CVD Coated Copper Substrate SRF Cavity research at Cornell University

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SRF2019 conference in Dresden, Germany
2019-7-2

Outline:

- Introduction of Chemical Vapor Deposition (CVD)
- Nb-Cu Cavities
  - Cavity preparation
  - Cavity test results and analysis
- Nb-Cu Sample study
- Nb_3Sn-Cu plates
- Conclusion

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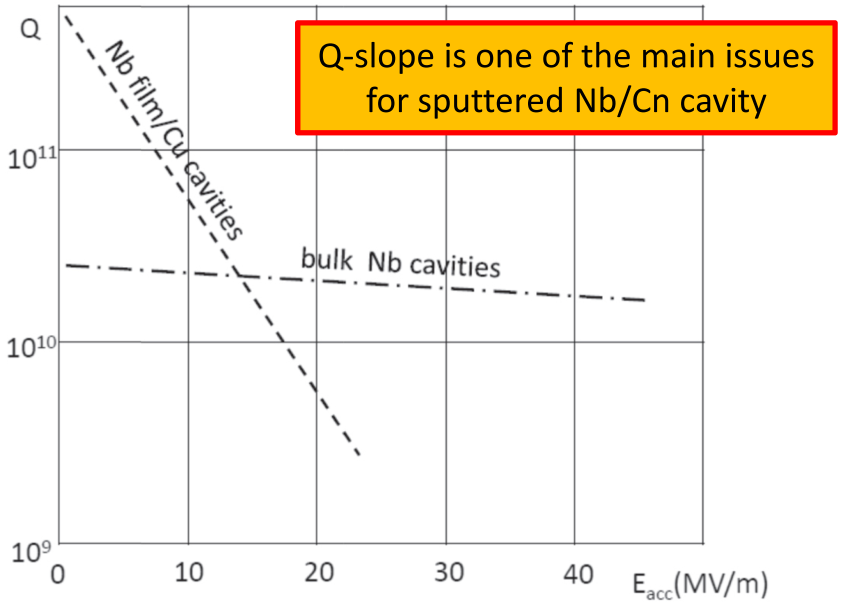
Advantages of Thin-Film Nb

- **Lower cost**
  - High RRR Nb ≈ 10x price of Cu
  - Can avoid expensive electron beam welding
- **Increased thermal stability**
  - Nb: 75 W/(m· K) -> Cu: 300-2000 W/(m·K)
- Can **avoid inclusions** caused by machining
- Can coat Nb-layer on **complex shaped** parts.

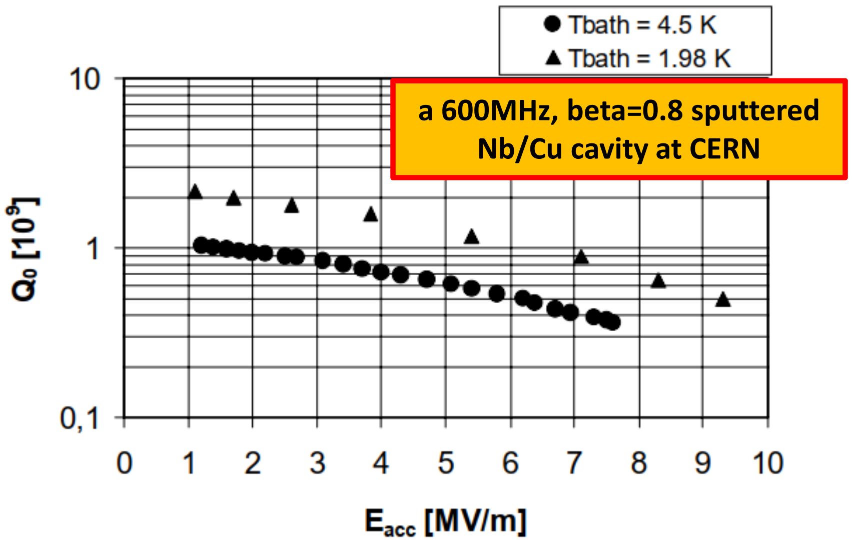
Why Do We Need CVD?

Advantages of CVD (as an alternative way of coating Nb-layer):

- Forms a metallurgical diffusion bond
  - Strong enough withstand High Pressure Rinses (HPR) and tumbling;
  - Creates good thermal contact;
- High deposition rate
  - 300 μm/hour;
  - Can make both thick and thin films of high-pure Nb;
  - Potentially CVD cavity is capable of doping/infusion.



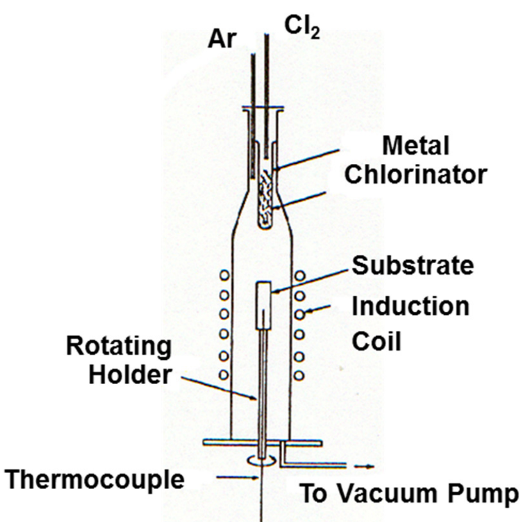
V Palmieri and R Vaglio, Superconductor Science and Technology, Vol. 29, Num. 1



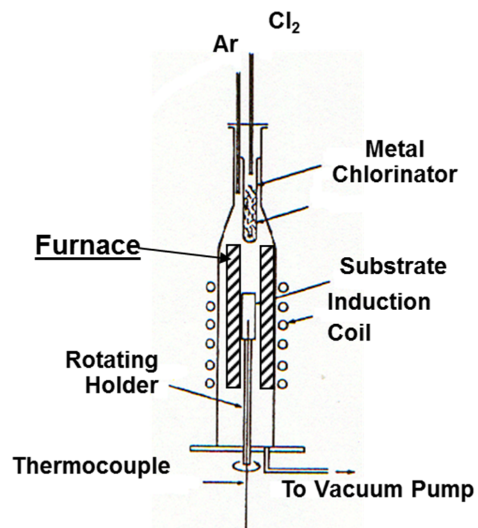
S. Bauer, et al. Proc. of SRF 1999

Introduction of CVD

- CVD is a vacuum deposition method;
- A substrate is heated up and exposed to precursors;
- Reaction/deposition takes place on the substrate surface and leaves thin-film coating on it.



Cold-Wall Process



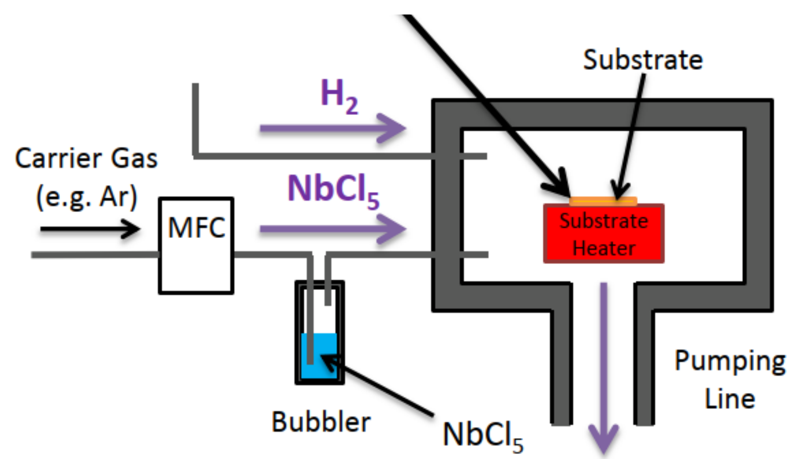
Hot-Wall Process

- **Cold-Wall Process:** Selective heating and preferential deposition;
- **Hot-Wall Process:** Isothermal heating and uniform temperature control.

