Fermilab

April 16, 2025

Recent Progress with SRF R&D

FERMILAB-SLIDES-25-0074-SQMS-TD

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U.S. DEPARTMENT of ENERGY
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Overview

- Surface Engineering Techniques
  - The role of oxygen impurities in enabling enhanced cavity performance
  - The importance of electropolishing for higher gradients
  - Identifying microscopic origins of loss to aid in the development of new processing techniques
- Technologies for Maintaining Cavity Performance in Accelerators
  - Identifying sources of flux trapping in Nb cavities
  - Successful application of plasma processing to new geometries
- Conclusion

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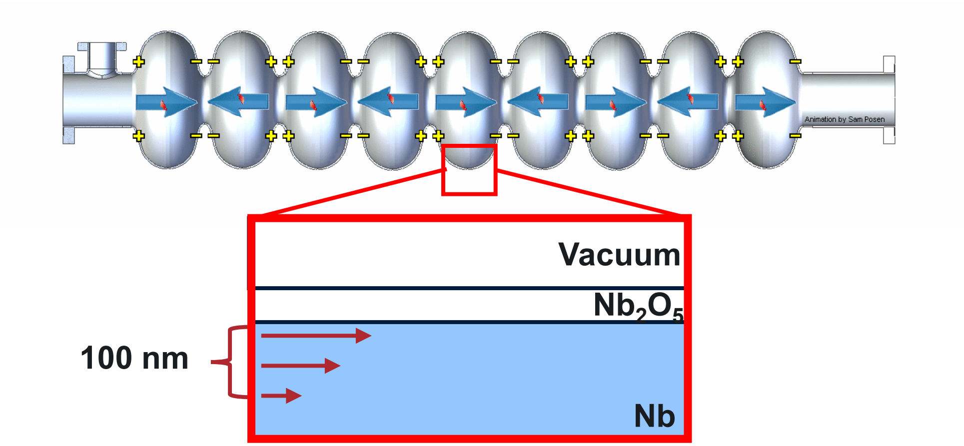
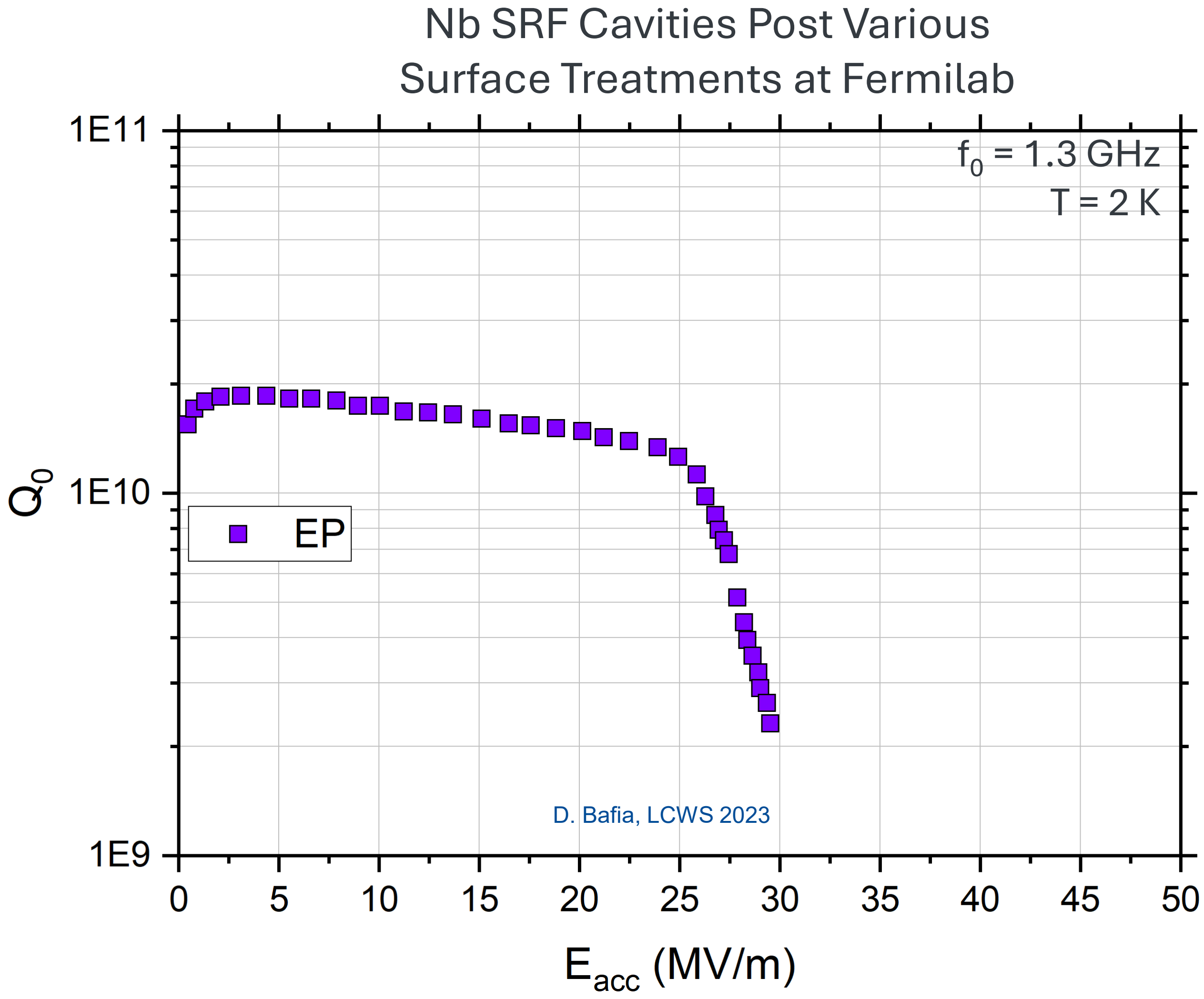
Quest for High Q_0 and Gradient with Impurities





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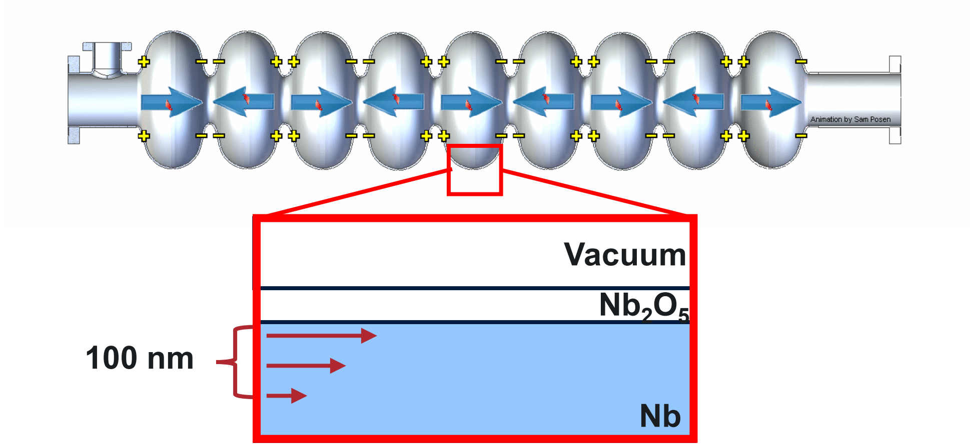
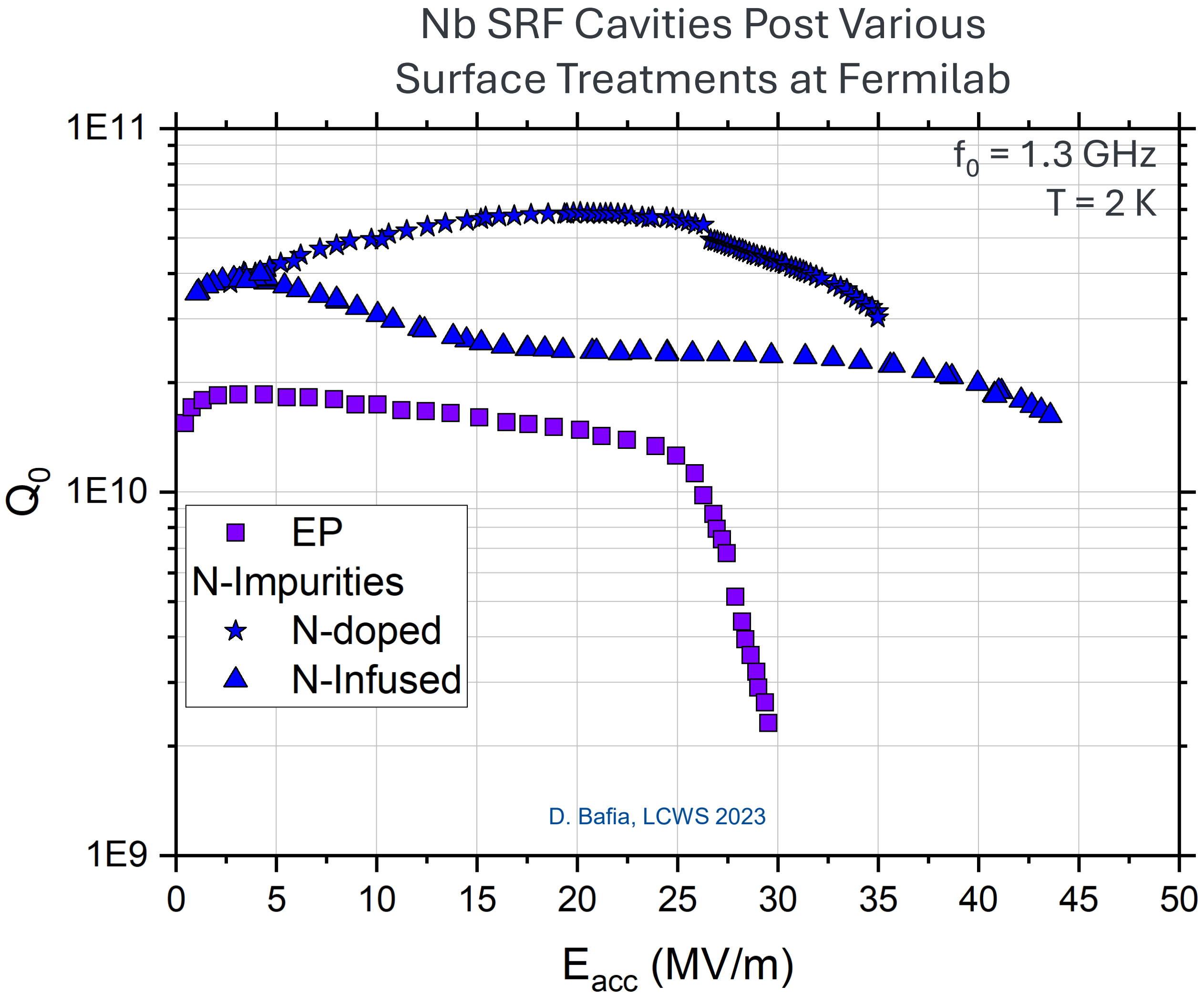


