First Demonstration of a ZrNb Alloyed Surface for Superconducting Radio-Frequency Cavities

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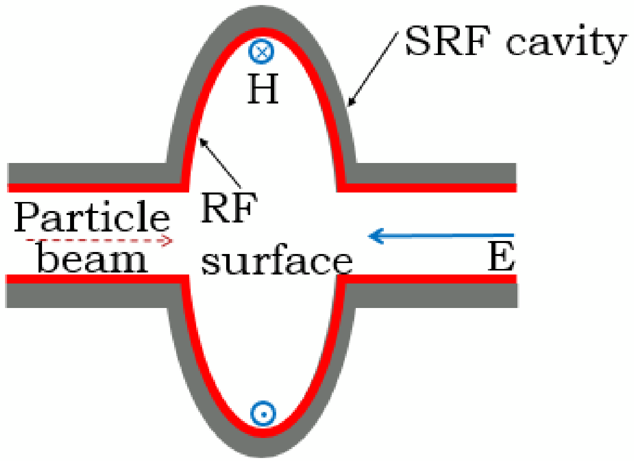
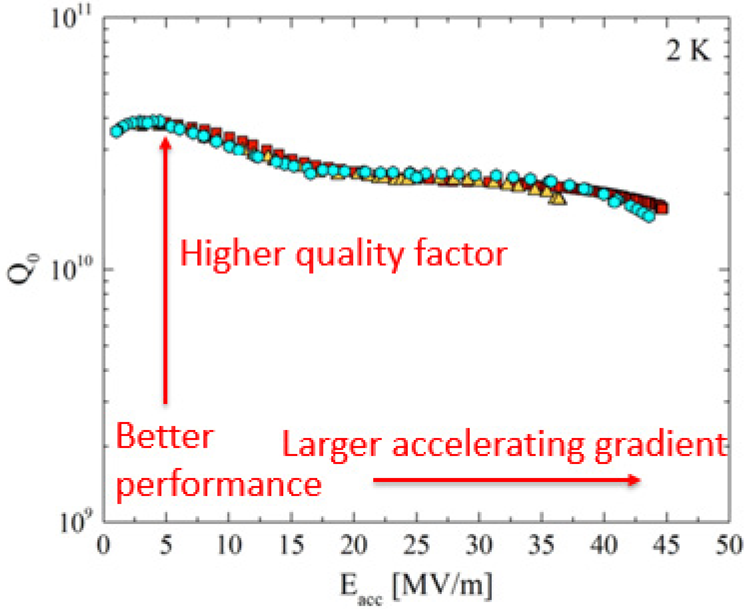
Opportunity for new RF material & surface

- Superconducting radio-frequency (SRF) cavities
  - Key component in particle accelerators
  - Applications: light source (synchrotron X-ray), colliders, etc.
- Nb approaches to the theoretical limits
  - Functional region: tens of nanometers at the cavity inner surface
  - Nb properties:
    - ✓ Critical temperature: T_c = 9.2 K
    - ✓ Typical cavity operation temperature: 2 K
    - ✓ Field penetration depth: ~40 nm
    - ✓ Theoretical limits: ~200 mT superheating field and ~50 MV/m E_{acc}



RF field and cavity inner surface

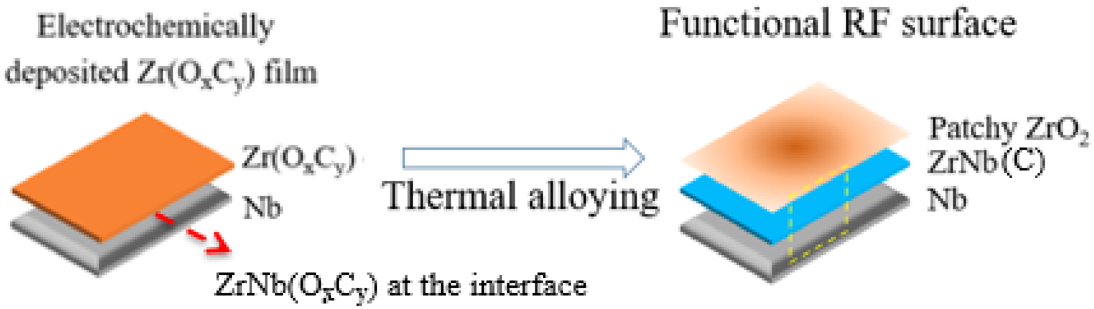


Nb SRF cavity performance

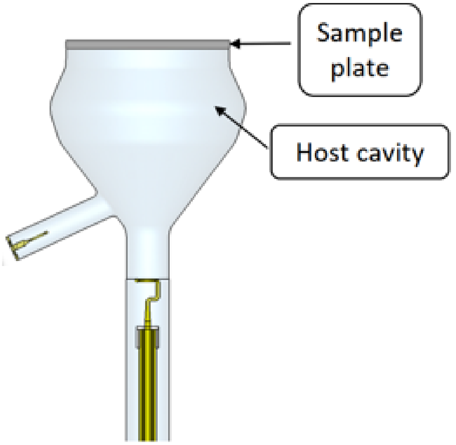
Adapted from A. Grassellino, et al., Supercond. Sci. Technol., 2017.

