Compact, High-Power Superconducting Electron Linear Accelerators for MW Industrial Applications

Jayakar ‘Charles’ Thangaraj on behalf of IARC@Fermilab

FERMILAB-SLIDES-22-116-DI-TD

Motivation: Taking SRF accelerator outside the "lab"

SRF for
basic science

⇒

SRF for
industry & society

- SRF relevant Industrial applications of particle accelerators? (Market pull)
- How to make SRF suitable for industrial settings? (Technology push: This talk)

Courtesy: R.Dhuley, FNAL

SRF accelerators – applications landscape

Current usage dominated by basic research needs: colliders, FELs, proton and neutron sources

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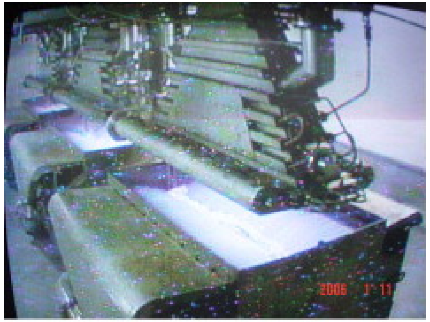
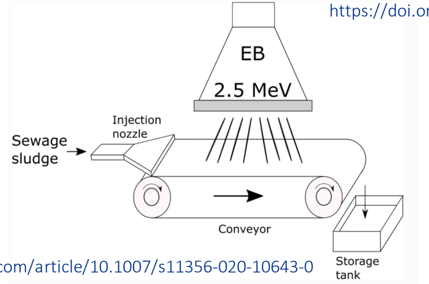
ess LCLS-II PIP-II

European XFEL ilc FRIB

Potential industrial applications: e-beam radiation treatment of flue gases, municipal/industrial wastewater, sewage



https://doi.org/10.1016/j.radphyschem.2012.01.030



https://link.springer.com/article/10.1007/s11356-020-10643-0

Constraints: Industrial applications and scope of SRF accelerators

Electron beam radiation processing applications

- Water/sludge/medical waste decontamination
- Flue gas cleanup
- Medical device sterilization
- Strengthening of asphalt pavements

Radiation processing requires:

- Beam energy: 0.5-10 MeV
- Beam power: >>100 kW

Industrial settings demand:

- Low capital and operating expense
- Robust, reliable, turnkey operation

http://accelconf.web.cern.ch/AccelConf/napac2016/talks/thb3io02_talk.pdf

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1-meter long SRF linac (niobium or Nb_3Sn cavities) operating at 10 MV/m can provide the required energy

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Small SRF surface resistance enables continuous wave (cw) operation, leading to high average beam power

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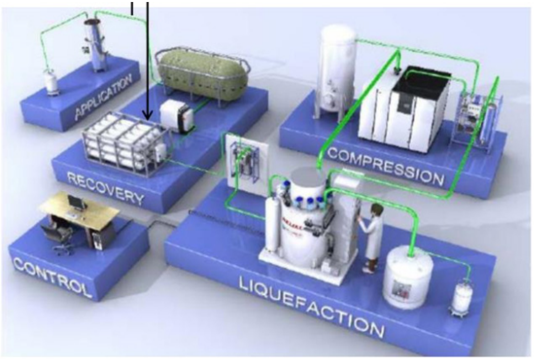
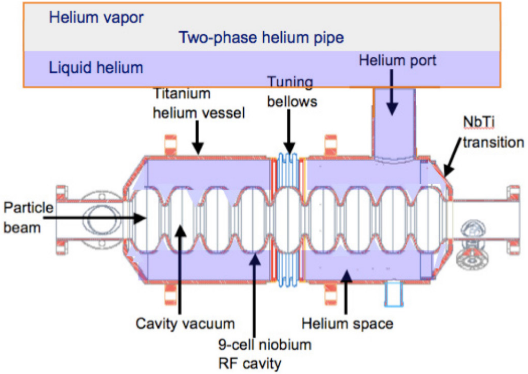
At present, SRF accelerators are designed to operate with complex liquid helium cryogenic systems!





