



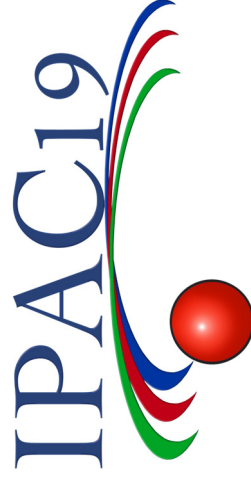
Flux Expulsion in SRF Cavities:

Discovery of Influencing Parameters and Implementation in LCLS-II Cryomodule Production

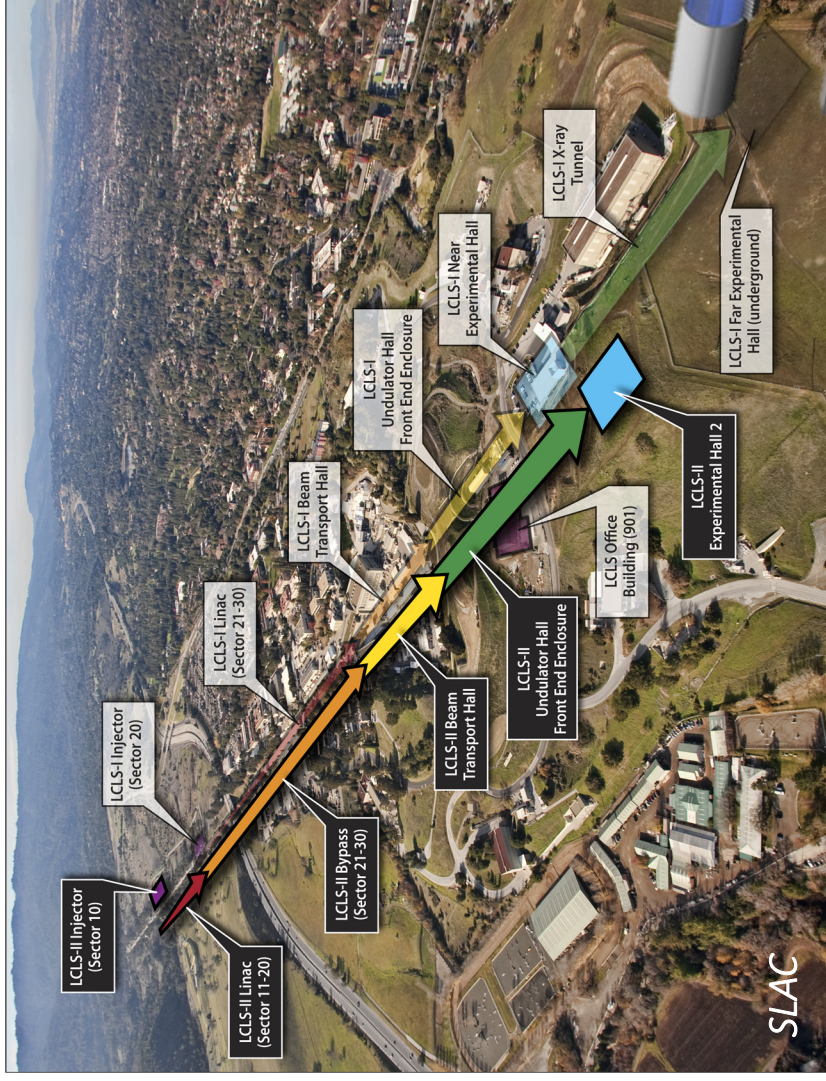
Sam Posen

IPAC 2019

