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SRF accelerators for industrial applications: USPAS Lecture 2021

Jayakar “Charles” Thangaraj , Fermilab

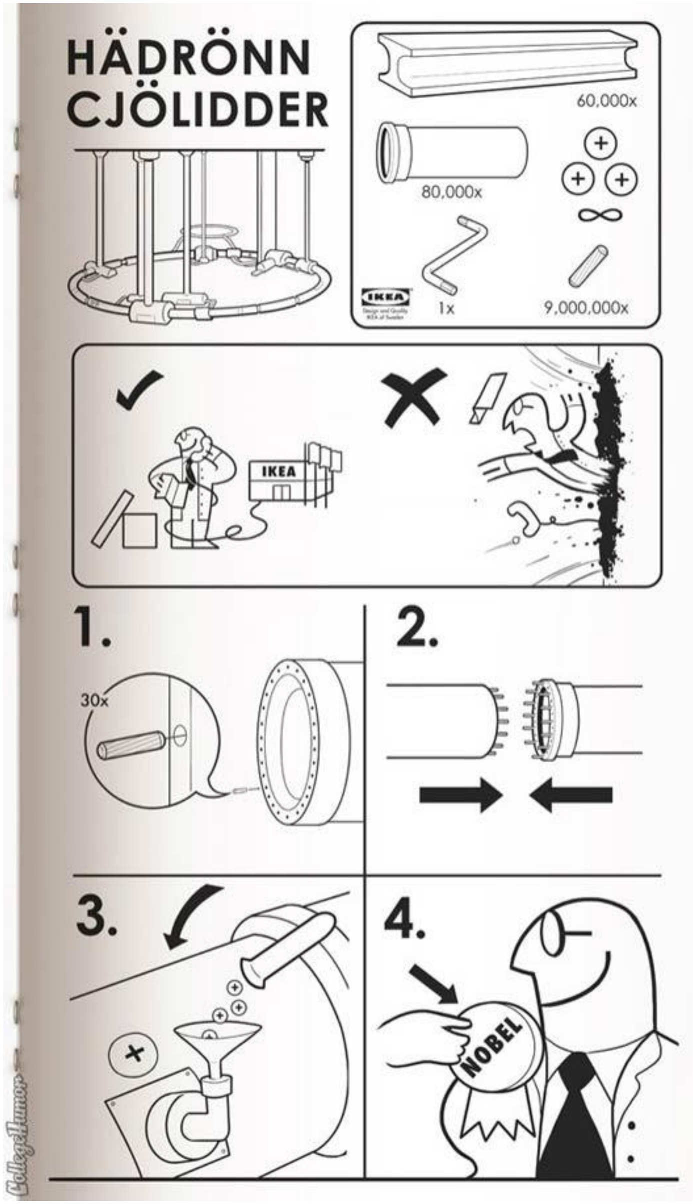
Acknowledgment to IARC Fermilab team + several others.

Accelerators for industry

- Accelerators for industrial applications:
  - Modest energy: few MeVs – tens of MeV
  - Modest and high power: tens of kW – hundreds of kW.

- Specific requirements:
  - Simplicity
  - Low cost
  - Reliability
  - Work in industrial environment (sometimes harsh)
  - Easy to operate
  - Small sizes
  - High efficiency

Think IKEA!



https://www.pinterest.co.uk/pin/857795678723322970/

Accelerators come in several sizes and shapes.

- Electrostatic (few keV – 10 MeV) – e.g. Dyanmitron, Cockroft-Walton, Pelletron

- Microtron – a cross of cyclotron but uses multi-pass
- Betatron – essentially a transformer but circular can reach several MeV's
- Rhodotron – recirculating through a coaxial cavity
- RF Linac (several MeV's) – normal conducting cavities
- Synchrotron
- Ion accelerators (different species)

A steady market

Commercial EB accelerator applications are vast

- EB welding
- EB melting
- EB sterilization
- EB curing
- Non-destructive testing
- Medical imaging
- Cargo inspection

OK….So, if there are accelerators already in market, why do we want SRF technology and what is so attractive with SRF?

Current vs New Accelerator Technology

- Bulk materials processing applications require multi-Mev energy for penetration or to generate x-rays and 100's of kW (or even MW) of beam power
- > few MeV accelerators are typically copper and RF driven
  - Inherent losses limit efficiency (heat vs beam power) = ops cost
  - Heat removal limits duty factor, gradient and average power ➔ physically large "fixed" installations = CAPEX

IBA Rhodotron

New Technology: Superconducting Radio Frequency (SRF)

- High wall plug power efficiency (e.g. ~ 75%)
  - Large fraction of the input power goes into beam
  - High power & efficiency enables new $ 1 Billion class SRF-based science machines ➔ driving large R&D efforts at labs
- Currently SRF-based science accelerators are huge with complex cryogenic refrigerators, cryomodules, etc. But this is changing!
- Recent SRF breakthroughs now enable a new class of compact, SRF-based industrial accelerators (lower CAPEX and OPS cost)

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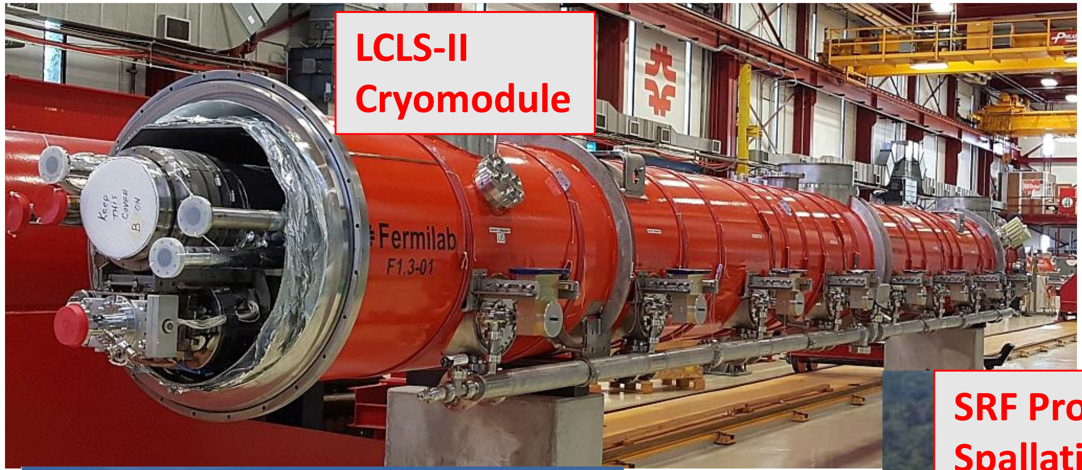
Superconducting Radio Frequency (SRF)

~ All new high beam power accelerators for discovery science employ SRF

- Why?
  - Because ~all RF power → beam power vs heating RF resonators
  - SRF➔ Higher gradient, more energy per unit length
- But current SRF “science” accelerators are large and complex



Summary: Superconducting radiofrequency (SRF) technology has revolutionized particle accelerators for science

Courtesy: R.Dhuley, FNAL

SRF benefits for large scientific machines

- High wall-plug efficiency
- High average beam power

Breakthroughs continue to ensue

- Niobium cavities achieve >50 MV/m in 2 K liquid helium
- Nb_3Sn cavities attain >20 MV/m in 4.5 K liquid helium

Courtesy: R.Dhuley, FNAL

SRF for basic science ⇨ SRF for industry & society

- SRF relevant Industrial applications of particle accelerators?
- How to make SRF suitable for industrial settings?