[N impurities]

- High Q_0: N-doping
- High Gradient: N-Infusion



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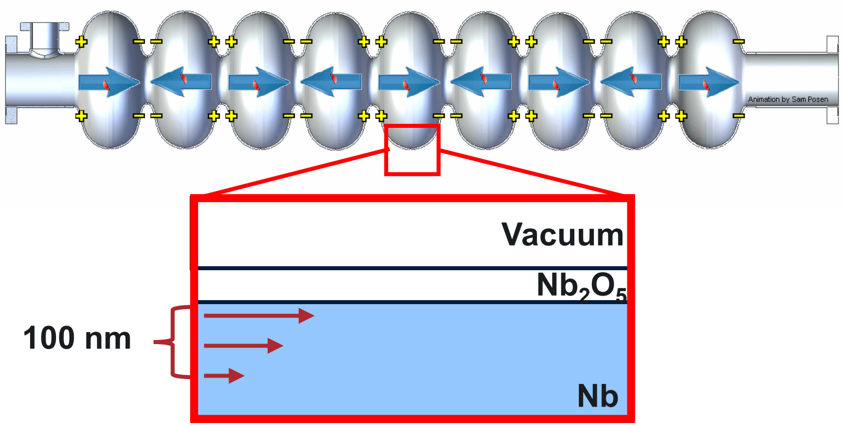
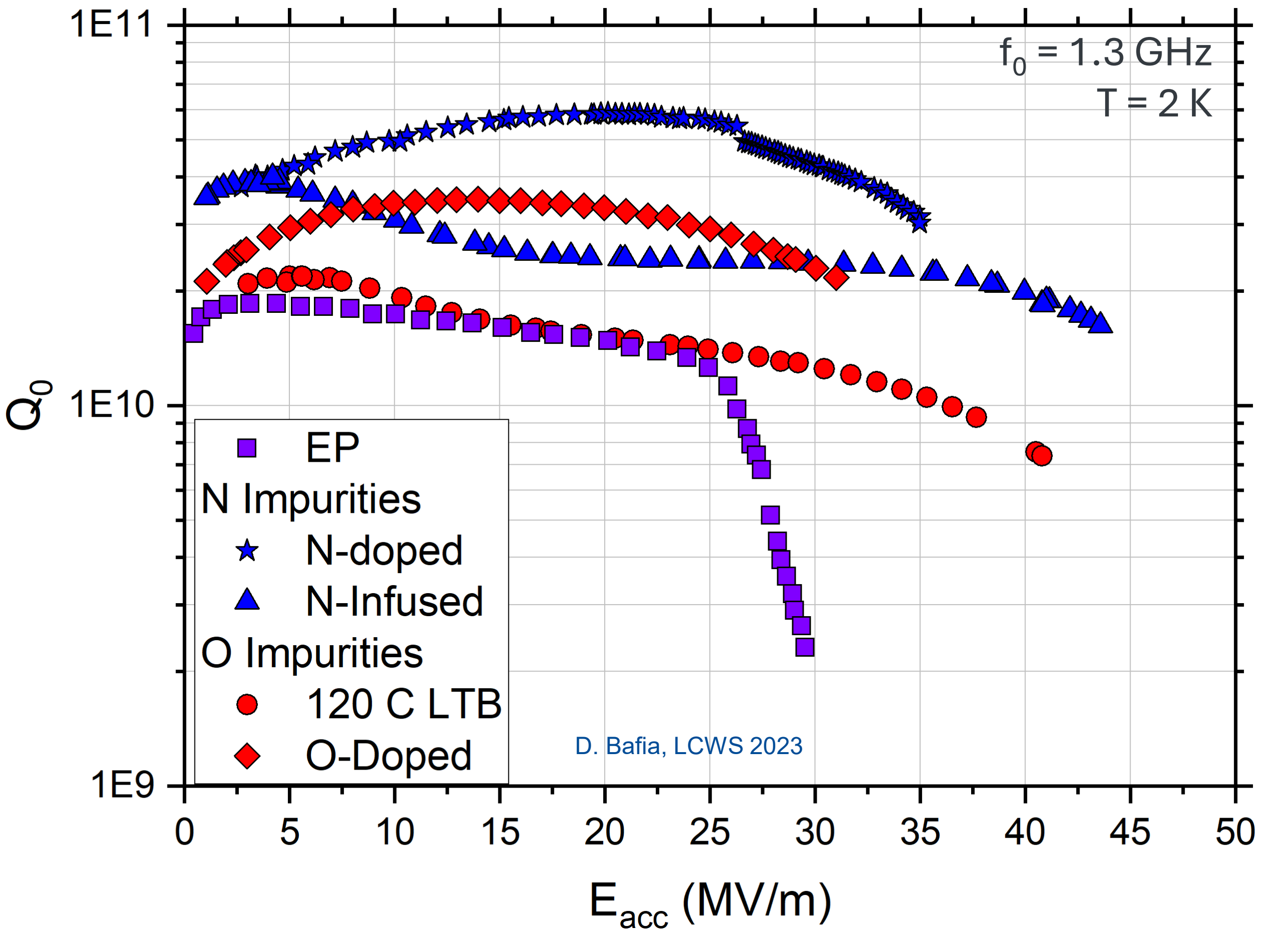


N impurities

- High Q_0: N-doping
- High Gradient: N-Infusion

Oxygen impurities:

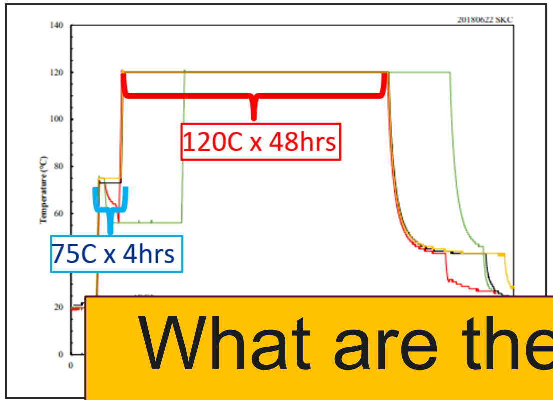
- High Gradient: Low Temp. Bake
- High Q_0: O-doping