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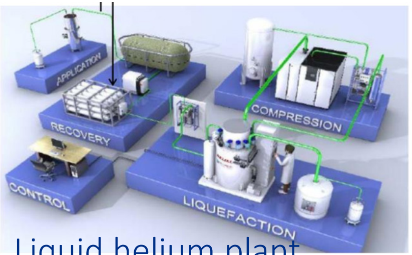
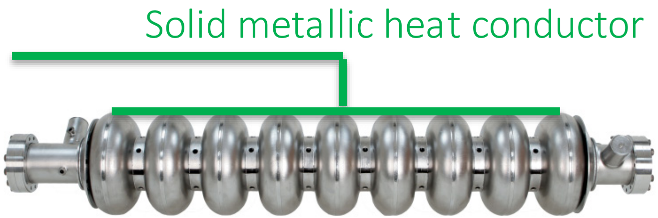
Simplifying SRF cryogenics for industrial settings

Remove cavity dissipation ***with*** thermal conduction ("conduction cooling")

(conventional liquid helium bath not required)



Liquid helium plant



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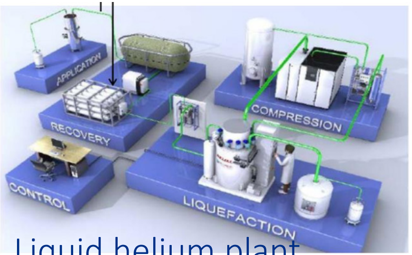

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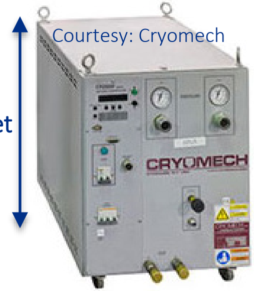
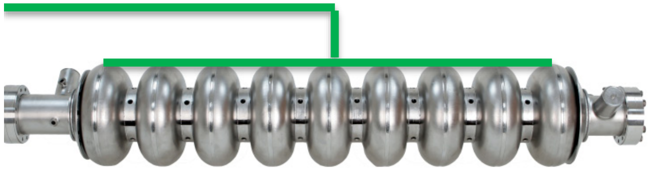


Compressor

Cryocooler



Absence of cryogenic liquids

- Compact, simplified construction
- No pressure vessel safety concerns
- Facilitates deployment in remote locations

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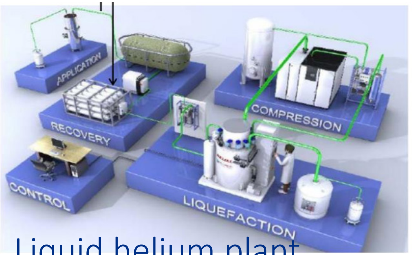

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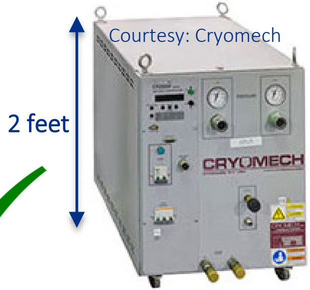

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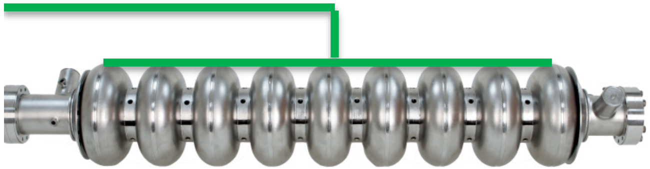

Cryocoolers offer

- Closed cycle cooling at ~45 K and ~4 K
- Compact, small footprint
- Reliability (MTBM > 2 years non-stop operation)
- Turnkey operation (no trained operator needed, turn ON/OFF with push of a button)

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Modern Technology Breakthroughs:

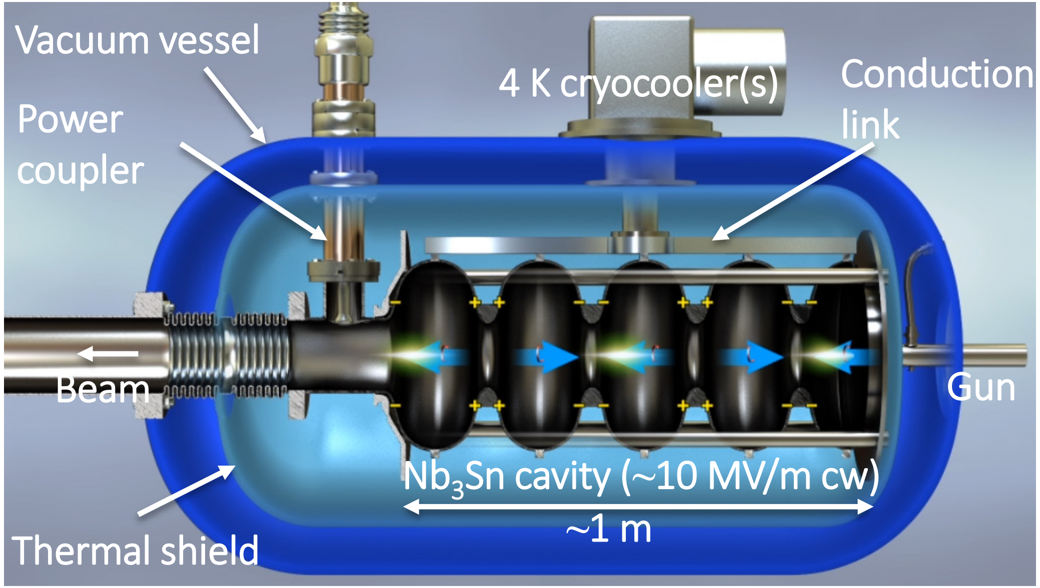
- Higher temperature superconductors: Nb_3Sn coated cavities dramatically lower cryogenic losses and allow higher operating temperatures (e.g. 4 K vs 1.8 K)
- Cryocooler Conduction Cooling: possible with low cavity losses➔ dramatically simplifies cryostats (no Liquid Helium !) using commercial cryocooler with higher capacity at 4 K enables turn-key cryogenic systems
- New RF Power technology: injection-locked magnetrons allow phase/amplitude control at high efficiency and much lower cost per watt
- Low-loss coupler: Couplers that dissipate very low heat while transporting high power
- Integrated electron guns: reduce accelerator complexity