Recent SRF 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)
- Commercial Cryocoolers: new devices with higher capacity at 4 K enables turn-key cryogenic systems
- Conduction Cooling: possible with low cavity losses➔ dramatically simplifies cryostats (no Liquid Helium !)
- New RF Power technology: injection locked magnetrons allow phase/amplitude control at high efficiency and much lower cost per watt
- Integrated electron guns: reduce accelerator complexity

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

Industrial applications and scope of SRF accelerators

Courtesy: R.Dhuley, FNAL

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:

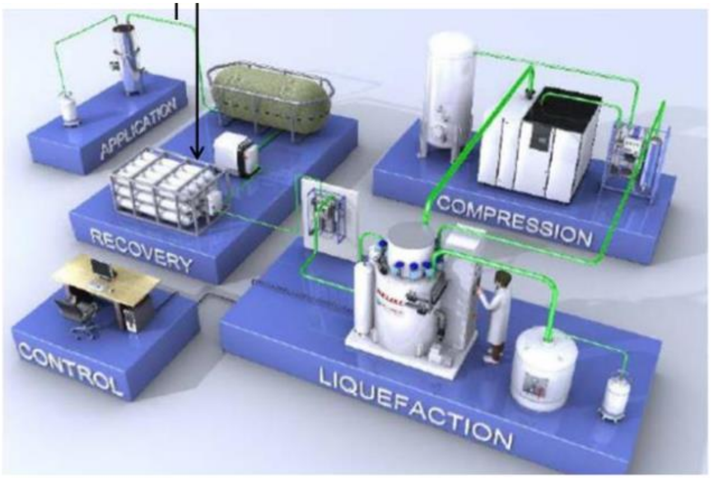
- Low capital and operating expense
- Robust, reliable, turnkey operation

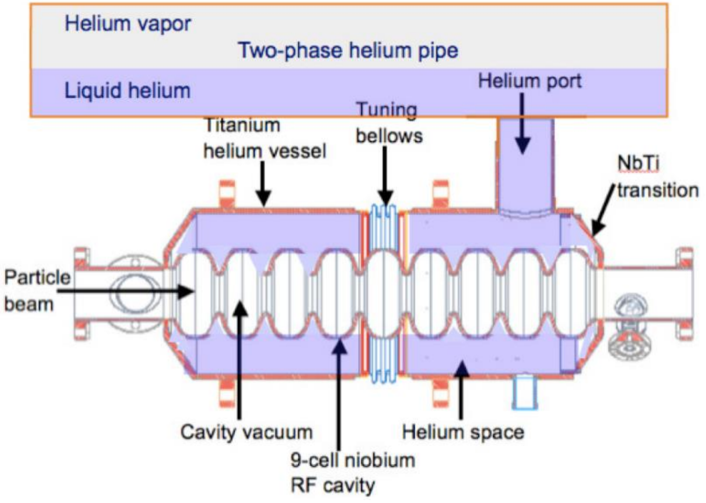
http://accelconf.web.cern.ch/AccelConf/napac2016/talks/thb3io02_talk.pdf

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

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

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





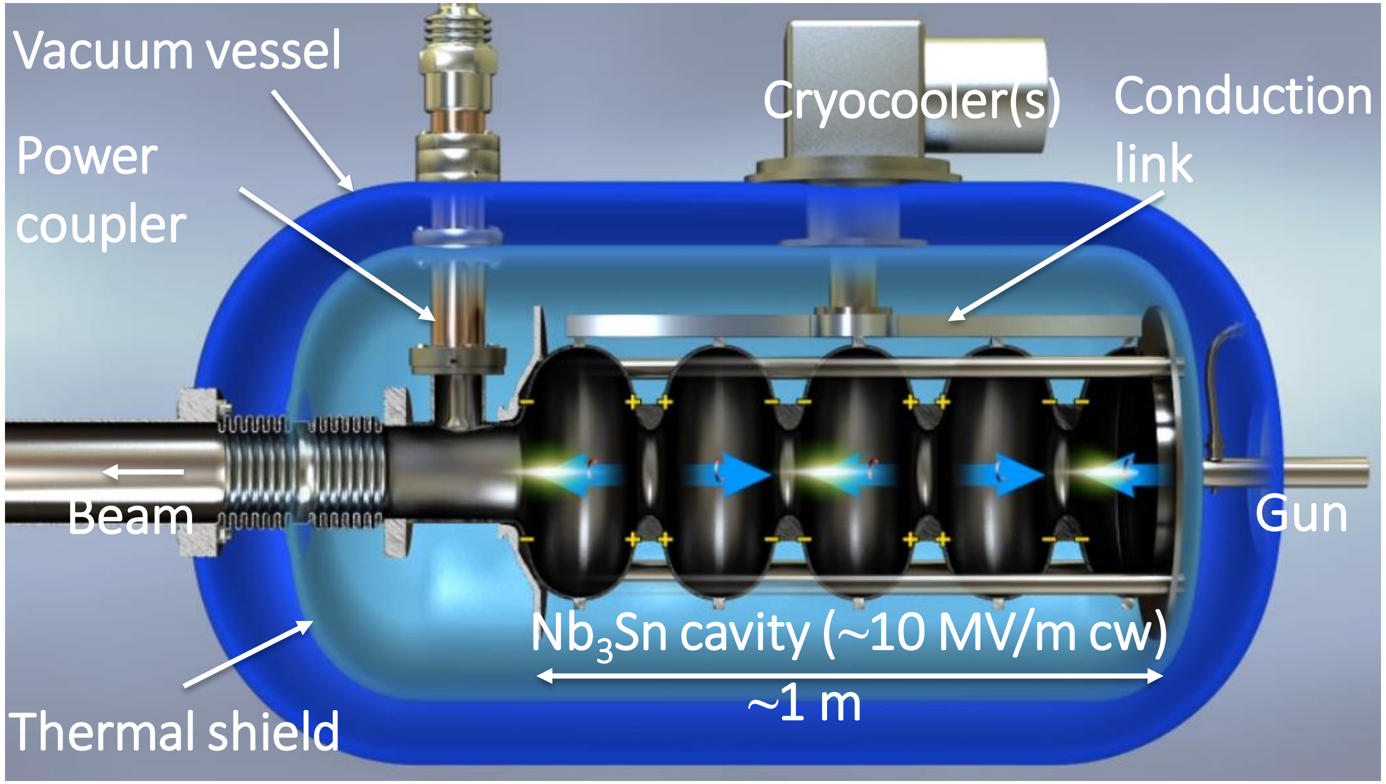
Why superconducting: HIGH Power (CW)

Technology	*Energy*	*Power*	*Issues/Potential*
Room temperature	Few MeV	Up to few hundred kW's	• Energy efficiency • Heat loss • Old(er) technology
Superconducting	10 MeV	100 kW- 1+ MW	• CW • Excellent energy efficiency • Reliable, cutting-edge technology based on science machines (>1 $B) • Compact cryogenics

Concept of a cryocooler conduction-cooled SRF accelerator

R.D. Kephart, ***SRF2015***, 2015. https://accelconf.web.cern.ch/srf2015/papers/frba03.pdf
Patents: US10390419B2, US10070509B2, US9642239B2

AN ILLUSTRATED EXAMPLE



All cryogenics integrated into the module

- Cryocooler 4 K stage cools the SRF cavity
- Cryocooler 45 K stage cools thermal shield/intercept
- Enclosed in a simple vacuum vessel

A new frontier in SRF is simplifying the cooling methods!