Cold EP + 2-Step Low-Temp Bake Enables 50 MV/m

Grassellino *et al.* https://arxiv.org/abs/1806.09824

Cold EP +



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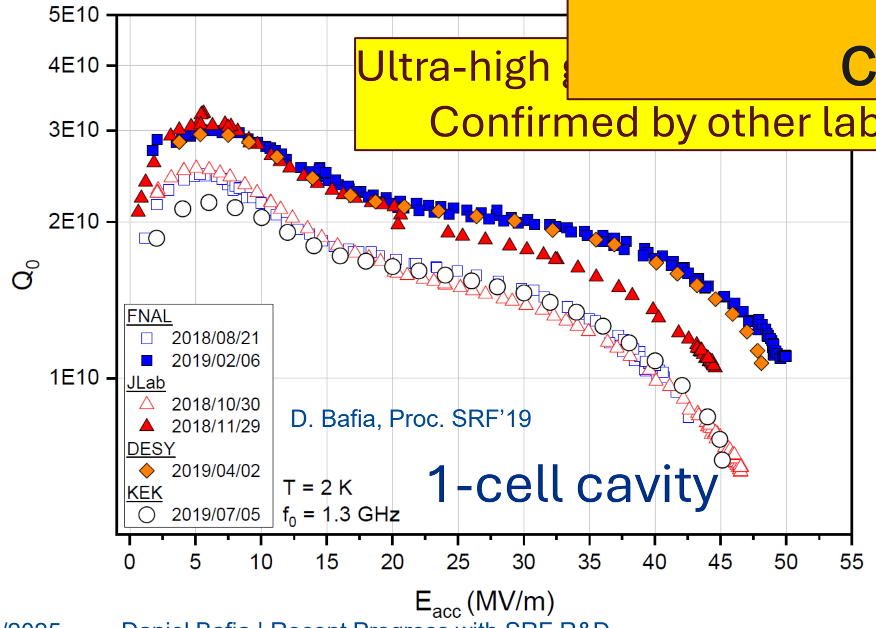
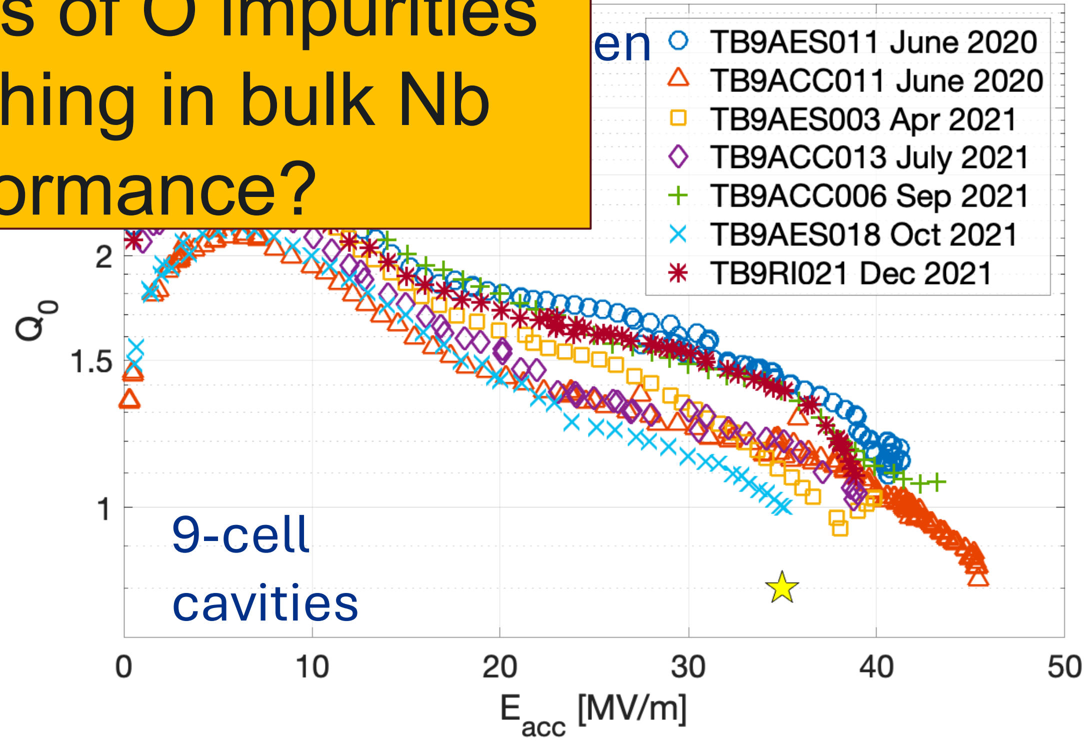


Transferred recipe to 9-cell cavities as part of ILC Cost Reduction effort

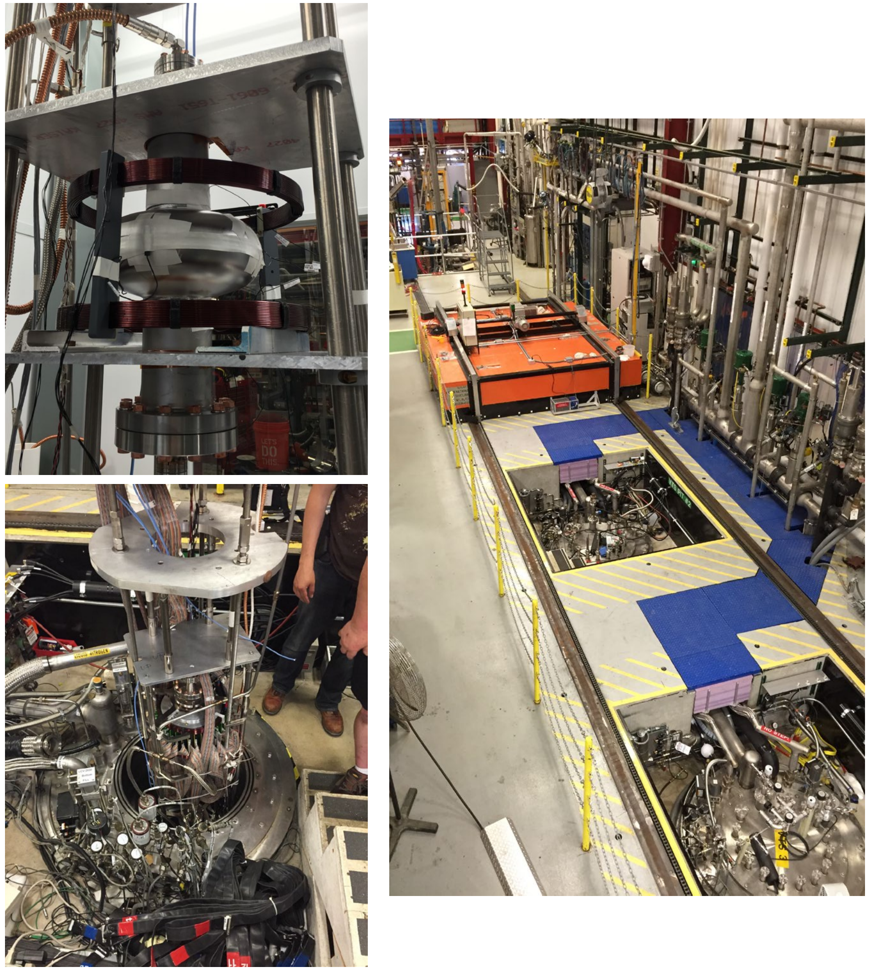
- Average E_{acc} = 40.4 MV/m!