- **Common method for coating Nb**:

1) $NbCl_5$ is vaporized;
2) Hydrogen is added;
3) The substrate is heated up to a temperature (e.g. 700 ºC);
4) Deposition takes place on the substrate;
5) Resultant gasses pumped away.

$2\ NbCl_5 + 5\ H_2 \rightarrow 2\ Nb + 10\ HCl$



Reactor diagram showing use of $NbCl_5$ to produce CVD niobium

P. Pizzol et al., "CVD Deposition of Nb Based Materials for SRF Cavities," in Proc. of IPAC 2016

Technical Challenges of CVD for SRF

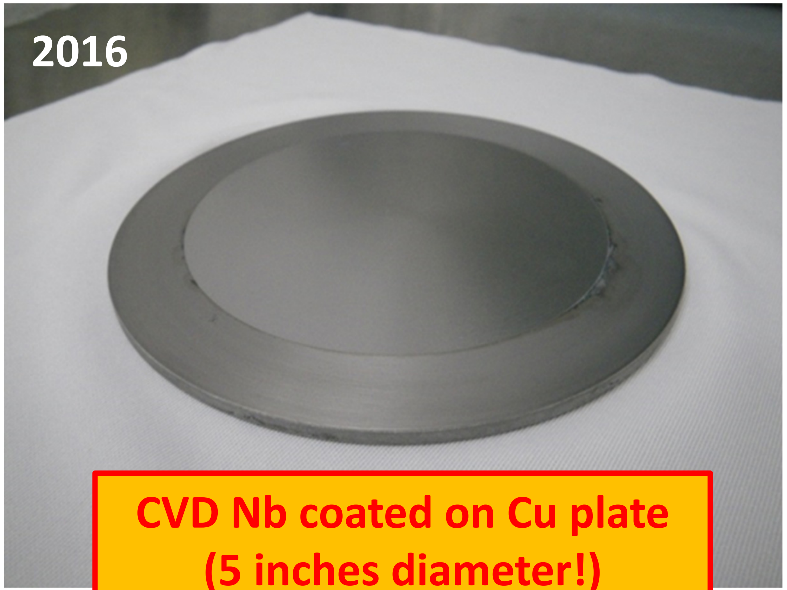
1) High Pure Nb;
2) Thick and strong Nb layer;
3) Coating Nb layer on large samples;
4) Coating Nb layer on a full-size cavity;
5) Low residual resistance (R_0);
6) High accelerating gradient (E_{acc}).
7) No severe Q-slope;

Bulk CVD Nb SRF cavity

Achievements in early CVD works done with Ultramet:

Excellent RRR results: > 250

RRR measurement system at Cornell



CVD Nb coated on Cu plate (5 inches diameter!)

Collaborated with Ultramet

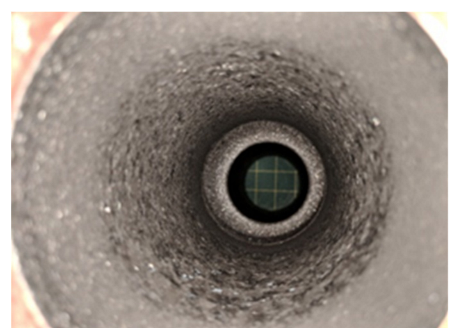
2017 DOE SBIR Phase-II:

"Fabrication and Testing of Thick Film CVD Niobium-Lined Copper SRF Cavities for High Gradient Applications"

The CVD niobium is bonded at the nuclear level to the copper cavity substrate resulting in excellent adhesion characteristics:

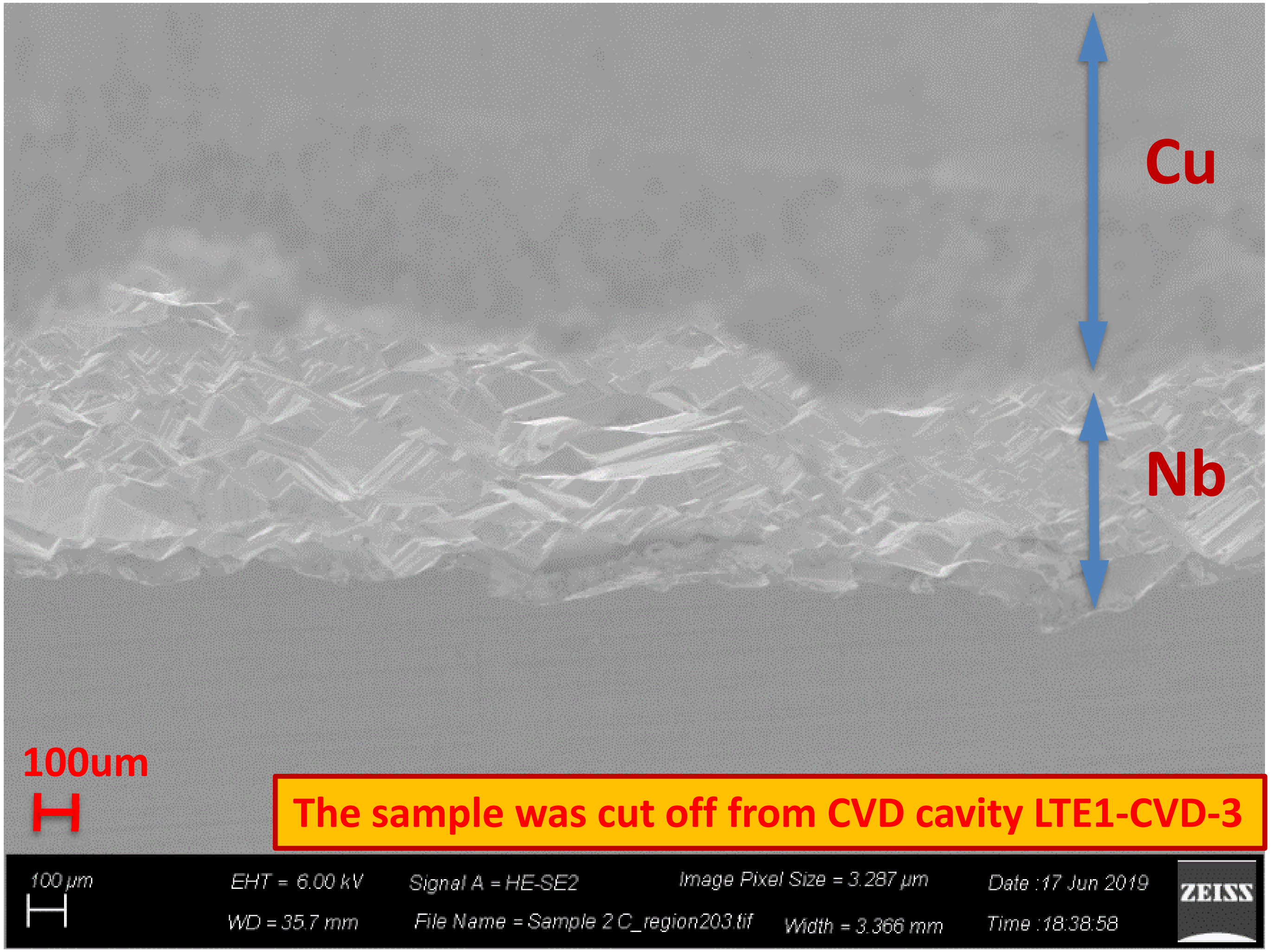
CVD processing at Ultramet

Half 1.3GHz single-cell cavity



1.3GHz single-cell CVD Nb-Cu cavity

Cross-section SEM of the CVD layer



- Average thickness of Nb layer > 200 um.
- Plenty room for surface treatment, e.g. EP, tumbling, etc.
- Capable of introducing impurity on surface, e.g. Doping/infusion.

