The In-Situ Mid-T Bake

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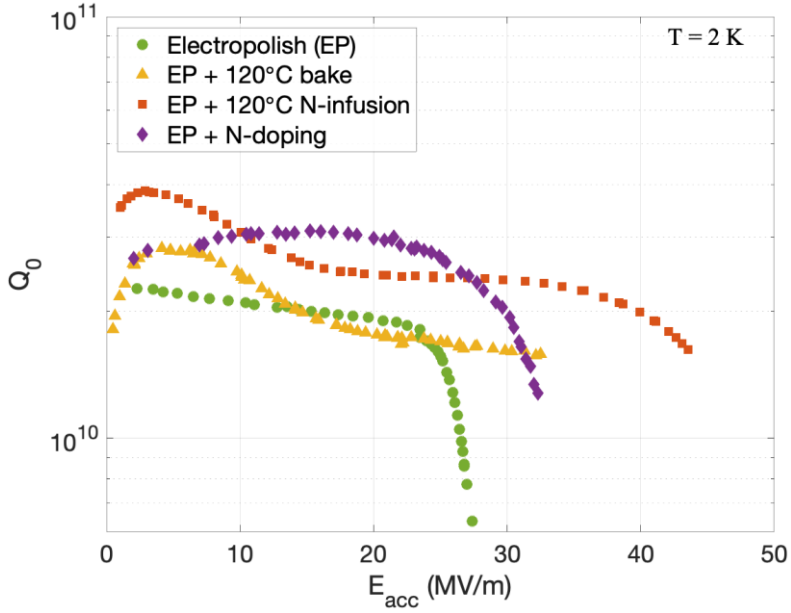
Ultralow Surface Resistance via Vacuum Heat Treatment of Superconducting Radio-Frequency Cavities

S. Posen, A. Romanenko, A. Grassellino, O.S. Melnychuk, and D.A. Sergatskov
Phys. Rev. Applied **13**, 014024 – Published 14 January 2020

Motivation

- Nitrogen infusion has shown huge potential for high Q high gradient performance
  - Raise cavity temperature to ~800 C (vacuum furnace) where oxide dissolves
  - Lower temperature to ~120 C
  - Introduce nitrogen which diffuses 10s of nm
- Difficulty in reproducing results outside of FNAL
  - Process involves cavity open to furnace at 800 C without post-furnace chemistry
  - Very strict furnace cleanliness required
- Key idea: try to dissolve oxide and add N, but do so without exposing interior surface of cavity to furnace



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Previous Experience with Heat Treatment to Dissolve Oxide

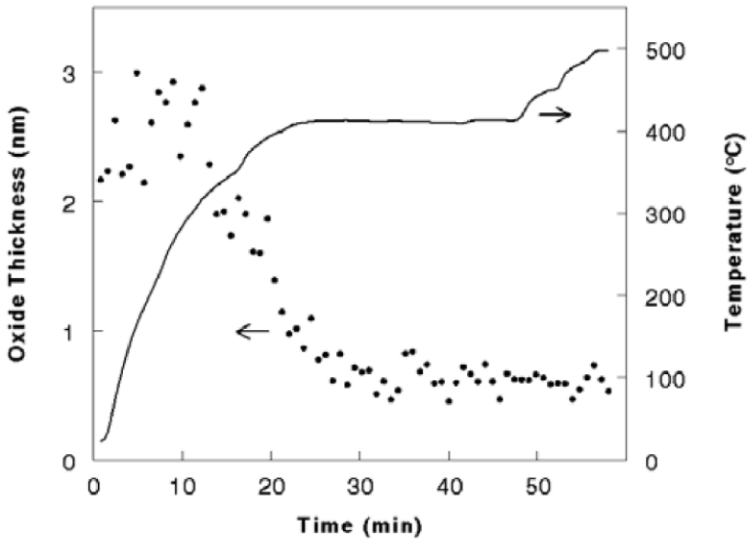

Figure 9.1: Oxygen to niobium ration as inferred from XPS results for heated niobium sample.

STUDY OF THE HIGH FIELD Q-SLOPE USING THERMOMETRY

Grigory Victorovich Eremeev, Ph.D.

Cornell University 2008

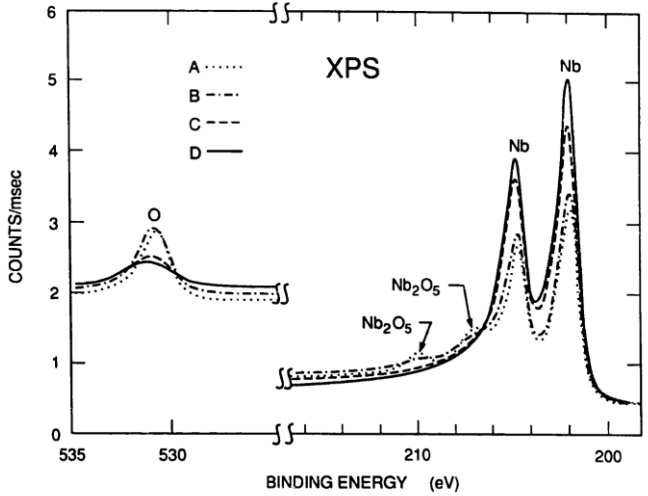

Fig. 2. Curve-fitted XPS spectra taken while oxidized Nb was warmed from 24°C to 350°C. Different curves correspond to temperature ranges shown in fig. 1.

Oxide overlayers and the superconducting rf properties of yttrium-processed high purity Nb *

F.L. Palmer **

Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853, USA

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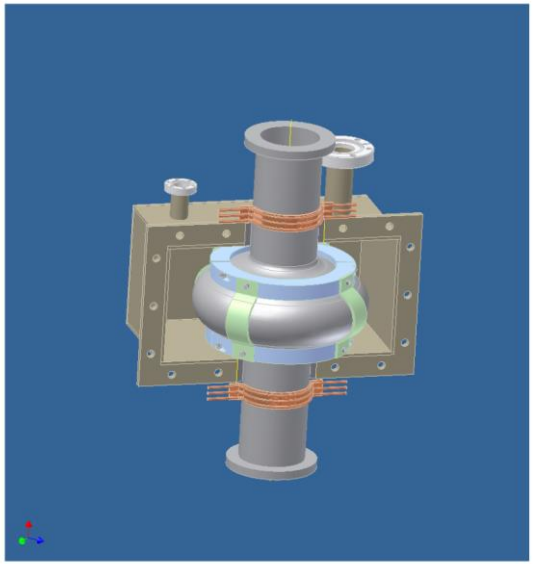

Figure 3.8: A sketch of the setup for high temperature baking of a one-cell 1.5 GHz cavity.

