A Compact Superconducting RF Accelerator for Electron Beam and X-ray Irradiation

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Industrial-scale electron accelerators – the Need

Energy and Environment
• Waste water and sludge
• In-situ applications
  – Sediments
  – Hydrocarbon upgrading

Industrial
• In-situ cross linking at deeper penetration
• Food and medical device sterilization without $^{60}$Co
• Radiation driven chemistry

Safeguards and Security
• Non-invasive and stand-off inspection
Industrial-scale electron accelerators – the Need

EBFGT

“The most important is the high power accelerators state-of-art. The power of existing accelerators allows for construction of flue gas treatment facilities for low and medium size power generation units. On the other hand, the reliability of such big machines is still regarded as not satisfactory (over 8500 hours of operation per year is required) and the price of this apparatus is high.”

# Industrial-scale electron accelerators – present status

<table>
<thead>
<tr>
<th>Continuous</th>
<th>Continuous</th>
<th>Pulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILU</td>
<td>Dynamitron</td>
<td>Mevex</td>
</tr>
<tr>
<td>1 – 10 MeV</td>
<td>0.5 – 5 MeV</td>
<td>5 – 25 MeV</td>
</tr>
<tr>
<td>20 – 100 kW</td>
<td>88 – 250 kW</td>
<td>250 kW – 2.5 MW</td>
</tr>
<tr>
<td>ELV</td>
<td>Rhodotron</td>
<td>– instantaneous</td>
</tr>
<tr>
<td>0.7 – 1.5 MeV</td>
<td>5 – 10 MeV</td>
<td></td>
</tr>
<tr>
<td>20 – 400 kW</td>
<td>50 – 560 kW</td>
<td></td>
</tr>
<tr>
<td>Elektron</td>
<td></td>
<td>Varian</td>
</tr>
<tr>
<td>5 – 10 MeV</td>
<td></td>
<td>3 – 15 MeV</td>
</tr>
<tr>
<td>15 – 150 kW</td>
<td></td>
<td>8 – 25 kW</td>
</tr>
</tbody>
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Industrial-scale electron accelerators – present status

- PET isotope production
- SPECT isotope production
- Possible Accelerator
- Proton Therapy

- Compact SRF (FNAL)
- IBA
- ILU & ELV
- Cenex
- Varian
- other

Beam Power (KW) vs. Energy (MeV) graph

- Mo-99
- +

Fermilab
What are we doing to address this need?

- Designing an accelerator that is:
  - High Energy – 10 MeV
  - High power – 250 – 1000 kW
  - Compact
  - Reliable
  - Turn-key
  - CW (@ 650 MHz)
What we are doing

We are combining a number of state-of-the-art technological advances into a simple to operate, compact, superconducting RF accelerator.

- Inexpensive (relatively)
- Efficient
  - > 80%, mains to e-beam
- Turn key operation
- High reliability
- ≤ 10 MeV
- ≤ 1000 kW
- ~ 0.7m Ø x 1.5 m long
Heat – the major villain

Eliminate liquid cryogens

• Conduction cooling
  – No LHe
• Commercial cryocoolers
  – 2W each @ 4 K
  – 12.5 kW
Conduction Cooling

Cold head(s) of the cryocooler(s) connected to cavities by high purity aluminum

Heat Budget
4 – 6 W
US patent applications
#15/280,107
#14/689,695
How do we accommodate the heat budget?

- Higher temperature superconductor
  - Very high quality factors
  - < 2.5 W @ 4K
- Low loss RF power couplers
  - 10 kW with < 0.7 W @ 4K
- Integrated electron gun
  - < 0.1 W @ 4K
Higher temperature SRF cavities

**Nb$_3$Sn Coated SRF Cavities**

- 1.3 GHz, 14 MV/m, Q=2x10$^{10}$ @ 4K
- At 650 MHz, we predict < 2.5 W @ 4K
- Sam Posen
  - $2.5M$ DOE Early Career Award
- First article @ FNAL within factor of 3 of Cornell performance
Low loss RF power couplers
FNAL and Euclid TechLabs

- Patent application # 15/278,299
- DOE OHEP grant to fund fabrication of two 1.3 GHz prototypes
- Testing this year
- Eliminates copper plating
**Integrated Electron Gun**
Reduces size and complexity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>9 MeV±5%</td>
</tr>
<tr>
<td>Current modulation range</td>
<td>0.1 μA - 1 mA</td>
</tr>
<tr>
<td>Beam loss at 4K</td>
<td>&lt;0.5 W</td>
</tr>
<tr>
<td>Cathode backward bombardment</td>
<td>&lt;1 W</td>
</tr>
<tr>
<td>Cathode blackbody radiation</td>
<td>&lt;200 mW</td>
</tr>
</tbody>
</table>
Reduce cost

Injection locked magnetron (PCT/US2014/058750)
- Reduce cost/watt by factor of 5 over IOT and solid state
- Efficiency > 80%
- Excellent phase and amplitude control

Conceptual scheme of a single 2-cascade magnetron transmitter allowing dynamic phase and power control
The Compact SRF Accelerator

- Low Heat-loss RF Coupler
- Cryo-cooler Cold Head
- Integrated Electron Gun
- Coated Cavities
- \(Nb_3Sn\)
- No LHe

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Fermilab
Biomass pretreatment

- Electron range
  - Hardwood (maple) - 6.4 cm
  - Switchgrass - 45 cm
- Dose required for wood
  - 750 kGy (?)
  - 1.2 tonne/hr @ 250 kW

Pictures courtesy of M. Driscoll, SUNY
Thank you