Cryocooler conduction-cooled SRF cavities for compact particle accelerators

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Topics for today

➢ Basics of Superconducting Radio Frequency cavities
➢ SRF based compact accelerators for industrial applications
➢ Fermilab R&D for conduction-cooled SRF cavity
➢ Fermilab design and development of compact SRF accelerators
➢ Summary and outlook
Some SRF basics
RF cavity working principle

• Metallic cells maintain a standing-wave RF field
• Particle bunches in phase with the RF field gain energy

- RF fields penetrate a penetration depth, $\delta$ in the metallic cell walls and dissipate heat in the surface resistance, $R_s$.
- A coolant on the outside extracts the heat and prevents the cavity from heating above its design temperature.
Why is RF surface resistance a key parameter?

• Dissipated power in the cavity is proportional to its surface resistance
• The cost of cooling the cavity (coolant fluid, temperature, fluid pumping power, etc.) scales with dissipated power
• With hundreds of cavities in a particle accelerator, the cavity cooling cost forms a significant fraction of accelerator operating cost

Keeping low RF surface resistance is therefore necessary to reduce the accelerator operating cost.
Normal conducting vs. superconducting cavities

How does the surface resistance compare?

Water cooled copper cavity at room temperature

\[ R_s = \frac{1}{\sigma \delta} = \sqrt{\frac{\mu_0 \omega}{2\sigma}} \]

\( \omega = \) angular frequency
\( \sigma = \) electrical conductivity

With \( \sigma \sim 5.8 \times 10^7 \) S/m at 1.5 GHz and 300 K, we get \( R_s = 10 \) mΩ

Liquid helium cooled niobium cavity \( \leq \sim 5 \) K

\[ R_s = R_{BCS}(T) + R_{res} \]
\[ \approx A \frac{\omega^2}{T} \exp\left(\frac{-1.85T_c}{T}\right) + R_{res} \]

At 1.5 GHz and 2 K, and neglecting the residual \( R_{res} \), we get \( R_s = 20 \) nΩ
Normal conducting vs. superconducting cavities

Ratio of surface resistance at 1.5 GHz:

\[
\frac{R_s(niobium,2K)}{R_s(copper,300K)} = \frac{20\,n\Omega}{10\,m\Omega} \approx 10^{-6}
\]

Penalty for 2 K cryogenics:

\[\eta_{Carnot} = 0.67\% \quad \eta_{plant} \approx 20\%\]

Even after accounting the premium for 2 K cryogenics, SRF drives down the cooling driven operating cost by a factor \(\sim 1000\)!

The significantly lower surface resistance in SRF also offers other benefits:

- Cavities can be operating with 100% RF duty cycle that facilitate production of high average power particle beams
- Cavities can be made with larger aperture (by relaxing shunt impedance) that reduce loss of high-power beams during transport through the cavity
**Nb$_3$Sn cavities further reduce the cryogenic penalty**

*Nb$_3$Sn cavities operate at ~4 K with performance similar to niobium cavities at 2 K*

- These are bulk niobium cavities with a few micron layer of Nb$_3$Sn on the RF surface

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SRF accelerators – applications landscape

Current usage dominated by basic research needs: colliders, FELs, proton and neutron sources

Potential industrial applications: e-beam radiation treatment of flue gases, municipal/industrial wastewater, sewage

https://link.springer.com/article/10.1007/s11356-020-10643-0
https://doi.org/10.1016/j.radphyschem.2012.01.030
https://link.springer.com/article/10.1007/s11356-020-10643-0
Tailoring SRF for industrial applications
Electron beam radiation processing applications
- Water/sludge/medical waste decontamination
- Flue gas cleanup
- Medical device sterilization
- Strengthening of asphalt pavements

Radiation processing requires:
- Beam energy: 0.5-10 MeV
- Beam power: >>100 kW

Industrial settings demand:
- Low capital and operating expense
- Robust, reliable, turnkey operation

1-meter long SRF linac (niobium or Nb₃Sn cavities) operating at 10 MV/m can provide the required energy

Small SRF surface resistance enables continuous wave (cw) operation, leading to high average beam power

At present, SRF accelerators are designed to operate with complex liquid helium cryogenic systems!
Simplifying SRF cryogenics for industrial settings

$\text{Nb}_3\text{Sn}$ cavity with 10 MeV dissipates
$\sim 6-8 \text{ W} @ \sim 4.5 \text{ K}$
(1 m x 10 MV/m cw; 650 MHz/1.3 GHz)

