Potential performance of N-doping and Nb_3Sn for FCC

Sam Posen
FCC Week
30 May 2017

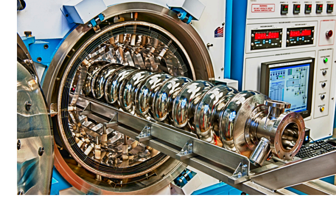
Fermilab/CERN Collaboration

- **Study N-doping and Nb_3Sn in frequency range appropriate for FCC**
- New high Q_0 technologies were harnessed to reduce cryopower requirements for LCLS-II

	FCC-ee ttbar	LCLS-II
# of cavities	>650	384
Duty factor	100%	100%
RF voltage	11 GeV	4 GeV

- Nb_3Sn cavities are under study and show great promise for high Q_0 operation at 4.4 K
- What are the potential of these technologies for FCC?

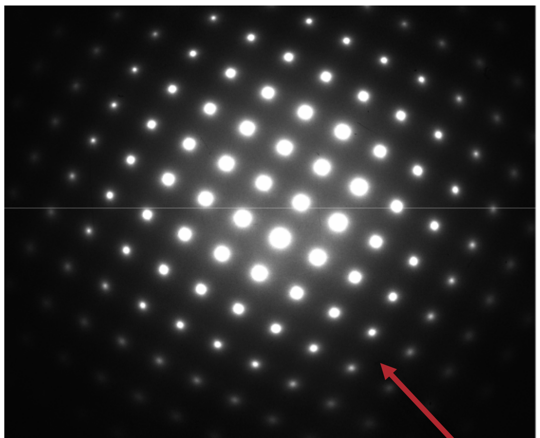
1. Nitrogen Doping and Minimizing Trapped Flux Losses

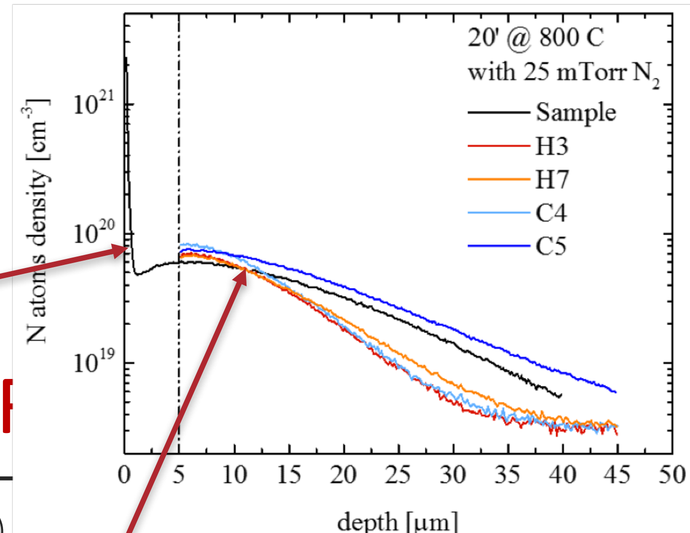


N-doping treatment – “2/6” recipe

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

Y. Trenikhina et Al, Proc. of SRF 2015





Nb

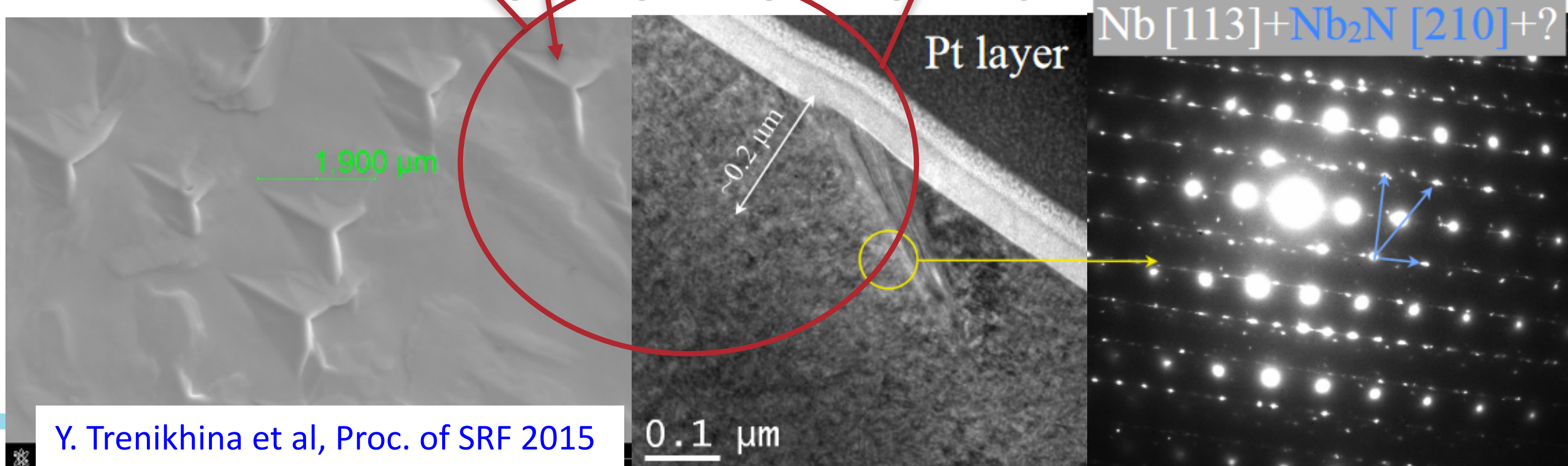
Final RF

N_2

Nb_xN_y

N Interstitial

N

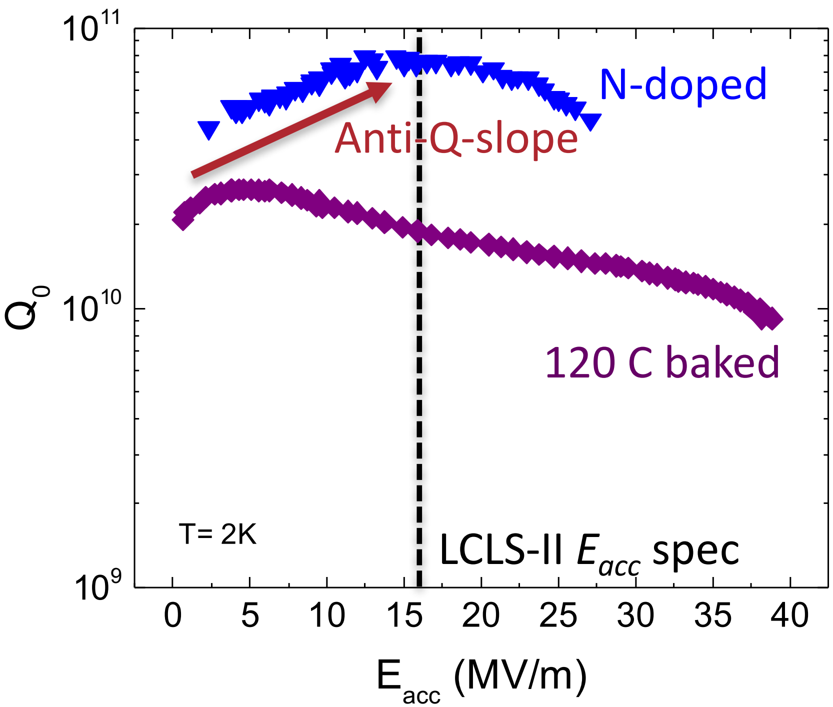


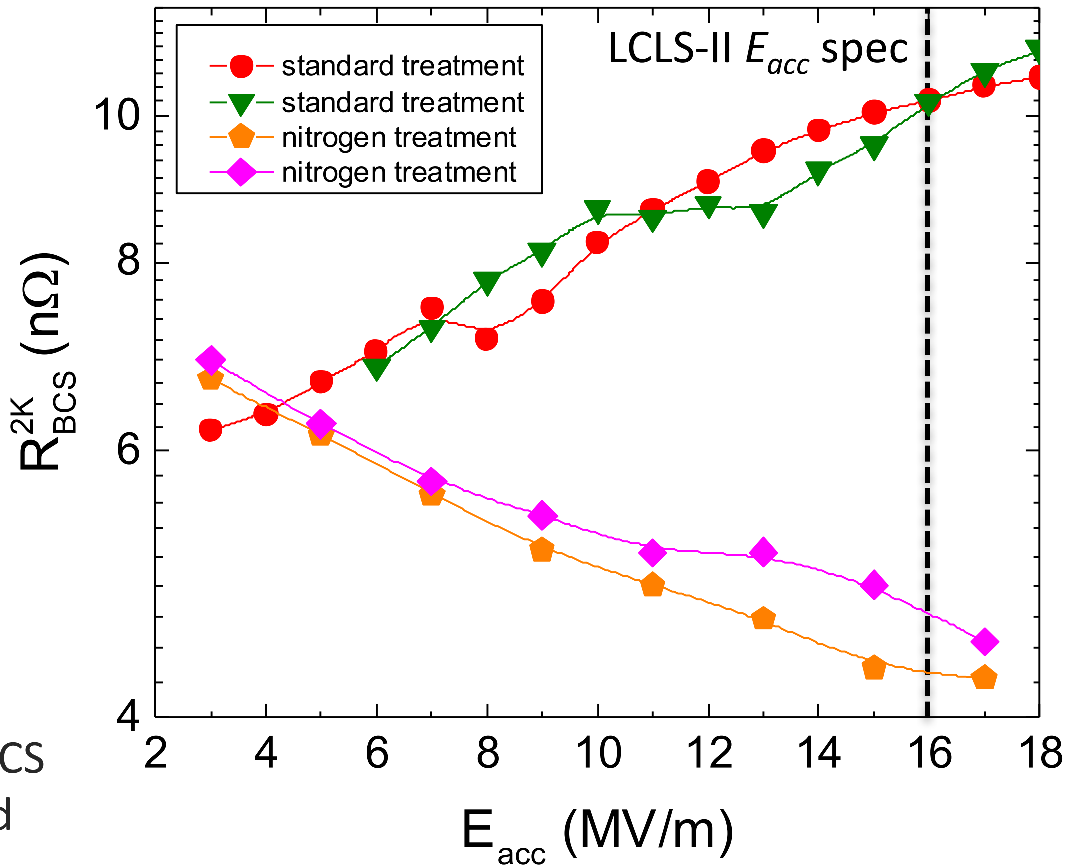
Y. Trenikhina et al, Proc. of SRF 2015

Slides adapted from M. Martinello

Fermilab

Reduction in BCS Resistance





Anti-Q-slope emerges from the BCS surface resistance decreasing with field

- >2x R_{BCS} improvement at 2 K, 16 MV/m
- Reduced quench field for "2/6" recipe, but generally >20 MV/m

A. Grassellino et al, 2013 Supercond. Sci. Technol. 26 102001 (Rapid Communication)
A. Romanenko and A. Grassellino, Appl. Phys. Lett. 102, 252603 (2013)

"Doping" and "Infusion"

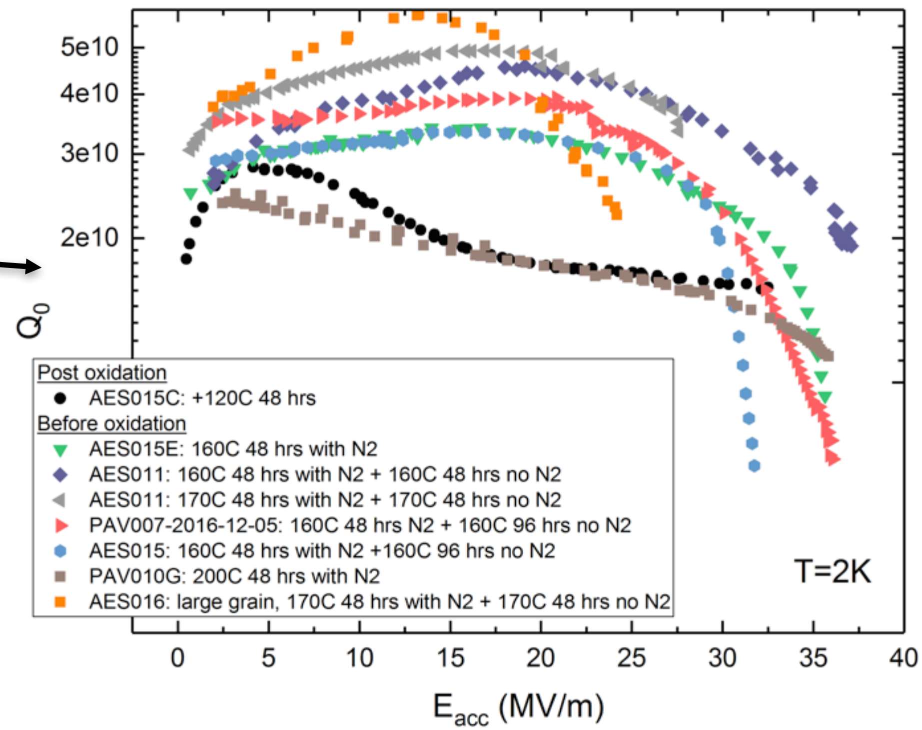
"2/6" Nitrogen "Doping"

