High Gradient and Q-factor SRF Performance at 1.3 GHz and 650 MHz

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IMCC’23

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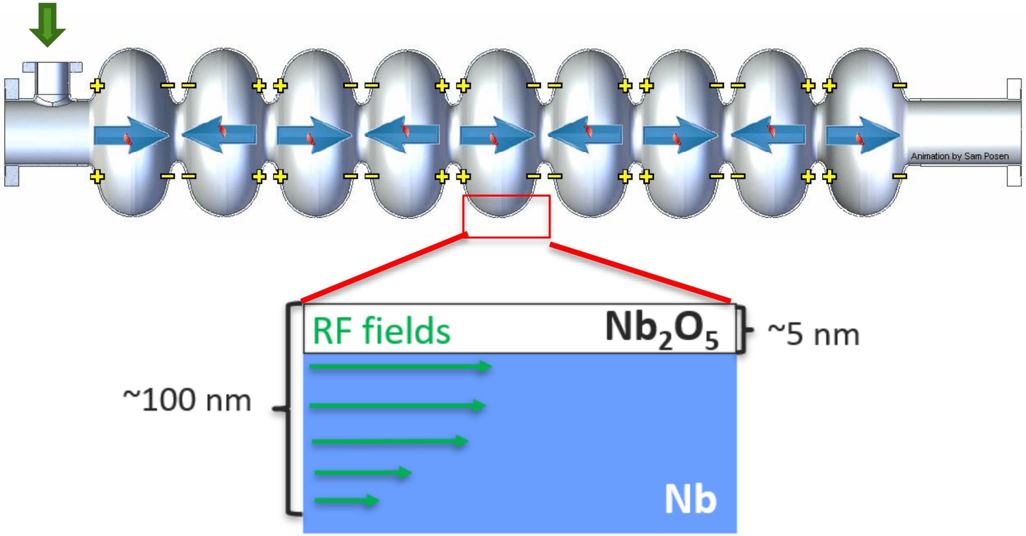
Introduction to Bulk Nb SRF Cavities

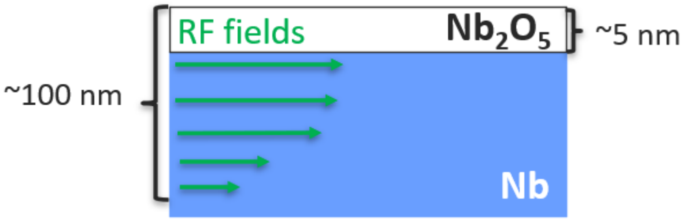
- Nb SRF cavities: most efficient engineered EM resonators ever created
- Mature, proven technology
  - LCLS-II + HE
  - EXFEL

RF power injected at resonant frequency



Performance governed by microscopic properties within the first ~100 nm from inner surface

