FERMILAB-SLIDES-24-0092-ETD

Highlighting the utilization of the compact superconducting accelerator to maximize the potential for X-Ray as an alternative modality

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Excellence in Sterilizing Medical Devices, 5th Edition

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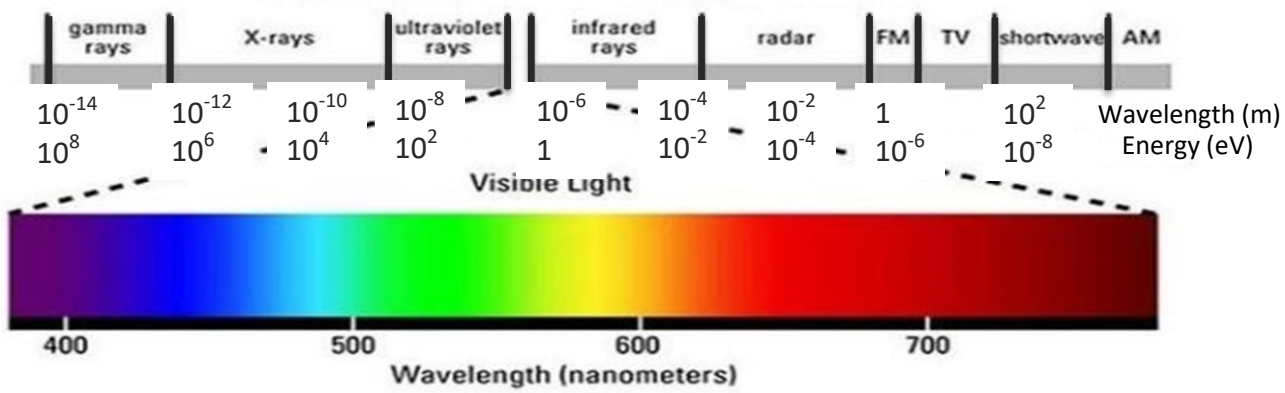
Ionizing Radiation

- Alpha
  - He2+
  - Very Shallow
- Beta
  - Electrons
  - Penetration depends on energy
  - 10 MeV, 5 cm in H_20
- (Photons)
  - Gamma
  - X-ray
  - 10s of cm in H_20
  - (UV light)



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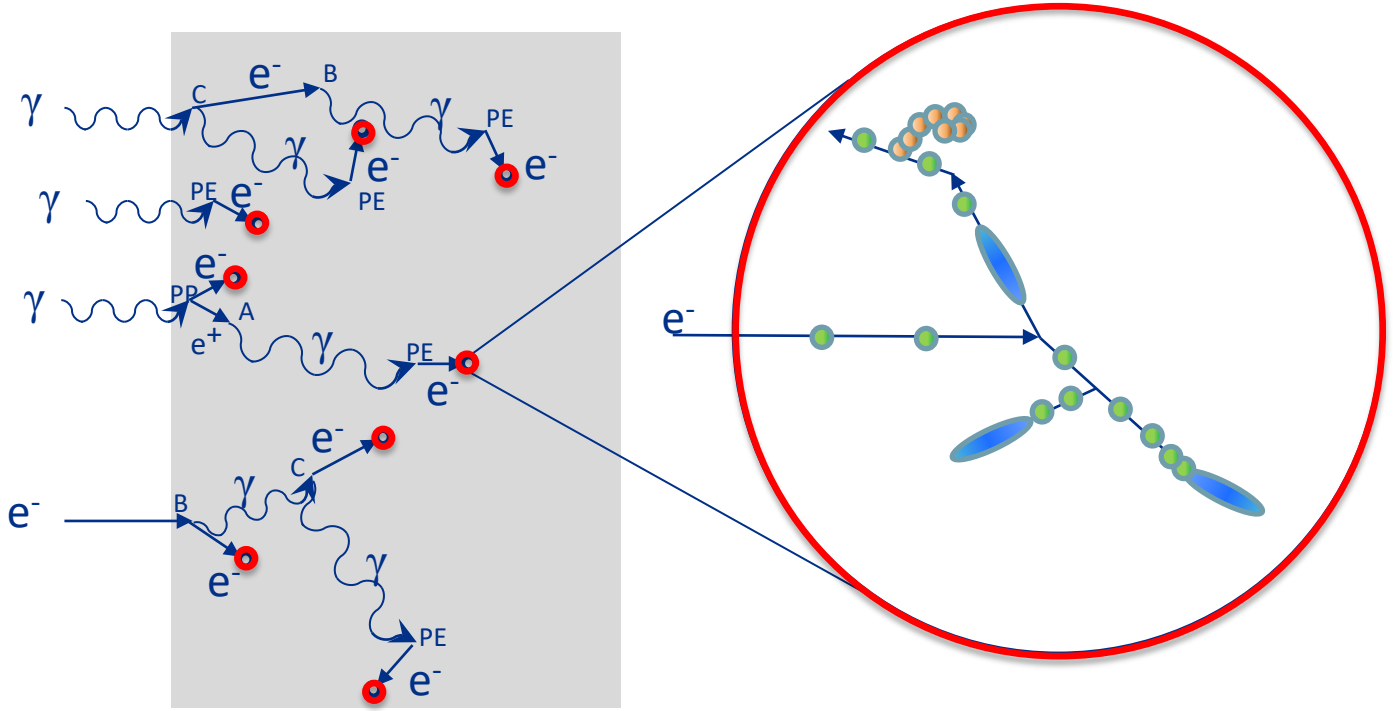
Photon Interactions with Atoms

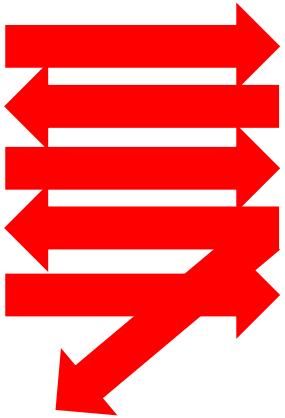


A - Positron Annihilation, B - Bremsstrahlung,
C - Compton Scattering,
PE - Photoelectric Effect, PP - Pair Production

- Spur: 0-100 eV, ~65%
- Blob: 100 – 500 eV, ~15%
- Short track: 500 – 5000 eV, ~20%

