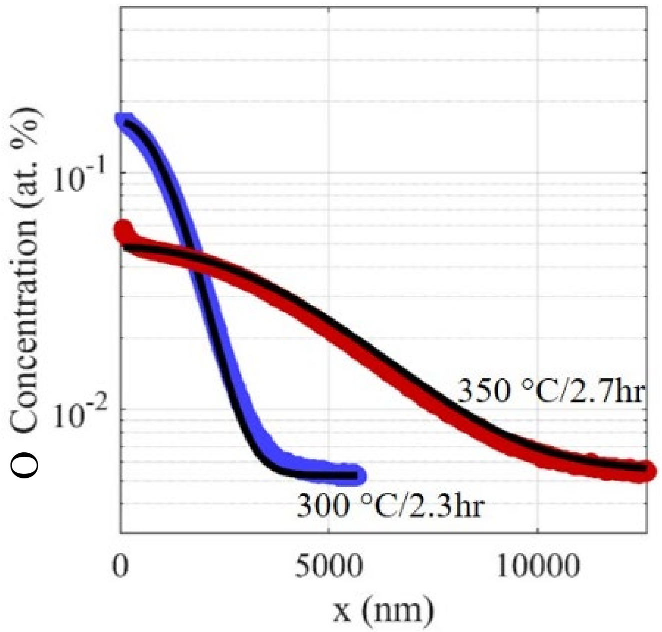
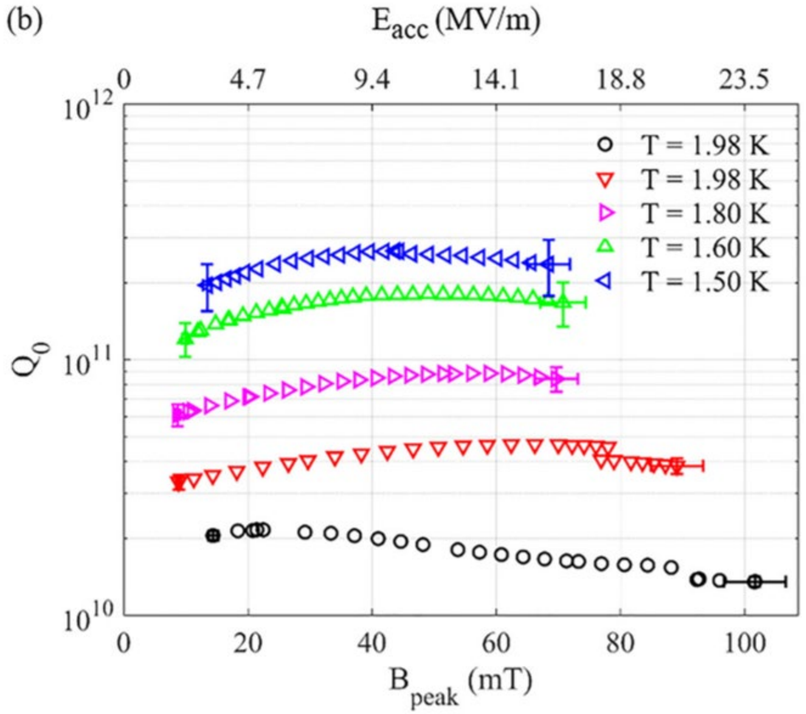
Tuning Nb Cavity Performance via Oxide Dissolution

Eric Lechner





TTC2022

January 25, 2022

Outline

- Motivation
- SIMS Results
- Oxide Dissolution Model
- Benefits

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- **Motivation**
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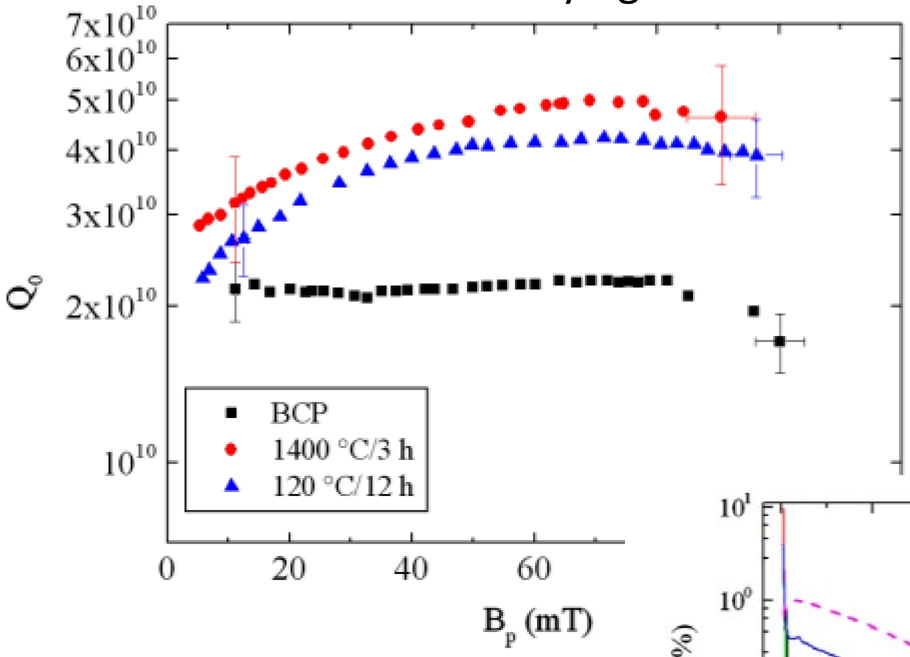
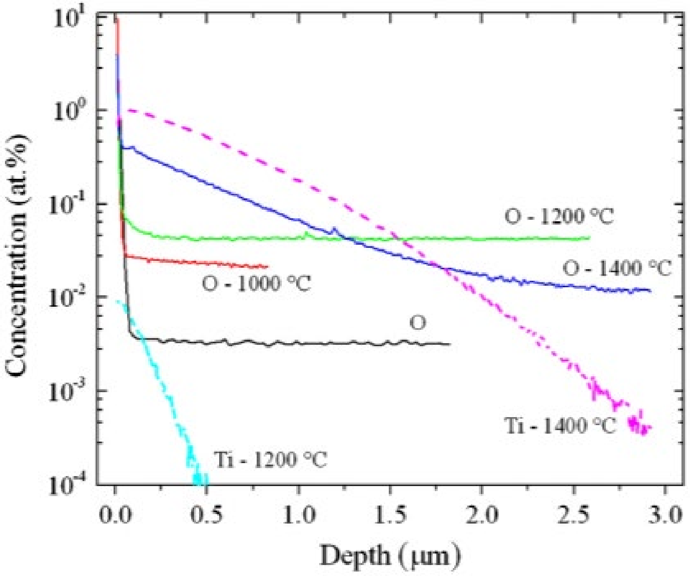
- **Oxide Dissolution Model**
- **Benefits**

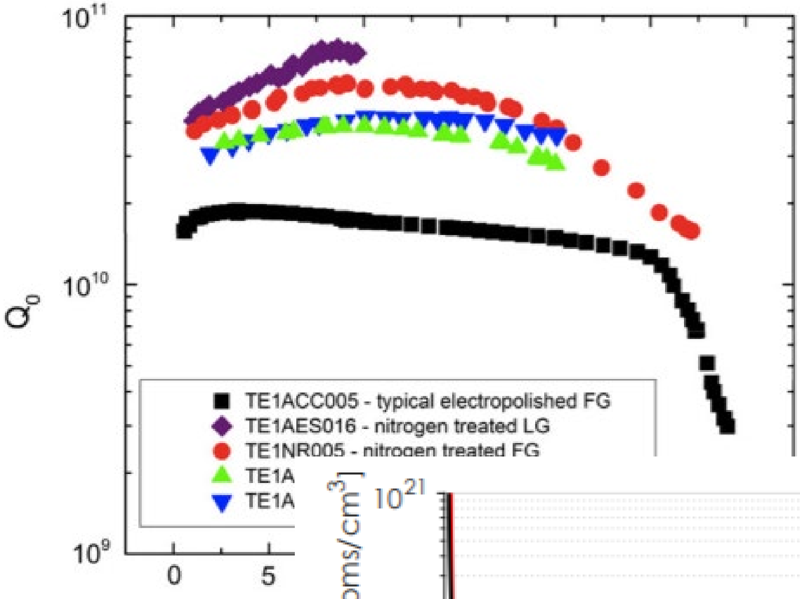
• Motivation - Impurity Alloying

[1] Ti-alloying

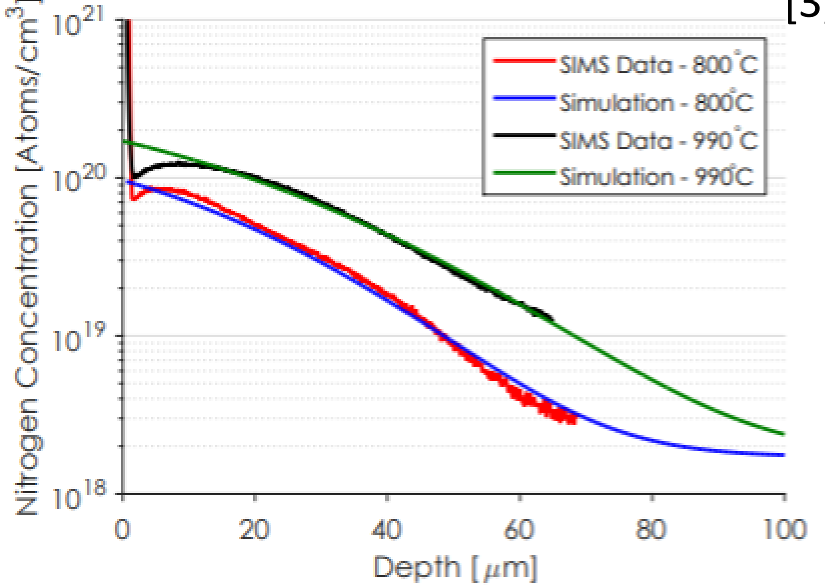




[2] N-alloying



[3]