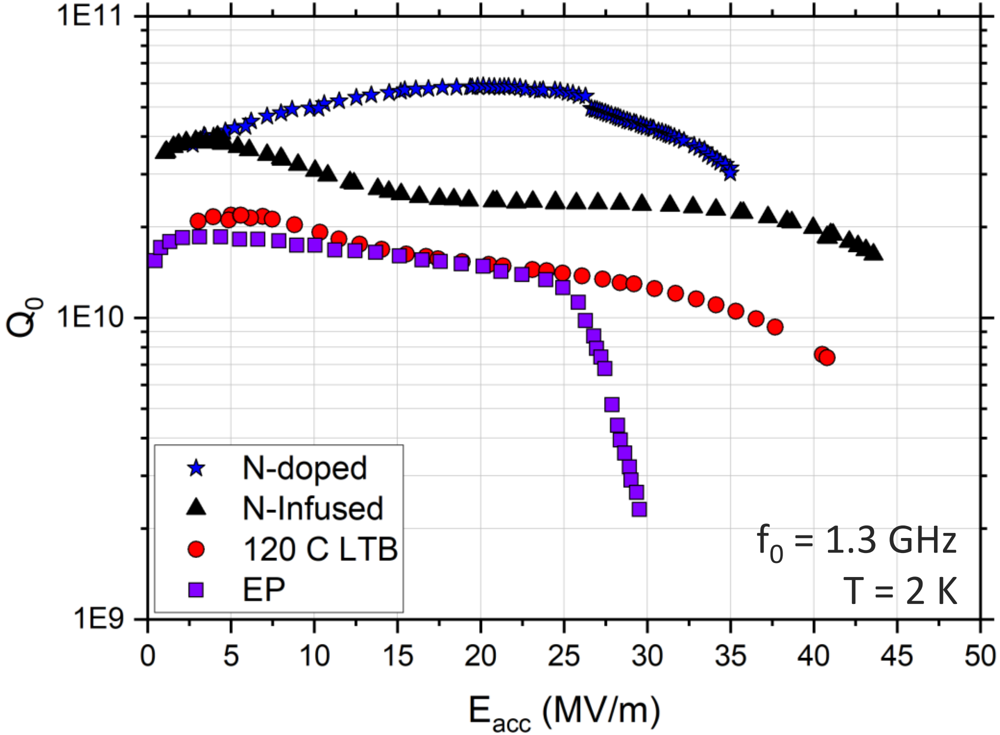
Surface Engineering of Nb SRF Cavities



Goal of SRF research: tailor surface properties *via* chemical and baking treatments to yield high Q_0 and E_{acc}

– Higher Q → lower cryogenic costs
– Higher gradient → less $$$ OR higher energy

Nb SRF Cavities Post State-of the-Art Surface Treatments

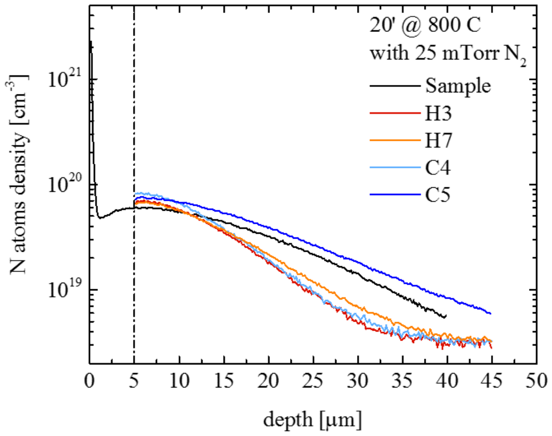


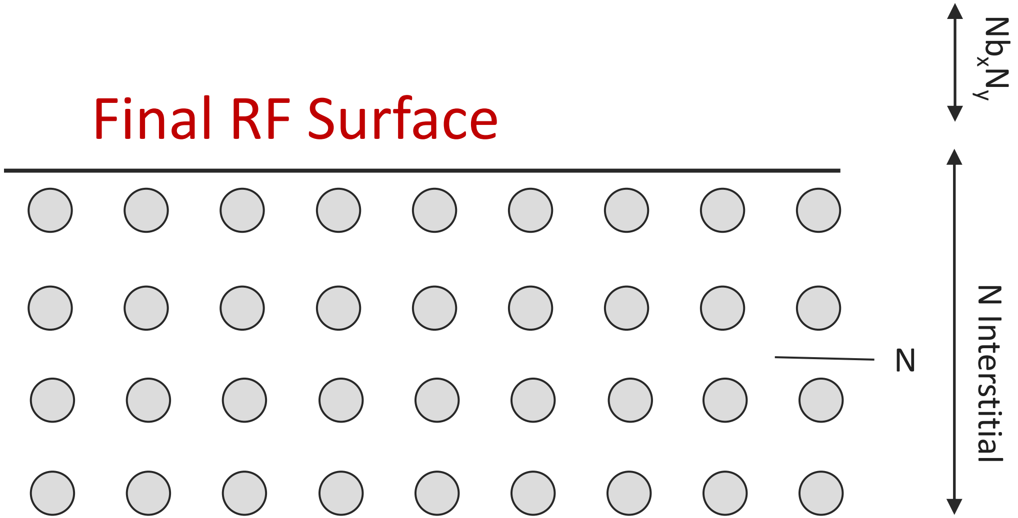
“2/6” Nitrogen-Doping Treatment

800C UHV, 3 hours → 800C N_2 p = 25 mTorr 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

Instead of N, recently learned that we can use O!