Our new strategy: ZrNb-alloyed cavity

- Simulation prediction
  - The Center of Bright Beam (CBB) theory collaborators recently predicted large enhancement of T_c and superheating field for ZrNb alloys as compared to Nb
- Experimental validation
  - Zr electrochemical deposition on the Nb surface



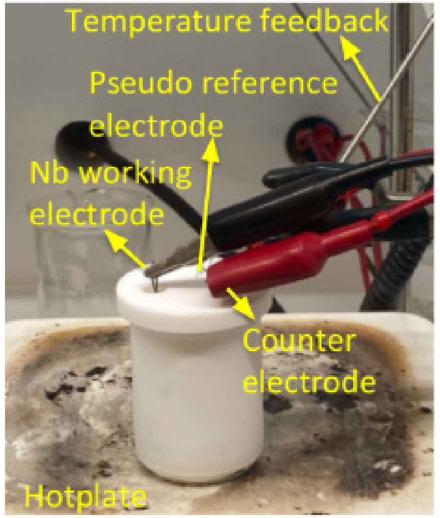
  - Post annealing
  - Scale up to Cornell sample test cavity



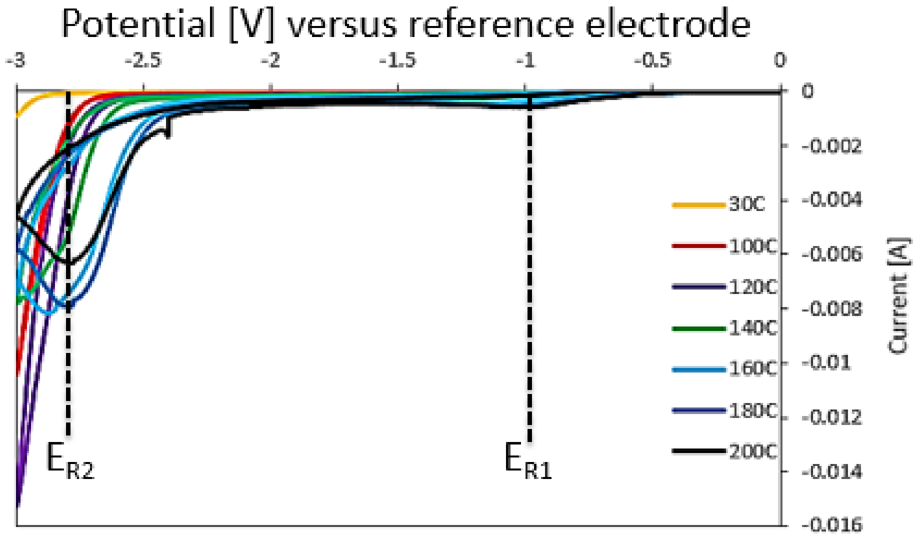
Zr electrochemical deposition

- Electrochemical method is suitable for deposition on the inner surface of a complicated 3-D cavity structure.
  - Cornell is establishing the electrochemical deposition technique for fabricating multiple material systems, e.g., ZrNb, Nb_3Sn...
- A novel low-T three-electrode process in inert-gas glovebox
  - Solution chemistry, deposition temperature, electrochemical potential, deposition time