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

120 C Nitrogen "Infusion"

800C UHV, 3 hours → 120C N_2 p = 25 mTorr 48 hours → UHV cooling

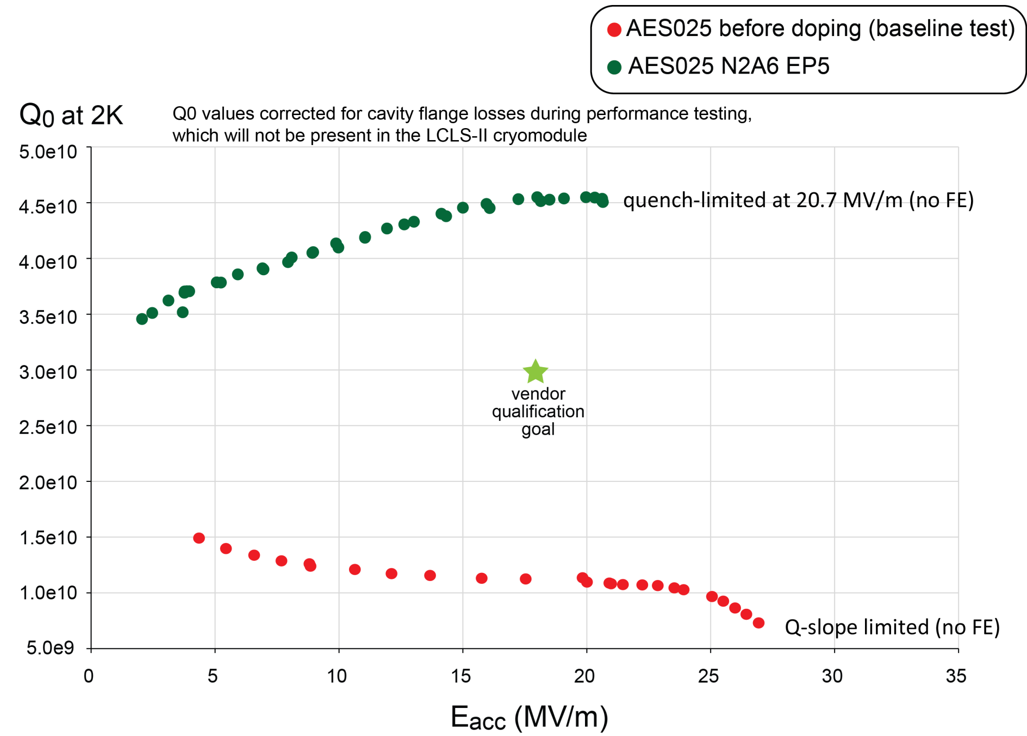
Can tailor treatment to application (optimize for Q_0 at a given E_{acc})



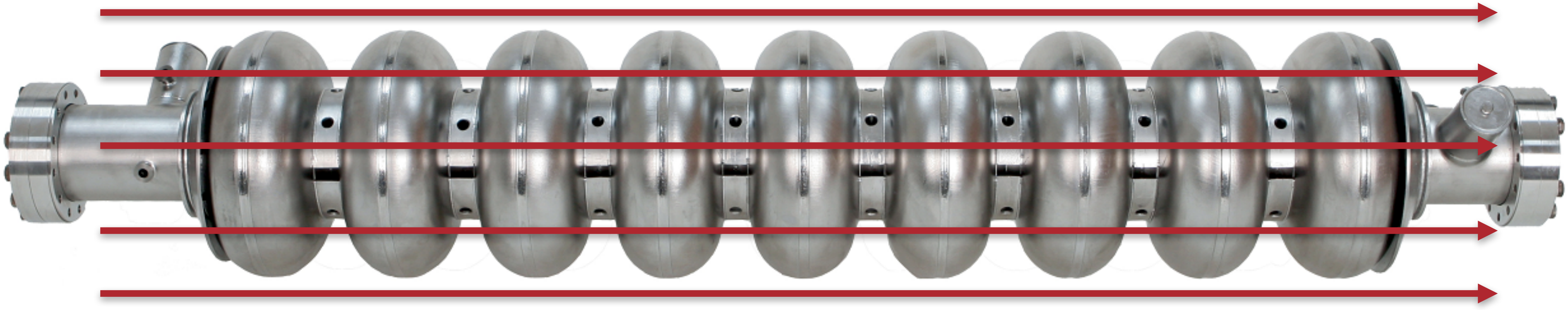
A. Grasselllino et al.
arXiv:1701.06077

Mature Technology – Transferred to Industry

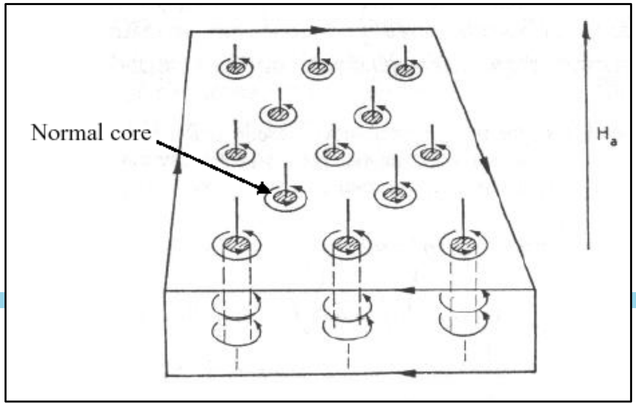
- SRF cavity vendors: from niobium material to N-doped cavities ready for qualification testing

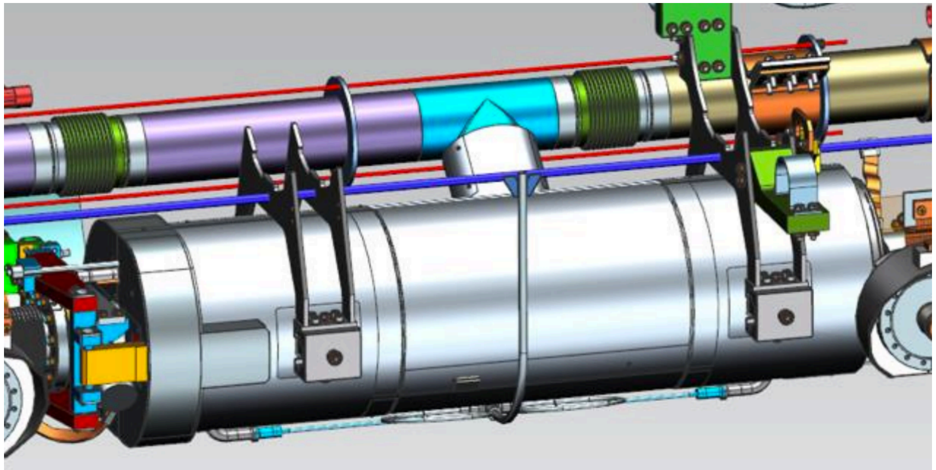


Effect of Trapped Magnetic Flux on Residual Resistance



- Sensitivity to trapped flux
  - 120 C ~0.3 nΩ/mG
  - N-doping ~1.0 nΩ/mG
- Minimizing trapped flux is crucial



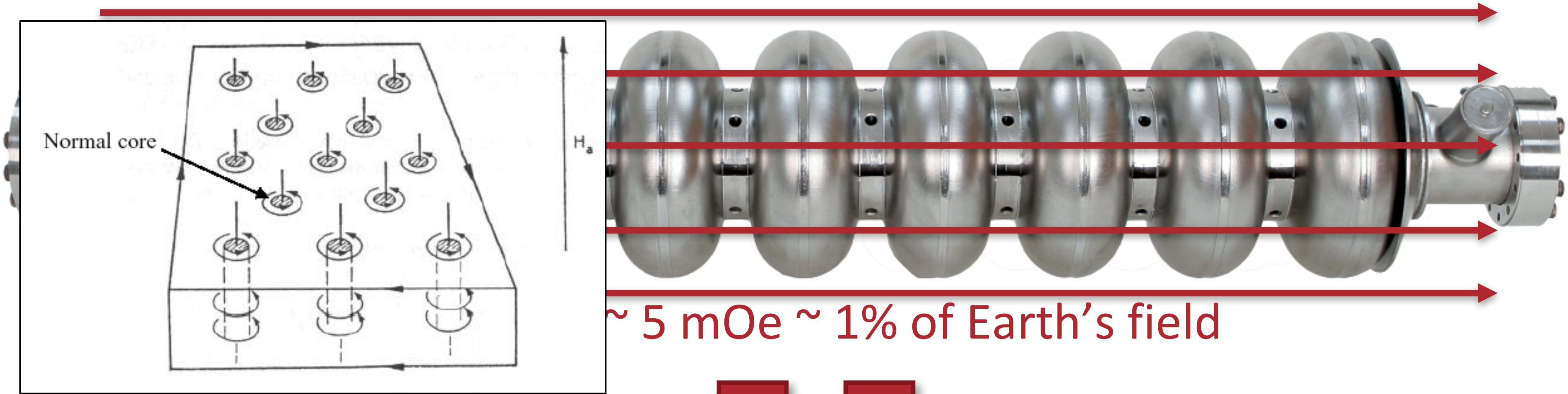


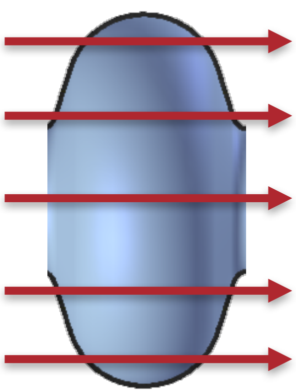
$H_{shielded}$ ~ 5 mOe ~ 1% of Earth's field

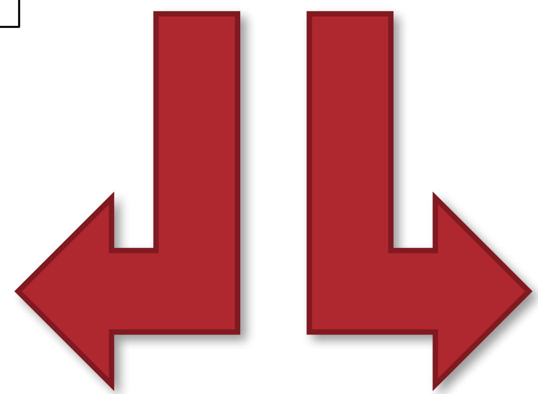
Flux image from Rose-Innes and Roderick, Introduction to Superconductivity