Depth profile of Nitrogen impurities





Slide adapted from M. Martinello

Outline

- Introduction to SRF
- Fundamental R&D Toward Improving Bulk Nb SRF Cavity Performance
  - Key Materials Science findings
  - Optimizing 1.3 GHz cavity performance
  - Applying findings to 650 MHz cavities
  - Optimizing EP for 650 MHz
- Key Technological Advancements Towards High Gradients
  - +50 MV/m recipe: cold EP + 2-step low-temp bake
  - Extending gradients further with the traveling wave design
  - Plasma processing
- Conclusions

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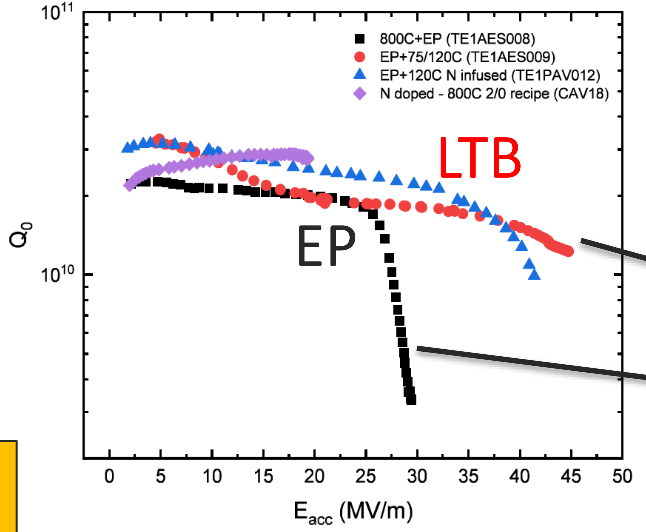
Coupling RF and Material Studies to Improve SRF Cavities

- Material science is critical to understand sources of improved SRF cavity performance
- Identified O as a key impurity in enabling high gradients and Q in cavities

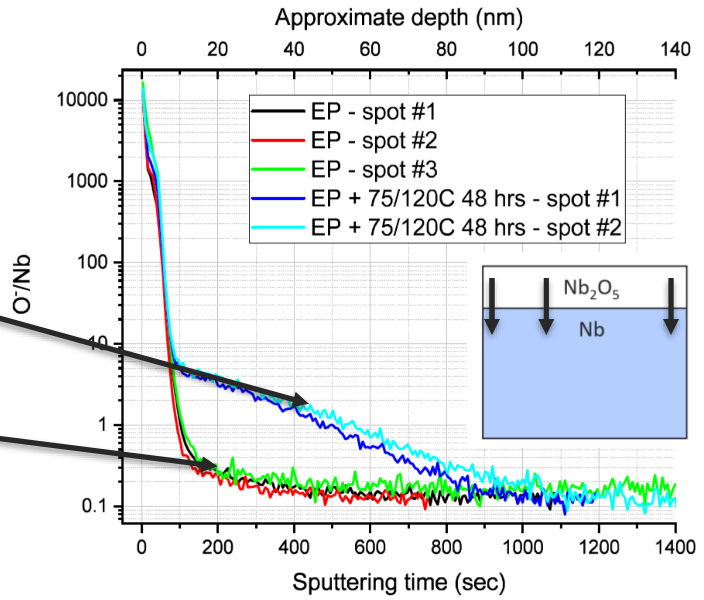
Can we tune cavity performance by tailoring O impurity profile?