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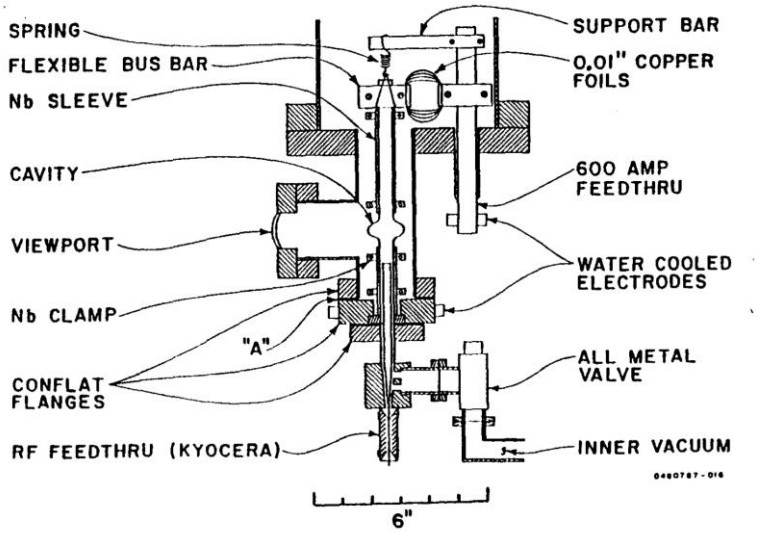

Figure 6. Ultra-high-vacuum furnace used to remove oxide layers from inner surface of cavities.

Surface Resistance of Superconductors--Examples from Nb - O Systems

F. Palmer

Fermilab

Previous Experience

- Palmer's study suggests that around 350 C the BCS and residual both become fairly small so it already looks interesting
- Also notes decrease in Tc observed with treatment

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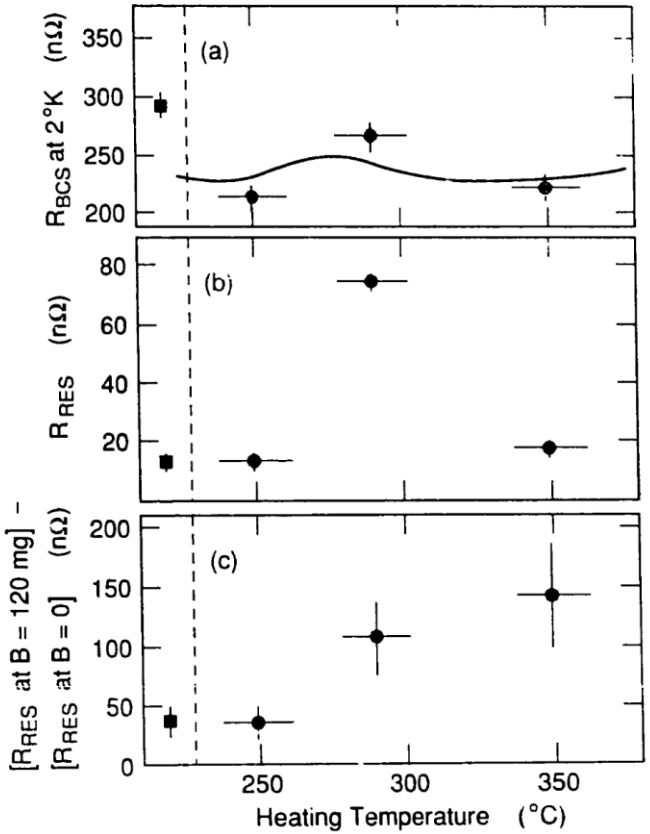
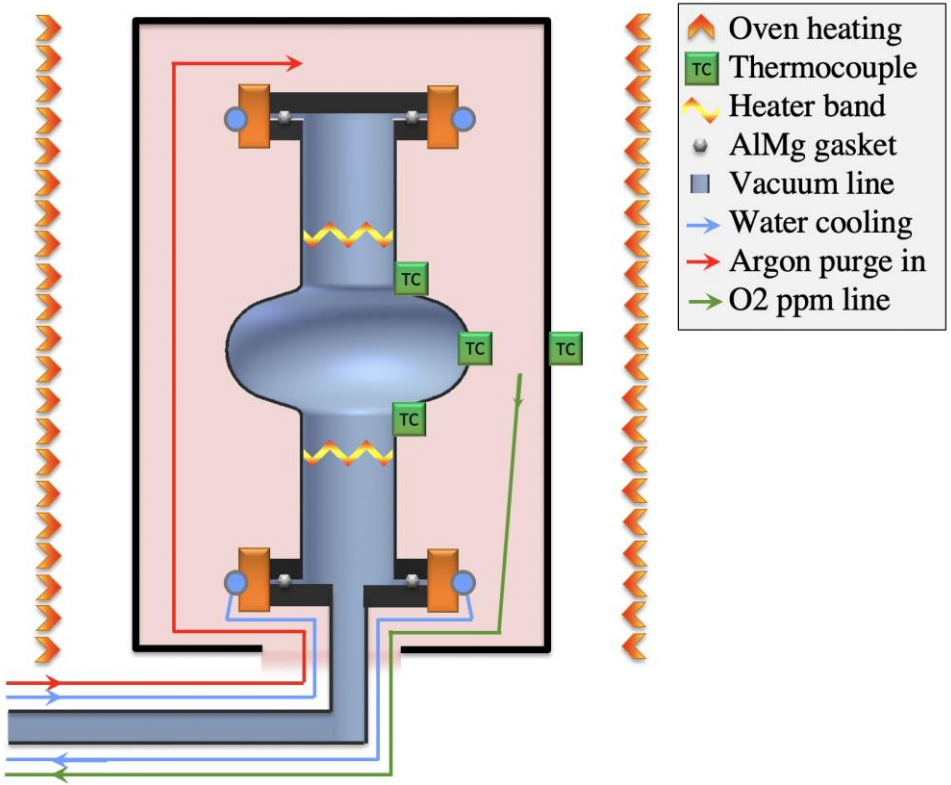
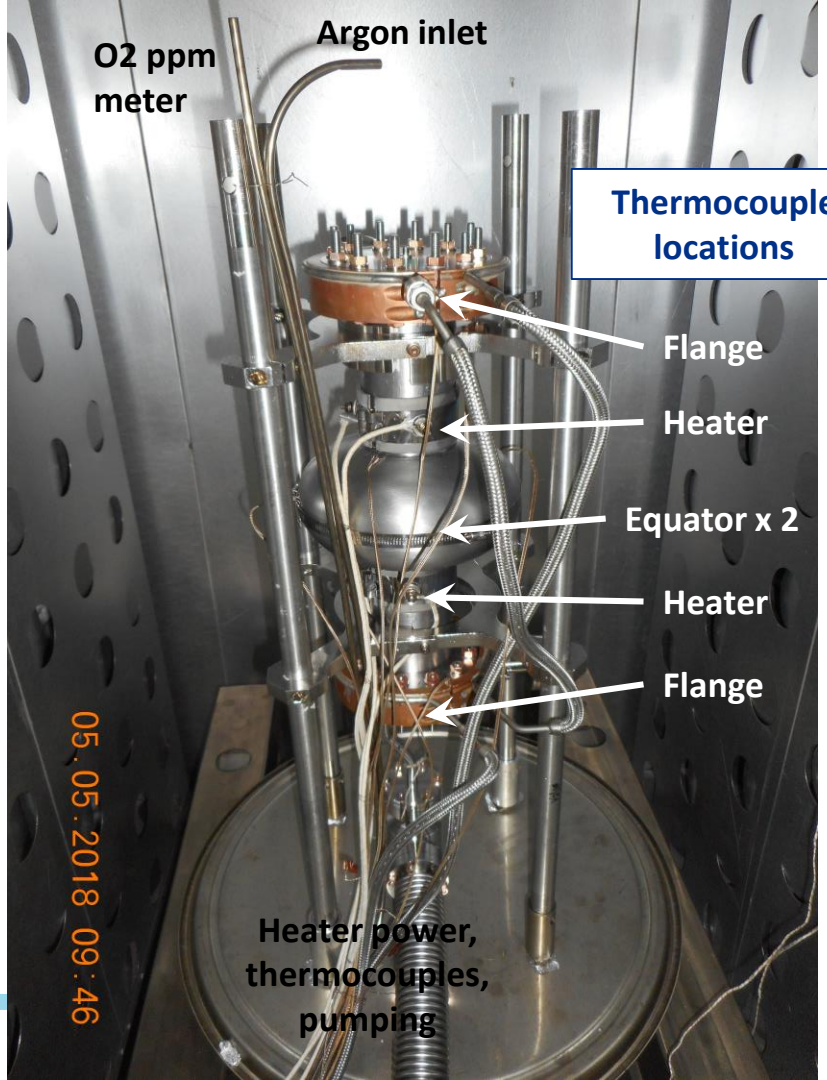