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CVD Cavity Preparation

LTE1-CVD-2:

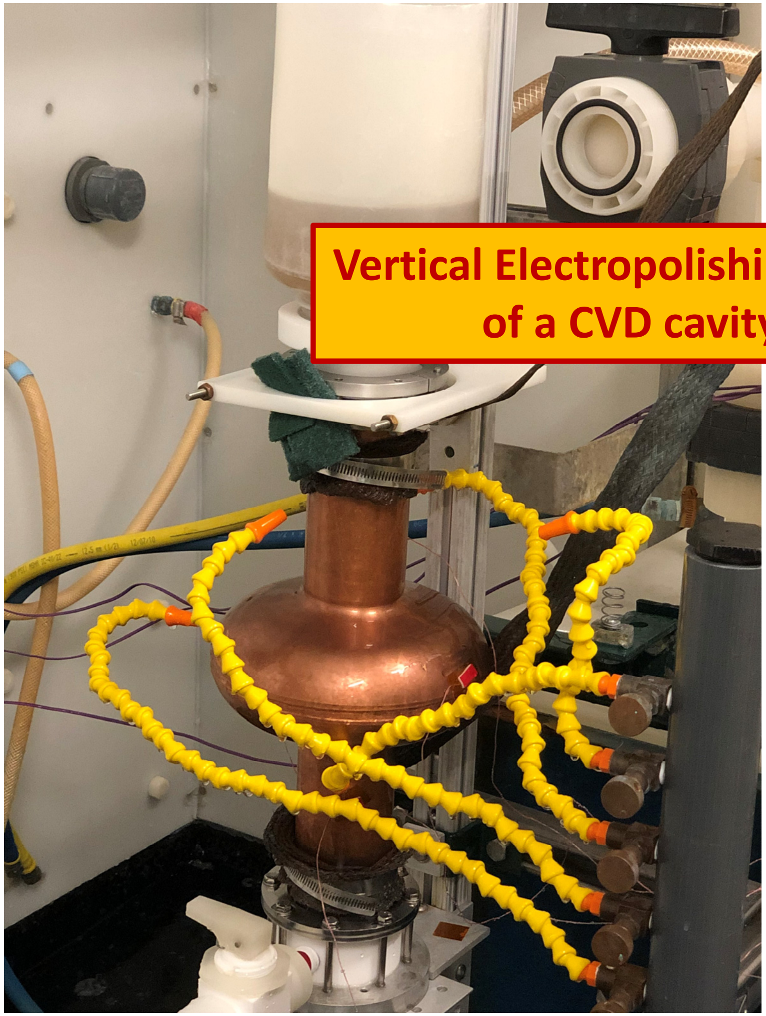
- **10 um VEP**
- VT: cooldown1 + cooldown2

LTE1-CVD-3:

- VT1: had cold leak;
- VT2: re-tighten flanges;
- VT3: **5 um VEP** ;
- VT4: re-HPR and re-test;
- VT5: dressed with T-map

LTE1-CVD-4:

- **Tumbling** and 10um EP



Vertical Electropolishing (VEP) of a CVD cavity

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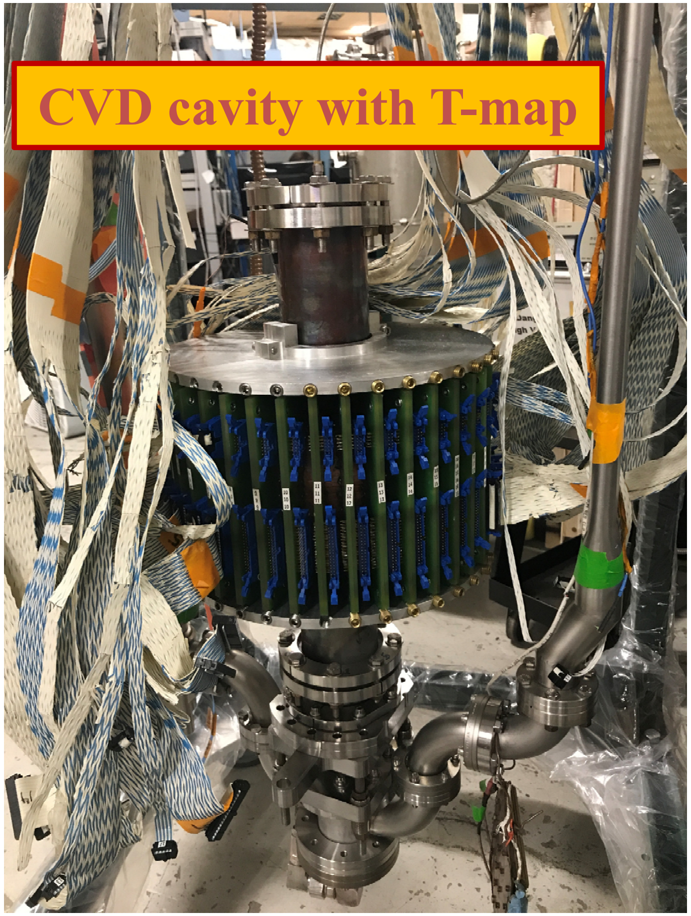
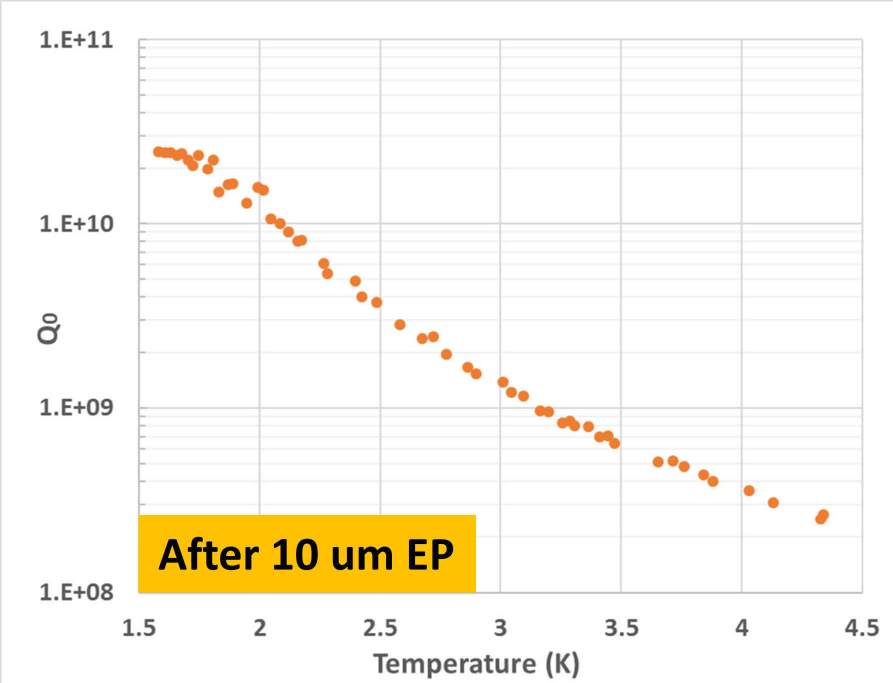
CVD Cavity Tests at Cornell University