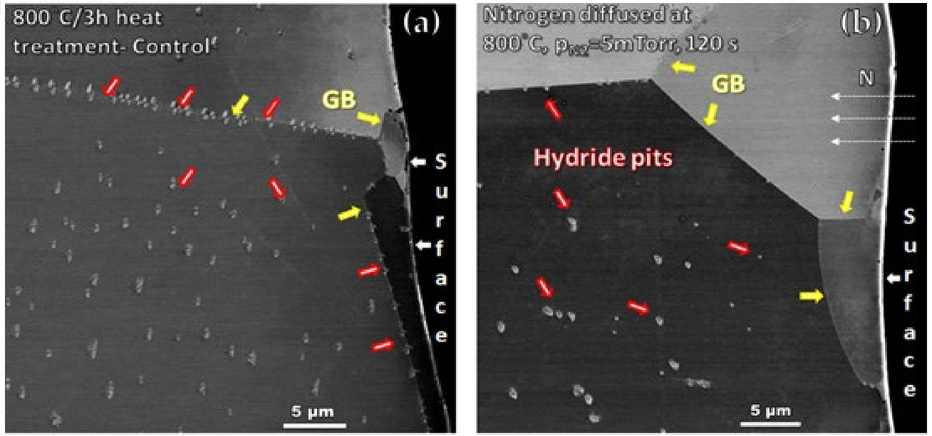


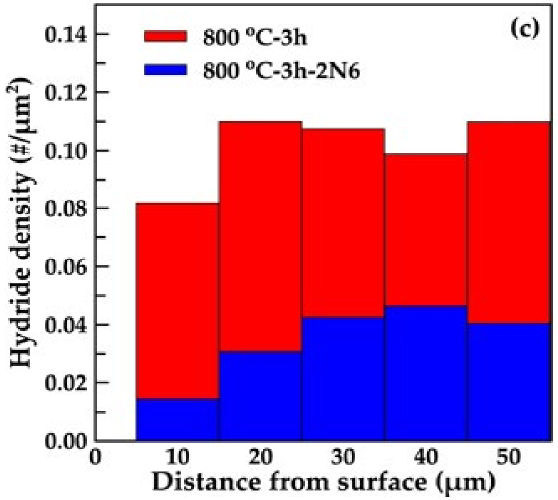
[1] P. Dhakal, et al. *Phys. Rev. Spec. Top. Accel. Beams* 16.4 (2013): 042001
[2] A. Grassellino et al. *Supercond. Sci. Technol* 26.10 (2013): 102001.
[3] D. Gonnella, Daniel, et al. *Proceedings of IPAC2016, Busan, Korea* (2016).

Motivation - Impurity Alloying: Benefits

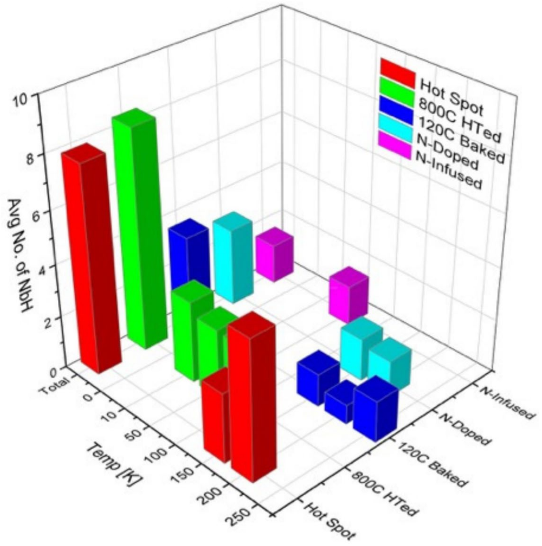
Hydride blocking

[1]



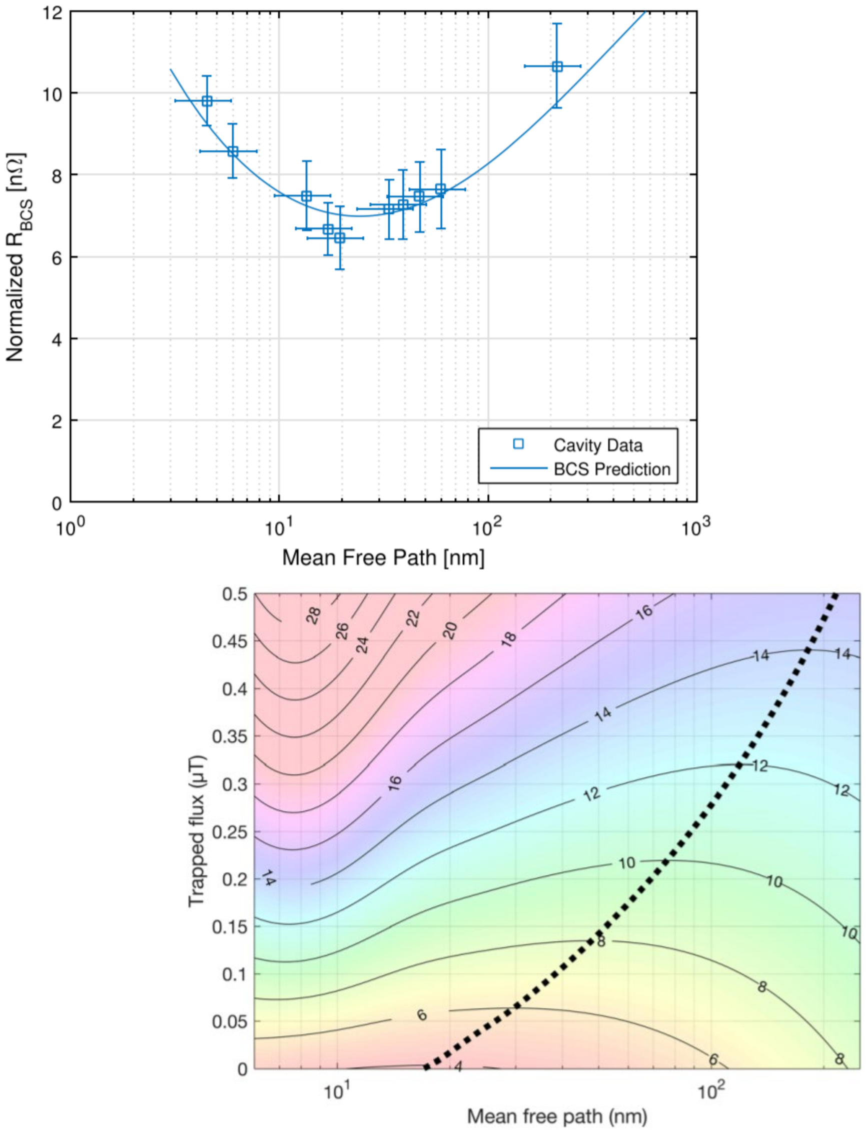


[2] Avg. No. of NbH appearance within 10 x 10 μm² unit area during cooling



Mean free path tuning

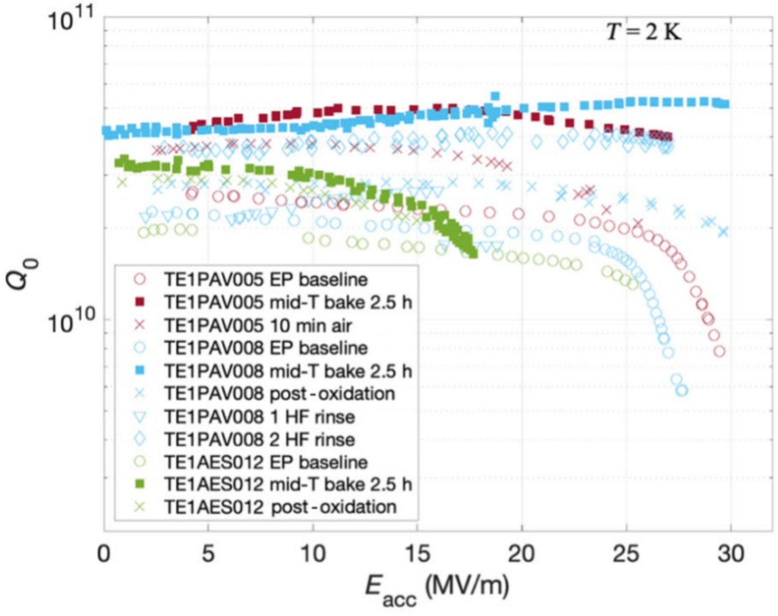
[3]



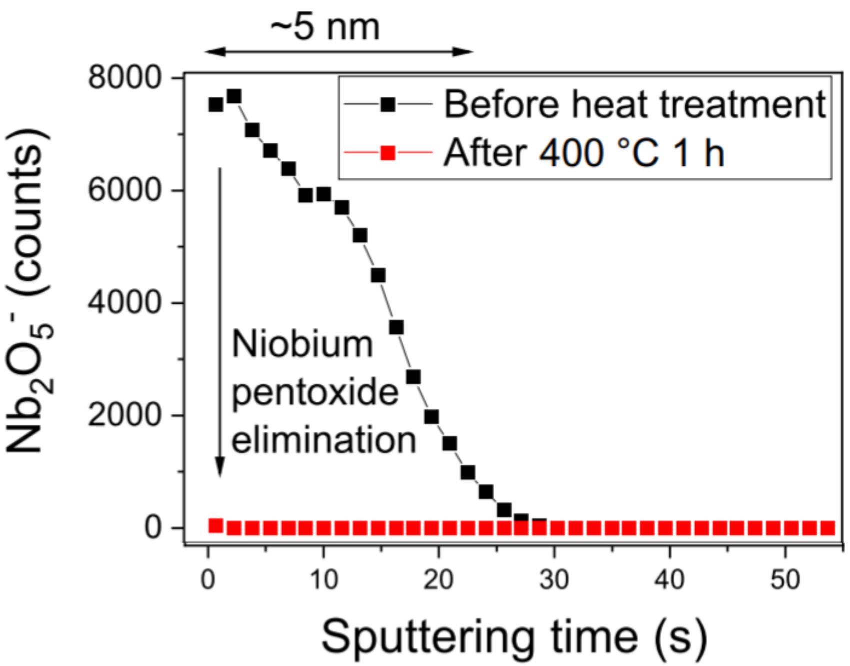
[1] Garg, P., et al. " *Superconductor Science and Technology* 31.11 (2018): 115007.
[2] Sung, Z. H., et al. *Proceedings of the International Conference on RF Superconductivity SRF*. 2019.
[3] Maniscalco, J. T., D. Gonnella, and M. Liepe. *Journal of Applied Physics* 121.4 (2017): 043910.