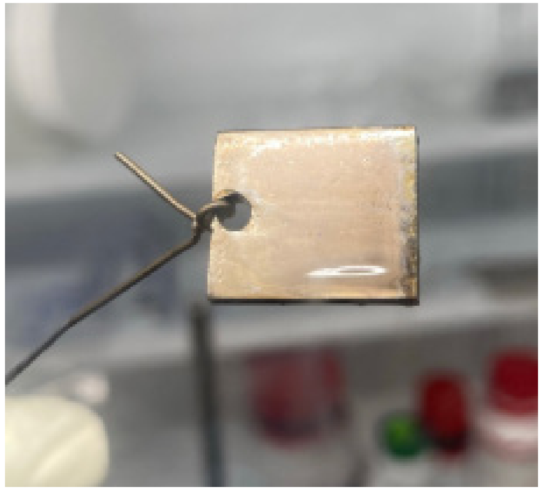
Electrochemical setup



Cyclic voltammetry

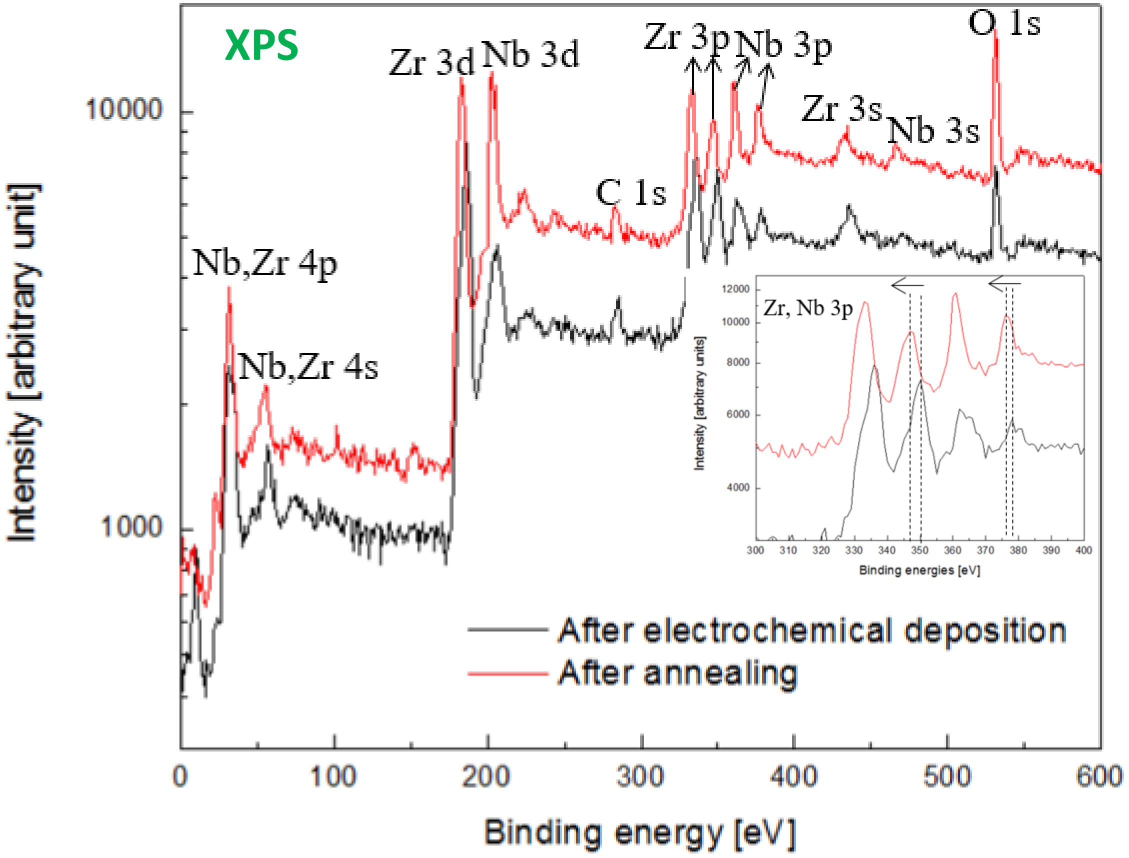


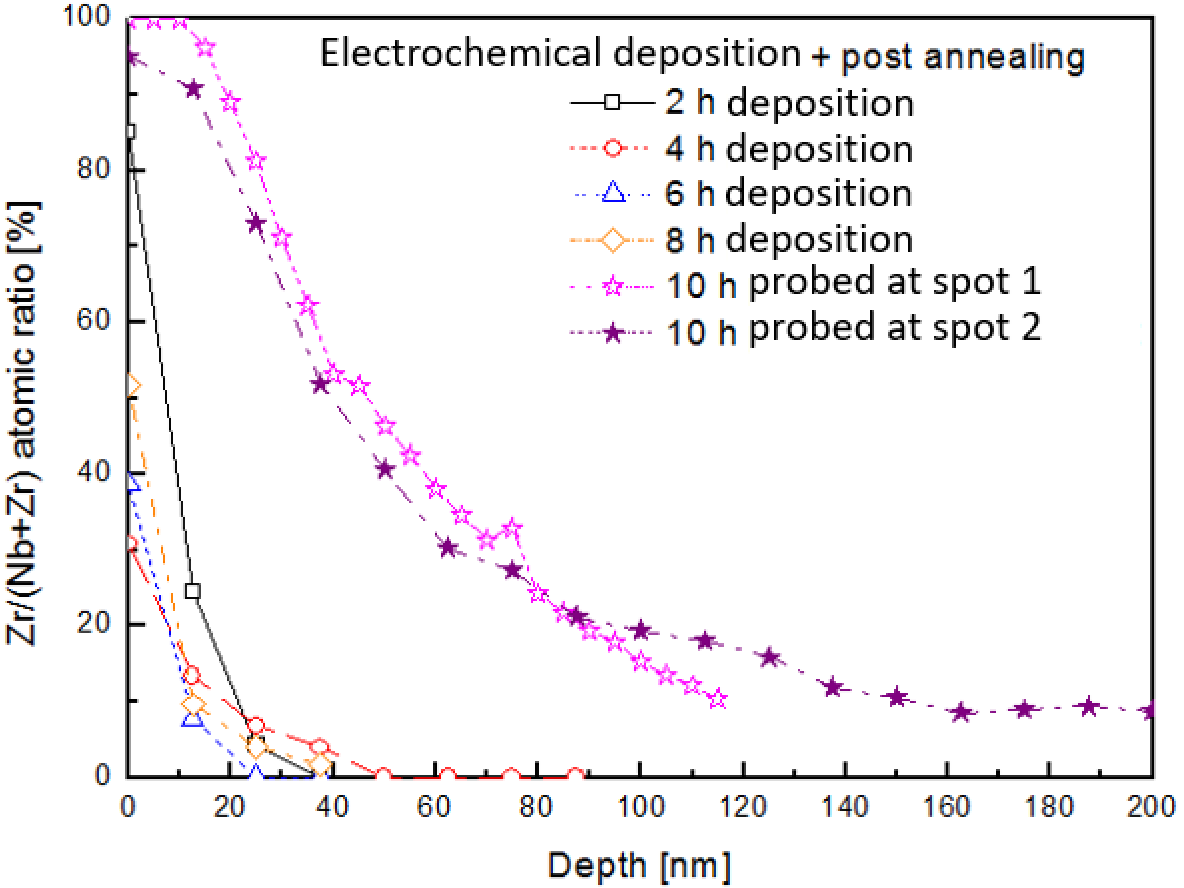
Film after 4 h deposition



ZrNb alloys & their surface profiles

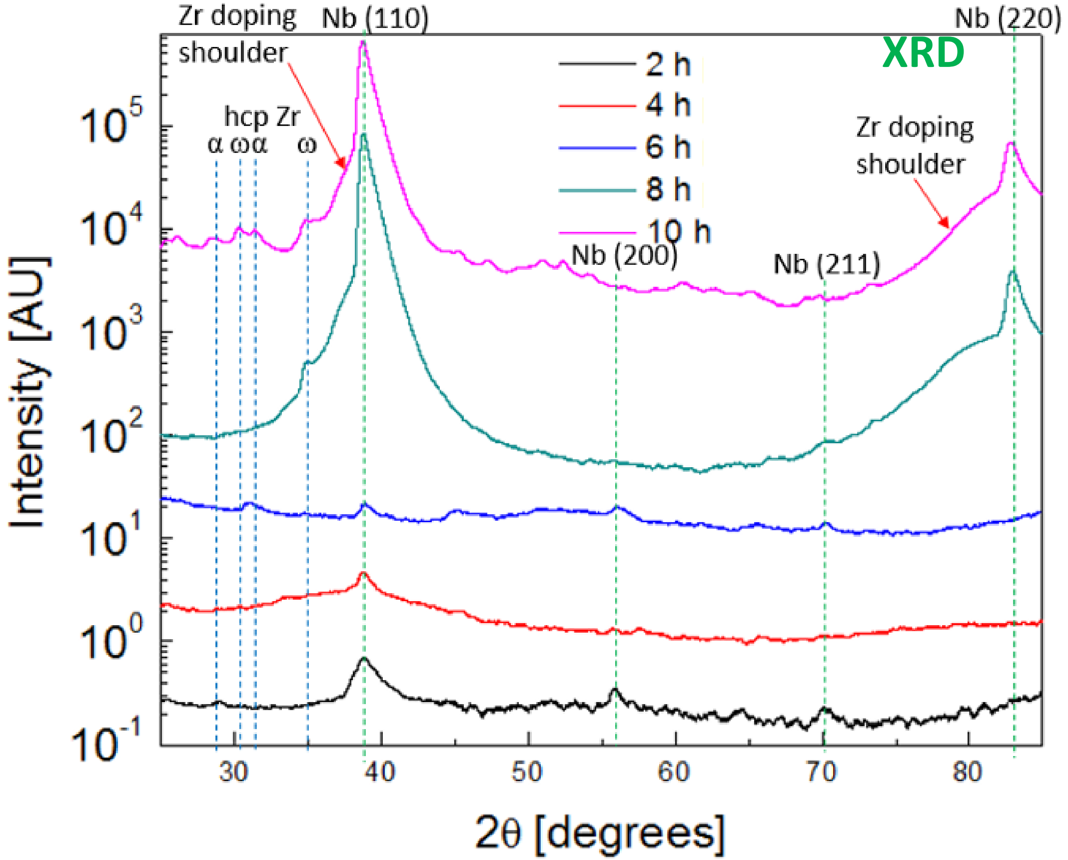
- Achieved ZrNb alloy as confirmed in elemental and phase measurements.
- Post annealing removed harmful impurities and improved alloying (XPS shifting).
