State of EB Accelerator Technologies & Future Opportunities

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Existing industrial accelerators

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

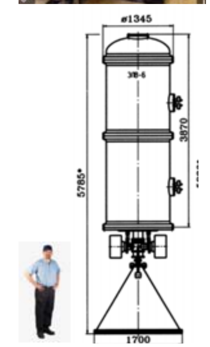
New technology: Compact SRF accelerator concepts

Current vs New Accelerator Technology

- Bulk materials processing applications require multi-Mev energy for penetration 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

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



Budker ELV-12

- 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 accelerator technology

- Superconducting radio-frequency cavities are building blocks of modern particle accelerators
- Much higher efficiency in converting RF power into beam power than copper cavities
- Standard technology: bulk Nb, cooled at 2 – 4 K

9-cell, 1.3 GHz cavity

- Recent advances in SRF R&D make possible the use of Nb_3Sn thin film operating at ≥ 4 K with higher efficiency than that of bulk Nb

[1] R. Kephart et al., "SRF, Compact Accelerators for Industry & Society", in Proc. of SRF'15, Whistler, BC, Canada, Sept. 2015, p. 1467

Design commonalities

- Thermionic gun for high-current beam
- Cryostat with Nb_3Sn SRF cavity for efficient acceleration
- Cryocoolers for efficient cooling
- Coaxial input power couplers for efficient coupling of RF into cavity

- Beam transport calculation and thermal analysis verified feasibility of the designs

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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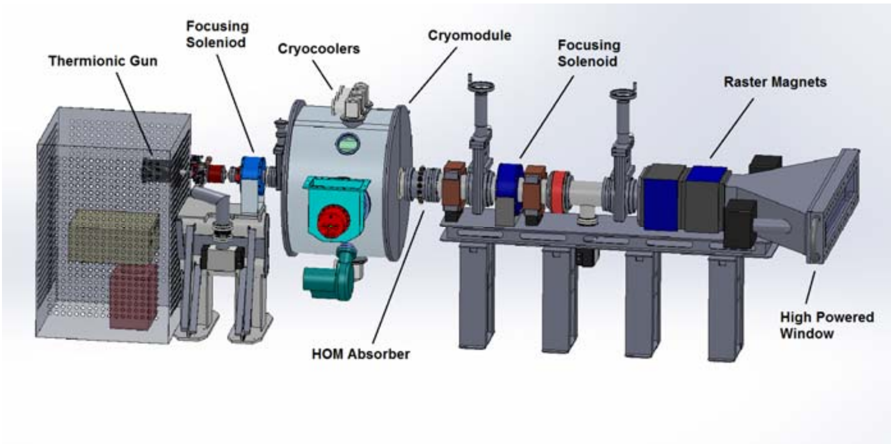
1 MeV, 1 MW SRF accelerator



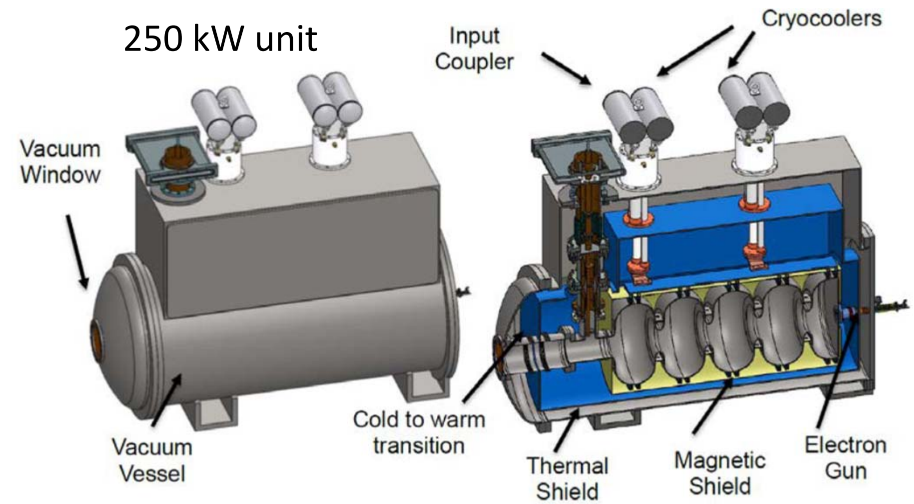
Jefferson Lab — G. Ciovati, R. Rimmer, F. Hannon, J. Guo, F. Marhauser, V. Vylet