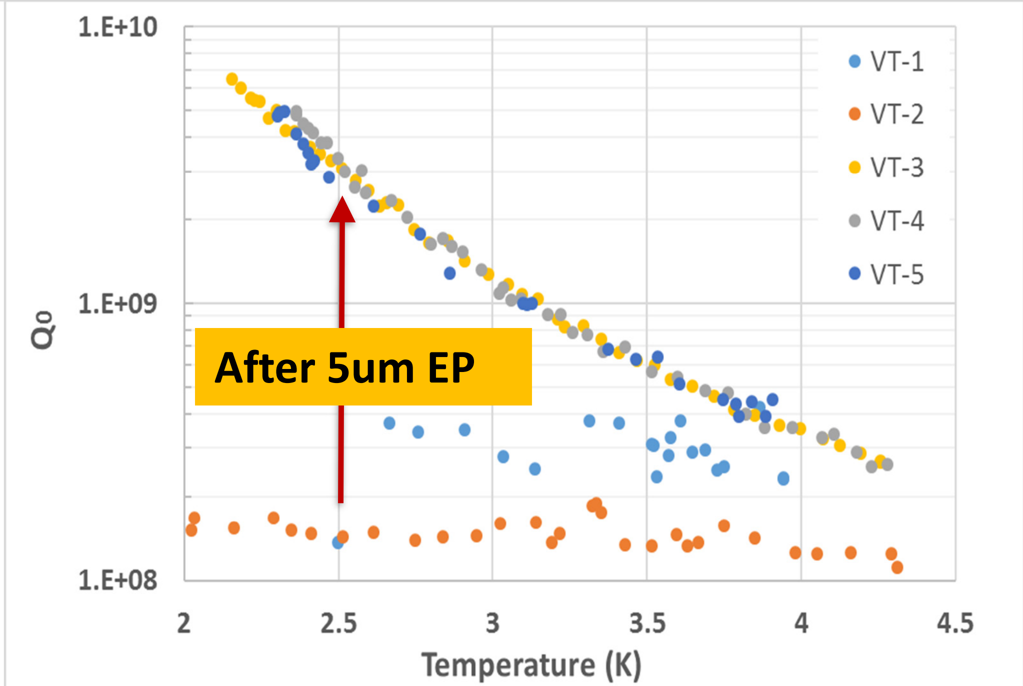
Instrumentation for Vertical Tests:

- Helmholtz coil,
- Slow-cool stinger,
- Cernox sensors,
- Fluxgate sensors,
- Variable input coupler.

Q_0 vs. Temperature



LTE1-CVD-2



LTE1-CVD-3

- Q_0 achieved **>1e10 at 2K** after light VEP, closed to a heavy EP'd 1.3GHz bulk-Nb SRF-cavity;
- **R_0 < 10 nΩ** for both cavity after light VEP;
- Before VEP, cavity Q_0 was dominated by R_0(~1000n Ω), but the cavity was still superconducting.

Flux Trapping Measurement of LTE1-CVD-2

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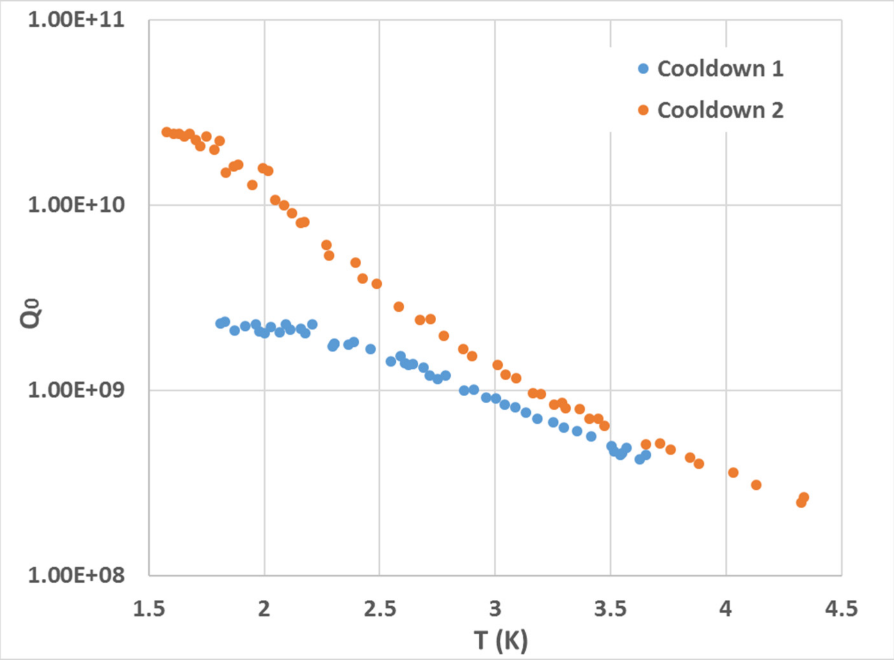
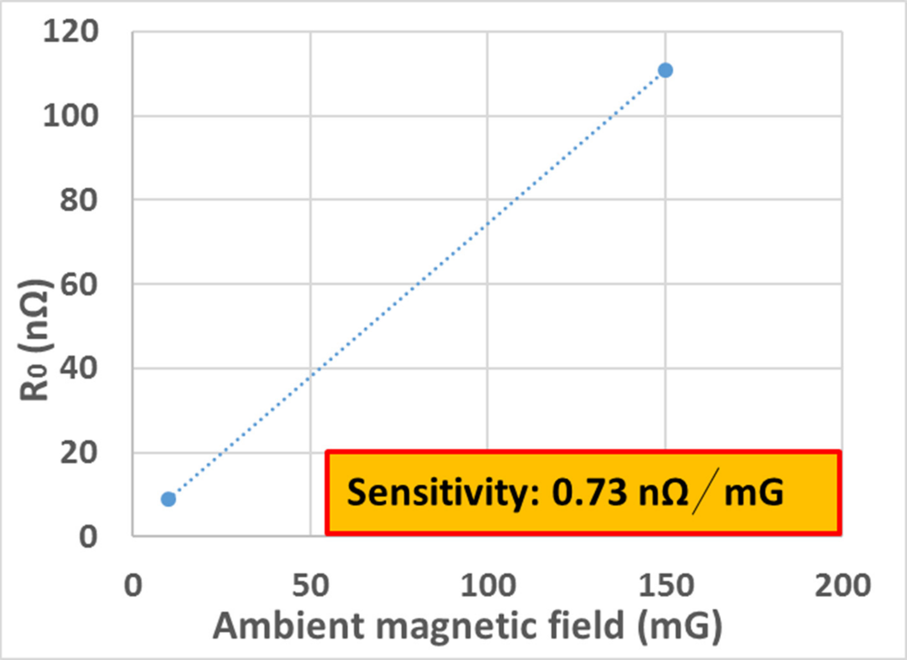
- Cavity preparation: CVD + 10 um VEP