The Photon-Electron Cascade

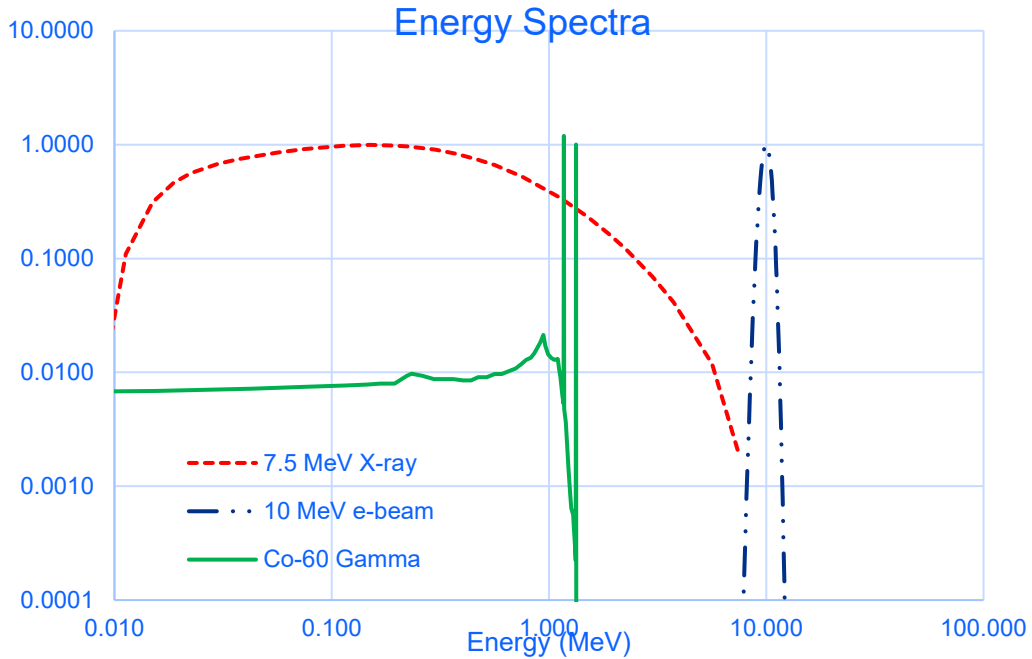
- Photons Produce Electrons
  - Compton Scattering
  - Photo-electric Effect
  - Pair Production
  - Photon Auger



- Electrons Produce Photons
  - Bremsstrahlung
  - Positron Annihilation
  - Electron X-rays
  - Fluorescence

- Electrons Produce Electrons
  - Electron Auger
  - Delta Rays (Knock-on)

Energy Spectra for each



The broad spectrum of energies for x-rays is the only reason for concern that they may not be <u>exactly</u> equivalent to gamma from Co-60.

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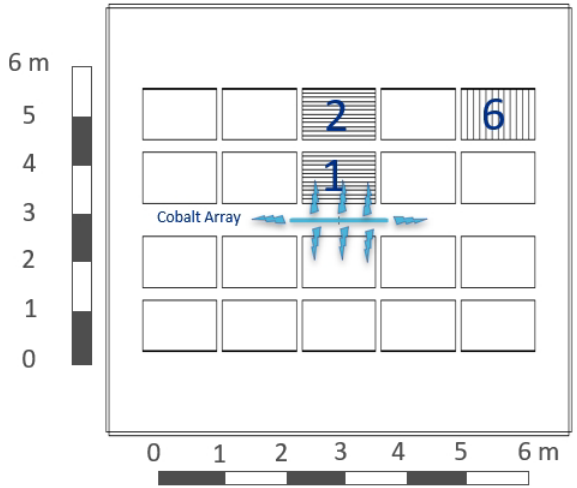
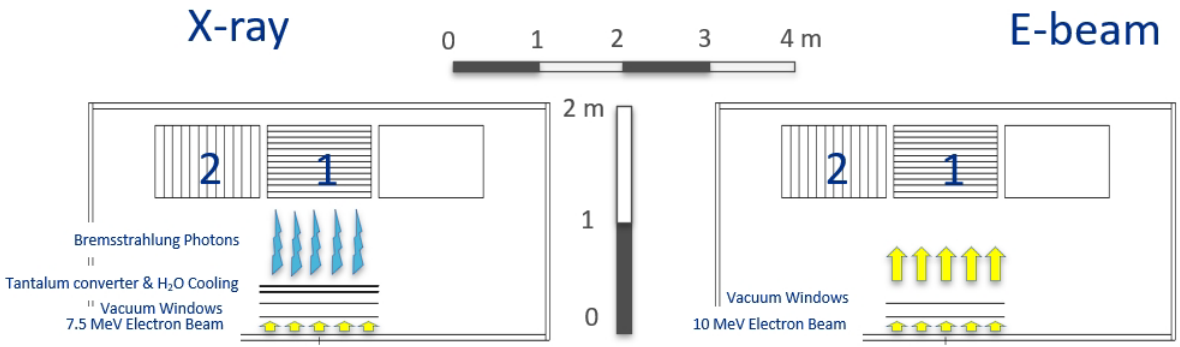
Simulated Geometry



Cobalt



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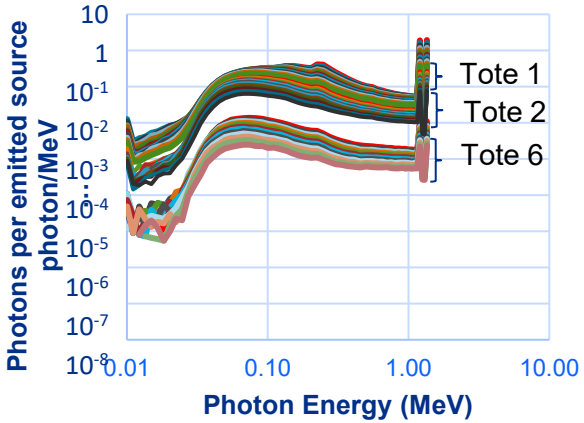
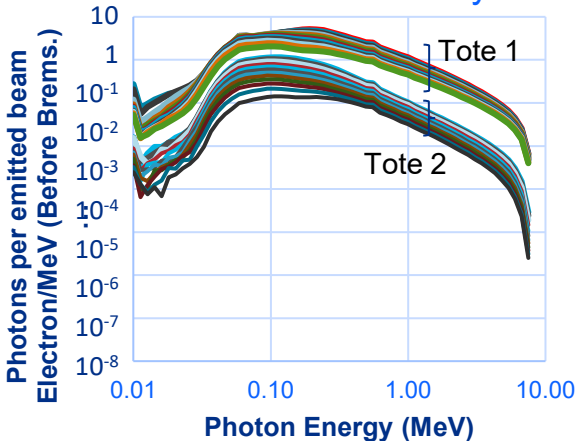
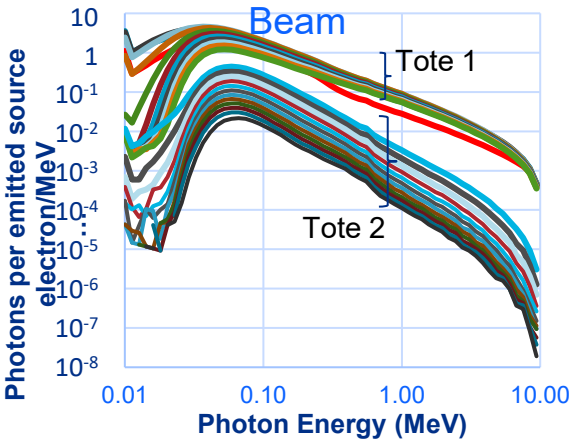
Photons in Totes - Cobalt



