Nb_3Sn: Lab to Machine ?

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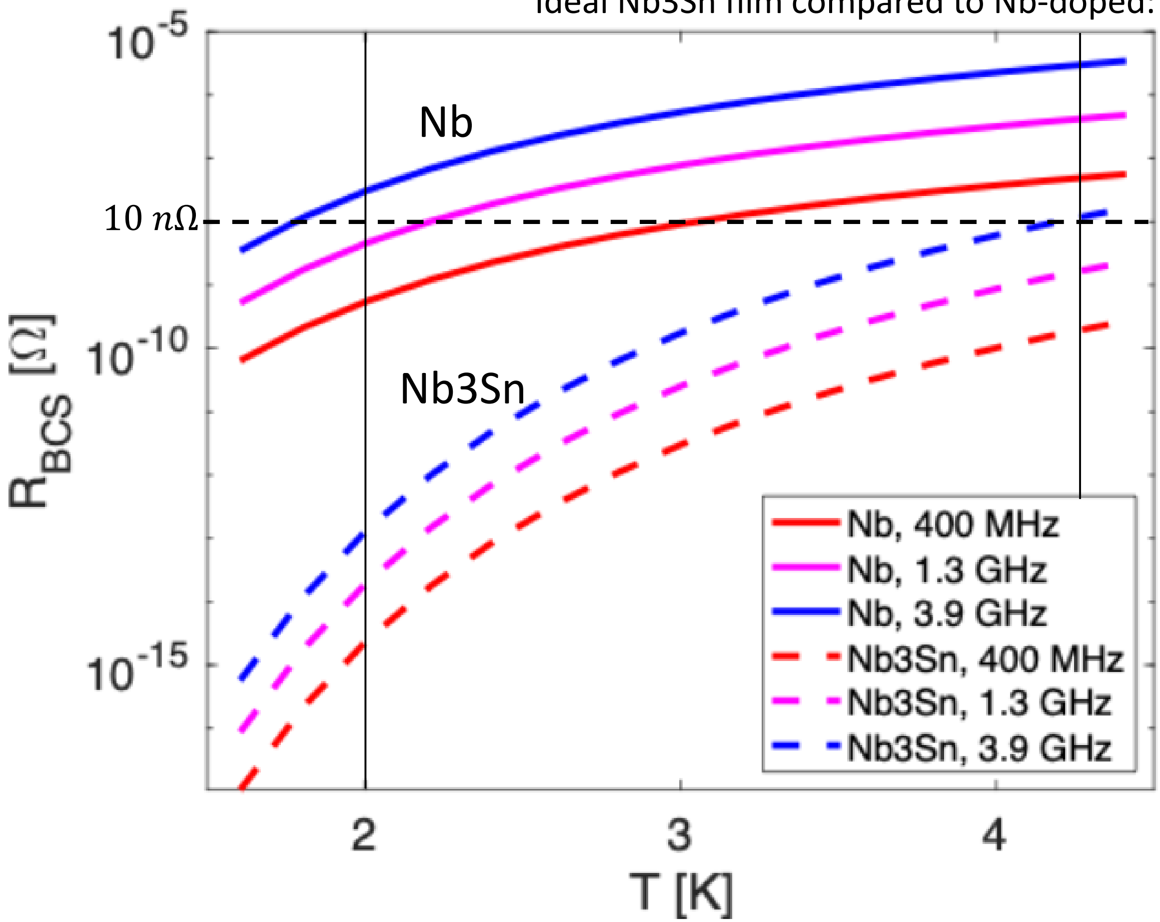
Feb 4-7, 2020

Note: Some qualitative thoughts to trigger ideas

Standard Mantra: Nb3Sn

- Potential for low R_s at 4.5K (and 2K)
- Potential for high gradient $100\ \mathrm{MV/m}$?

Ideal Nb3Sn film compared to Nb-doped: Courtesy S. Posen



SRF Accelerator “Landscape”

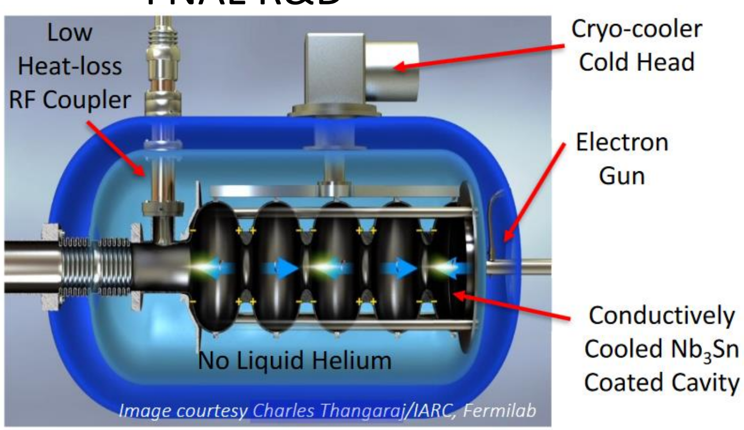
	Some Examples	Frequencies [MHz]	Voltage [MV/m]	?
Circular colliders & storage rings	LHC, FCC, KEKB, CESR, Light sources	350-500, 800	5 – 15	
Linear Colliders & FELs	XFEL, LCLS2, ILC	1300, 3900	20-35	
High Intensity	SNS, ESS, PIPII	650-800	7 – 20	
Nuclear Physics	FRIB, HIE-ISOLDE, ATLAS..	~100-400	6 – 10, 20	
ERLs & RLs	CEBAF, Test facilities, e-cooling	700, 1300	15-20	
Special Applications	Crab/Deflecting cavities, Medical	400, 3900	~25	
Compact/cheap e-accelerators	Studies	600-800, 1300?	~10	