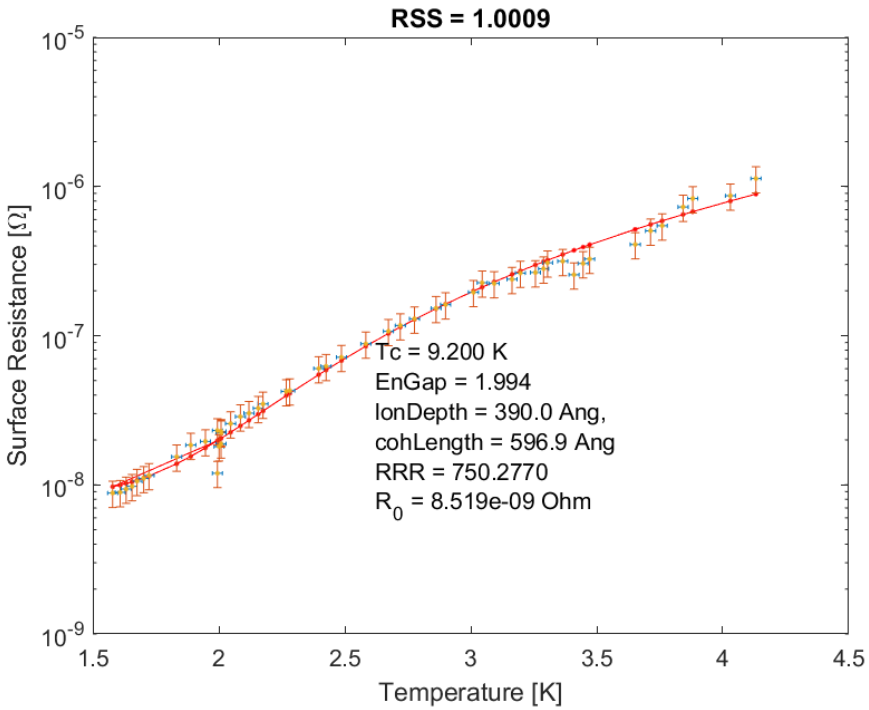
Q_0 vs temperature curve



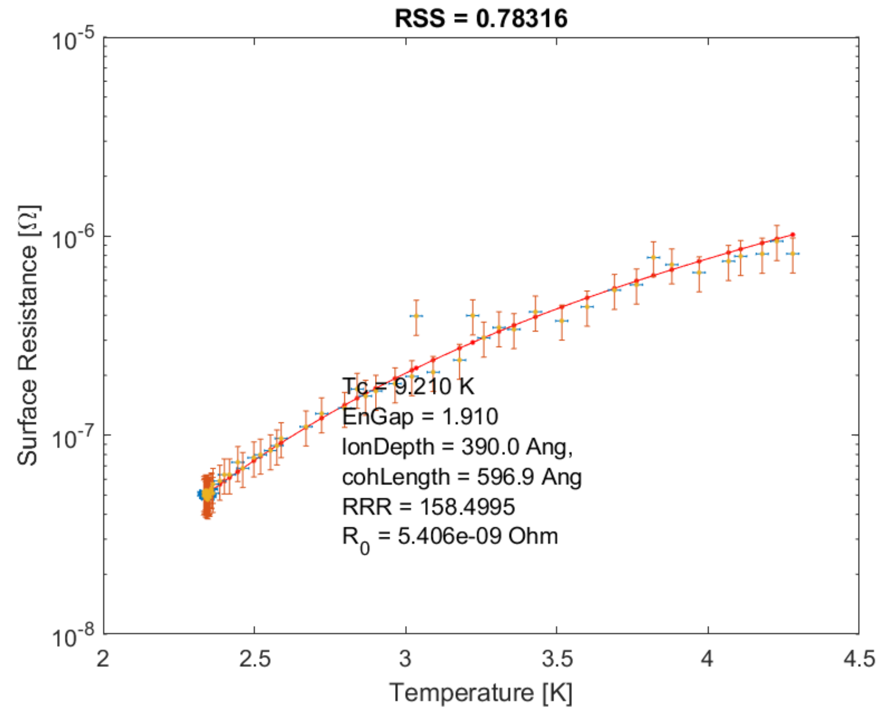
R_0 vs ambient magnetic field curve

- Cooldown 1: with 150 mGauss ambient magnetic field;
- Cooldown 2: with <10 mGauss ambient magnetic field;
- **The sensitivity is very closed to a EP'd bulk Nb cavity.**

Superconducting Parameters Fitting



LTE1-CVD-2 (VT2)

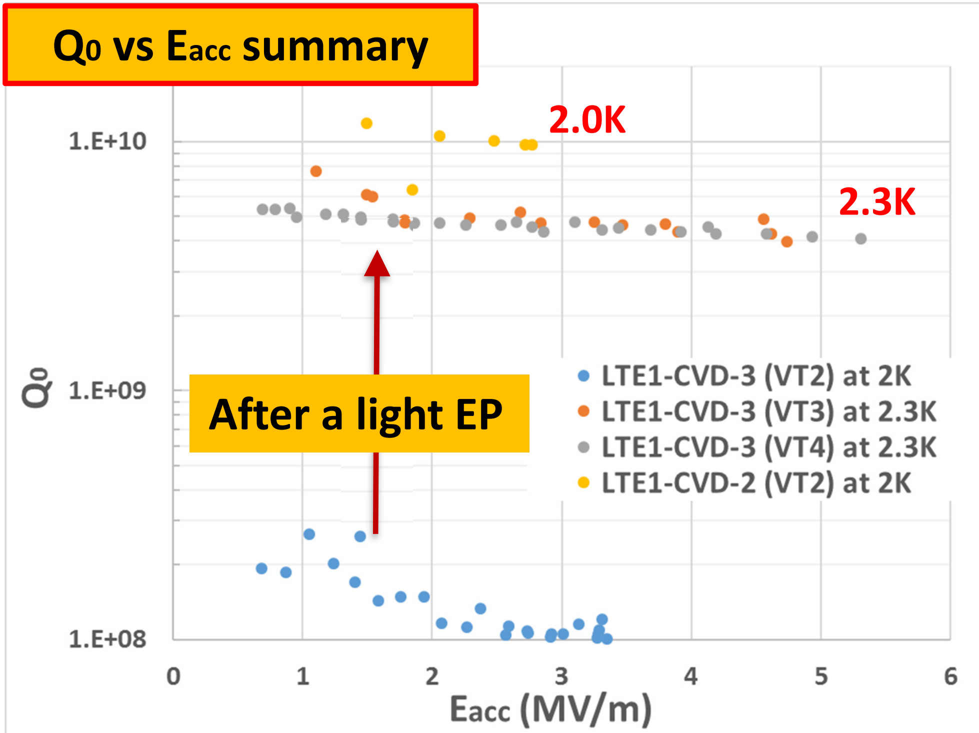


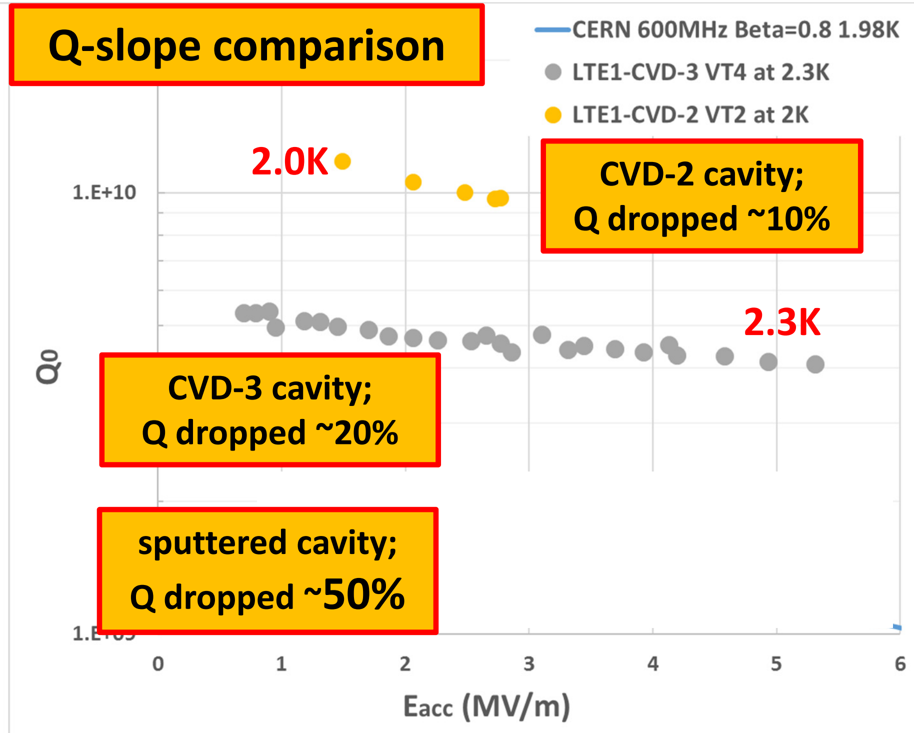
LTE1-CVD-3 (VT4)

	Mean free path (nm)	Tc (K)	Energy Gap	R_0 (nΩ)
LTE1-CVD-2 (VT2):	**4500**	9.20	1.994	**8.5**
LTE1-CVD-3 (VT4):	**948**	9.21	1.910	**5.4**