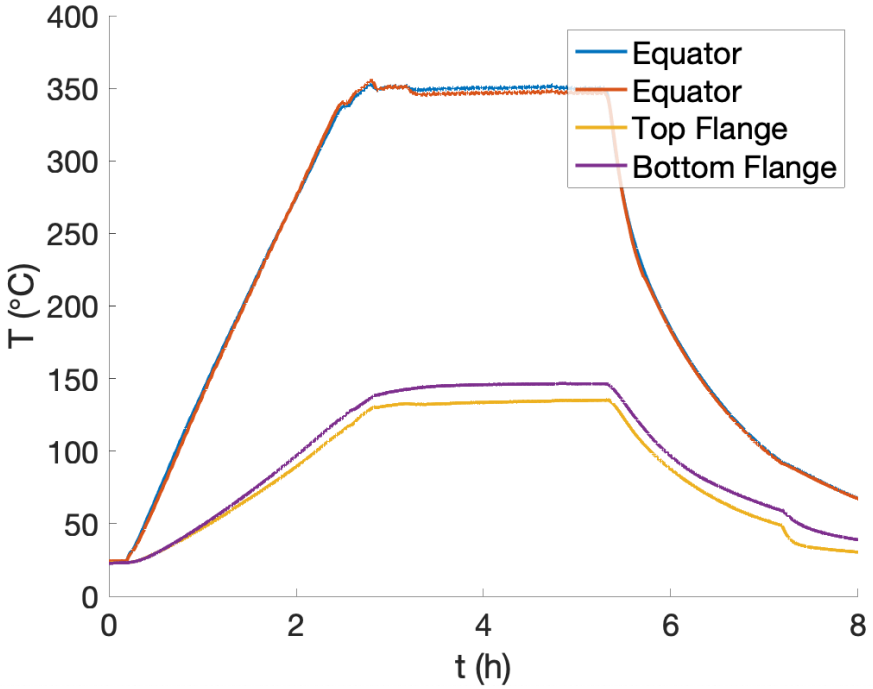
Fig. 3. BCS resistance at 2 K (a), residual resistance (b), and enhancement of residual resistance due to a 120 mG field applied during cooldown (c) for an oxidized Nb cavity after warming in vacuum to the indicated temperature. Square points show values prior to oxidation. See text for explanation of solid line in (a).