Fermilab	Jefferson Lab	Cornell University

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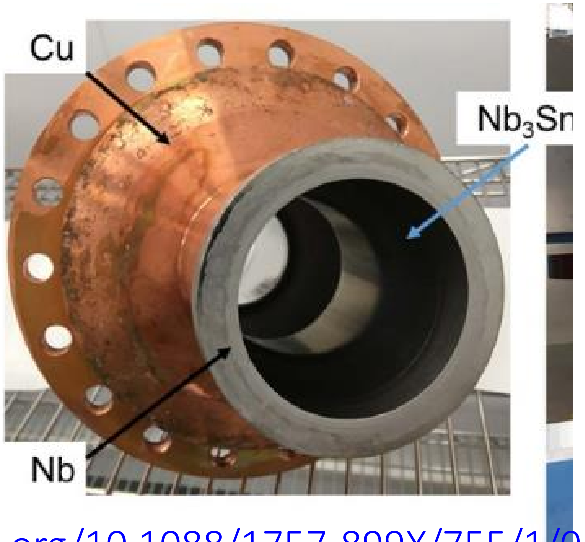
- 650 MHz
- welded niobium rings

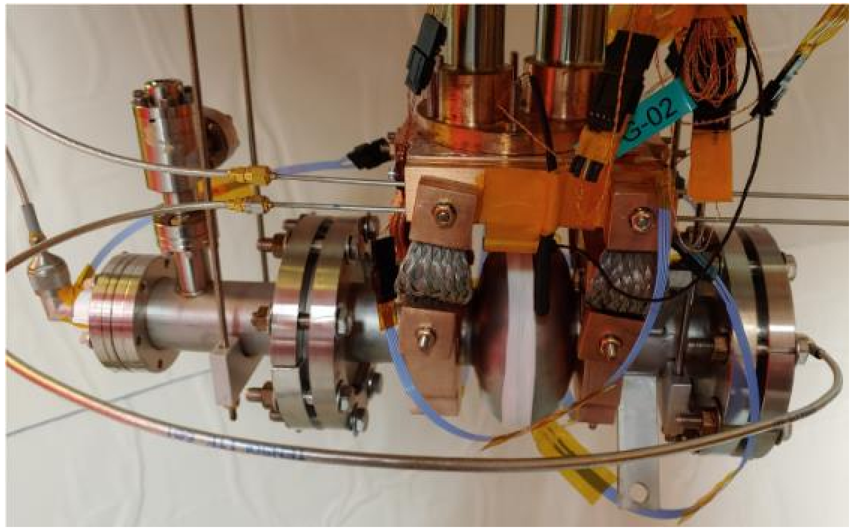
Jefferson Lab



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

Types of industrial accelerators

- Dept. of Energy provided funding to develop novel accelerator designs to address need for industrial application in the energy and environment applications

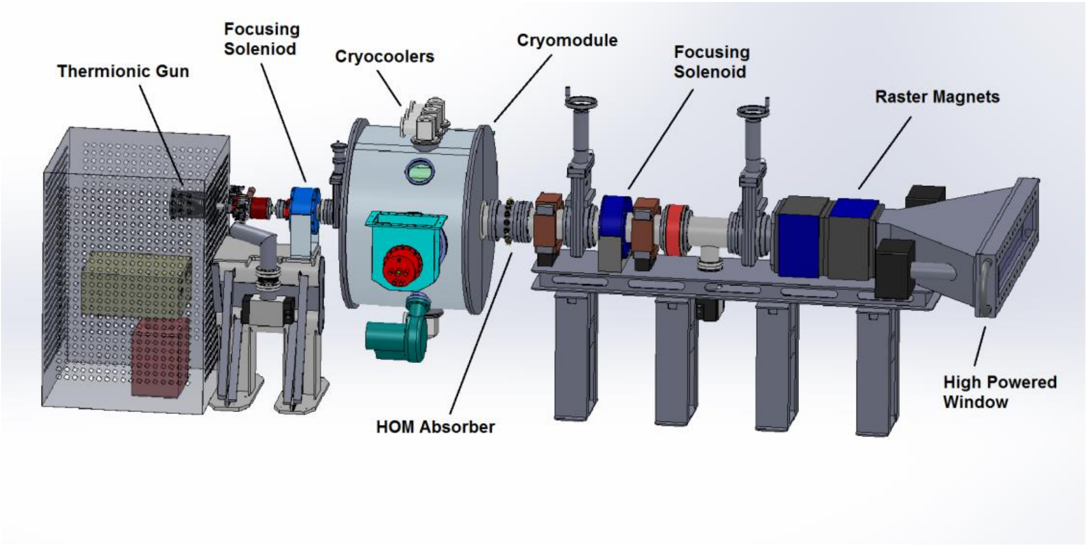
Table 2. Target performance for high power electron accelerators for E&E applications:

	Type 1 Demo/Small Scale	**Type 2 Medium Scale Low Energy**	**Type 3 Medium Scale High Energy**	**Type 4 Large Scale High Energy**
Example Applications	*R&D, Sterilization, industrial effluent streams*	*Flue Gas, Waste water*	*Wastewater, sludge, medical waste*	*Sludge, Medical waste, Env. remediation*
Electron Beam Energy	0.5-1.5 MeV	1-2 MeV	10 MeV	10 MeV
Electron Beam Power (CW)	>0.5 MW	>1 MW	>1 MW	>10 MW
Wallplug Efficiency	>50%	>50%	>50%	>75%
Target Capital Cost*	<$10/W	<$10/W	<$10/W	<$5/W
Target Operating Cost†	<1.0M$/yr	<1.5M$/yr	<1.5M$/yr	<12M$/yr

U.S. DEPARTMENT OF ENERGY | Office of Science

Ongoing work!!

