Compact, high power SRF Accelerators for Industrial Applications

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Superconducting Radio Frequency (SRF)

~ All new high beam power accelerators for discovery science employ SRF

- Why?
  - Because ~all RF power \(\rightarrow\) beam power vs heating RF resonators
  - SRF \(\rightarrow\) Higher gradient, more energy per unit length

- But current SRF “science” accelerators are large and complex
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 \(\Rightarrow\) 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 \(\Rightarrow\) 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)
Recent SRF Technology Breakthroughs:

- **Higher temperature superconductors**: Nb$_3$Sn 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**
Can now contemplate a **simple** SRF accelerator*

- 650 MHz elliptical cavity (well understood, industrial vendors)
- Commercial 4K cryo-coolers (2.5 W available now, 3-5 W soon)
- Modular design scales to MW class industrial applications
- Compact ➔ lower shielding cost, lower CAPEX
- Accelerator system <3000 lbs enables **mobile** applications

* FNAL patents pending
Vision: Build a high power SRF industrial accelerator*

We will combine state-of-the-art technological advances to create a simple, compact, high power, superconducting RF based industrial accelerator.

• Efficient
  – > 75%, mains to e-beam
• Turn key operation
• High reliability
• ~10 MeV electron beam
• > 250 kW
• ~ 0.7m Ø x 1.5 m long
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
- Upgrade of heavy oil, flare gas

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)
In-situ Environmental Remediation

• Since e-beams can disinfect or destroy organic compounds
• One can envision mobile SRF based accelerators for environmental remediation & decontamination.

• Examples
  – Clean soil contaminated by chemical spills
  – Remove hydrocarbons from soil
  – Destroy biohazards or toxins
  – Remove PCB’s from dredge spoil
  – Provide an alternative to incineration

• Requires robust, reliable, compact, mobile accelerators that can be “brought to the problem”
In-Situ Cross-Link of Materials

Electron accelerators are widely used to cross link materials

• High power mobile accelerators enable entirely new construction techniques that can alter materials properties after placement
  – e.g. Improve the strength, toughness, and/or temperature range

• One applications: Improved Pavement
  – US Army Corps of Engineers partnership (FY17 ERDC funding)

• Collaborating to create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime

• U.S. spends > $ 50 B/yr to grind off and replace asphalt!
Nb3Sn vs Nb

Comparison to niobium

Conventional niobium cavity at 4.2 K

Nb3Sn cavity at 4.2 K

$20 \times$ more efficient than Nb at 4.2 K!

Data taken at 4.2 K
1.3 GHz ILC single-cells
Higher temperature SRF cavities

Nb$_3$Sn Coated SRF Cavities

- 1.3 GHz, 14 MV/m, $Q=2\times10^{10}$ @ 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
Progress of Nb$_3$Sn Films

Substantial progress in performance over last year

650 MHz 1-cell: First 650 MHz coating

Machining completed on multicell sample cavity

Cavity is welded, going to baseline test soon
Beam Physics: Simulated Integrated Electron Gun

Reduces size and complexity

<table>
<thead>
<tr>
<th></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>
Simulations of the Cavity

- (Top) Bunch acceleration along the cavity (RMS energy).
- (Bottom Left) Transverse (x-x’) phase-space distribution.
- (Bottom Right) Transverse beam charge density distribution.

Particle losses in simulations < 10^-5. (This is important for the heat budget)
• Beamdynamics simulation was performed using TRACEWIN.
• 1M macro particles corresponds to 100mA beam current was tracked through the beamline.
• Initial distribution was generated using Twiss parameters and beam emittance obtained from RF gun simulation.
Beamdynamics Simulation from external injection (2)

- Output beam distribution at the end of the beamline
Conduction Cooling R&D

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

Estimated heat budget for entire accelerator = 4 – 6 W @ 4K

Remove heat by conduction only!

US patent applications

#15/280,107

#14/689,695
Conduction Cooling R&D

- Testing with commercial cryocooler
  - Goal = eliminate liquid cryogens
  - Materials and technology
    Development in progress

- Funded by $ 1.4 M LDRD Project
Challenges

• Magnetic shield
  - SRF cavities are very sensitive to trapped magnetic fields
  - need < few mG to keep RF heat dissipation under cryocooler budget
  - penetrations and access ports are to be carefully designed

• Interfaces with e-gun, power coupler, beam outlet port

Magnetic shield with penetrations

Vacuum vessel
Thermal shield
Cavity

Shut-off valve at beam outlet
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
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
Radiation Shielding: Development of a computer model

- A 3-D computer model was developed to address absorbed dose rate in the water and evaluation of back scattered particles energy distribution at 4K and 70 K in the cryostat.

- A realistic Model was prepared by accounting EM fields in SRF cavities, 3-D geometry of elements, materials and their thickness.