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

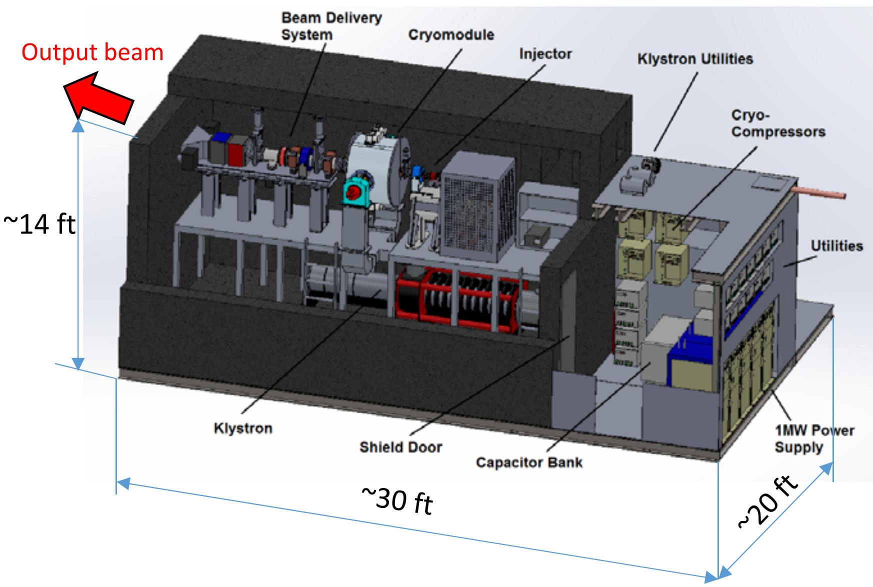


Fermilab

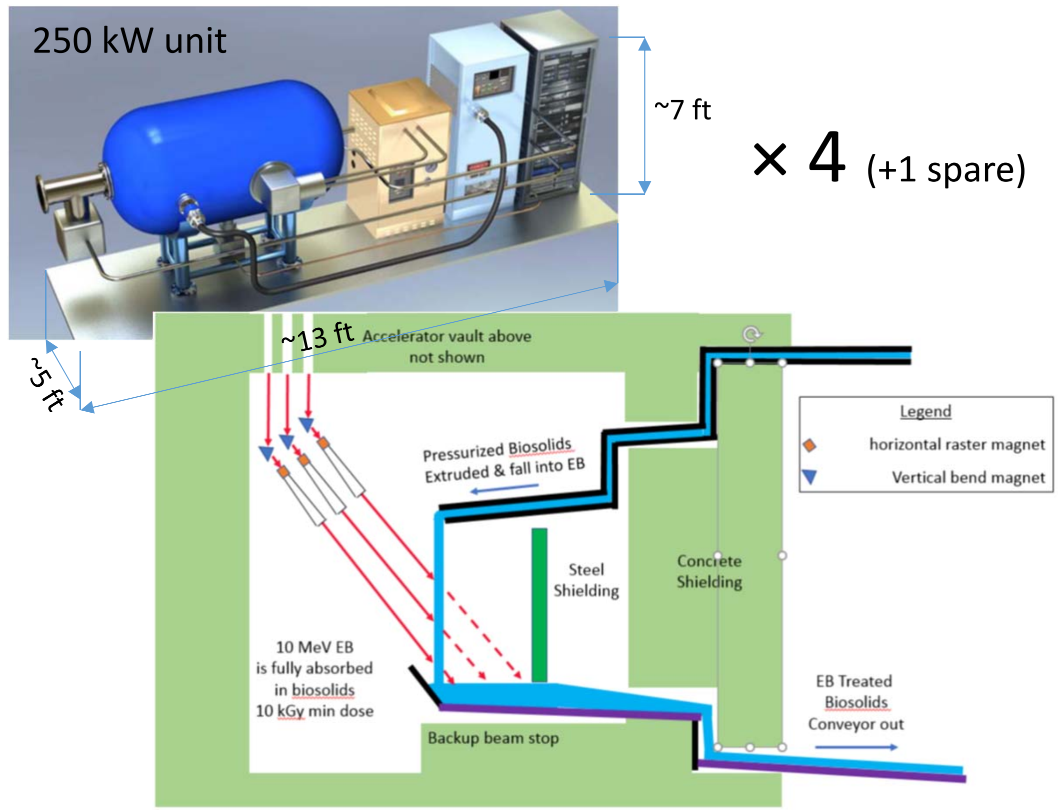
[3]

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.

