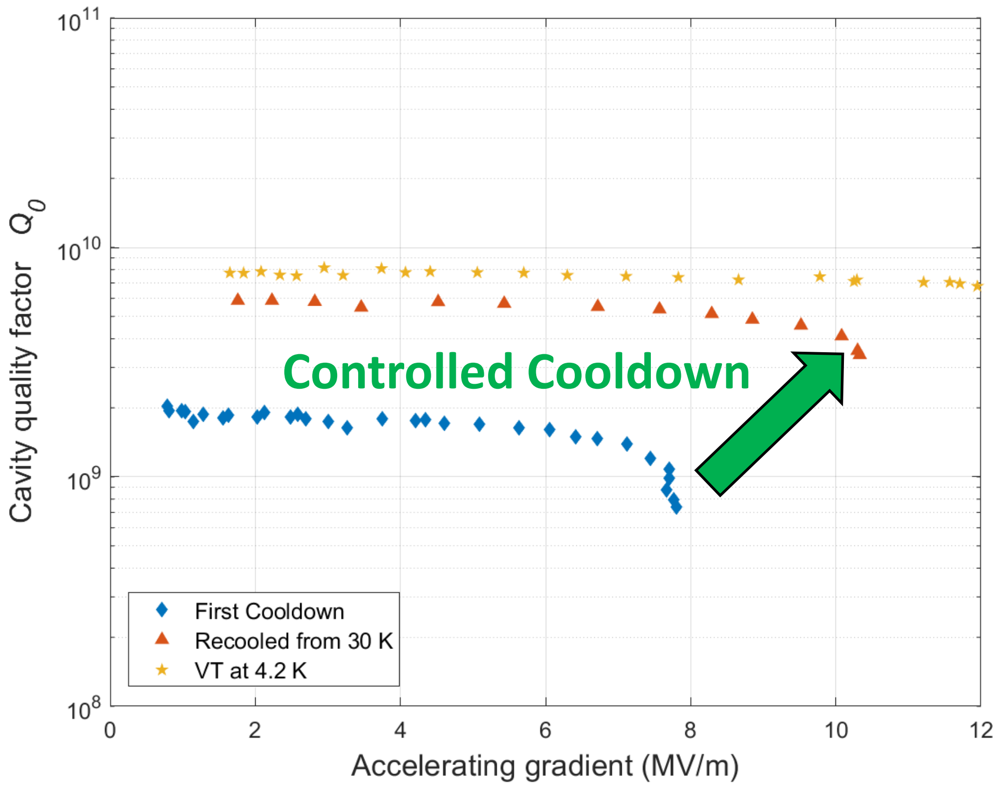


Proof-of-Principle Demonstrations

Initial studies completed at Cornell, Fermilab, JLab: Cornell University

- 2.6 GHz Nb_3Sn cavity
- Beam clamp design for **thermal gradient control**
- **First demonstration** of stable RF operation at **10 MV/m**!
- **Controlled cooldown** required



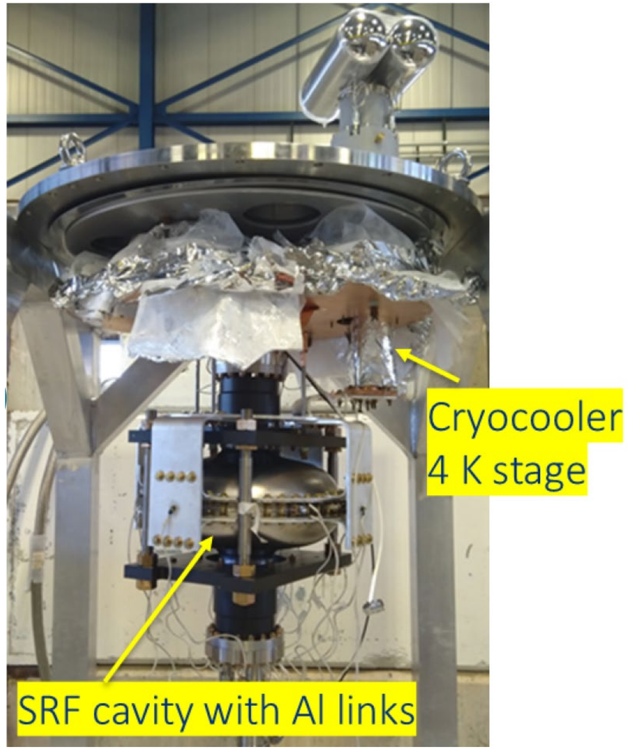


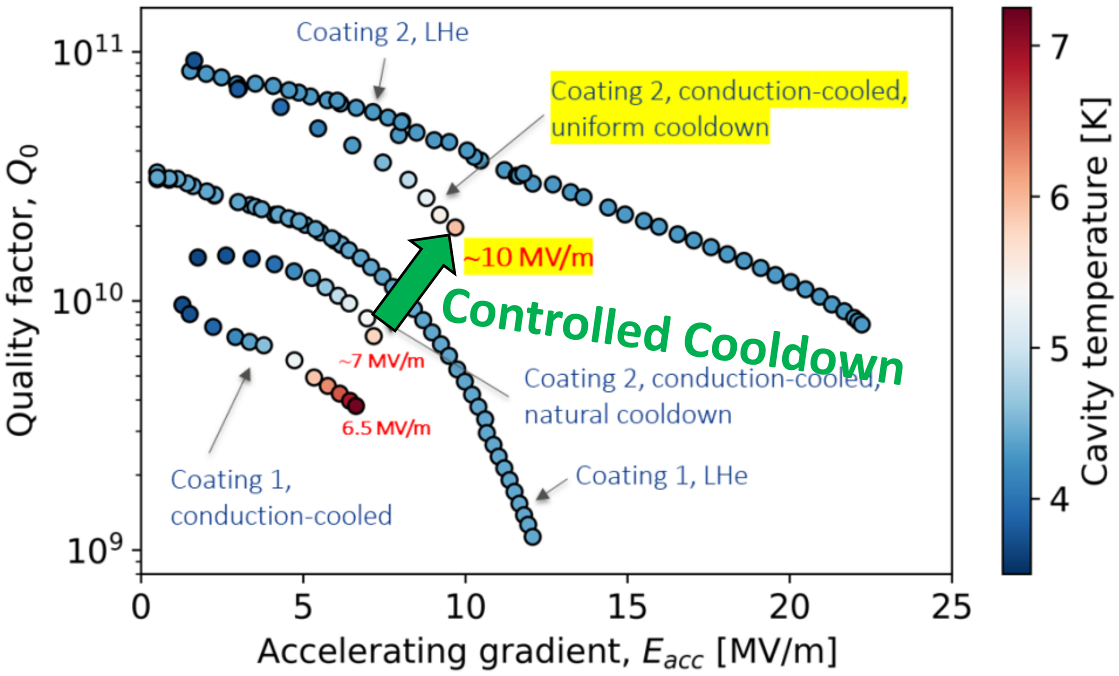
N. Stilin et al, *arXiv:2002.11755v1* (2020)