Use commercial, off-the-shelf 4 K cryocoolers
(helium plant not required)

Cryocoolers offer
- Closed cycle cooling at $\sim 45 \text{ K}$ and $\sim 4 \text{ K}$
- Compact, small footprint
- Reliability (MTBM $> 2$ years non-stop operation)
- Turnkey operation (no trained operator needed, turn ON/OFF with push of a button)
Simplifying SRF cryogenics for industrial settings

Remove cavity dissipation with thermal conduction (conduction cooling)
(conventional liquid helium bath not required)

Absence of cryogenic liquids
- Compact, simplified construction
- No pressure vessel safety concerns
- Facilitates deployment in remote locations
**Vision:** Develop compact, turnkey e-beam source for environmental and industrial applications (~10 MeV, >>100 kW)


**Pathway:** Nb$_3$Sn SRF cavities
- cw operation enables high average beam power
- Low Rs (high $Q_0$) @ >4 K allows conduction-cooling using 4 K closed-cycle cryocoolers

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Fermilab R&D for a conduction-cooled SRF cavity
Conduction cooled $\text{Nb}_3\text{Sn}$ SRF development

**Goal:** demonstrate 10 MV/m cw on an $\text{Nb}_3\text{Sn}$ cavity with cryocooler conduction cooling

**Our choice:**
- Single cell 650 MHz, $\text{Nb}_3\text{Sn}$ coated niobium cavity
- Cryomech PT420 cryocooler
  (2 W @ 4.2 K with 55 W @ 45 K)
- High purity aluminum for the conduction cooling link
Cavity preparation for conduction link attachment

Conceptualization of conduction cooling

\[ P_{\text{diss}} = \frac{1}{2} R_0 \int |H_s|^2 ds \]

- Weld Nb rings near the equator
- Provide holes for bolting the thermal link

Development of conduction cooling

E-beam weld recipe development
- Full penetration
- Avoid weld beads on the RF surface

Ring-welded single cell 650 MHz cavity

Conduction ring

Cavity shell

RF surface

Holes for bolting the thermal link

Courtesy: C. Grimm (Fermilab)
Characterization of thermal resistance

1. Cavity-link (niobium-aluminum) bolted thermal contacts

Test joint details

- Al plate
- Nb plate
- Indium foil (4 mil)
- Steel disc spring (to apply force)

Joint thermal resistance

> Indium’s flow pressure (~2 MPa)

Selected design: 4 mil indium, ~4 kN force

2. Thermal characterization of high purity aluminum

Setup for measuring 4 K thermal conductivity, contact resistance

4 K cryocooler
X6
X5
Al (N5) plate #2
Sensors

Torque (75 in-lb)

Indium foil (4 mils)

4 mm thick Al plate

Heater

R = 1.0” (~45°)

Thermal conductivity found to be near the lower band of 5N, no deterioration from bending

Bolting force ~4 kN
Conduction link design and performance verification

Al conduction link bolted to the Nb rings around the cavity

RF + thermal simulations

Nb$_3$Sn surface resistance (BCS from SRIMP + 10 nΩ)

Thermal conductivities, contact resistance, cryocooler capacity

FEA verification of thermal conductance of the link

Simulated conductance ($P_{diss}/ΔT$) ≈ 2.6 W/K

Conduction-cooled SRF cavity measurement setup


**Euclid Techlabs**

RF system
- 10 W cw @ 650 MHz, 1.3 GHz
- Resonance locking
- \( P_r, P_p, P_v, \tau_L \) measurements

**Magnetic shield** (~15 mG)

**Vacuum vessel**

**Two-stage cryocooler**
- 55 W @ 45 K
- 2 W @ 4.2 K

**Thermal shield** (cooled by the 45 K stage)

**SRF cavity with Al link** (cooled by the 4 K stage)

**Cryocooler**
- 4 K stage
- SRF cavity with Al links

**SRF cavity**
- 0.8 m
First results with the conduction-cooled $\text{Nb}_3\text{Sn}$ cavity


[10.1088/1361-6668/ab82f0](https://doi.org/10.1088/1361-6668/ab82f0)

Conduction cooling with $<1\text{ G}$ disc springs

- $Q_0 = 10^{10}$ at $E_{\text{acc}} = 1\text{ MV/m}$
- max $E_{\text{acc}} = 6.6\text{ MV/m}$

4.4 K LHe, 2 mG background

Conduction cooling

30 G background

Cavity temperature [K]

[Steel (magnetic)]

disc springs $\sim 30\text{ G}$ led to large flux trapping
1) Improved Nb$_3$Sn coating