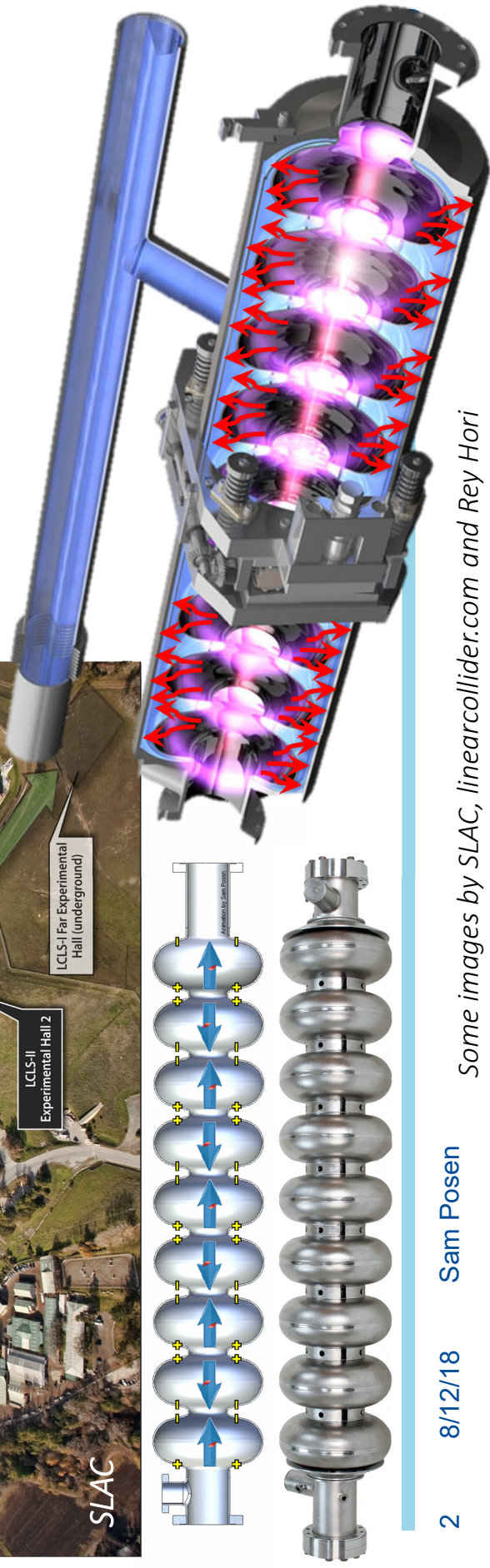
Melbourne, Australia



High Q_0 and LCLS-II



- LCLS-II: XFEL at SLAC
- 35 SRF cryomodules built at Fermilab and JLab, each with eight high- Q_0 9-cell 1.3 GHz N-doped Nb cavities
- CW SRF linac for high rep. rate x-ray beams

