Progress on a conduction cooled SRF cryomodule at Fermilab

Ram C. Dhuley
(with contributions from Fermilab AD/ME, APS-TD/SRF, and IARC@Fermilab)

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Cryocooler conduction cooled SRF

- Helium liquefier $\rightarrow$ Closed cycle cryocooler $\rightarrow$ reliable cryosystem
- Liquid helium bath $\rightarrow$ Conduction links $\rightarrow$ simpler cryomodule
- Simpler and more reliable cryosystem makes the SRF technology attractive for building compact accelerators for industrial applications

**Concept of cryocooler conduction cooled SRF**

**Rendering of a compact, conduction cooled SRF accelerator for industrial applications**
Conduction cooled SRF R&D at Fermilab

- Development and performance testing of cryocooler conduction-cooled SRF cavities (2018-22)
  - Demonstrated 10 MV/m cw on a single-cell 650 MHz Nb$_3$Sn cavity conduction cooled by a Cryomech PT420 cryocooler
  - [https://doi.org/10.1088/1757-899X/1240/1/012147](https://doi.org/10.1088/1757-899X/1240/1/012147) and [https://doi.org/10.1088/1361-6668/ab82f0](https://doi.org/10.1088/1361-6668/ab82f0)

- Design studies of high average power e-beam accelerators (2019-22)
  - Designed a 10 MeV, 1000 kW avg. power e-beam conduction cooled SRF accelerator for wastewater treatment
  - [https://doi.org/10.1103/PhysRevAccelBeams.25.041601](https://doi.org/10.1103/PhysRevAccelBeams.25.041601)

- e-beam SRF accelerator development (2021–ongoing)
  - **Build and operate a 1.6 MeV, 20 kW e-beam machine** [this talk]
  - **Build a 8 MeV, 20 kW e-beam machine for mobile applications** [J. Thangaraj talk; WG3 today 2:17 PM]
e-beam SRF accelerator development

- Motivation – Development of an alternative to Co-60 radiation sources for the medical devices sterilization industry
  - e-beam based X-ray sources is an attractive alternative
    - ~15 kW X-rays provide comparable radiation dose to ~1 MCi of Co-60
    - 150-200 kW e-beam is needed to produce 15-20 kW X-rays!
  - The high average-power e-beam requirement can be realized via cw operation of an SRF accelerator
  - Fermilab’s staged approach
    - Build components, integrate, and operate a 1.6 MeV, 20 kW e-beam machine
      - Integrated thermionic electron gun
      - Cryocooler conduction-cooled Nb₃Sn SRF cavity
      - Low heat leak power coupler
      - Low heat leak and magnetically shielded cryostat
      - Solid state RF power source
      - Beam delivery
    - Use experience and lessons learnt to build 8 MeV, 200 kW e-beam machine to produce X-rays for the medical devices sterilization industry
1.6 MeV, 20 kW conduction-cooled SRF accelerator cryostat

Cryocoolers
(Two thermal stages – 4 K, 45 K)

Thermionic electron source
(integrated with the cavity)

Vacuum vessel

Magnetic shield
(single layer, room T)

Thermal shield
(conduction cooled to the 45 K stage)

1.5-cell Nb$_3$Sn cavity (650 MHz)
(conduction cooled to the 4 K stage)

Power coupler

Beam outlet

~1 m diameter
**Component details**

**SRF cavity and heat load estimation**

<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>

Manageable with 2x Cryomech PT420 coolers
Component details

Verification of conduction cooling (RF + thermal simulation)

2 x cryocooler mounting pads

5N aluminum thermal link

FEA verification of thermal link performance

Surface Temperature (K)

$T_{max} \sim 6.51\,\text{K}$
Component details

- **Integrated thermionic cathode**
  - Courtesy: I. Gonin, V. Yakovlev, T. Nicol (Fermilab)

- **Low loss coupler (<1 W to 5 K)**
  - Courtesy: S. Kazakov (Fermilab)

- **Cryocoolers and compressors**
  - Courtesy: M.I. Geelhoed (Fermilab)

- **650 MHz, 20 kW solid state RF amplifiers**
  - Courtesy: C. Edwards (Fermilab)
Current status

- 1.5-cell SRF cavity → delivery expected in November 2022
- Power coupler → delivery expected in February 2023
- Thermionic gun → delivery expected in March 2023
- Cryostat
  - Cavity conduction links → fabricated and ready for assembly
  - Thermal shield → in procurement
  - Magnetic shield → in final design
  - Vacuum vessel → in final design
- LLRF and SSAs → at hand, to be commissioned in early 2023
- Test cave and water/electrical utilities → ready
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- DOE HEP Accelerator Stewardship (R.C. Dhuley)

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- Fermilab LDRD (S. Posen)
- DOE Early Career Award (S. Posen)

Funding for building the 1.6 MeV, 20 kW e-beam SRF accelerator
- US National Nuclear Security Administration (T. Kroc, R.C. Dhuley)

Thank you