- **Enable compact industrial SRF accelerators at a low cost**

Fermilab vision for SRF industrial accelerators

Vision: Develop compact, turnkey e-beam source for environmental and industrial applications (~10 MeV, >>100 kW)

R.D. Kephart, *SRF2015*. https://accelconf.web.cern.ch/srf2015/papers/frba03.pdf
Patents: US10390419B2, US10070509B2, US9642239B2



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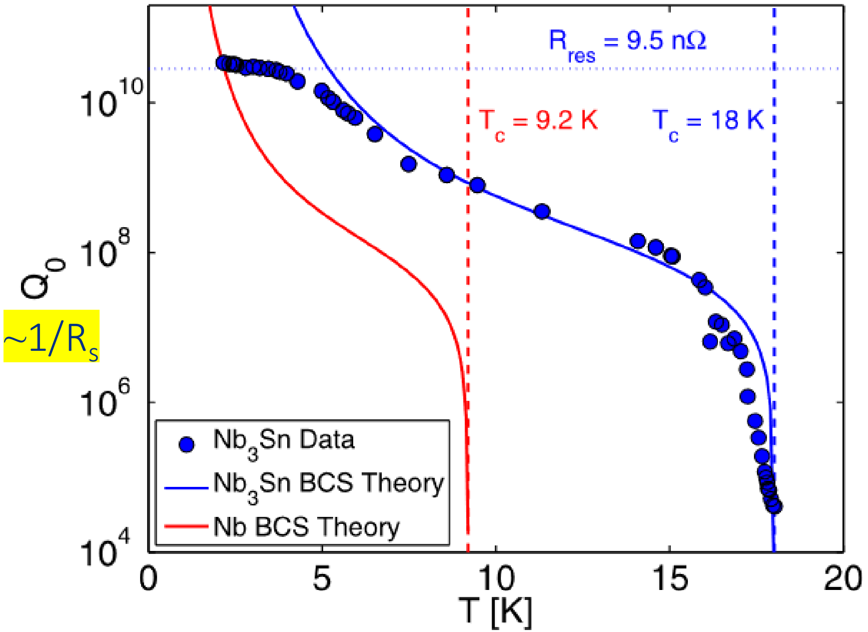
Nb_3Sn cavities dramatically changes the game

Nb_3Sn cavity with 10 MeV dissipates ~10 W @ ~4.5 K (1 m x 10 MV/m cw; 650 MHz/1.3 GHz)

Use commercial, off-the-shelf 4 K cryocoolers (helium plant not required)