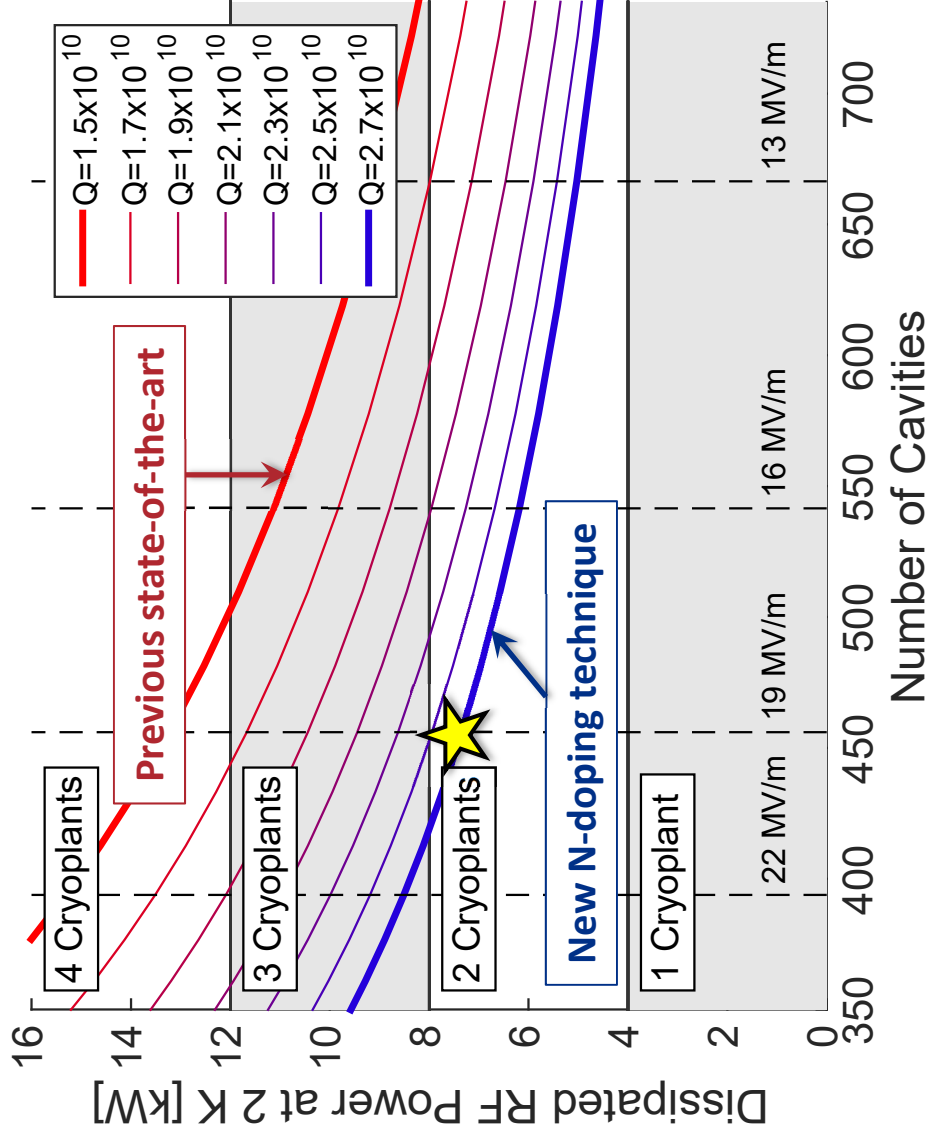


$Q_0 \rightarrow$ Cryogenic Infrastructure, Operating Cost

$$P_{diss} \sim E_{acc}/Q_0$$

(for fixed E_{max})

8 GeV CW SRF Linac



Lower cost

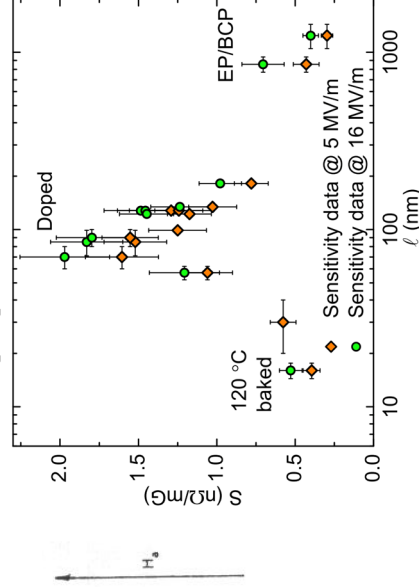
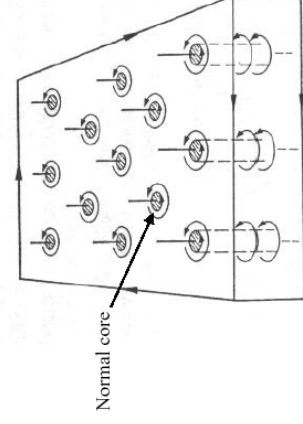
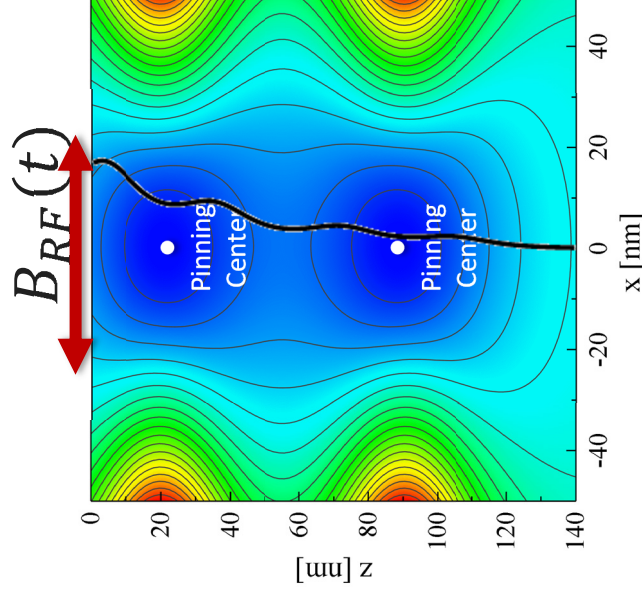


