Acknowledgement

G. Ciovati, U. Pudasaini, H. Vennekate (JLAB)
R. Dhuley, S. Posen, G. Eremeev (FNAL)
N.J. Stilin, M. Liepe (CORNELL)
G. Rosaz, L Vega Cid… (CERN)
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OUTLINE

• Introduction

• Low Cost & Sustainability
  - For large scientific instruments
  - For compact accelerators for societal needs

• Minimize cryogenic losses

• Higher Operation Temperature
  - Nb/Cu
  - Nb₃Sn development (on Nb, Cu)
    - Alternate Materials & Structures

• Current developments for cryo-cooled SRF cavities

• Conclusion
CURRENT SRF TECHNOLOGY FOR ACCELERATORS

Technology of choice for large accelerators for science around the world
CEBAF, SNS, XFEL, LCLS-II, RIA, PIP-II,
Future machines: EIC, FCC

Based on bulk Nb

Rely on 2K operation

Costly Construction
Large cryoplants
Costly Operation
Envisioned Large Accelerators for Science

“duty to society” to design efficient machines – E. Jensen

SRF Cavity Development for Lower Cost and Sustainable Accelerators, A.-M, Valente-Feliciano, APS April Meeting 2022
LOW COST & SUSTAINABILITY FOR ACCELERATORS

Compact accelerators for societal needs

Environmental remediation (water, waste treatment),
Medical instrument sterilization, medical isotopes production,
Engineering of material and surfaces with altered properties radiation driven chemistry,
Food preservation
ADS systems

Need for a new class of compact, high-power accelerators, with drastically reduced cryogenic requirements

located on a mobile platform, in a university or hospital room.

simple, reliable, and cost effective

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LOW COST & SUSTAINABILITY FOR ACCELERATORS

• Increase efficiency – klystron, RF power sources

  SRF cavities
  Low-loss SC resonators: Advanced surface processes

• Lower costs of construction & operation
  Operation at 4 K: New Materials, composite materials
  materials and structures more efficient
  than bulk Nb combined with higher
  thermal conduction substrates.

  N doping & O alloying
  New materials – High $T_c$, high $H_{sh}$
  $\text{Nb}_3\text{Sn}/\text{Nb}$, $\text{Nb}_3\text{Sn}/\text{Cu}$
  $\text{MgB}_2$
  SIS on bulk Nb or Nb/Cu

New cooling schemes

Energy efficient accelerator concepts

Energy Recovery

Sustainability Aspects of Energy Recovery Linacs (ERL)
Bettina Kuske

Sustainable Accelerator R&D, Ben Shepherd
Increase efficiency & lower cryogenic losses

N doping

Q-factor x2 or more resulting in cavity-cooling electricity bills slashed by up to 4 times

O Alloying

2-4 times more efficient

Ito, H., et al. Progress of Theoretical and Experimental Physics (2021) 071G01
Lower cost for CW accelerators at low frequency

Nb/Cu Technology: proof of principle with LEP2, LHC, ALPI machines

- Increased temperature stability due to Cu substrate higher thermal conductivity
- Operation at 4.5 K, generating capital and operational cost savings
- Material cost saving, particularly for low frequency structures
- Easily machinable and castable structures

Perspectives for significant cryomodule simplification.

High current storage ring colliders: FCC, EIC and CEPC

SRF Thin Film Development @ JLab
Next Generation SRF Cavities Based on Advanced Coating Technology for CW Accelerators

Novel deposition techniques exploiting species energetics offer opportunities to improve and manipulate film structure and performance.

Nb$_3$Sn on Nb - Latest developments

Intermetallic A15 phase – $T_c = 18.3$ K
Operation at 4.2 K with $Q \sim$ Nb at 2 K
$H_{SH}$ promises 100 MV/m
Brittle material

Thus far only reached $\sim 25\%$ of its potential
Towards Nb₃Sn multi-cells and cryomodules

- Two Nb₃Sn-coated C75 five-cell cavities were tested in a pair, but suffered performance degradation following pair-assembly.
- Mechanical vulnerability due to brittleness of the material during the assembly and processing.
Alternative Deposition Methods for Nb$_3$Sn

Dual cathode system for sequential deposition on 2.45 GHz cavities

Full control on thickness, potentially smoother
Pushing Nb$_3$Sn Further

• Nb$_3$Sn/Cu

High-temperature DCMS of stoichiometric target at low argon pressure
Advantages: simplicity and the possibility to produce homogenous layers of Nb3 Sn on complex shapes.