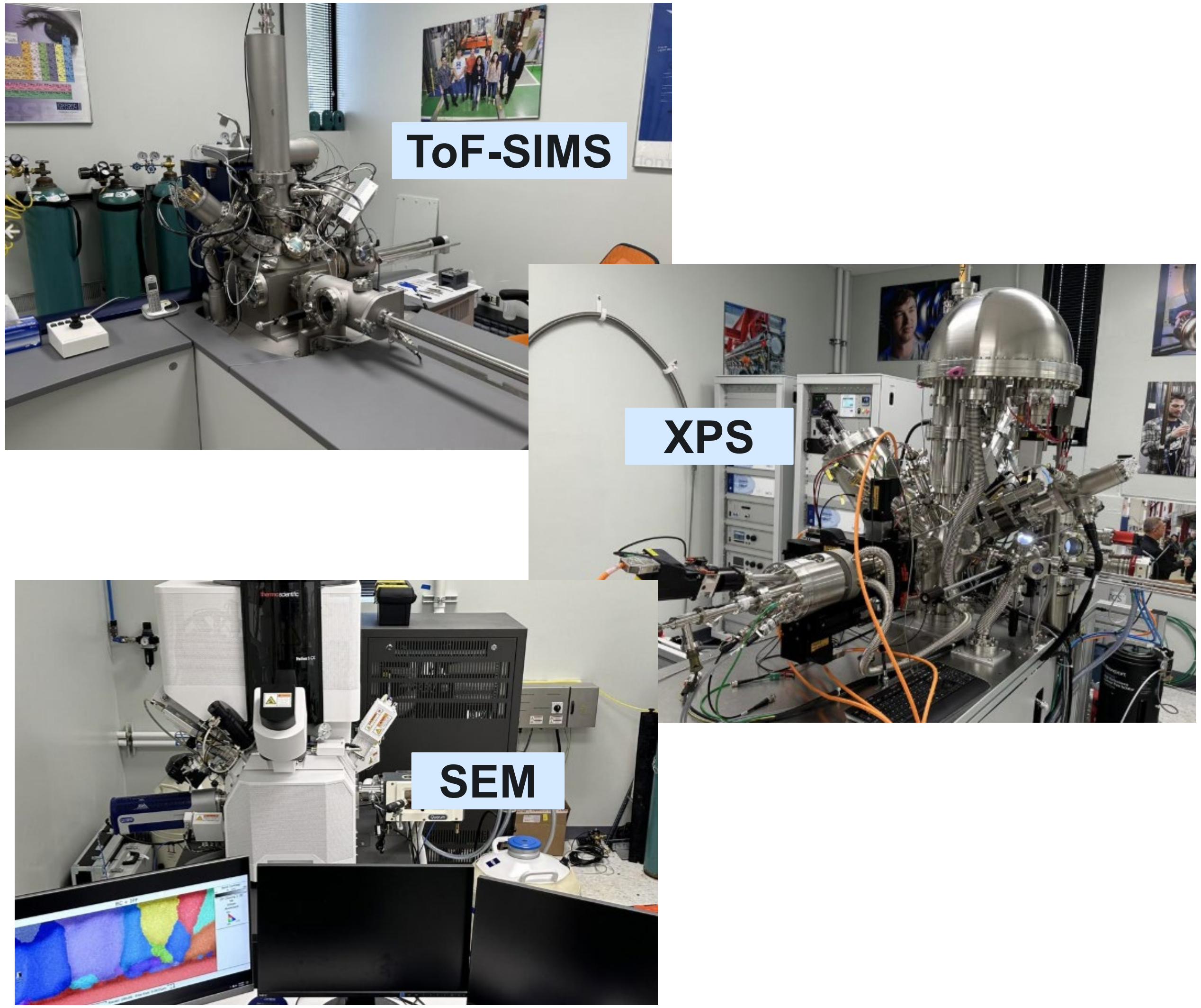
What are the roles of O impurities and electropolishing in bulk Nb cavity performance?

