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**
  - He\(^{2+}\)
  - Very Shallow

- **Beta**
  - Electrons
  - Penetration depends on energy
  - 10 MeV, 5 cm in H\(_2\)O

- **(Photons)**
  - Gamma
  - X-ray
  - 10s of cm in H\(_2\)O
  - (UV light)
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)
The broad spectrum of energies for x-rays is the only reason for concern that they may not be exactly equivalent to gamma from Co-60.
Simulated Geometry

Cobalt Array

X-ray

E-beam

Bremsstrahlung Photons

Tantalum converter & H2O Cooling

Vacuum Windows 7.5 MeV Electron Beam

Vacuum Windows 10 MeV Electron Beam
Bremsstrahlung Efficiency

![Graph showing bremsstrahlung efficiency for thin and thick targets.](image)

**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).
Bremsstrahlung Efficiency
Efficiency

- Total efficiency = Bremsstrahlung efficiency * Accelerator efficiency

Accelerator efficiency versus RF source efficiency - 250 kW

- L-Band
  - 5% DF
- SRF
- VHF Recirculating

- L-Band
  - 25% DF
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$_3$Sn 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

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

NNSA 1.5-cell cavity

![Graph showing quality factor, Q_0, versus accelerating gradient, E_{acc}, with data points for liquid helium and cryocooler tests.]

Target for NNSA:
- 20 kW prototype:
  - $E_{acc} \approx 7$ MV/m
  - $Q_0 \approx 1 \times 10^{10}$

Fermilab
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$_3$Sn 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

Approx. 2m
Prep for Electropolish
Electron Source & RF Coupler

Gap 150 µm, I, mA vs. DC, V

- MICHELLE
- I = 0.255*V^(3/2)
- Average HWL
- Min. HWL
- Max. HWL
Complete System - CW, 10 MeV, 1 MW compact SRF e-beam accelerator

- 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

<table>
<thead>
<tr>
<th>Frequency</th>
<th>SRF Nb$_3$Sn (DC)</th>
<th>L-Band Linac</th>
<th>L-Band Linac</th>
<th>Recirculating VHF (DC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MHz</td>
<td>650</td>
<td>1300</td>
<td>1300</td>
<td>107.5</td>
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<tr>
<td>Length</td>
<td>M</td>
<td>1.6</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Energy</td>
<td>MeV</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Average Beam Power</td>
<td>kW</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>%</td>
<td>100</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Pulsed Beam Power</td>
<td>kW</td>
<td>250</td>
<td>5000</td>
<td>1000</td>
</tr>
<tr>
<td>Power for Refrigeration</td>
<td>kW</td>
<td>40</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Pulsed Ohmic Losses in the Linac</td>
<td>kW</td>
<td>N/A</td>
<td>540</td>
<td>540</td>
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<tr>
<td>Pulsed RF Power</td>
<td>kW</td>
<td>N/A</td>
<td>5540</td>
<td>1540</td>
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<tr>
<td>Average RF Power</td>
<td>kW</td>
<td>250</td>
<td>277</td>
<td>385</td>
</tr>
<tr>
<td>Average Ohmic Losses</td>
<td>kW</td>
<td>N/A</td>
<td>27</td>
<td>135</td>
</tr>
<tr>
<td>Beam Current</td>
<td>mA</td>
<td>25</td>
<td>500</td>
<td>100</td>
</tr>
</tbody>
</table>

Accelerator efficiency versus RF source efficiency - 250 kW

- SRF
- RF
- Magnetron
- Solid State RF
- IOT & Klystron
- L-Band RF
- L-Band 5% DF
- L-Band 25% DF
- VHF Recirculating
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?