Advancements in HF-Free Bipolar Pulsed Electropolishing for Next Generation Superconducting Cavities

Hui Tian, Mingqi Ge, presented by Rongli Geng

Jefferson Lab

U.S. DEPARTMENT of ENERGY

Outline

- ➢Motivation.
- ➢Bipolar pulsed EP setup and pulse-control system.
- ➢Characteristic studies for Nb cavity process optimization (removal rate, surface morphology).
  - ✓ Effect of cathodic voltage.
  - ✓ Effect of anodic voltage.
  - ✓ Effect of electrolyte concentration.
  - ✓ Effect of pulse duration.
- ➢Nb cavity results with BPEP.
- ➢Extension to Nb_3Sn.
- ➢Conclusion.

Motivation

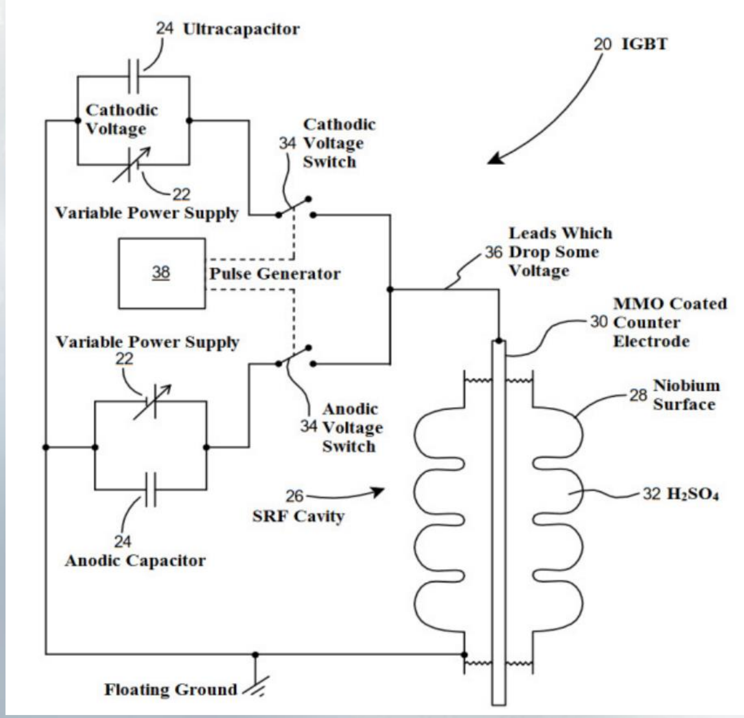
- Eliminate use of HF ⟶ less hazard and environmental impact.
- No harmful by-products (no sulfur → no RF degradation vs. traditional EP).
- Precise control of surface removal-removal rate ⟶ < 0.01 nm/pulse.
- More cost-effective than other surface processes → good commercialization potential[1]

1. E. J. Taylor, M. E. Inman, T. D. Hall "Electrochemical system and method for electropolishing superconductive radio frequency cavities", U.S. Pat No. 9 006 147, April 14, 2015; Japanese Pat No. 6 023 323, October 14, 2016; European Pat No. 2 849 908, February 15, 2017.

Setup and Pulse-Control System

Electrode setup:

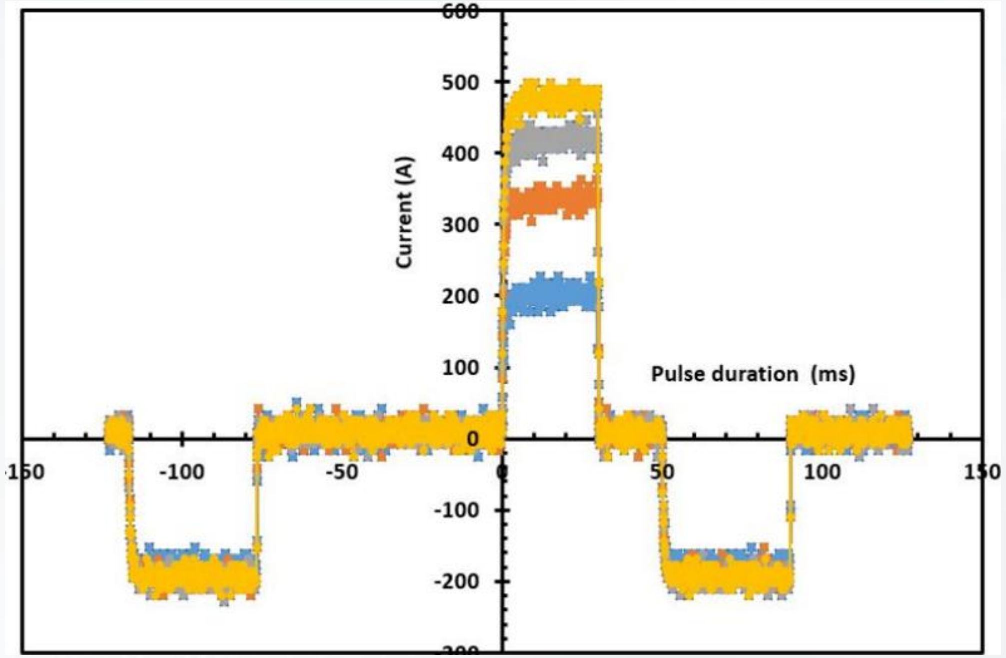
- Working electrode: Nb/Nb_3Sn cavity
- Counter electrode: mixed metal oxides (MMO)-coated Cu rod
- Electrolyte: Diluted H_2SO_4 or NaoH, HCl.



US patent 11,955,324 B2 (2024), Hui Tian, John C. Musson, Matthew Creed Burton, Anne-Marie Valente-Feliciano, Larry Phillips