~1/R_s



S. Posen et al., Appl. Phys. Lett. 106, 082601 (2015)

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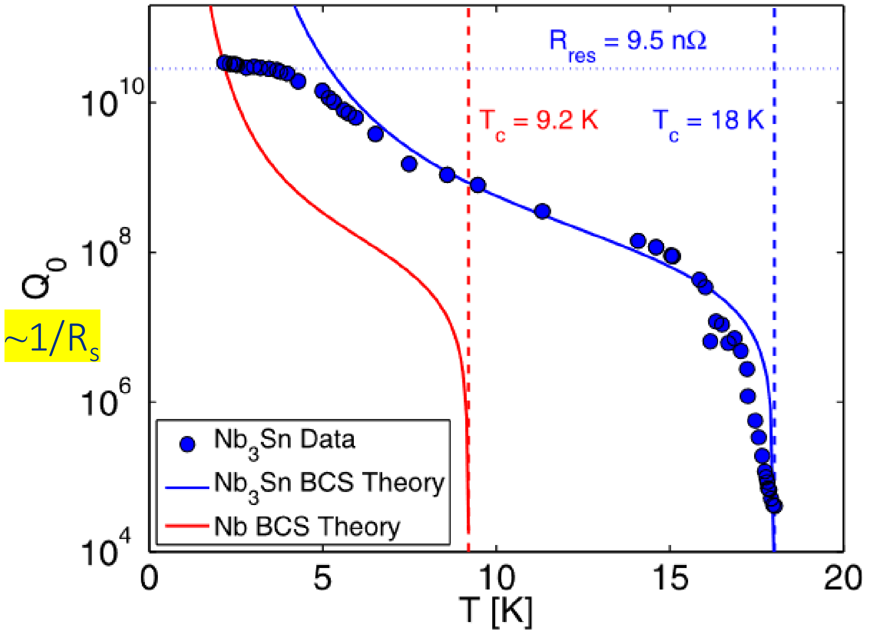

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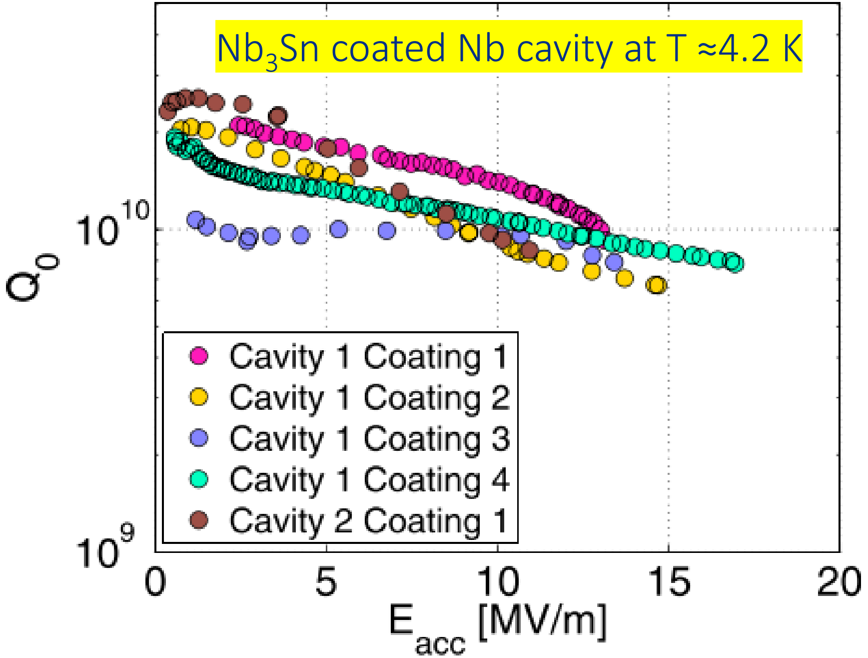


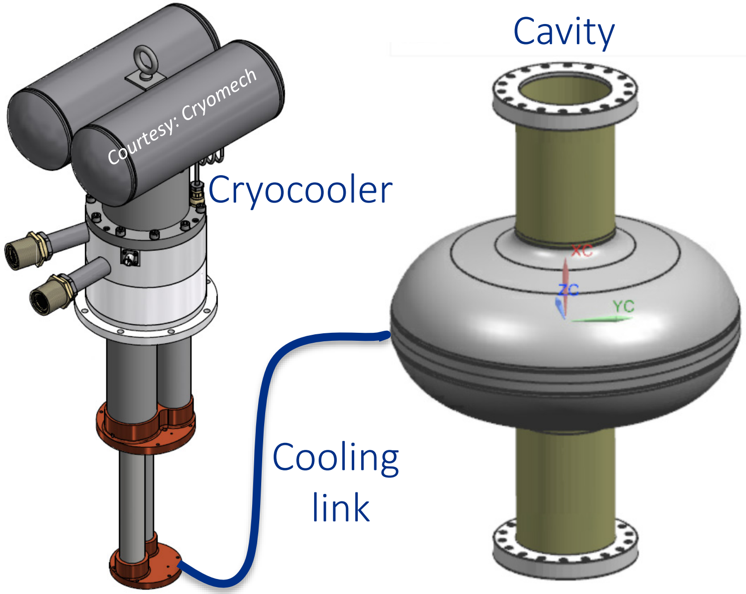
S. Posen et al., Appl. Phys. Lett. 106, 082601 (2015)