See G. Wu, SRF2015

Magnetic Flux Expulsion

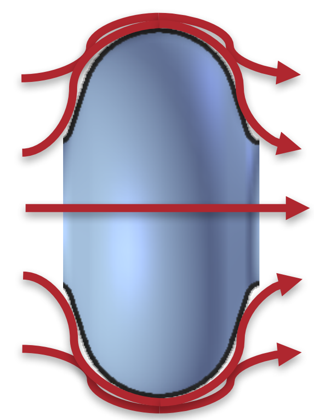






Trapped flux increases R_{res}

Closer to intrinsic R_{res}



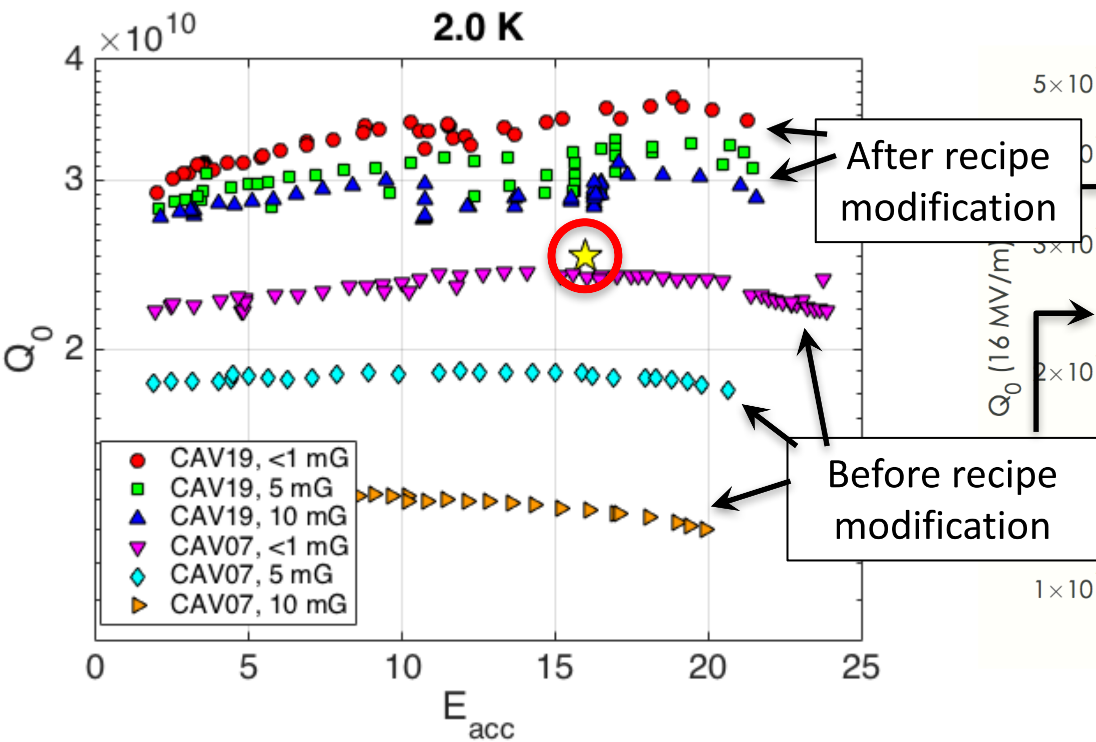
Magnetic Flux Trapping

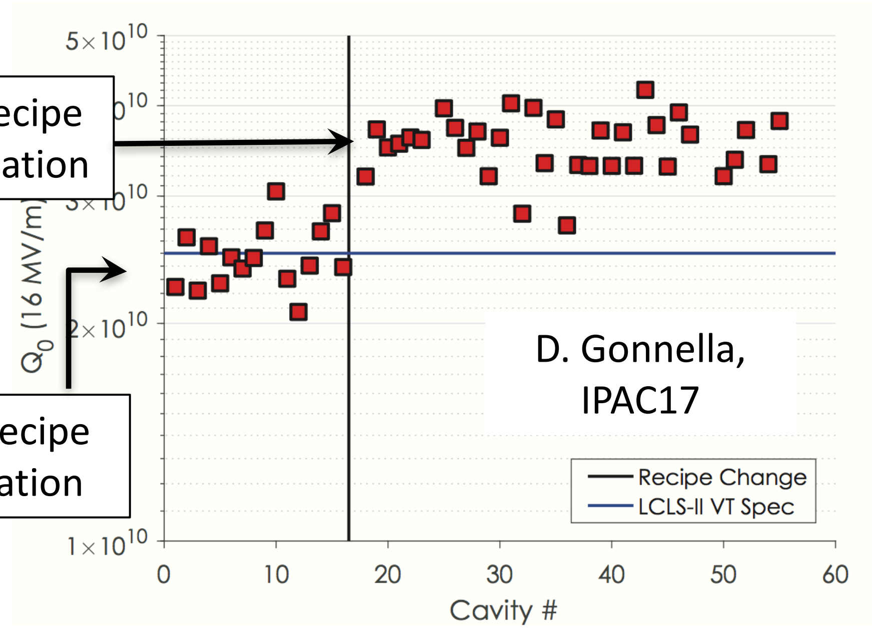
Magnetic Flux Expulsion

Flux image from Rose-Innes and Roderick, Introduction to Superconductivity

LCLS-II – Recipe Change to Promote Expulsion

- After seeing results of first batch of 16 cavities, planned for modifications for next batch
- Modified recipe – 900 C now standard
- Significant Q0 improvement following modification



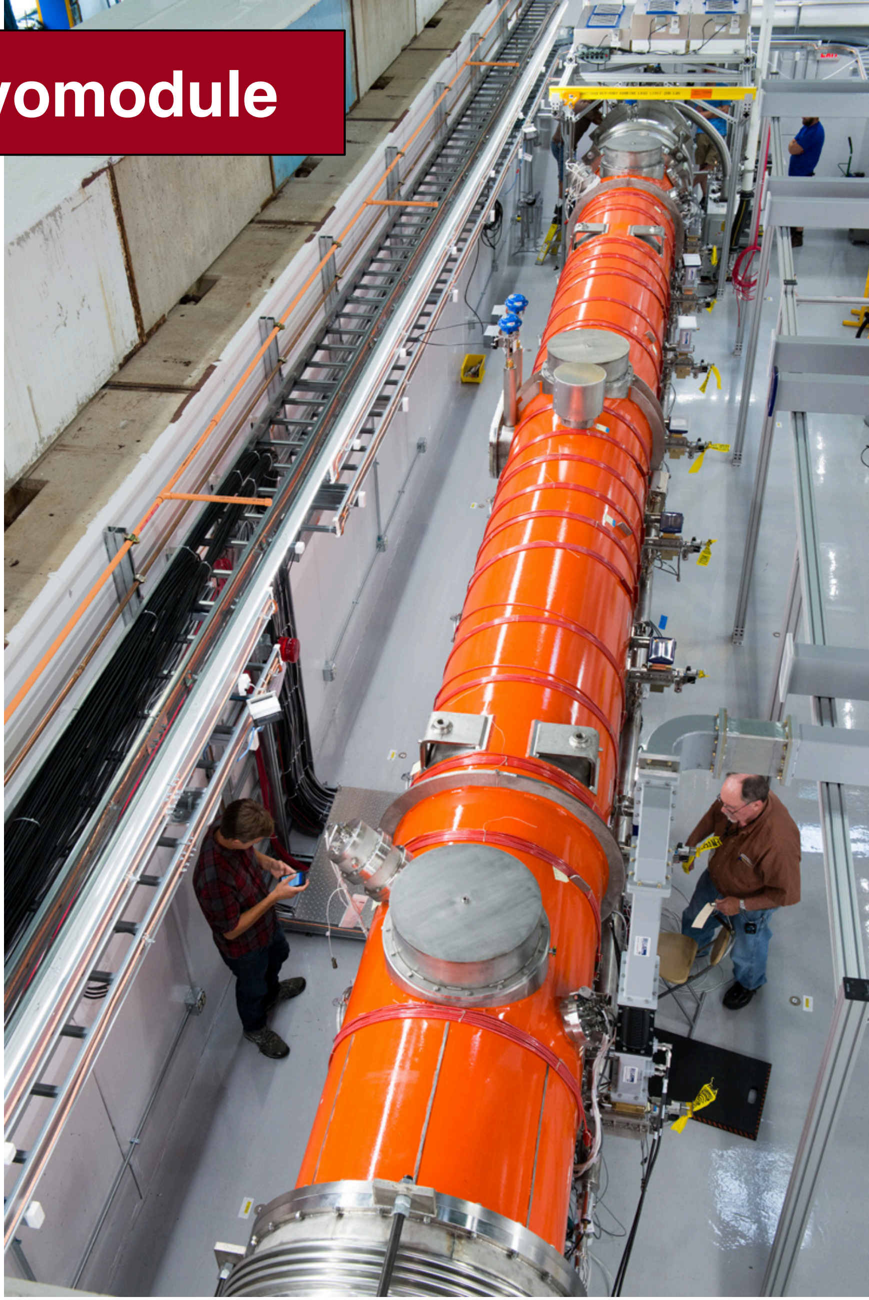


Fermilab Prototype LCLS-II Cryomodule

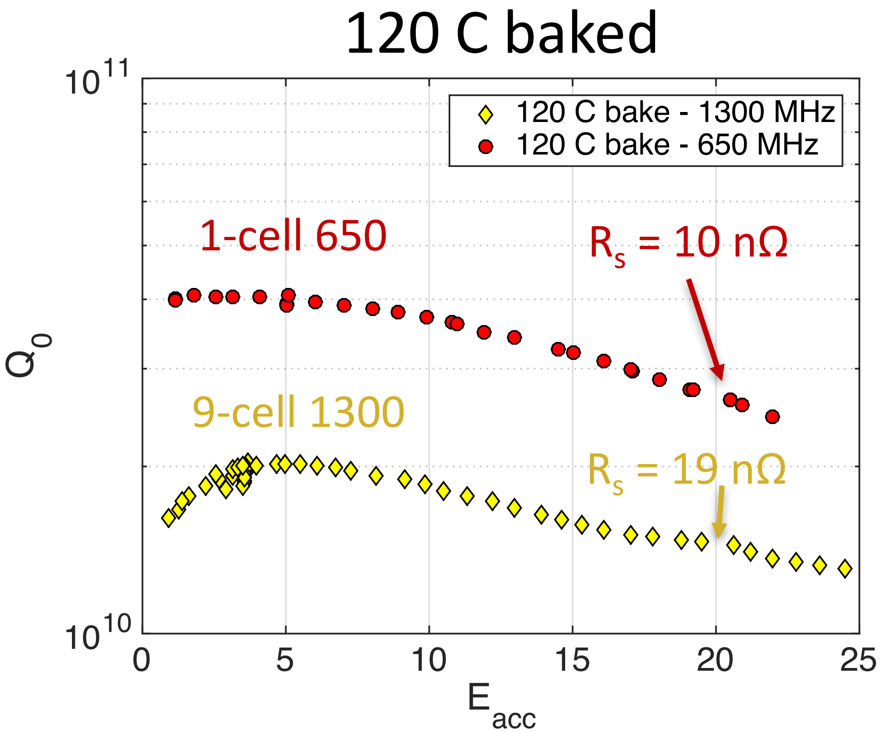
Cavity	Usable Gradient* [MV/m]	Q0 @16MV/m* 2K Fast Cool Down
TB9AES021	18.2	2.6E+10
TB9AES019	18.8	3.1E+10
TB9AES026	19.8	3.6E+10
TB9AES024	20.5	3.1E+10
TB9AES028	14.2	2.6E+10
TB9AES016	16.9	3.3E+10
TB9AES022	19.4	3.3E+10
TB9AES027	17.5	2.3E+10
Average	**18.2**	**3.0E+10**
Total Voltage	**148.1 MV**	