- O (as wide bandgap ZrO_2) and C (unclear motif) were significant.
- Deposition time strongly affects surface profiles and thus their RF properties.

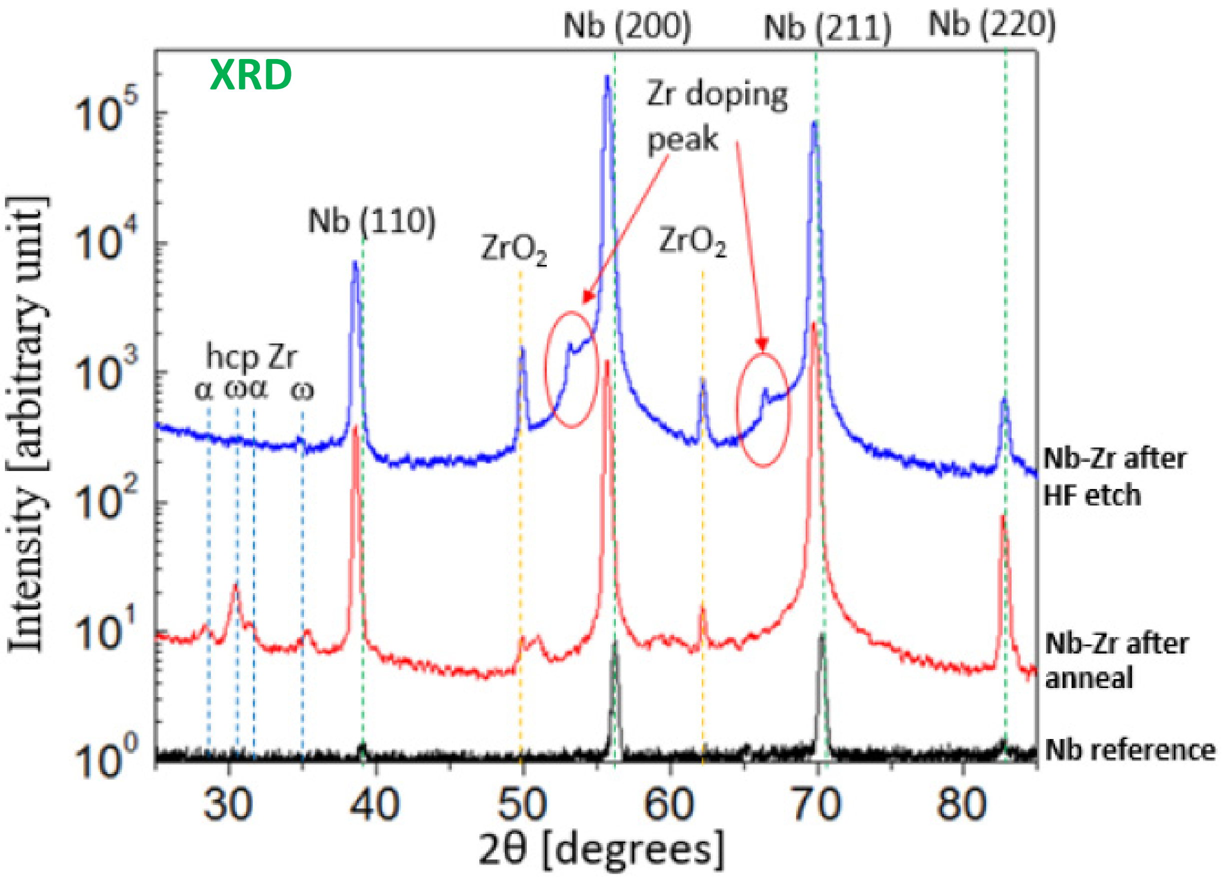




Locking an ordered, cubic ZrNb phase

- Obtaining cubic ZrNb is essential to ensuring a high Tc.
- Achieved substitutional doping of Zr into bcc Nb for cubic ZrNb alloying.
- Our X-ray diffraction matches with local electron diffraction (Zhaslan Baraissov & Prof. David A. Muller).