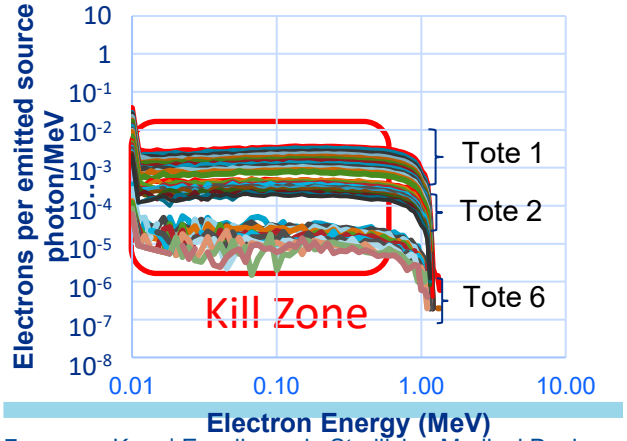
Photons in Totes - X-ray



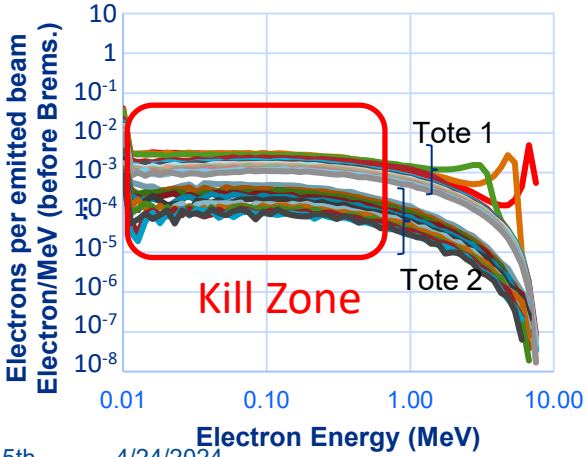
Photons in Totes - Electron Beam



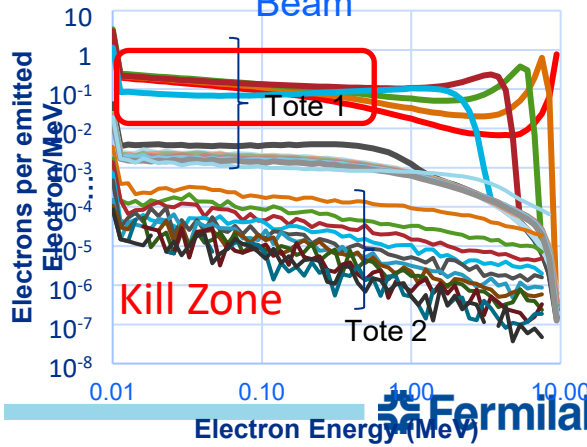
Electrons in Totes - Cobalt



Electrons in Totes - X-ray



Electrons in Totes - Electron Beam



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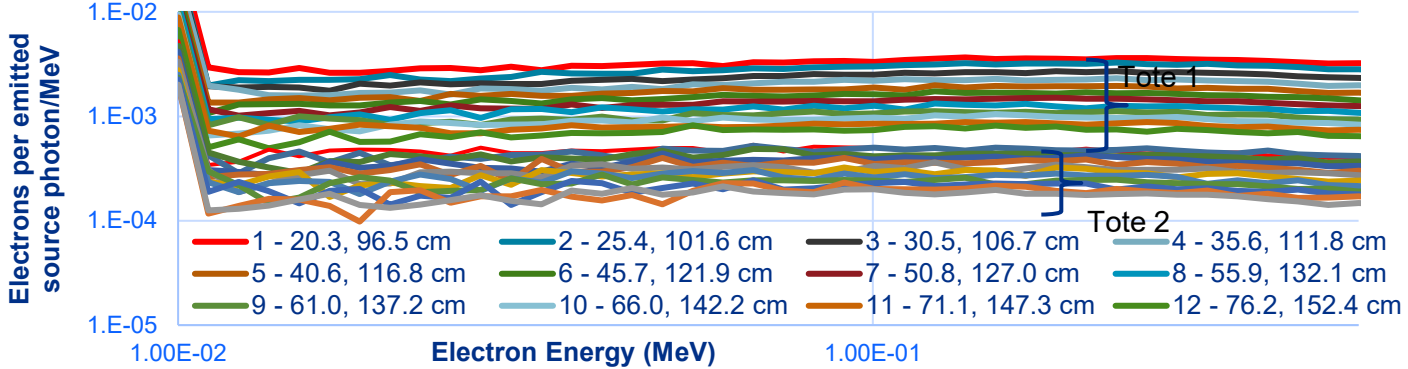
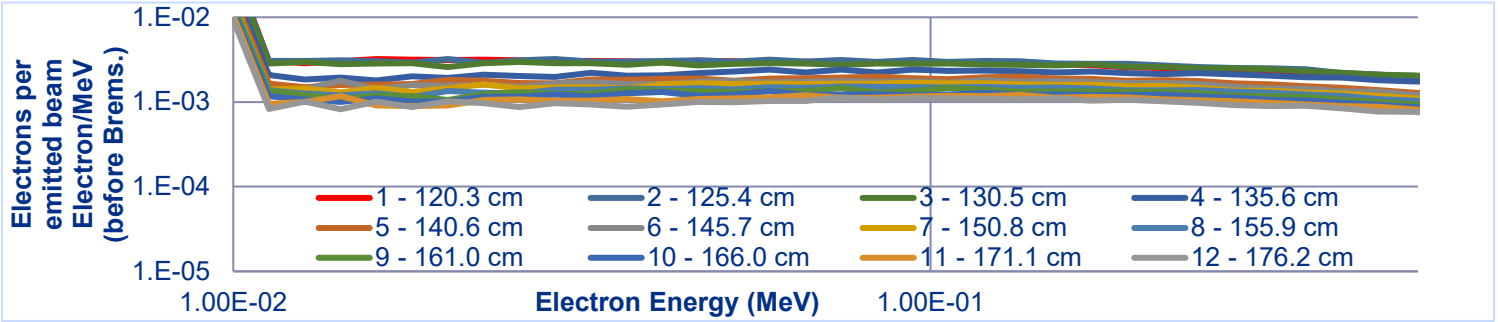
Electrons In Totes

