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Compact SRF Accelerator applications: USPAS Lecture

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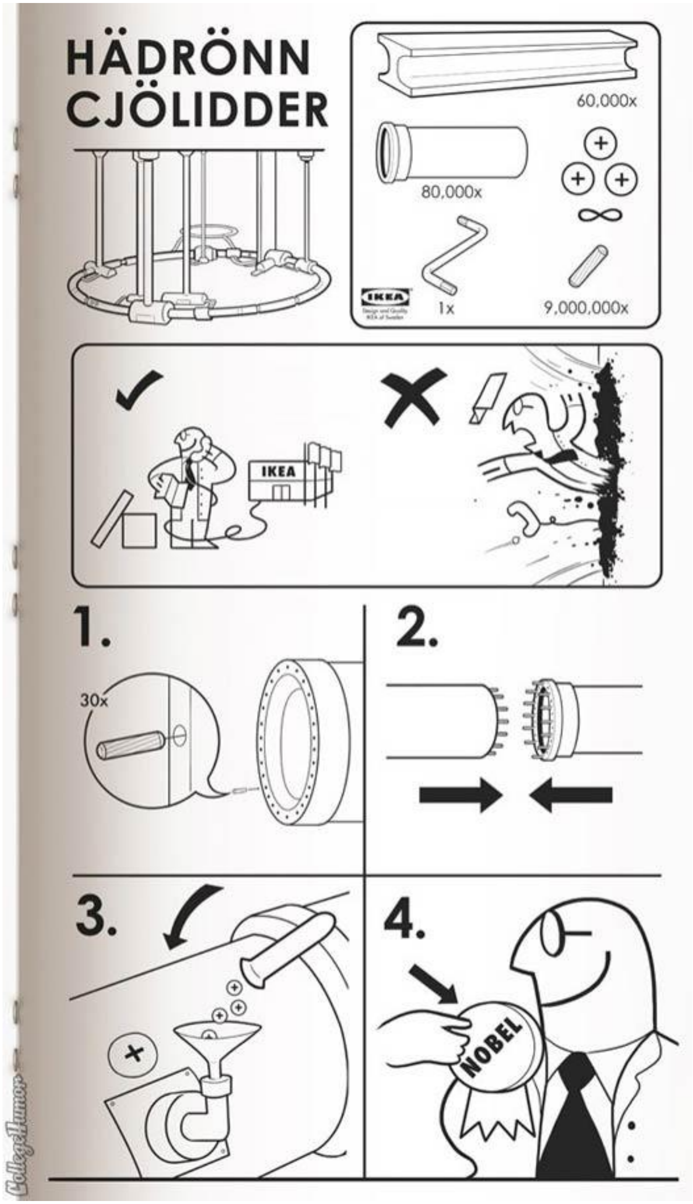
Accelerators for industry

- 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/85779567872322970/



Accelerators comes 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)

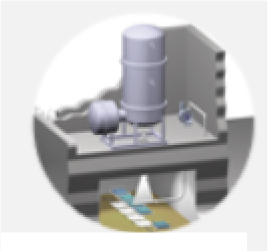
A steady market

Commercial EB accelerator applications are vast

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

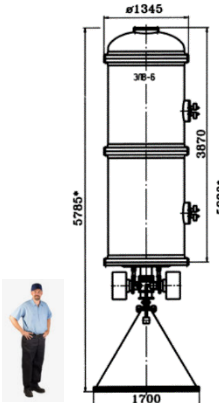
Current vs New Accelerator Technology

- 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 Dynamitron

IBA Rhodotron



Budker ELV-12

New Technology: Superconducting Radio Frequency (SRF)