Proof-of-Principle Demonstrations

Initial studies completed at Cornell, Fermilab, JLab: Fermilab

- 650 MHz Nb_3Sn cavity
- Nb rings welded at equator for heat extraction
- Reached 10 MV/m after **controlled cooldown**



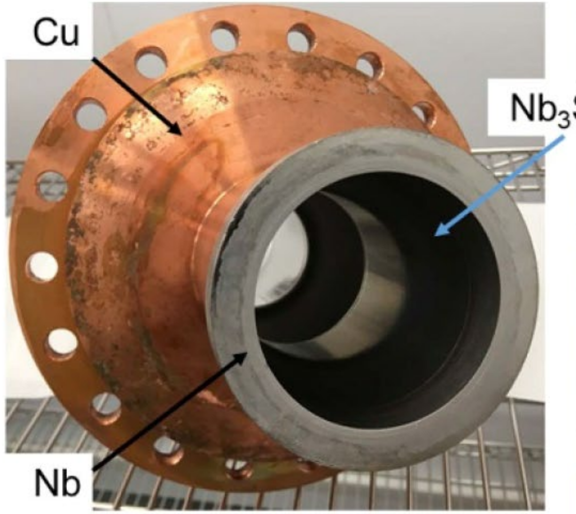


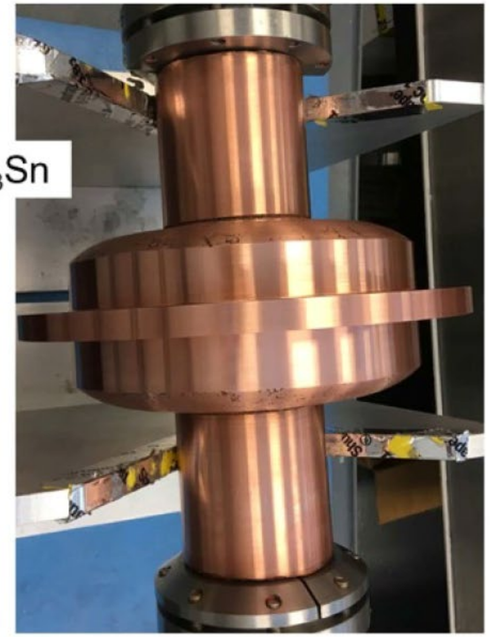
R.C. Dhuley et. al, https://doi.org/10.1088/1757-899X/1240/1/012147

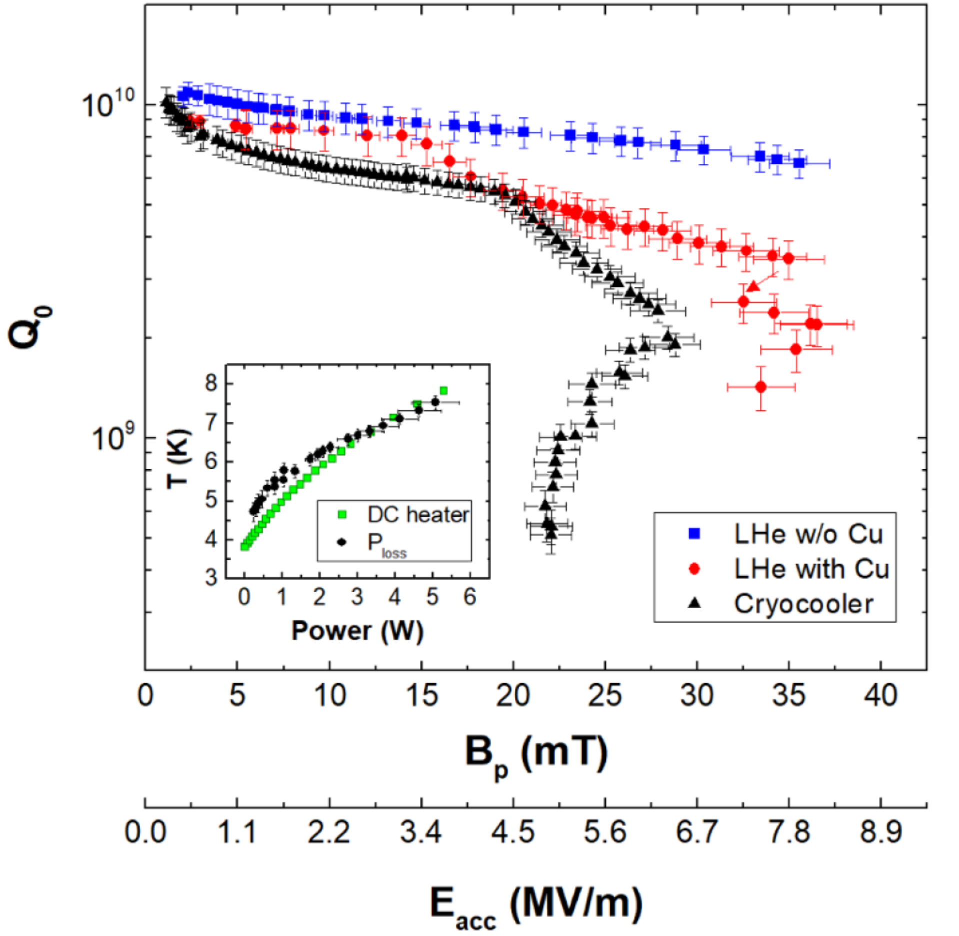
Proof-of-Principle Demonstrations

Initial studies completed at Cornell, Fermilab, JLab: Jefferson Lab

- 1.5 GHz Nb_3Sn cavity
- 5 mm **copper layer electroplated** to cavity exterior
  - Offers better thermal conduction across cavity
- Performance possibly limited by strain on Nb3Sn layer





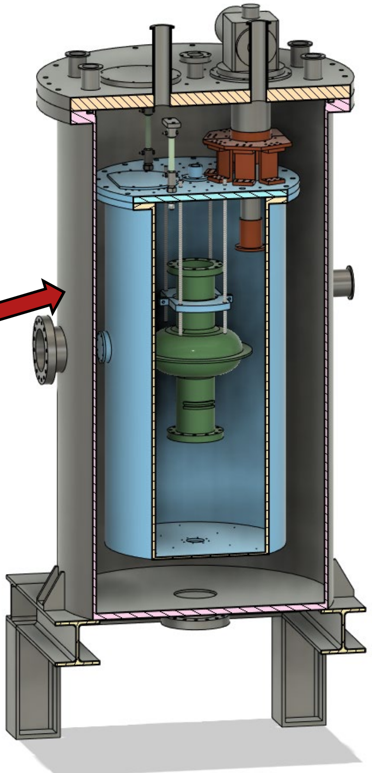


G. Ciovati et. al, https://doi.org/10.1088/1361-6668/ab8d98

Proof-of-Principle Demonstrations

Similar studies ongoing at KEK & IMP:

Cavity cooling test under construction
- Chamber and components were prepared for conduction cooling R&D
- Conduction-cooled high-power test of Nb_3Sn cavity planned at FY2022



Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

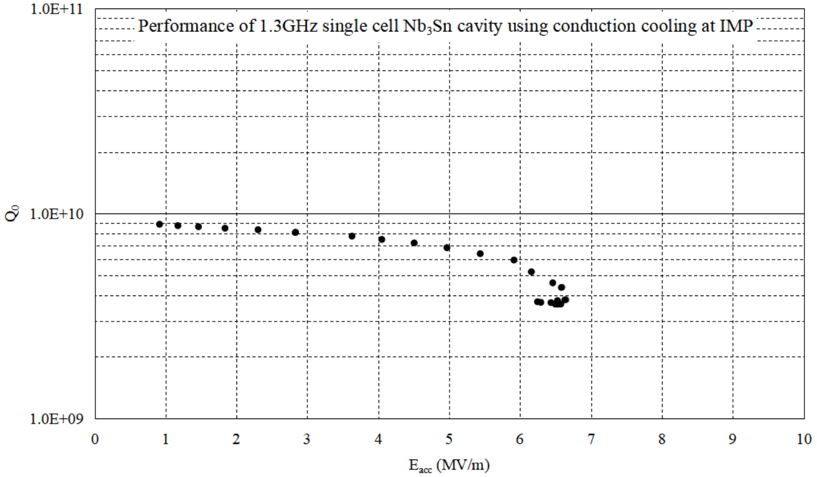
Courtesy of Kensei Umemori

First test performance:
- Q_0 at low field ~9E9
- $E_{acc,max}$ ~6.6 MV/m

Structural optimization and improvement of the conduction cooling is ongoing

Good thermal stability at the dissipation power of below 3.2W

Precise slow-cooling of **2-10min/K**



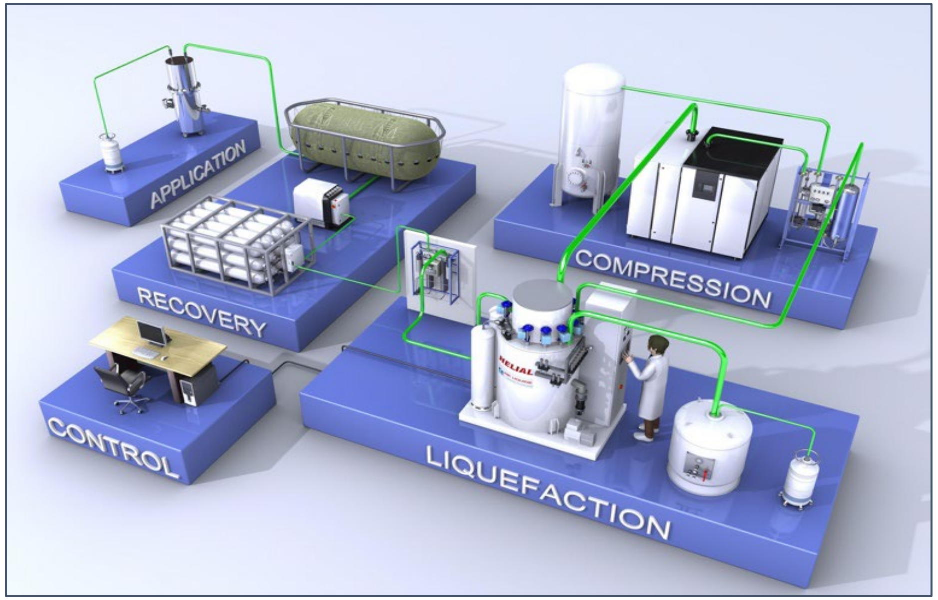
Courtesy of Ziqin Yang

Motivation

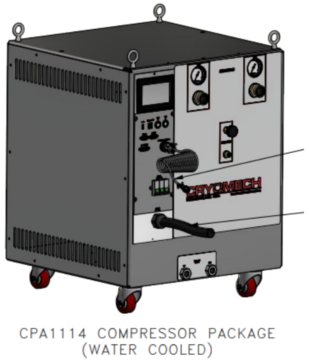
We've shown conduction-cooled cavities are possible… why bother?

→ Makes SRF technology accessible to small-scale operations

Current infrastructure requirements:



Conduction cooling



< 1 meter

Significantly lower costs, very low-maintenance (robust), turn-key operation (no expertise)

Motivation

Applications for small-scale operations:

- **Energy and environment**
  - Sterilizing waste water, sludge, medical waste
  - Flue gas treatment
  - Remediation of contaminated soil
  - Asphalt treatments (durability)
- **Medicine**
  - Radioisotope production
- **Security & defense**
  - Cargo inspection
- **Industry**
  - Producing biofuel
  - Curing carbon fiber composites
- **… and many more!**

Typical beam parameters

- Moderate Energy: 1 – 10 MeV
- High Current: ≥ 100 mA
- High Avg. Power: ≥ 1 MW

Decontamination cross section for a 10 MeV beam into a high-clay-content 5% contaminated soil

U.S. DOE Report, "Accelerators for America's Future"
U.S. DOE Report, "Workshop on Energy and Environmental Applications of Accelerators"