1 MeV, 1 MW SRF accelerator



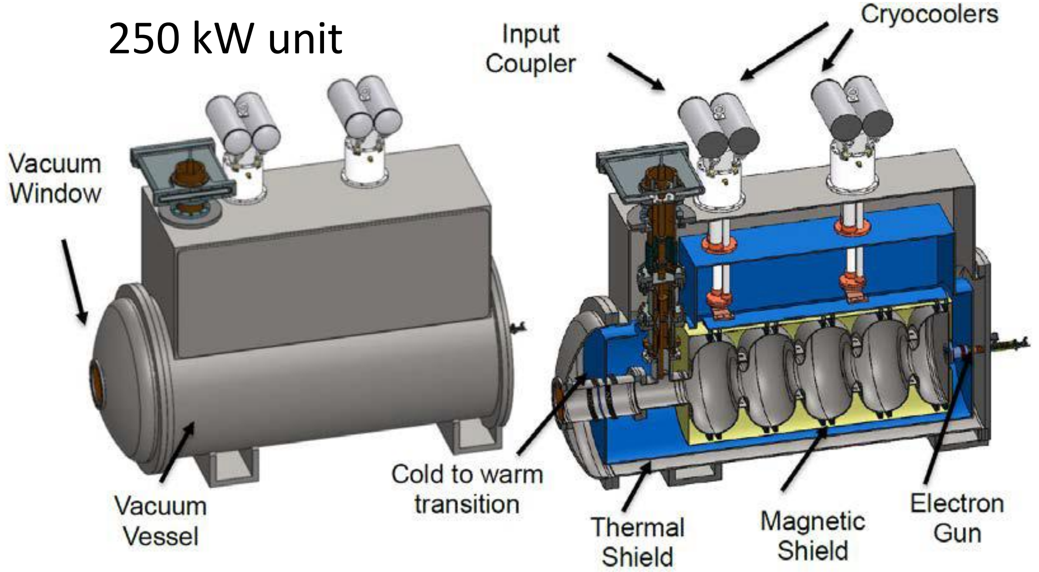
Jefferson Lab — G. Ciovati, R. Rimmer, F. Hannon, J. Guo, F. Marhauser, V. Vylet

Advanced Energy Systems, Inc. — J. Rathke, T. Schultheiss

General Atomics — J. Anderson, B. Coriton, L. Holland, M. LeSher

10 MeV, 1 MW SRF accelerator

250 kW unit



Fermilab — R. Kephart , V. Yakovlev, N. Solyak , I. Gonin , S. Kazakov , T. Khabiboulline , O. Prokofiev , S. Posen T. Kroc, C. Cooper, J. Thangaraj, R. Dhuley, M. Geelhoed

Northern Illinois University — Philippe Piot

Colorado State University — Sandra Biedron

Euclid Techlabs — A. Kanareykin

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 1000 kW facility	MWRD of Greater Chicago
II (2017-18) / J.C.T. Thangaraj	Conceptual design of a 1000 kW module and economic analysis of a 10000 kW facility	
III (2019-in progress) / R.C. Dhuley	Practical cryogenic design and cost analysis of a 1000 kW module (Publication in preparation)	GENERAL ATOMICS

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

LETTER • OPEN ACCESS

First demonstration of a cryocooler conduction cooled superconducting radiofrequency cavity operating at practical cw accelerating gradients

R C Dhuley[1], S Posen[1], M I Geelhoed[1], O Prokofiev[1] and J C T Thangaraj[1]

Published 20 April 2020 • © 2020 IOP Publishing Ltd
Superconductor Science and Technology, Volume 33, Number 6
Citation R C Dhuley *et al* 2020 *Supercond. Sci. Technol.* 33 06LT01

Article PDF

Figures ▾ References ▾

Superconductor Science and Technology

VIEWPOINT • FREE ARTICLE

Towards a cryogen-free practical gradient cw SRF accelerator

Andrew J May[1,2,3]

Published 8 January 2021 • © 2021 IOP Publishing Ltd
Superconductor Science and Technology, Volume 34, Number 2
Citation Andrew J May 2021 *Supercond. Sci. Technol.* 34 020502

Article PDF

References ▾

Open Access

Design of a cw, low-energy, high-power superconducting linac for environmental applications

G. Ciovati, J. Anderson, B. Coriton, J. Guo, F. Hannon, L. Holland, M. LeSher, F. Marhauser, J. Rathke, R. Rimmer, T. Schultheiss, and V. Vylet

Phys. Rev. Accel. Beams **21**, 091601 – Published 4 September 2018

New opportunities (and *challenges*) with compact industrial SRF-based accelerators

Future Accelerator Applications

Energy and Environment

- Treat Municipal Waste & Sludge
  - Eliminate pathogens in sludge
  - Destroy organics, pharmaceuticals in waste water
- In-situ environmental remediation
  - Contaminated soils
  - Spoils from dredging, etc

Industrial and Security

- Catalyze Chemical reactions to save time and energy
- In-situ cross-link of materials
  - Improve pavement lifetime
  - Instant cure coatings
- Medical sterilization without Co60
- Improved non-invasive inspection of cargo containers

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

New technology can enable new applications (including mobile apps)

Emerging Application where SRF can play a game changing role

- Medical device sterilization : A brief background, Co-60, a story!
- “Forever chemicals”
- Pavement application
- Wastewater application . Let me start with this one

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 is the TRL and trends? Where is the cost driver?

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

Safety and redundancy for certain application? Portability etc.

COST DRIVERS: Cost estimate for 1 MeV, 1 MW SRF EB facility (a very specific application chosen as example)

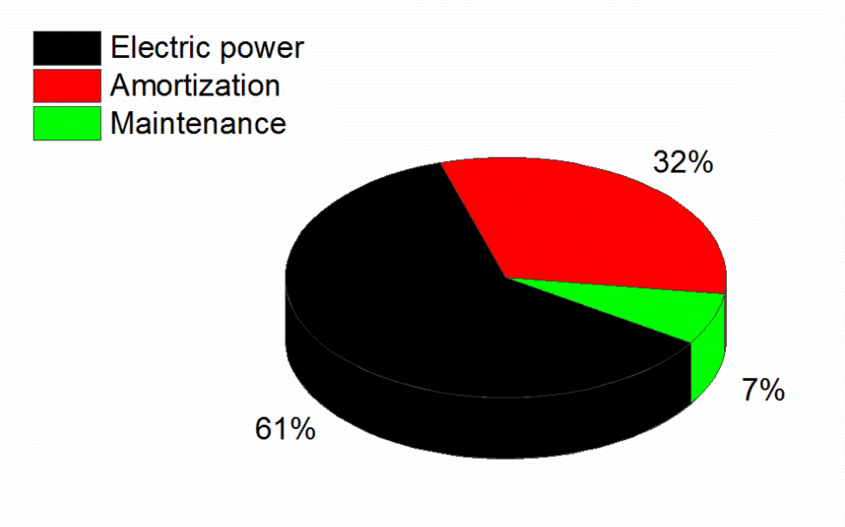
Capital Cost	
SRF Accelerator	$4,500,000
Infrastructure	$2,750,000
Total	$7,250,000
Investment (20%) Amortization(15yr @ 8%)	$1,450,000 $670k/yr

Operating Cost (8,000 hrs/yr)	
Power[a)]	$159.2/hr
Cooling water	None (air-cooled chillers)
Maintenance[b)]	$145k/yr
Total	$1,418,600/yr
Total Cost (Capital + Op.)	**$261/hr** **$2,088,600/yr**