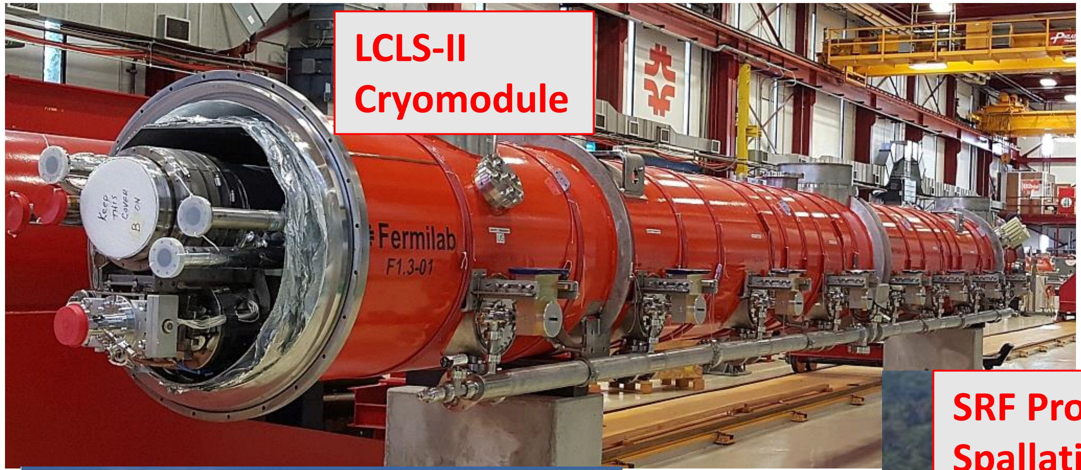
- High wall plug power efficiency (e.g. ~ 75%)
  - Large fraction of the input power goes into beam
  - High power & efficiency enables new $ 1 Billion class SRF-based science machines ➔ driving large R&D efforts at labs

- 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)

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



LCLS-II Cryomodule

FNAL FAST ILC cryomodule with RF

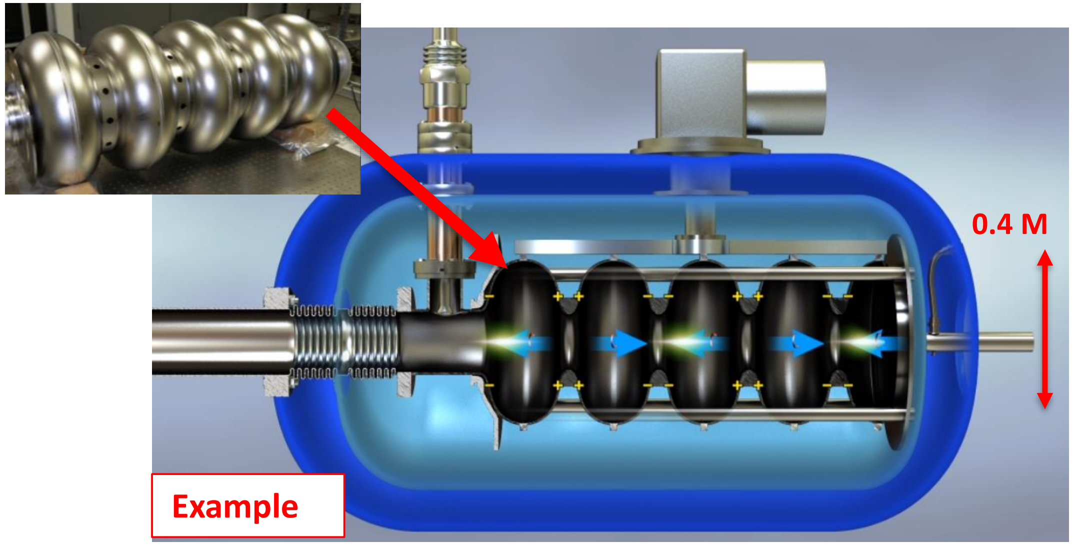
CBEAF CW electron linac 2 K cryoplant

SRF Proton Linac Spallation Neutron Source at ORNL

Why superconducting

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

Ideas integrated into a simple SRF accelerator



Final machine parameters

- Energy: ~ 10 MeV
- Power: 250 kW – 1 MW
- Compact
- Simple, reliable
- Affordable

- 650 MHz elliptical cavity (well understood from PIP-II)
- Modular design scales to MW class industrial applications