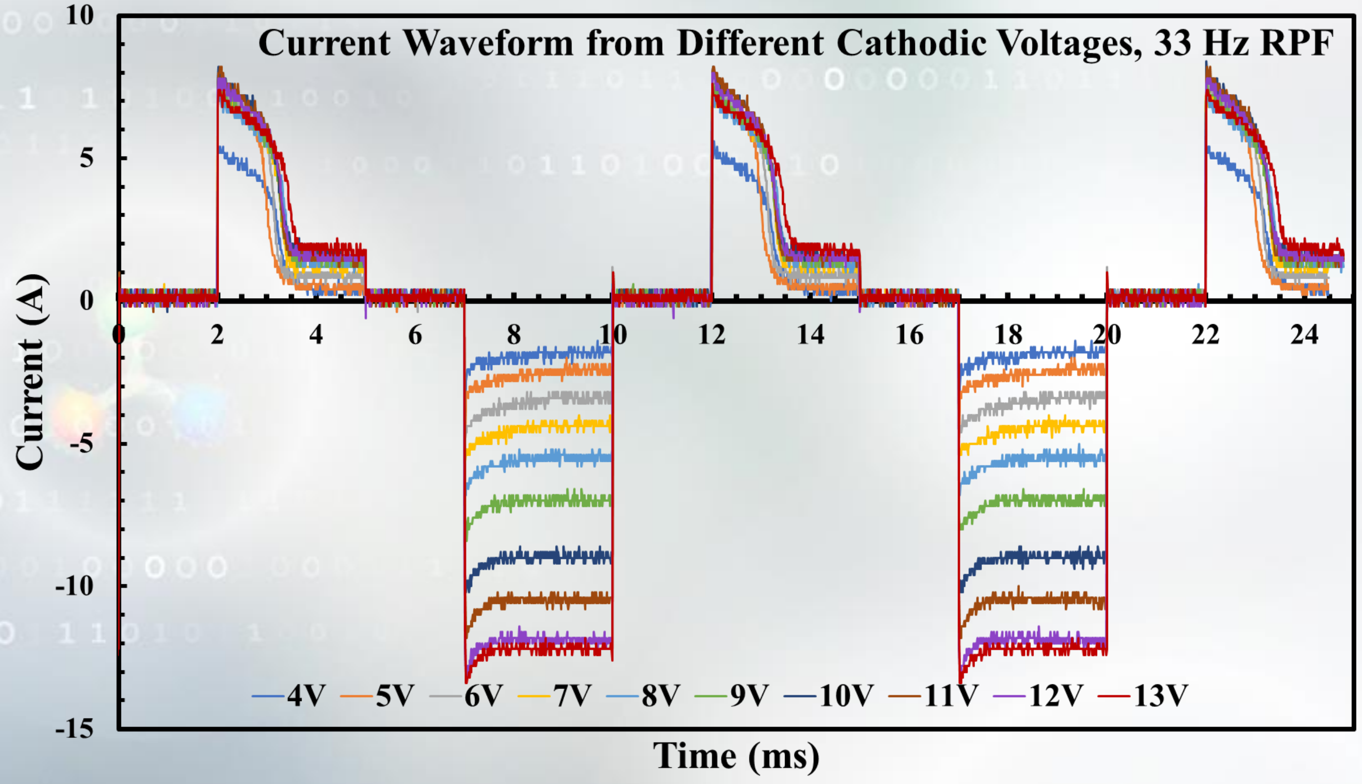
Upgraded BPEP Power & Control System

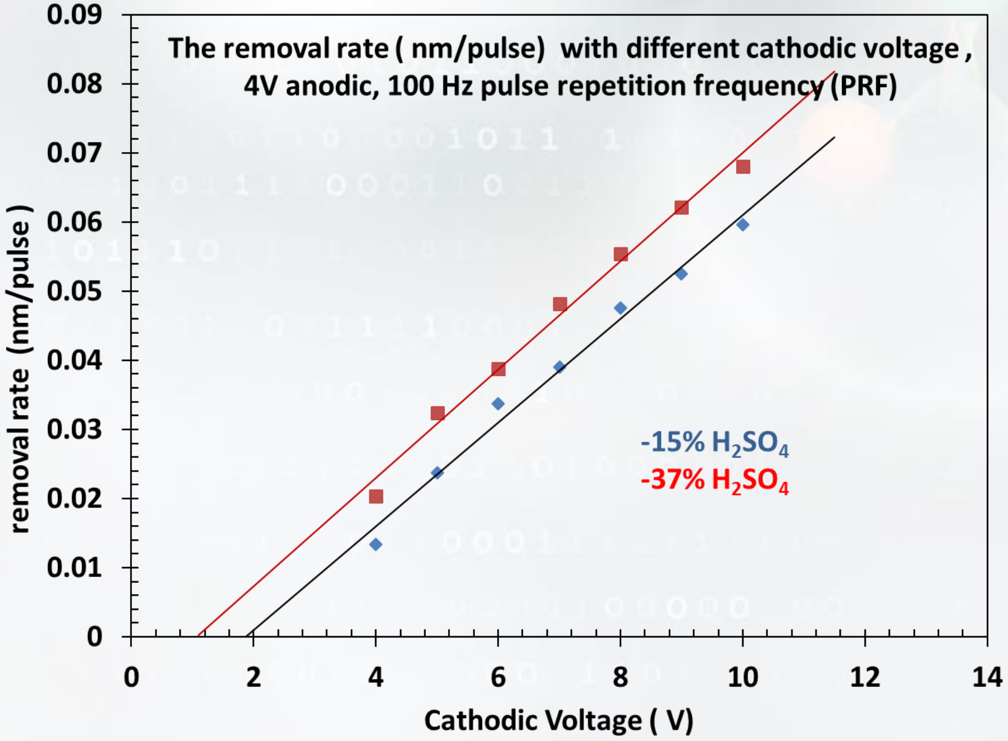
- ✓ 500-F ultracapacitor banks with parallel IGBT switches.
- ✓ Enlarged counter electrode area for improved uniformity.
- ✓ Optimized pulse control delivering ~2000 A for multi-cell cavities.



Output pulse waveform of upgraded pulse control system - test with a resistive load

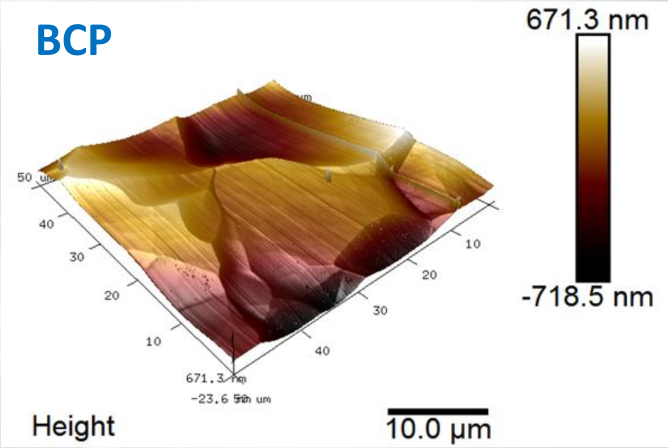
BPEP Characteristic: Mechanistic Insights into Cathodic Voltage Effects

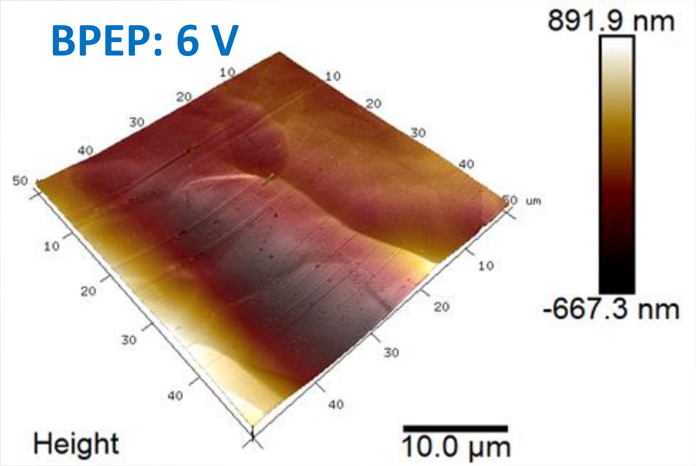


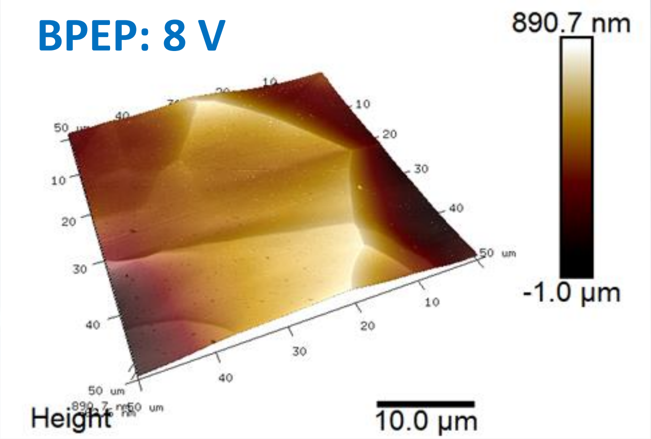


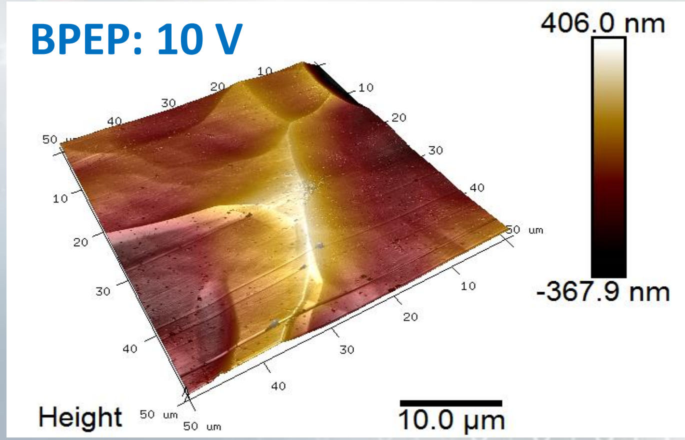
Removal rate: Increases linearly with cathodic voltage; governed by local current density.