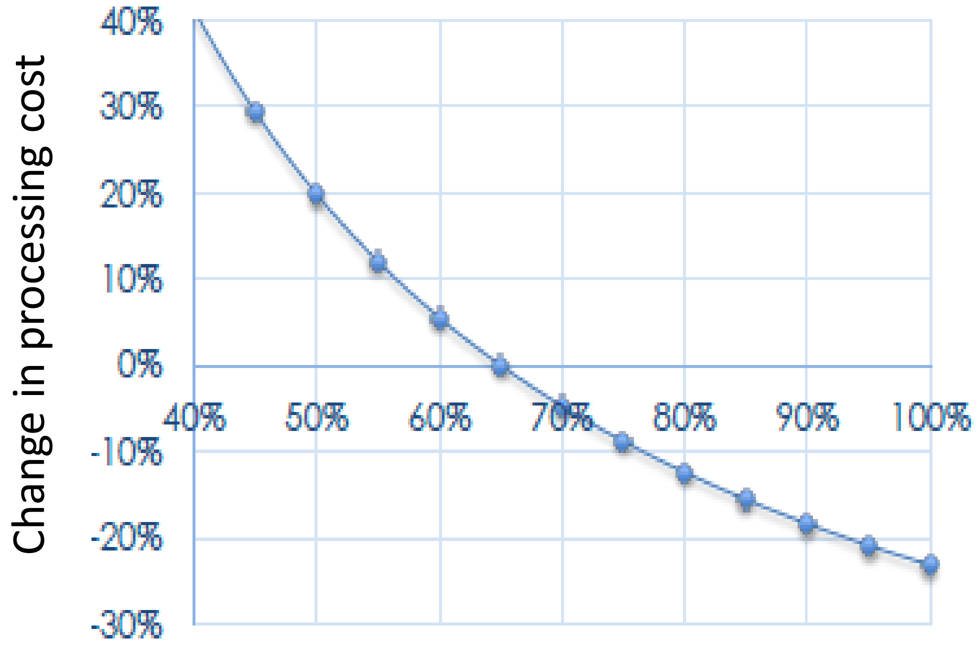
Assumptions

a) 2.274 MW (Elec. Eff.: 42%) @ $0.07/kWh
b) 2% capital/year
c) No dedicated operator

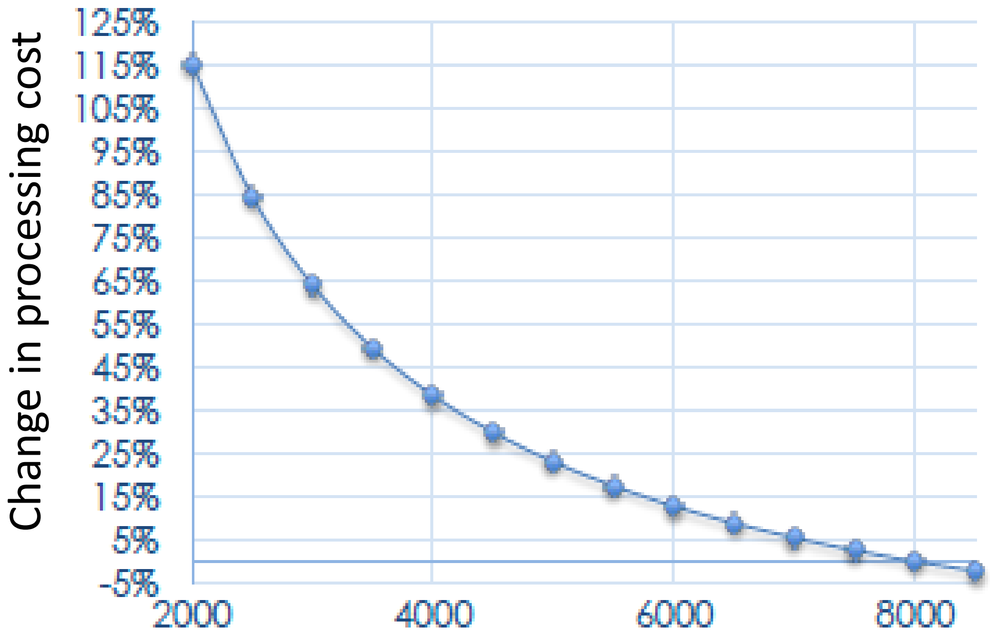
QUESTION: Can you see the cost driver?



Processing cost sensitivity…[drives tech development]



Change in efficiency of RF Source (65%)



Operational hours (8000/yr)

Current technology: klystron (65%), IOT (70%)

In development: magnetrons (90%)

RF is the driver and we want high reliability to break even quickly

Processing cost per Application

	1 MeV, 1 MW		10 MeV, 1 MW
	WASTEWATER		SLUDGE
Dose requirement	1 kGy	4 kGy	10 kGy
Processing cost	$0.13/m³ ($0.482/kgal)	$0.51/m³ ($1.93/kgal)	$19.7/dry ton
Cost of current technologies (other than EB) [4]	$0.25/m³ – $1.00/m³		>$50/dry ton
Daily Processed Volume	45,000 m³ (11.9 Mgal)	11,250 m³ (3.0 Mgal)	278 dry ton (1.3 Mgal with 25% biosolid waste)
Required Flow Rate (gpm)	9,050	2,260	984
Comments [4]	Color, Odor, Coliform bacteria removal	Kill >99% of bacteria	Inactivate some radiation resistant organisms

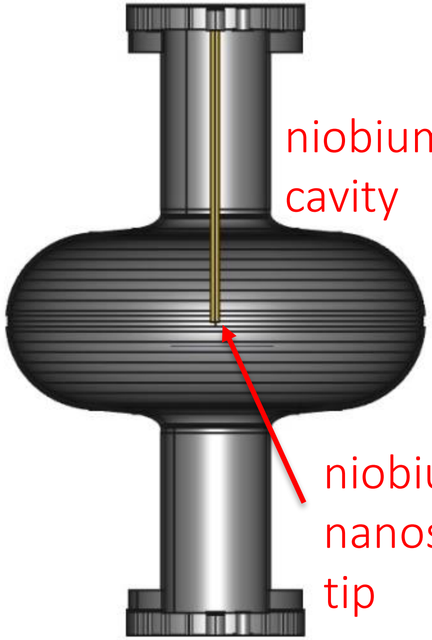
[4] S. Henderson and T.D. Waite, Workshop on Energy and Environmental Applications of Accelerators, U.S. Deptof Energy, June 24-26, 2015. (https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf)