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**

Solicitation for advancing industrial accelerators

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

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

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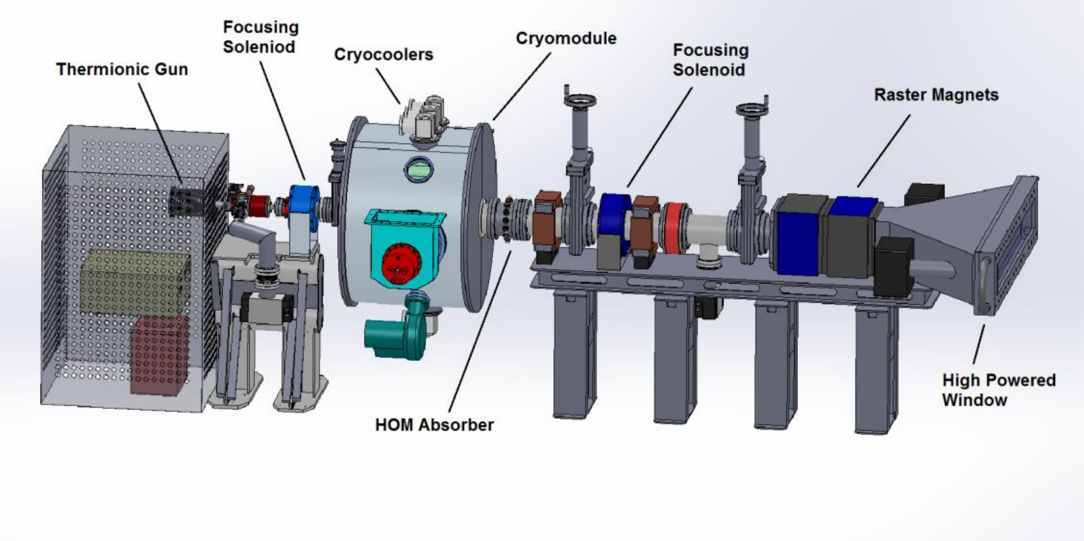
1 MeV, 1 MW SRF accelerator



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

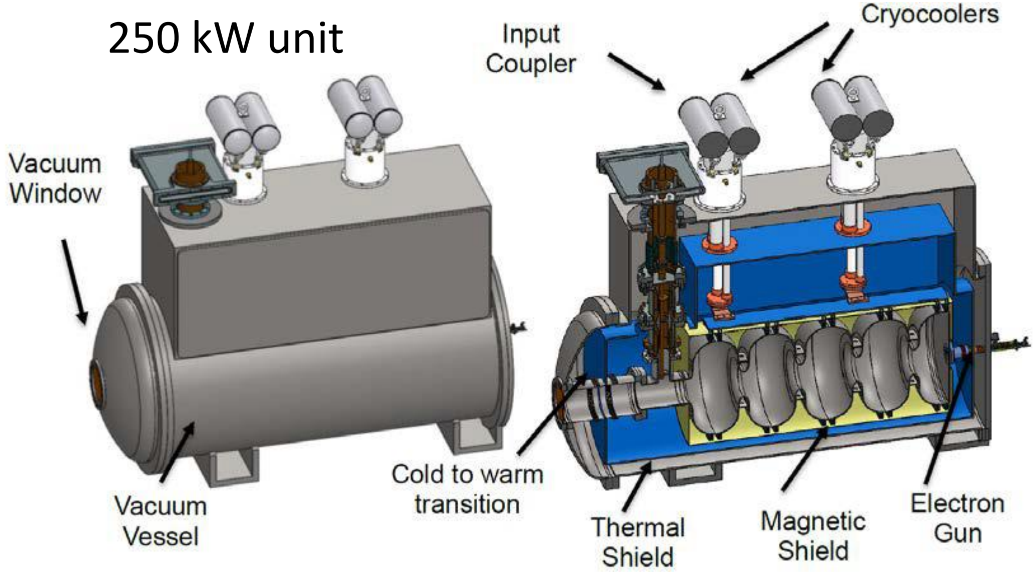
Advanced Energy Systems, Inc. — J. Rathke, T. Schultheiss

