A conduction-cooled SRF cavity: Apparatus and first results

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Goal: To demonstrate cryogen-free SRF cavity operation

Take out liquid helium (and its complexities)

Cool SRF cavities conductively with 4 K cryocoolers

Key thermal design criterion

- SRF cavities dissipate heat during operation (dynamic heat load)
- Cryocoolers have limited 4 K cooling capacity
- Need a high thermal conductance link to extract this dynamic load and transport to the cryocooler.
Cavity-cooler thermal link: Our design approach

Surface magnetic fields dissipate most heat near the equator

\[ P_{\text{diss}} = \frac{1}{2} R_s \int |H_s|^2 ds \]

E-beam weld niobium rings around the equator to attach a thermal link

O. Prokofiev
Cavity-cooler thermal link: Our design approach

Use high purity (5N) aluminum as the thermal link material

Measure and design low thermal resistance pressed niobium-aluminum contacts

Construct a thermal link for distributed cooling around the cavity equator

R. C. Dhuley et al., *Cryogenics* 93, 86-93, 2018

R. C. Dhuley et al., *IEEE TAS* 29(5), 0500205, 2019
Conduction cooled cavity test setup

Vacuum vessel
- SS304
- 5 feet tall

Cryocooler
- Cryomech PT420 (2 W @ 4.2 K with 55 W @ 45 K)

Magnetic shield
- MuMetal
- Room temperature
- <10 mG total field at the cavity location

Cavity and shield supports
- Ti64 rods

MLI wrapped thermal shield
- Cooled by cryocooler stage-1
- Copper 101 top plate
- Aluminum 1100 shell

SRF cavity
- Cooled by cryocooler stage-2
- Elliptical single cell, 650 MHz
- Niobium or Nb$_3$Sn coated
Conduction cooled cavity test setup

RF driver with feedback for PLL
Conduction cooled cavity test setup
Cool down characteristics

The cryostat cooled to its base temperature within 24 hours
- Cryocooler stage I < 30 K, thermal shield top plate ≈ 32 K
- Cryocooler stage II ≈ 2.95 K
- Cavity cell ≈ 5 - 5.8 K (measured at multiple locations)

A possible reason for the significant cryocooler-cavity ΔT
- The estimated heat leak to cryocooler 4 K stage is ≈ 450 mW, mostly coming via the RF cables
- This heat flows through the cavity body (4 mm thick niobium), then through the thermal link, and into the cryocooler
First results: Accelerating gradient > 1.5 MV/m

- First measurements used a single cell, 650 MHz, niobium cavity
- Cryocooler had available ~1.55 W @ 4.2 K after accounting for the static leaks
Projections for a Nb$_3$Sn coated cavity with the existing link

Need to know the cavity RF surface and cryocooler temperatures

- $T_{cavity, RF}$ is estimated from $Q_0$, $T_{cryocooler}$ is measured

![Graph showing the relationship between accelerating gradient and temperature]
Projections for a Nb$_3$Sn coated cavity with the existing link

Assume no changes to the link
- $T_{\text{cavity,RF}} = 5.7$ K
- $T_{\text{cryocooler}} = 5.1$ K

$$E_{\text{acc}} \propto \frac{1}{\sqrt{R_{\text{BCS}}(T) + R_{\text{residual}}}}$$

Nb$_3$Sn $<<$ Niobium (see plot)  
Nb$_3$Sn has demonstrated as low as 10 nΩ

Projected $E_{\text{acc}}$ for Nb$_3$Sn with different residuals

<table>
<thead>
<tr>
<th>Surface resistance in Nb$_3$Sn [nΩ]</th>
<th>$E_{\text{acc}}$ [MV/m] with the existing conduction-cooling link</th>
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<tbody>
<tr>
<td>20 (residual = 10)</td>
<td>11.5</td>
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<tr>
<td>60 (residual = 50)</td>
<td>6.5</td>
</tr>
<tr>
<td>110 (residual = 100)</td>
<td>5.0</td>
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</tbody>
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https://www.classe.cornell.edu/~liepe/webpage/researchsrmp.html
Summary and outlook

First ever demonstration of accelerating gradients on a cryogen-free, cryocooler conduction-cooled SRF cavity

- Niobium cavity produced >1.5 MV/m with a 2 W @ 4.2 K cryocooler

- There is considerable scope for improving the thermal management in our setup
  - Ongoing: mitigation of static heat leak

- An Nb$_3$Sn coated cavity is projected to yield >10 MV/m accelerating gradients on our existing setup
  - Tests are planned for the near future
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Thank you.