Conduction cooled Nb_3Sn SRF development

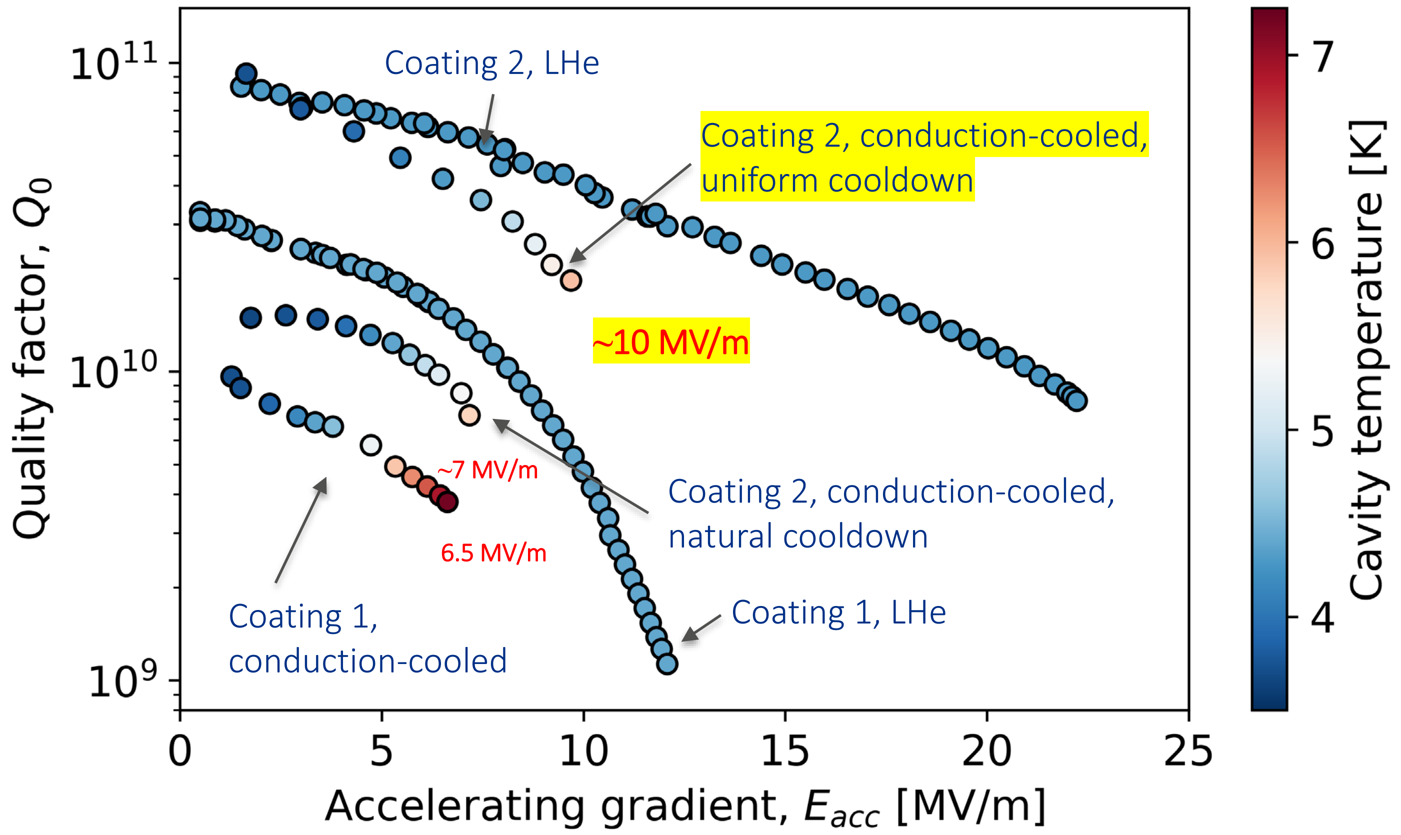
Goal: demonstrate 10 MV/m cw on an Nb_3Sn cavity with cryocooler conduction cooling

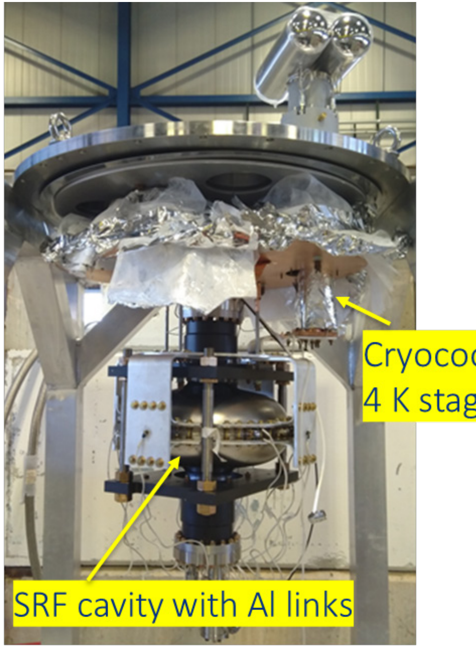
Our choice:

- Single cell 650 MHz, Nb_3Sn coated niobium cavity
- Cryomech PT420 cryocooler (2 W @ 4.2 K with 55 W @ 45 K)
- High purity aluminum for the conduction cooling link



Recent results with Nb_3Sn coating (R.C. Dhuley arXiv:2108.09397v1)





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A new frontier in SRF is simplifying the cooling methods!