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

[2] G. Ciovati *et al., https://arxiv.org/abs/1802.08289*

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

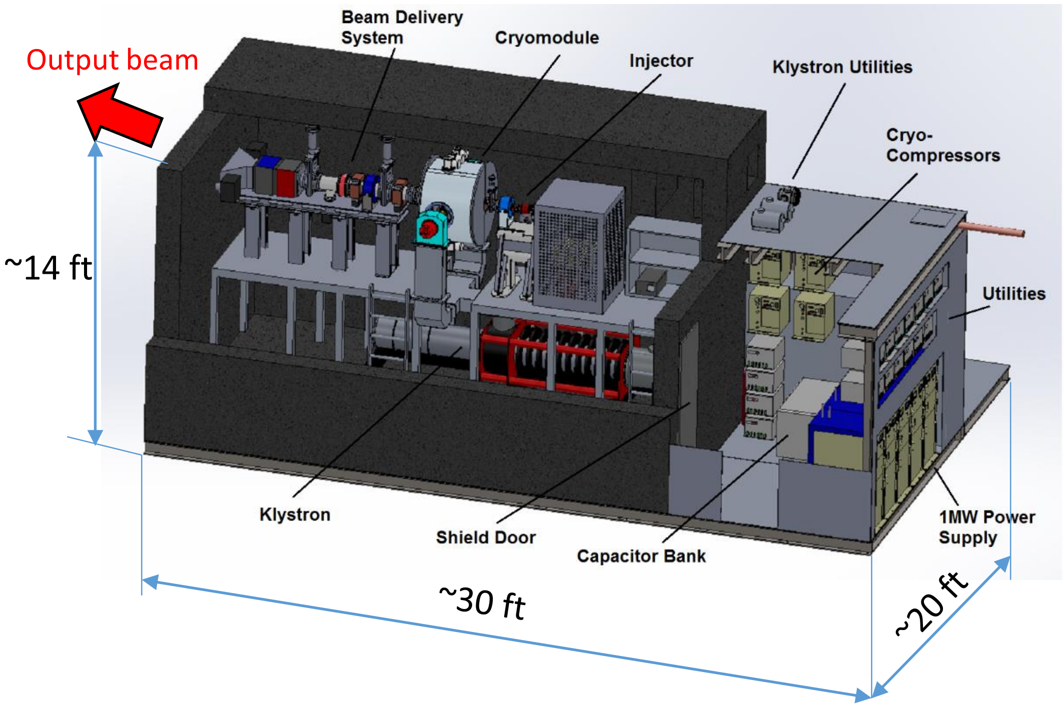
Colorado State University — Sandra Biedron