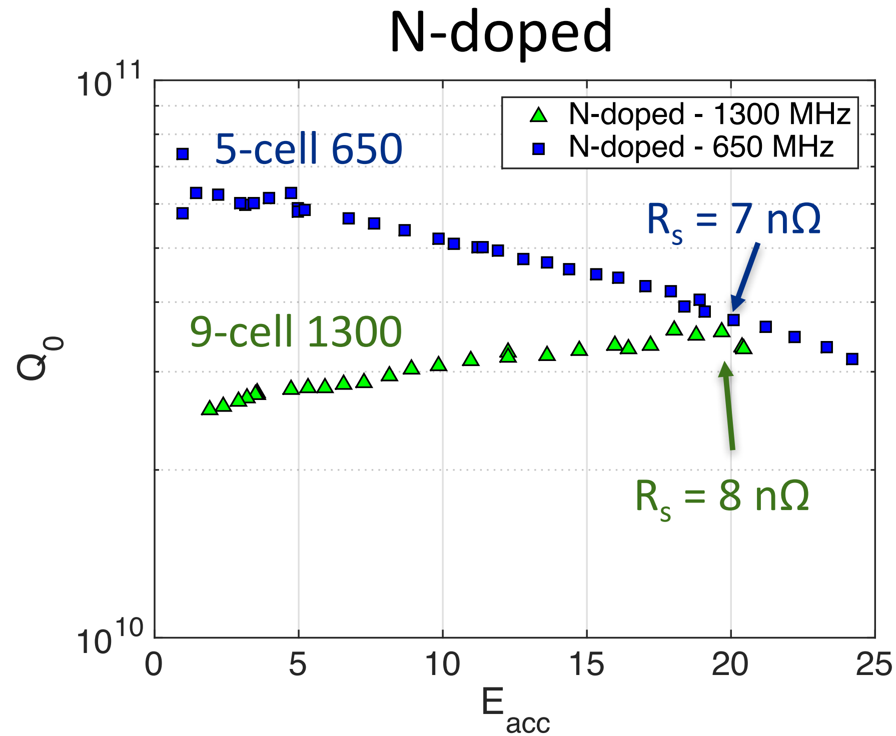
Spec: 133 MV

Spec: 2.7×10^{10}

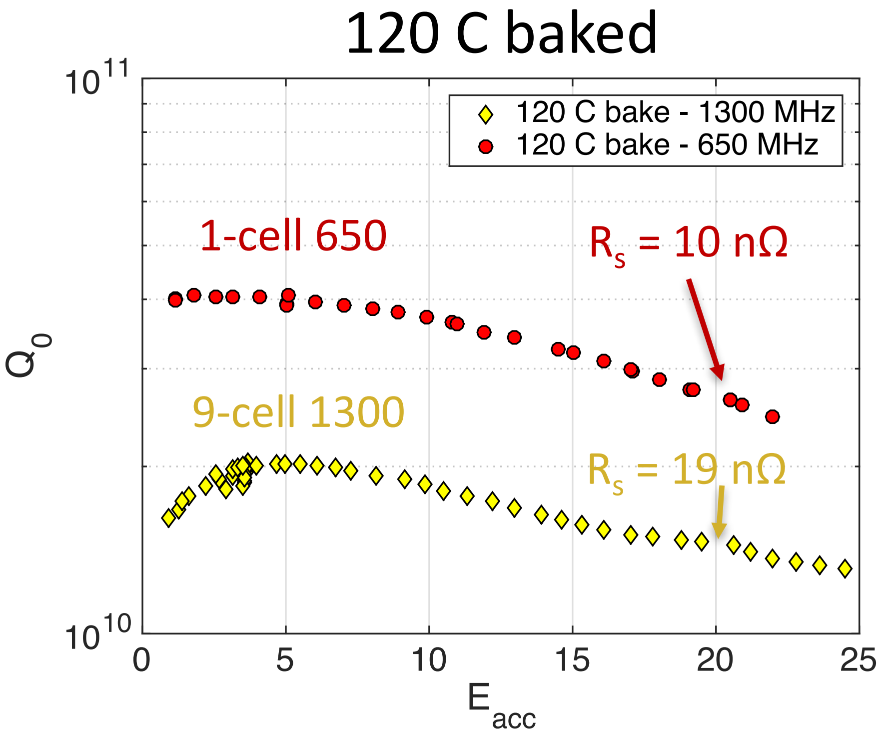


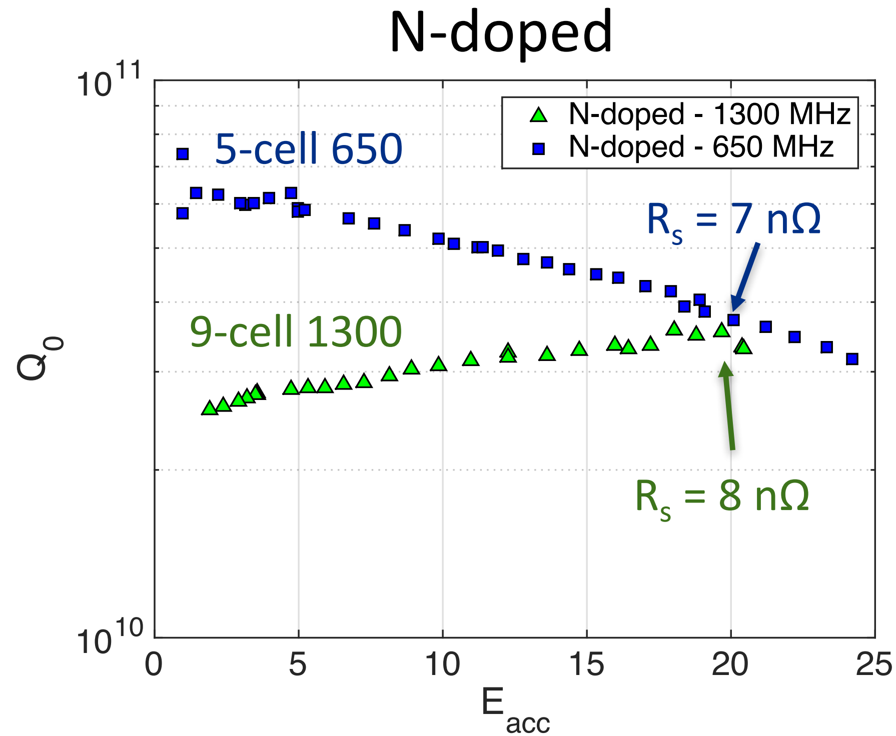
Variation with Frequency

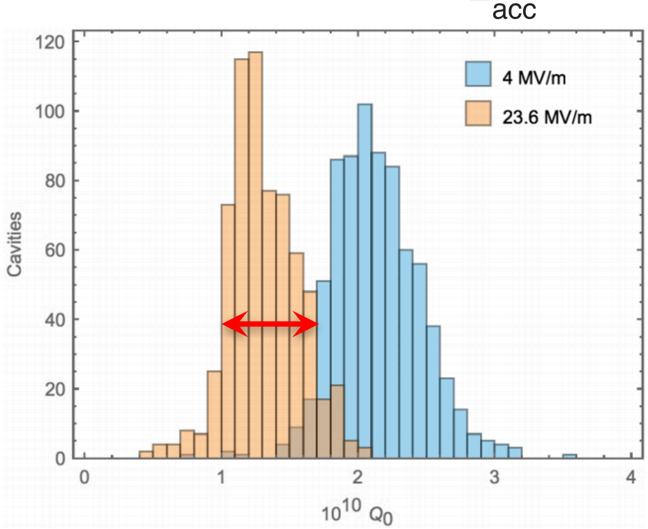




Variation with Frequency

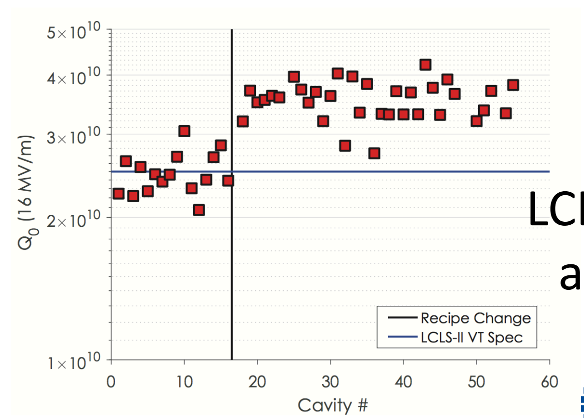






XFEL: ~18-27 nΩ at 23.6 MV/m

Can improve mag. shielding, flux expulsion



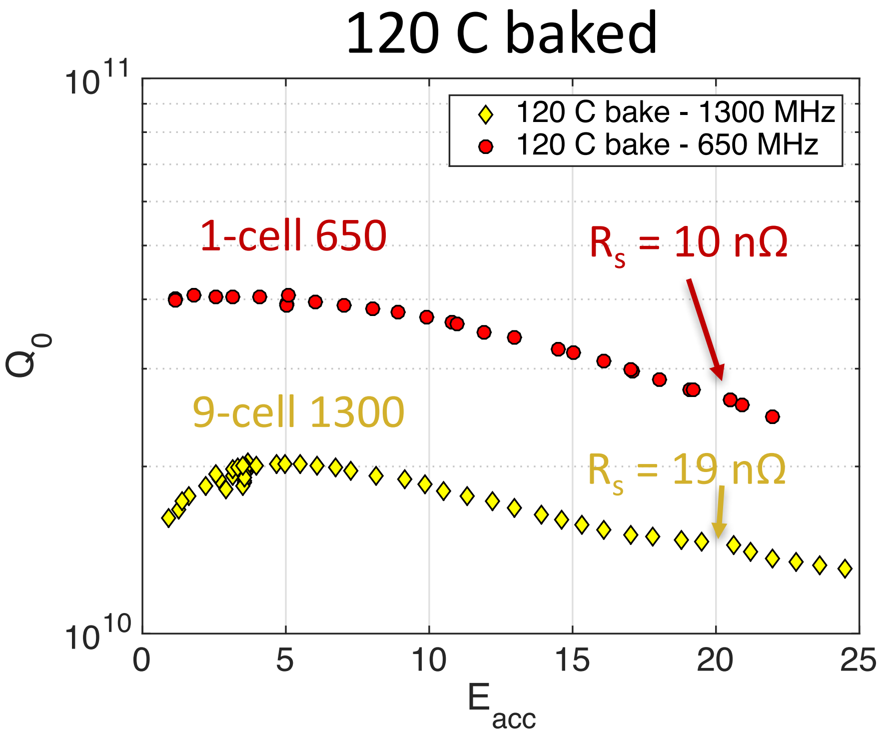
LCLS-II: <10 nΩ at 16 MV/m

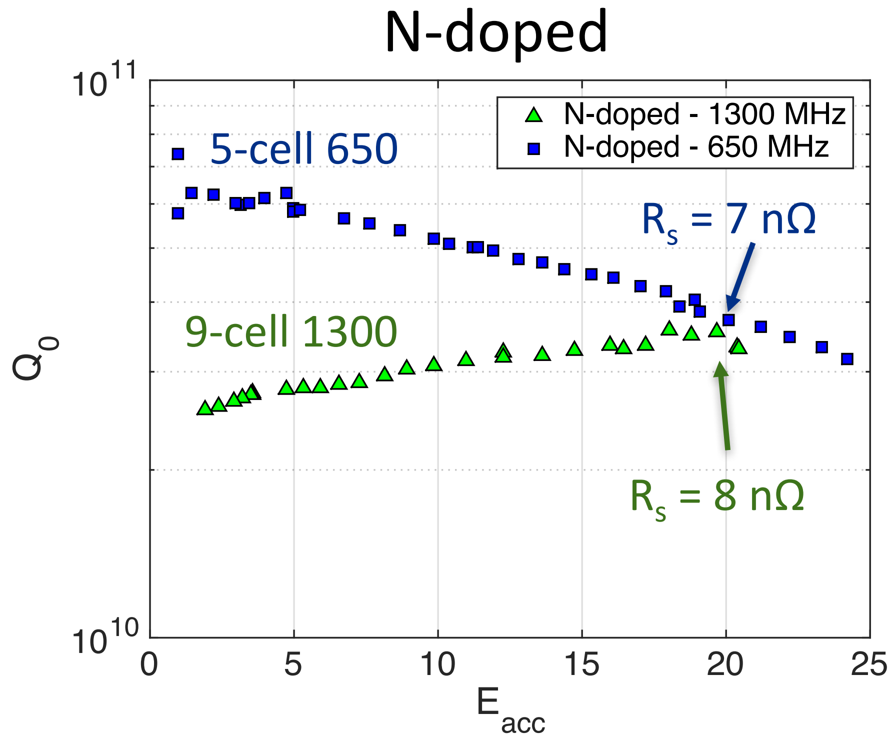
D. Reschke et. al, *PRAB* 20, 042004 (2017)

D. Gonnella, IPAC17

Fermilab

Variation with Frequency





- Use decomposition to help interpolate to **800 MHz** at 20 MV/m (using expected scaling for BCS and residual resistance)
  - 120 C baked: 12 nΩ
  - N-doped: 8 nΩ

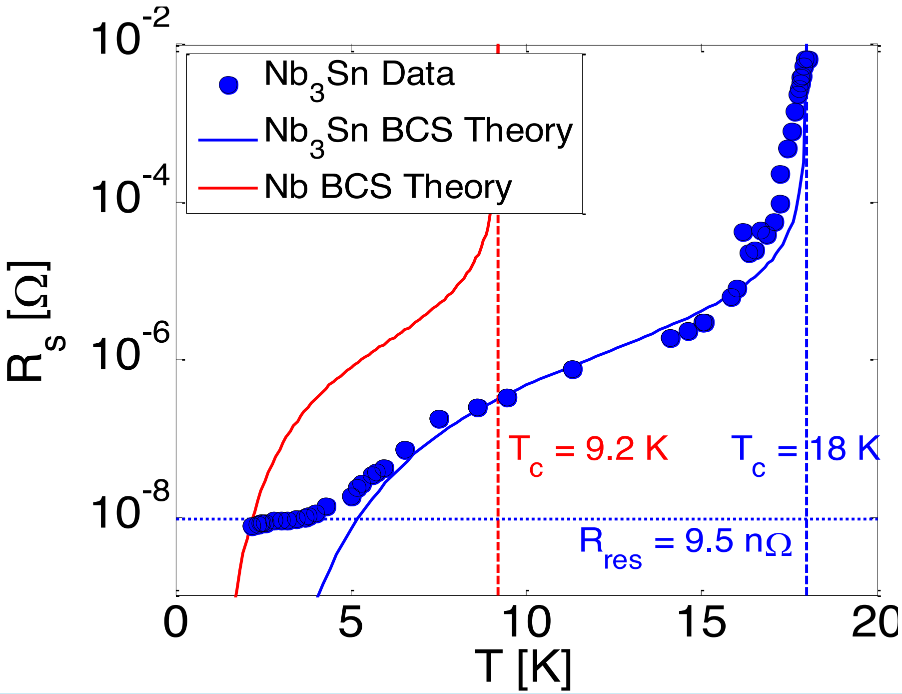
*Additional details given in appendix slides. Frequency scaling from M. Martinello et al. [to be published]