Development of SRF based field emission sources

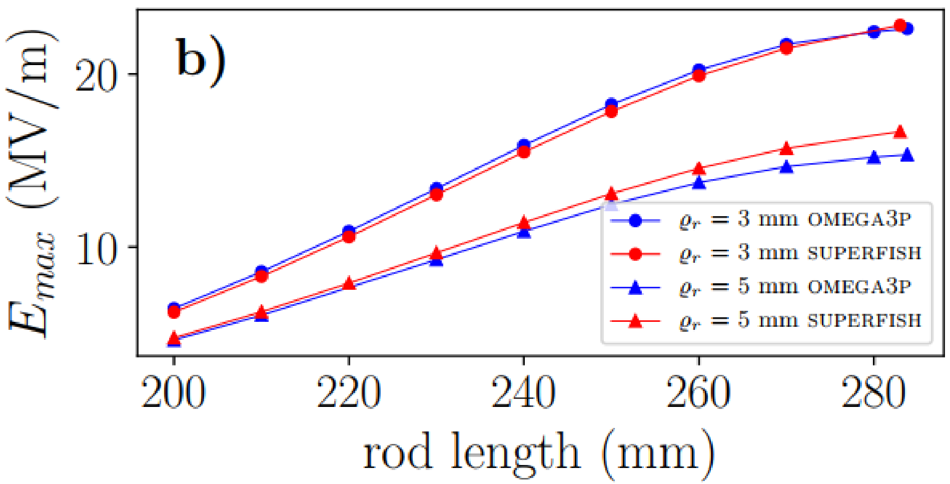
PI: Dr. Philippe Piot (NIU/Argonne National Lab.)

NIU-Fermilab collaboration

- field emission cathode with nanostructured surface located in high e-field region of an SRF cavity
- use cw operation to produce high repetition rate field emission (high I_{avg})



Cathode surface e-field
(650 MHz cavity, 1.6 W cryo-cooling)

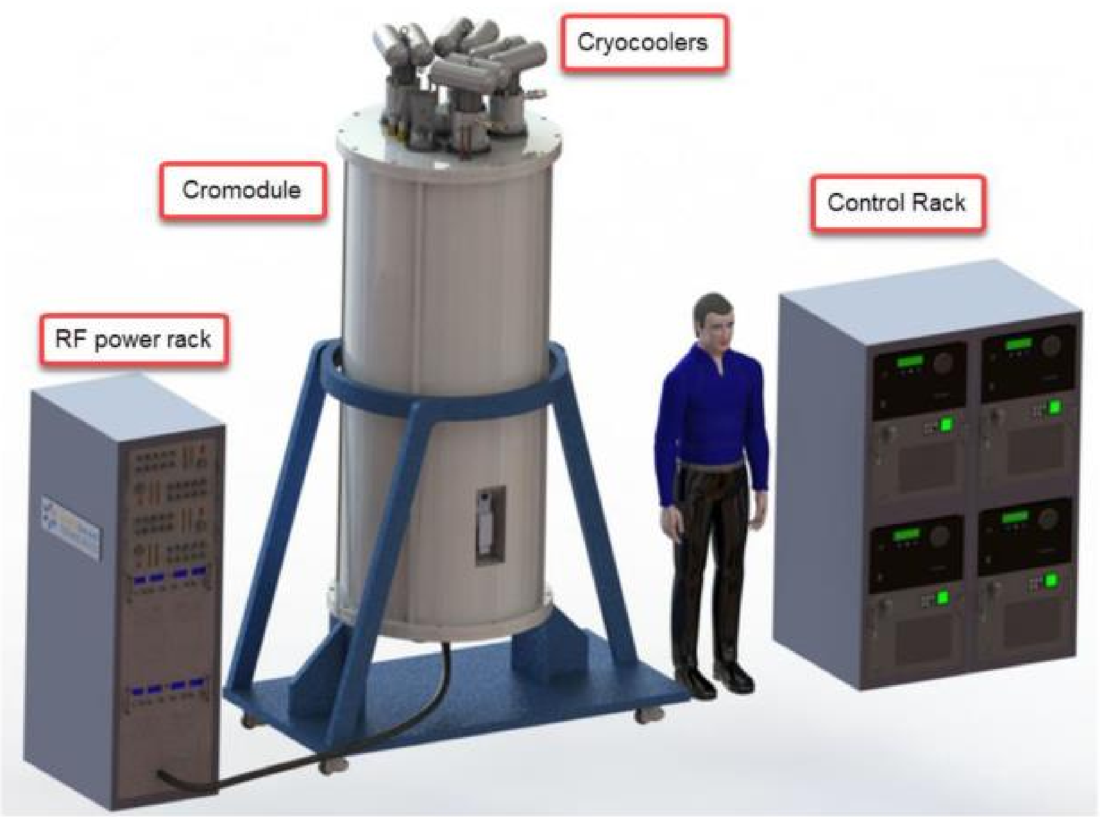


Mohsen *et al.*, http://accelconf.web.cern.ch/ipac2019/papers/tupts083.pdf

Cryocooled based standalone SRF modules

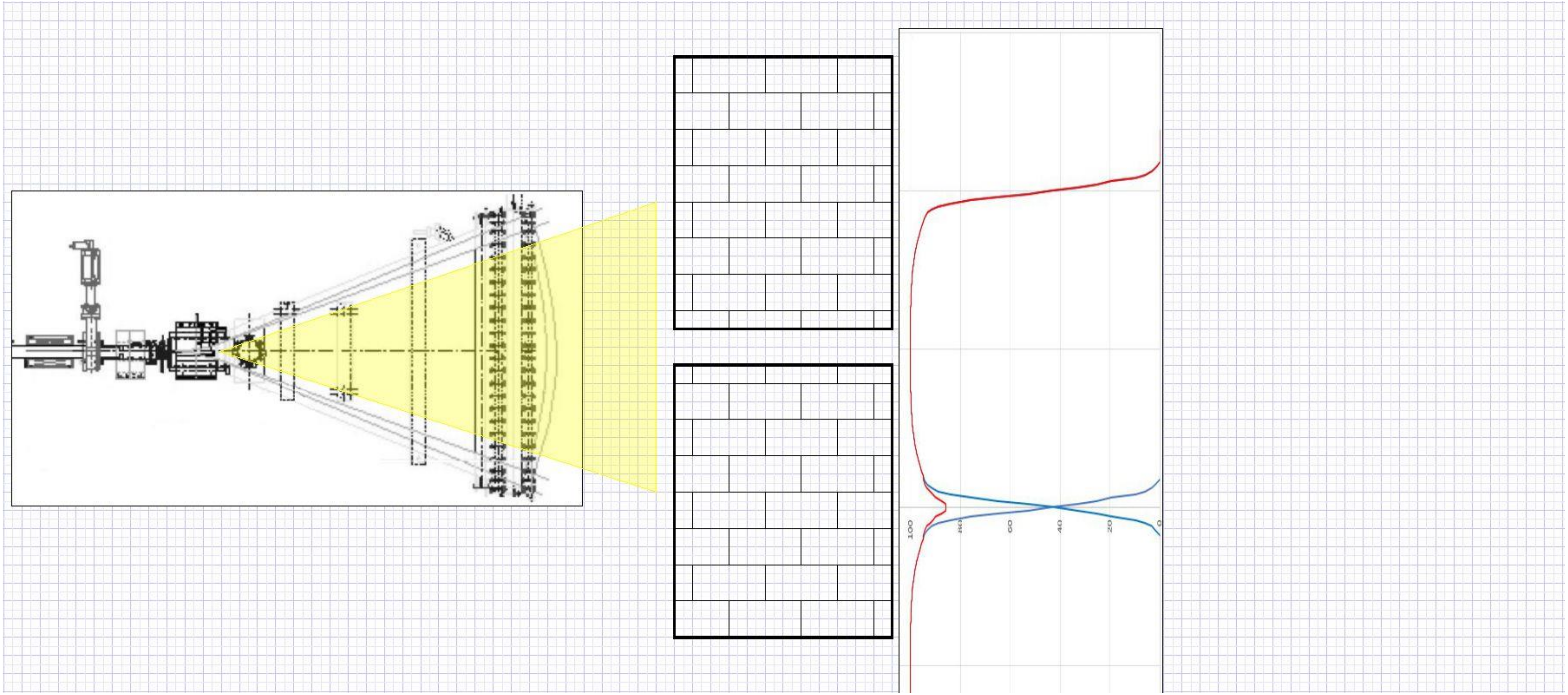
Cryocooled SRF has already been picked up by the particle accelerator industry!