- **Larger MFP indicates clean and pure Nb.**

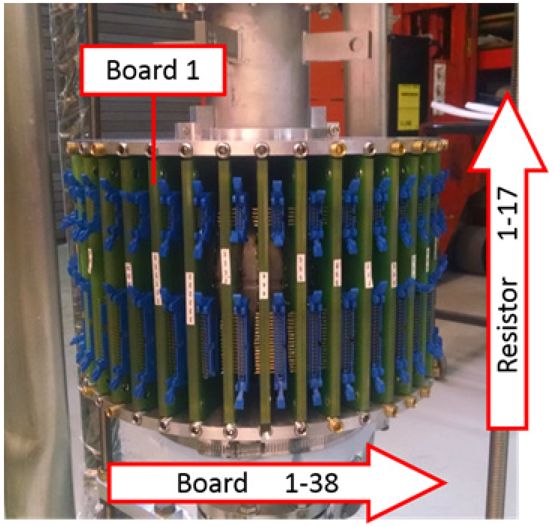
Q_0 vs. E_{acc} & Q-Slope Comparison





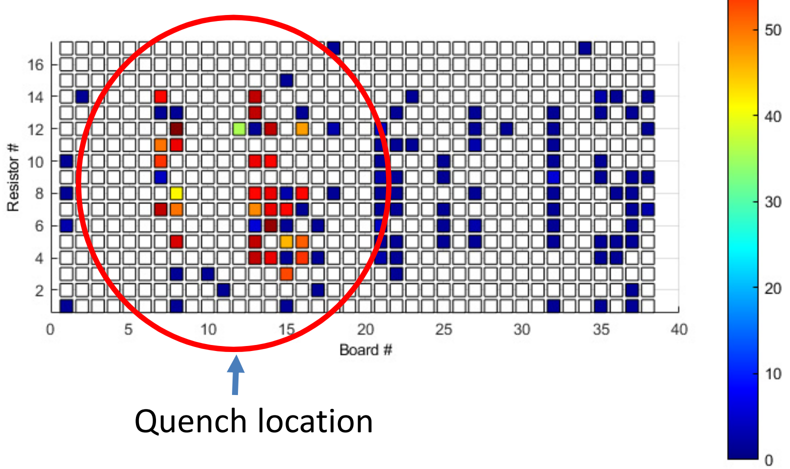
- Q_0 vs. E_{acc} curve is flat, **no severe Q-slope observed**;
- Quench field is low (~5 MV/m);

Temperature Mapping Results

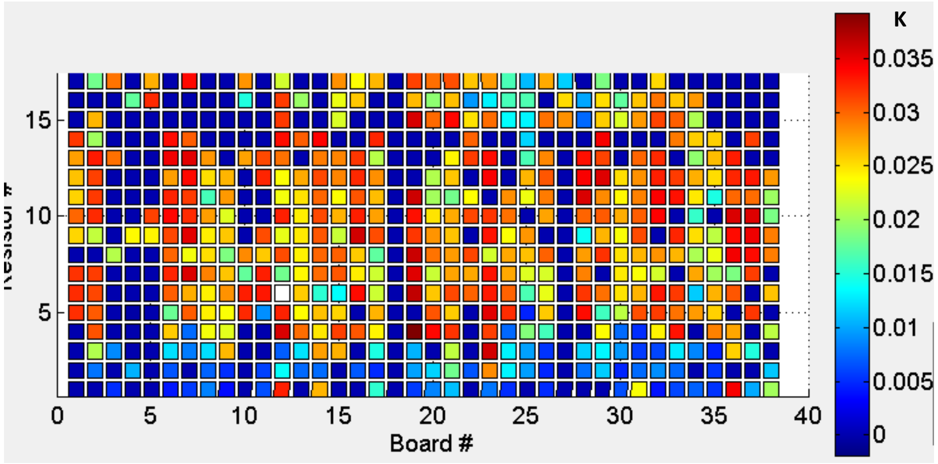


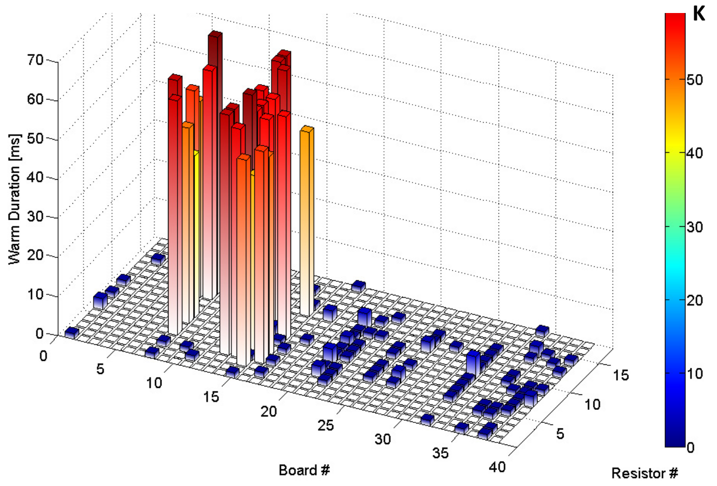
T-map set up for the test

Quench location detection:



Quench location





LTE1-CVD-3 T-map results at Eacc = 3.28MV/m

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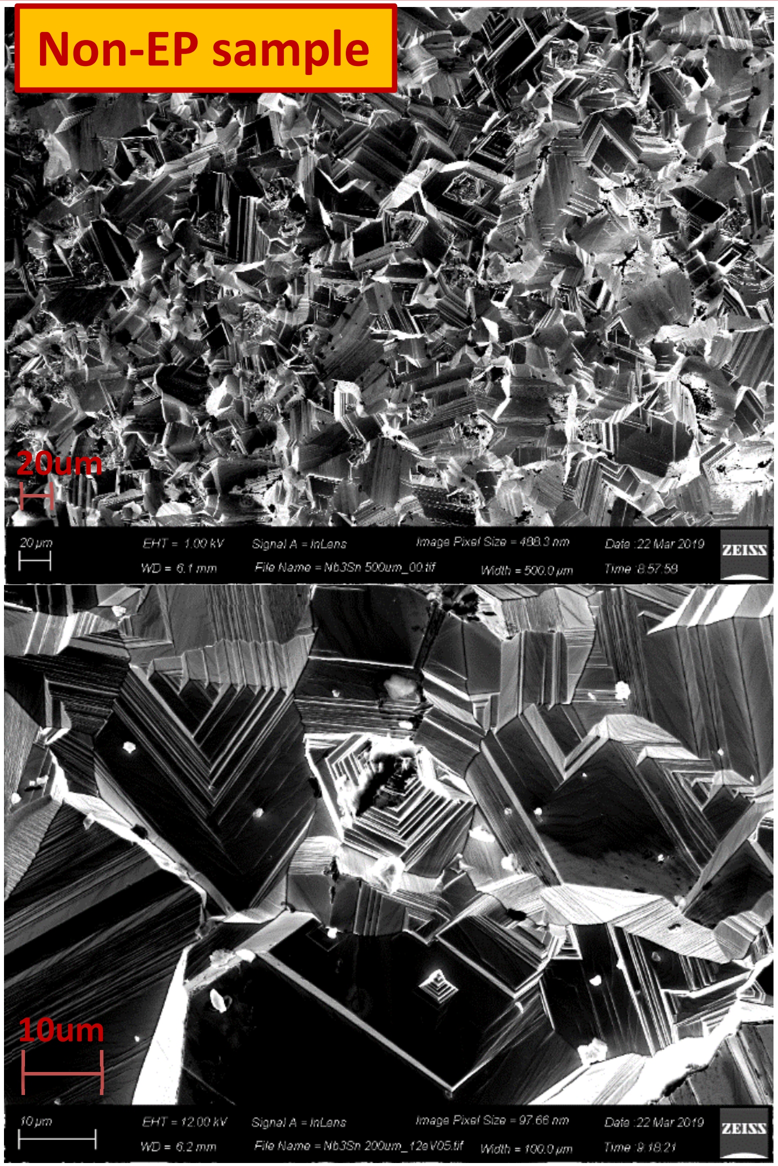
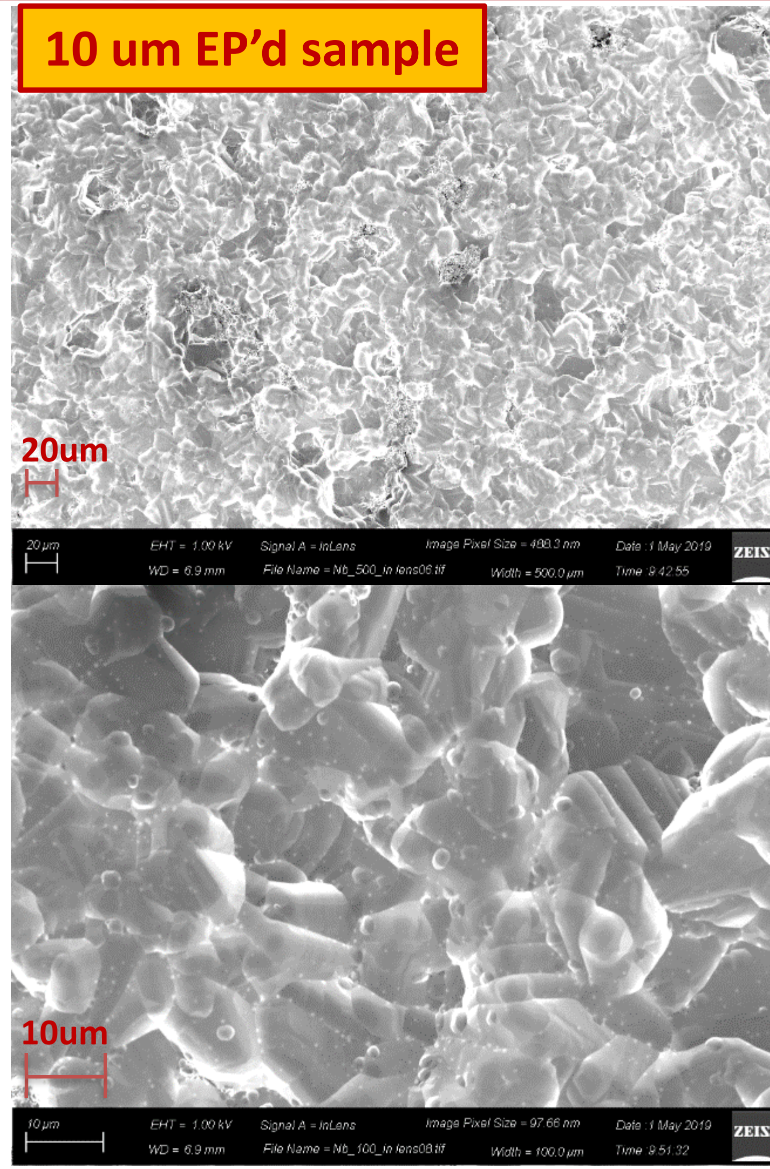
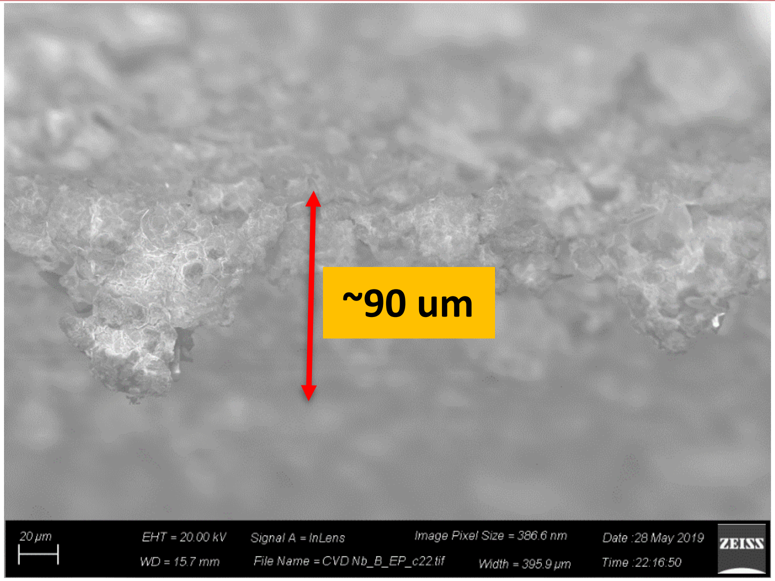
SEM Scan Comparison