Euclid Techlabs — A. Kanareykin

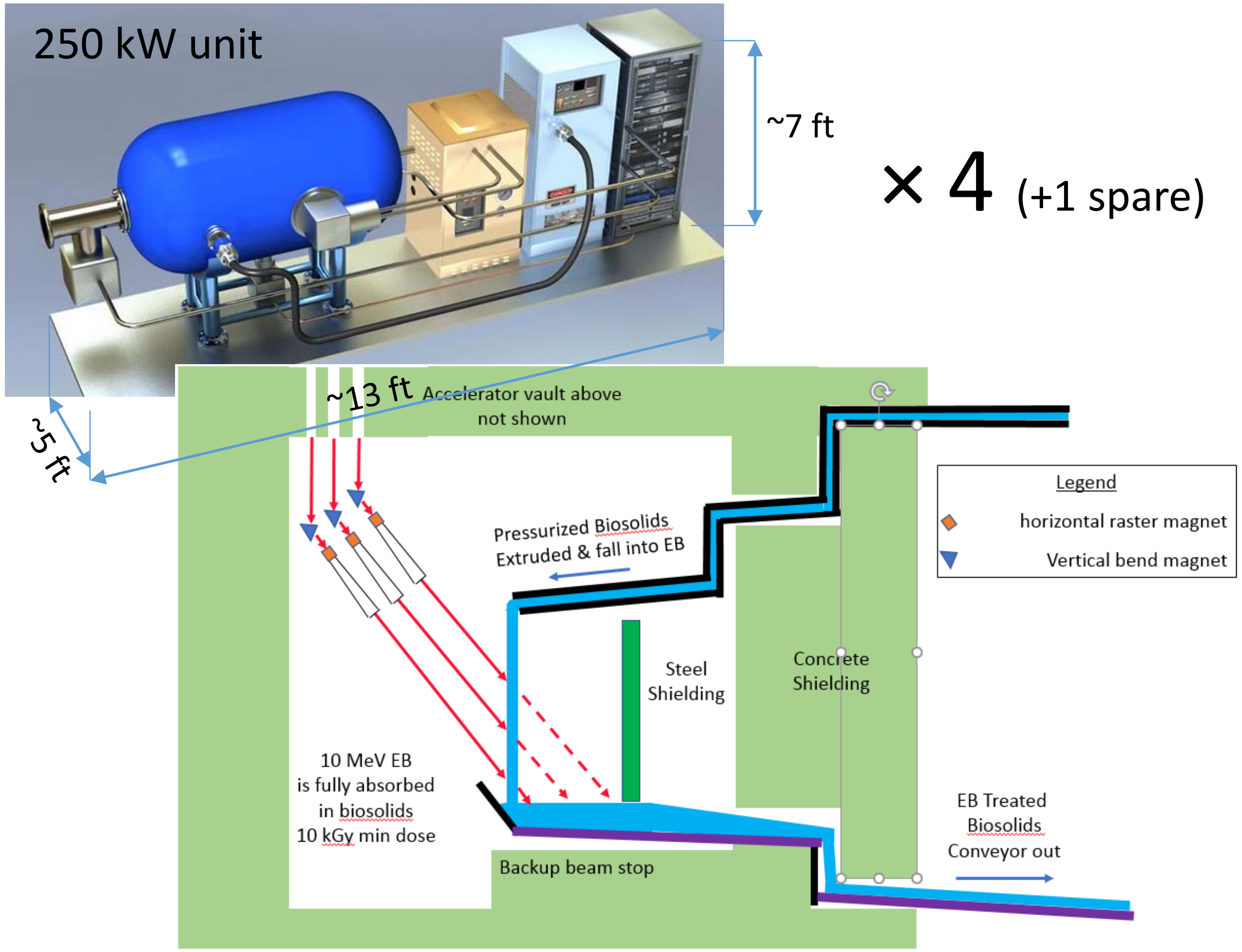
[3] *http://lss.fnal.gov/archive/test-fn/1000/fermilab-fn-1055-di.pdf*

Facilities Layout

1 MeV, 1 MW EB facility



10 MeV, 1 MW EB facility



× 4 (+1 spare)

New opportunities 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.

<u>New</u> technology can enable <u>new</u> applications (including mobile apps)

Economics of SRF E-beam treatment

(acknowledgment to: Gianluigi Ciovati, JLab)

arXiv.org > physics > arXiv:1802.08289

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Physics > Accelerator Physics

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, V. Vylet

(Submitted on 22 Feb 2018)

The treatment of flue gases from power plants and municipal or industrial wastewater using electron beam irradiation technology has been successfully demonstrated in small-scale pilot plants. The beam energy requirement is rather modest, on the order of a few MeV, however the adoption of the technology at an industrial scale requires the availability of high beam power, of the order of 1 MW, in a cost effective way. In this article we present the design of a compact superconducting accelerator capable of delivering a cw electron beam with a current of 1 A and an energy of 1 MeV. The main components are an rf-gridded thermionic gun and a conduction cooled beta= 0.5 elliptical Nb3Sn cavity with dual coaxial power couplers. An engineering and cost analysis shows that the proposed design would result in a processing cost competitive with alternative treatment methods.