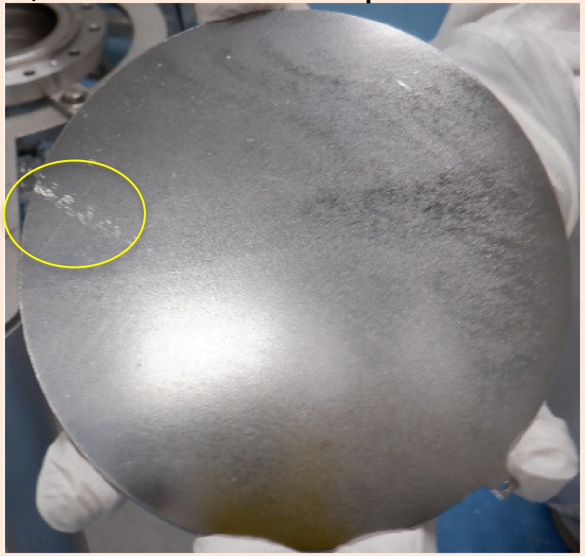




Scaling up to Cornell sample test cavity

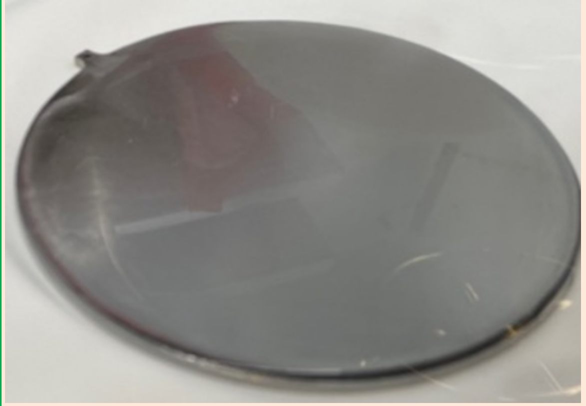
Baseline RF test

1,Before Zr deposition



- ✓ Fine grain Nb
- ✓ Electropolished
- ✓ 800 °C baked
- ✓ 5 µm light EP

2, *In situ* HF cleaning



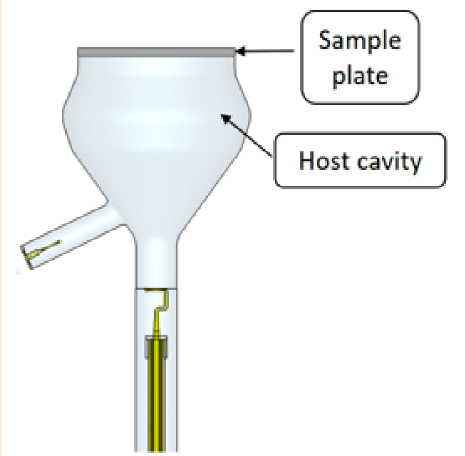
- ✓ In the glovebox
- ✓ Removed surface oxides & impurities

3, After Zr deposition

- ✓ Same parameters as sample study
- ✓ Except that 7 times lower electrochemical current
- ✓ Thinner film

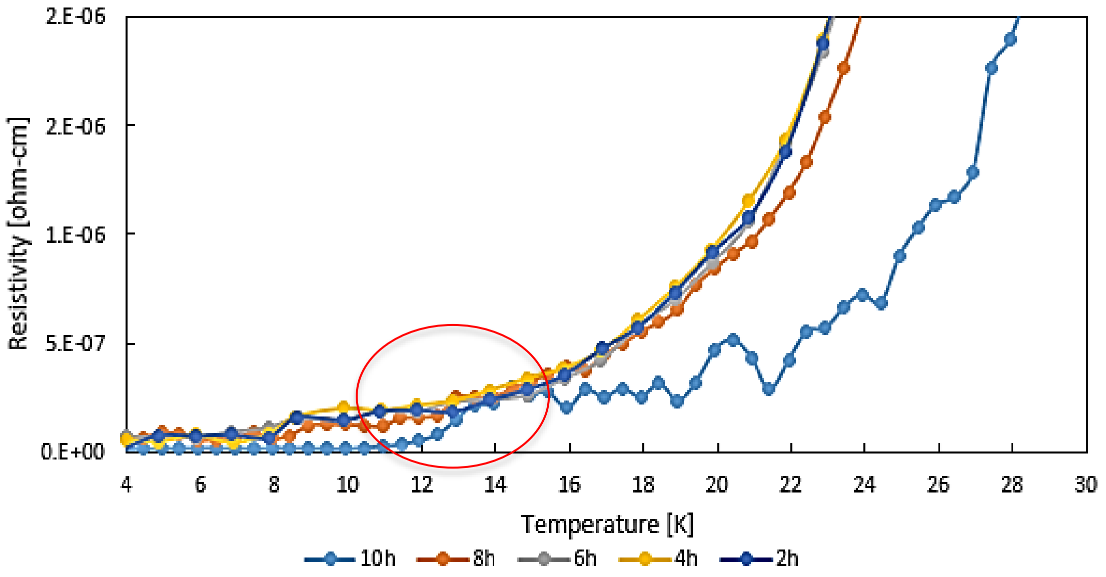
4, After thermal annealing

ZrNb alloy RF test



Critical temperature of electrochemically made ZrNb

- Four-probe resistance tests using PPMS showed 13 K Tc for thick films, while wire bonding affects testing on thinner films.