• Motivation – Mid-T bake

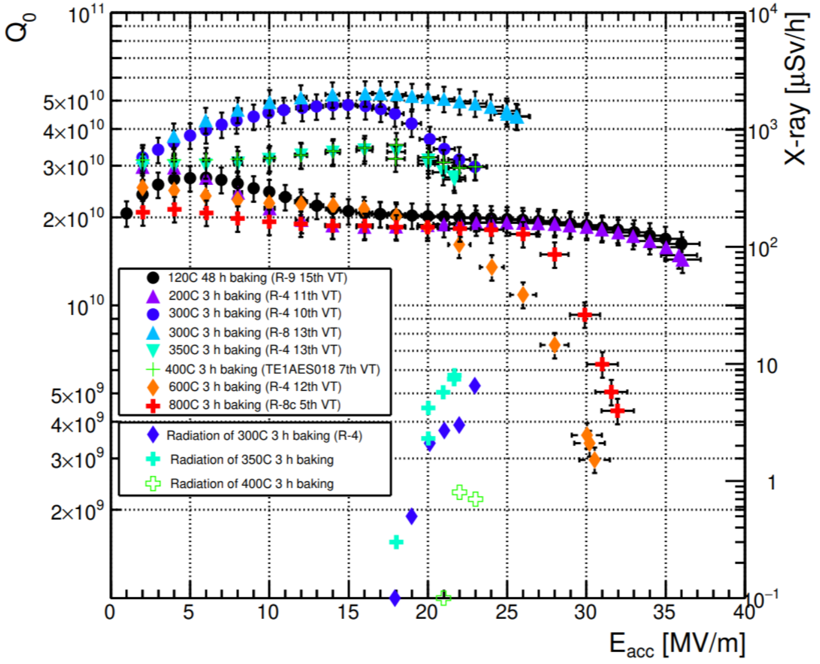
[1]



[2]



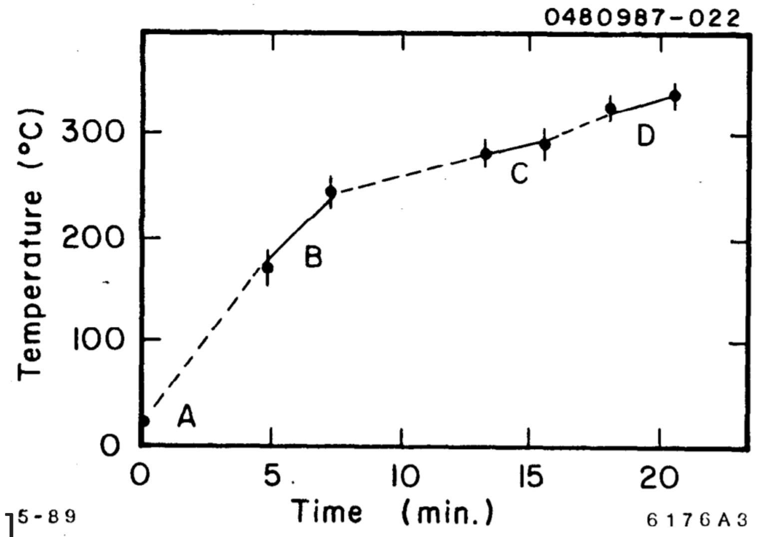
[3]

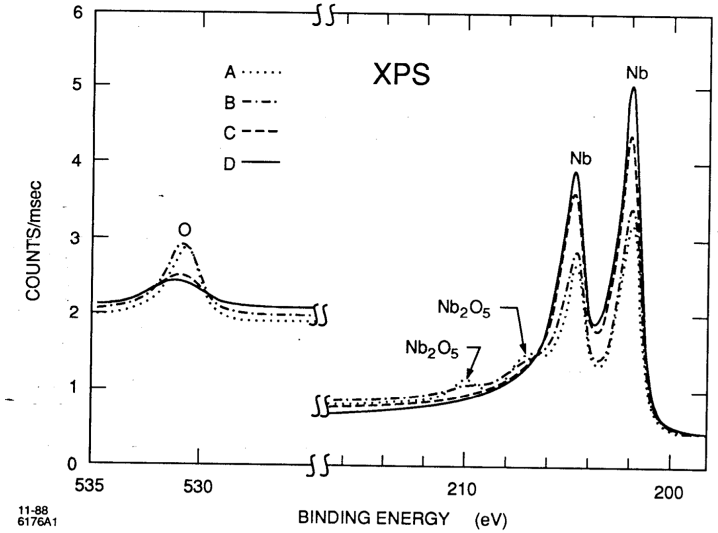


[1] Posen, S., et al. *Physical Review Applied* 13.1 (2020): 014024.
[2] Romanenko, A., et al. *Physical Review Applied* 13.3 (2020): 034032.
[3] H. Ito et al. Progress of Theoretical and Experimental Physics, 2021;, ptab056

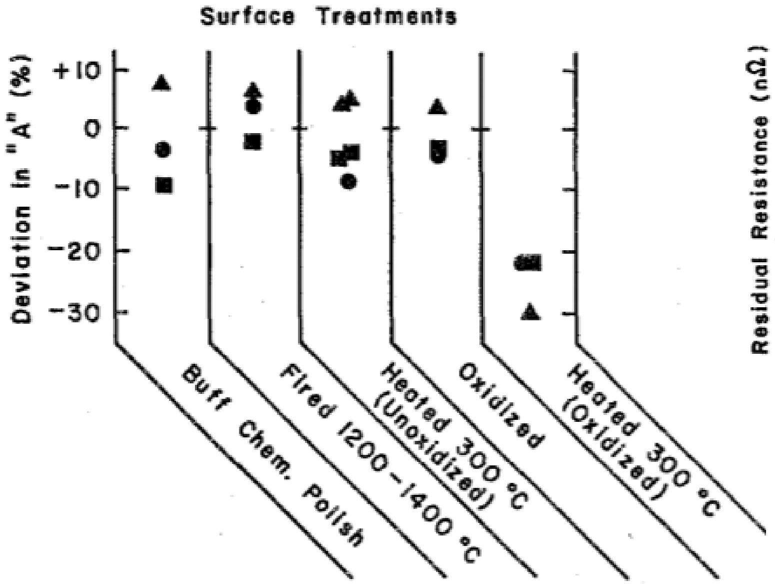
• Motivation – Previous Works

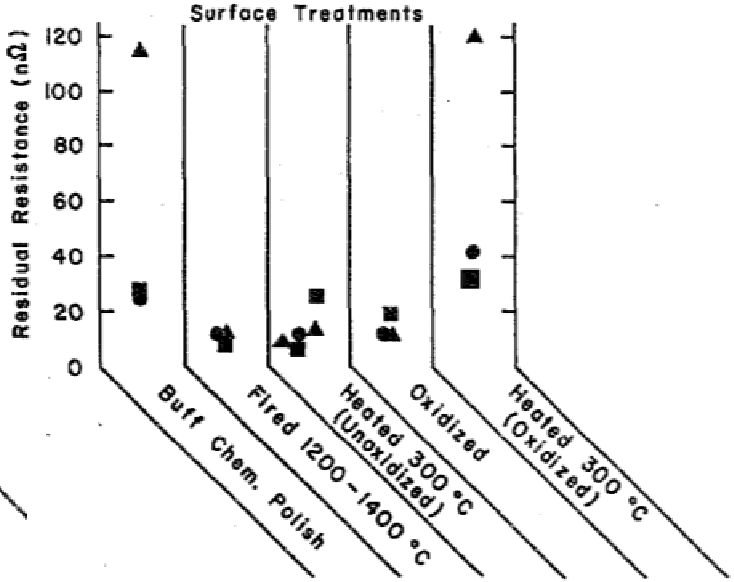
[1]





[2]





[1] F. Palmer, R. Kirby, F. King, and E. L. Garwin, Nucl. Instrum. Methods. Phys. Res. A: **297**, 321 (1990).
[2] F. Palmer, IEEE Transactions on Magnetics **23**, 1617 (1987).

Outline

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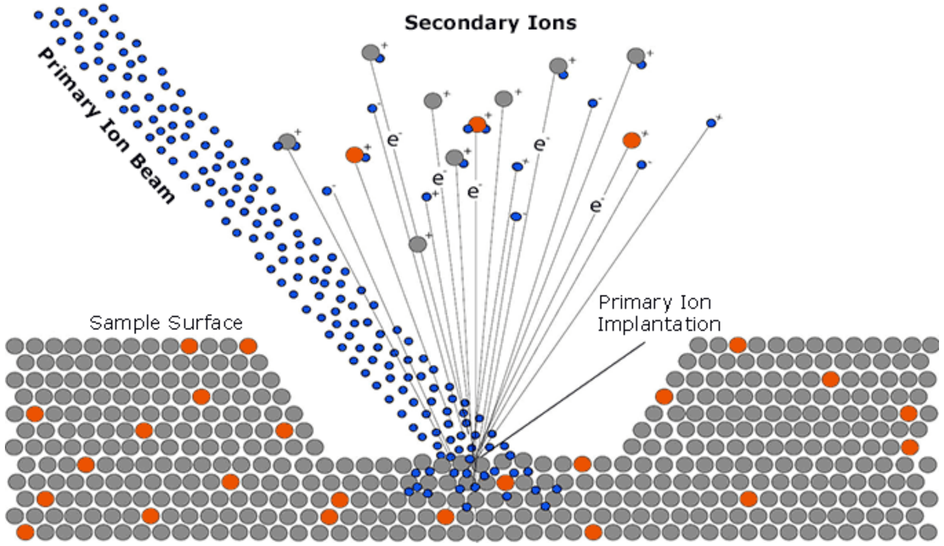
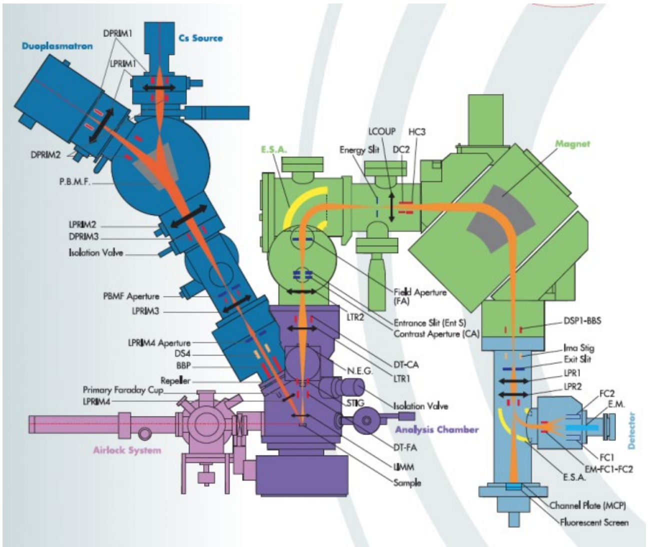
- Oxide Dissolution Model
- Benefits