IMPLEMENTATION
Compact Cryomodules

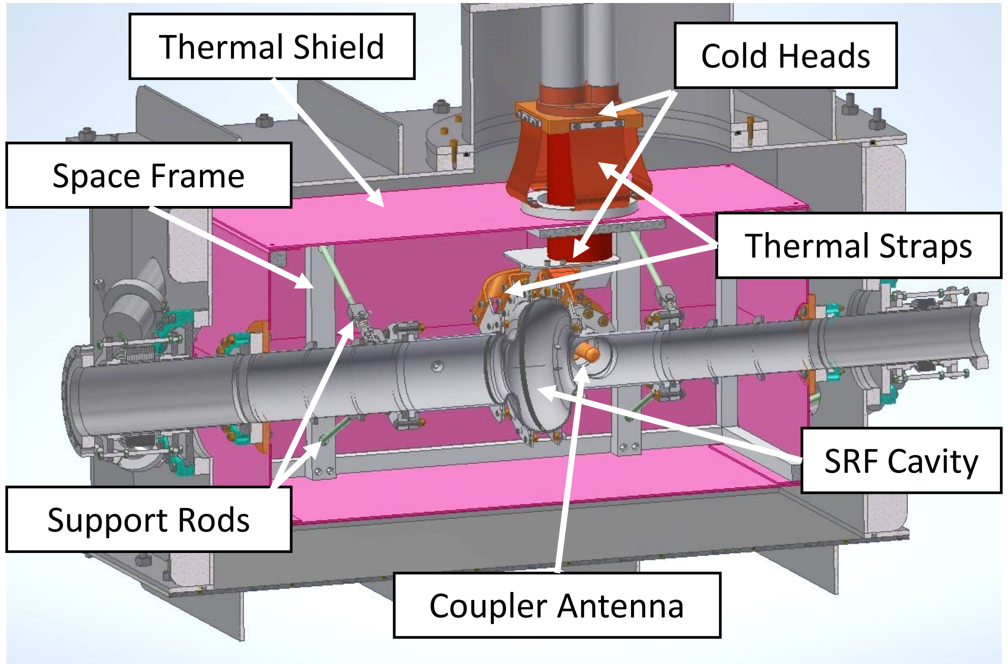
Cornell University

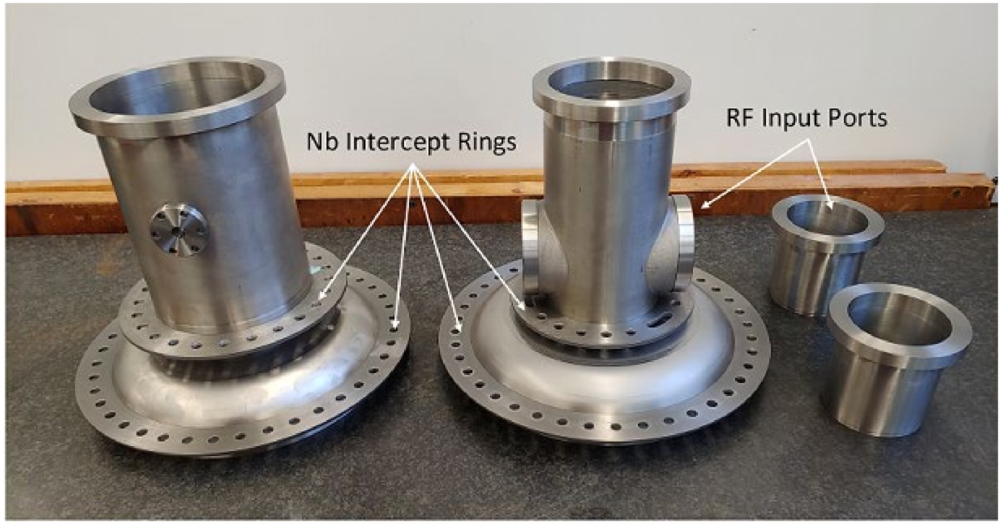
R&D Project – General Application

Beam Current	100 mA
Energy Gain	1 MeV
Average Power	100 kW

- Single-cell 1.3 GHz Nb_3Sn cavity
- Feature: 5N aluminum foil straps at cryocooler connections for flexibility + high thermal conductivity
- **Nb rings** at cavity equator (2) and near cavity irises (2)

- 1 PT420 + 1 PT425 cryocoolers (Cryomech)
  - Total capacity: 4.1 W at 4.2 K and 110 W at 45 K
- **Cavity thermal modelling** shows reasonable heat loads
  - **21.3 W** at 45 K
  - **1.65 W** at 4.2 K



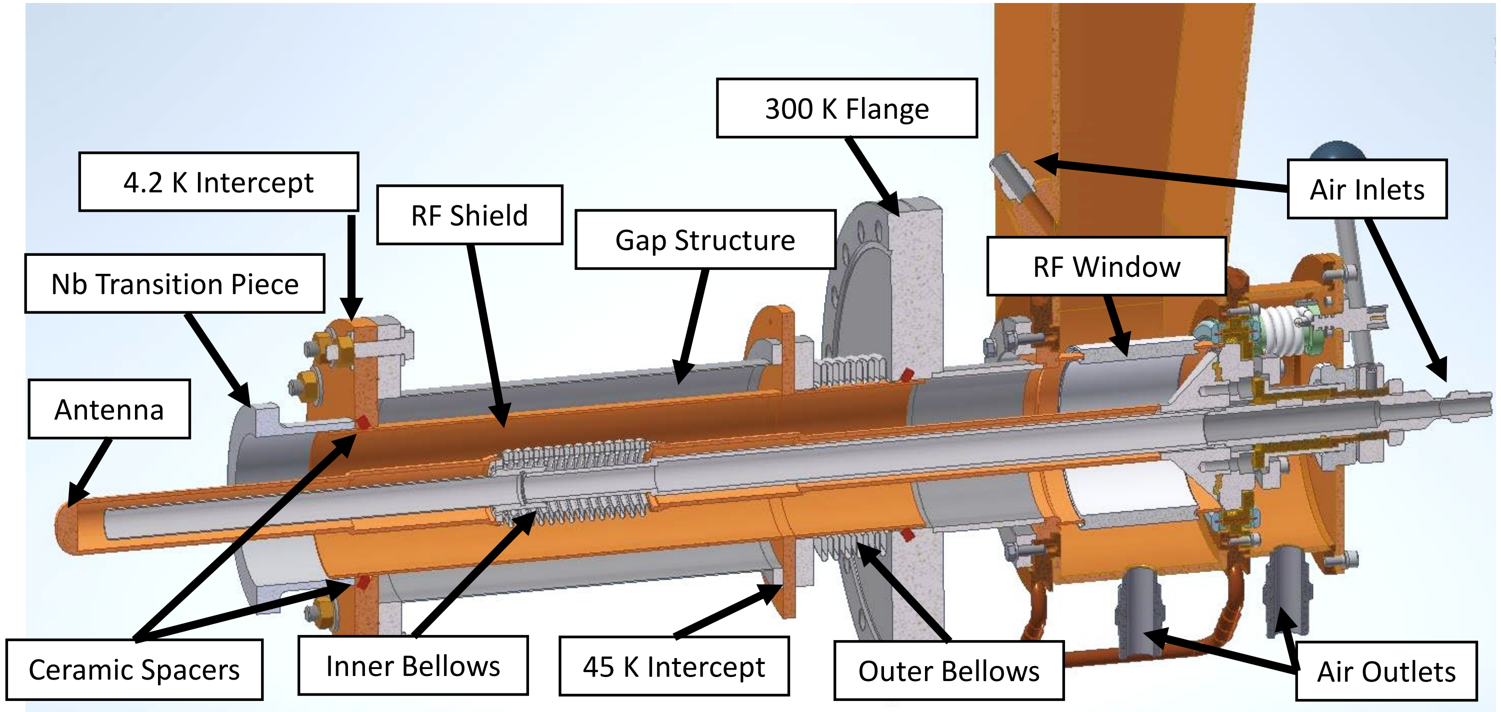


New challenge: implement **simplified high-power input coupler** in a conduction cooling scheme