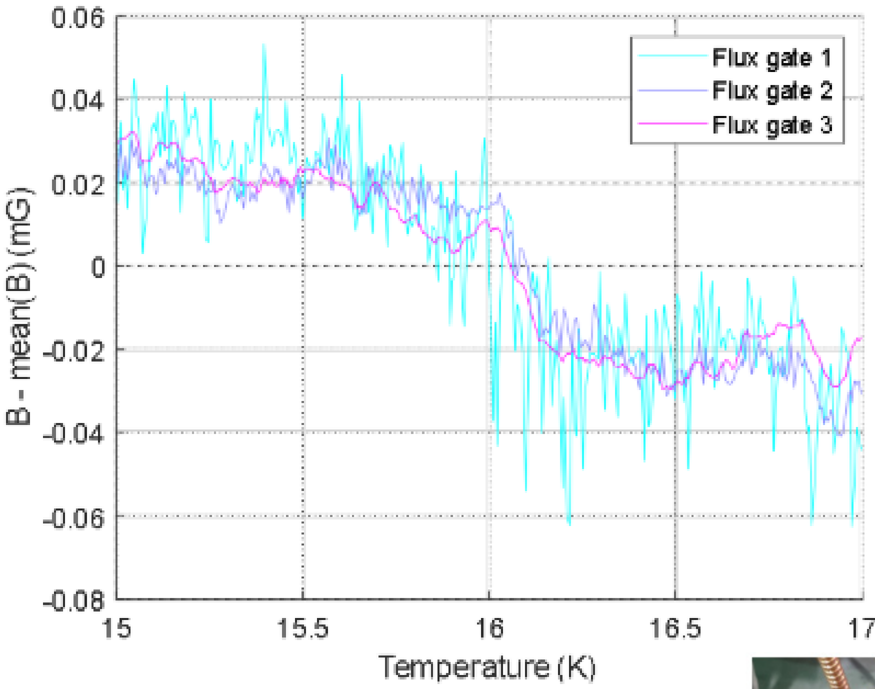


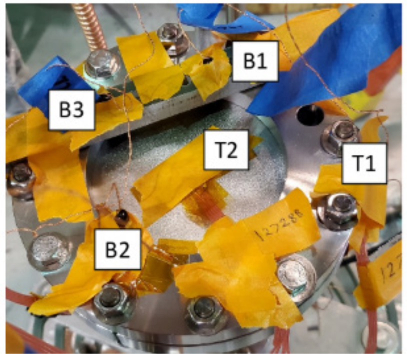
- Both values are higher than literature-reported 11 K Tc for random ZrNb alloys and 7.4 K Tc for sputtered ZrNb films.

J. M. Corsan, et al., J. less-common met, vol. 15, 1968.

A. Cavalleri, et al., J. Phys. Condens. Matter, vol. 1, 1989.

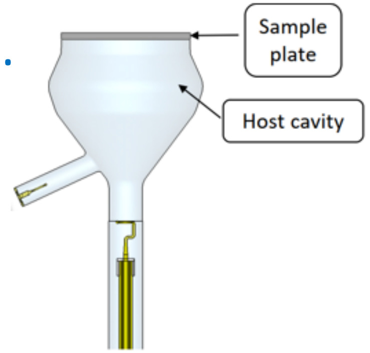
- Flux expulsion tests during slow warm up showed our scaled-up samples (thinner film, different Zr profile) have 16 K Tc.