Lower cost



Maintaining High Q_0 with Background B-Field

- Very sensitive to Q_0 degradation – want to maintain the highest Q_0 enabled by N-doping
- Flux trapped during cooldown dissipates heat, lowers Q_0
- For practical magnetic shielding, we expect some residual ambient field at the cavity



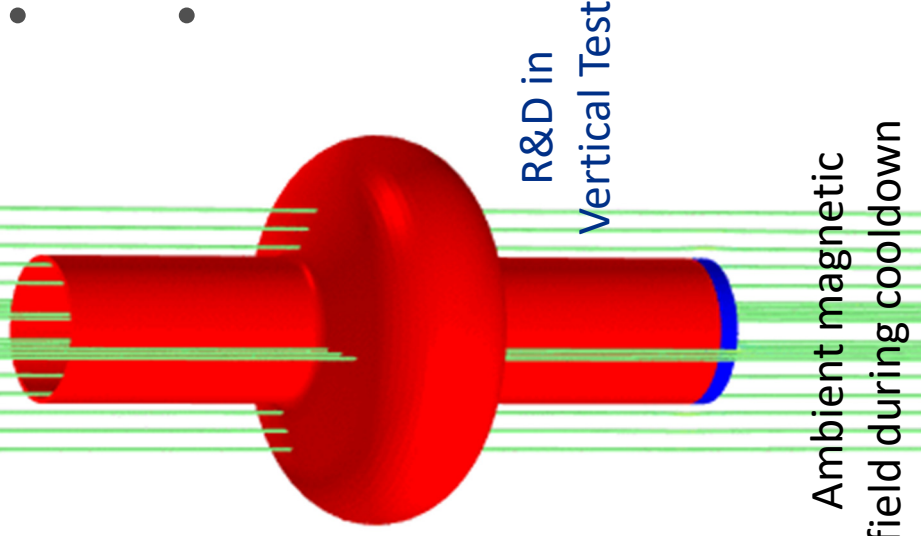
- Minimizing trapped flux:
 - Magnetic shielding
 - Magnetic hygiene
 - **Flux expulsion (new)**

Some studies of added surface resistance per field trapped:
 M. Martinello et al., Appl. Phys. Lett. 109, 062601 (2016)
 M. Checchin et al., Supercond. Sci. Technol. 30 034003 (2017)

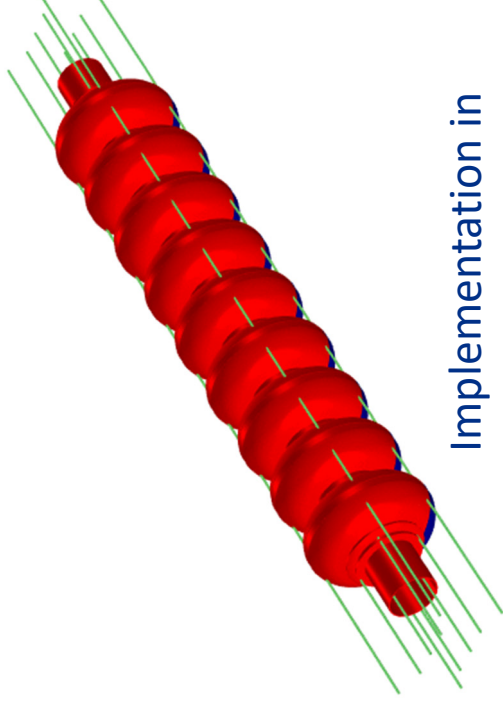
Magnetic Flux Expulsion

Animation by S. Posen and M. Hassan

- Meissner Effect – well below T_c , niobium tends to expel applied magnetic flux
- However, flux can become trapped in superconductor during cooldown
- Only within the last 5 years has R&D made it possible to reliably achieve strong expulsion during cooldown