→ Various design modifications to optimize **heat load distribution** and **reduce cost**

- **Warm RF window** only
- **Copper "RF shield"** reduces heat load at 4.2 K
  - Adapted and further modified from Fermilab design[1]
- **Quarter-wave transformer** at inner bellows achieves < 60 dB reflections

- **Thermal modelling** shows low heat loads
  - **17.49 W** at 45 K
  - **0.16 W** at 4.2 K



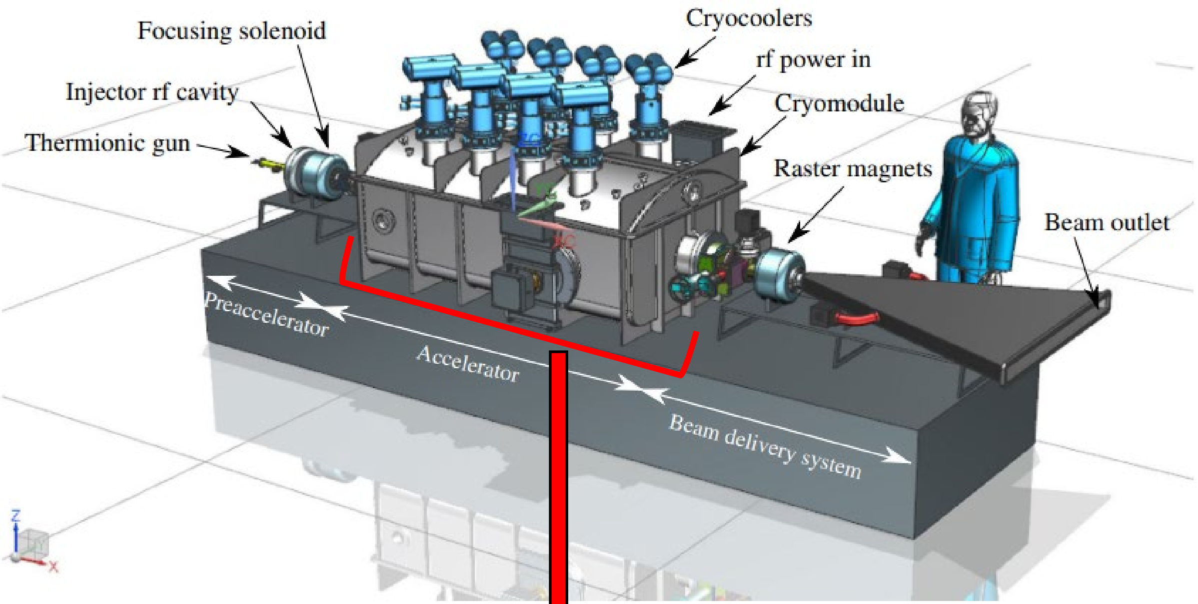
[1]R.C. Dhuley *et al.*, *Phys. Rev. Accel. Beams* **25**, 041601 (2022)

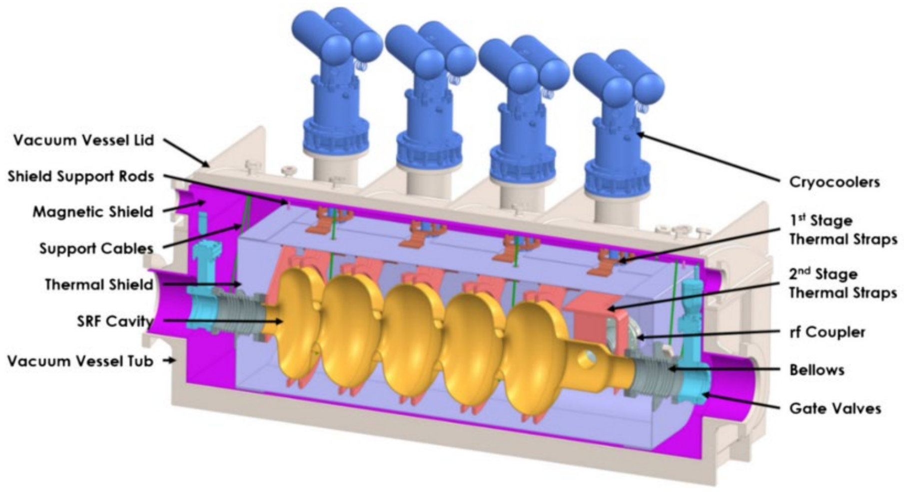
IARC @ Fermilab

Application: Wastewater Treatment

Beam Current	100 mA
Beam Energy	10 MeV
Average Power	1 MW

- Pre-accelerator (RT gun + injector cavity + sol.)
- Accelerating cryomodule
  - 5-cell 650 MHz Nb_3Sn cavity
  - Twin coaxial FPC
  - 6 PT420 + 2 PT425 cryocoolers (Cryomech)
- Beam delivery (raster magnet + beam horn)
- Design: treat up to 12 million gallon / day



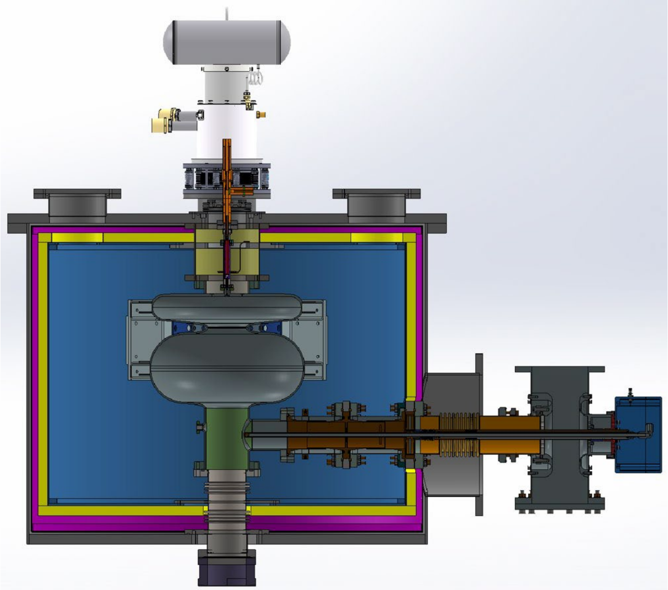


See: R.C. Dhuley *et al.*, *Phys. Rev. Accel. Beams* **25**, 041601 (2022)
"Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications"

IARC @ Fermilab → Core Team: Ram Dhuley, Christopher Edwards, Jayakar Thangaraj, Tom Kroc