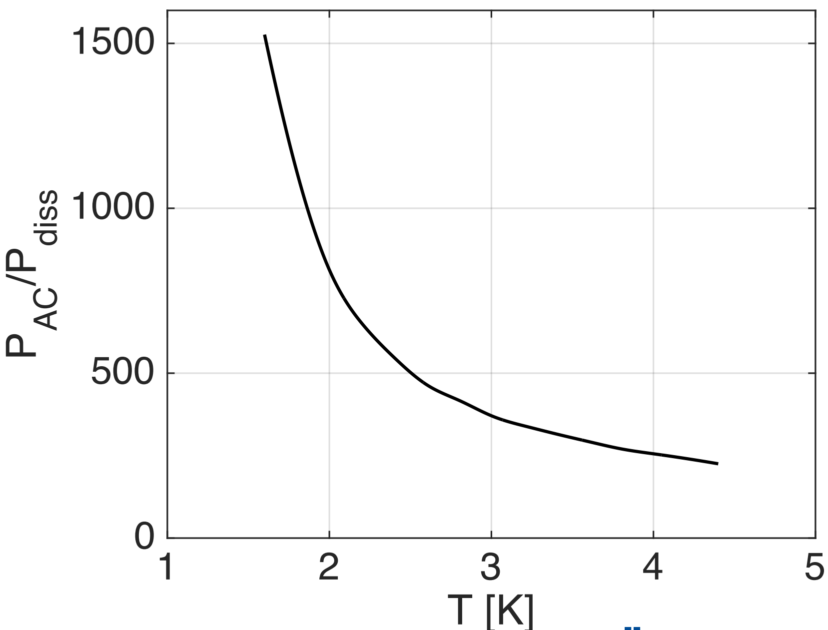
2. Nb_3Sn

Higher $Q_0(T)$ with Nb_3Sn

- Large $T_c \sim 18$ K
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76T_c/T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

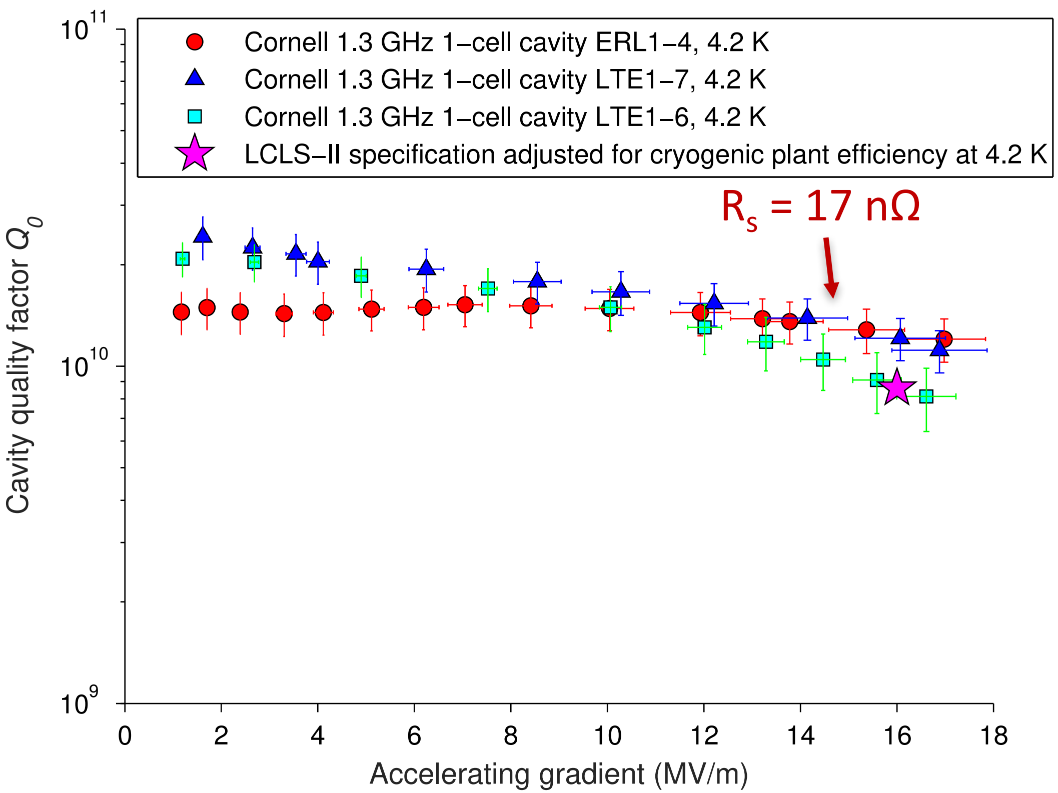
CERN cryogenic plant

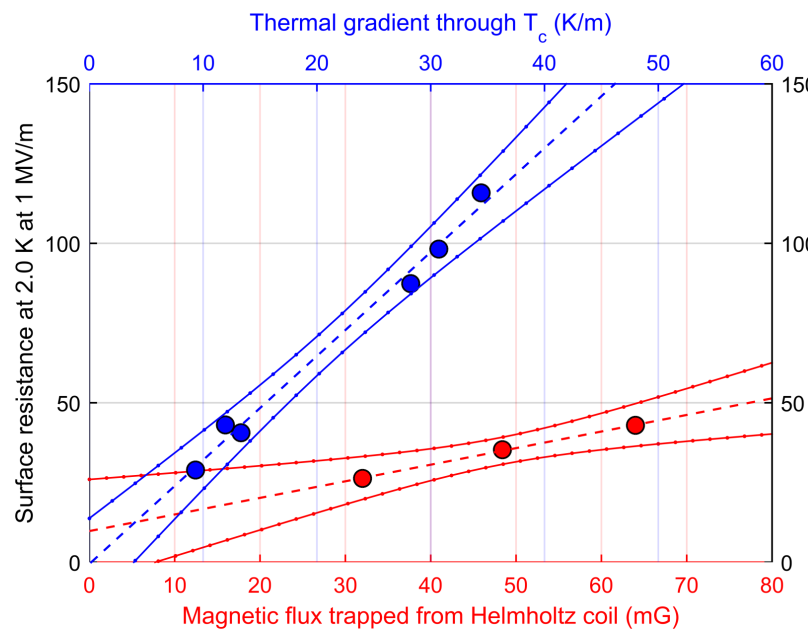




State-of-the-Art

- Cornell: repeatable achievement of 14-17 MV/m with Q~10^{10} at 4.2 K in 1.3 GHz 1-cell cavities





D. Hall, TTC 2017

S. Posen and D. Hall, SUST 30 033004 (2017).

State-of-the-Art

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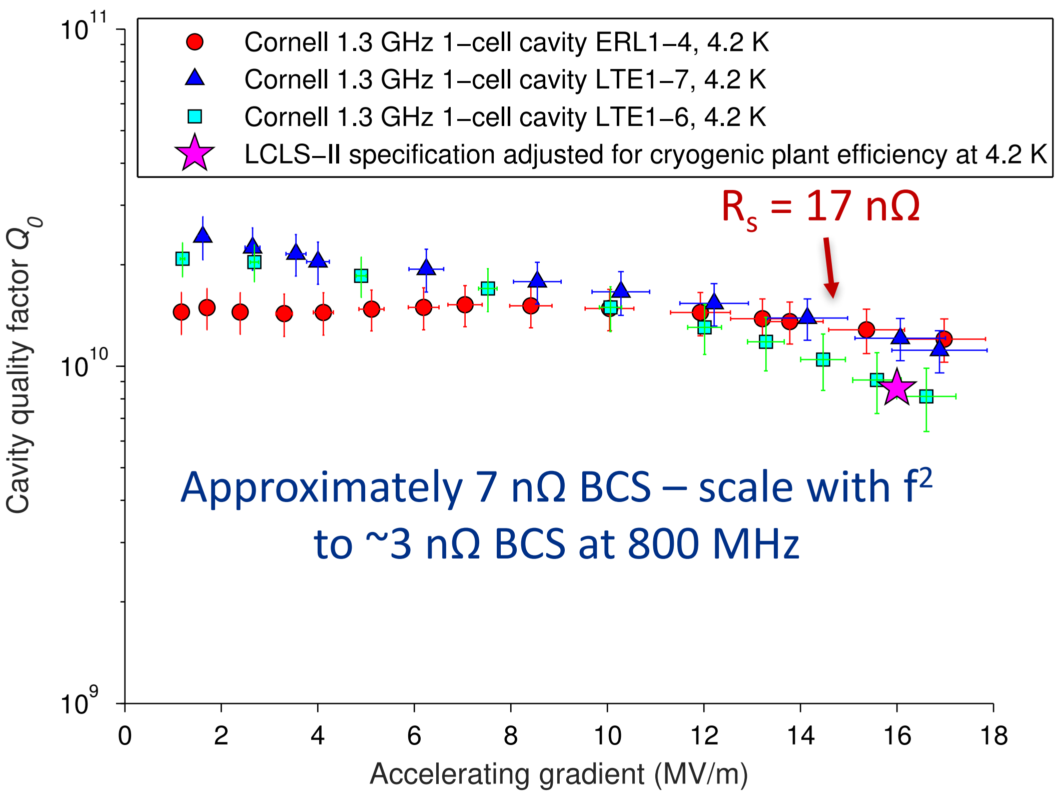
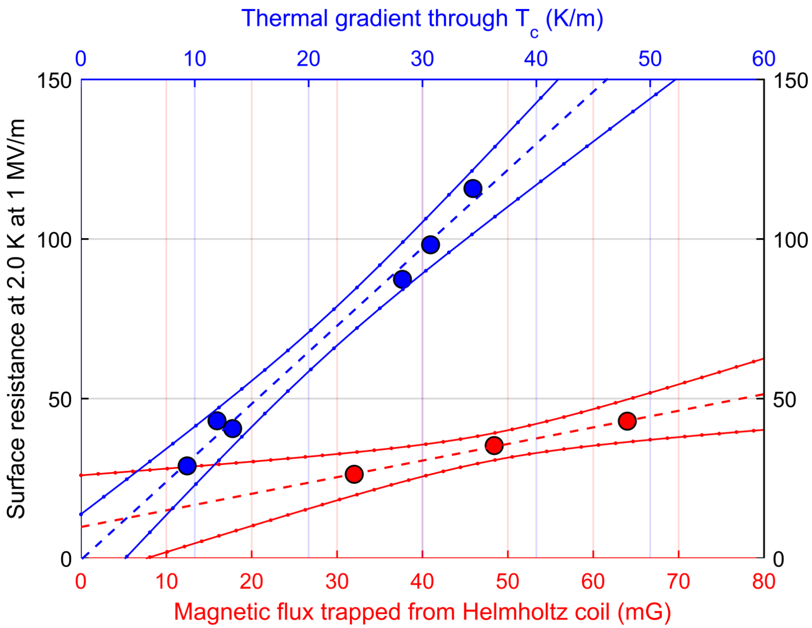




D. Hall, TTC 2017

S. Posen and D. Hall, SUST 30 033004 (2017).

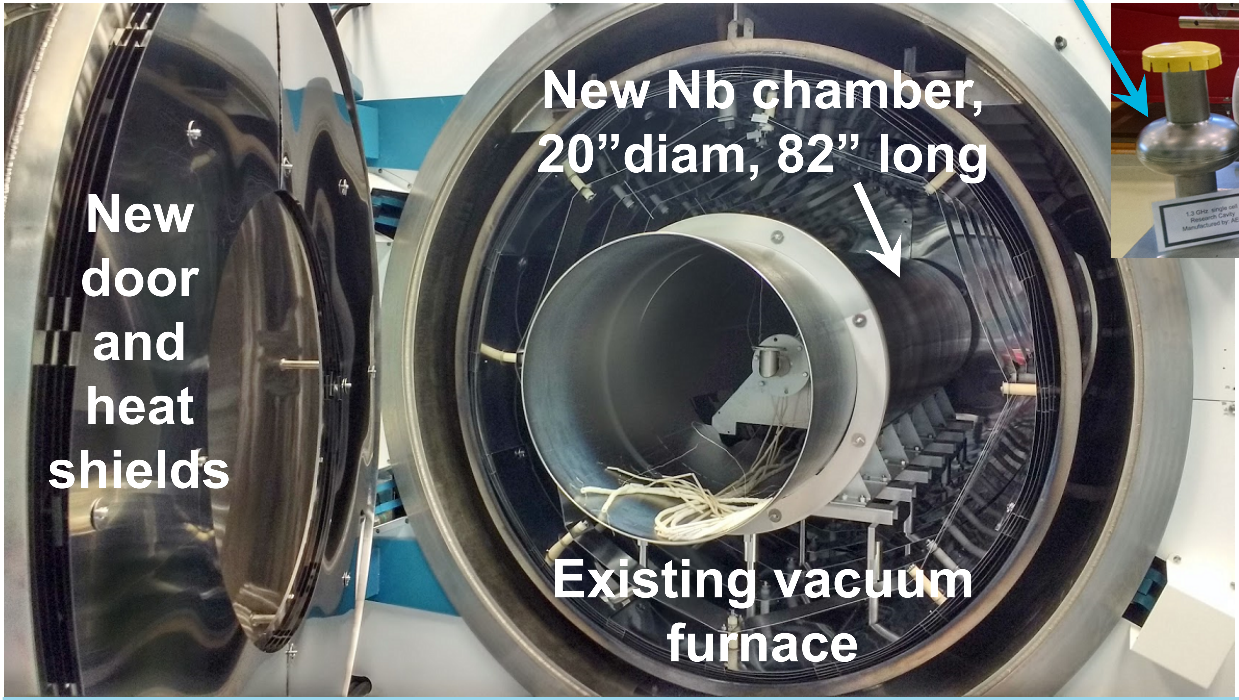
Future studies to reduce trapped flux may be able to significantly lower residual resistance