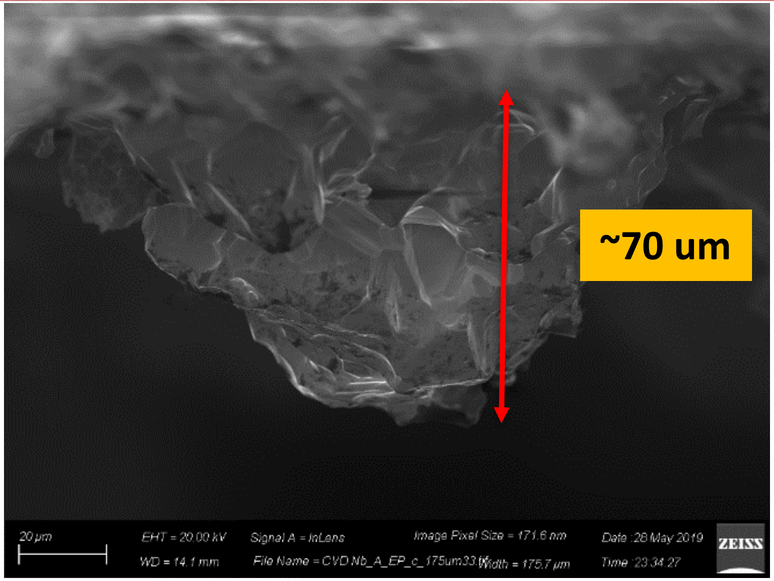


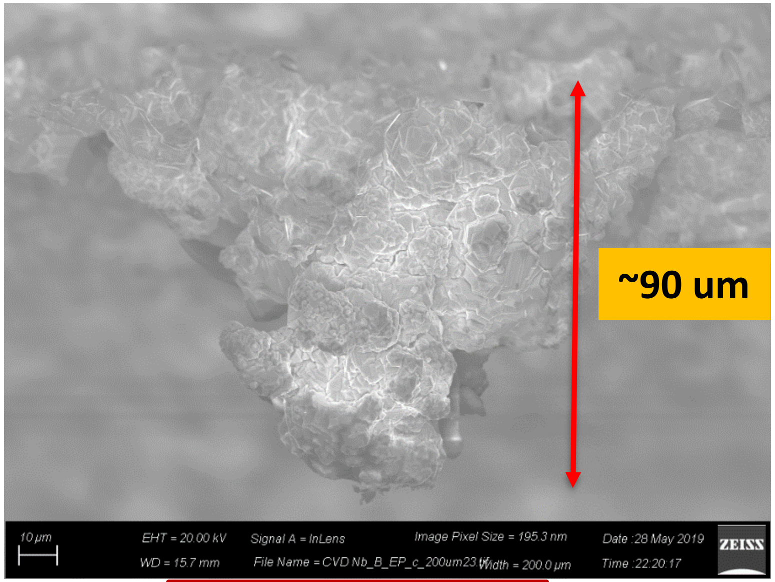


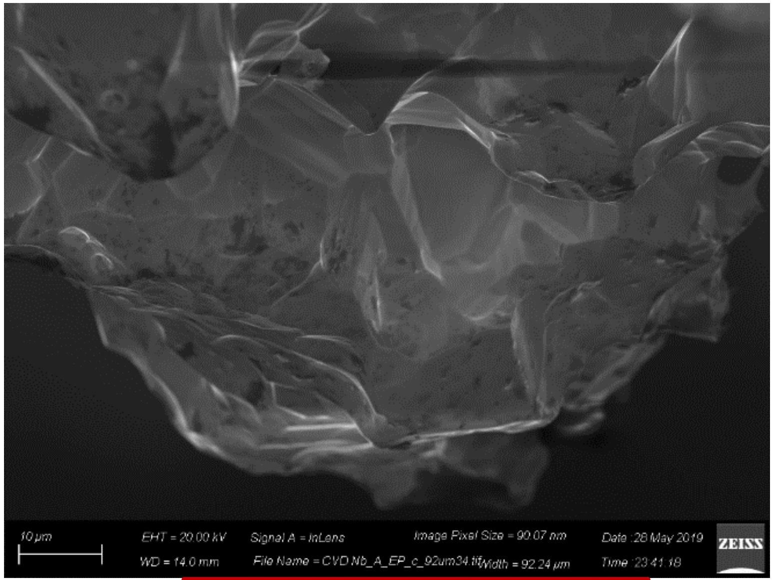
- **Round edge after EP.**

Cross-Section SEM Comparison









Non-EP sample

10 um EP’d sample

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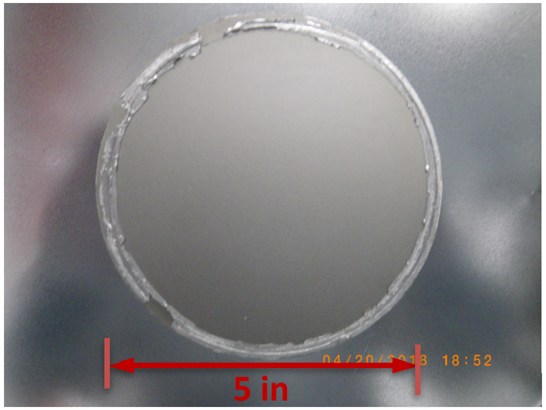
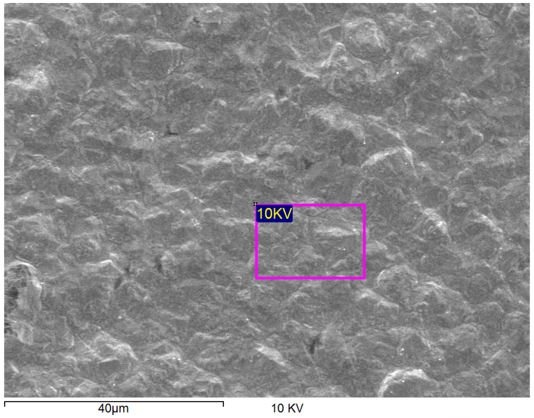
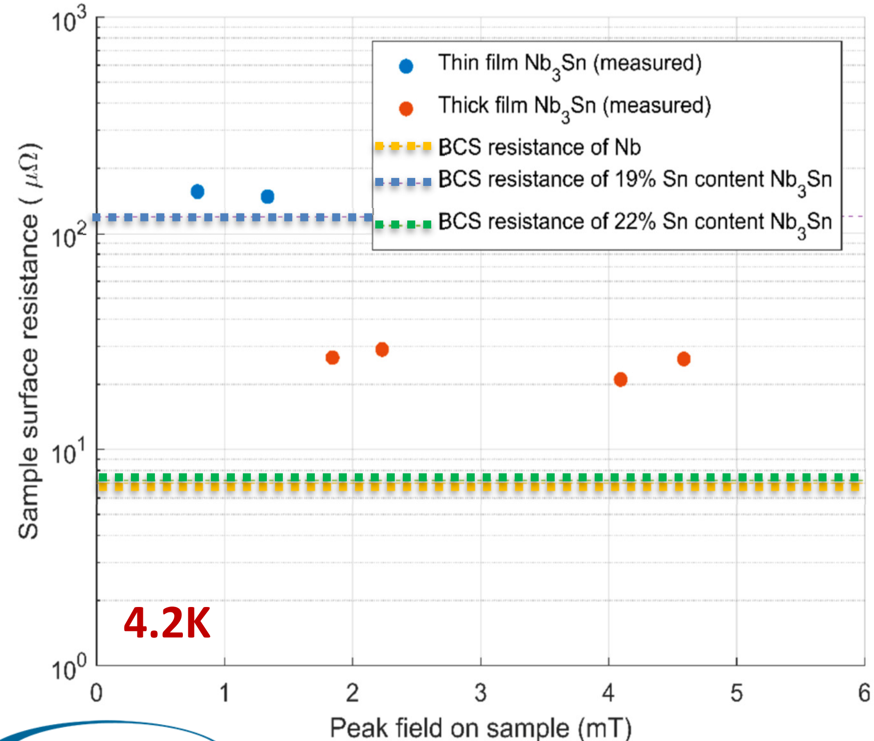
CVD Nb_3Sn-Cu Plates

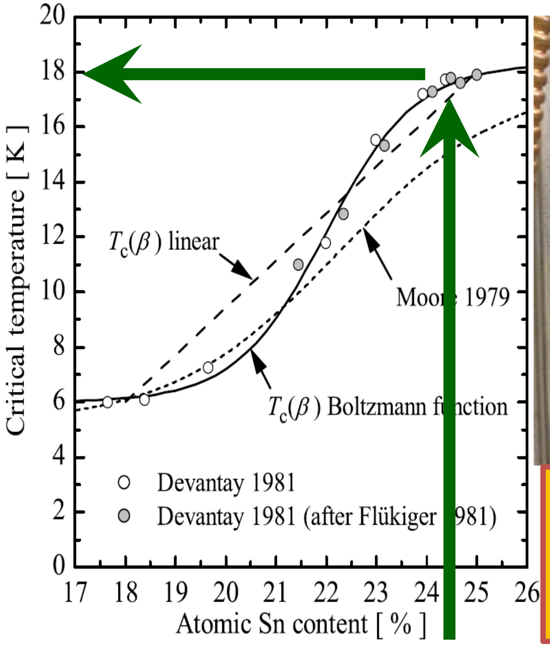




- **5 inches** large and uniform Nb3Sn layer;
- Atomic Sn content: **19-22%.**



T_c vs. Tin Content



24 to 25% target

A. Godeke, Supercond. Sci. Tech, 2006

The plate tested on 4GHz Cornell sample host cavity

ULTRAMET ADVANCED MATERIALS SOLUTIONS

Conclusion

1) High Pure Nb (RRR > 250, large MFP);
2) Thick and strong Nb layer (>200um; HPR tumbling and EP);
3) Coating Nb layer on large samples;
4) Coating Nb layer on a full-scale cavity;
5) Low residual resistance ($R_0 < 10$ nΩ);
6) No severe Q-slope up to 5MV/m;
7) high accelerating gradient (E_{acc}).

Acknowledgement

The CVD works are strongly supported by DOE SBIR program (All the SBIR awards have been awarded to Ultramet):

- 2005 SBIR DOE Phase I: "Cost-Effective, High-Performance, High Purity Niobium Superconducting Radio Frequency Cavities"
- 2012 SBIR DOE Phase I: "Advanced Manufacturing and Testing of Seamless High Purity Niobium Superconducting Radio Frequency Cavities"
- 2013 SBIR DOE Phase I: "Barrier Coating Development for the Manufacture and Testing of Superconducting Radio Frequency Cavities"
- 2016 SBIR DOE Phase I: "Low Temperature CVD Process Development for Forming Niobium Layers on Copper"
- 2017 SBIR DOE Phase II: "Fabrication and Testing of Thick Film CVD Niobium-Lined Copper SRF Cavities for High Gradient Applications"
- 2018 SBIR DOE Phase II: "CVD Process Development of Thin Film Triniobium-Tin on Copper SRF Cavities"
- 2019 SBIR DOE Phase I: "Advanced Horizontal CVD Reactor Development for Increased Process Efficiency to Produce Seamless Thick-Film CVD Niobium-Lined Copper SRF Cavities"

Thank You!