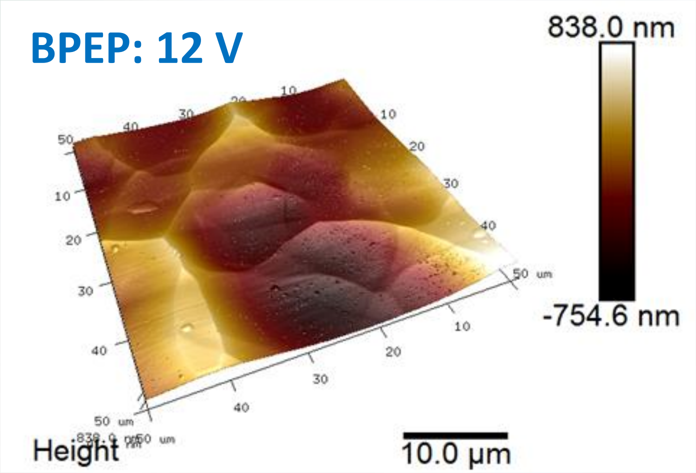
BPEP Characteristic: Mechanistic Insights into Cathodic Voltage Effects-2

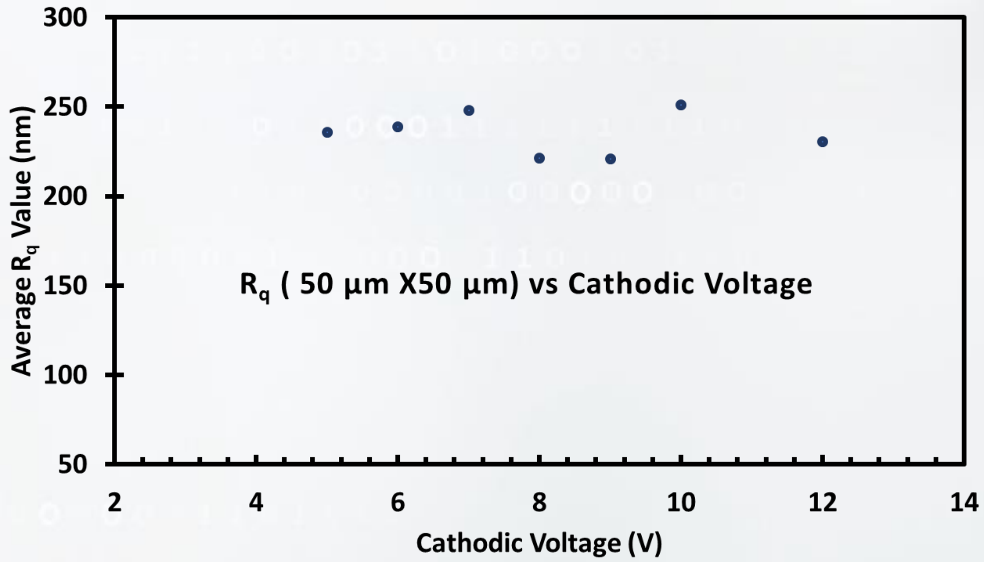






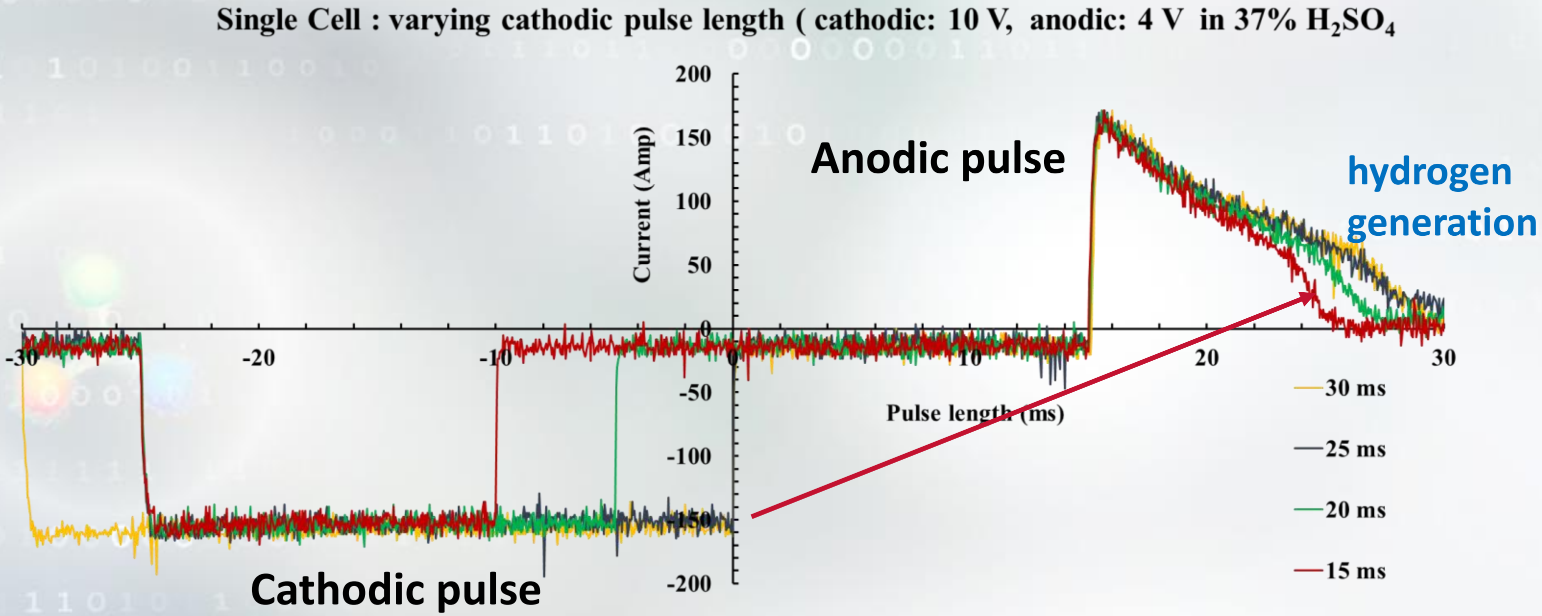


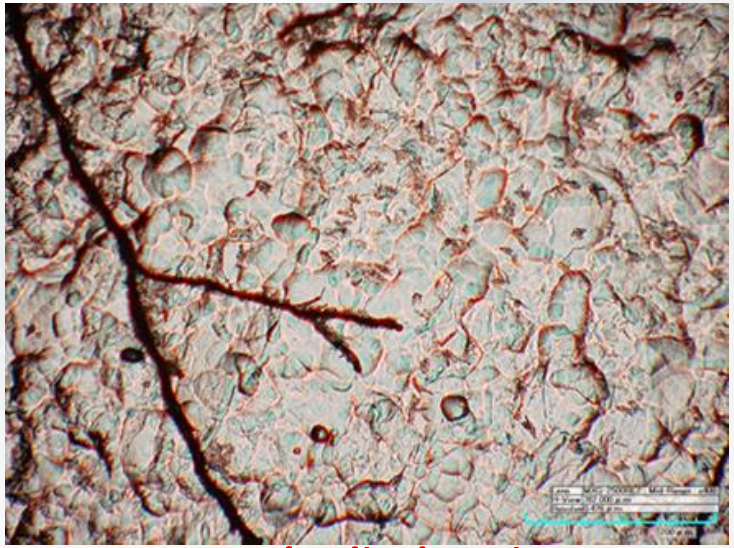




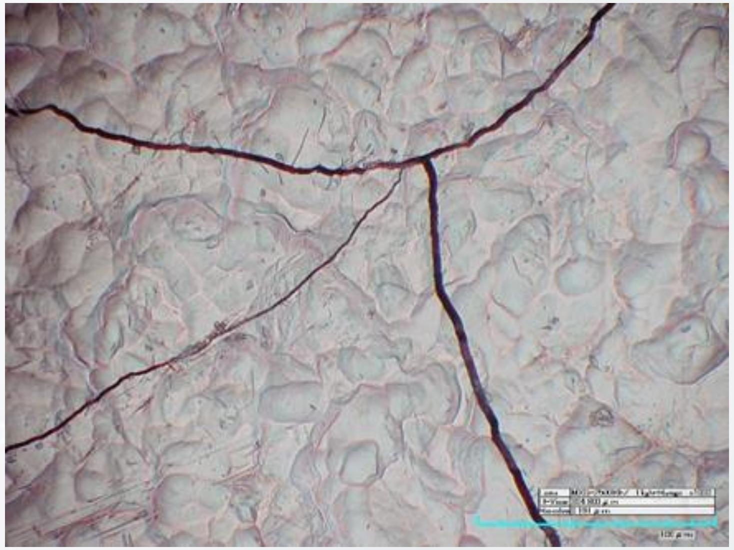
Surface roughness : independent of applied cathodic voltage