SIMS Results - Secondary Ion Mass Spectrometry

[1]



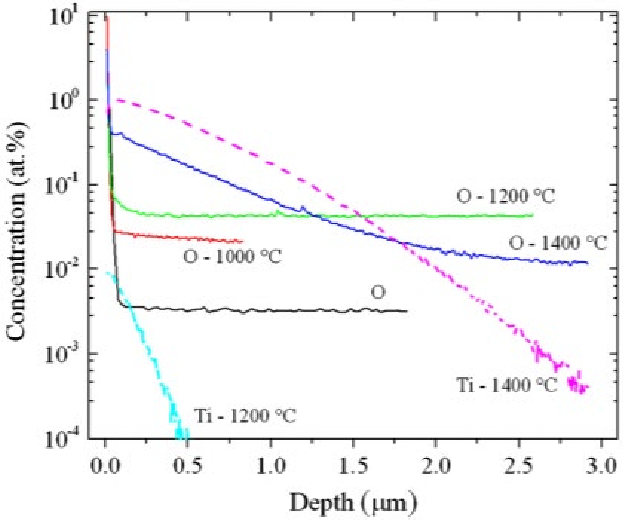
[2]



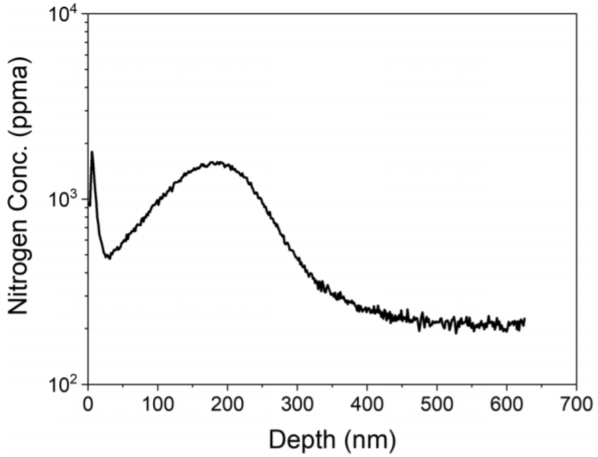
Why SIMS?

- Part per million impurity concentration required
- High depth resolution is required.

[3]



[4]

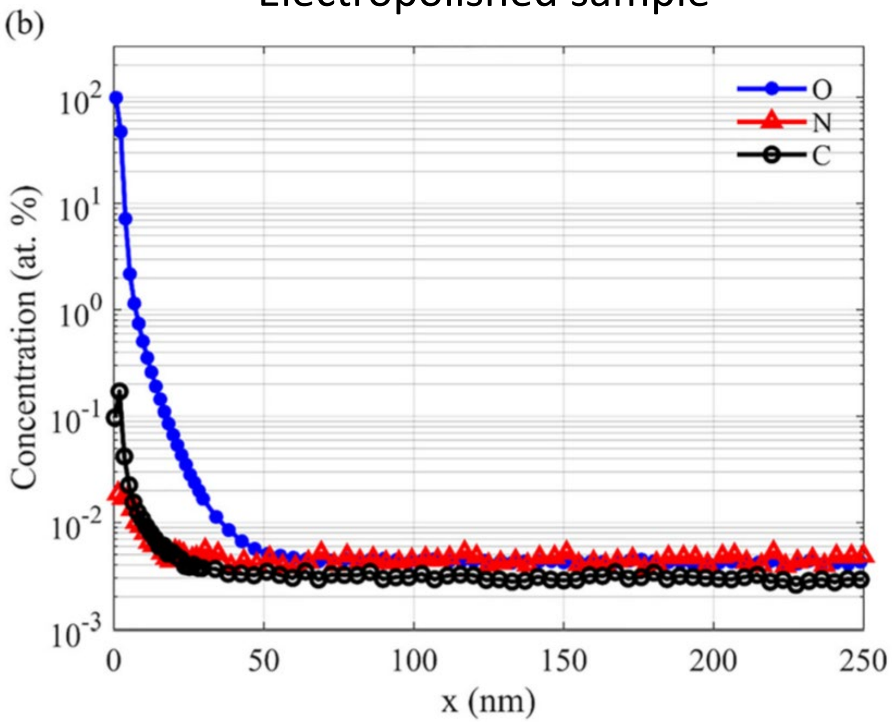


$$RSF = (\Phi C I_m t)/(z I_s)$$

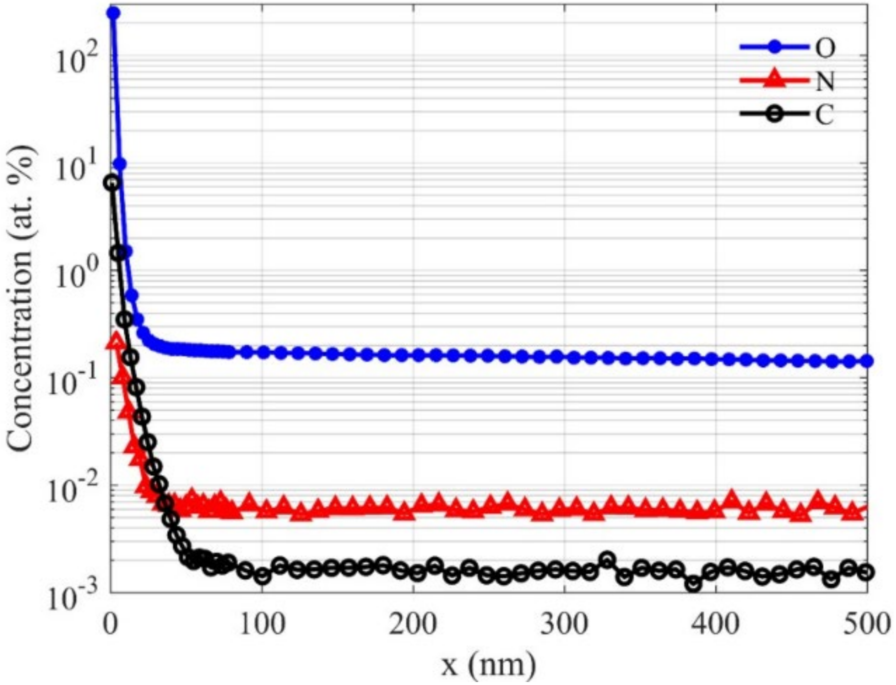
[1] https://www.cameca.com/products/sims/technique
[2] Cameca: IMS 7f-GEO www.cameca.com/instruments-for-research/ims7fgeo.aspx
[3] P. Dhakal, et al. *Phys. Rev. Spec. Top. Accel. Beams* 16.4 (2013): 042001
[4] Angle, Jonathan W., et al. *J. Vac. Sci. Technol. B* 39.2 (2021): 024004.

SIMS Results – Shallow Depth Profile

Electropolished sample



300 °C/2.3 hours



- Clean Nb has background C,N,O impurity concentrations at ~0.005 at. %

- After vacuum annealing at 300 C for 2.3 hr we find a large enhancement in O.
- C and N have diffusion coefficients 2-3 orders of magnitude less than O
- O concentrations similar to that of N in N-alloyed cavities

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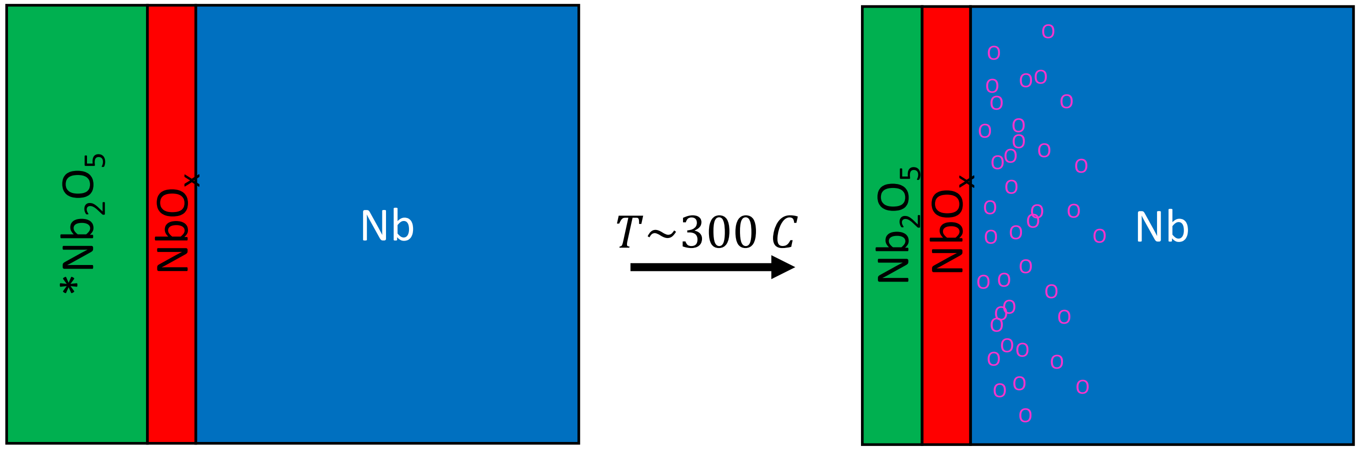
• Ciovati's Native Oxide Dissolution and O Diffusion Model