- Suspected cause for Q-slope degradation was thin regions (coating 1)
- Added extra SnCl$_2$ nucleation agent relative to previous coating to attempt to improve uniformity (coating 2)
- New coating (coating 2) showed substantial improvement (over coating 1)
Getting to 10 MV/m cw

2) Improve magnetic hygiene around the cavity during cooldown (remove magnetic disc springs)

3) Controlled, spatially-uniform cooldown of the cavity across Nb$_3$Sn $T_c = 18$ K (reduces thermocurrent induced flux trapping)
Results with new Nb$_3$Sn coating (R.C. Dhuley arXiv:2108.09397v1)

Coating 1, LHe
Coating 2, LHe
Coating 2, conduction-cooled, uniform cooldown
Coating 2, conduction-cooled, natural cooldown
Coating 1, conduction-cooled

Quality factor, $Q_0$

Accelerating gradient, $E_{acc}$ [MV/m]
Conduction link performance, cavity thermal stability

Comparison of measured and simulated link thermal conductance

Computed cavity surface temperature at steady state with ~10 MV/m cw
- Ring temperature = 5.95 K, RF dissipation = 2.4 W

\[ \Delta T_{\text{spatial}} \sim 0.12 \text{ K} \]

Courtesy: Dr. Roman Kostin (Euclid Techlabs, LLC.)
A new frontier in SRF is simplifying the cooling methods!

- **Fermilab**
  - 650 MHz
  - welded niobium rings

- **Jefferson Lab**
  - 1.5 GHz
  - Cold sprayed + electrodeposited copper

- **Cornell University**
  - 2.6 GHz
  - Copper clamps

https://doi.org/10.1088/1757-899X/755/1/012136

Design and development of e-beam accelerator based on conduction cooled SRF cavities

- Design studies for a 10 MeV, 1000 kW accelerator
- Prototype development of a ~1.6 MeV, ~20 kW accelerator
Design of a 10 MeV, 100 mA e-beam accelerator

✓ RF design of a 5-cell 650 MHz cavity
✓ Beam transport simulations
  (external injection 300 keV → 10 MeV)
✓ Calculation of 4 K heat load, cryocooler selection
✓ Design and thermal simulations of conduction link
✓ Cryostat design and integration
  (thermal and magnetic shield, vacuum vessel, couplers)
✓ Cost assessment of the 10 MeV accelerating module

Design and multiphysics simulation of a conduction-cooled 5-cell SRF cavity

Design of the complete accelerator cryomodule

Courtesy: B. Coriton and K. Zeller (GA)
Prototype cryogen-free SRF electron accelerator development

Goal: Component production, integration, and demo of a 1.6 MeV, 20 kW accelerator

650 MHz Nb$_3$Sn cavity (Cryoload $\approx$3.8 W @ 5 K)

Integrated thermionic cathode

Low heat leak coupler (<1 W)

Courtesy: I. Gonin, V. Yakovlev (Fermilab)

Courtesy: S. Kazakov (Fermilab)
Prototype cryogen-free SRF electron accelerator development

**Cryostat assembly**
- Thermionic gun
- 2 x 2 W cryocooler
- Cryostat with magnetic and thermal shields
- Coupler (PIP-II style)
- 20 kW SSA

**20 kW Solid State RF Amplifier**

**Cryomech PT420 coolers**

~1 m

 Courtesy: M.I. Geelhoed (Fermilab)
New R&D facilitated by cryocooler-cooled SRF cavities
Development of SRF based field emission sources

PI: Dr. Philippe Piot (NIU/Argonne National Lab.)

NIU-Fermilab collaboration
- field emission cathode with nanostructured surface located in high e-field region of an SRF cavity
- use cw operation to produce high repetition rate field emission (high $I_{avg}$)

Mohsen et al., https://doi.org/10.1016/j.nima.2021.165414
Cryocooled based standalone SRF modules

Cryocooled SRF has already been picked up by the particle accelerator industry!


A SRF QWR cooled by pulse tube coolers for beamline upgrade at Argonne National Laboratory
Summary and outlook

➢ Fermilab has demonstrated 10 MV/m cw gradient with conduction-cooled SRF cavity
   ➢ This is an enabler for high-efficiency e-beam sources for industrial uses of electron irradiation

➢ Design and development of prototype SRF based compact e-beam accelerators is in progress

➢ Conduction-cooled SRF has opened new avenues for SRF R&D
   ➢ Universities as well as industry has already capitalized on this new opportunity
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Thanks for your attention!

Questions?