• Energetic condensation: give energy to ions themselves to achieve A15 phase

• Bronze method: deposit Nb on CuSn and anneal to diffuse Sn into Nb layer
MgB₂/Cu RF Cavities for Cryogen-free RF Systems

$T_c \approx 40$K

$\Delta_s = 2.3\text{meV}$, 2D, in-plane s-orbital $T$ [K]

$\Delta_p = 7.1\text{meV}$ 3D, out-of-plane p-orbitals

Challenges:
Fragile, damage with exposure to moisture
Needs protective layer

HPCVD, PE-ALD
S-I-S Multilayers

High gradients at 4K Operation

A. Gurevich, T. Kubo

C. Sundhal et al.

Re-HiPIMS

Compounded complexity
Materials compatibility interfaces

Nb$_3$Sn Enhancement

Cavity's interior

\[ H_{\text{Nb}} \]

\[ H_{\text{applied}} \]

\[ d_{\text{SC}} \]

A. Gurevich, T. Kubo

C. Sundhal et al.

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Electron beam radiation processing applications

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 m long SRF linac (Nb 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.

All cryogenics integrated into the module:
- Cryocooler 4 K stage cools the SRF cavity
- Cryocooler 45 K stage cools thermal shield/intercept
- Enclosed in a simple vacuum vessel

Increasing power capacity at 4.2 K

Conduction cooling setup at Fermilab


2-stage Cryocooler
- Cryomech PT420
  1. 55 W @ 45 K
  2. 2 W @ 4.2 K

Thermal shield
- Cooled by cryocooler stage-1

Vacuum vessel
- SS304, 5 feet tall

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

SRF cavity (650 MHz, Nb$_3$Sn)
- Cooled by cryocooler stage-2

SRF Cavity Development for Lower Cost and Sustainable Accelerators, A.-M. Valente-Feliciano, APS April Meeting 2022
650 MHz conduction-cooled cavity at Fermilab


650 MHz Nb/Nb$_3$Sn cavity with thermal links

Al conduction link bolted to the Nb rings around the cavity

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

RF + thermal simulations

Thermal conductivities, contact resistance, cryocooler capacity

FEA verification of thermal conductance of the link

Simulated conductance ($P_{\text{diss}}/\Delta T$) ≈ 2.6 W/K
650 MHz conduction cooled cavity test results

**Figure:**
- **cw Eacc vs Q0 for Nb3Sn coated, 650 MHz, single cell cavity**
- **Quality factor, Q0**
  - 10^11
  - 10^10
  - 10^9
- **Accelerating gradient, Eacc [MV/m]**
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
- **Cavity temperature [K]**
  - 4
  - 5
  - 6
  - 7
- **Coating 1, conduction-cooled**
- **Coating 1, LHe**
- **Coating 2, conduction-cooled, uniform cooldown**
- **Coating 2, conduction-cooled, natural cooldown**
- **~10 MV/m**
- **~7 MV/m**
- **6.5 MV/m**

**References:**

**Additional Information:**
- SRF Cavity Development for Lower Cost and Sustainable Accelerators, A.-M, Valente-Feliciano, APS April Meeting 2022
Ongoing Work

• Design of a 10 MeV, 1 MW, conduction-cooled e\textsuperscript{-} accelerator

• Design and production of a 1.6 MeV, 20 kW, conduction-cooled SRF e\textsuperscript{-} accelerator
  Prototype electron accelerator development (1.6 MeV, 20 kW)
1.3 GHz conduction-cooled SRF gun cavity at Euclid BeamLabs

Development of conduction-cooled cryomodule for ultra-fast electron microscopy (UEM)

Thermal analysis to find stable points of operation at Eacc=10 MV/m, CW
The cryomodule (without cavity) was assembled and the cryocooler 2nd stage achieved the base temperature of 2.5 K.