One-dimensional diffusion equation [1]

$$\frac{\partial c(x,t)}{\partial t} = D(T)\frac{\partial^2 c(x,t)}{\partial x^2} + q(x,t,T). \qquad c(x,t) = v(x,t) + u(x,t)$$

Solutions to the diffusion equation

$$v(x,t) = \frac{v_0}{\sqrt{\pi D(T)t}} e^{-x^2/(4D(T)t)} + c_\infty \ -superficial\ dissolved\ oxygen$$

$$u(x,t) = \frac{u_0}{\sqrt{\pi D(T)}} \int_0^t \frac{k(T)e^{-k(T)s}}{\sqrt{t-s}} e^{-x^2/(4D(T)(t-s))} ds \ -\ oxide\ dissolution$$

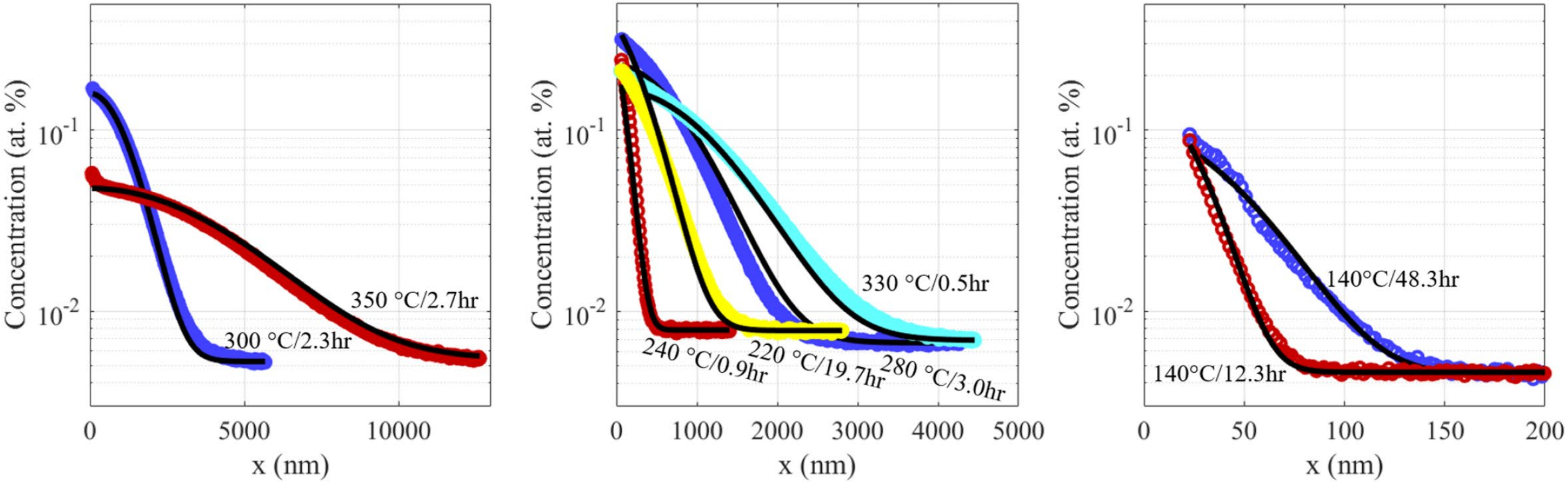
Arrhenius equations

$$D(T) = D_0 e^{-E_{aD}/RT} \ -\ oxygen\ diffusion$$

$$k(T) = Ae^{-E_{ak}/RT} \ -\ oxide\ dissolution$$

[1] Ciovati, Gianluigi. *Applied physics letters* 89.2 (2006): 022507.

Ciovati's Model – SIMS O Concentration Depth Profiles



- Measurements are consistent with Ciovati's model
- Predictability and ability to tune interstitials by changing only temperature and time of vacuum anneal
- Oxygen source is the native oxide