Materials Science to Identify Origins of Limitations

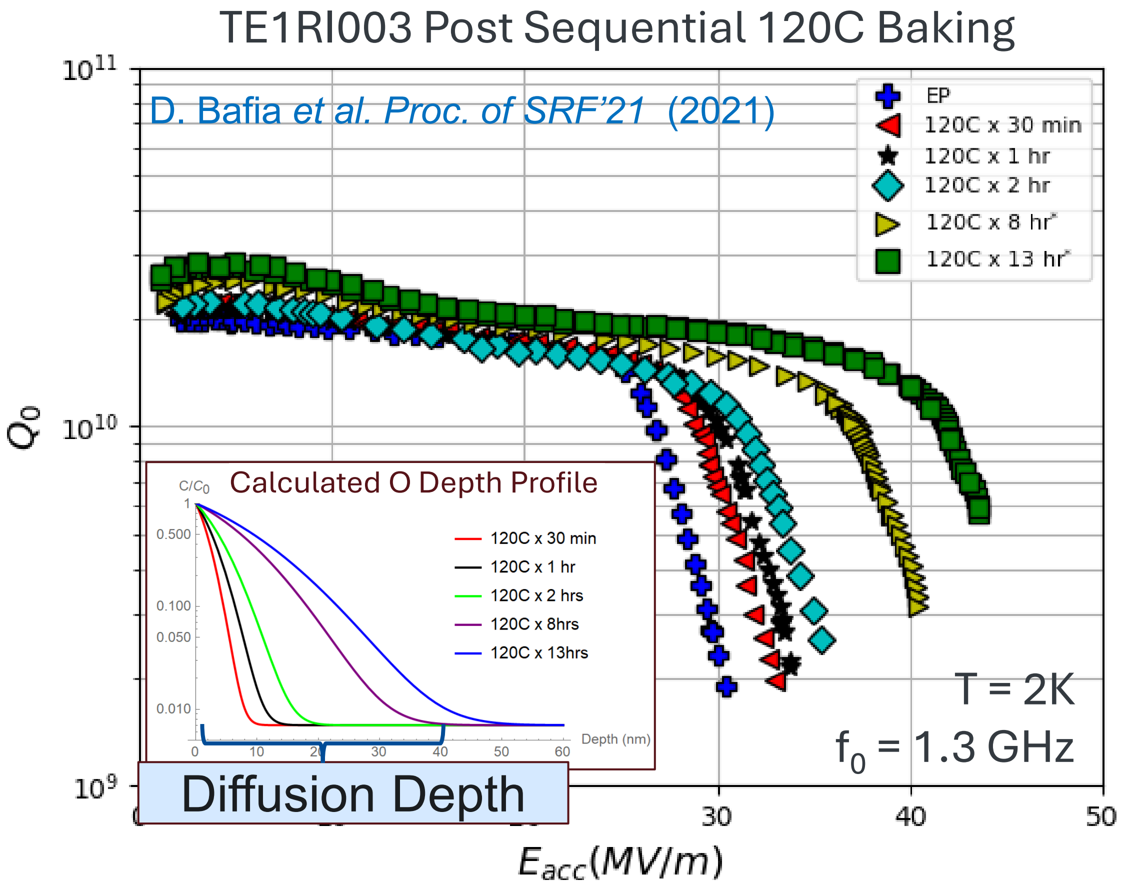
Cavity RF Measurements

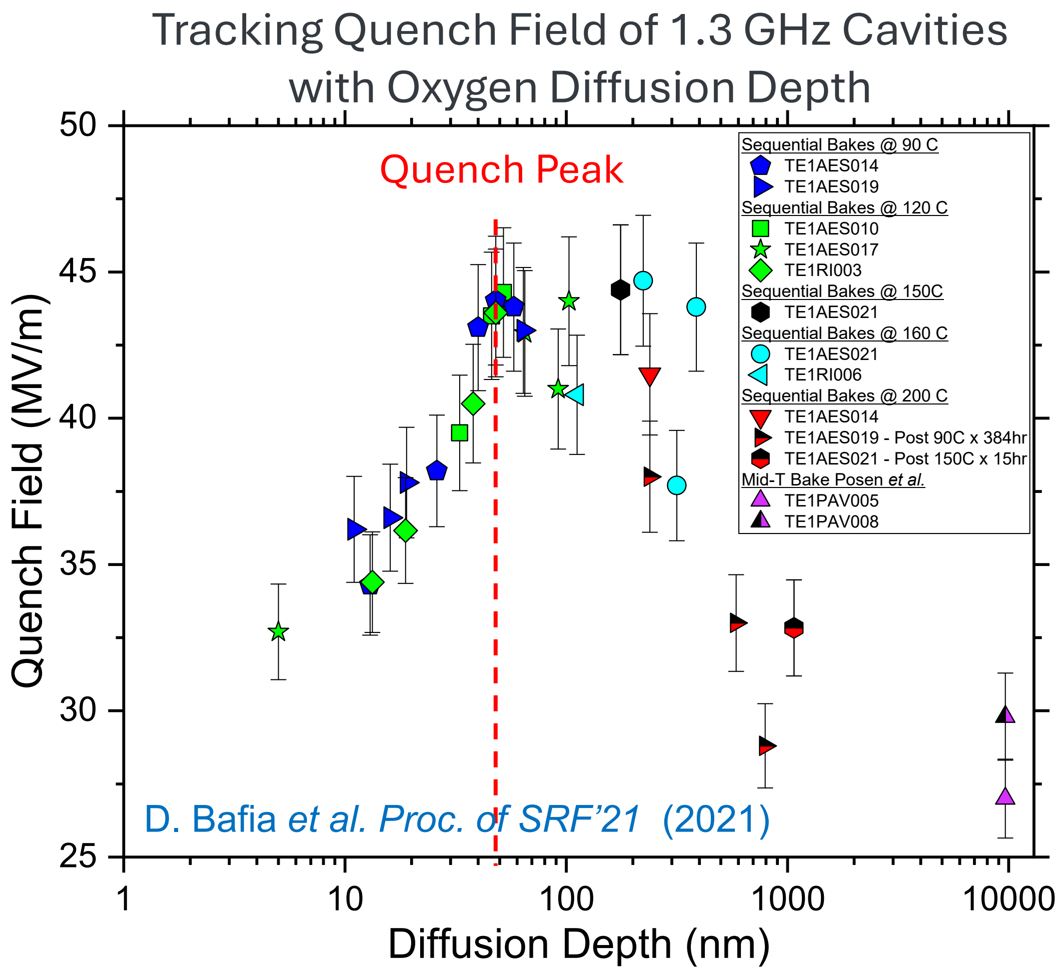


(Cryo) Material Studies



Oxygen Impurities Enable High E_{acc} in 1.3 GHz





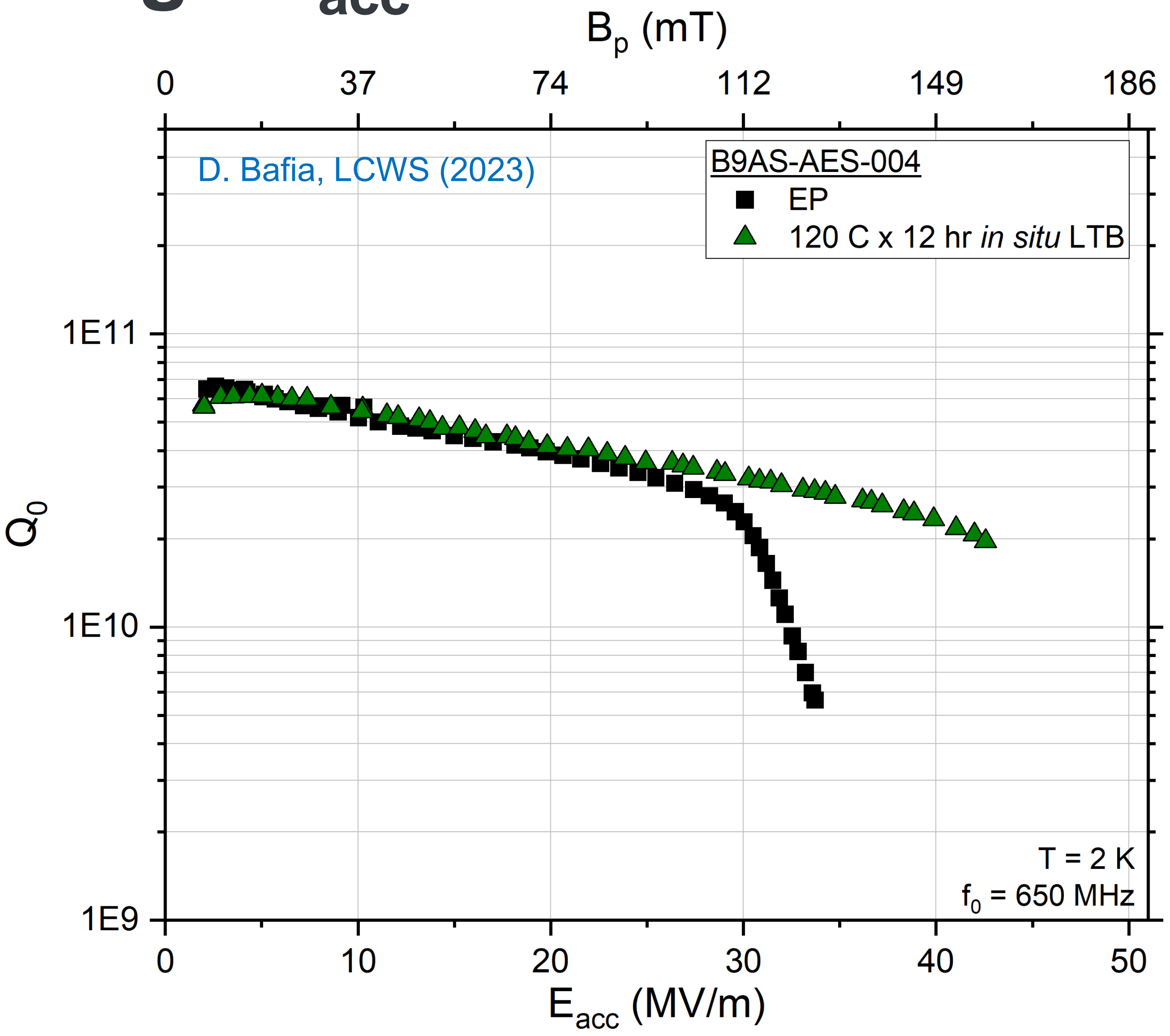
- Able to tune performance simply by diffusing oxygen via low temperature baking
- Quench peak of 44 MV/m (187 mT) when we diffuse 46 nm → Achieved via 120 C x 12 hr baking

Oxygen Also Enables High E_{acc} in 650 MHz

Do we also see B_p=187 mT in 650 MHz cavities with the same surface treatment (120 C x 12 hr)?

Cavity B9AS-AES-004

- Quench @ 158 mT



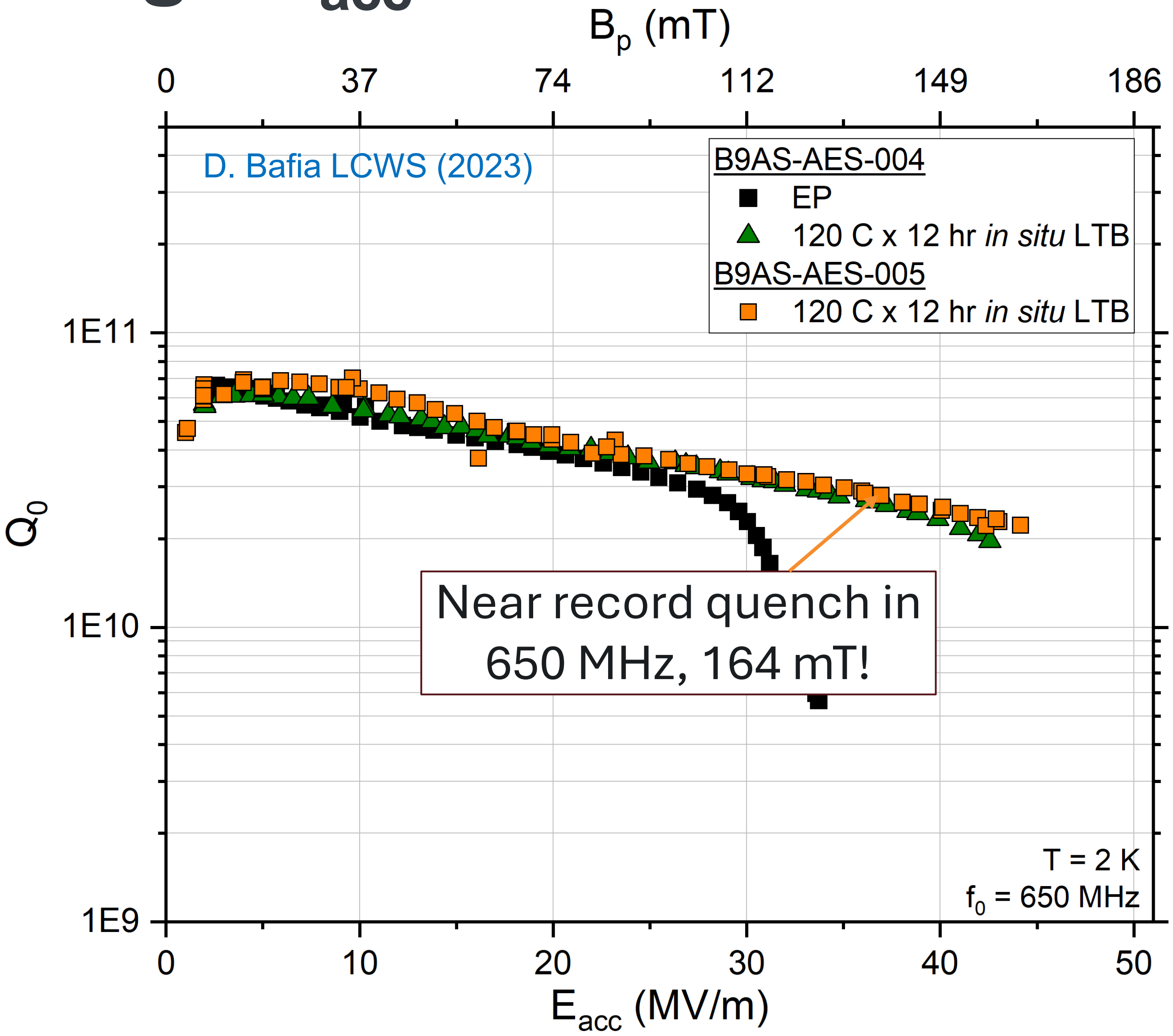
Oxygen Also Enables High E_{acc} in 650 MHz

Do we also see B_p=187 mT in 650 MHz cavities with the same surface treatment (120 C x 12 hr)?