BPEP Characteristic: Mechanistic Insights into Cathodic Pulse Duration Effects





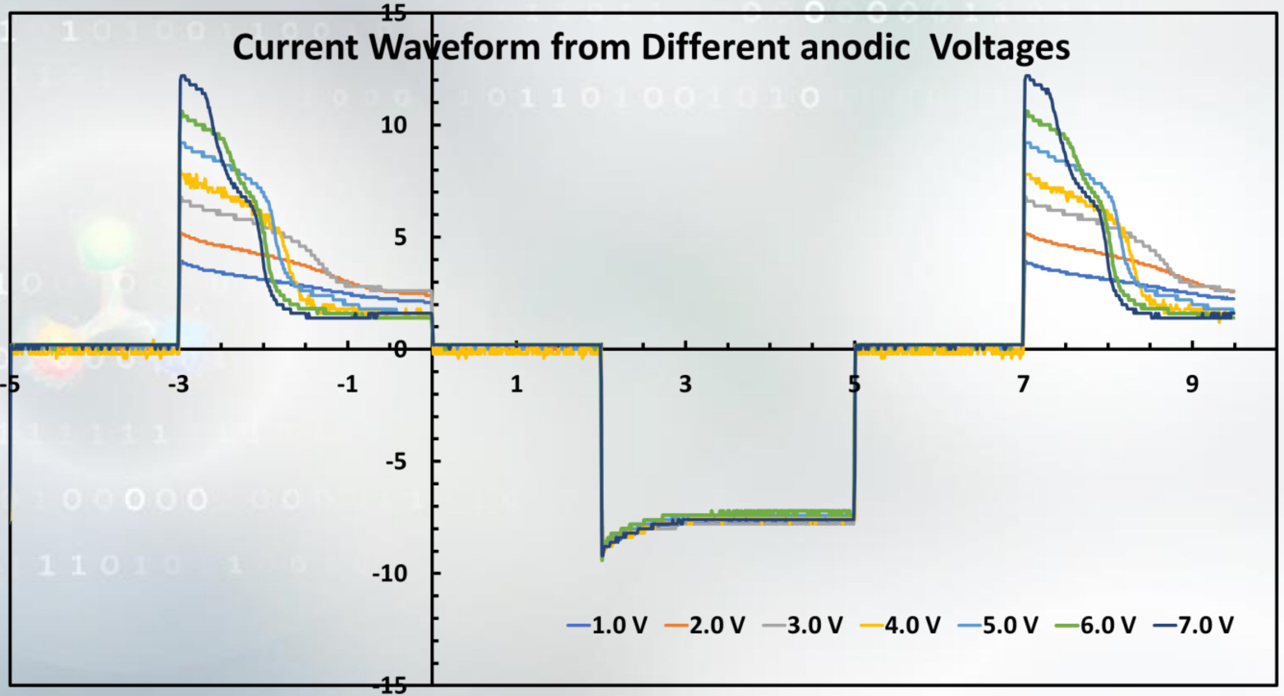
Long cathodic duration : 30 ms

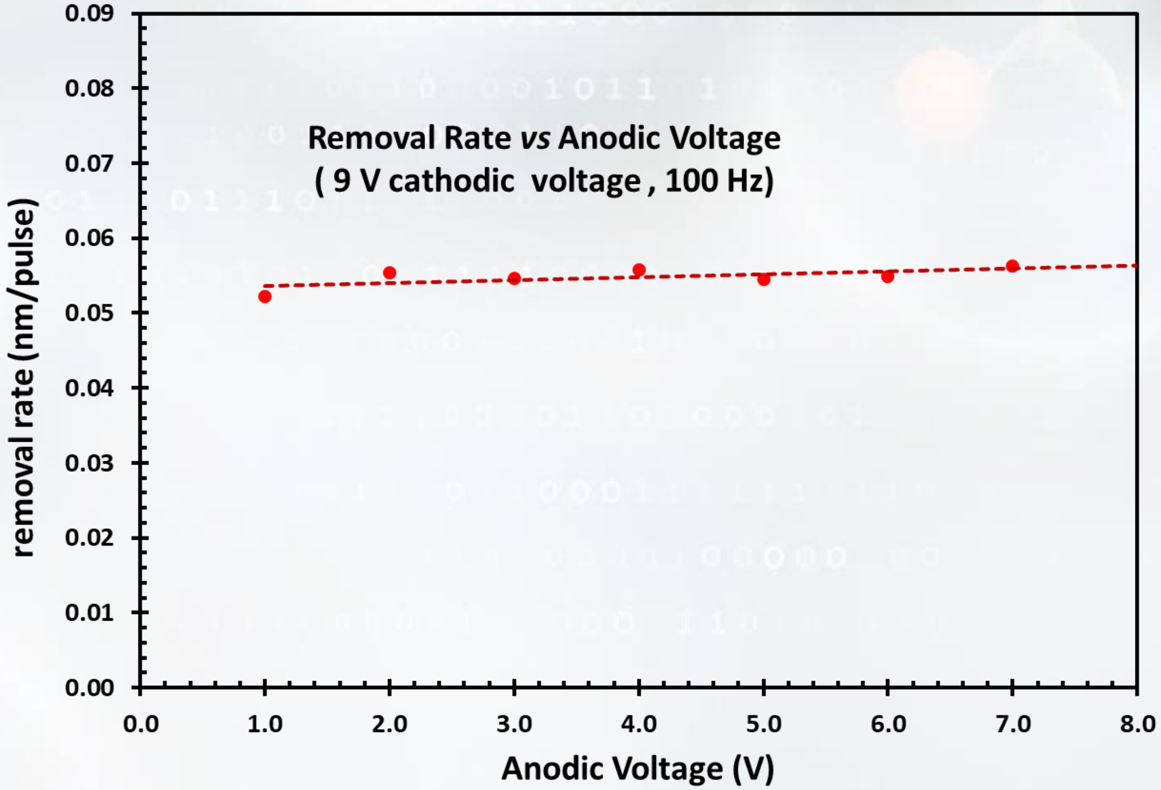


High cathodic voltage: 12 V

- Shorter cathodic pulses and moderate voltages yield smoother surfaces.
- Maintaining a thin oxide layer helps suppress hydrogen generation and prevents Nb surface cracking.

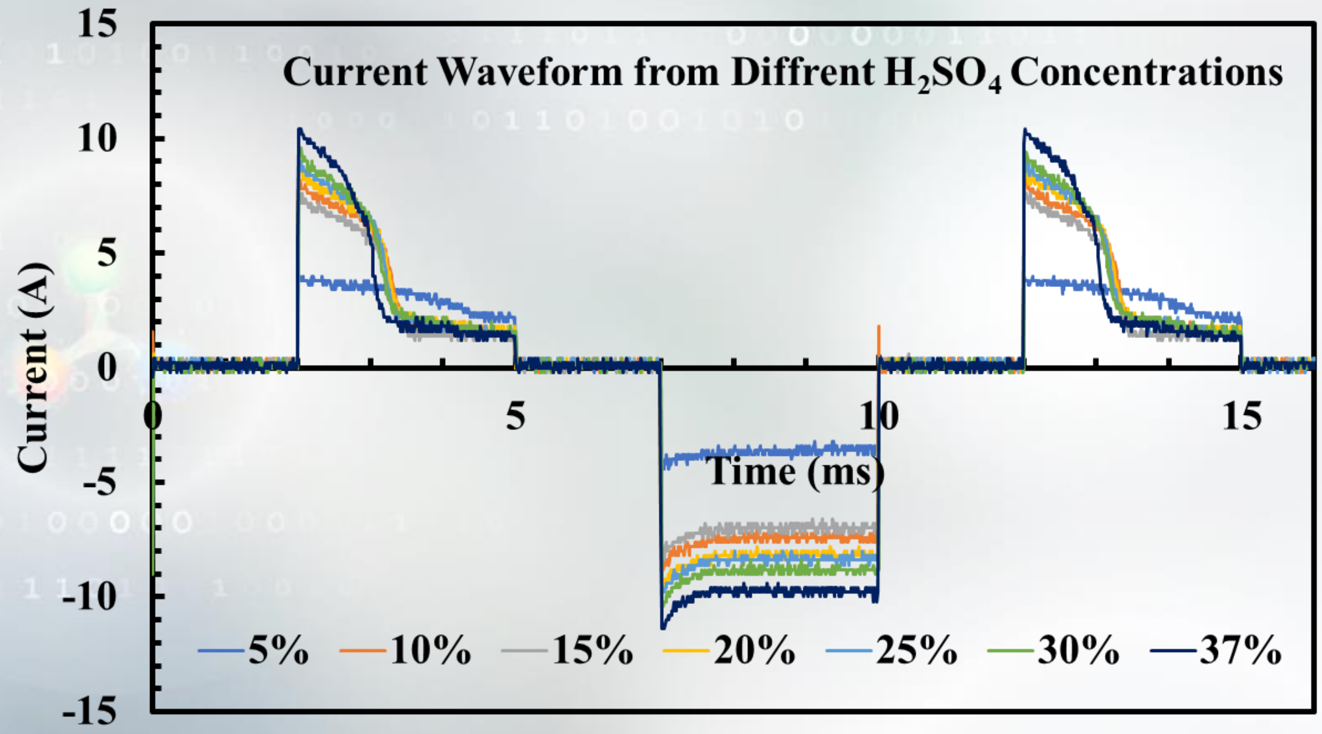
BPEP Characteristic : Mechanistic Insights into Anodic Voltage