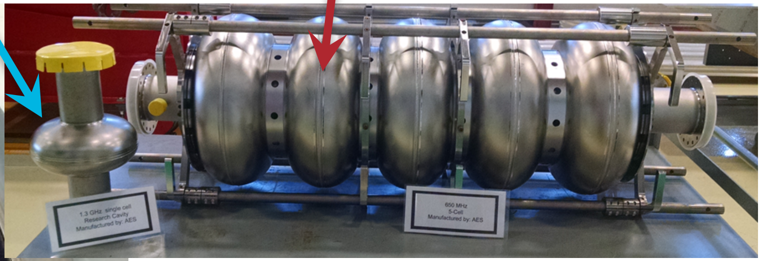
Scaling up to Low Frequency Multicell Cavities

- Fermilab: large Nb_3Sn SRF coating apparatus recently commissioned
- First samples and first cavity coated in early 2017
- Collaboration with CERN to coat 800 MHz cavities

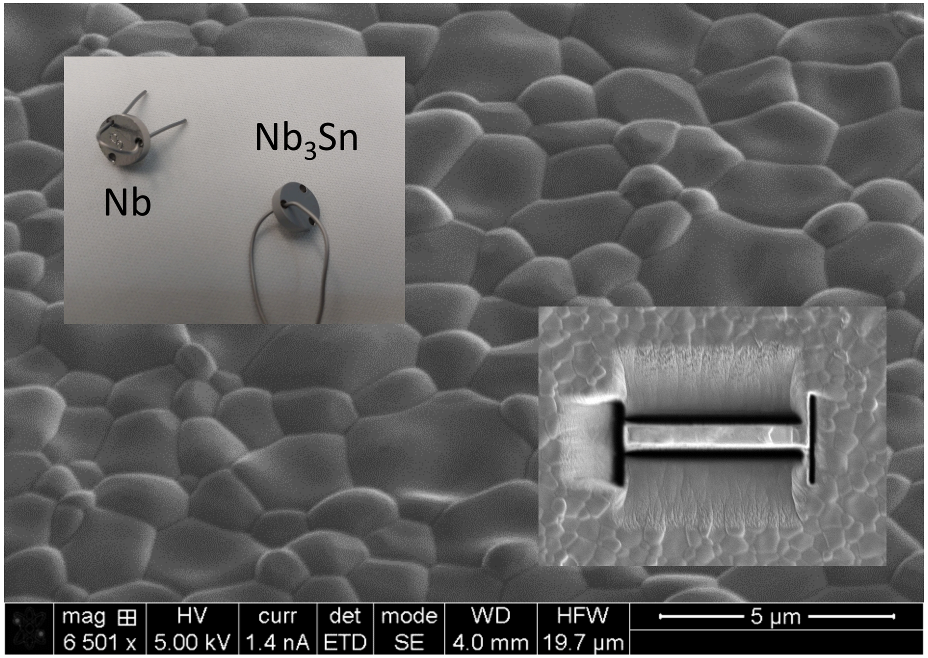
1.3 GHz 1-cell (current state of Nb_3Sn R&D)

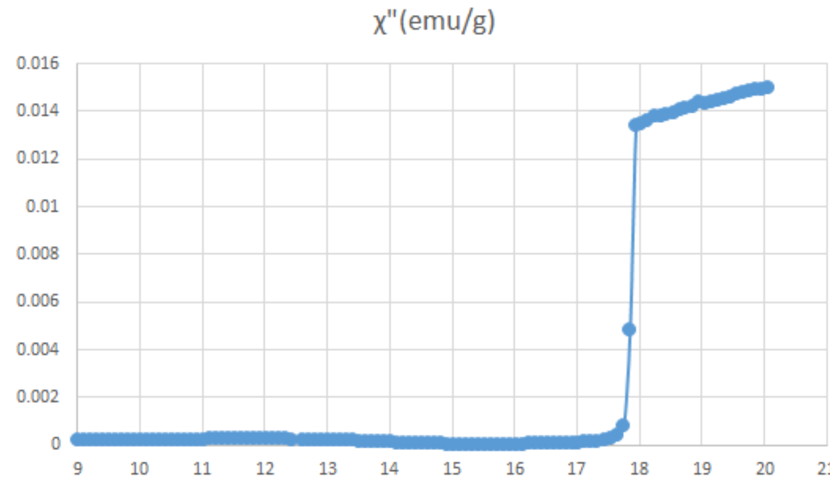
650 MHz 5-cell (future)

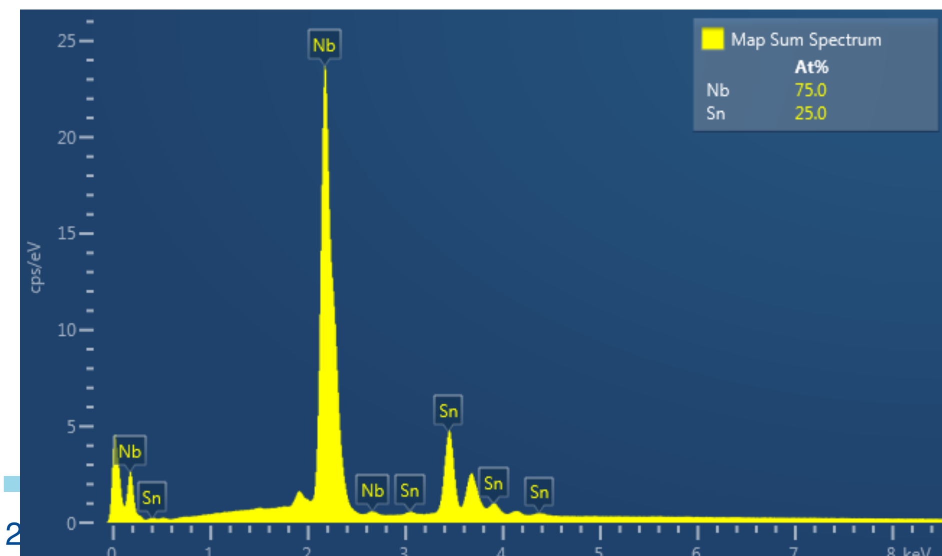


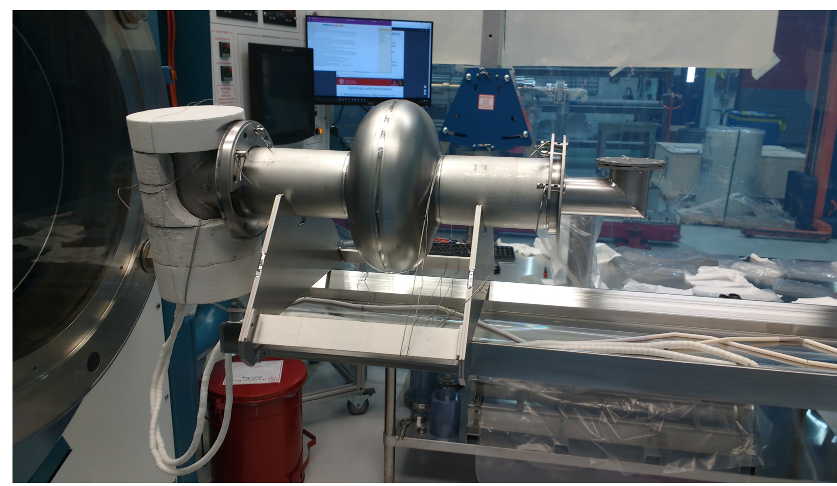


First Nb_3Sn Samples via Vapor Diffusion at FNAL









Sample measurements by Yulia Trenikhina (FNAL),
Jae-Yel Lee (Northwestern), and Zuhawn Sung (FNAL)

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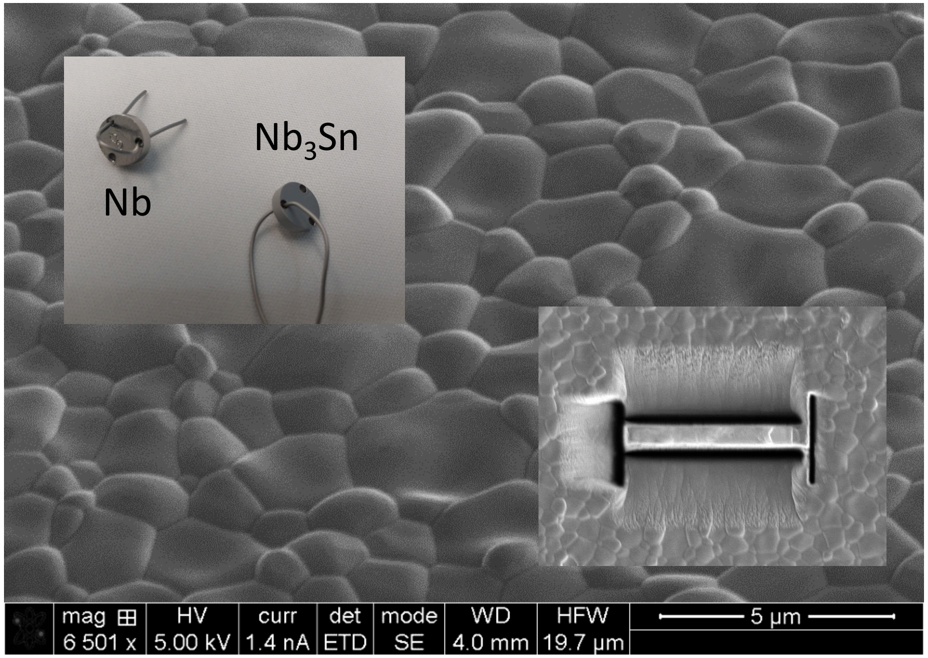
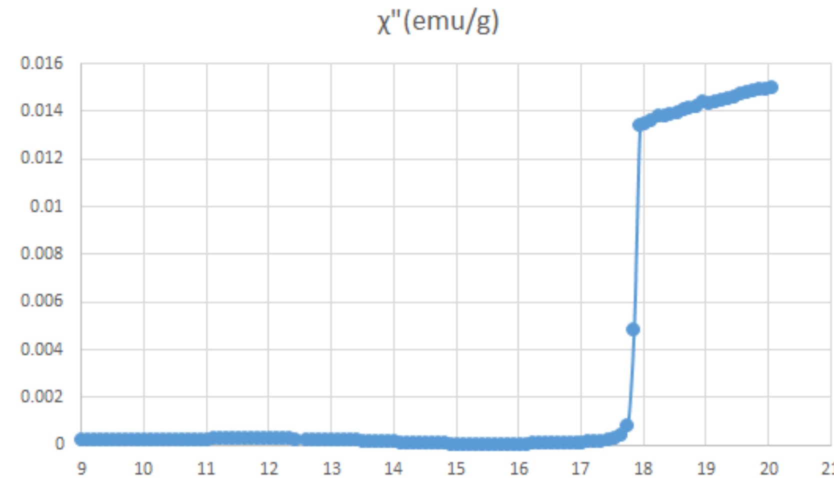
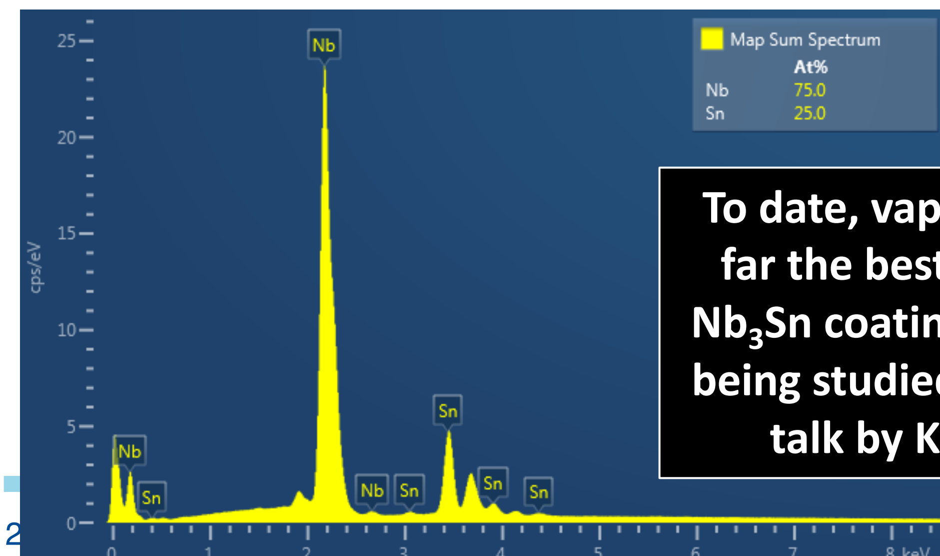
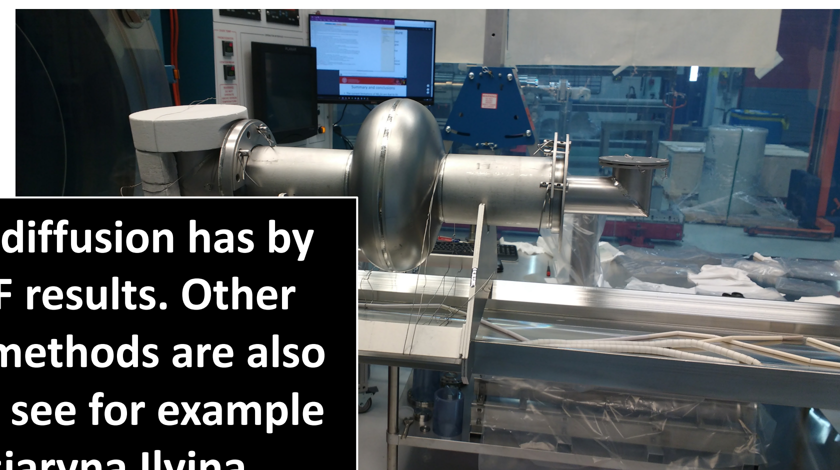