RF Data on Variously Processed Cavities to be Cut



A. Romanenko *et al.*, SRF'19, THP014

TOF-SIMS Data on Cavity Cutouts



A. Romanenko, TTC'2020, CERN

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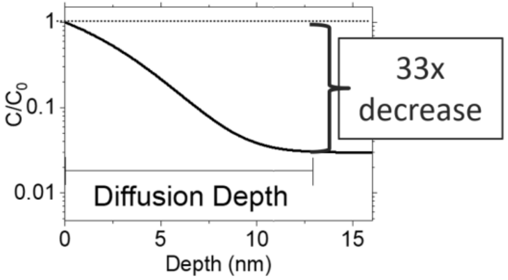
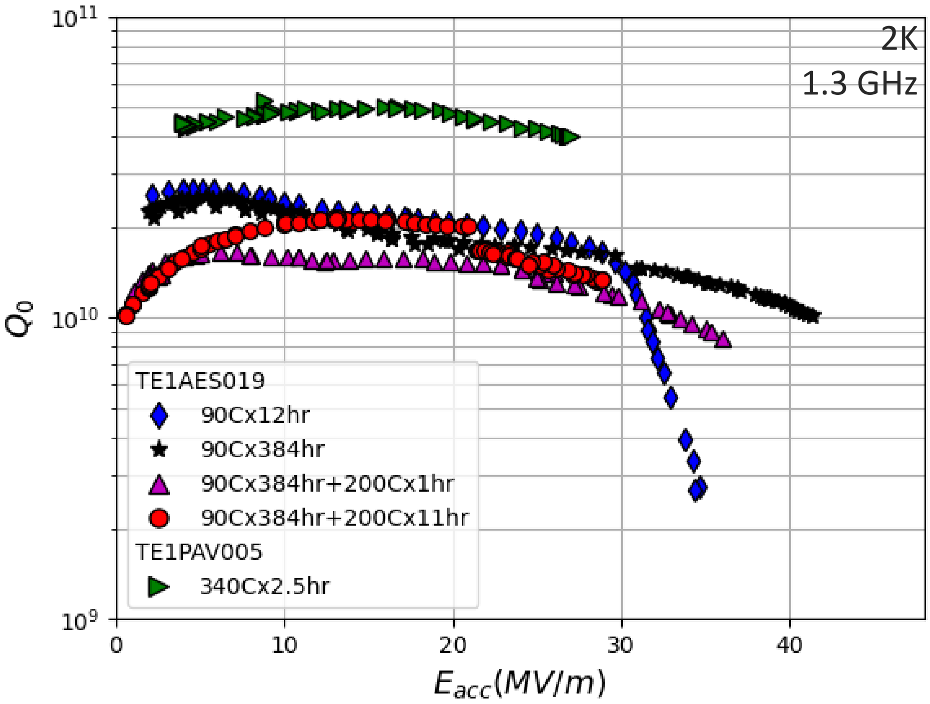
Tuning Cavity Performance with Oxygen Impurities

- Single cavity subjected to sequential baking and RF testing to study the evolution of cavity performance
- O diffusion: ability to tune between high Q_0 or high gradient!

One key parameter:



Q vs E Evolution with Increasing O Diffusion



D. Bafia et al, Proceedings of SRF'2021, THPTEV016

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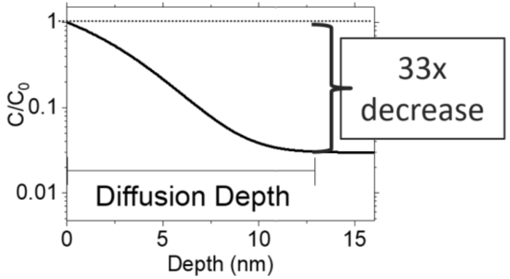
Optimizing Cavity Q_0 By Tailoring O Impurity Profile

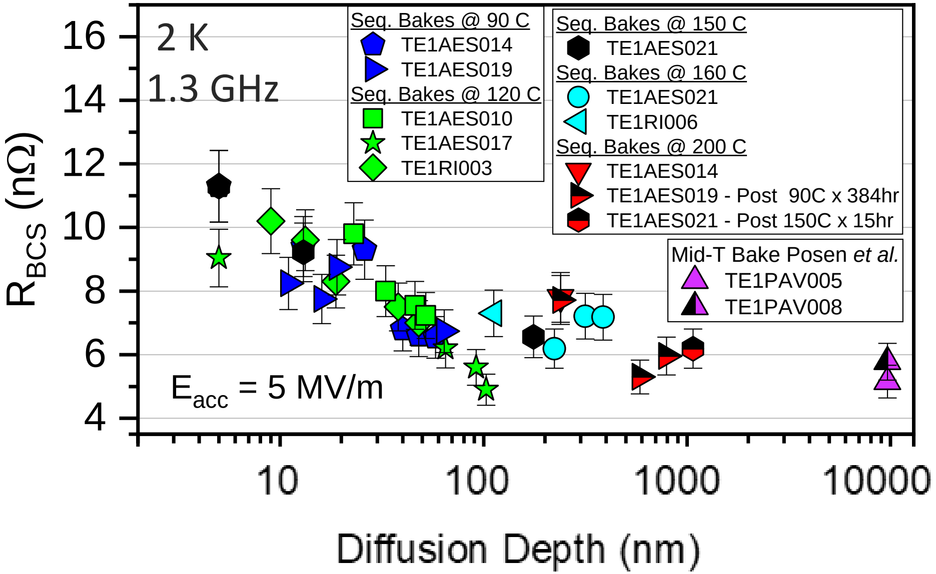


- Maximizing Q_0 requires minimizing R_{BCS}

$$Q_0 \propto \frac{1}{R_{BCS} + R_0}$$

- Gradually introduced more oxygen into the RF surface of cavities and tracked R_{BCS} evolution
  - 100+ cavity RF tests