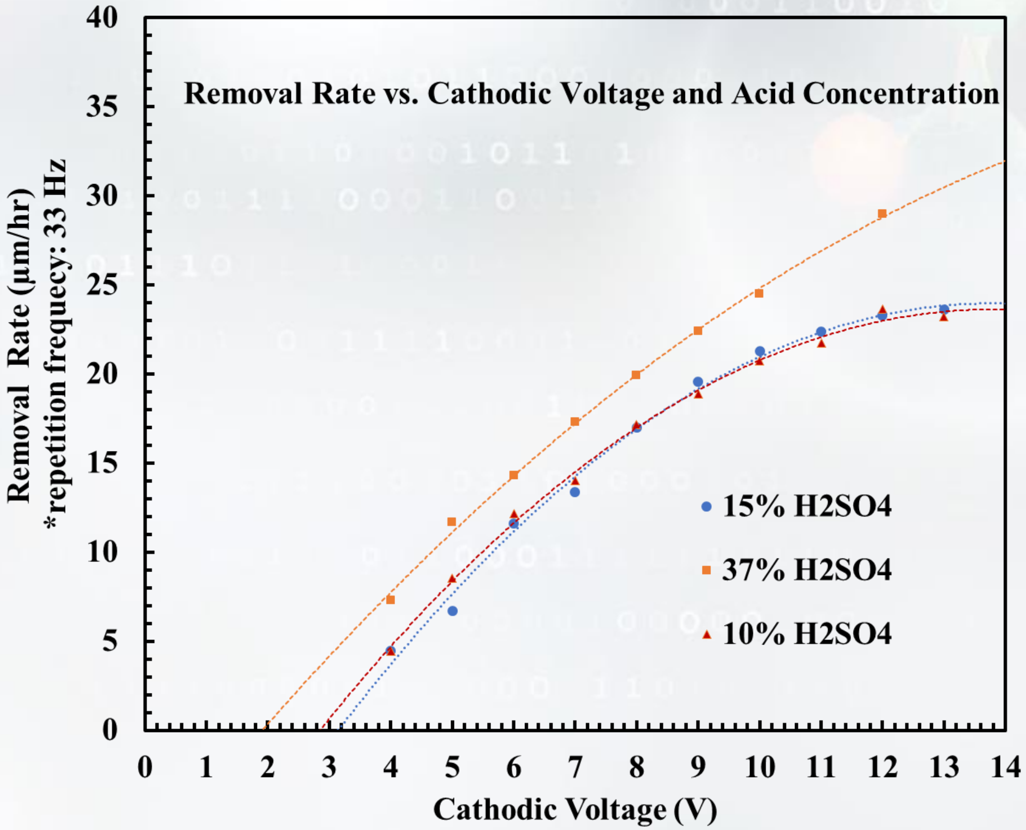




Removal rate: Independent of anodic voltage

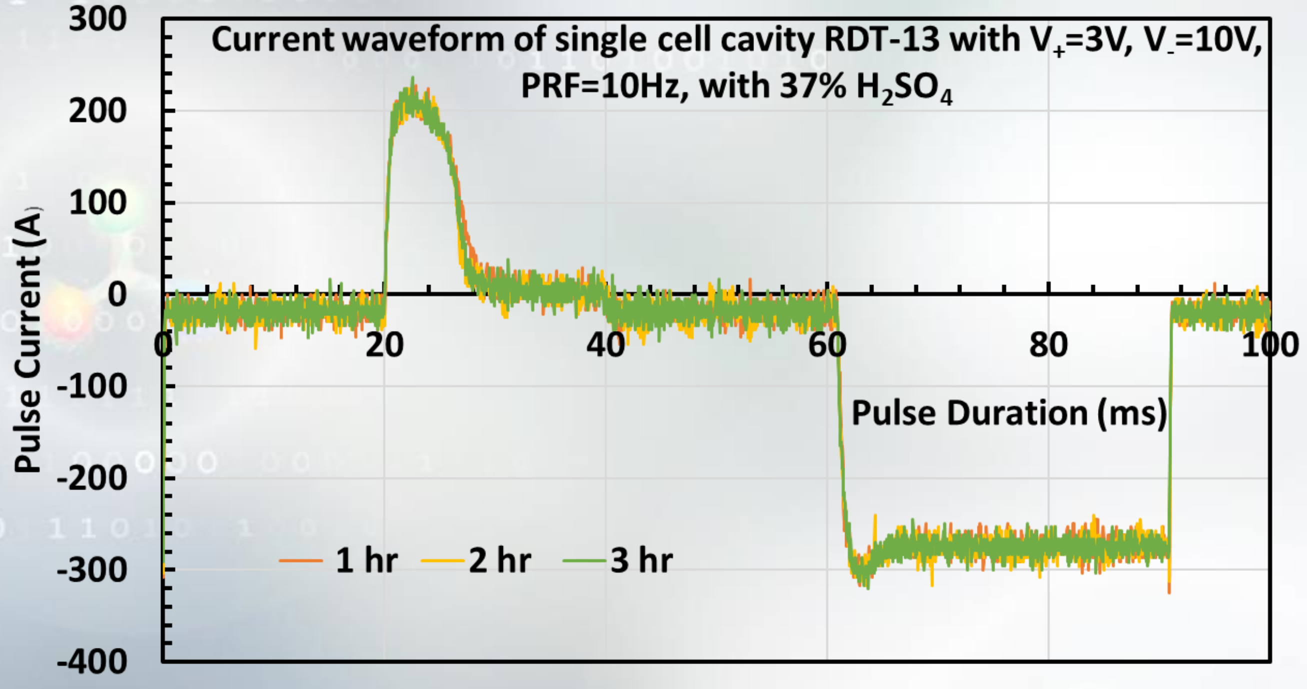
BPEP Characteristic : Mechanistic Insights into electrolyte concentration