$\underline{superficial\ dissolved\ oxygen}$

$v_0 = 3.5$ O % nm

$E_{aD} = 119.9$ kJ/mol

$D_0 = 0.075\ \mathrm{cm^2/s}$

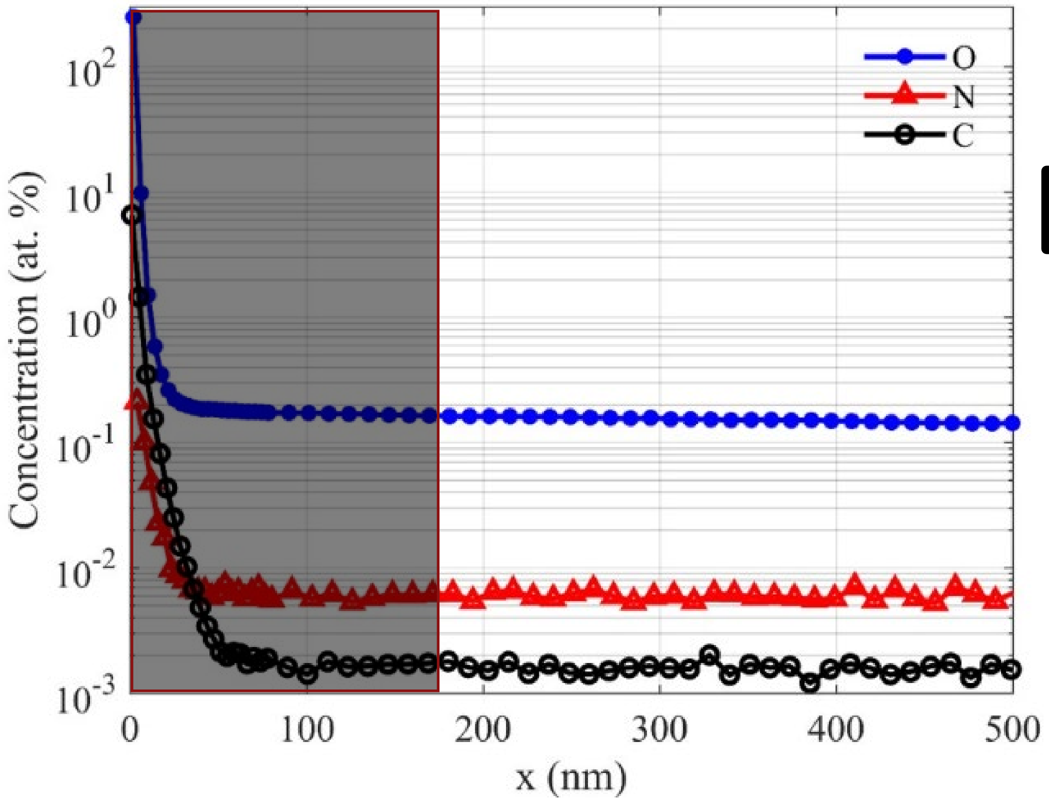
$\underline{oxide\ dissolution}$

$u_0 = 200$ O % nm

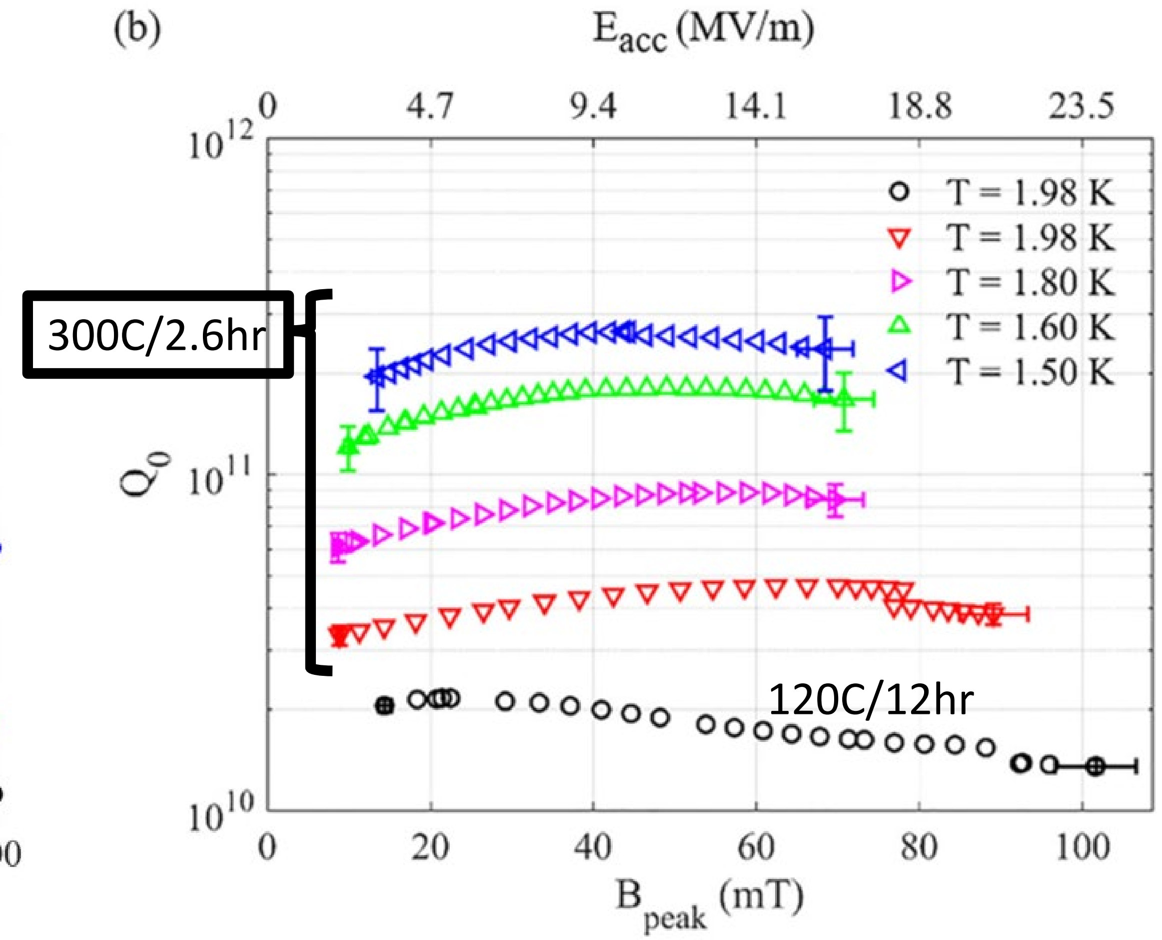
E_{ak} =131 kJ/mol

A = 0.9×10^9 1/s

RF - Results



- Electropolish 180 nm off the surface to remove any contribution of C and N



- High Q_0 still exists! Oxygen is the main alloying interstitial

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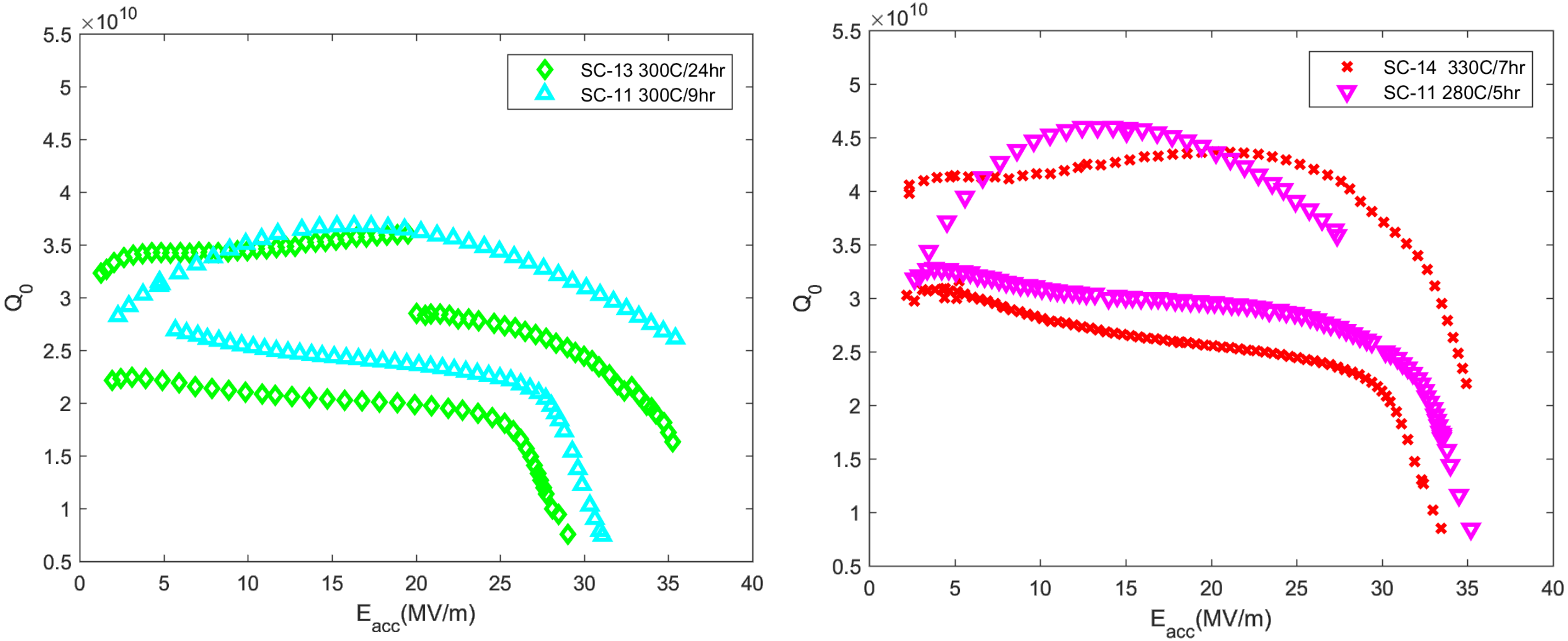
High Q_0 and High E_{acc}

1.3 GHz Single Cell RF Tests



- Reproducibly high Q
- E_{max} that match or exceed the baseline EP HFQS

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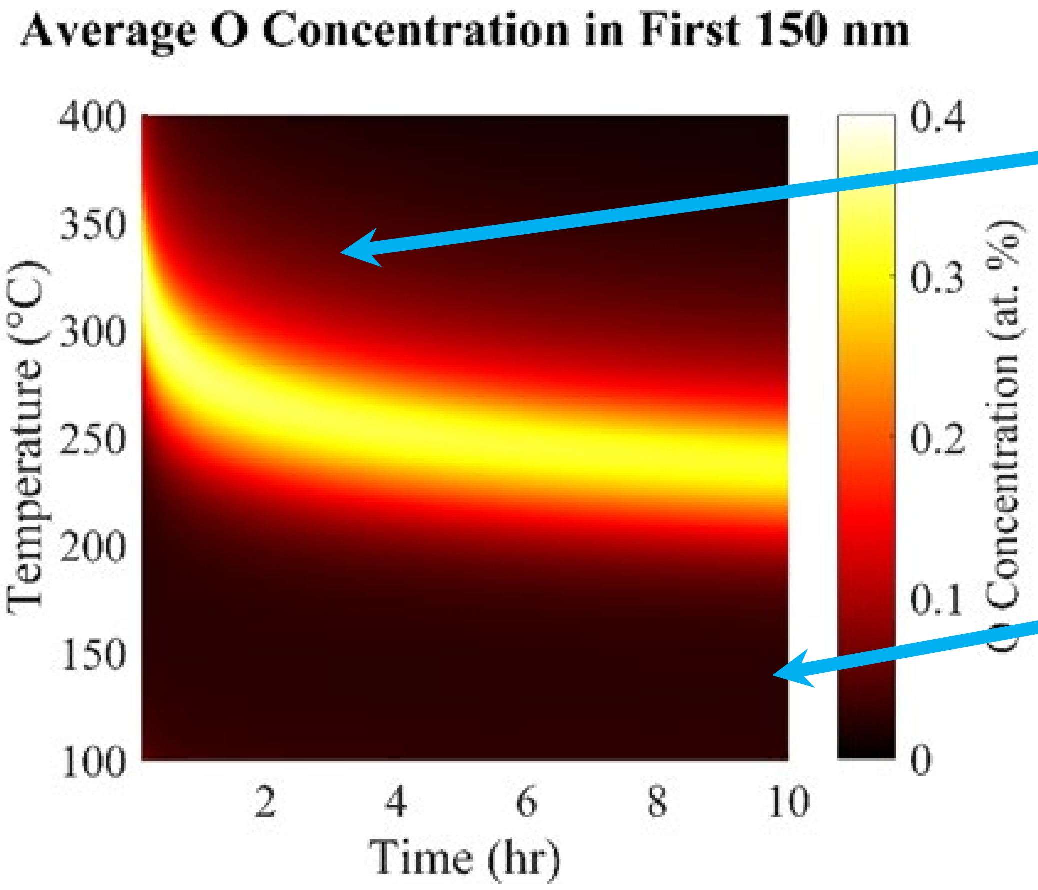
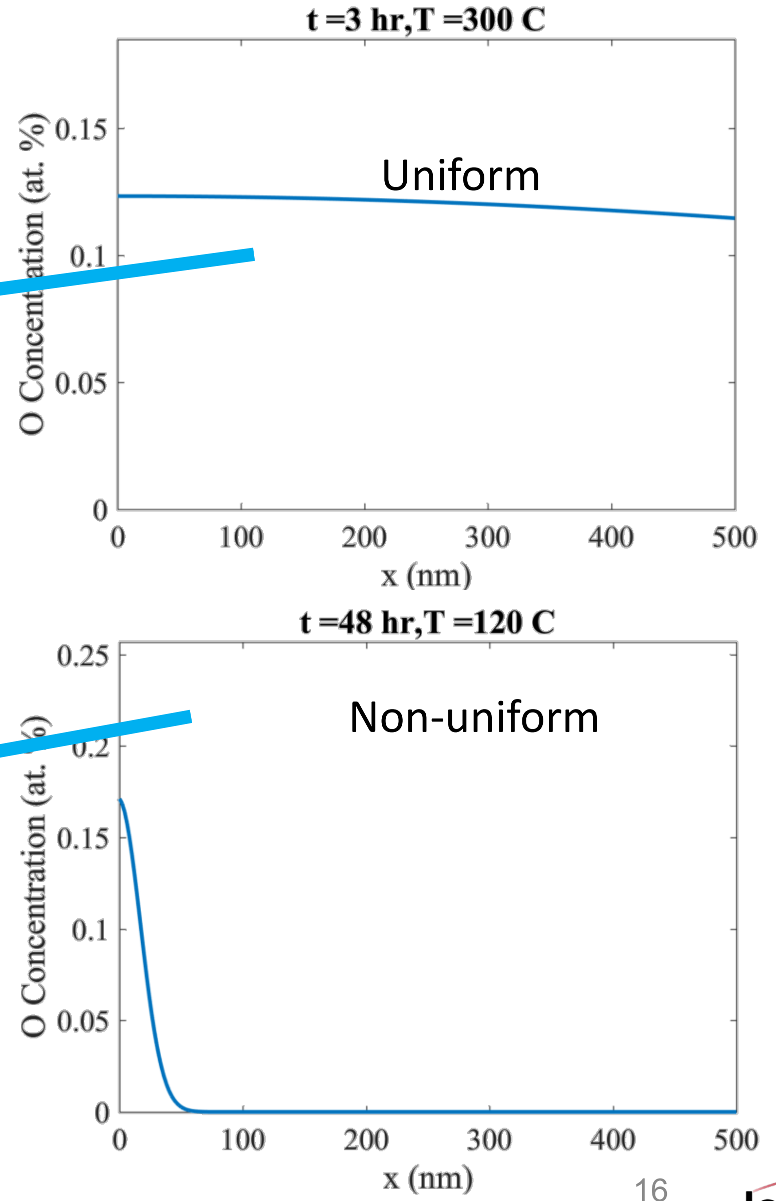
Oxygen Content