D. Bafia, TTC'22



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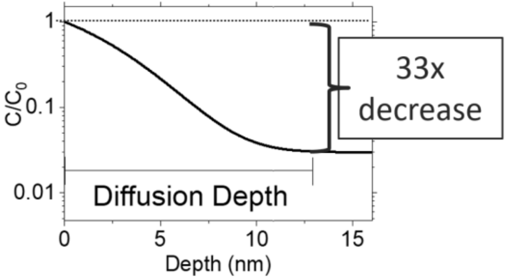
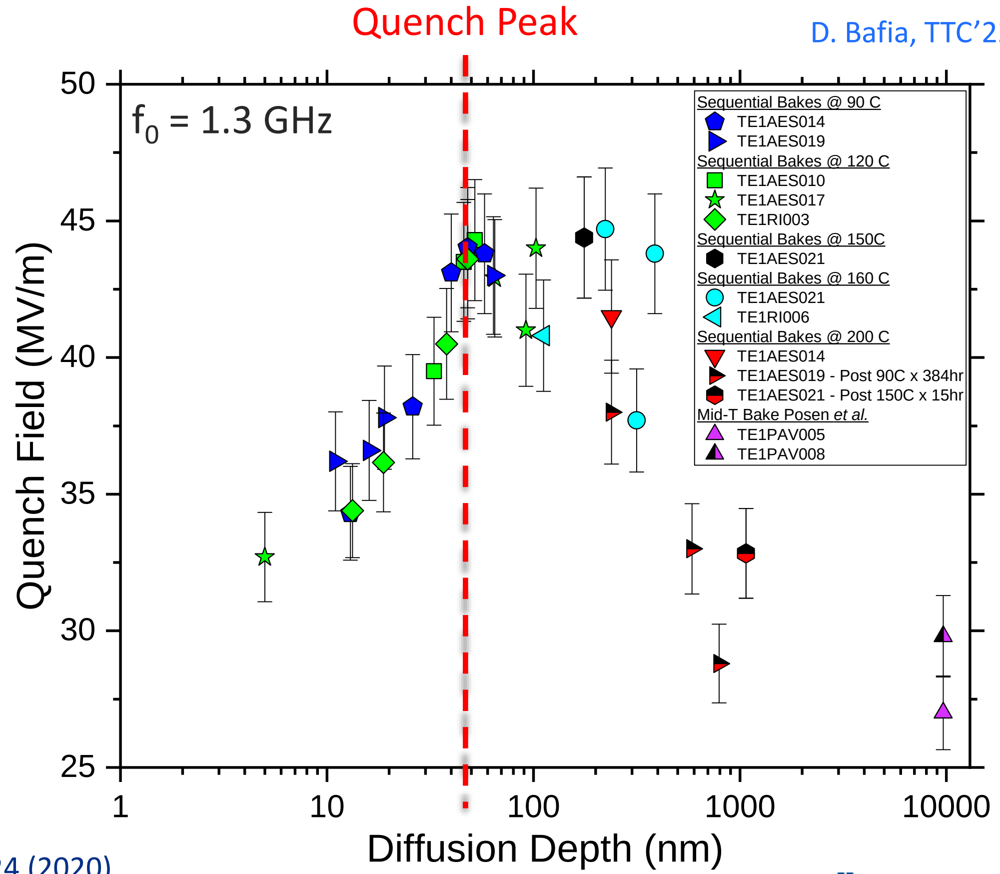
Optimizing Cavity Gradient by Tailoring O Impurity Profile