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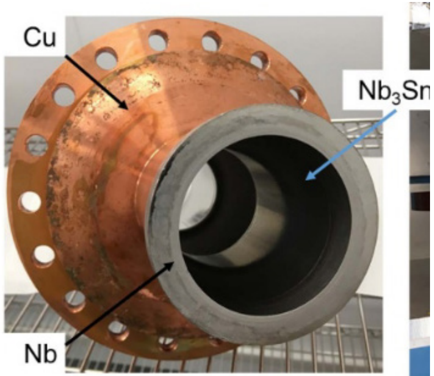
- 650 MHz
- welded niobium rings

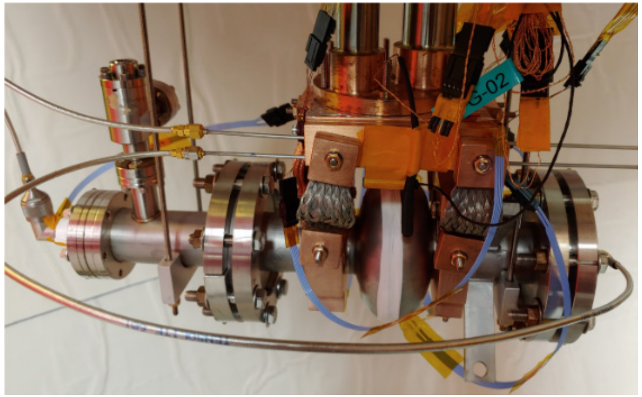
Jefferson Lab



https://doi.org/10.1088/1757-899X/755/1/012136

- 1.5 GHz
- Cold sprayed + electrodeposited copper

Cornell University



https://arxiv.org/abs/2002.11755

- 2.6 GHz
- Copper clamps

Design and development of e-beam accelerator based on conduction-cooled SRF cavities

- Design studies for a 10 MeV, 1000 kW accelerator
- Building a prototype of a ~1.6 MeV, ~20 kW accelerator

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Design and economics studies of industrial scale SRF electron accelerators (10 MeV, >>100 kW)

Supported by US Dept. of Energy HEP Accelerator Stewardship Program

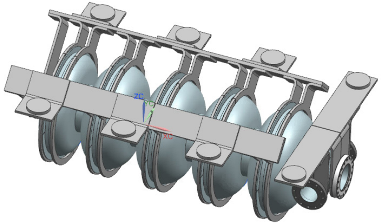
Phase (year) / Fermilab PI	Activity	Stewardship partner
I (2016-17) / R.D. Kephart	Conceptual design of a 250 kW and economic analysis of a 1 MW facility	MWRD of Greater Chicago
II (2017-18) / J.C.T. Thangaraj	Conceptual design of a 1 MW module and economic analysis of a 10 MW facility	
(2019-2022) / R.C. Dhuley	Practical cryogenic design and cost analysis of a 1 MW module (PRAB 2022)	General Atomics

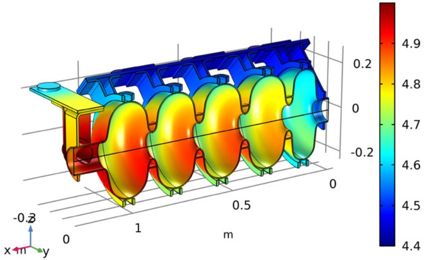
Design reports available at: https://iarc.fnal.gov/publications/

Design of a 10 MeV, 100 mA e-beam accelerator

- ✓ RF design of a 5-cell 650 MHz cavity
- ✓ Beam transport simulations (external injection 300 keV → 10 MeV)
- ✓ Calculation of 4 K heat load, cryocooler selection
- ✓ Design and thermal simulations of conduction link
- ✓ Cryostat design and integration (thermal and magnetic shield, vacuum vessel, couplers)
- ✓ Cost assessment of the 10 MeV accelerating module