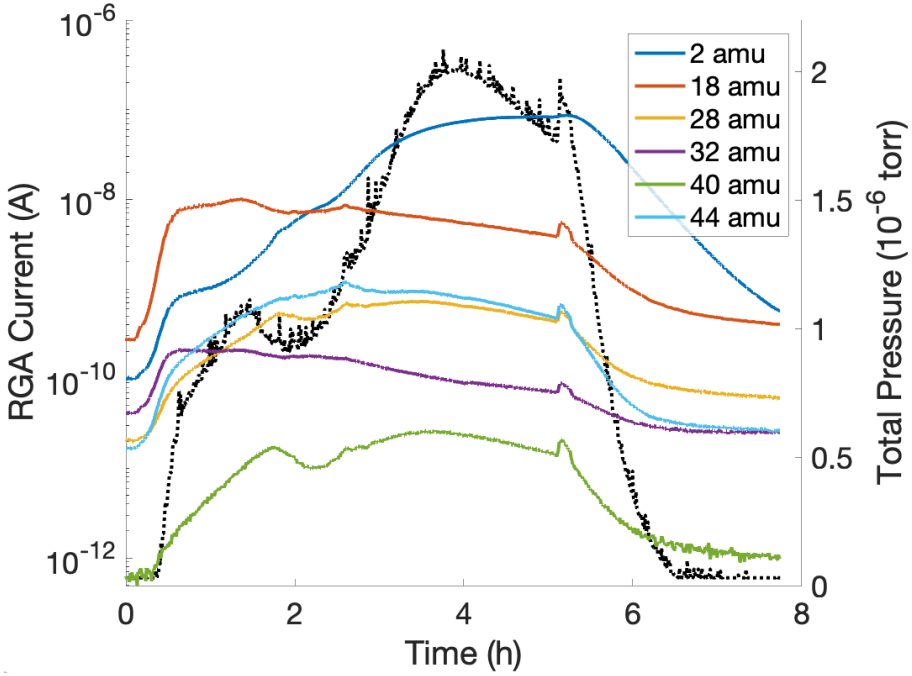
Mid-T Bake Apparatus





Mid-T Bake Process





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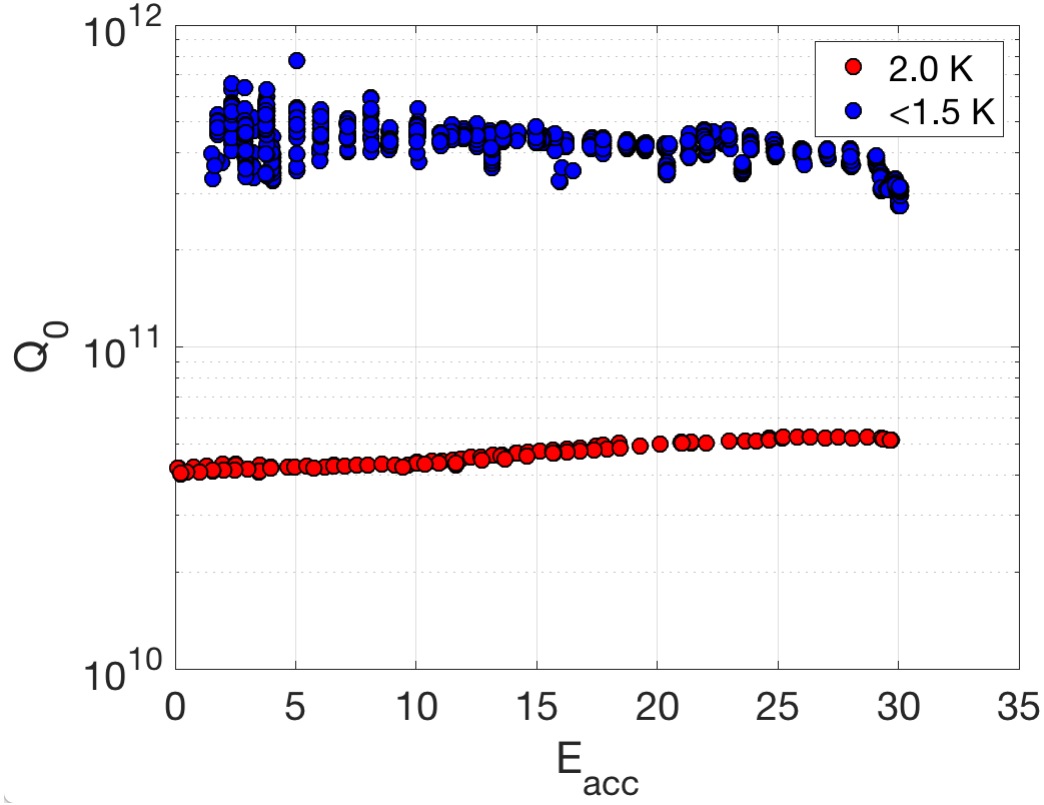
Extremely Encouraging First VTS Results: TE1PAV008



- Overcoupled for whole range
- Qe1 ~ 9e9
- Qe2 ~ 3e11
- Decays at 2.1 K with Q_0 ~ 2.5e10 agree very well with those at 2 K
- 9e9x3.3e11 = 2.97e21
- Qe1xQe2 gives 2.65e21

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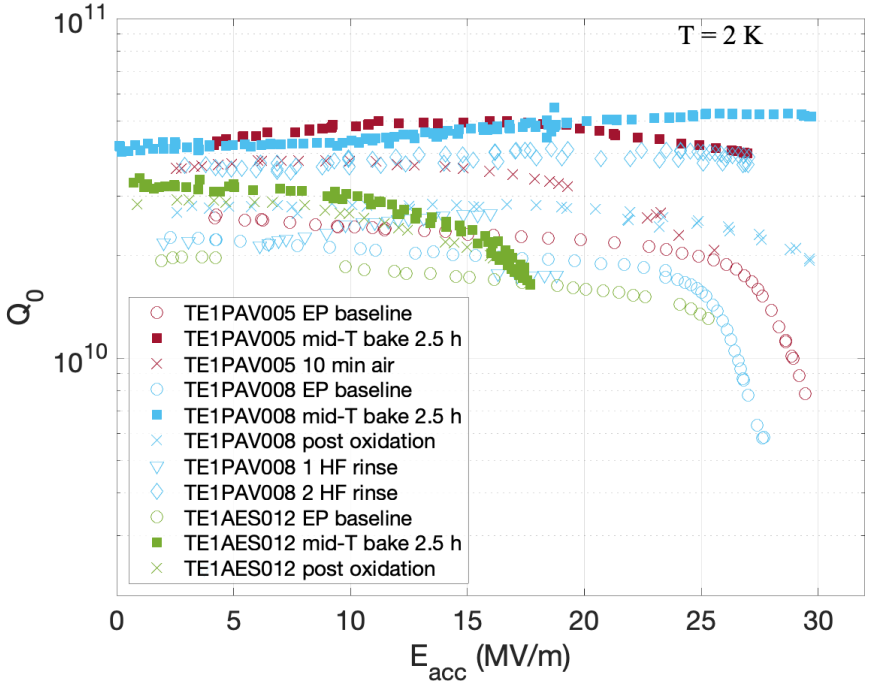
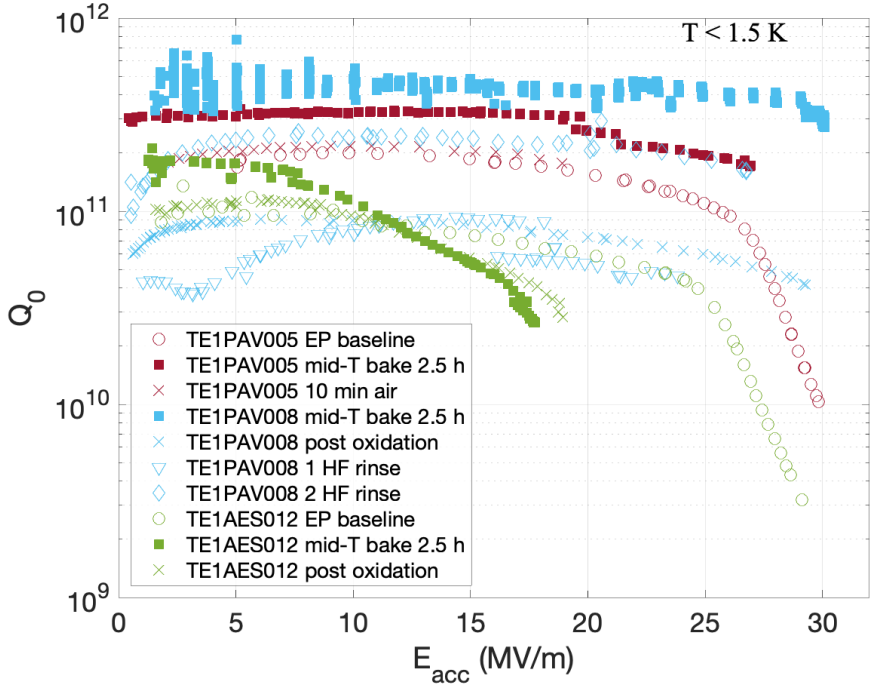
RF Results – EP Baseline