Subjects: **Accelerator Physics (physics.acc-ph)**
Cite as: arXiv:1802.08289 **[physics.acc-ph]**
(or arXiv:1802.08289v1 **[physics.acc-ph]** for this version)

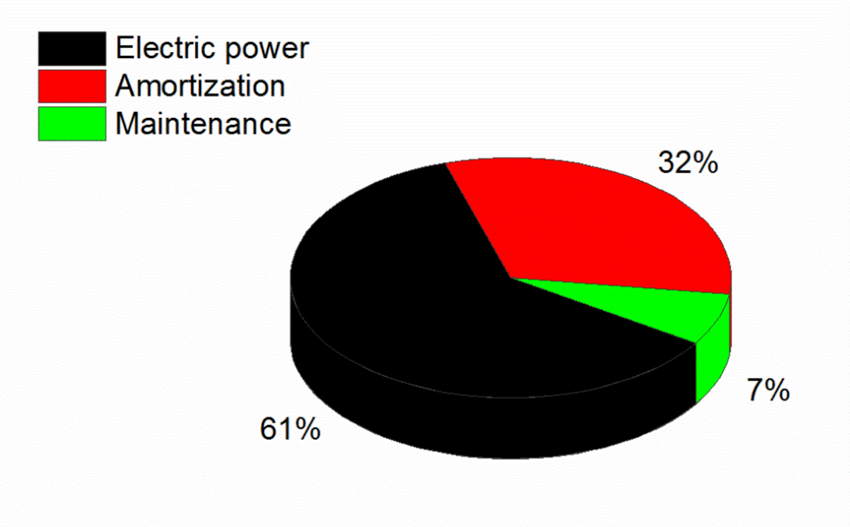
Cost estimate for 1 MeV, 1 MW SRF EB facility

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

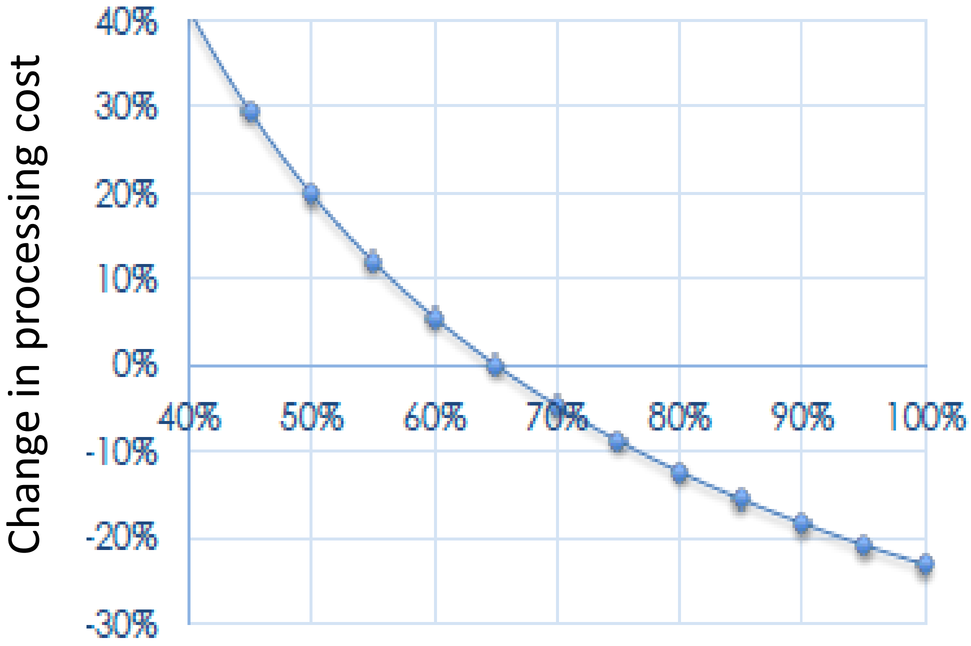
Operating Cost (8,000 hrs/yr)	
Power[a)]	$159.2/hr
Cooling water	None (air-cooled chillers)
Maintenance[b)]	$145k/yr
Total	$1,418,600/yr
Total Cost (Capital + Op.)	**$261/hr** **$2,088,600/yr**