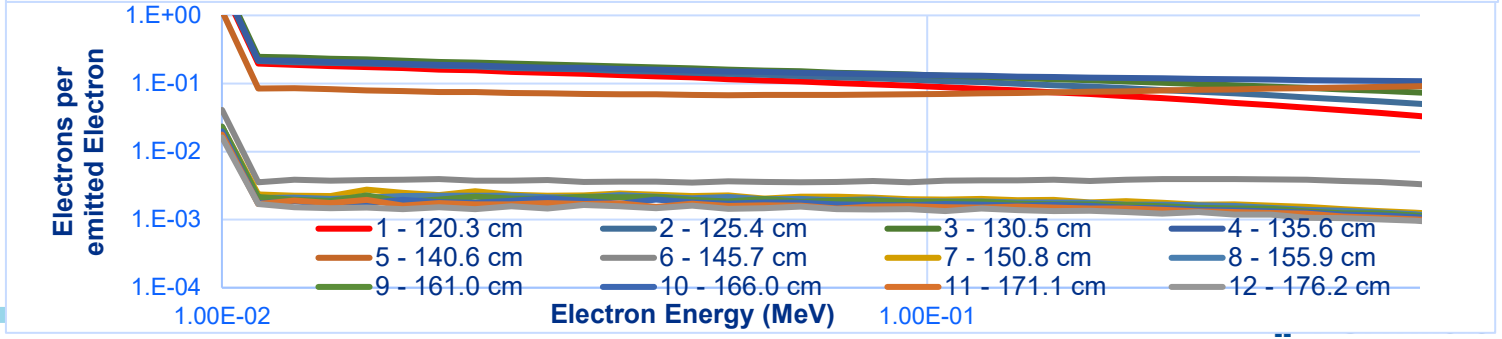
Cobalt



X-ray



Electron Beam



Bremsstrahlung Efficiency

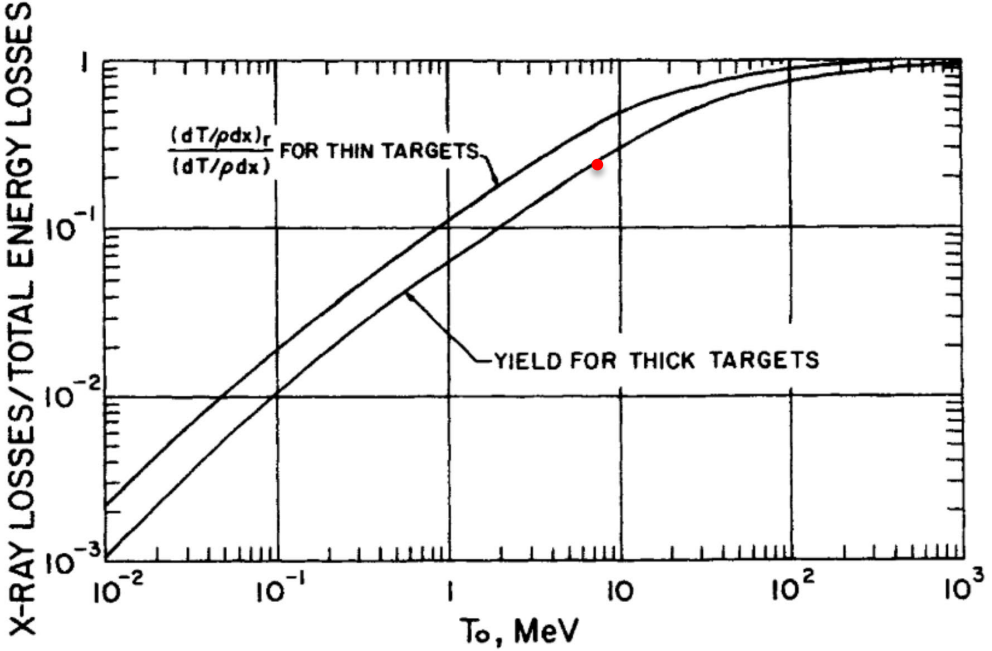


FIGURE 9.4. Fraction of electron energy losses that are spent in bremsstrahlung x-ray production in thin (upper curve) or thick (lower curve) tungsten targets (data after Berger and Seltzer, 1983). Upper curve: Eq. (9.2); lower curve: radiation yield (fraction of the incident electron kinetic energy T_0 that goes into x-ray production as the particle slows to a stop in a thick target).

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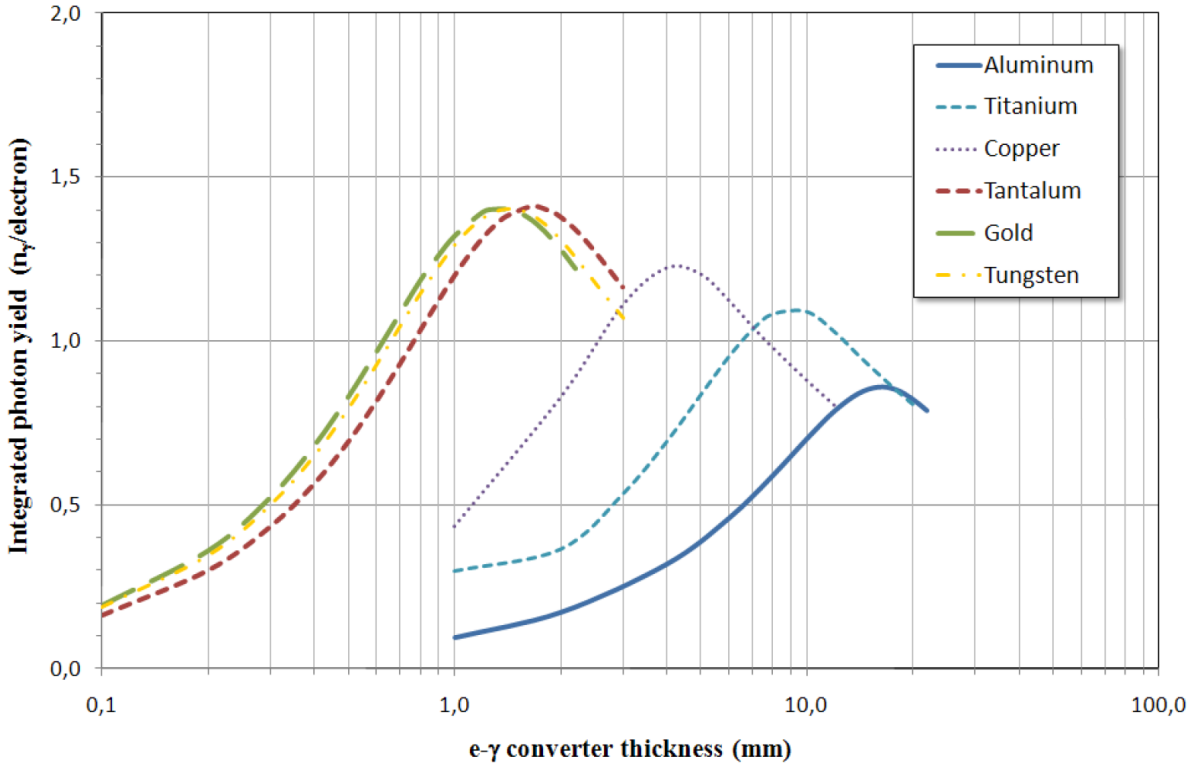
Bremsstrahlung Efficiency