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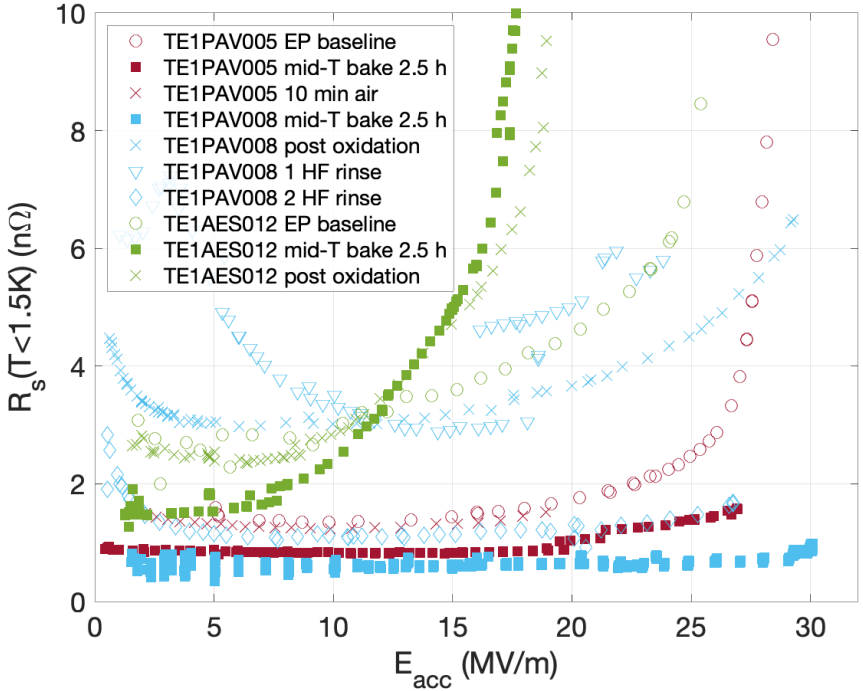
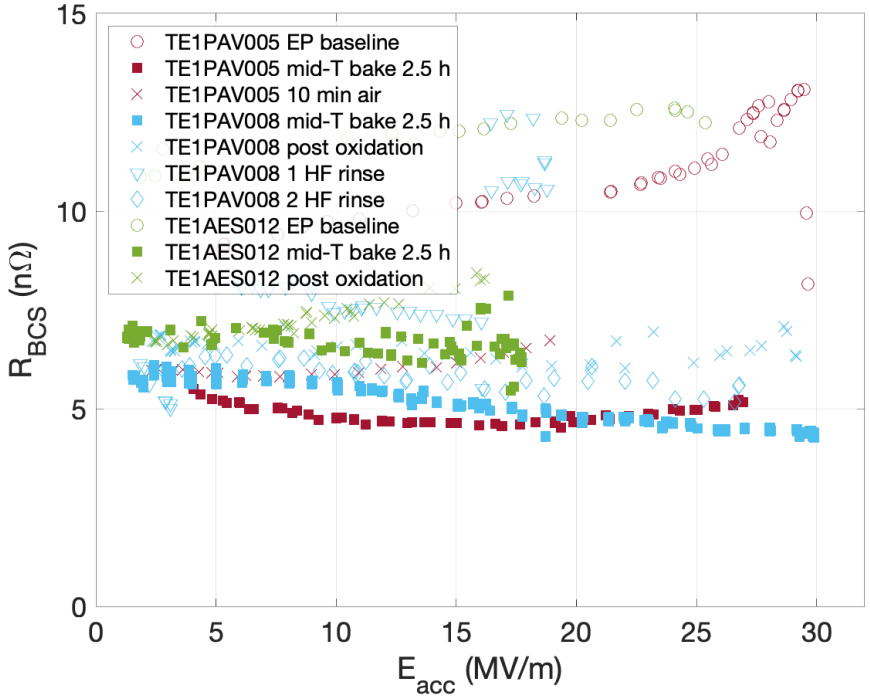
Decomposition – EP Baseline