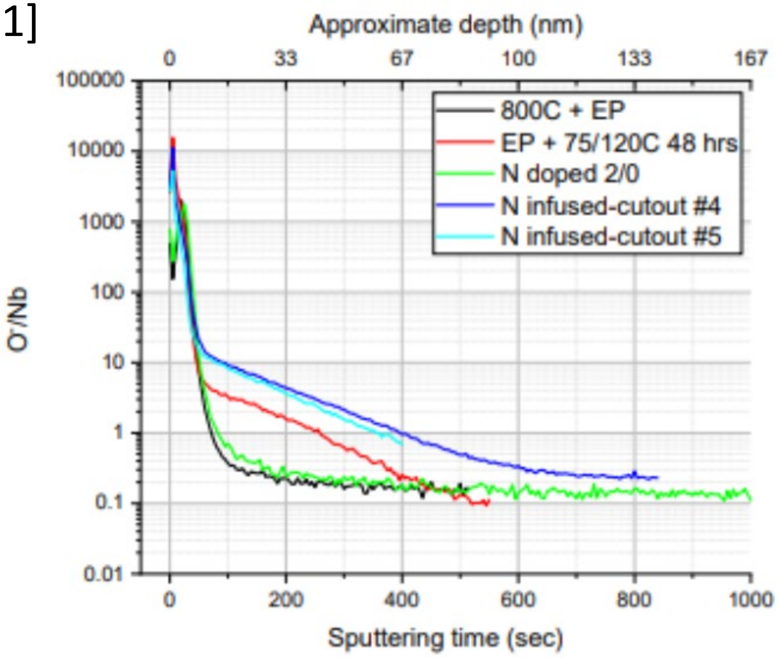




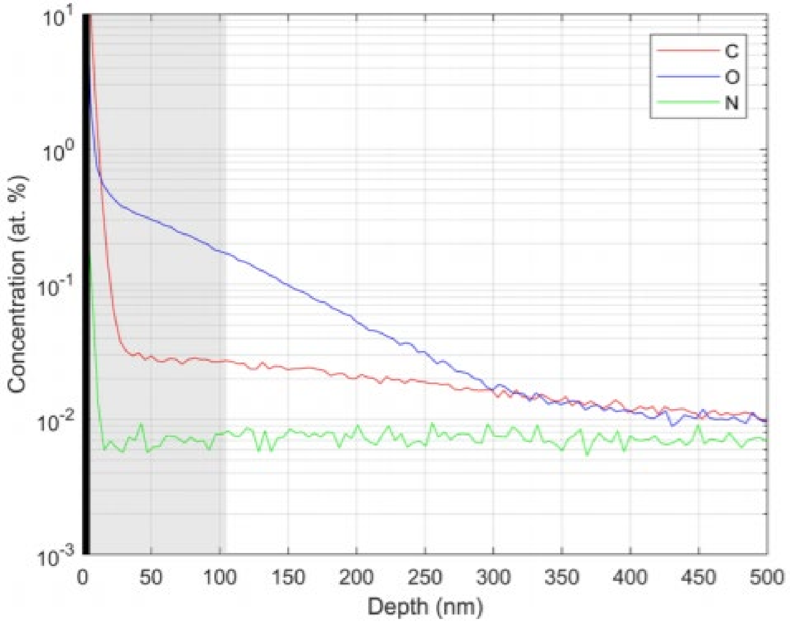
- O tunability
- Uniform or non-uniform O-profiles

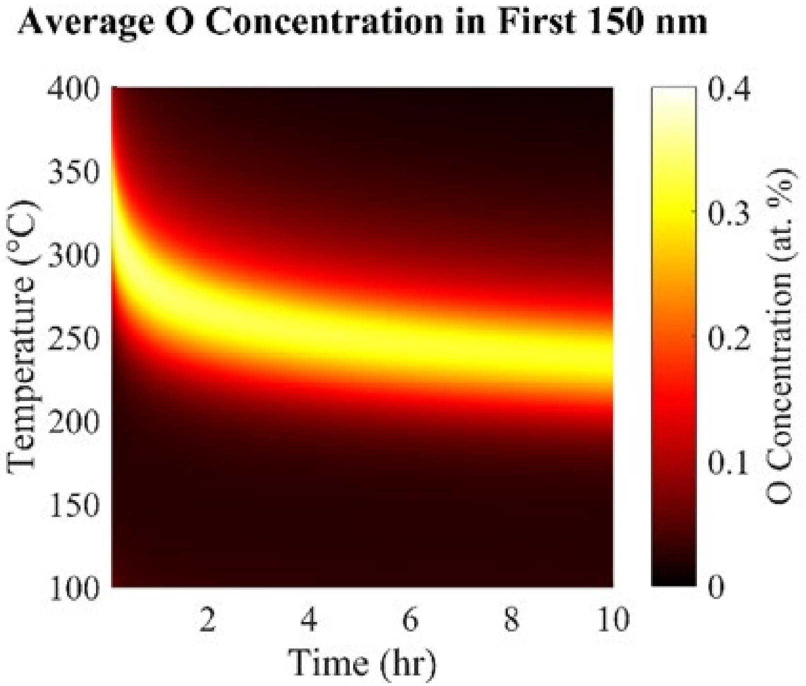
Role of Oxygen in Infusion Recipes?

[1]



[2]





- Can N infusion-like recipes be developed using this model?

[1] A. Romanenko, , in *19th International Conference on RF Superconductivity* (JACoW, Dresden, 2019).
[2] J. Maniscalco, et al., in *19th International Conference on RF Superconductivity* (JACoW, Dresden

Outline

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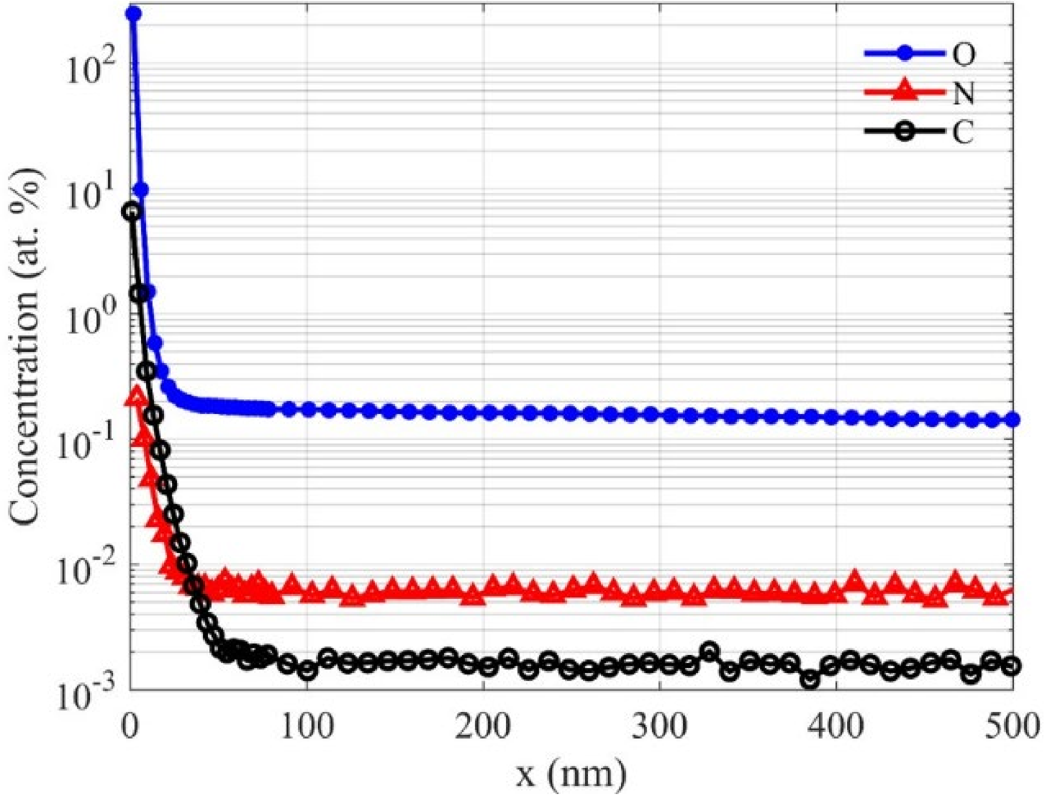
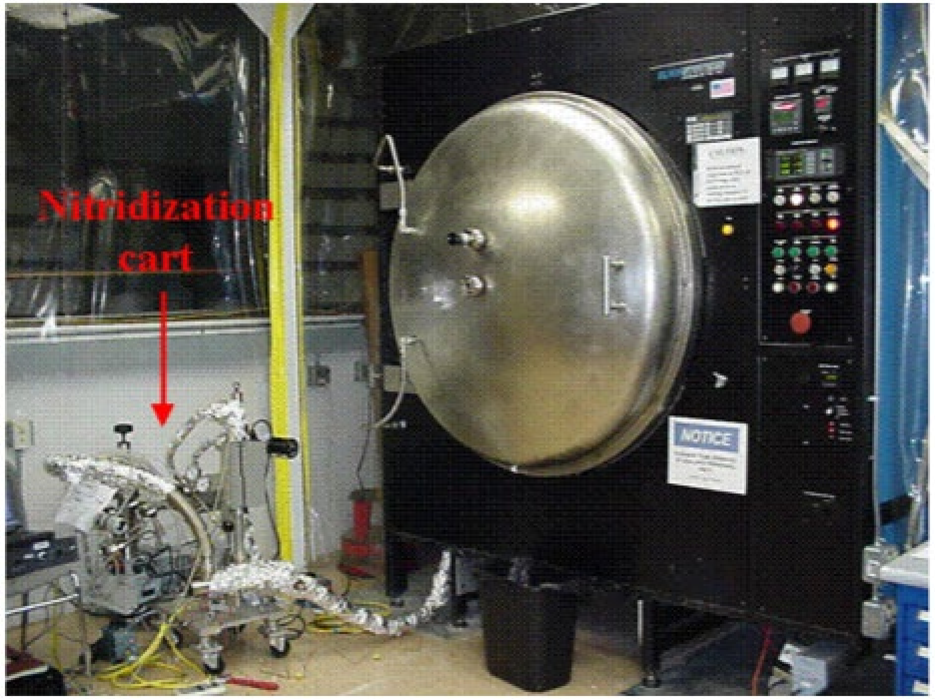
- **Benefits**