S. Kutsaev *et al.*, https://ieeexplore.ieee.org/document/9119112/



A SRF QWR cooled by pulse tube coolers for beamline upgrade at Argonne Natl. Lab.

Medical device sterilization: A major application.



Capacity considerations (Courtesy: T.Kroc FNAL)

- 1 Mci = $3.7x10^{16}$ decays/second
  - Total energy released – 2.505 MeV/decay
  - 15 kW
  - Typical irradiation bunker – 30-60 kW of “beam” power
- Electron beam machines can provide this easily
- X-ray must overcome inefficiency of Bremsstrahlung process
  - 200 – 400 kW of electron beam power
  - Then must include efficiency of electron beam production

Capacity considerations

- Gamma (typical capacity is 2-4 MCi)
  - ~10 kGy/hr
  - 3.4 m^3/h/MCi @ 25 kGy
- *Electron Beam*
  - *~20 MGy/hr*
- X-ray
  - ~60 kGy/hr
  - 2.8 m^3/h/100 kW @ 25 kGy (including target losses)

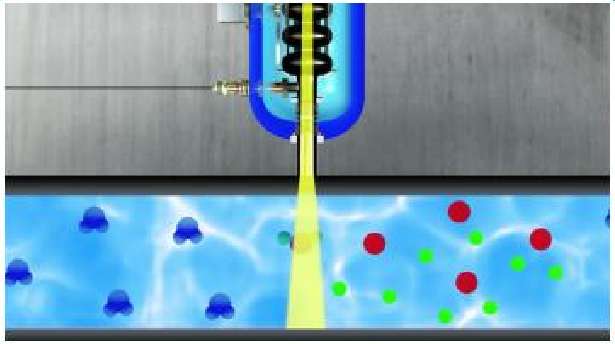
1 MCi gamma ≈ 120 kW X-ray <- Need high power e-beam sources to match current and emerging neeeds.

Multitool

Courtesy: C.Cooper, FNAL

Wastewater Multitool that Treats Contaminant X in Water

Military
- Explosives, PCBs, TCE
- Treat military PFCs problem today…
- ~200 military facilities
- $Bs of emerging contaminants



Industrial
- Chemical manufacturing, textiles, medical
- Point source contamination
- Reduce/Re-use

Energy Production
- Point source contamination
- Total water re-use
- ~10,000 large processing facilities

Municipal
- Treat PFCs, pharmaceuticals, bacteria/viruses
- Quick to respond to EPA regulation
- > 16,500 public treatment facilities

Food & Beverage
- Reduce/Re-use
- Condition incoming water
- Clean in place process

Courtesy: C.Cooper, S.Grdanovska FNAL

Electron Beam Treatment of Water

$$H_2O \xrightarrow[\text{Beam}]{\text{Electron}} OH^-, H^+, e^-_{aq}, H_2, H_2O_2$$

- Increases dewaterability
- Removal of toxic chemicals not removed in conventional domestic water treatment: Pharmaceuticals, Agricultural run off, Fuel additives (MTBE), PCBs, PFAS/PFOA - perfluorinated compounds
- Reduction in pathogens
- No toxic residuals (no secondary waste generation)
- Increased phosphorus recovery

Picture of conventional e-beam

Conventional E-Beam technology shown to remove many contaminants in water but →

- **Low Throughput**
- **Energy Intensive**
- **Large Nonportable Footprint**

Fresh from the press….

CNN health

Makeup may contain potentially toxic chemicals called PFAS, study finds

By Sandee LaMotte, CNN

Updated 7:46 PM ET, Tue June 15, 2021

(CNN) — The "No PFAS in Cosmetics Act" was introduced in the US House and Senate on Tuesday, following the release of a new study that found high levels of a marker for toxic PFAS substances in 52% of 231 makeup products purchased