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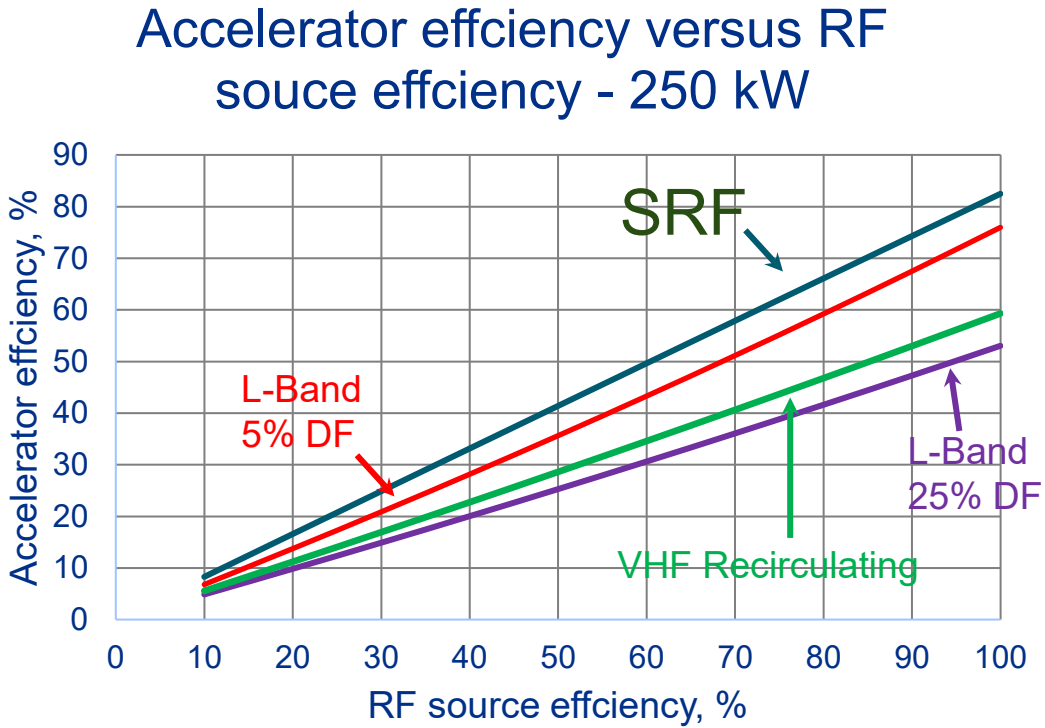
Efficiency

- Total efficiency = Bremsstrahlung efficiency * Accelerator efficiency



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Status of SRF

- Technology of choice for discovery science
  - SNS
  - LCLS-II
  - PIP-II
- High gradient, cutting edge (but requires)
  - Large infrastructure
  - Skilled workforce

How to transfer to industry?

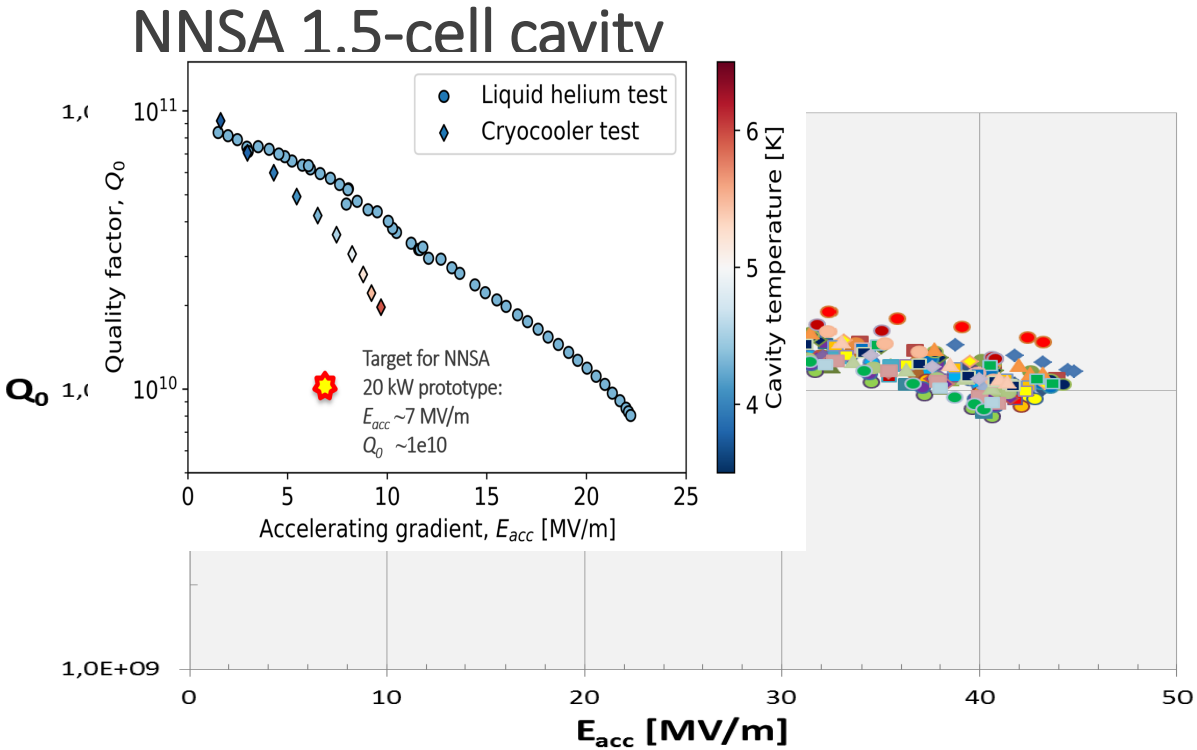
- Why? - Enhances security
  - NNSA/ORS REDUCE Objective
    - reduce reliance on radioisotopes through the development of alternative sources of radiation
- Why? – Opens new applications
  - Environmental
  - Powerful X-ray sources
    - Medical device sterilization
- How?
  - Simple – reduced gradient
  - Robust – must survive transition to industrial environment
  - Easy to use – less reliance on skilled workforce
  - Reliable – predictable maintenance schedule

What enables industry transfer?

- Conduction Cooling w/cryocoolers
  - Eliminates liquid cryogenic system
  - Use simple cryomodules
- Nb_3Sn coating
  - Puts operating temperature in cryocooler range
  - Operating temperature increases from 2K to 4K
- Integrated electron source
  - Minimizes heat from ambient
  - More compact, no LEBT
- Low heat-leak RF coupler
  - Minimizes heat from ambient

Heat load at ~5 Kelvin	Value [W]
RF dissipation in cavity (with Q_0 = 1e10)	1.46
Gun static heat leak	0.08
Cathode radiation to cavity (temp = 1373 K)	0.22
Conduction through cavity supports	0.1
Conduction through outlet beam pipe	0.1
Thermal radiation to cavity from thermal shield	0.1
Thermal radiation to cavity through beam pipe window	0.24
Beam loss (1e-6 of 20 kW = 0.02 W)	0.02
Coupler static + dynamic at 20 kW cw	1.0
Total	3.5