• Benefits – Furnace

[1]



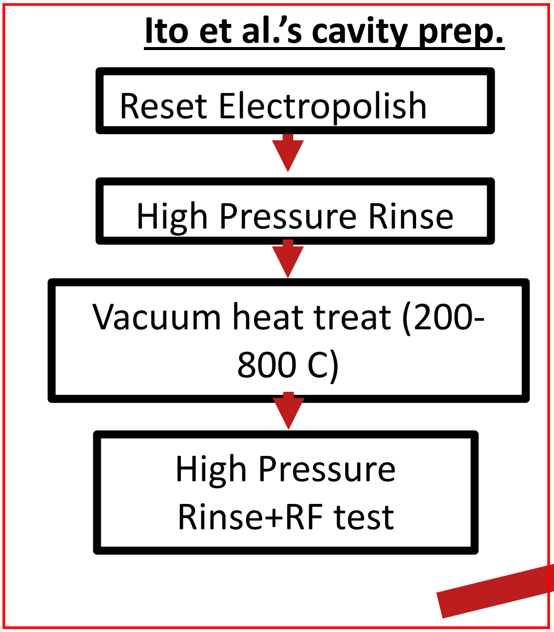


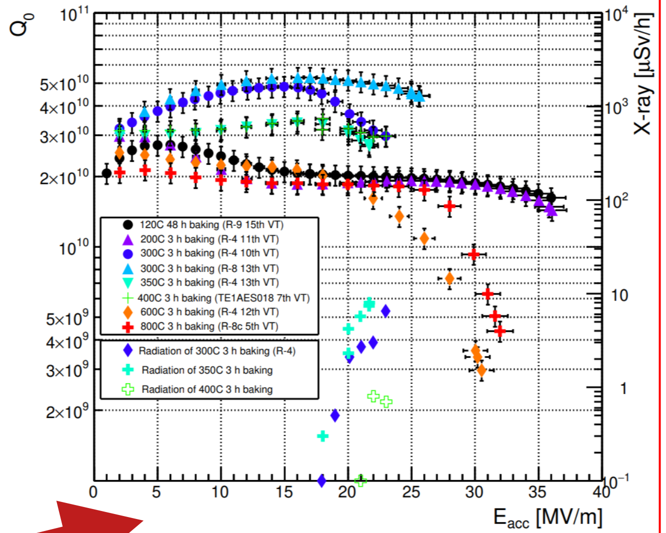
- O source is the oxide, no gas injection required

[1] Ciovati, G., et al. *Physical Review Special Topics-Accelerators and Beams* 13.2 (2010): 022002.

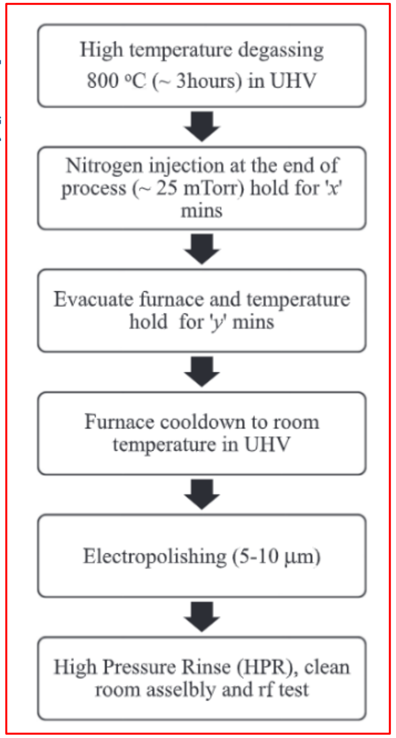
Benefits - Simplicity

[1] O-alloying

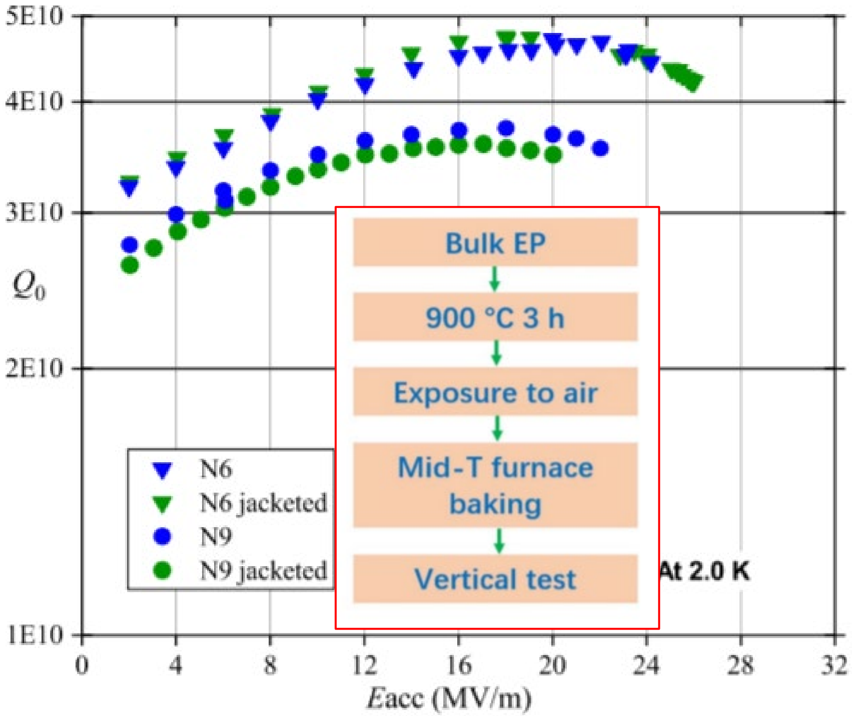




[2] N-alloying



[3] How simple can O-alloying get?



- Simple process

[1] H. Ito et al. Progress of Theoretical and Experimental Physics, 2021;, ptab056
[2] P. Dhakal *Physics Open* (2020): 100034.
[3] F. He, et al. *Superconductor Science and Technology* 34.9 (2021): 095005.

• Benefits – Inherently Conformal

[1]

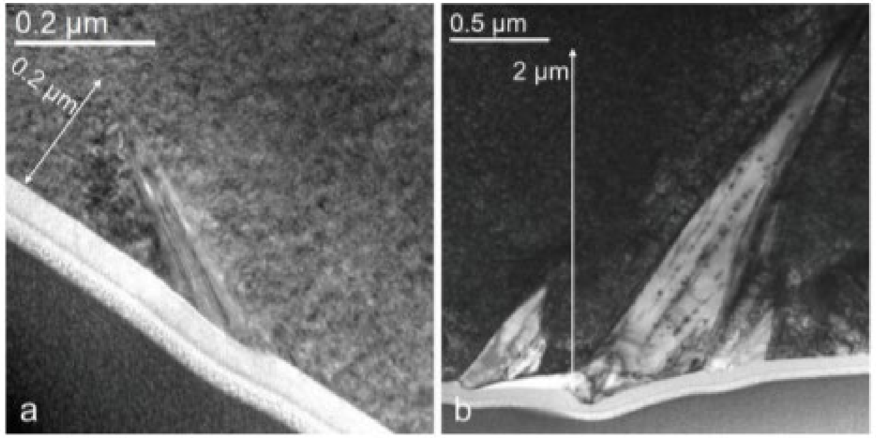
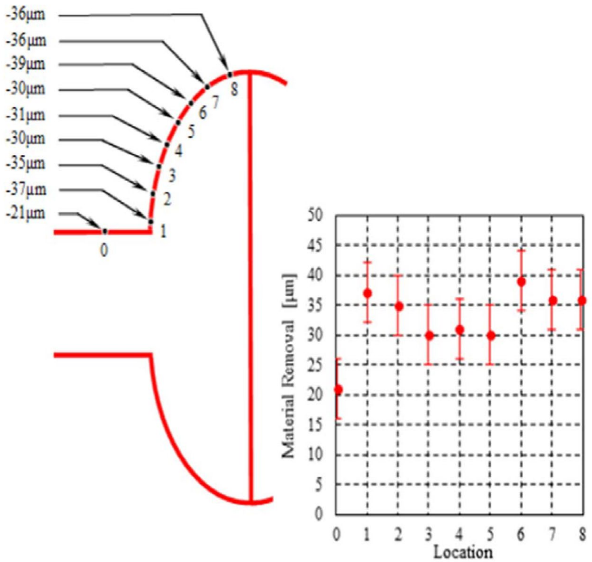


Figure 4: TEM image of Nb sample baked with nitrogen gas at 800°C for (a) 2 min, (b) 20 min

[2]



[3]

- The oxygen source is conformal to the surface of the cavity
  - Uniformity of O interstitials

[1] Y. Trenikhina Proc. of SRF2015, Whistler, BA, Canada (2015)
[2] Crawford, Anthony C. Nucl. Instrum. Methods. Phys. Res. B 849 (2017): 5-10.
[3] De Silva, S. U., and Jean R. Delayen. *Physical Review Special Topics-Accelerators and Beams* 16.8 (2013): 082001.

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Conclusions/Where next?

Conclusions

- Using SIMS, we measured O,C, N concentration depth and showed major enhancement in O impurities
- RF and SIMS measurements confirmed that the alloying effect of vacuum annealing is due primarily to oxide dissolution and diffusion
- Constrained a model of native oxide dissolution for predictive O-alloying

Where next?

- Heat treat additional cavities to evaluate performance scaling with O content.
- Explore the role of tailored impurity diffusion profiles within the RF penetration depth
- Explore multiple dissolutions or multi-step temperature profile

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Virginia Tech (SIMS)

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JLab

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NCSU

Fred Stevie

JLab Staff

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Questions?

RF surface resistance tuning of superconducting niobium via thermal diffusion of native oxide

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