Assumptions

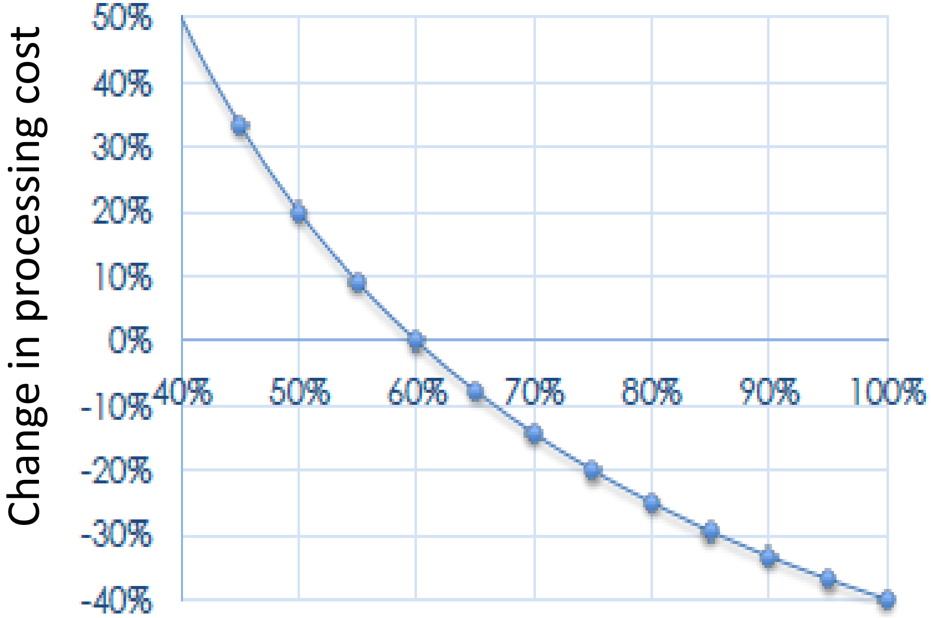
a) 2.274 MW (Elec. Eff.: 42%) @ $0.07/kWh
b) 2% capital/year
c) No dedicated operator



Processing cost sensitivity to Design Parameters



Change in efficiency of RF Source (65%)