Simple – reduced gradient



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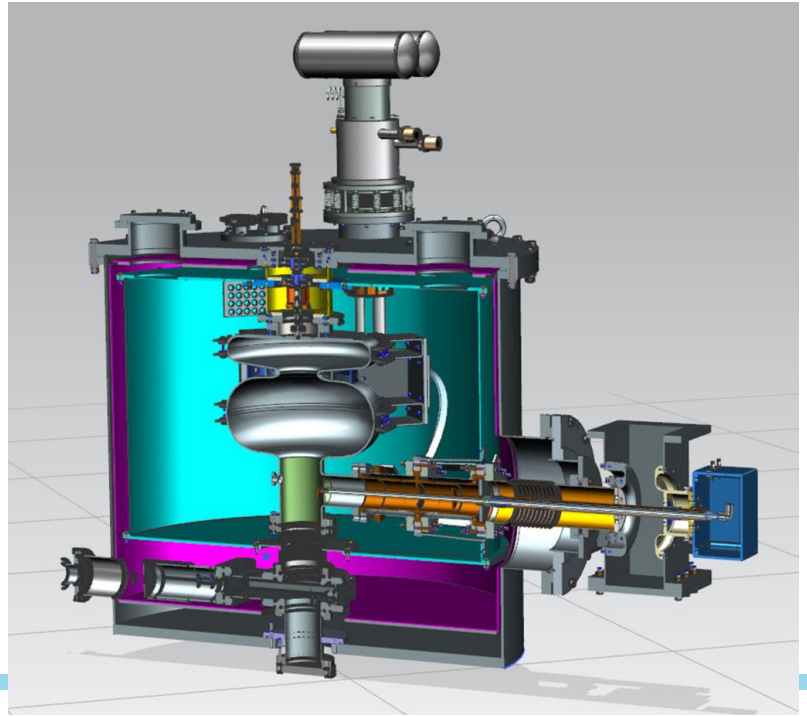
Status of development

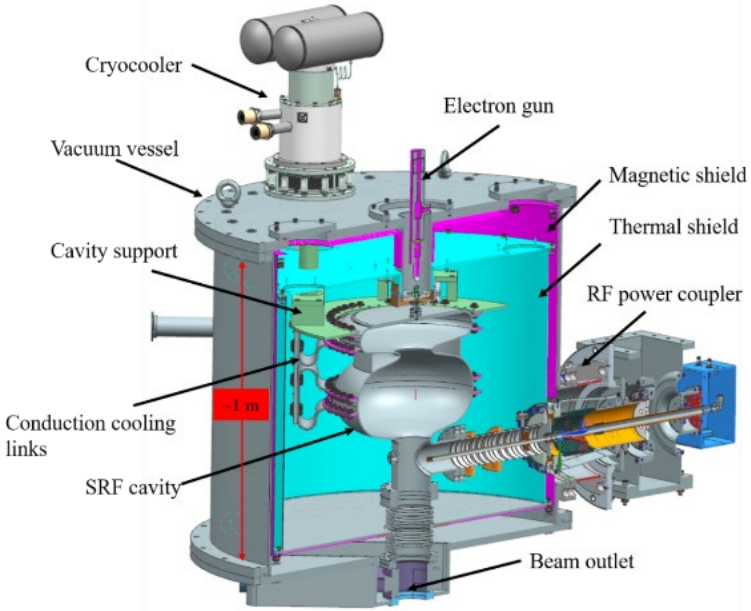
- 20 kW, 1.6 MeV, 650 MHz prototype
  - To validate the integration of the enabling technologies



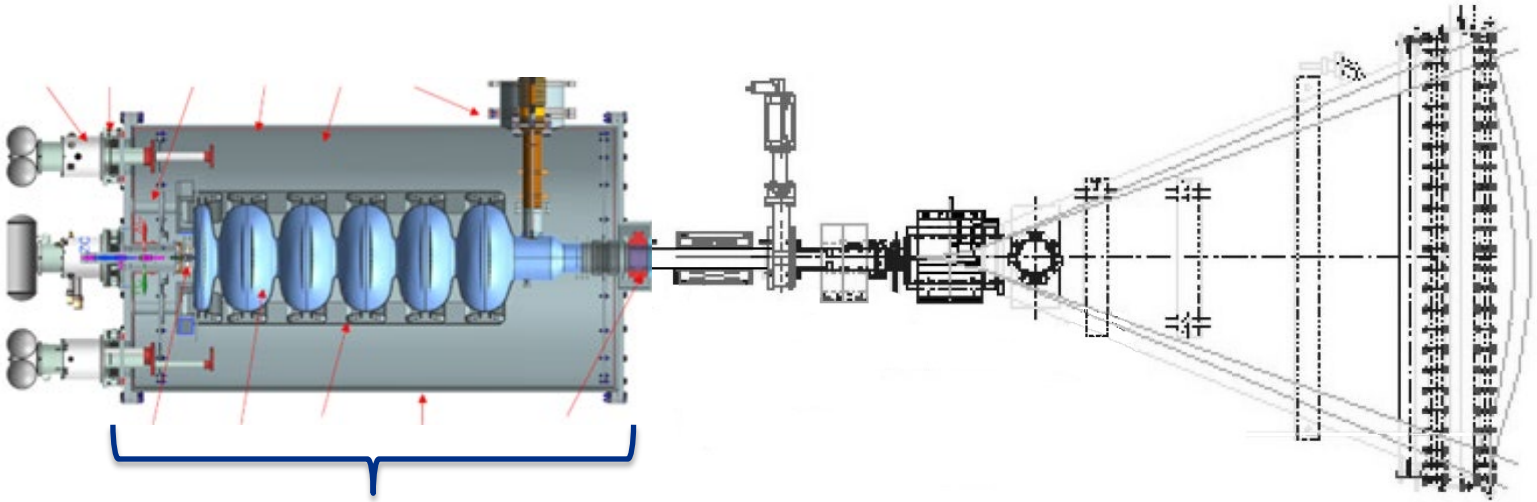
Design of CW, 1.6 MeV, 20 kW compact SRF e-beam accelerator

Development specifically directed towards medical device sterilization

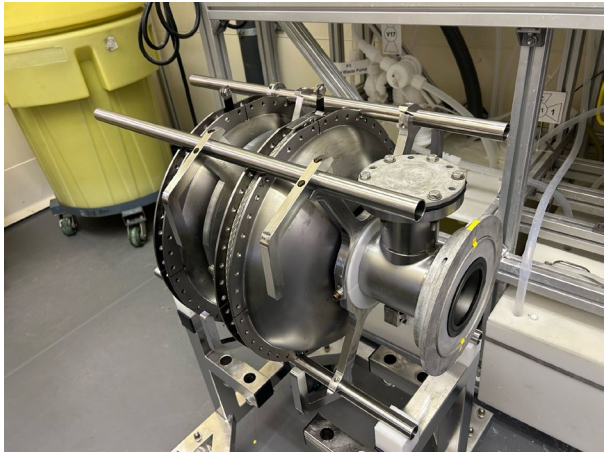
- Integrated Electron Gun – 0.3 W
- Nb_3Sn Coated Cavities – 1.9 W
- Low heat-loss RF coupler – 1.0 W
- Beam loss, etc – 0.3 W
- Total = 3.5 W
- Conduction Cooling w/ Cryocoolers – 2 or 3
- 1.6 MeV, 20 kW, 650 MHz
- Demonstration of the integration of the technologies
- To be completed in FY24