Animation by S. Posen and M. Hassan



Ultra-high quality factors in superconducting niobium cavities in ambient magnetic fields up to 190 mG

Cite as: Appl. Phys. Lett. 105, 234103 (2014); <https://doi.org/10.1063/1.4903808>
Submitted: 29 October 2014 . Accepted: 27 November 2014 . Published Online: 10 December 2014
A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk



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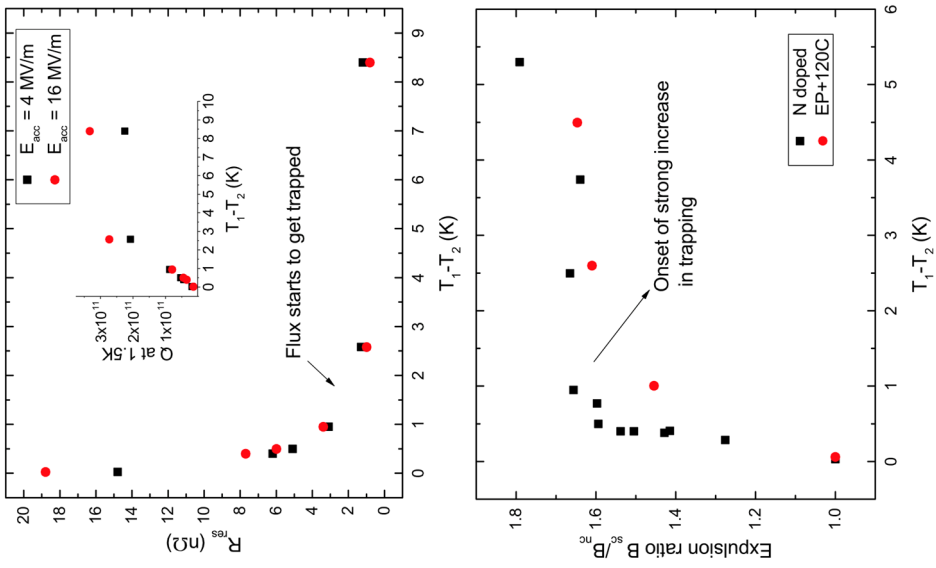
Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around T_c
Journal of Applied Physics 115, 184903 (2014); <https://doi.org/10.1063/1.4875655>
Impact of nitrogen doping of niobium superconducting cavities on the sensitivity of surface resistance to trapped magnetic flux

Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around T_c

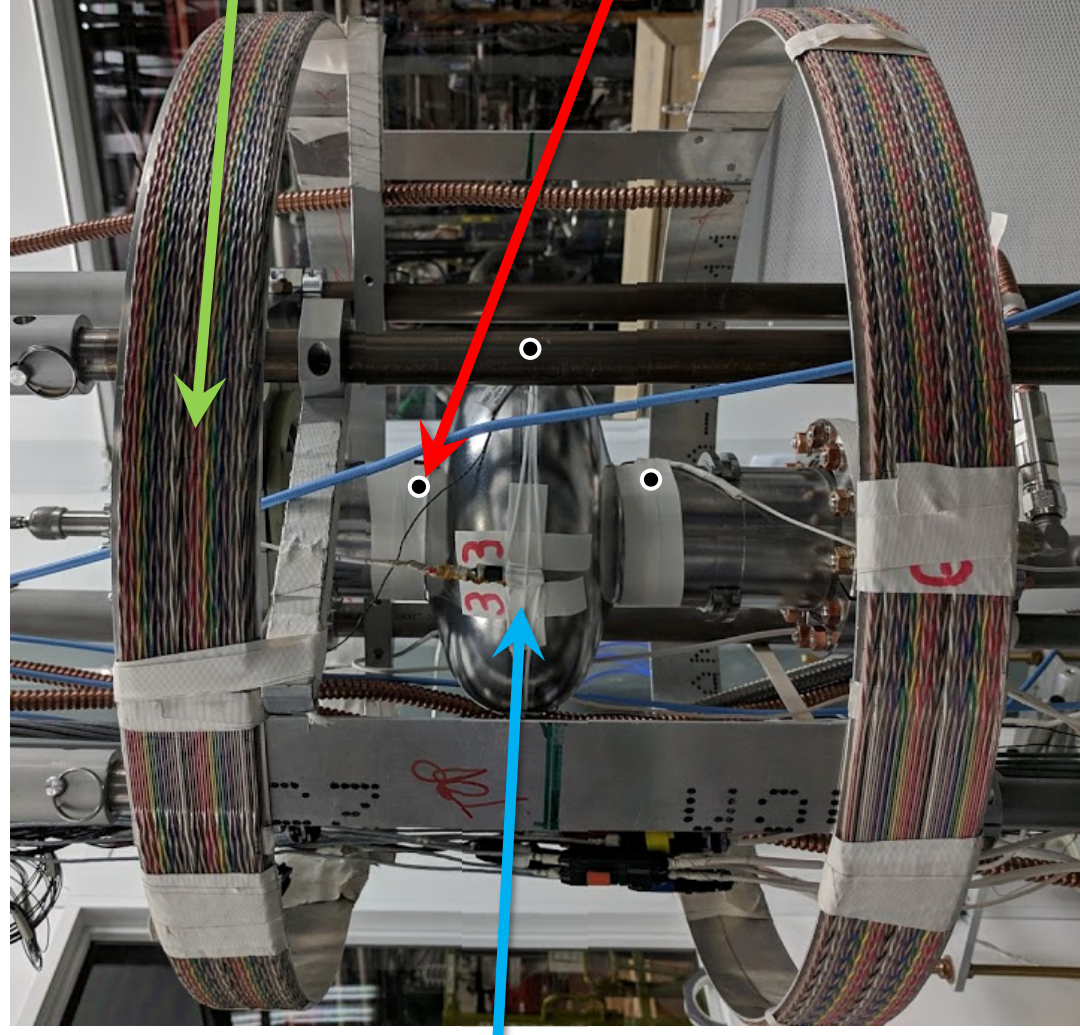
Cite as: J. Appl. Phys. 115, 184903 (2014); <https://doi.org/10.1063/1.4875655>
Submitted: 07 March 2014 . Accepted: 28 April 2014 . Published Online: 09 May 2014
A. Romanenko, A. Grassellino, O. Melnychuk, and D. A. Sergatskov



- **Fast/High massflow cool-down** leads to **large thermal gradients** which promote strong flux expulsion
- **Slow/low massflow cool-down** → poor flux expulsion