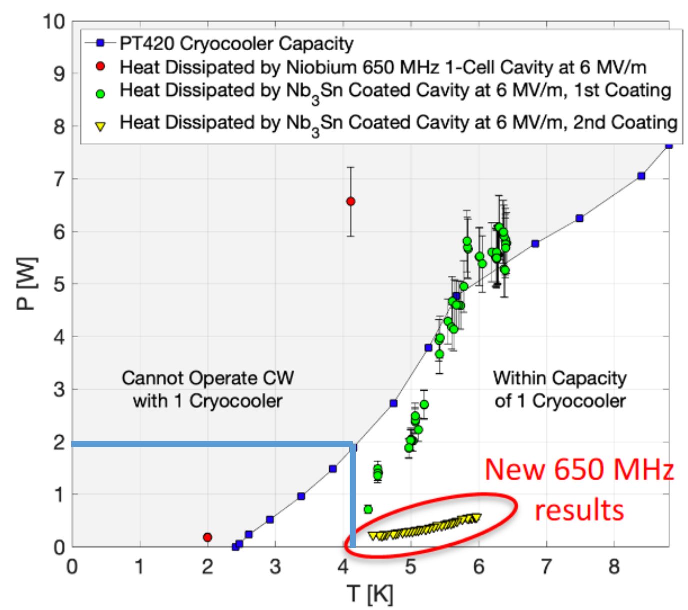
**Note: By no mean comprehensive but some qualitative examples

Cheap/Compact Accelerators

- Idea is great – but in real world best cryomodules have a static load of ~10W*. Dynamic load at real cavities at operating gradients are perhaps ~10W*
- Present cryo-coolers is at best 2W. Not extremely scalable & conducting cooling requires better adaptation.

FNAL R&D





*maybe this can halved at best

Storage rings & Colliders

- Typically needs a few MV/m. 4.5K operation of Nb-films on Cu already a success story at LEP & LHC
- Limitation not really from Q0 but from RF power – 100's kW due to high beam current
  - With the exception of electron-positron colliders needing 10 GV (FCC)
- Another limitation is HOM couplers reaching higher & higher powers
  - Future path could be additive manufacturing. Nb_3Sn coating on ingot-Nb-antennas (or better yet Cu/Al-antennas)

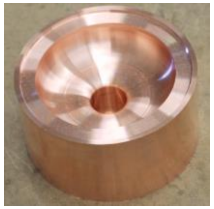
Bulk Nb

3D Printing

Linear SC-Linacs

- Reference today: 35 MV/m with bulk-Nb at 1.3 GHz
  - Is it worth all the trouble to go for Nb3Sn for saving just cryogenic power - yes

- One breakthrough could come if
  - Coat **Nb3Sn** on **Cu-or-Al** – conductively cooled for high-Q_L operation (low beam loading, pulsed)
  - Keep **2K** (or 4.5K) operation but at higher frequencies & gradients: **~3-4 GHz*** → machined or 3D printed cavities
  - Smaller RF waveguides, compact cryostats
  - Make Nb3Sn film "magnetically insensitive"



- Or in combination with 1.3 GHz in double harmonic acceleration. Also high s/c-band cavities can be realized into mobile applications

*Studies at Cornell & FNAL show promising results freq > 1.3 GHz

Proton (HI) Linacs

- Today's limit in proton linacs is not necessarily gradient or Q_0. Mostly RF power limited.
- For low-velocity cavities (TEM-like), there is already Nb-Cu technology close to bulk-Nb cavities (HIE-ISOLDE). Added benefit from Nb3Sn not critical
- Also no axial symmetry may require special coating R&D – similar to deflecting/crab cavities. Try Nb3Sn on HL-LHC crab cavity prototypes
- Can you double the quench limit at lower frequencies (~100-400 MHz) ?

SNS

HIE-ISOLDE

HIE-ISOLDE

ERLs & Special Applications

- The main mantra: medium gradient, CW, high current with low beam loading
  - Nb-Cu at 15-20 MV/m ~800 MHz is already interesting
- High current –CW implies lower frequencies. The main benefit of Nb3Sn could be operation at 4.5K. This implies a strong control of microphonics for high-Q_L (conductive cooling)
  - Since “zero beam-loading”, Nb3Sn can push the CW-gradient closer to a pulsed machine for a large scale ERL (ex: LHeC at 60 GeV)
- Medical accelerators (ex: ADAM) use 20-30 m of Cu linac (s/c-band) for ~250 MeV. Reduce this to few-meters
- Deflecting cavities (non-axial) are typically at lower frequencies. Nb3Sn on Cu could significantly help to improve field evolution during quench – machine protection
- Other applications such as axion-like searches or quantum-related experiments

General Comments

- Accelerator compatibility requires dealing with real world mess. So Nb3Sn needs an "industrialization" break-through
- Its applications could/should be decoupled from bulk-Nb (starting with the substrate)
- Think special applications
  - Higher frequencies (s/c-band), higher quench fields, HOM couplers
- Think cheap fabrication techniques
  - Machining/3D printing of cheaper-Nb, Cu, Al….
- One day in the far future, we might even dream of in-situ coating of Nb3Sn inside existing SC-accelerators