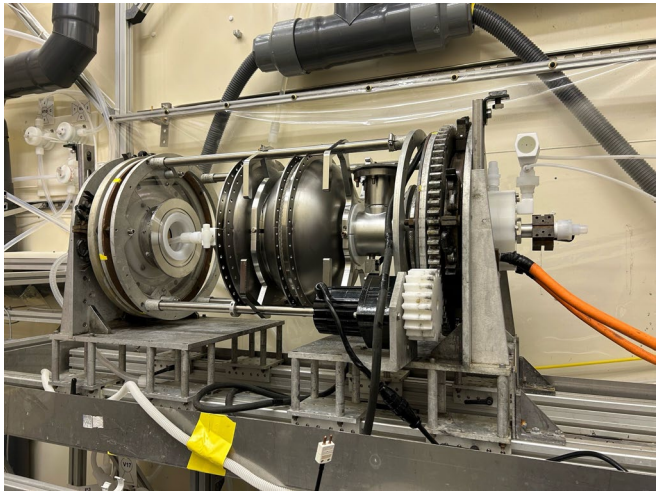


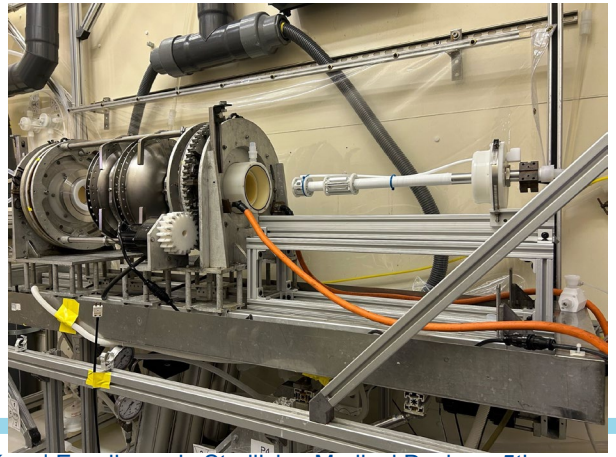
Ultimate Goal: 7.5 – 10 MeV, > 200 kW



Prep for Electropolish







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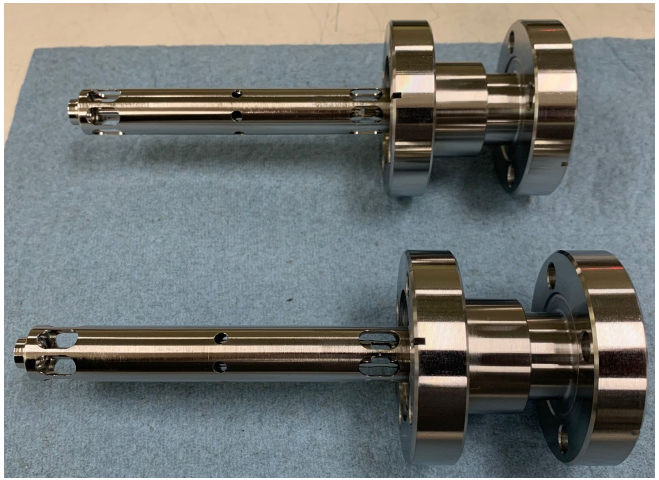
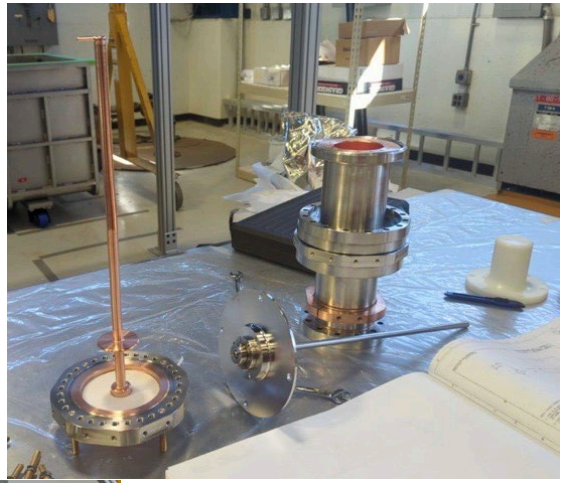
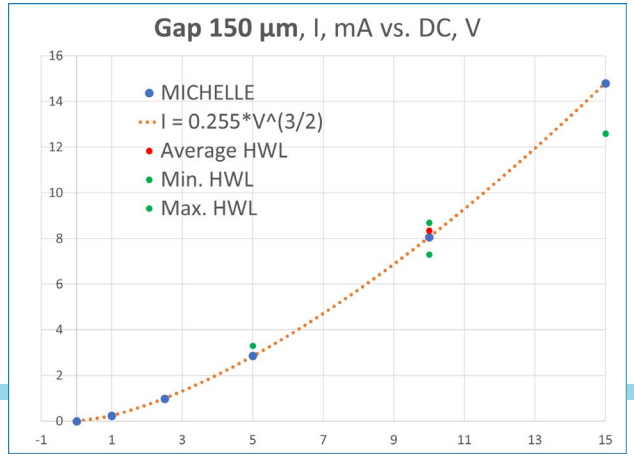
Electron Source & RF Coupler







Complete System - CW, 10 MeV, 1 MW compact SRF e-beam accelerator

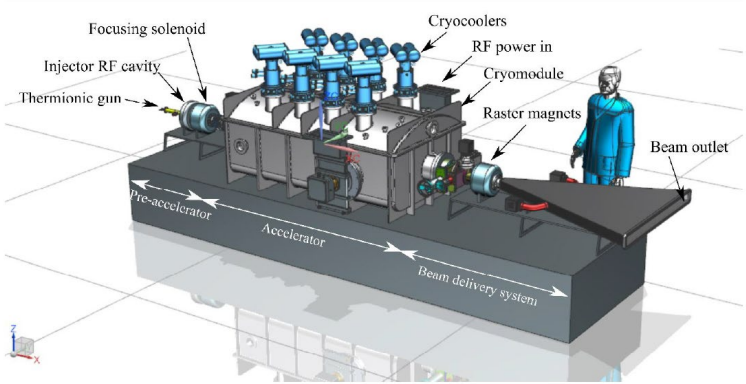


Figure 1: E-beam accelerator components and layout. The overall size is ~4 m long (end-to-end), ~2 m wide, and ~2 m tall.