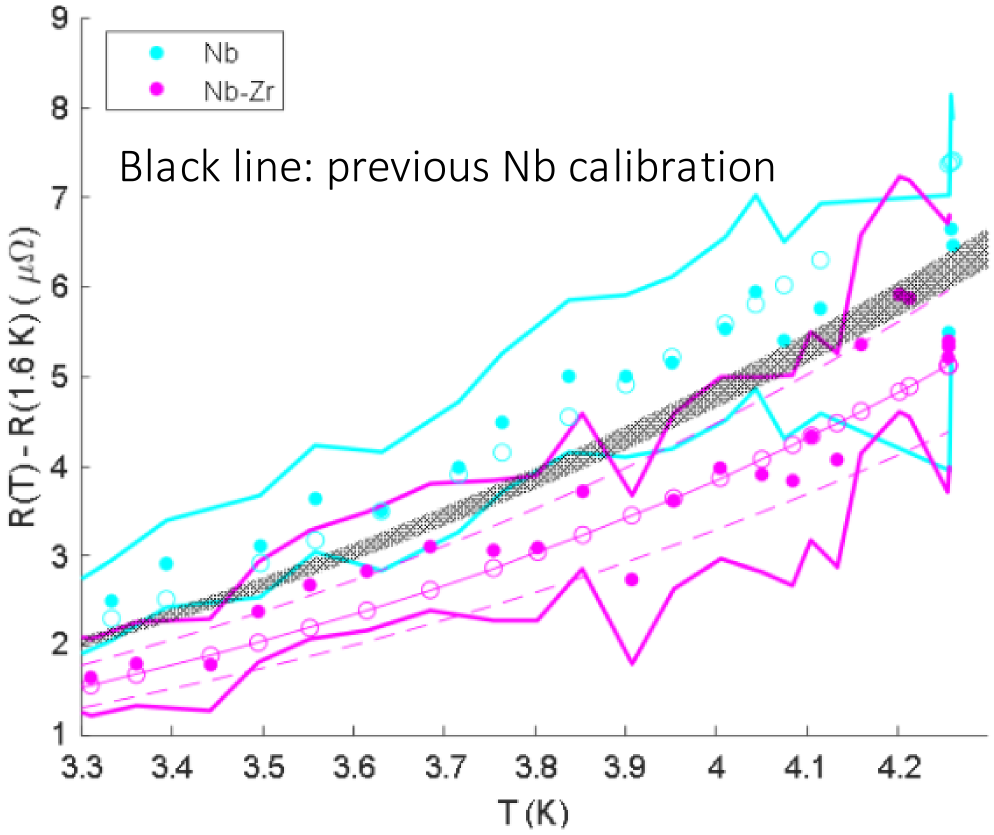


BCS resistance vs. T (by Thomas Oseroff‡)

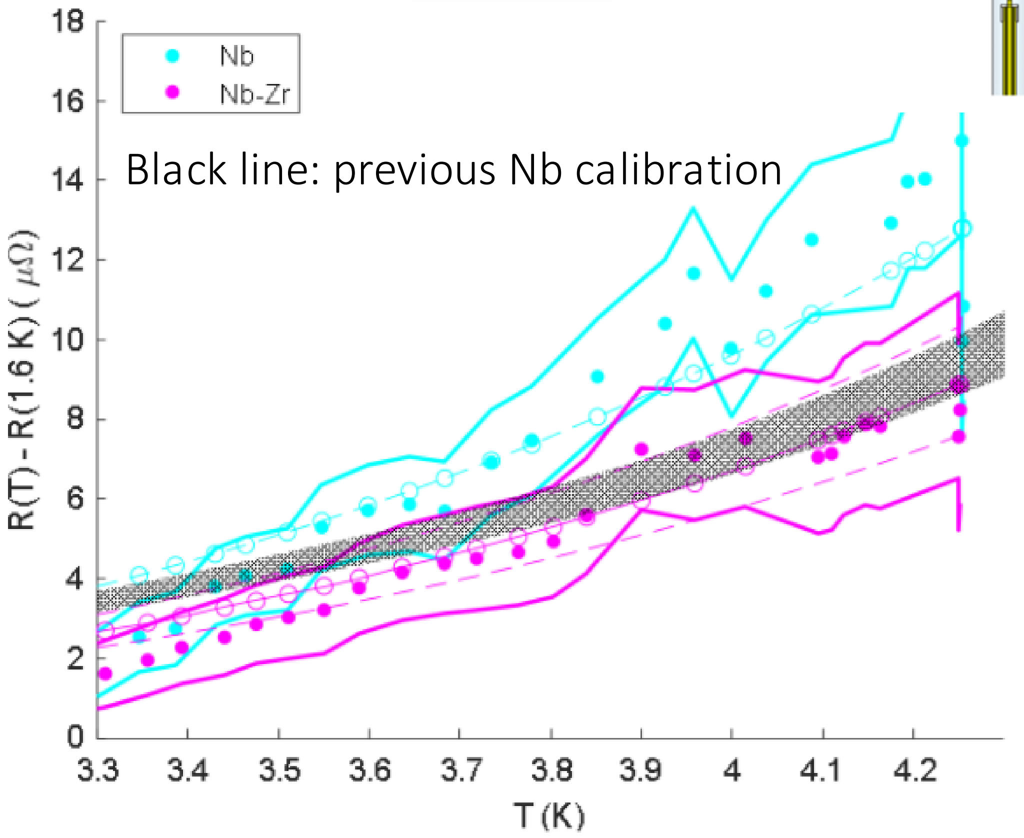
- Observed ZrNb trends lower BCS resistance at near 4 K, especially at 5.2 GHz.
- This resistance reduction can be explained by a thin layer of high Tc ZrNb.



4 GHz



5.2 GHz



Filled circles & thick lines: measurements and uncertainty;
Open circles & dashed lines: simulated values and uncertainty.