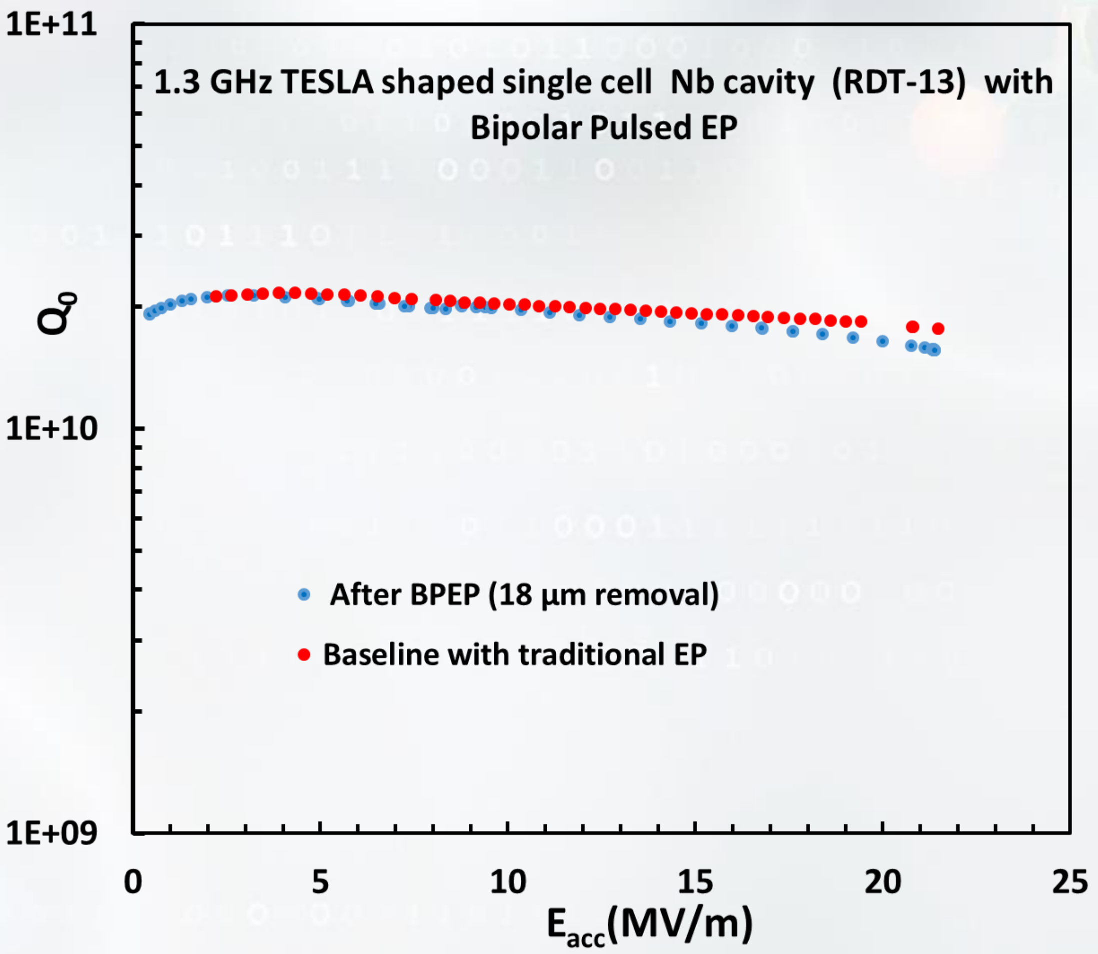




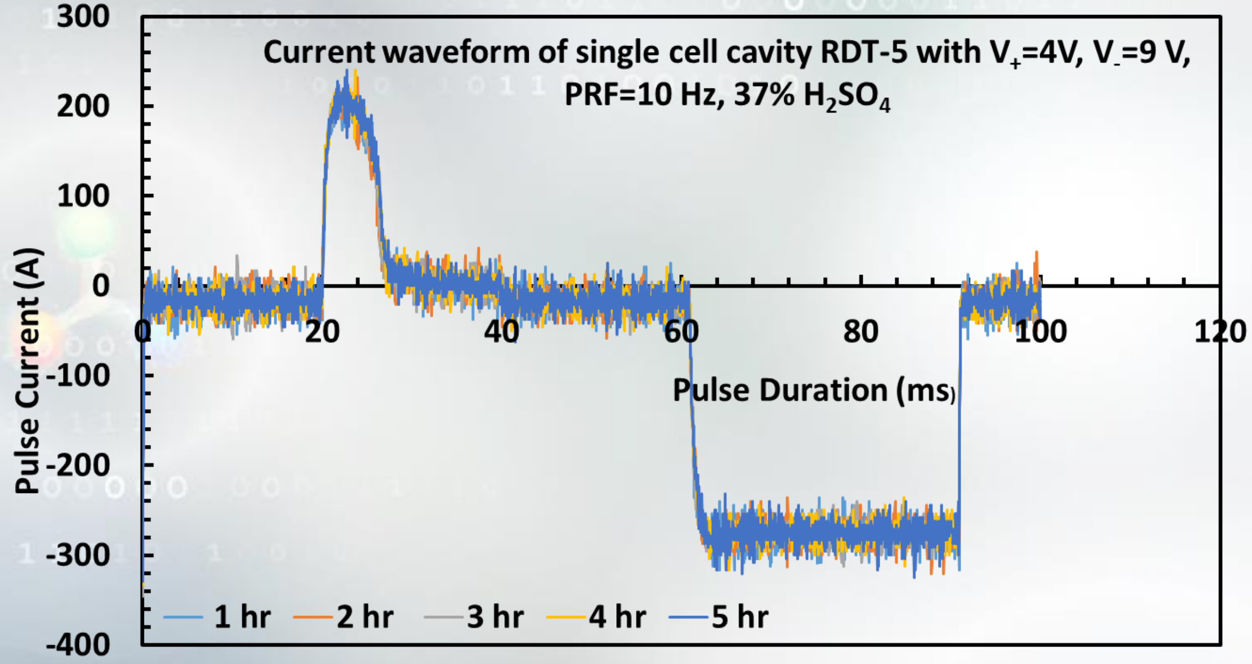
Higher removal rates achieved with higher-conductivity electrolyte (37% H_2SO_4), supporting process efficiency improvements.

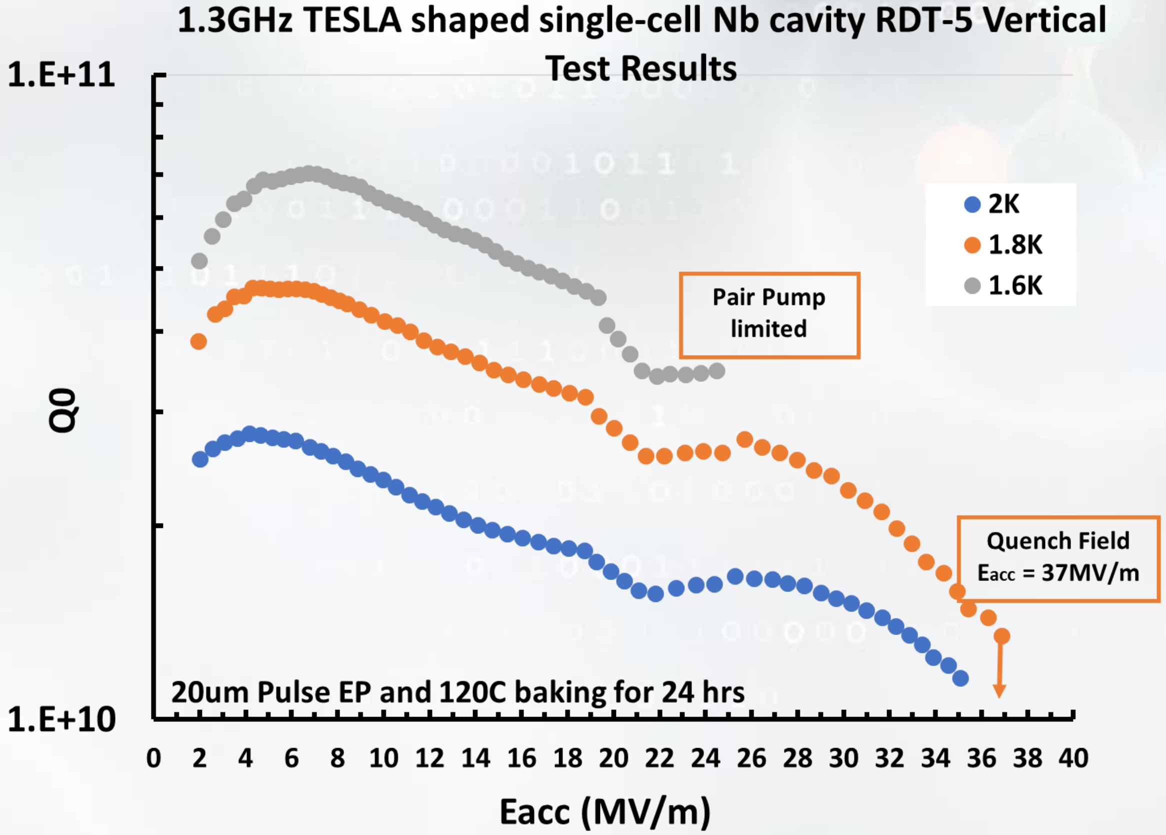
RF test result of single cell Nb cavities processed by BPEP