Cavity B9AS-AES-004
- Quench @ 158 mT

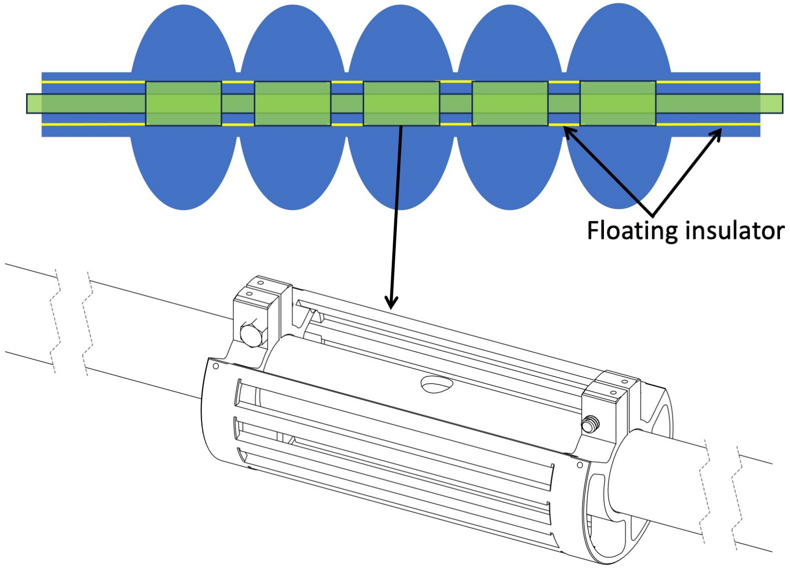
Cavity B9AS-AES-005
- Quench @ 164 mT

1.3 GHz cavity studies are applicable to lower frequencies, but still some limitation → Electropolishing



Unlocking Record-Breaking Performance in 650 MHz: Optimized Electropolishing

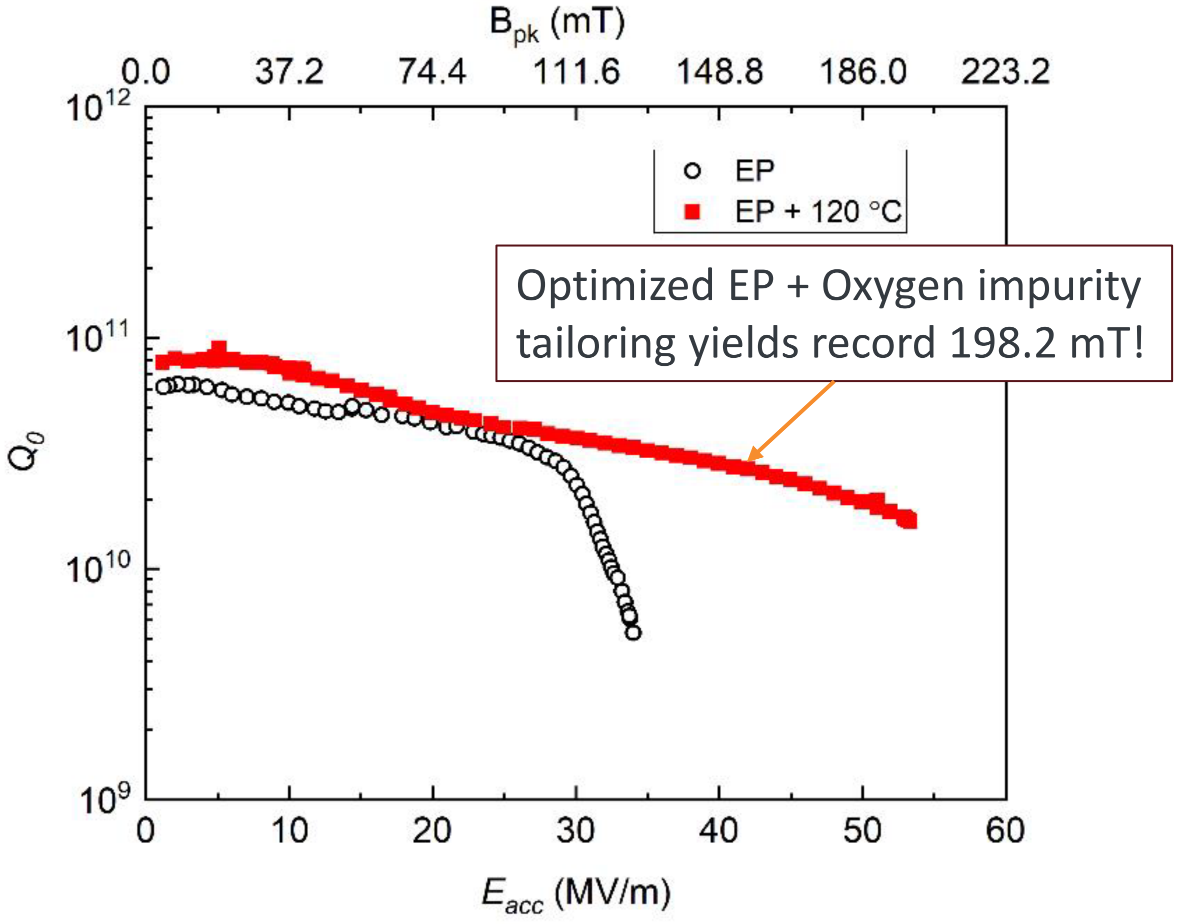
V. Chouhan *et al.*, *NIMPRA* **1051**, 168234 (2023)



Cathode-N

New, optimized cathode design for HB 650 MHz to prevent H uptake and minimize surface roughness

650 MHz Cavity Post Optimized EP and 120 C baking



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Another Promising Path Toward High Q/G: N

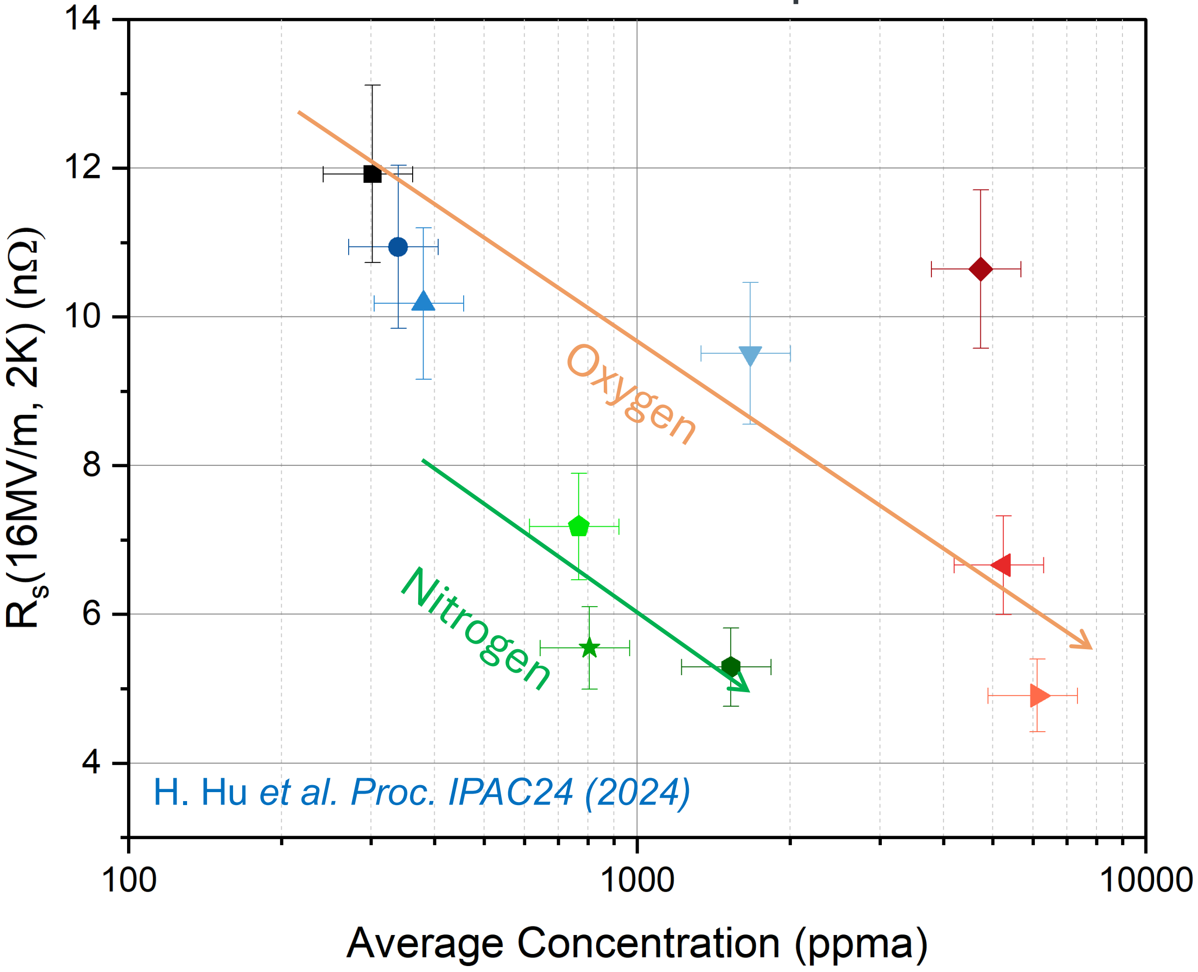
Question: Oxygen vs nitrogen-based treatments - which is better?