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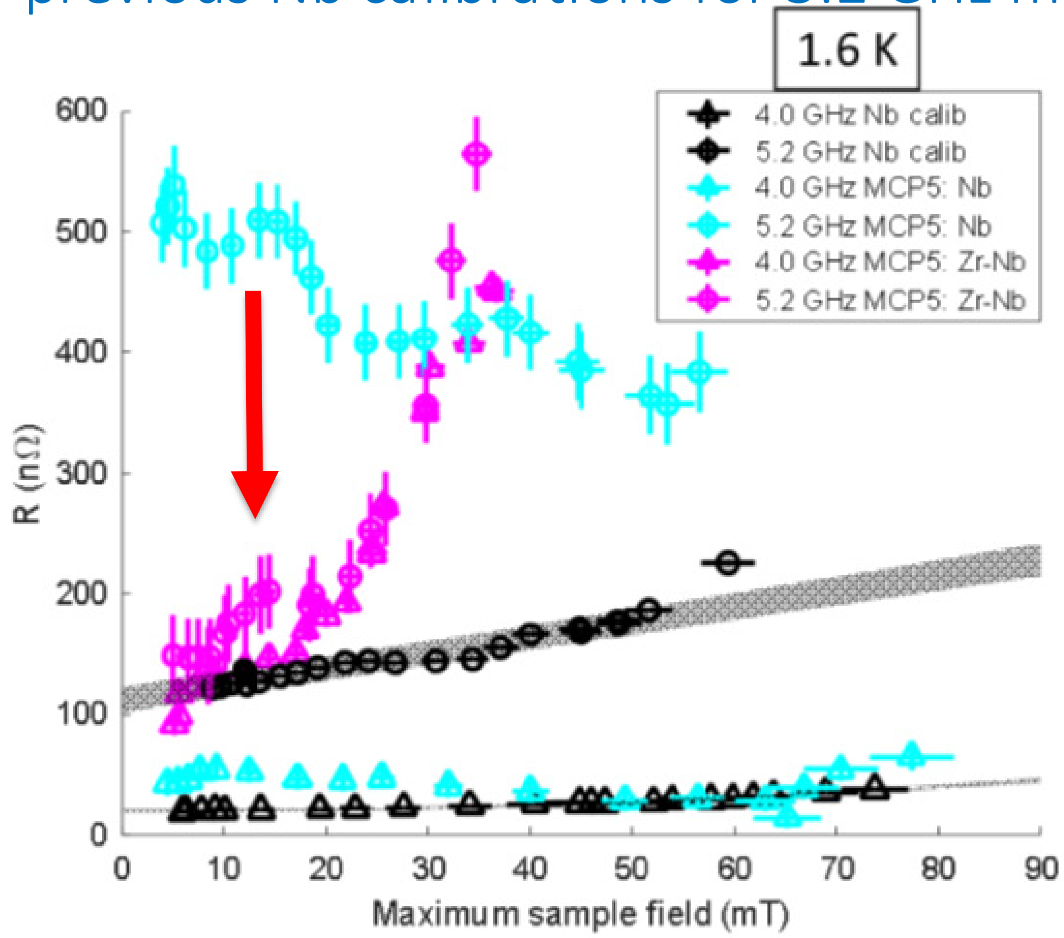
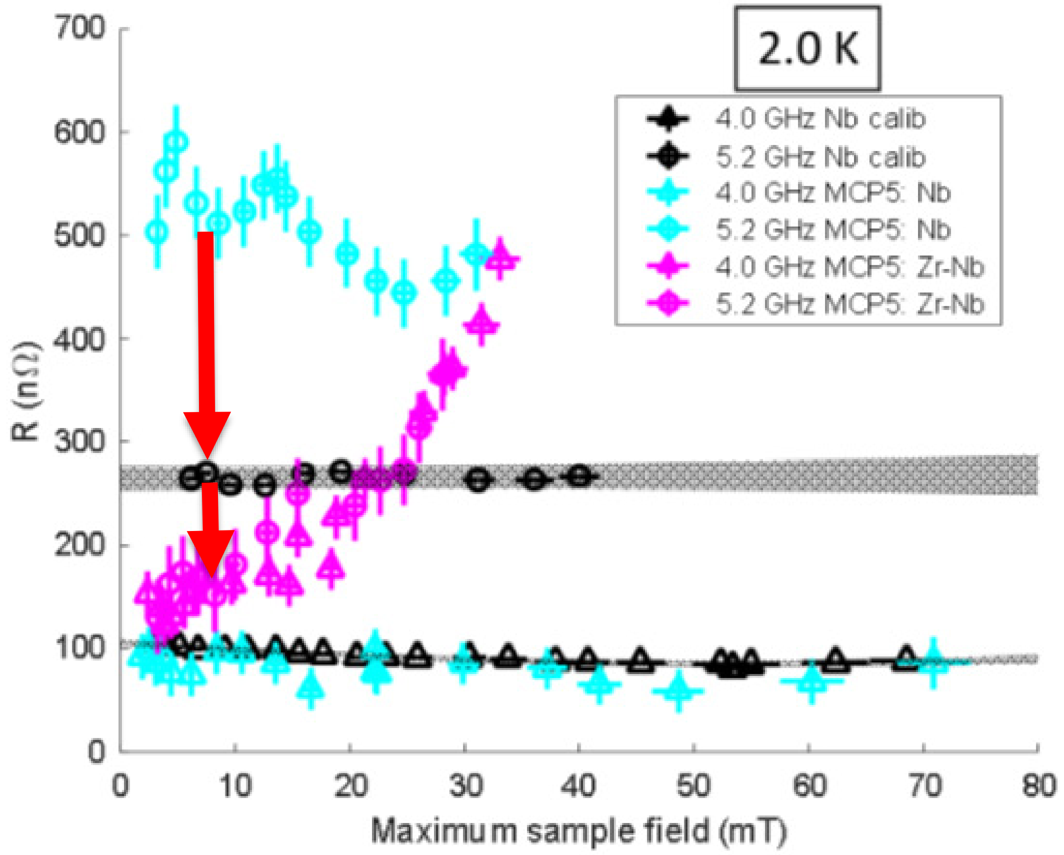
Surface resistance vs. field (by Thomas Oseroff‡)

- Quenched at 35-40 mT both frequencies (note that admin. limit is ~100 mT).
- At 2 K and low fields, ZrNb surface resistance is lower than Nb baseline and previous Nb calibrations for 5.2 GHz measurements.





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Conclusions and future work

- Developed a ZrNb alloying process via electrochemical deposition.
- Demonstrated cubic ZrNb surface alloys yielding T_c up to 16 K (higher than literature results).
- First RF measurements indicate a mild reduction in high temperature (near 4 K) surface resistance consistent with a thin film with 16 K Tc.
- We plan to fabricate ZrNb-alloyed TESLA cavities and provide their results soon.

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Thank you for your attention!