Application: Medical Device Sterilization

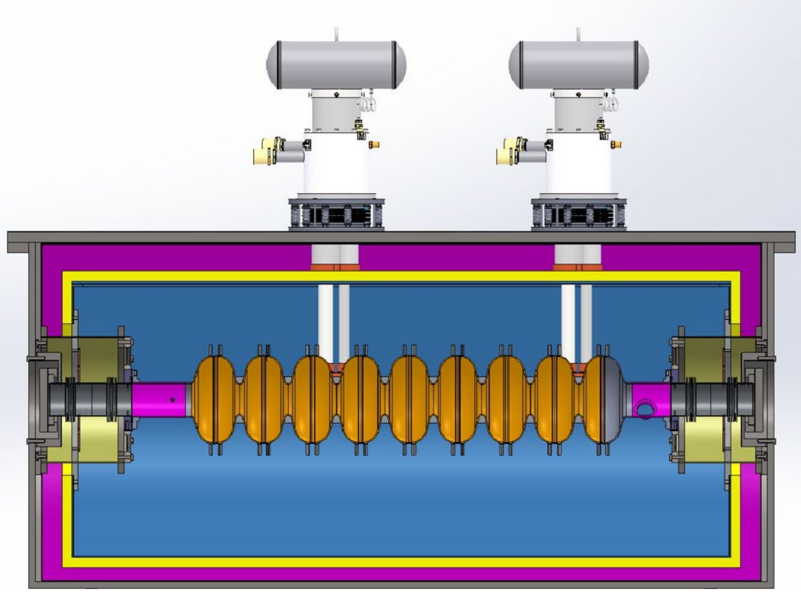
- Beam power: 20 kW
- 1.5-cell 650 MHz Nb_3Sn cavity
- Multi-year funded program, looking to replace Co-60 with accelerator-based ionizing radiation



Cryomodule Design – Tom Nicol

Application: Improved Pavement Processing

- Beam power: 200 kW
- 9-cell 1.3 GHz Nb_3Sn cavity
- Multi-year funded program, interested in the ability to modify pavement in-situ



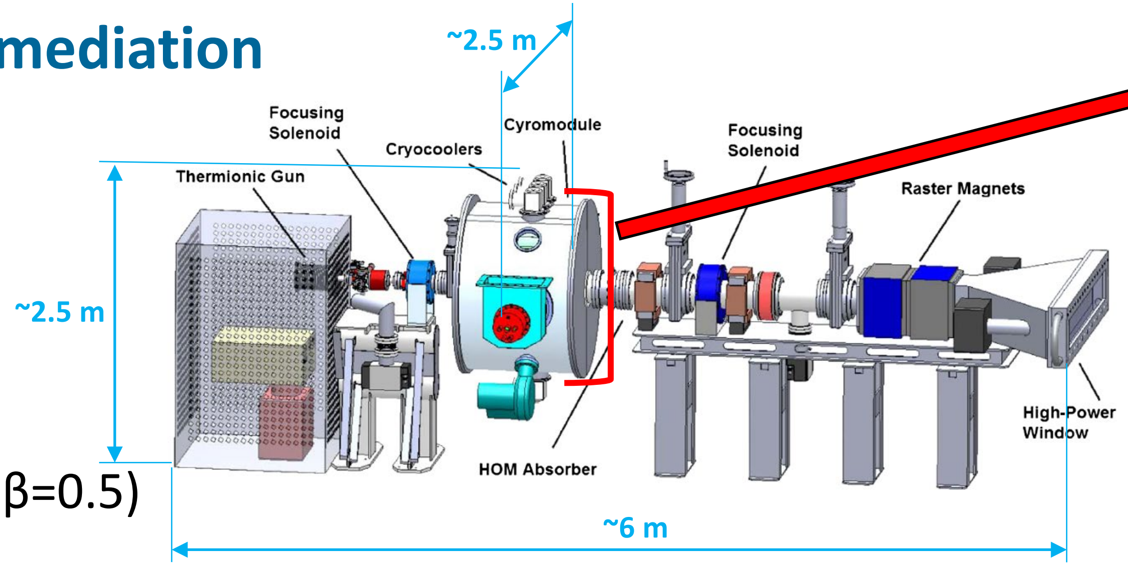
Cryomodule Design – Tom Nicol (under development)

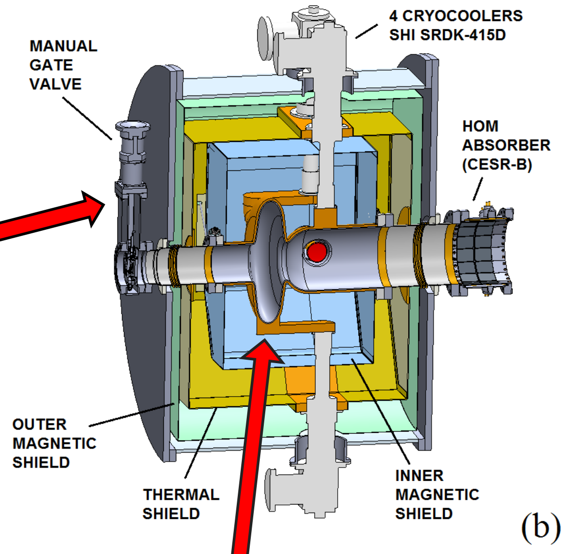
Courtesy of Chris Edwards

Jefferson Lab · GENERAL ATOMICS

Application: Environmental Remediation

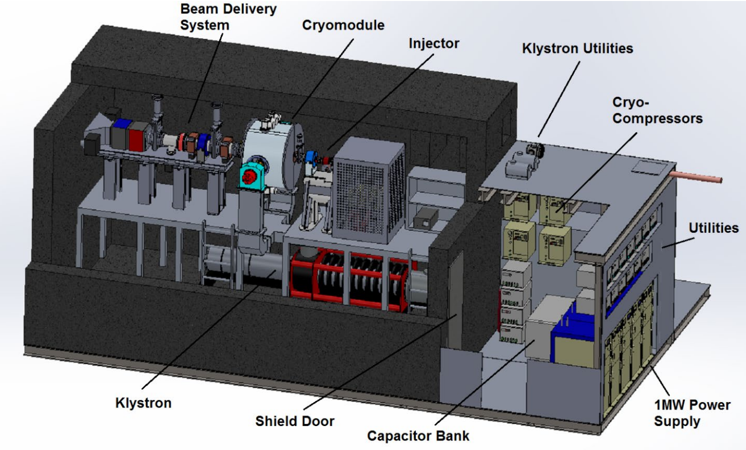
Beam current	1 A
Final energy	1 MeV
Beam power	1 MW





Cu/Nb/Nb_3Sn SRF cavity

- Single-cell 750 MHz Nb_3Sn cavity (β=0.5)
  - Cu electroplated exterior
- Twin coaxial FPC
- 4 GM cryocoolers (each 1.5 W at 4.2 K)
- Beam generation and delivery systems
- Possible use in flue gas treatment