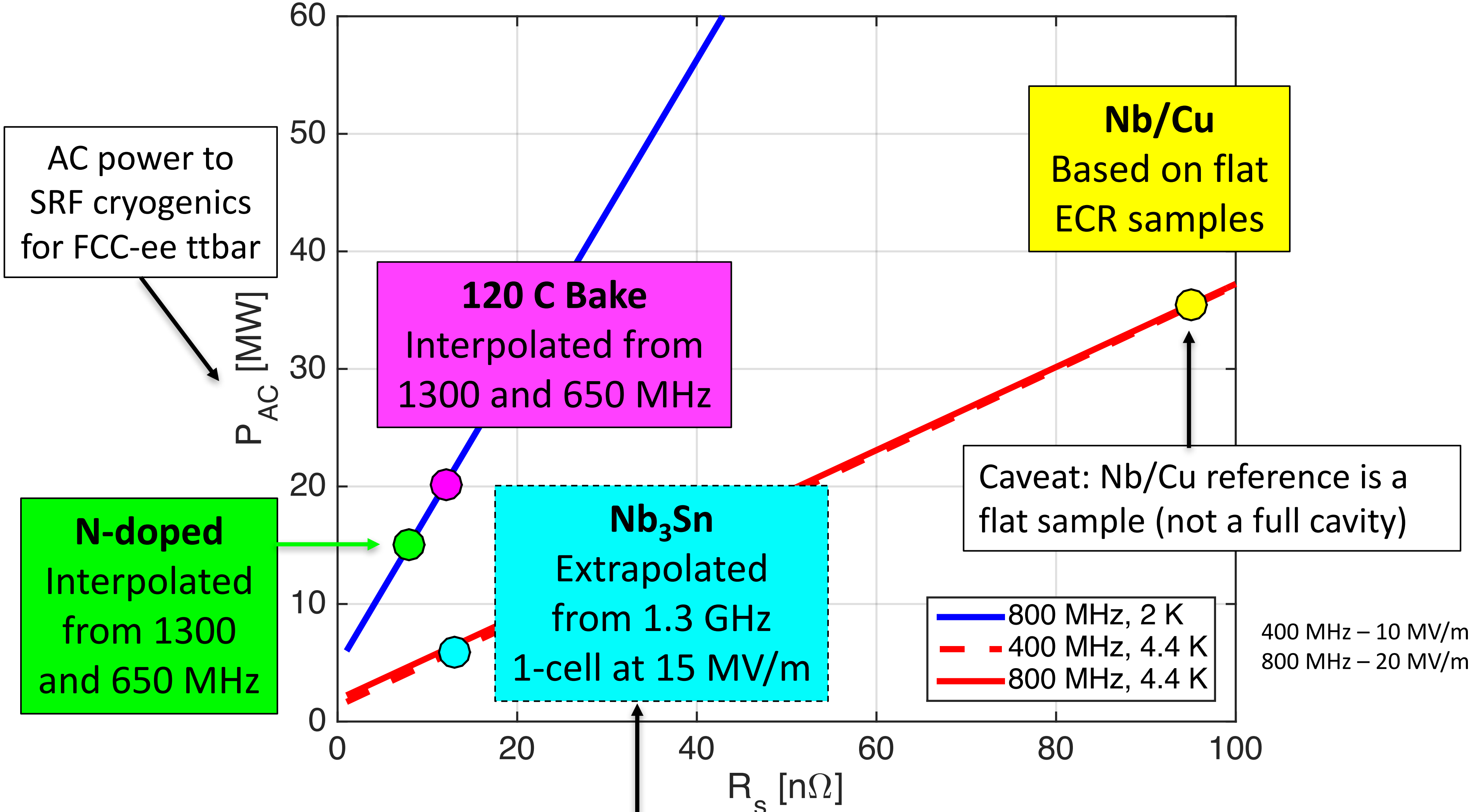


To date, vapor diffusion has by far the best RF results. Other Nb_3Sn coating methods are also being studied – see for example talk by Katsiaryna Ilyina

Sample measurements by Yulia Trenikhina (FNAL), Jae-Yel Lee (Northwestern), and Zuhawn Sung (FNAL)

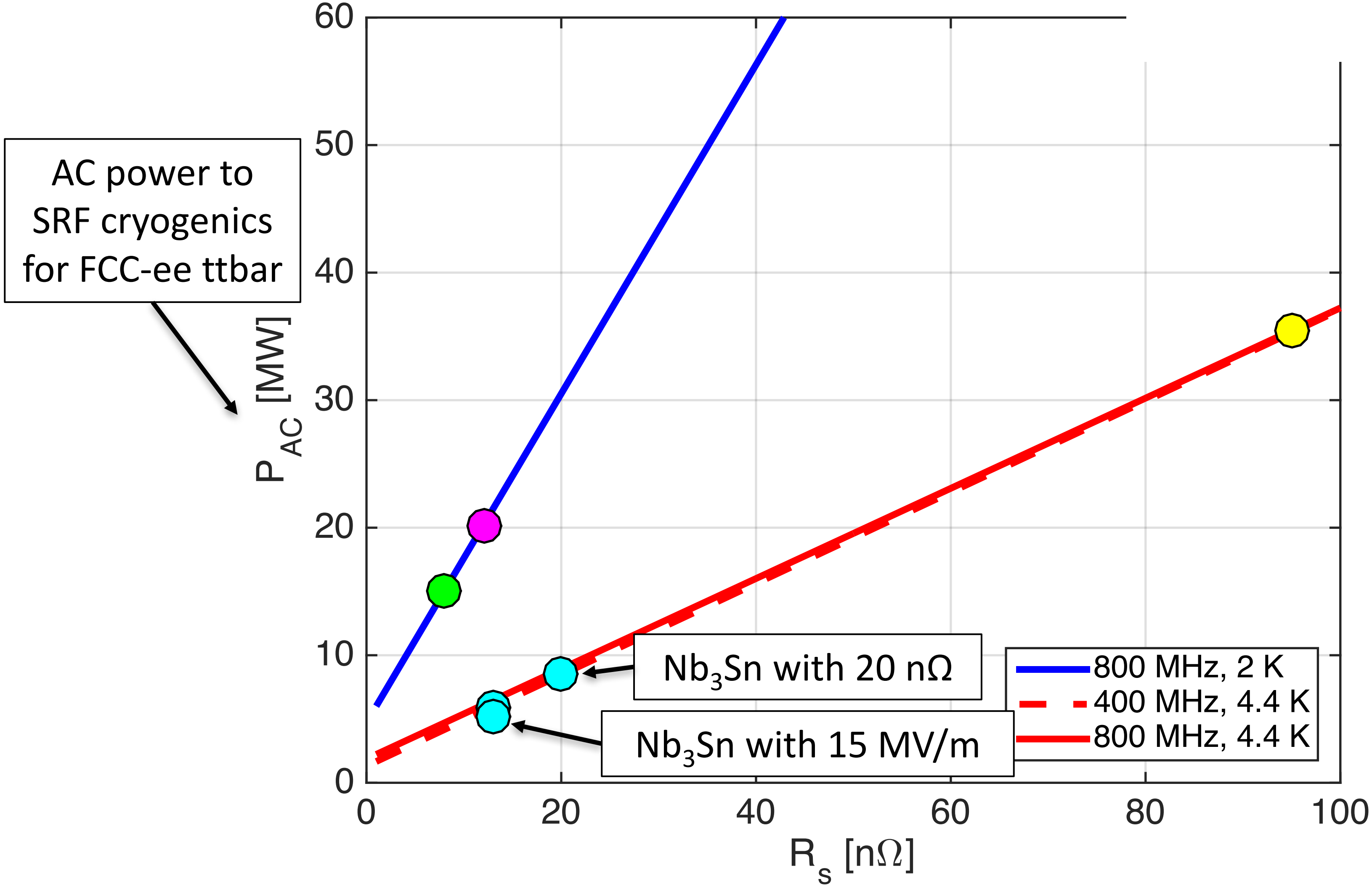
3. Predicting Potential for FCC

Potential of Different SRF Cavity Treatments



Caveat: Nb_3Sn reference is a 1.3 GHz 1-cell cavity (not a multicell, not low frequency) with quench limit below 20 MV/m

Potential of Different SRF Cavity Treatments



Summary

- Treatments applied in production to 1300 MHz cavities could be readily applied to 800 MHz cavities for FCC
- 1300 MHz and 650 MHz data were drawn on to try to estimate predicted performance at 800 MHz
- Nitrogen doping shows promise for minimizing cryopower requirements; positive results so far from LCLS-II production
- 120 C baking has relatively low cryogenic power requirements; proven in >800 cavities for XFEL (and others)
- Control of flux losses is crucial to residual resistance in all cases: magnetic 1) hygiene, 2) shielding, 3) expulsion
- Nb_3Sn promising at 4.4 K; R&D advancing for multicells & continuing to push performance

Acknowledgements

- Many thanks to Alex Melnychuk, Martina Martinello, and Anna Grassellino for contributions
- Many thanks to Sarah Aull for helping to make AC power calculations consistent with CERN

