First Cavity Results from the Cornell SRF Group's Nb$_3$Sn Program

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Nb$_3$Sn has $T_c$ of $\sim 18$ K, vs $\sim 9$ K for Nb: much lower BCS $R_s(T)$

- Significant reduction in losses at same temperature
- Possibility to operate at higher temperatures: $LHe$ at atmospheric pressure? Cold gas?
- Smaller cryo plant and less grid power
  - Application to CW SRF linacs for light sources, small scale accelerators (closed He gas cryogenic system for universities/hospitals), industrial applications (wastewater and flue gas treatment, isotope production)
- Higher predicted superheating field $\sim 400$ mT, nearly twice Nb
  - Application to high energy SRF linacs: reduce # of cavities
Previous SRF Research with Nb$_3$Sn

1.5 GHz single cell Nb$_3$Sn cavity

- Excellent $R_s$ at low fields, but large increase in $R_s$ with field ("Q-slope") above $\sim 5$ MV/m
- Various suggested causes: intergrain losses, bad stoichiometry, and vortex penetration at lower critical field $B_{c1}$

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$B_{c1}$ is the onset of metastability. Above $B_{c1}$, an energy barrier prevents vortex penetration, but surface defects of size $\sim \xi$ lower barrier.

Is $\xi$ of Nb$_3$Sn so small that $B_{c1}$ is the limit?

$\xi$ of Nb $\sim$ 20-30 nm
$\xi$ of Nb$_3$Sn, NbN, MgB$_2$ $\sim$ 3-4 nm

If vortices penetrate at $B_{c1}$, all alternative SRF materials would be severely limited.
Cornell Cavity Coating Chamber

- Degas: 1 day
- Nucleation: 5 hours
- Coating: 3 hours
- Surface diffusion: 0.5 hours

See THPO066, SRF11 for details of coating process and commissioning process using samples.

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Cornell Nb$_3$Sn Coated Cavity

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Breakthrough Nb\textsubscript{3}Sn Cavity

- New Nb\textsubscript{3}Sn cavity: ERL shape (similar to TESLA), single cell, 1.3 GHz
- Tested after very slow cool (>~6 min/K)
- Excellent performance, especially at 4.2 K
- The first accelerator cavity made with an alternative superconductor that far outperforms Nb at usable gradients
Breakthrough Nb₃Sn Cavity

Very low $R_{res} \sim 10$ nΩ, similar to most Wuppertal cavities

Huge (factor of $\sim 10$) $Q_0$ improvement at 4.2 K medium fields compared to Wuppertal

~ 20x more efficient than Nb at 4.2 K

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Limiting Defect at 2K

- Localized pre-heating just below first quench
- Defect – not a fundamental limit
- Can reach higher fields by fixing defect

Before quench, $E_{\text{acc}} = 13 \text{ MV/m}$, $Q_0 = 1 \times 10^{10}$
• No sign of $Q_0$ change near $T_c$ of niobium: excellent Nb$_3$Sn coverage!
• High $T_c$ of 18.0 K close to maximum literature value
• Extract material parameters from this data
### Fits to Material Parameters

- **Parameter** | **Value**
  - $\lambda_L(0)$ [nm] | $89 \pm 9$
  - $\xi_0(0)$ [nm] | $7.0 \pm 0.7$
  - $T_c$ [K] | $18.0 \pm 0.1$
  - $\Delta/k_B T_c$ | $2.4 \pm 0.1$
  - $l$ [nm] | $3.7 \pm 0.5$
  - $R_{res}$ [nΩ] | $9 \pm 2$
  - $\lambda_{eff}(0)$ [nm] | $(1.5 \pm 0.2) \times 10^2$
  - $\xi_{GL}(0)$ [nm] | $3.2 \pm 0.2$
  - $\kappa$ | $47 \pm 6$
  - $B_c(0)$ [T] | $0.47 \pm 0.06$
  - $B_{c1}(0)$ [T] | $0.027 \pm 0.005$
  - $B_{sh}(0)$ [T] | $0.33 \pm 0.05$

- Good agreement with literature values for ideal Nb$_3$Sn
- See paper for derivations

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**Fits to Material Parameters**

- **Surface Resistance vs. Temperature**
  - $T_c = 18.000$ K
  - $\Delta$ = 2.449
  - $l_{onDepth}$ = 885.0 Ang,
  - $\xi_{cohLength}$ = 110.0 Ang
  - RRR = 0.6218
  - $R_0 = 9.358e-009$ Ohm

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• $B_{c1}$ of Nb$_3$Sn sample measured directly via $\mu$-SR by Anna Grassellino et al.

• $B_{c1} \sim 20$-30 mT agrees with cavity measurement
Cornell Nb$_3$Sn Cavity and $B_{c1}$

$B_{c1}$ range: $27 \pm 5$ mT

Well above $B_{c1}$ without strong Q slope!
$\Rightarrow$ Energy barrier keeps Meissner state metastable, even with small $\xi$ of Nb$_3$Sn.

$B_{c1}$ is NOT a fundamental limitation!
Conclusions

• **Current status**: Nb$_3$Sn is **now a promising alternative SRF material** for certain future accelerators: Cornell cavity demonstrated at 4.2 K, usable gradients ~12 MV/m, $Q_0$ of $10^{10}$, 20 times higher than Nb
  – Q-slope seen in previous cavities not a fundamental problem

• **Near future**: fix high performing but defect limited cavity, or coat new one—expect even higher gradients

• **Longer Term R&D Plan**: Develop **surface preparation methods** for Nb$_3$Sn to push performance (as has been done in Nb over many years)

• **Eventual Hope**: Prevent non-fundamental limitations to reach fields close to **ultimate limit**, $B_{sh} \sim 400$ mT