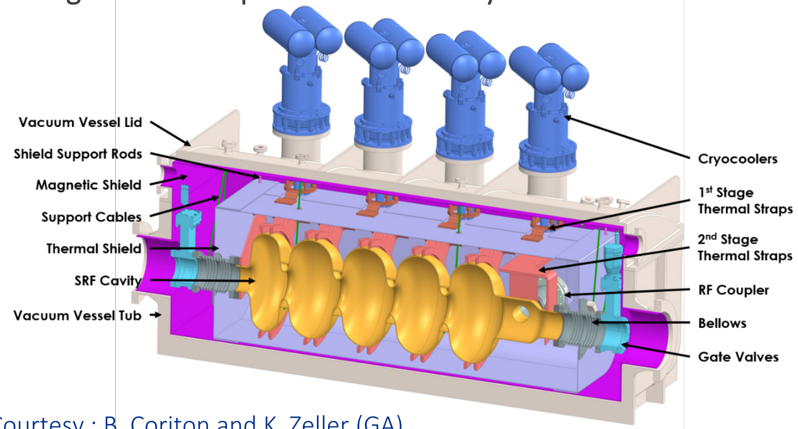
Design and multiphysics simulation of a conduction-cooled 5-cell SRF cavity





Courtesy : R. Kostin (Euclid Techlabs)

Design of the complete accelerator cryomodule



Courtesy : B. Coriton and K. Zeller (GA)

Cost economics for wastewater application

Capital Investment	
Entire SRF accelerator system	$5.13M
Infrastructure	$3.00M
Investment (20%)	$1.63M
Amortization (15 yrs @ 8%)	$760k
Operating Cost	
Power ($/W)	$162 /hr
Maintenance	$163k /yr
Total operating cost	$278 /hr
Processing Cost (¢/ton/kGy)	13.5

Cost of a SRF module	5,134
1 MW RF Power Source [13]	**3,200**
Cryomodule	**1,554**
Cryocoolers w/ He Compressors	492
650MHz Nb_3Sn Cavity	402
RF Couplers	282
Vacuum Vessel	100
Beamline (HOM, Bellows, Valves)	104
Auxiliary Hardware (Chillers, Pumps)	93
Magnetic Shield	65
Thermal Shield	16
Electron Injector	**217**
Beam Delivery System	**125**
Beam Diagnostics & Controls	**38**

Fixed cost: At 1 MW, the fixed cost is dictated by the RF source.
SRF cryomodule cost is $1.55 per watt of beam power

Variable cost: At 1 MW, the processing cost is proportional to the electrical cost. Efficient RF sources can reduce processing costs. Magnetrons can bring the cost to <10 (¢/ton/kGy).

Total cost: Dose of 1kGy @ 12 MGD per day. Capital cost=$8/W

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 041601 (2022)

Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications

R. C. Dhuley,* I. Gonin, S. Kazakov, T. Khabiboulline, A. Sukhanov, V. Yakovlev, A. Saini, N. Solyak, A. Sauers, and J. C. T. Thangaraj
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

K. Zeller and B. Coriton
General Atomics, San Diego, California 92186, USA

R. Kostin
Euclid Techlabs, LLC, Bolingbrook, Illinois 60440, USA

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Emerging Application where SRF can play a game changing role

Warning: Most of this at R&"D" SRF Tech and customer/application expectations should be kept in focus

VERY VERY IMP Questions to always ask yourself:

What is the cost economics? What type of cost? CAPEX or OPEX?

What is the business model?

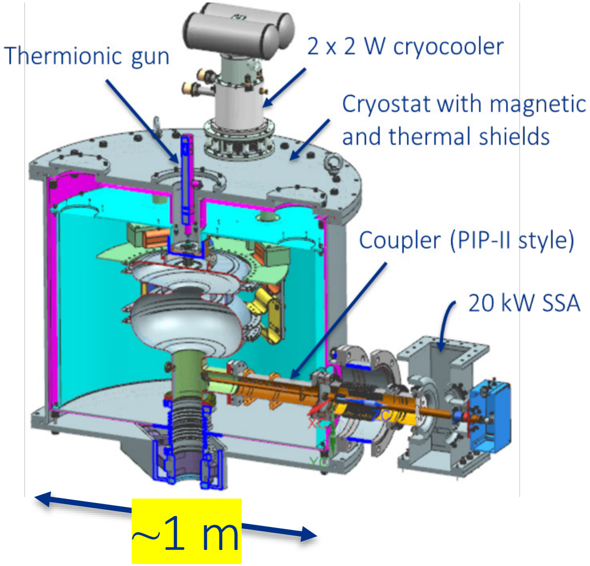
What are the TRLs and trends? Where is the cost driver?

What is the customer willing to pay for? Regulatory challenges?

Safety and redundancy for a certain application? Portability etc.