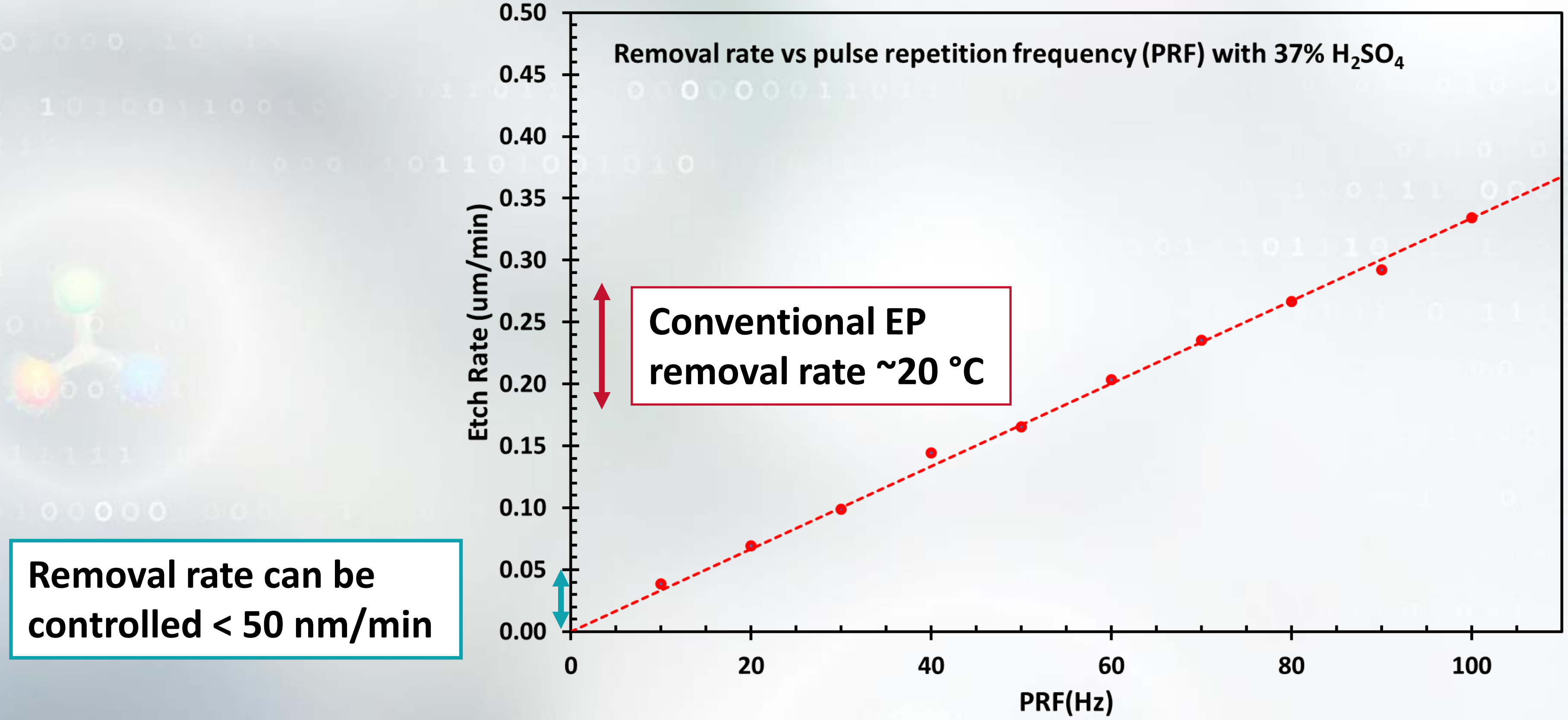


RF test result of single cell Nb cavities processed by BPEP





Precise Removal Rate Control: Enabling Final Surface Processing of Nb Cavities, Nb_3Sn ?

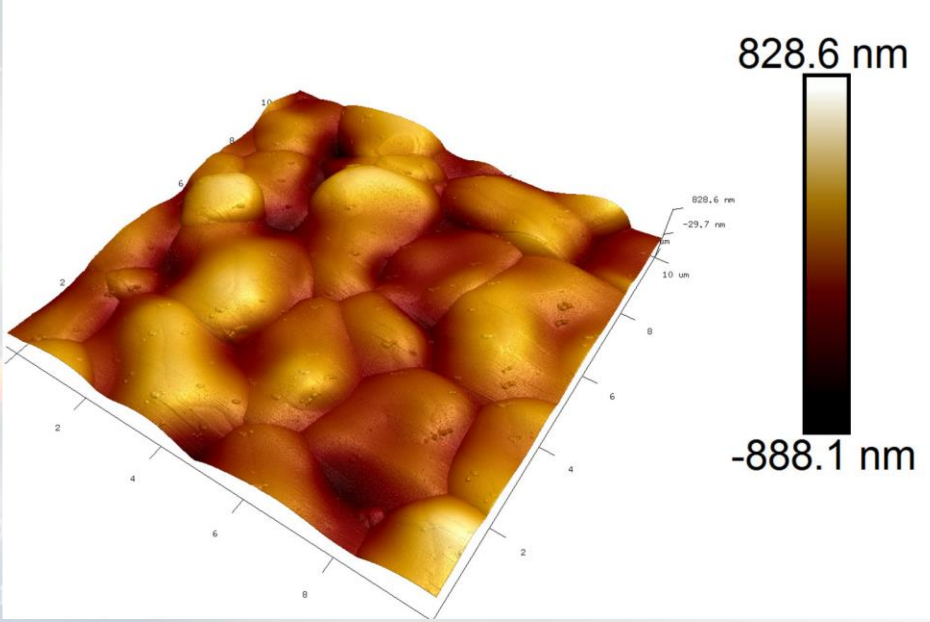


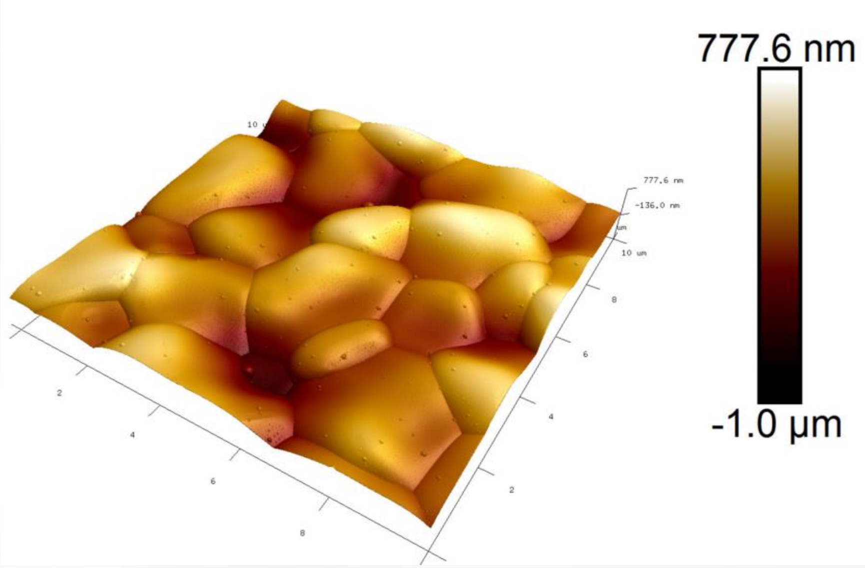
Surface removal rate of Nb with BPEP strongly depends on pulse repetition frequency (PRF)

- Tunable removal rates: Adjustable from hundreds of nm/min (comparable to conventional EP)
- Precision finishing: Reduced to tens of nm/min for shallow, controlled removal — potentially ideal for final Nb_3Sn surface processing

Nb_3Sn Surface Morphology Changes Confirms BPEP Effectiveness with H_2SO_4 Electrolyte