- The Nb cavity will be coated with Nb$_3$Sn at Fermilab
- The Nb/Nb$_3$Sn cavity will be tested in the conduction cooling cryomodule
  - Aim at $E_{\text{acc}} = 10$ MV/m for 1.6 MeV beam
- The cryomodule will be delivered to BNL to produce the beam and beam quality studies
- Development of high thermal conductivity coatings by cold-spray
Conduction cooling at Cornell University

2.6 GHz Nb$_3$Sn cavity (ILC design)

- Focus on compact design (2.6 GHz)
- Uses Cryomech PT420-RM cryocooler
- 1.8 W @ 4.2 K with 55 W @ 45 K
- Copper thermal straps & beam-tube clamps connect cold head to cavity


1$^{st}$ demonstration of stable CW operation @ 10 MV/m
Reaches $E_{\text{acc}}$ relevant to industrial applications
< 1 W dissipated heat at max fields
$Q_0$ approaching 4.2 K vertical test
Cavity performance improved via temperature cycling / better cooldown!
Conduction cooling setup at Cornell University - Test results

- **Thermal gradient** across Nb/Nb$_3$Sn produces **thermoelectric currents**, leading to **trapped flux**

- Two improved cooldown methods:
  1. **Passive** gradient reduction via temperature cycling
  2. **Active** gradient reduction via beam-tube clamp heaters

**Thermal analysis**

- Agreement between **ANSYS Simulation** and **Experiment** temperatures
  - Simulation heat load & cold head temperature set to 10 MV/m values

- Extracted thermal conductivity for niobium cavity also shows good agreement

- Numerical simulations accurately predict thermal behavior
Design of 1 MeV, 1 MW conduction cooled cryomodule at JLab

- Designed for a CW $e^{-}$ accelerator for environmental remediation

750 MHz, $\beta=0.5$, Cu/Nb/Nb$_3$Sn CAVITY

Conduction cooling of 1.5 GHz cavity at JLab

- 1.5 GHz single-cell Nb cavity with Nb$_3$Sn thin film
- ≥ 5 mm thick Cu layer deposited by cold-spray (~76 µm) and
- Apiezon N grease and an estimated 46 MPa contact pressure at the equator ring interface.
1.5 GHz conduction cooled cavity test results at JLab

- Cool-down across $T_c$ controlled by switching the cryocooler on & off
- Amplitude of microphonics at $B_p = 10$ mT: 13.8 Hz pk-to-pk
- Maximum $B_p = 29$ mT ($E_{\text{acc}} = 6.5$ MV/m)

Avg. temperature measured at the equator (~7.5 K) consistent with ANSYS analysis for 5 W RF heat load ($0.18$ W radiation heat load, $0.58$ W static heat load, $0.7$ W/K contact thermal conductance)
Multi-metallic Cavity at 952 MHz

- Development of a multi-metallic Cu/Nb/Nb$_3$Sn 952 MHz single-cell cavity
- The cavity will be tested in a horizontal test cryostat at General Atomics with 3 cryocoolers, aiming at $B_p = 45$ mT
Pushing Nb$_3$Sn Further

- Current process:
  1. Nb$_3$Sn vapor diffusion on Nb substrate (cavity)
  2. cold spray 1$^{st}$ copper layer
  3. copper plating (time intensive)

  → direct deposition on copper

Challenge: Sn vapor process temperatures too high for Cu

Nb$_3$Sn/Cu with advanced deposition methods impart energy to ions themselves
  → HiPIMS or hybrid deposition
CONCLUSIONS

Lowering cost & increasing sustainability is a MUST in SRF developments for

- Large facilities
- Compact accelerators for societal needs

Progress in past years has brought forth advanced surface processing, refined and novel techniques for alternate materials for increased efficiency and for lowering cost of construction & operation for large accelerator SRF systems

Cryogen-free operation at 4.5 K is within reach with Nb$_3$Sn based SRF systems opening the door for exciting developments in medicine, science, energy, industry

- Pursue R&D on Nb$_3$Sn on Nb and on Cu: continue Sn vapor technique refinements & reproducibility, novel deposition techniques to reach the full potential of the material
- Explore other materials and structures (SIS multilayers)
- Substrates high quality but cost-effective, and with integrated cooling channels