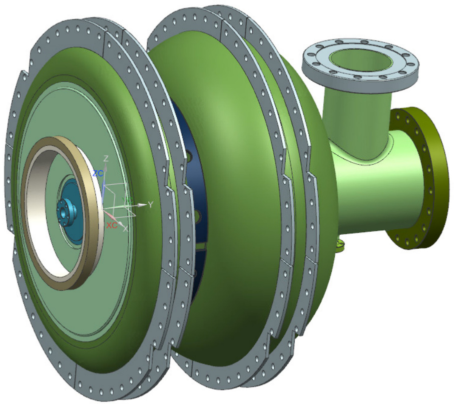
Goal: Component production, integration, and demo of a 1.6 MeV, 20 kW accelerator

Cryostat assembly



20 kW Solid State RF Amplifier

650 MHz Nb_3Sn cavity (Cryoload ≈3.8 W @ 5 K)



Cryomech PT420 coolers

Future Accelerator Applications

Energy and Environment

- Treat Municipal Waste & Sludge
  - *Eliminate pathogens in sludge*
  - *Destroy organics, and pharmaceuticals in wastewater*
- In-situ environmental remediation

Industrial and Security

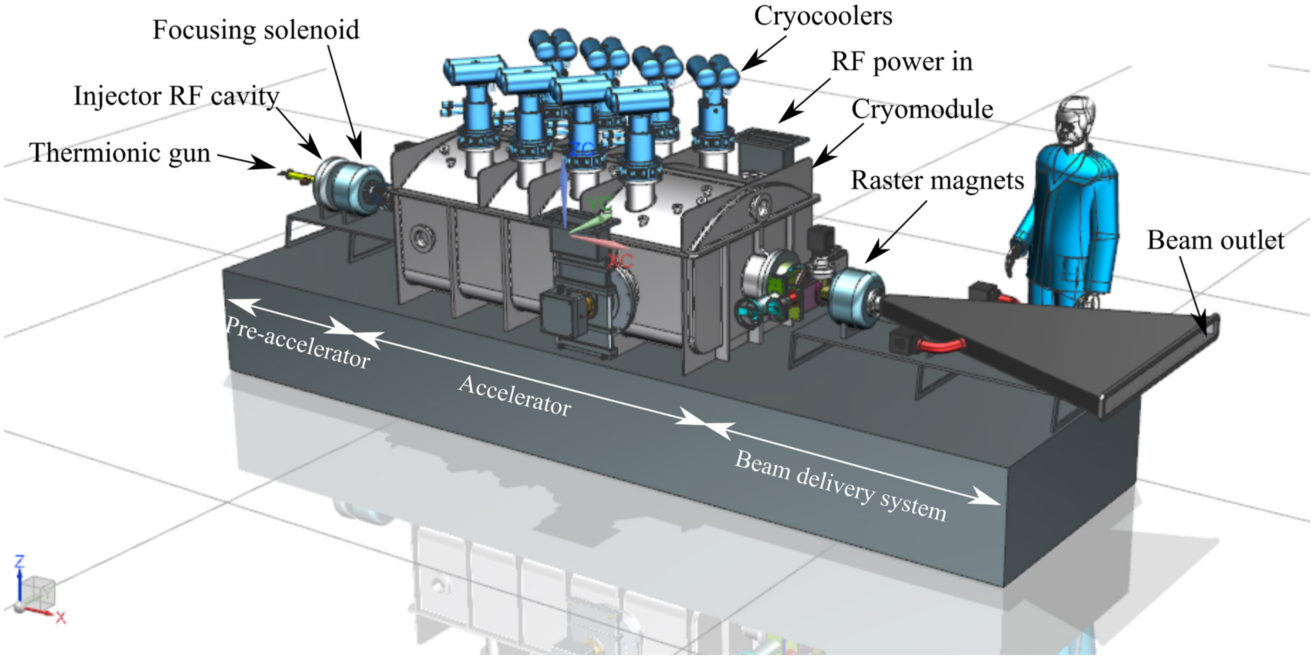
- In-situ cross-link of materials
  - Improve pavement lifetime
  - Instant cure coatings
- Medical sterilization without Co60

These new applications need cost effective, energy efficient, high average power electron beams.

New technology can enable new applications (including mobile apps)

Summary and outlook

SRF accelerators for industrial applications push innovation, open new applications with enormous R&D opportunities



2 m x 2 m x 4 m

Part of work funded by an Accelerator Stewardship grant to Fermilab by U.S. DOE, Office of Science, OHEP. Thanks to collaborators in General Atomics (San Diego, CA) and Euclid TechLabs (Bolingbrook, IL).

Thanks for your attention!