- Compared the performance of cavities processed with various levels of nitrogen vs oxygen impurities

$$Q_0 \propto \frac{1}{R_s}$$

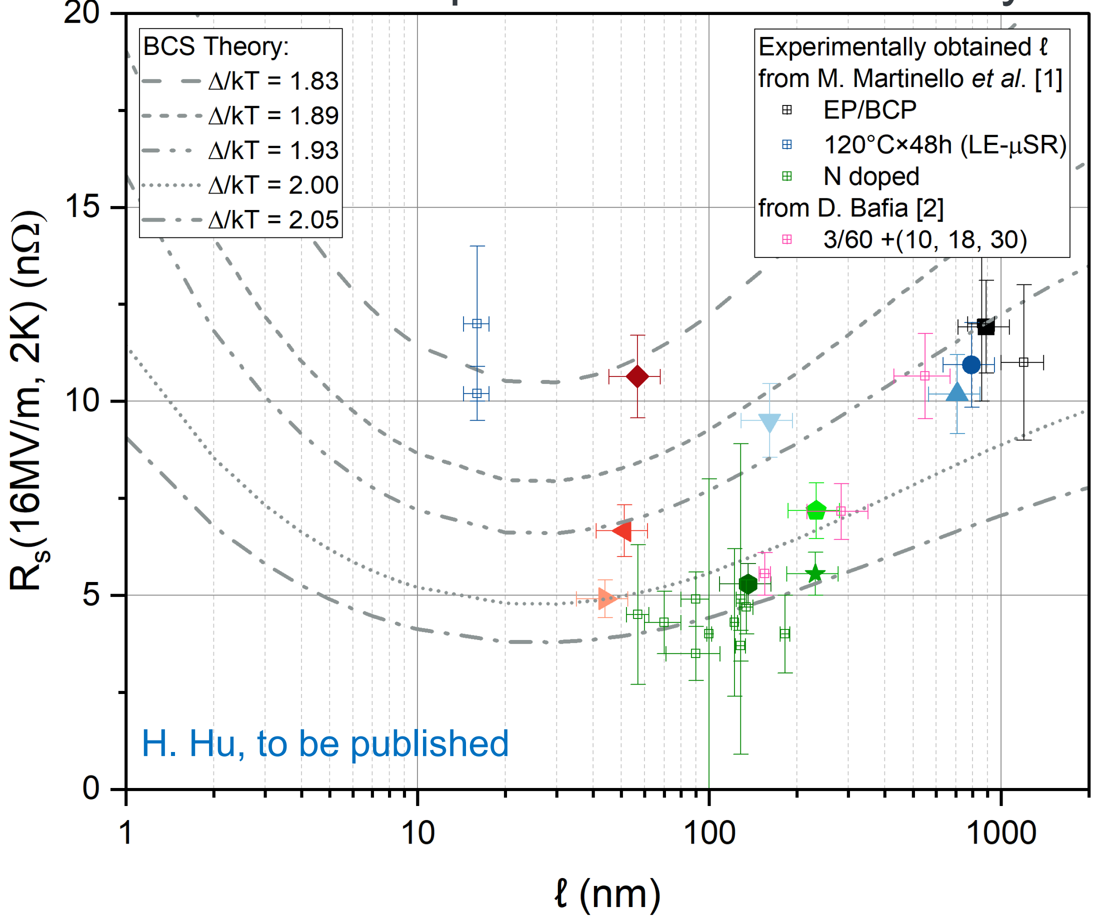
- N is ~10x more effective than O at reducing R_s!

Surface Resistance vs Average Concentration of Impurities



Model for Improved Performance: H Capture

Surface Resistance vs Mean Free Path: Comparison with BCS Theory

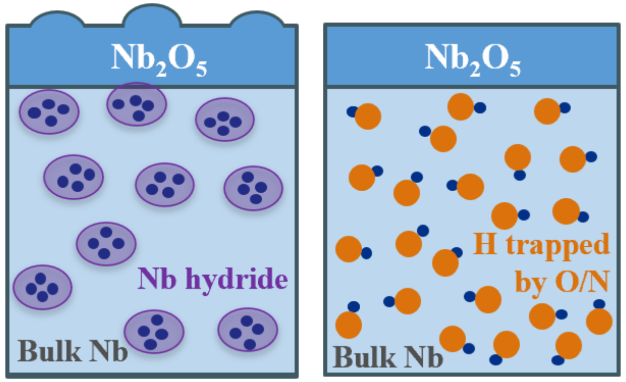


[1] D.C. Ford et al., *Supercond. Sci. Technol.* 26, 095002 (2013).

N interstitial yields a simultaneous reduction in MFP and increase in SCing gap

- Binding energy of N to H > O to H[1]

	Nb_{128}	$Nb_{128}H$	$Nb_{128}O$	$Nb_{128}N$	$Nb_{128}C$
Charge on bonded Nb (e)	-0.01/0.01	0.14	0.12/0.23	0.21/0.31	0.26/0.37
Charge on interstitial atom (e)	-	-0.65	-1.35	-1.63	-1.76
Binding energy (eV)	-	-2.41	-7.02	-7.39	-8.48
Lattice strain energy (eV)	-	0.11	0.83	0.83	0.96



N might better prevent the formation of hydrides in Nb!

Nitrogen is a promising impurity for higher Q_0/G!

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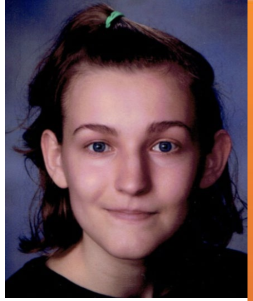
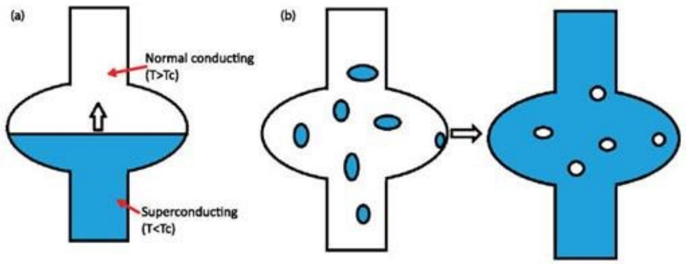
Identifying Sources of Flux Trapping in Nb Cavities

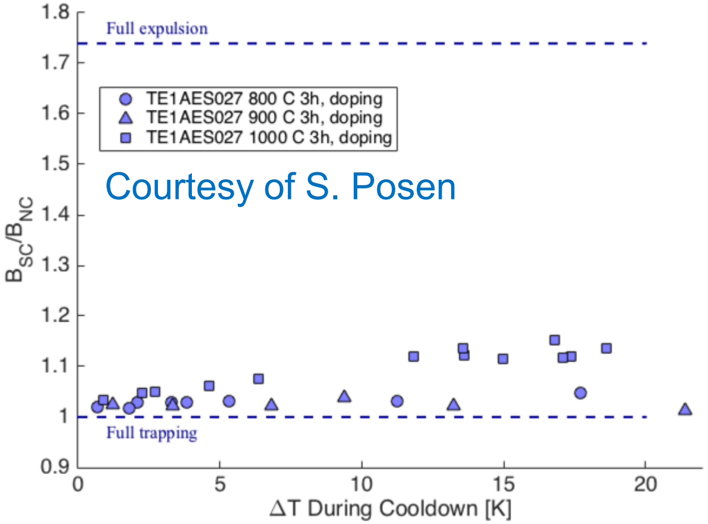


All cryomodules have some level of ambient magnetic field

- Flux can be trapped at strong pinning centers

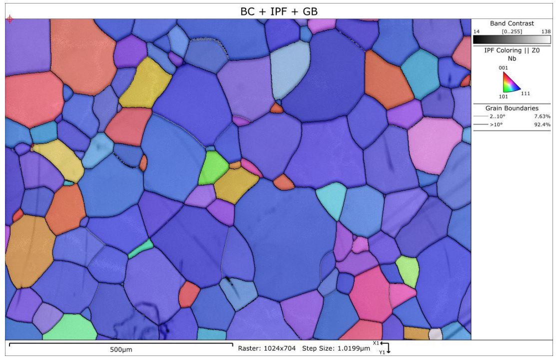


- What are these pinning centers? Can we identify a material spec for vendors to minimize them?
- Use low RRR cavities, which poorly expel flux, to identify them!