D. Bafia, TTC'22





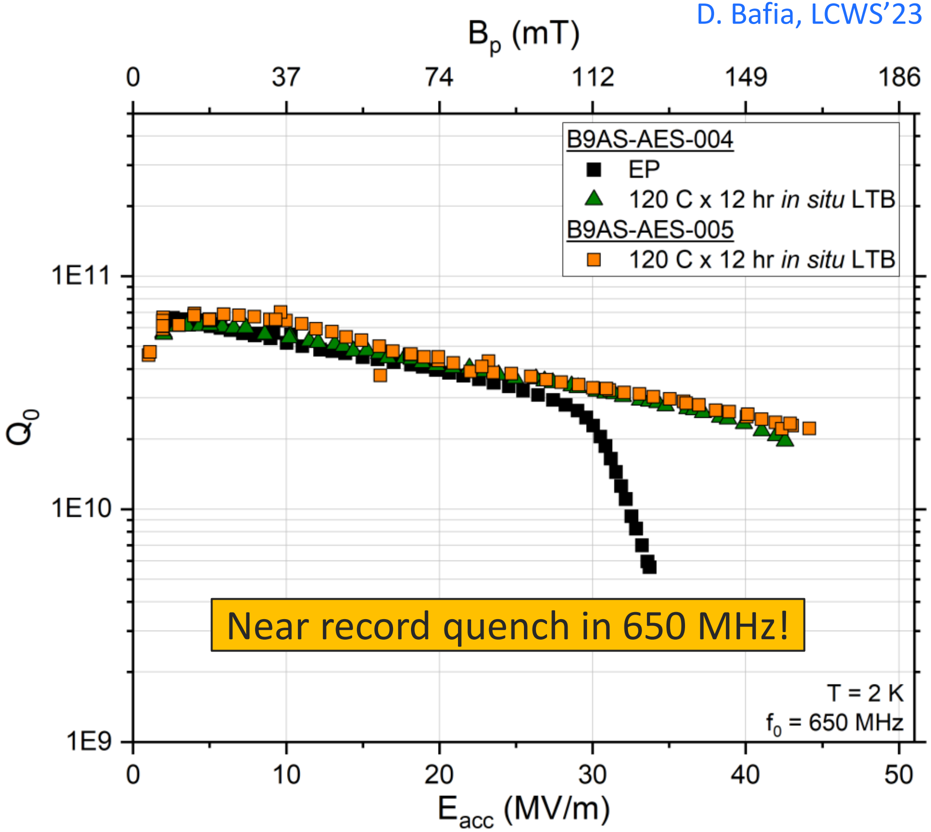
- Gradually introduced more oxygen into the RF surface of cavities and tracked quench
- Found a peak in quench field when oxygen diffuses 46 nm!

Mid-T Bake data comes from S. Posen *et al.*, PRA **13**, 014024 (2020)

Application of Quench Peak Findings to 650 MHz Cavities

- Subjected a 650 MHz cavity to a surface treatment which introduced O to a depth of 46 nm
- From 1.3 GHz studies expect high quench field:
  - We achieved get 44 MV/m!
- Quench optimization studies on 1.3 GHz are applicable to 650 MHz
- Non-optimal electropolishing likely limiting performance

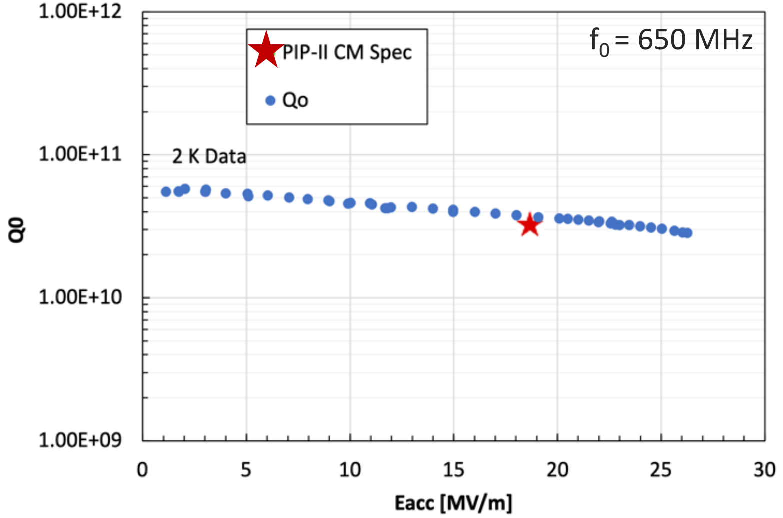
D. Bafia, LCWS'23

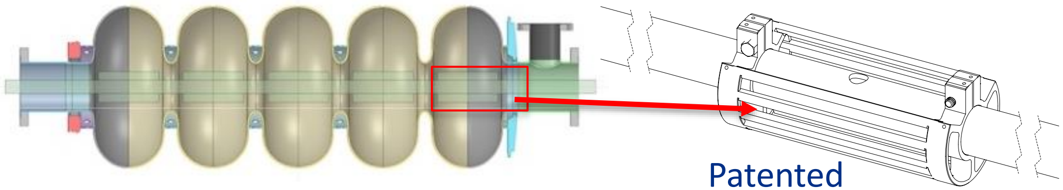


Improving 650 MHz Performance Further *via* Optimized EP

V. Chouhan, to be presented at SRF'23

- Proper electropolishing (EP) is critical in enabling excellent cavity performance
  - Smooth surface, minimal uptake of H
- Developed a novel cathode and optimal EP parameters for 5-cell 650 MHz cavities for PIP-II





Optimized design and parameters yields unprecedented performance in high-β 650 MHz EP'd cavities!