New technology can enable new applications (including mobile apps)

Economics of SRF E-beam treatment

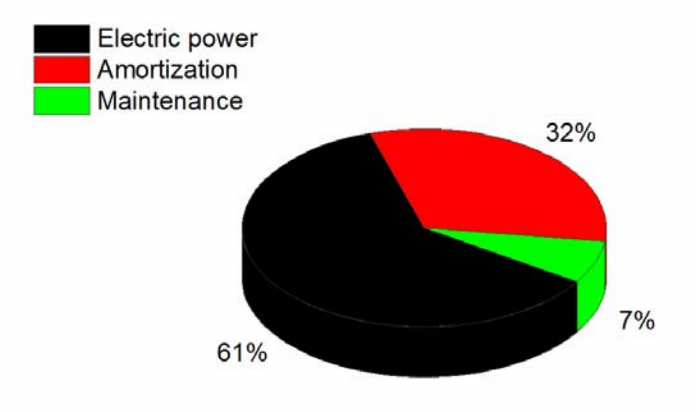
Cost estimate for 1 MeV, 1 MW SRF EB facility

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

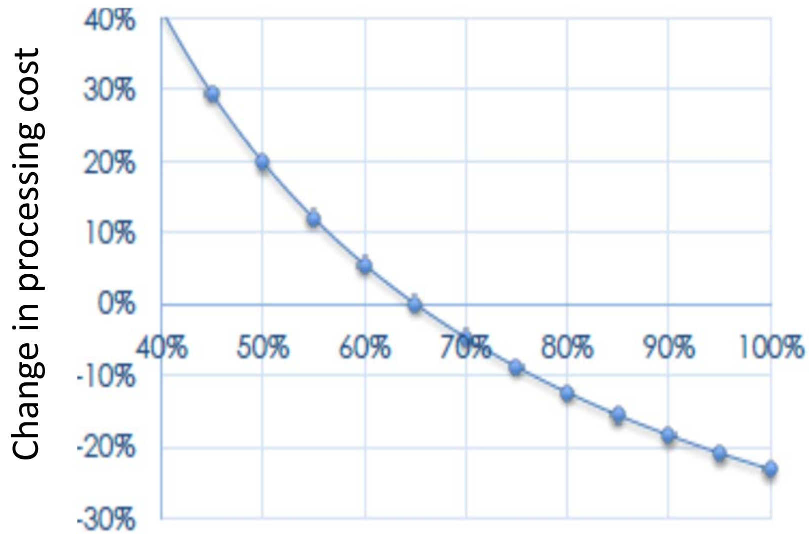
Operating Cost (8,000 hrs/yr)	
Power[a)]	$159.2/hr
Cooling water	None (air-cooled chillers)
Maintenance[b)]	$145k/yr
Total	$1,418,600/yr
Total Cost (Capital + Op.)	**$261/hr** **$2,088,600/yr**

Assumptions

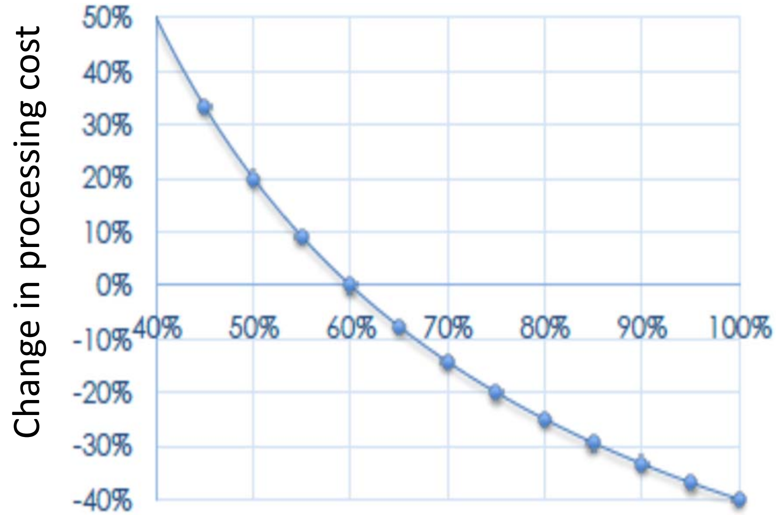
a) 2.274 MW (Elec. Eff.: 42%) @ $0.07/kWh
b) 2% capital/year
c) No dedicated operator