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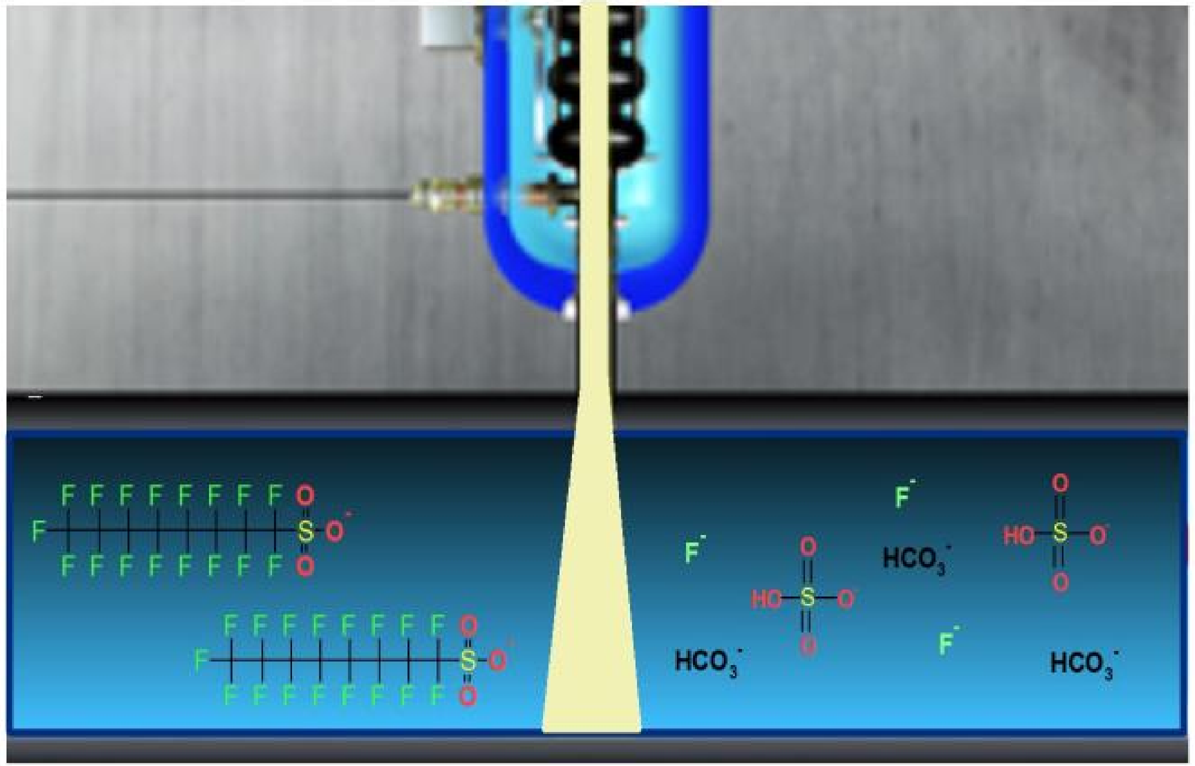
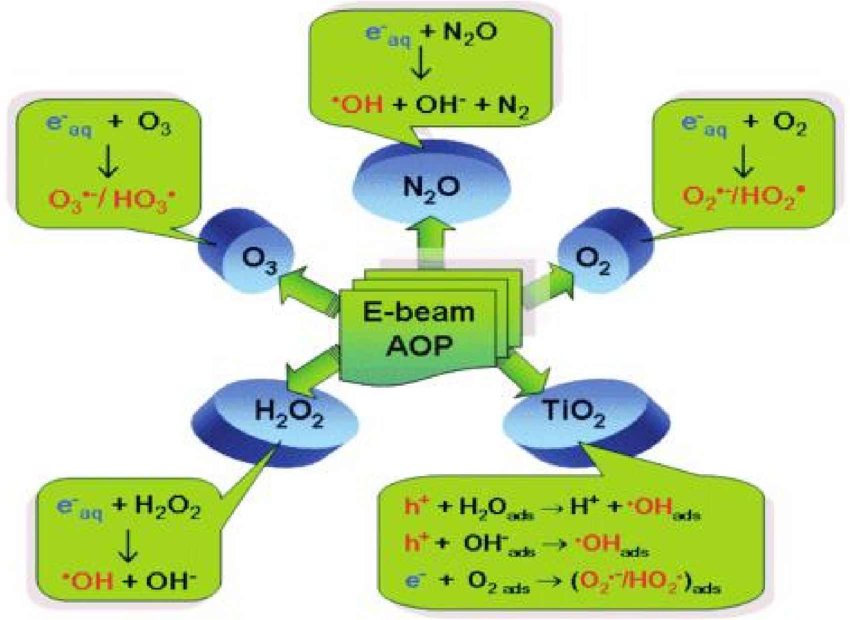
E-Beam Treatment of PFASs

Courtesy: C.Cooper, FNAL

- Per- and polyfluoroalkyl substances (PFAS) are a group of man-made chemicals including PFOA and PFOS.
- They are found in the blood serum of 99% of people in the world wit no conventional treatment technique.
- E-beam can breakdown PFASs to salts, CO2 and water. Currently investigating large scale application.





Multiple different breakdown pathways from e-beam . Aqueous electrons and hydroxyl radicals thought key for PFAS destruction.

Challenges on the 'roads ahead':

- 94% of road in the US are asphalt.

- > 50 B$/year in renewing asphalt pavement

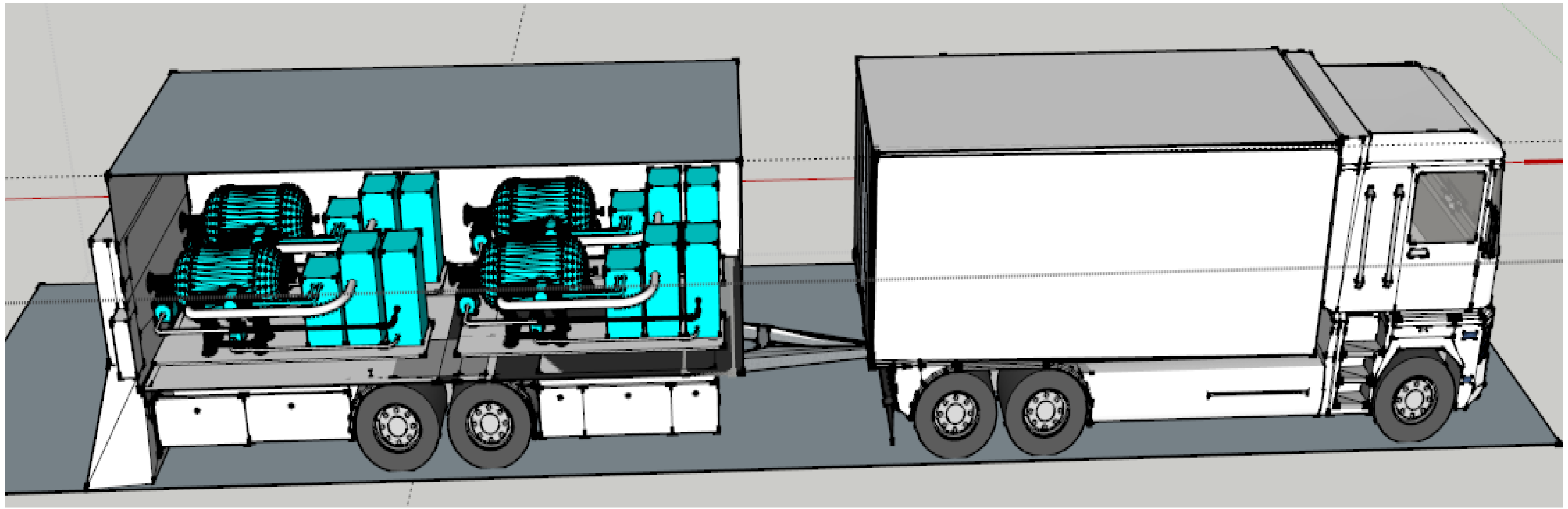
Source: http://asphaltmagazine.com/94percent/

- Asphalt pavement damage is largely due to cracks of the bitumen binder under heavy load. Oxidation, water freezing and thawing in cracks all create a continuous and expensive cycle of renewal, exacerbated in colder climates

- Despite attempts to improve asphalt pavement, the materials and fabrication method have changed little for several years.

Leverage accelerator technology to extend pavement lifetime

- IARC at Fermilab has partnered with U.S. Army Corps of Engineers ERDC via an interagency agreement on a R&D project to extend the lifetime of pavement using modern accelerator technology
- Our technology will improve the strength, toughness and the service of the paved surfaces.



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Many emerging areas that SRF accelerators can add value

Conclusions

- Lot of activity is on-going with a goal to make an entirely new class of industrial SRF-based electron accelerators that use no liquid cryogens
- Mobile, high energy, high power, high efficient electron accelerators can enable a variety of entirely new industrial applications
- Several applications may have enormous market potential
- If you are an interested in working with Fermilab Tech or from Fermilab, talk to me for opportunities!
- If interested in commercialization of our tech, we have resident experts at IARC and OPTT. I will be happy to put you in touch.
- Questions??????