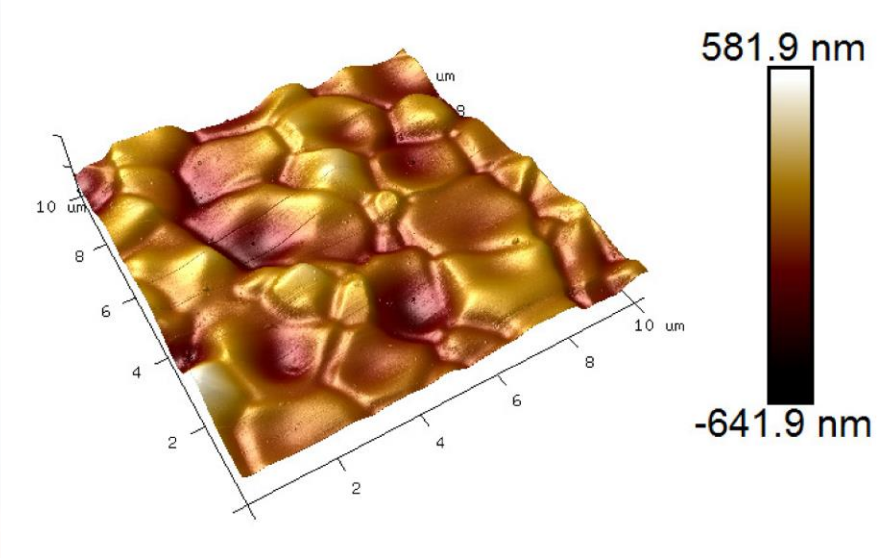
Before BPEP





Surface removal: 100 nm under high cathodic voltage

After BPEP

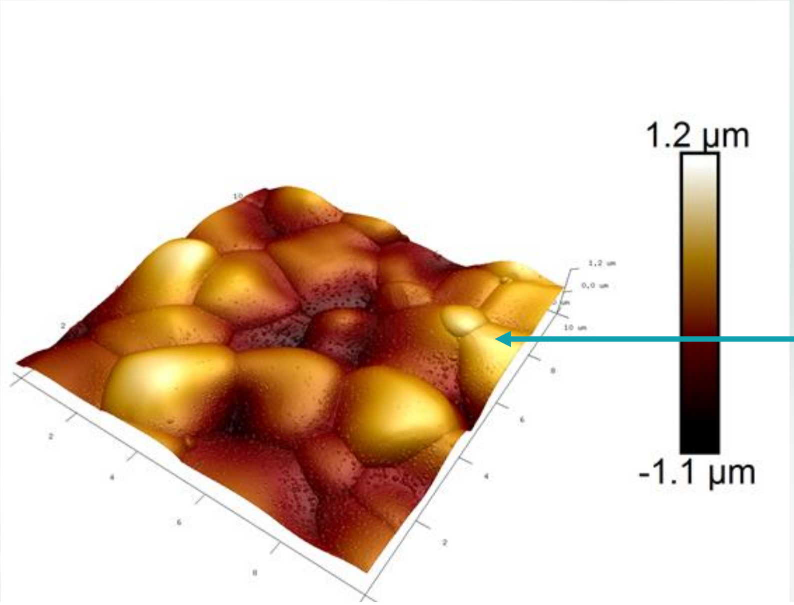


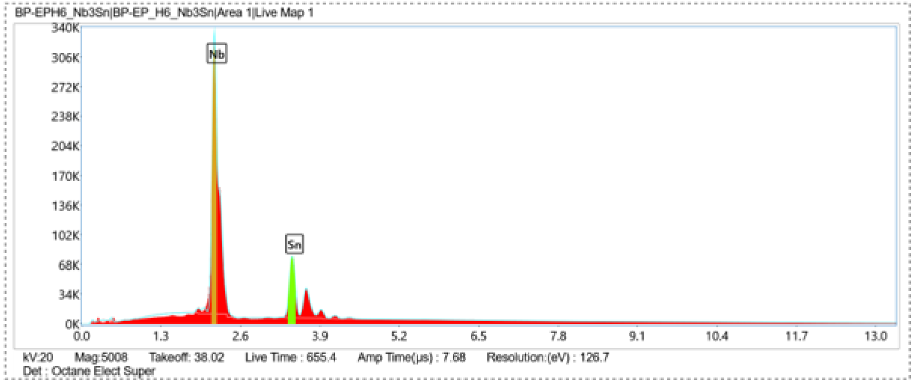
Surface removal: 200 nm under low cathodic voltage .

Nb_3Sn surface morphology confirms BPEP effectiveness with dilute H_2SO_4 electrolyte, achieving controllable material removal.

*** Surface removal measured by depth profiling before and after BPEP**

Before BPEP

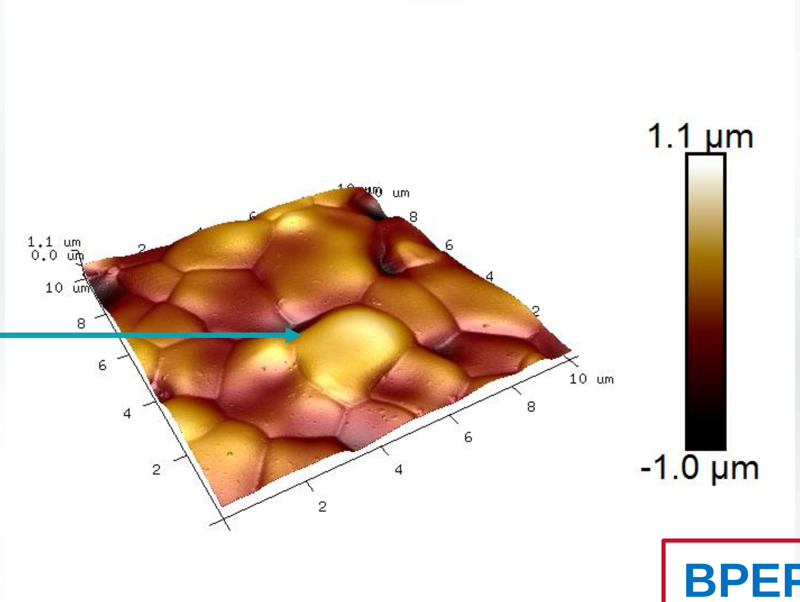


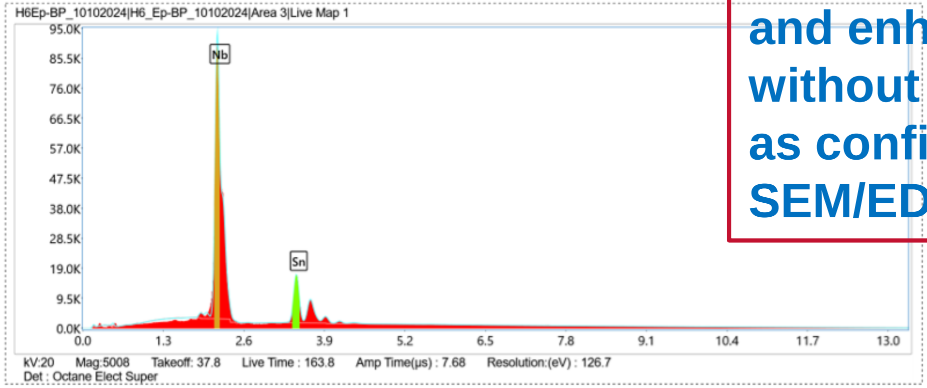


eZAF Quant Result - Analysis Uncertainty: 8.34 %

Element	Weight %	MDL	Atomic %	Error %	Net Int.	R	A	F
Nb L	67.2	0.06	72.4	4.6	4203.8	0.7614	0.6545	1.0041
Sn L	32.8	0.11	27.6	4.7	1115.0	0.7867	0.6544	1.0043

After BPEP





eZAF Quant Result - Analysis Uncertainty: 6.76 %

Element	Weight %	MDL	Atomic %	Error %	Net Int.	R	A	F
Nb L	72.2	0.13	76.8	4.5	4745.4	0.7631	0.6619	1.0038
Sn L	27.8	0.23	23.2	5.3	968.4	0.7884	0.6437	1.0042

BPEP removes Sn droplets and enhances surface quality without preferential etching, as confirmed by AFM and SEM/EDS analyses

Conclusion

- BPEP system at Jefferson Lab enables efficient and effective surface treatment of Nb SRF cavities.
- Systematic mechanistic and surface studies establish a strong foundation for optimizing BPEP process parameters (cathodic/anodic voltage, pulse duration, PRF) in Nb cavity fabrication.
- RF tests of single-cell Nb cavities demonstrate the effectiveness of BPEP treatment.
- Preliminary Nb_3Sn results with controllable BPEP are highly promising, with ongoing studies paving the way for next-generation Nb_3Sn cavity performance.

BPEP provides a controllable, HF-free surface treatment for Nb — with potential for Nb_3Sn cavities and promising results for next-generation SRF performance.

Acknowledgments

- Jefferson lab :

Mark Lester, John Musson, Uttar Pudasaini, Olga Trofimova, Phil Denny, Derrick Dail, Christiana Wilson.

- Summer SULI & REU* Students

Bradley Straka (2017 & 2018), Hannah Hu* (2019)

- This work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177

QUESTIONS?