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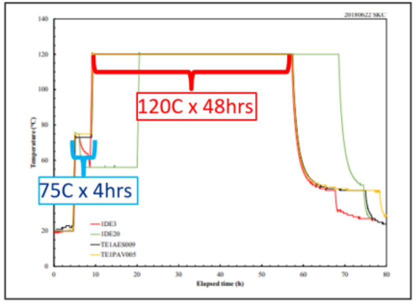
New Cold EP + 2-Step Low-Temp Bake Enabling 50 MV/m

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

Cold EP +



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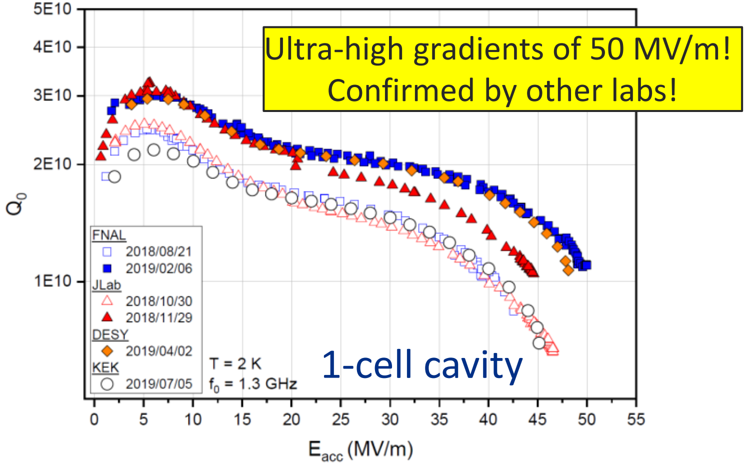
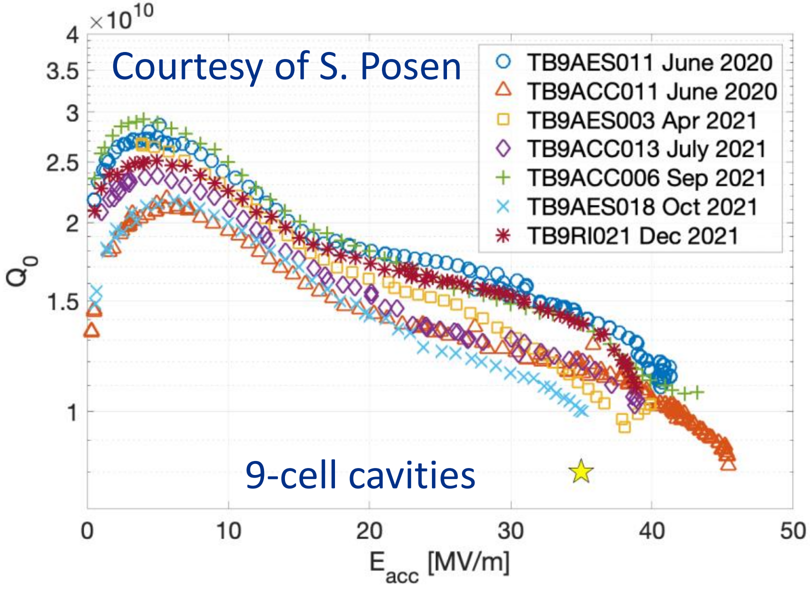