Processing cost sensitivity to Design Parameters



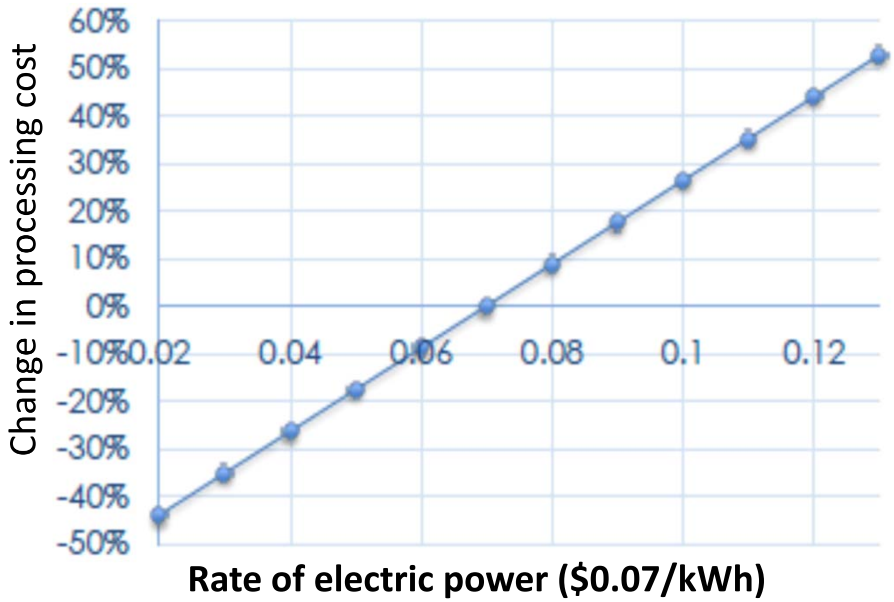
Change in efficiency of RF Source (65%)

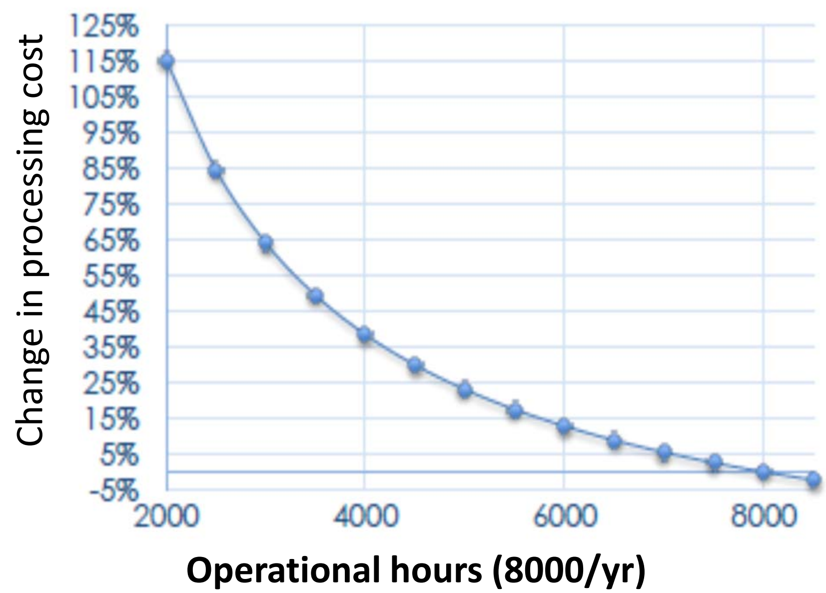


Change in dose deposition efficiency (60%)

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

GC1

[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)

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GC1 I used $10M capital cost, woth 20% investment and 15 years amortization at 8% -> $935k/year, which adds to the operating cost of $1.072/year = $2M/year. 1MW at 10 kGy would give 278 dry ton/day at 70% dose efficiency

Gianluigi Ciovati, 3/28/2018