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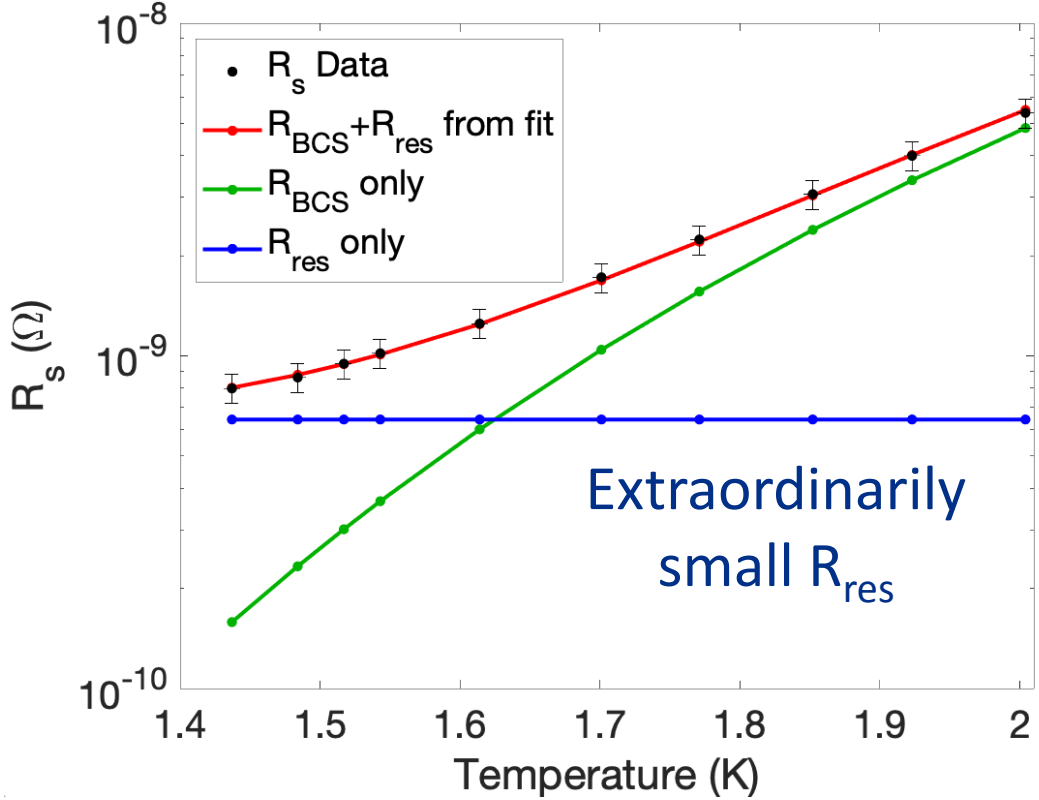
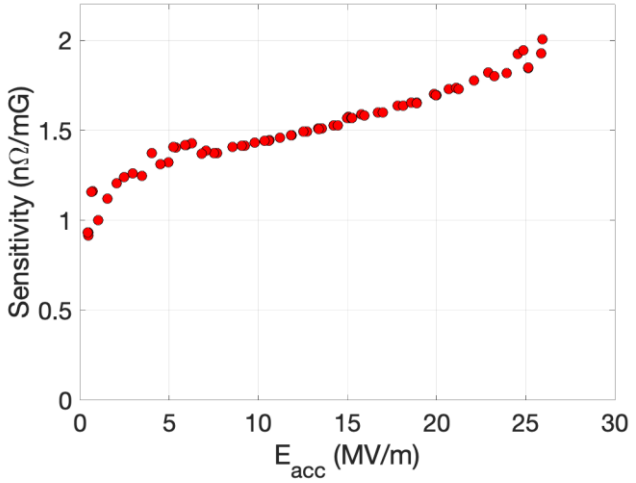
SRIMP Fit to Material Parameters





Cavity	T_c (K)	l (nm)	Δ/k_BT_c
TE1PAV005	8.94 ± 0.15	48 ± 24	2.07 ± 0.03
TE1PAV008	9.04 ± 0.15	167 ± 84	2.10 ± 0.03
TE1RI006	8.93 ± 0.15	62 ± 31	2.10 ± 0.03

N-doped-like properties and sensitivity

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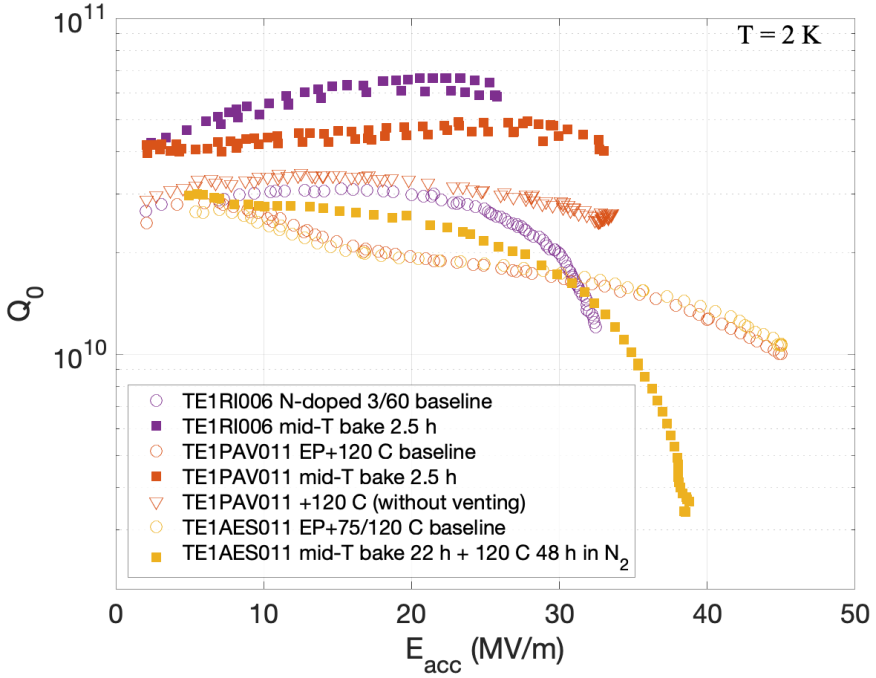
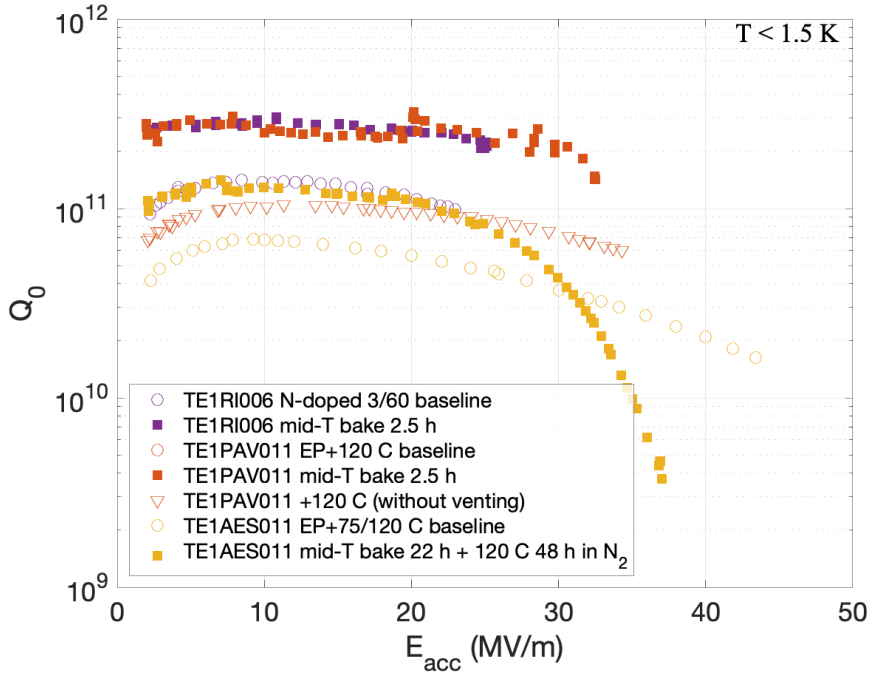
120 C and N-Doped Baseline