Appendix. Assumptions, Calculations, References

Assumptions

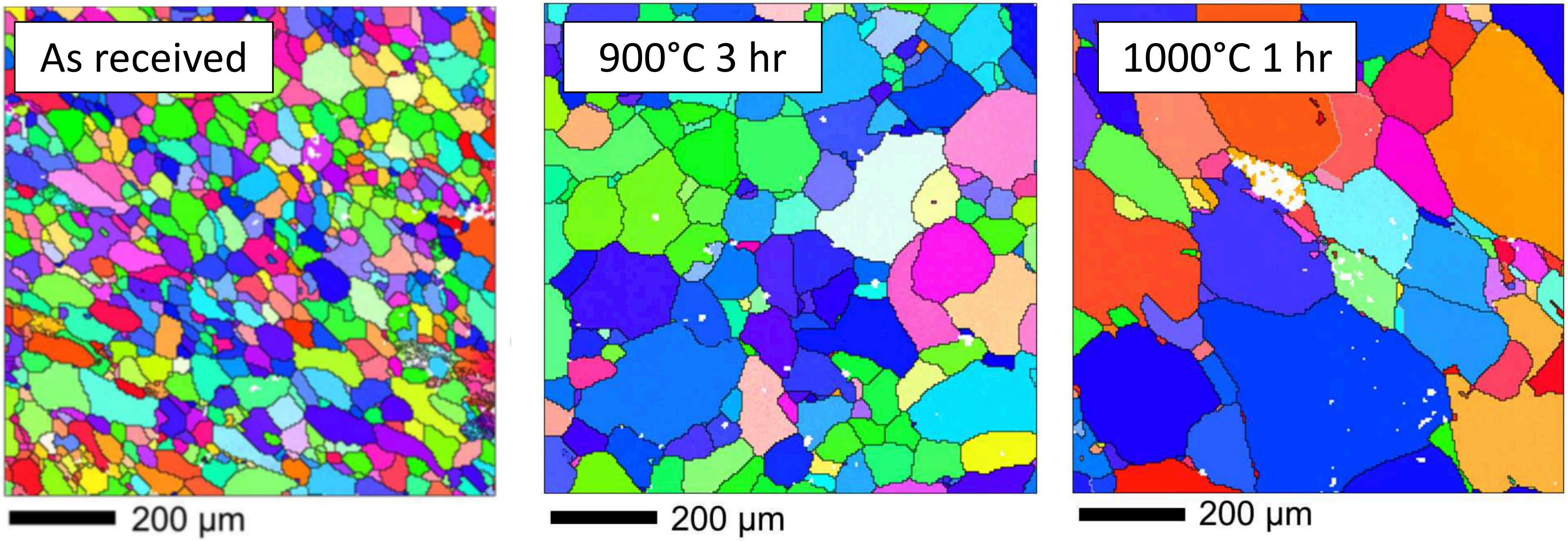
- R/Q per cell – 400 MHz: 85 Ω; 800 MHz: 84 Ω
- G – 400 MHz, 800 MHz: 280 Ω
- B_{pk}/E_{acc} – 400 MHz, 800 MHz: 4.1 mT/MV/m
- Static load – 5 W/m
- R_s – 400 MHz: 61.51*exp(0.009411*Bpk) + 4 [nΩ]
- [Private communication, S. Aull, CERN]

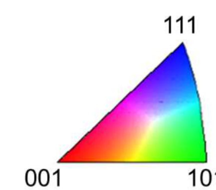
- COP^{-1} – 2 K: 808 W/W; 4.4 K: 224 W/W
- [W. J. Schneider, et al. Gradient optimization for SC CW accelerators. *PAC 2003*, pp. 2863–2865, 2003.]

Cavity Prep	N-doped bulk Nb	120 C baked bulk Nb	Nb/Cu	Nb_3Sn
Level of Technical Maturity	Production (LCLS-II or XFEL) / R&D (1- and 5-cell cavities) / 800 MHz interpolation		Production (LHC) / R&D (flat plates)	R&D (1-cell) / goal
F [MHz]	1300 / 650 / 800		400	1300 / 800
T [K]	2	2	4.5	4.5
R_{BCS} @ field [nΩ @ MV/m]	4.5 @ 16 / 2 @ 16 / 3 @ 16	11 @ 20 / 3 @ 20 / 4.5 @ 20		7 @ 16 / 3 @ 16
Primary R_{res} source	Flux: 1.5 / 0.8 / 1.1 nΩ/mG	Flux: 0.5 / 0.3 / 0.4 nΩ/mG	Under study, also Q-slope	Under study, also flux
R_{res} [nΩ]	2 + 3 mG trapped: 6.5 / 4.4 / 5.3	6 + 3 mG trapped: 7.5 / 6.9 / 7.2		10 / 10
Approximate R_{tot} [nΩ]	16 MV/m: 11 / 6.4 / 8.3	20 MV/m: 18.5 / 9.4 / 11.6	10 MV/m: 320 / 104	15 MV/m: 17 / 13
Reference	M. Martinello [to be published]		S. Aull, SRF 2015	S. Posen and D. Hall, SUST 2017; D. Hall TTC 2017

Backup

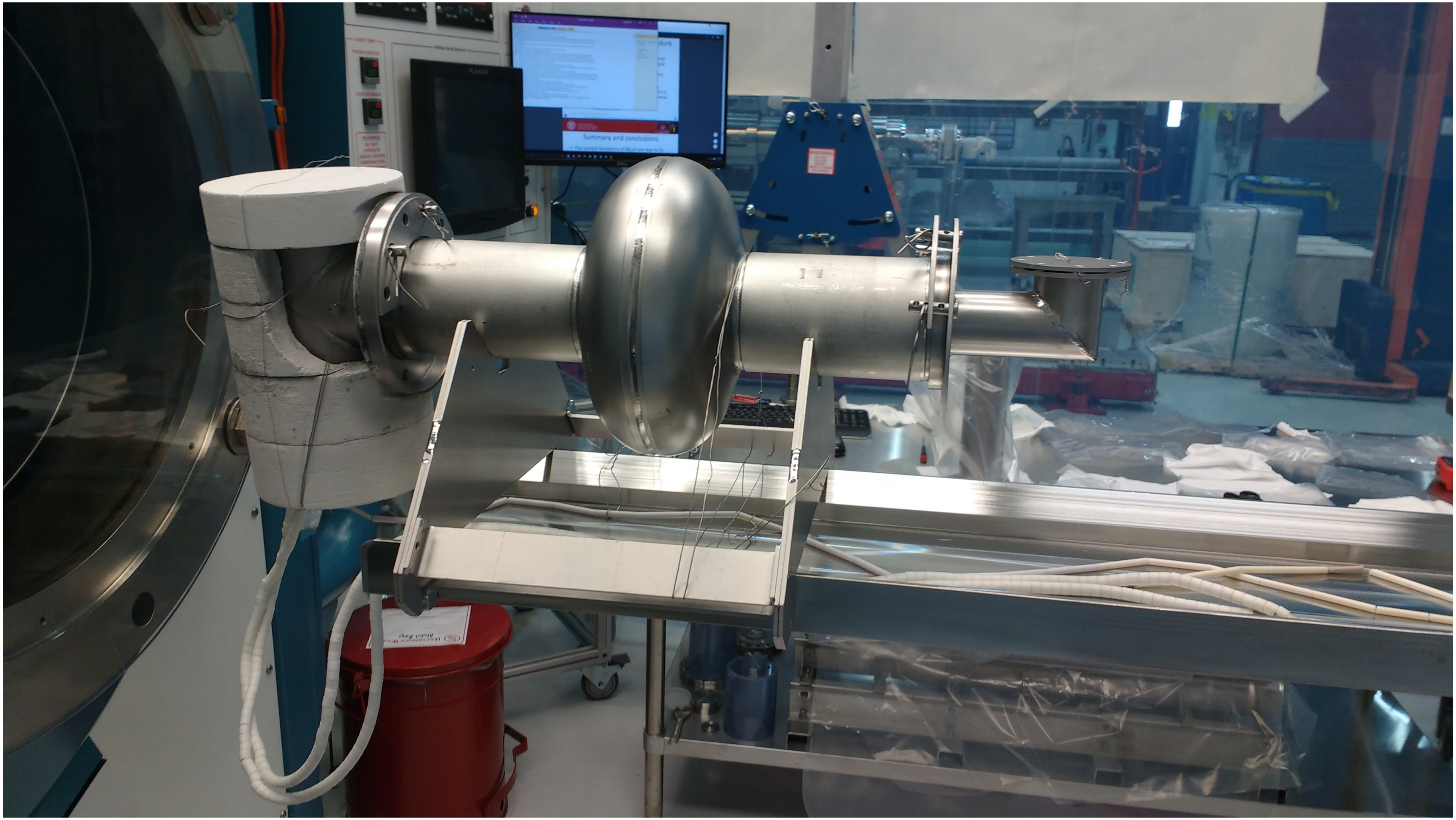
Flux Expulsion and High Temperature Treatment





- Experiments suggest trapping is linked to dislocations (e.g. grain boundaries)
- High temperature treatment reduces pinning

First Fermilab Nb_3Sn Cavity Coated



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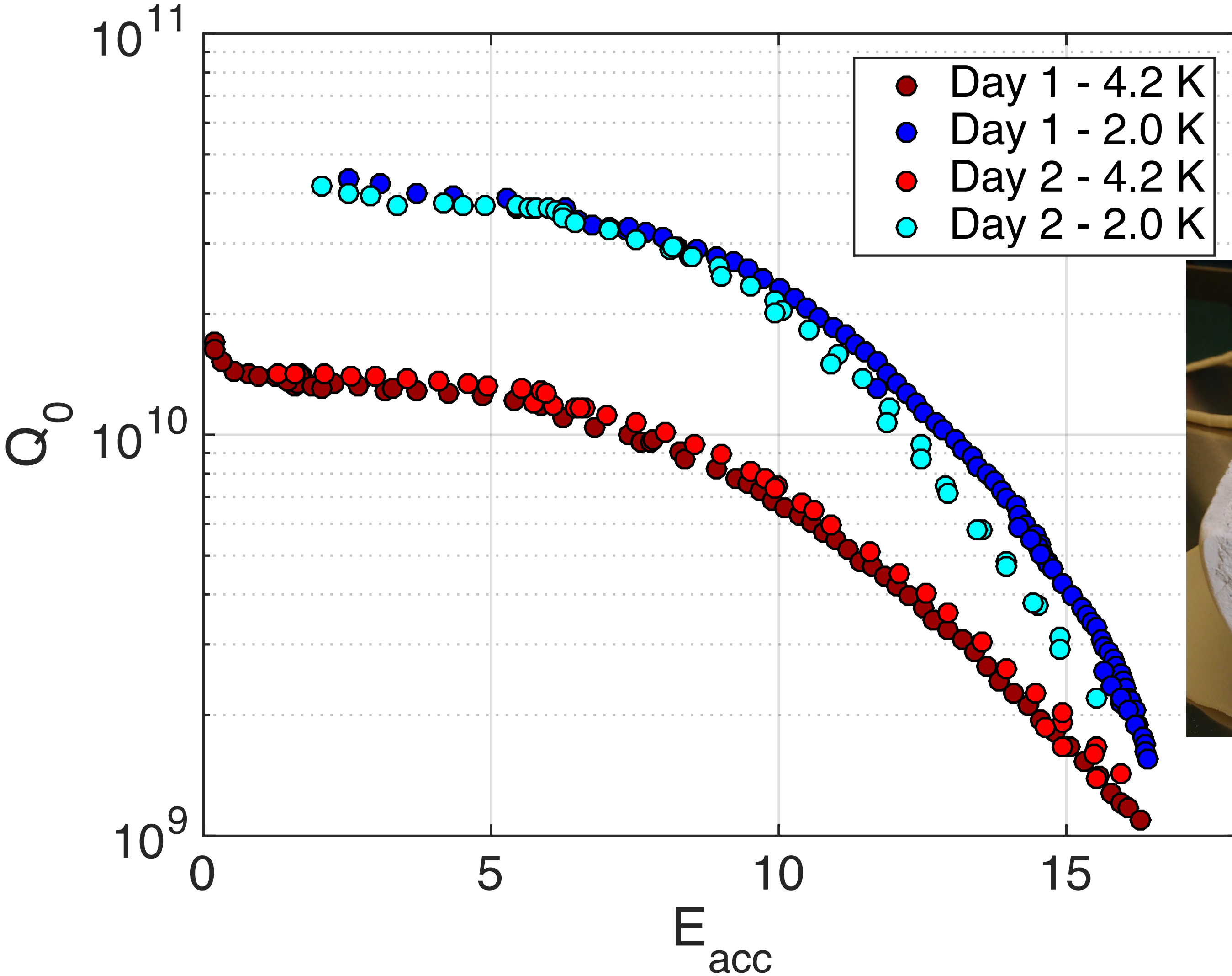

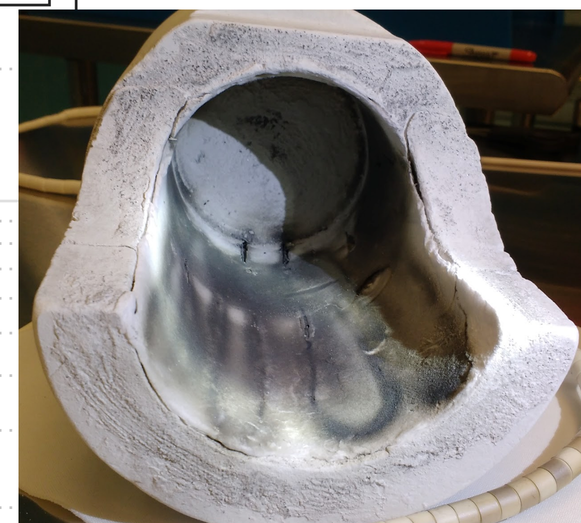

- D. Gonnella IPAC17