Example of a facility layout using a 1 MW CW commercial klystron

G. Ciovati *et al.*, *Phys. Rev. Accel. Beams* **21**, 091601 (2018)
US Patent 10,932,355 *High-current conduction cooled superconducting radio-frequency cryomodule*

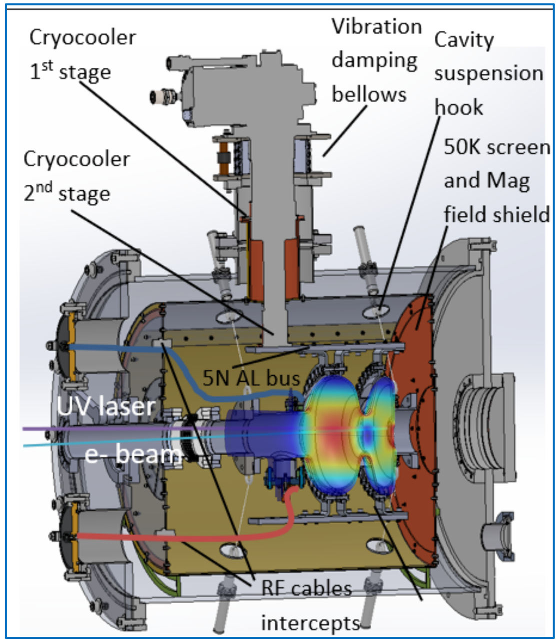
euclid BEAMLABS

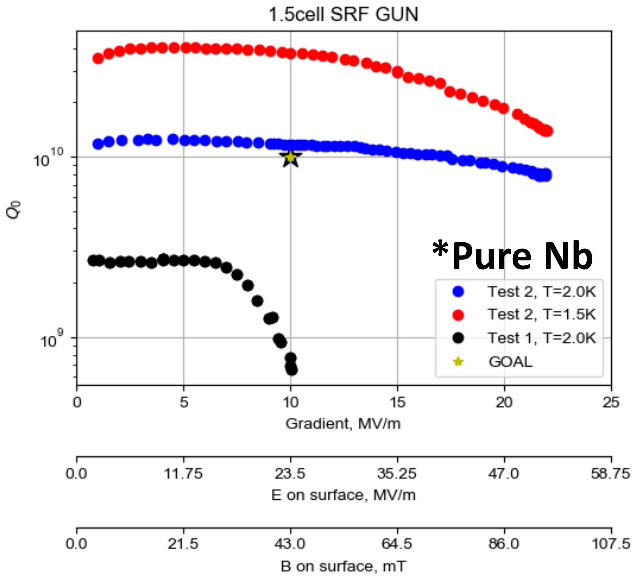
Application: SRF Photogun for MeV UED/UEM

Beam energy	1.655 MeV	1.655 MeV
Charge	5 fC	0.5 pC
Laser pulse length, rms	6.4 fs	6.4 fs
Beam bunch length, rms	167 fs	741 fs

- 1.5-cell 1.3 GHz Nb_3Sn cavity
- One cryocooler is enough to cool Nb3Sn gun at 4K
- Conduction cooling is simple and affordable.
- **Final goal** – user facility at BNL Accelerator Test Facility

- Successful test of pure Nb photogun at 2 K
- 4 K test of Nb_3Sn photogun had low Q_0 and HFQS





Assembled cryomodule

See: R.Kostin et al., "Conduction cooled SRF photogun for UEM/UED applications", UED 308081, 23-rd ATF user meeting, 2020.

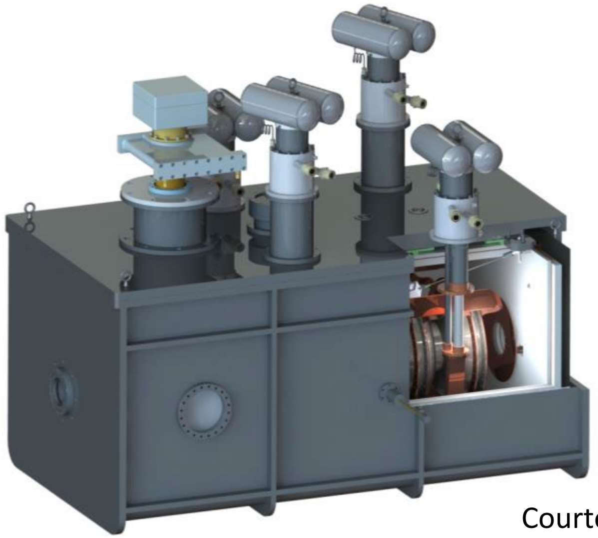
R.Kostin et al., "Status of Conduction Cooled SRF Photogun for UEM/UED", proc. of IPAC21, TUPAB167.

*DoE SBIR Phase II Grant #DE-SC0018621

RadiaBeam + IARC Fermilab

Application: Deployable Conductively Cooled Cryostat

- Small, mobile cryostat with no cryoplant requirement
- Target design: 4.5-cell 650 MHz Nb_3Sn Cavity
- Utilizes 4 PT420 cryocoolers (Cryomech)
- Currently in fabrication to test with a single-cell 650 MHz cavity in the last quarter of this year



Courtesy of Sergey Kutsaev

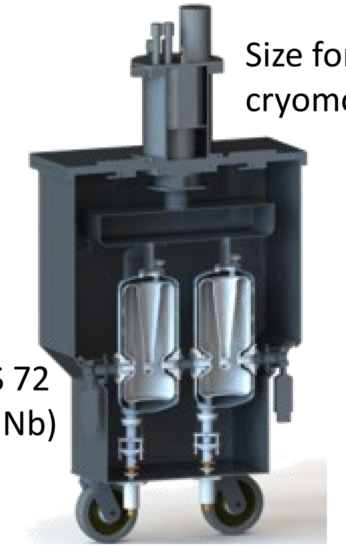
RadiaBeam Argonne NATIONAL LABORATORY Fermilab

Application: Standalone Cryomodule for SC Nb_3Sn QWRs

- Current QWRs for ion linacs are ~ 1 m long
- Nb_3Sn enables higher frequency (small) & lower loss
- ATLAS upgrades, medical isotope production

218 MHz cavity (Nb_3Sn)

ATLAS 72 MHz (Nb)



Size for a two-cavity cryomodule (218 MHz)