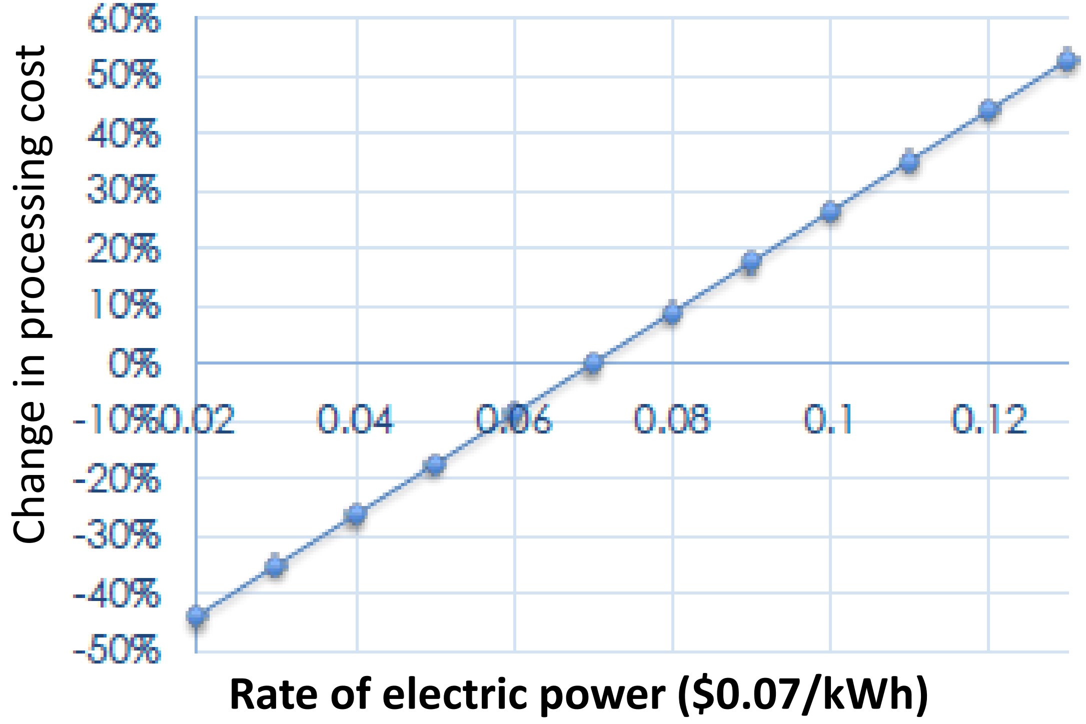


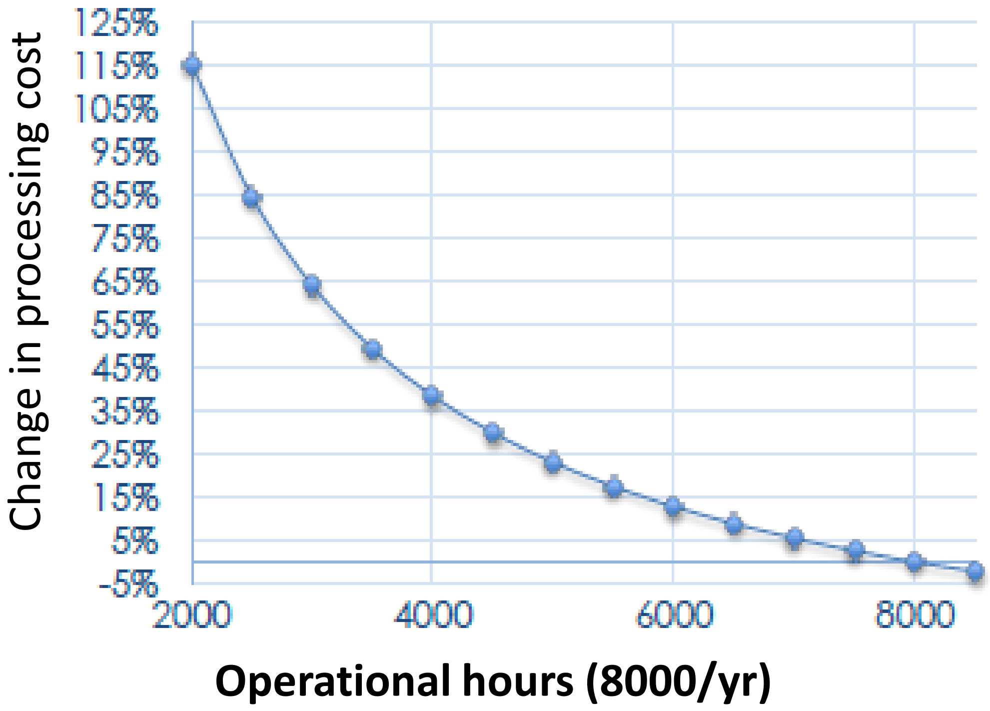
Change in dose deposition efficiency (60%)

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

In development: magnetrons (90%)

Processing cost sensitivity to Operation Parameters



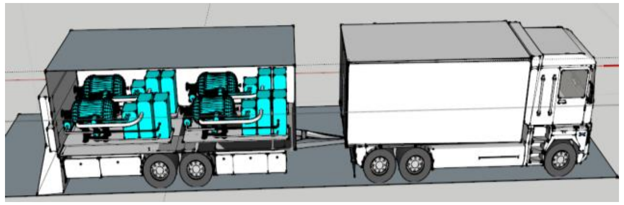


Processing cost per Application

	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)

Emerging application in pavement application



Opportunities	• Improved Pavement Performance • Special Purpose Coatings (Anti-Skid, Corrosion Resistant, Chemical Resistant) • Heavy-Duty Thick Film Industrial Coatings
Partners	• ERDC U.S. Army Corps
Near Term Goals	• Deliver on the first year commitments to ERDC • Beam-Material interaction R&D . At Fermilab, we have small developmental 10 MeV accelerator to perfom such experiments on samples.

Many emerging areas that SRF accelerators can add value

Fermilab

Conclusions

- The Illinois Accelerator Research Center at Fermilab is partnered with U.S. government agencies to create the first article of 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 a student interested in working with Fermilab, talk to me for opportunities! I will be happy to help.