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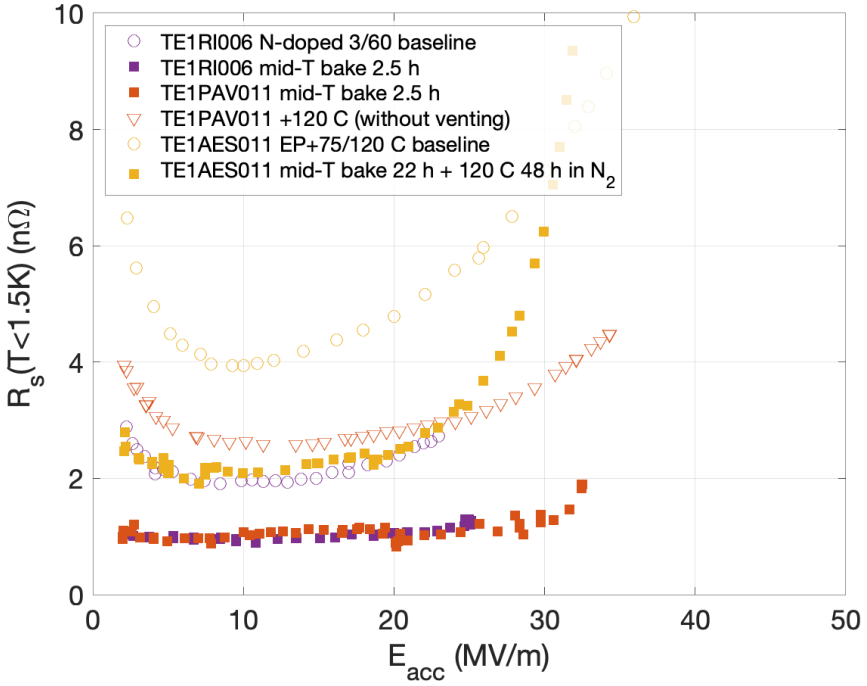

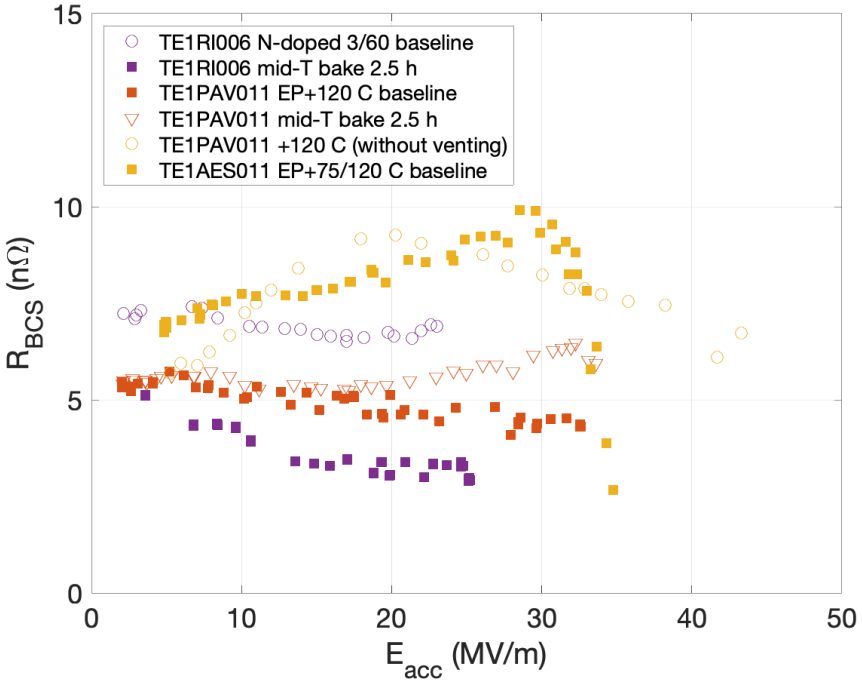

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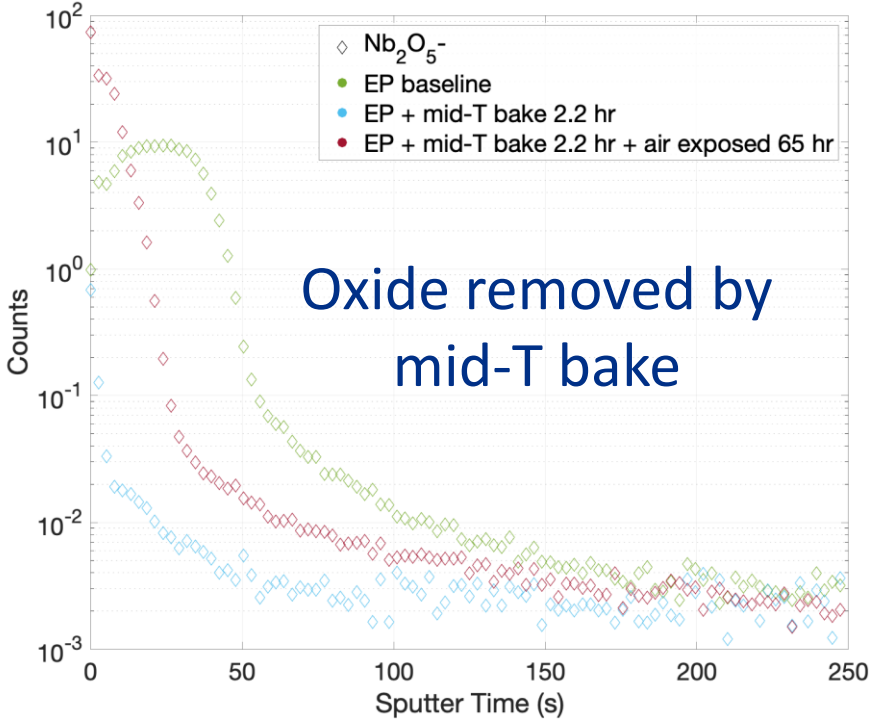
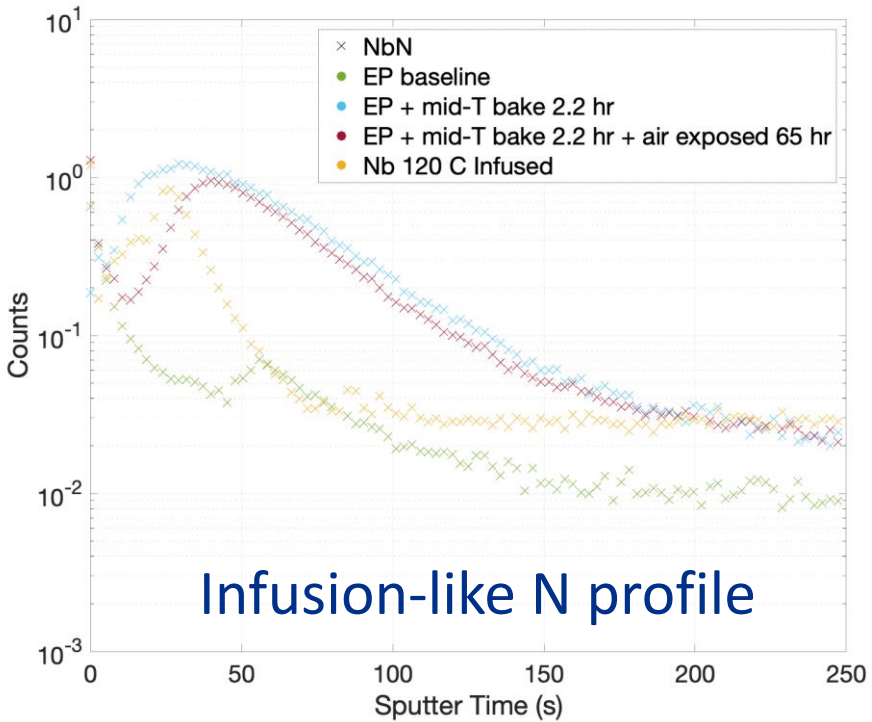
SIMS