Courtesy of Mike Kelly

SUMMARY

Summary

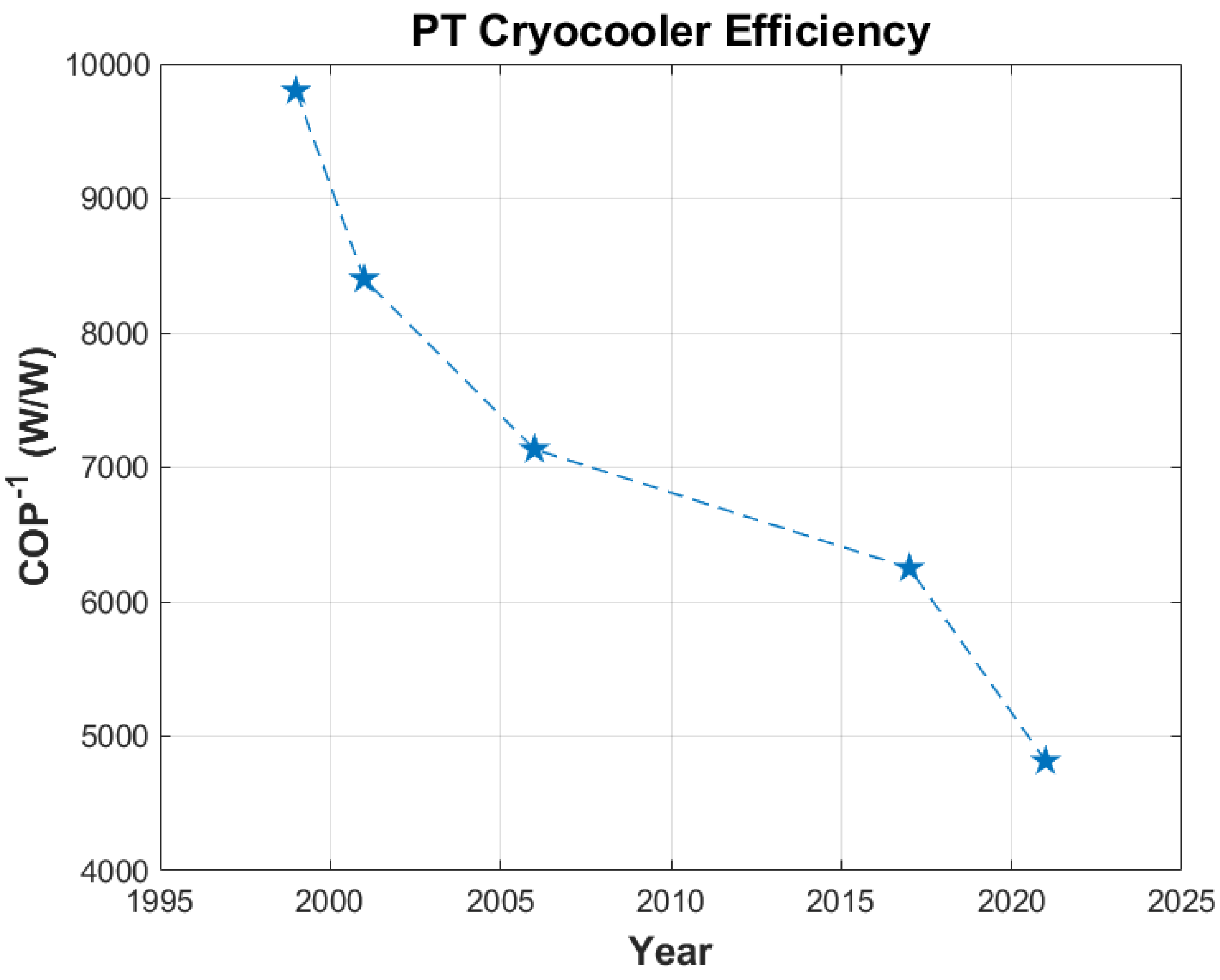
- Highly efficient Nb_3Sn cavities + simple, robust cryocoolers = **compact cryomodules**
- Successful demonstrations of this concept have been completed at multiple labs
  - More are on the way around the world
- Several projects are underway to fully develop compact cryomodules
  - Designed to address various applications in different fields
- **Bright future for this technology**!

Thank you to the following people for their significant contributions:

Fermilab: Grigory Eremeev, Sam Posen, Ram Dhuley, Christopher Edwards, Jayakar Thangaraj, and Tom Kroc
Jefferson Lab: Gigi Ciovati
KEK: Kensei Umemori
IMP: Ziqin Yang
Euclid: Roman Kostin
RadiaBeam: Sergey Kustaev
Argonne: Mike Kelly

Thank you for your attention!

Extra: Cryo Efficiency



- Not nearly as efficient as large cryoplants
  - Compare to 200 – 800 W/W (COP^{-1})
  - Only intended for small-scale use

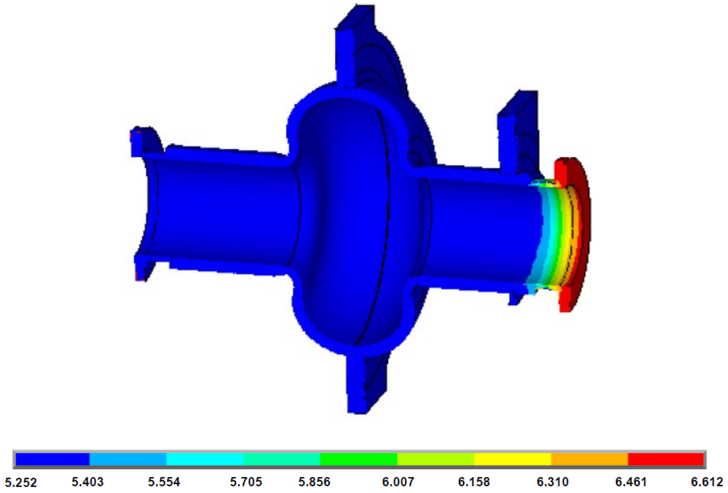
Extra: JLab prototype

Prototype conduction-cooled single-cell SRF cavity

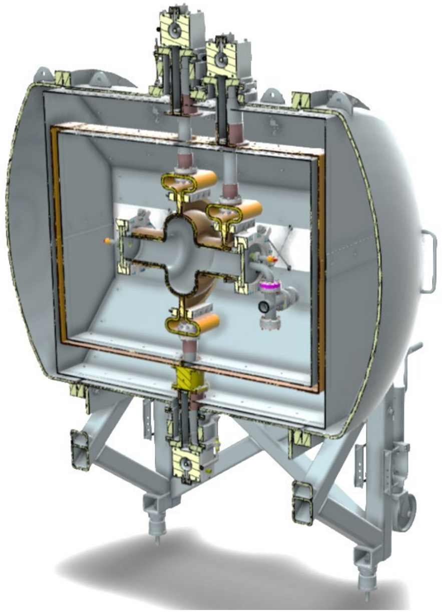
Jefferson Lab
Thomas Jefferson National Accelerator Facility

GENERAL ATOMICS

952 MHz $Cu/Nb/Nb_3Sn$ cavity



FE thermal analysis with RF heat + 6 W on one end + 1 W uniformly distributed



The cavity will be tested in a cryostat at General Atomics in 2022

Courtesy of Gigi Ciovati