Transferred recipe to 9-cell cavities as part of ILC Cost Reduction effort

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



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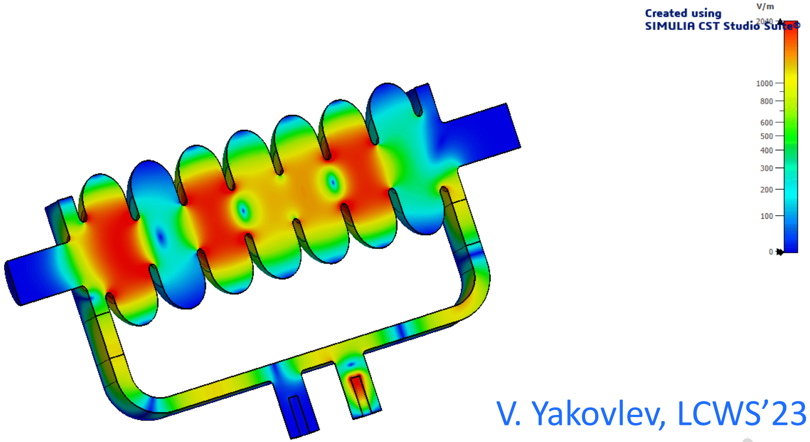
Extending Gradients Further with the Traveling Wave Design

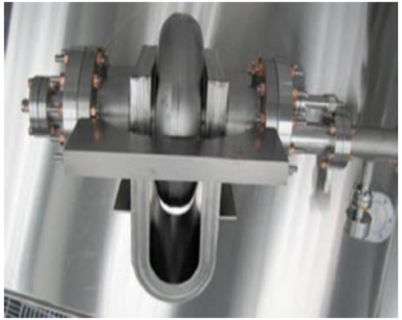
- Standing wave Nb cavities limited E_{acc} by H_{sh}
- Alternative: Niobium traveling wave structure
  - RF power returned *via* feedback Nb waveguide → Lowers peak fields in cavity
  - Possible to achieve E_{acc} > 70 MV/m!!

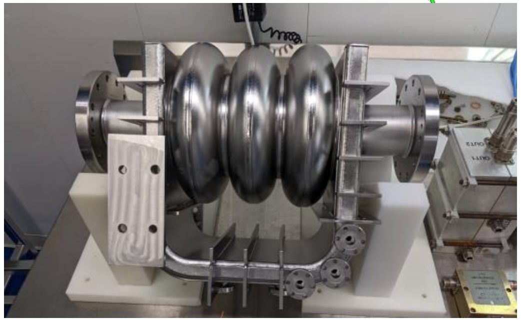


V. Yakovlev, LCWS'23

Current Status:

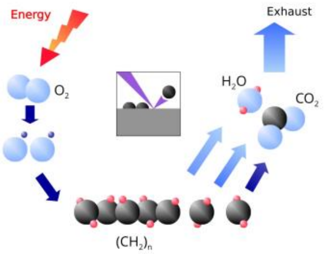
- 1-cell: designed, treated (BCP), and tested
  - Achieved 26 MV/m in RF testing
- 3-cell: designed and treated (BCP)
  - Tuning just completed
  - RF testing scheduled for this summer
  - TW operation demonstrated at room temp!
- 0.5 m structure currently being designed in collaboration w/ Cornell

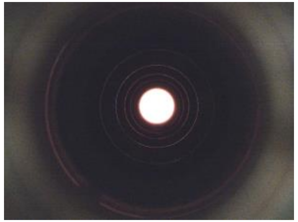




*Euclid Techlabs DOE SBIR DE-FG02-06ER84462 and DE-SC0006300.

Plasma Processing Applied to LCLS-II-HE vCM





B. Giaccone, et al. arXiv:2201.09776 (2022)
S. Posen *et al.* PRAB **25**, 042001 (2022)

RF test after plasma processing demonstrated that:

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

Plasma processing procedure for 1.3GHz CMs is fully validated

Plasma processing **can also eliminate multipacting:**

- Possible to **address both FE and MP in situ in CMs** → decreased CM testing and commissioning time, increased reliability during machine operation

Cavity	Multipacting Quenches		
	Before plasma		After Plasma
	1st cooldown	2nd 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**

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Conclusions & Future Directions

- Bulk Nb SRF cavities are a mature, ready-to-go technology for use in a muon collider

Recent advancements in R&D push the limits of cavity performance

- Impurity tailoring enables tuning cavity performance for high gradient or high Q
- Electropolishing optimization shown to extend gradient reach
- Cold EP + 2-step baking yields gradients above 50 MV/m
- Initial traveling wave cavity demonstrate promising results, opening the door to > 70 MV/m
- Plasma processing enables *in situ* mitigation of FE and MPing in CMs

Thank you for your attention!