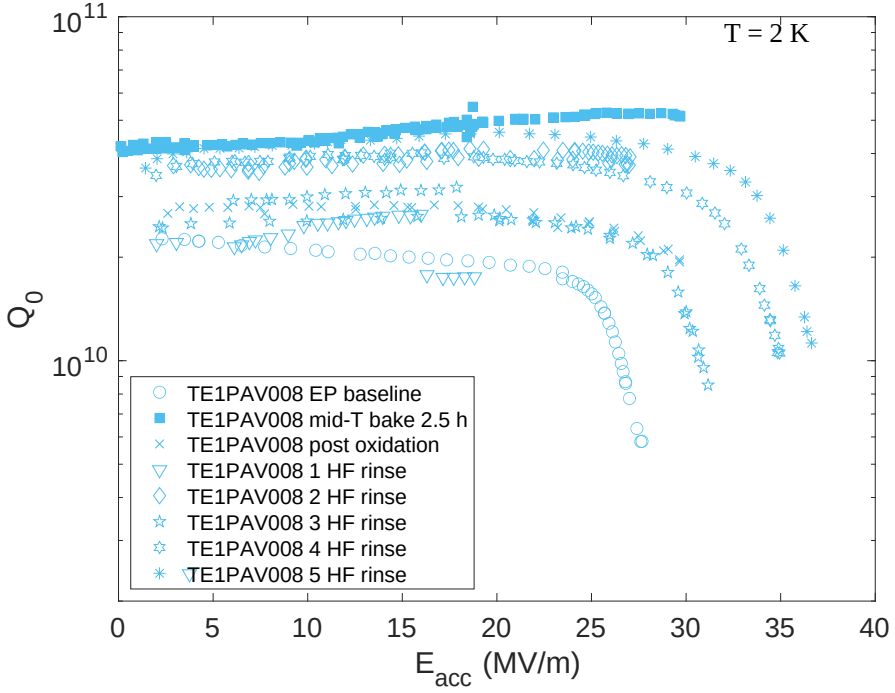


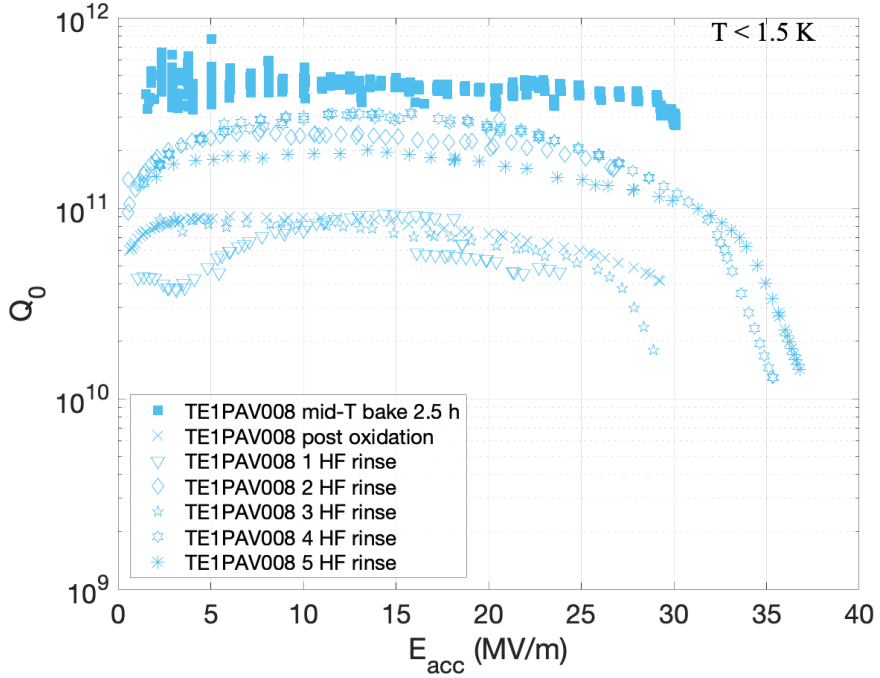


- For for more details/further studies, see A. Romanenko's talk

HF Rinse Study

- Now pursuing optimization of mfp via light removal, e.g. HF rinse
- Intriguing trend towards higher fields – interestingly opposite of HFQS HF study





Summary

- Mid-T bake: Heat treatment to temperature ~300-400 C to dissolve oxide, with cavity assembled and under vacuum
- Cavities tested without exposing to air (also after exposing to air)
- Surprising N-doping/infusion-like effect observed in Q vs E curves, material properties, sensitivity, and SIMS
- Q_0 values of 3-4×10^{11} were measured <1.5 K and 20 MV/m, higher than has been reported previously in the literature for such conditions
- Residual resistance of just 0.63 ± 0.06 nΩ was measured at 16 MV/m
- Future work: optimize process to create 120C-infusion-like N-profile, to try to achieve >40 MV/m gradients enabled by 120C-infusion

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