Extractor: 50 um Ti single foil design with window 80mm x 1250mm (current density = 0.1mA/cm²)
The Compact SRF Accelerator (for scale)
The Compact SRF Accelerator

- Low Heat-loss RF Coupler
- Cryo-cooler Cold Head
- Integrated Electron Gun
- Nb$_3$Sn Coated Cavities
- No LHe
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>
<thead>
<tr>
<th>Example Applications</th>
<th>Type 1 Demo/Small Scale</th>
<th>Type 2 Medium Scale Low Energy</th>
<th>Type 3 Medium Scale High Energy</th>
<th>Type 4 Large Scale High Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;D, Sterilization, industrial effluent streams</td>
<td>0.5-1.5 MeV</td>
<td>1-2 MeV</td>
<td>10 MeV</td>
<td>10 MeV</td>
</tr>
<tr>
<td>Flue Gas, Waste water</td>
<td>&gt;0.5 MW</td>
<td>&gt;1 MW</td>
<td>&gt;1 MW</td>
<td>&gt;10 MW</td>
</tr>
<tr>
<td>Wastewater, sludge, medical waste</td>
<td>&gt;50%</td>
<td>&gt;50%</td>
<td>&gt;50%</td>
<td>&gt;75%</td>
</tr>
<tr>
<td>Sludge, Medical waste, Env. remediation</td>
<td>&lt;$10/W</td>
<td>&lt;$10/W</td>
<td>&lt;$10/W</td>
<td>&lt;$5/W</td>
</tr>
<tr>
<td>Target Operating Cost†</td>
<td>&lt;1.0MS/yr</td>
<td>&lt;1.5MS/yr</td>
<td>&lt;1.5MS/yr</td>
<td>&lt;12MS/yr</td>
</tr>
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This two-day workshop will include expert speakers on the current state of wastewater treatment, a summary of the science of using e-beam technology for treatment of waste, the current state of e-beam accelerator technology, a tour of Fermilab National Accelerator Lab, panel discussions with water treatment experts, breakout discussions and a summary close-out session.

**Title:**
Workshop on Application of Electron Beam (EB) Technology on Wastewater and Biosolids Treatment

**Purpose:**
- Promote use of e-beam technology for wastewater and biosolids treatment
- Inform water treatment professionals about e-beam technology and opportunities
- Provide feedback to NSF to open future funding opportunities

**Format:**
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Post conference a report will be issued with findings and recommendations.

**Where:**
Illinois Accelerator Research Center, Fermi National Accelerator Lab
1 MeV, 1 MW SRF accelerator

G. Ciovati, R. Rimmer, F. Hannon, J. Guo, F. Marhauser, V. Vylet
J. Rathke, T. Schultheiss

J. Anderson, B. Coriton, L. Holland, M. LeSher


10 MeV, 1 MW SRF accelerator

250 kW unit

T. Kroc, C. Cooper, J. Thangaraj, R. Dhuley, M. Geelhoed

Philippe Piot
Sandra Biedron
A. Kanareykin

Facilities Layout

1 MeV, 1 MW EB facility

10 MeV, 1 MW EB facility

250 kW unit

Output beam

~14 ft

~30 ft

~20 ft

~7 ft

× 4 (+1 spare)

Legend:

- horizontal raster magnet
- Vertical bend magnet

Jefferson Lab

Jayakar Thangaraj | Compact SRF accelerator applications: USPAS Lecture
Application: Waste Water/Sludge Treatment

- Electron beams create highly reactive species
- Demonstrated effective for:
  - Disinfection of municipal bio-solids
  - Destruction of organics, pharmaceuticals
- Yet, despite demonstrations ~no market penetration
- Why? Municipalities are conservative; don't finance R&D
  - High power, cost effective, industrial accelerators have not been available to deploy* e.g. *http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf
  - Compact SRF accelerators can change this situation
- IARC is partnered with the Chicago Metropolitan Water Reclamation District (MWRD)
  - Operate largest treatment plant in the world
  - Identified multiple areas to evaluate EB
  - Bio-solids, cell lysis, destroy pharmaceuticals

Accelerator above is 3 stories tall!
Application: Co $^{60}$ Replacement

• Electron beams can be used directly or to create x-rays to accomplish many tasks currently accomplished with Co60 radioisotopes
  – National security concerns with radioisotopes in large panoramic irradiators since they could potentially be used by terrorists to create dirty bombs
  – Pressure from congress on NNSA to find alternatives
  – FNAL recently completed a study for NNSA on impediments to change.
    • One impediment is the need for high power, reliable, cost effective electron accelerators
    • Need materials data on effects of gamma, electrons, x-ray to enable recertification of legacy products

• New Possibilities:
  – Cheap, compact, simple, industrial electron accelerators can enable “in line” sterilization at the point of manufacture
In-situ Environmental Remediation

- Since e-beams can disinfect or destroy organic compounds
- One can envision mobile SRF based accelerators for environmental remediation & decontamination.

**Examples**
- Clean soil contaminated by chemical spills
- Remove hydrocarbons from soil
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Conclusions

• Exploiting recent lab breakthroughs one can create high average power, CW, SRF-based electron linacs that are simple and cost effective for industrial applications

• 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 electron accelerators can enable a variety of entirely new industrial applications

• Several applications may have enormous market potential