- Energy: ~ 10 MeV
- Power: 1 MW
- High reliability
- Low cost

- Designed for 12 million gallons/day
- Projected ~$8M capital cost
- ~13.5 ¢/ton/kGy
- Dewatered biosolid sludge
- Pre-anaerobic digester thickened Waste Activated Sludge

Control System

- Full-stack, integrated hardware-software control platform based on Edge computing
- 100% Open Source, Free
- designed for remote access
- Role-based access
  - Know who touched what and when

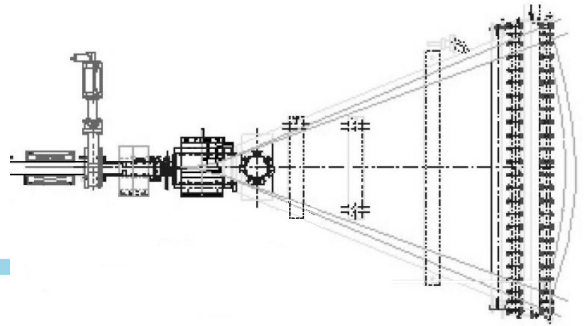
- Multiple device interfaces
  - Serial (Bluetooth, RS232, RS485, UART, USB, Modbus, TCP, analog, etc.
- Scalar, vector, and image data archiving,
- SMS alarming
- Post-mortem triggers
- Logbook
- Scalar and vector displays

- Access logging
- Settings logging
- Device and application role based access
- Zero code user application builder
- Personalized user application launcher

Blinky-Lite  https://www.blinky-lite.se

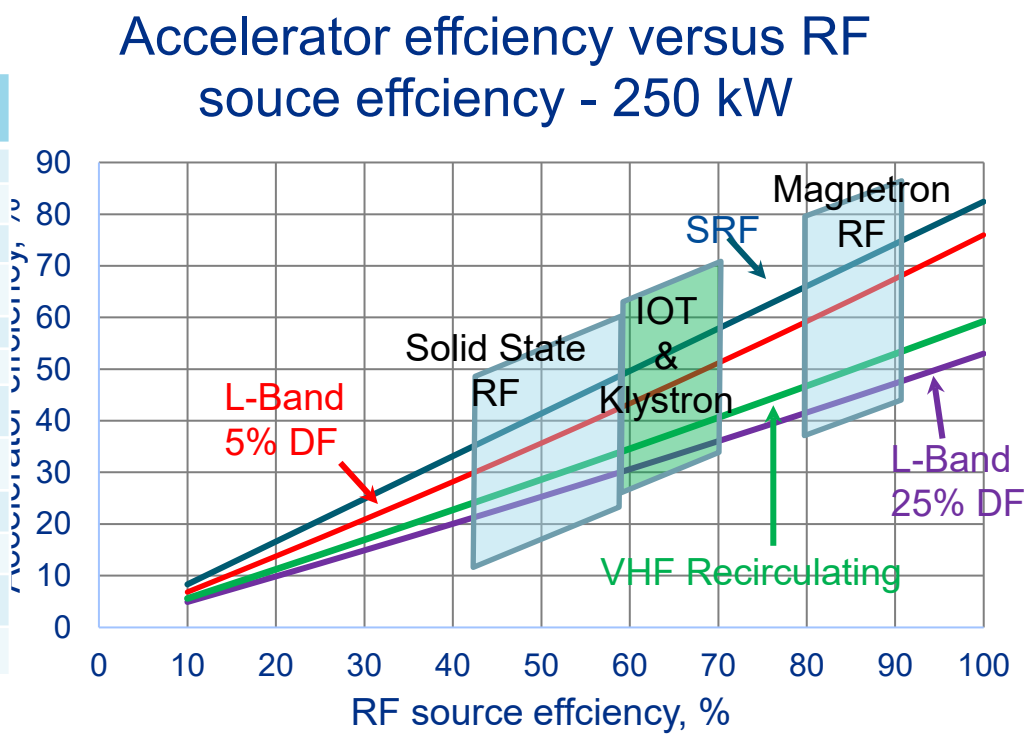
ACCELERATE – Jlab, FNAL, FIU: (GA)

- Vacuum Chamber Construction
  - What vacuum chamber properties drive cost?
  - Is there a transition where two chambers are less expensive than one larger one?
    - Is this driven by volume of the structure or window heating for megawatt systems?
  - Are internal support structures (posts or septa) viable with beam interruption during sweep?
- Window Heating
  - What are the constraints for cooling vacuum windows (e-beam, X-ray) and converters (X-ray)?
    - How much energy can materials dissipate naturally?
    - What temperatures are acceptable?
  - What are the capabilities of forced air cooling?
  - Are water cooling channels possible? Just along the edge? Or can there be cross members?
    - Does beam need to be interrupted as it passes over cross member?
  - Can 2-D scanning (zig-zag) help?



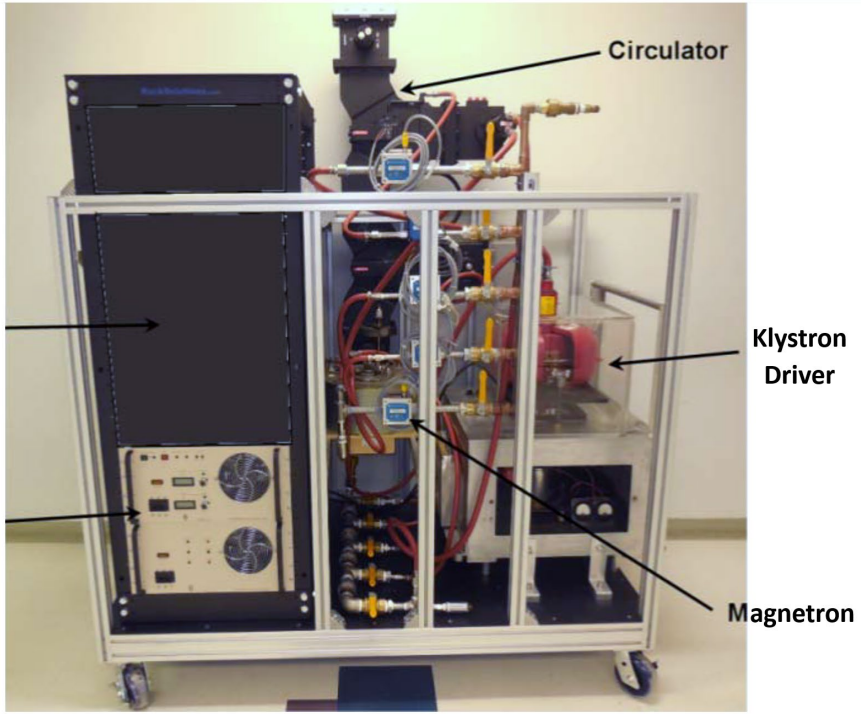
Use Energy as Efficiently as Possible

		SRF Nb_3Sn (DC)	L-Band Linac	L-Band Linac	Recirculating VHF (DC)
Frequency	MHz	650	1300	1300	107.5
Length	M	1.6	3.25	3.25	2 (diam.)
Energy	MeV	10	10	10	10
Average Beam Power	kW	250	250	250	250
Duty Factor	%	100	5	25	100
Pulsed Beam Power	kW	250	5000	1000	250
Power for Refrigeration	kW	40	N/A	N/A	N/A
Pulsed Ohmic Losses in the Linac	kW	N/A	540	540	86 (DC)
Pulsed RF Power	kW	N/A	5540	1540	N/A
Average RF Power	kW	250	277	385	336
Average Ohmic Losses	kW	N/A	27	135	86
Beam Current	mA	25	500	100	25



Magnetron Requirements

- Consistent, long lifetime (> 10,000 hours)
- Simple replacement of tube
- Ancillary systems also need attention
  - High Voltage power supply
- Who will pay for NRE?



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Thank you

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