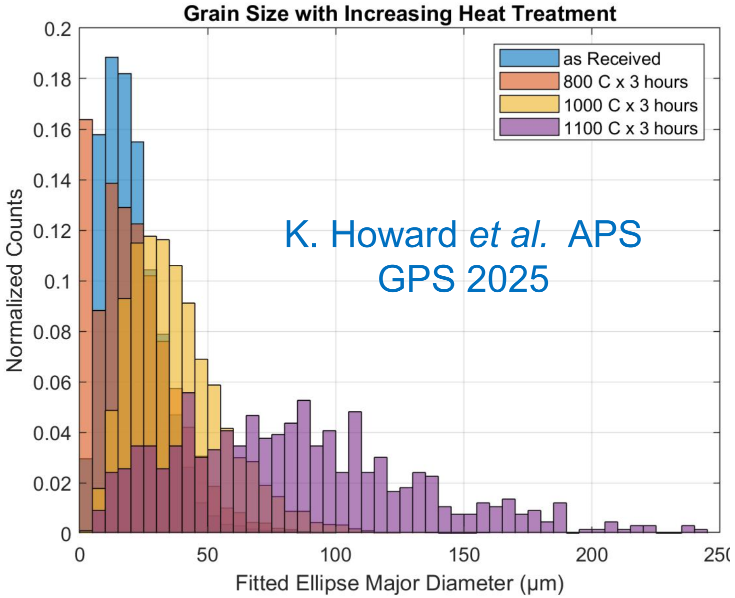


Courtesy of S. Posen

Coupling materials and RF measurements on low RRR material to identify pinning centers

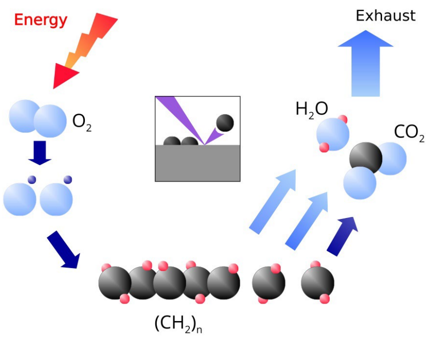


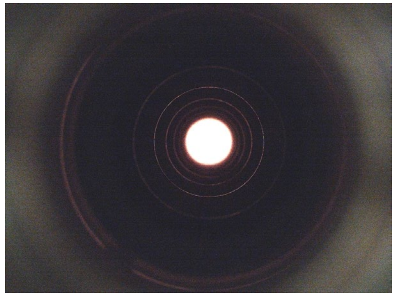
K. Howard *et al.* APS GPS 2025



K. Howard *et al.* APS GPS 2025

Plasma Processing Applied to LCLS-II-HE vCM





Vacuum cart – Downstream

RF system, computers

Plasma processing procedure for 1.3GHz CMs is fully validated

RF test after plasma processing demonstrated that:

- **vCM performance** is **preserved**
- Plasma processing did not introduce any contamination: vCM **still FE-free**

B. Giaccone, et al. PRAB **25**, 102001 (2022)

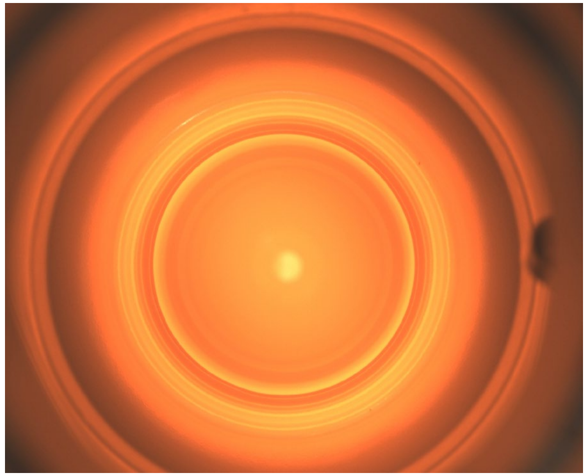
S. Posen *et al*. PRAB **25**, 042001 (2022)

Plasma processing **can also eliminate multipacting:**

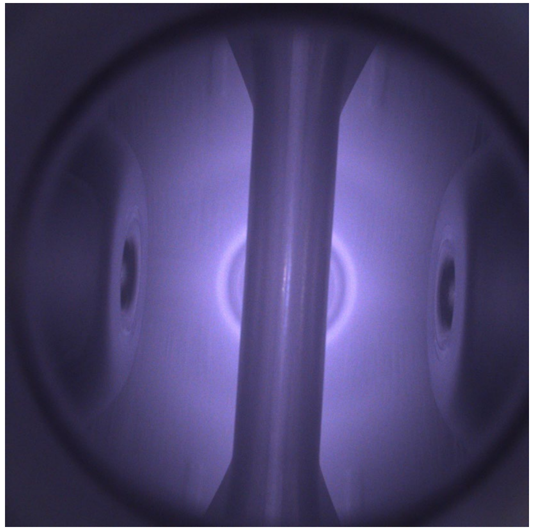
- Possible to **address both FE and MP in situ in CMs,** decreasing CM testing time, commissioning time, and increasing the reliability during machine operations.

Cavity	Multipacting Quenches		
	Before plasma		After Plasma
	1^{st} cooldown	2^{nd} cooldown	
1	/	**157**	**0**
2	135	106	205
3	41	44	53
4	**68**	**3**	**0**
5	**10**	**16**	**0**
6	46	7	69
7	68	33	82
8	**128**	**108**	**0**

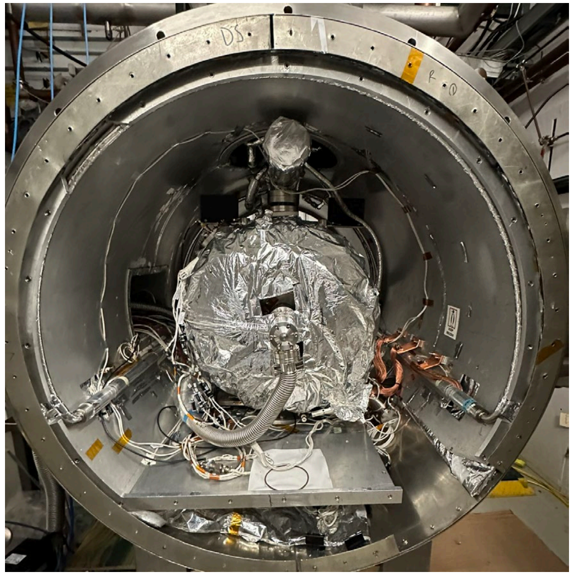
Applying Plasma Proc. to ILC and SSR Cavities

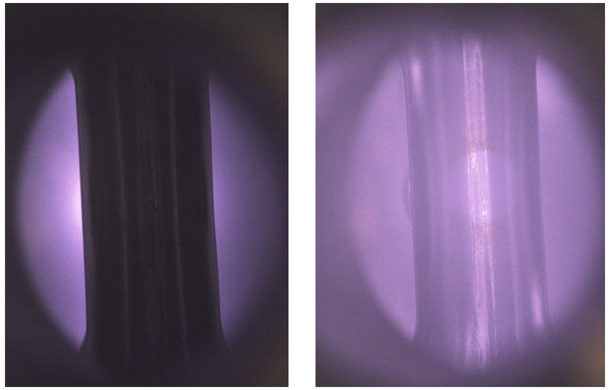


Plasma ignited in ILC cavity



Plasma ignited in SSR1 cavity





Courtesty of B. Giaccone

- Successfully demonstrated plasma processing in 1.3 GHz ILC cavities
  - Will help to preserve the ambitiously high gradients
- Developing plasma processing for PIP-II cavities:
  - Single Spoke Resonators Type 1 (SSR1): developed initial recipe at Fermilab, collaborating with IJCLab for further development and demonstration on cavity.
  - SSR2: Developed initial recipe and conducted first test of application of plasma processing on SSR2 preproduction cavity assembled in cryostat, showing promising results.
  - LB 650: Fermilab, INFN LASA and CEA-Saclay started preliminary work to investigate PP feasibility.

Conclusion

By correlating RF performance with materials science, we have gained microscopic insights into Nb SRF cavity loss mechanisms, enabling targeted mitigation strategies to optimize performance

- Demonstrated gradients of > 50 MV/m in both 1.3 GHz and 650 MHz cavities
- Ability to tune performance for high Q_0 or high G simply by diffusing oxygen via in situ baking
- Identified nitrogen as a potential impurity for simultaneously high Q_0 and high G
- New optimized EP setup and enhanced understanding
- Adapting plasma processing to various cavity geometries
- Advancements in Nb_3Sn technology (not covered in this talk)

We are prepared to apply these findings (and more) to [insert SRF accelerator of choice here]!!

Thank you!