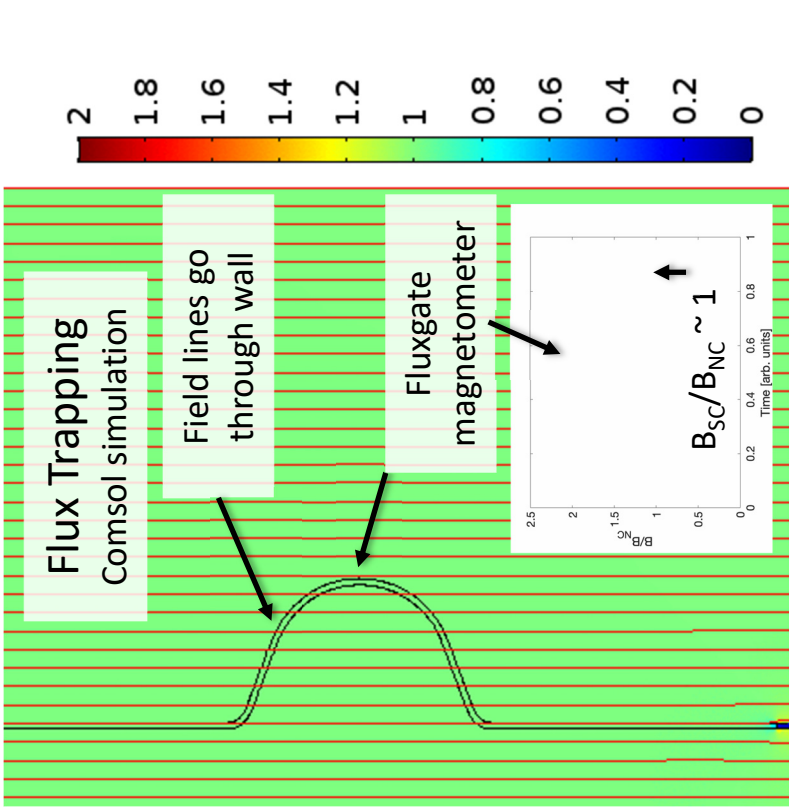
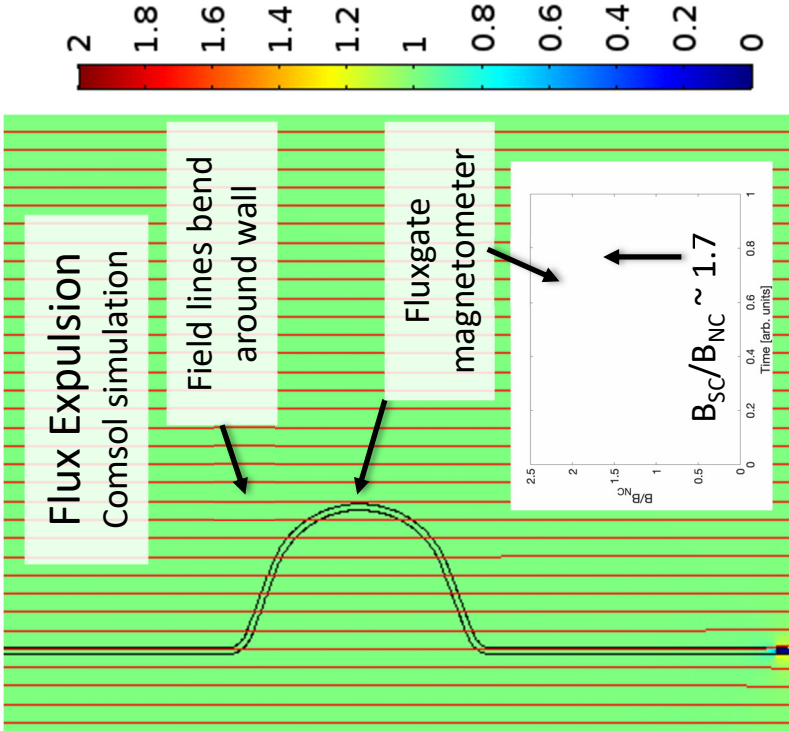
Measuring Flux Expulsion in Vertical Dewar Test



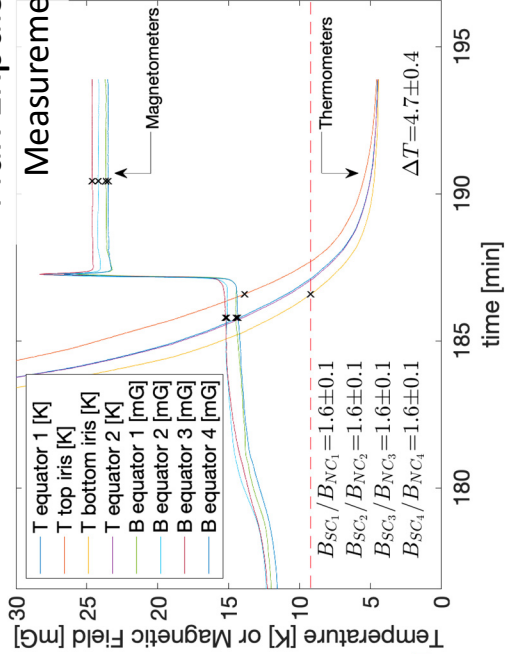
**Magnetic
field coils**
(tens of mG
applied field)

**Temperature
Sensors**
(Top, middle,
bottom of cell)

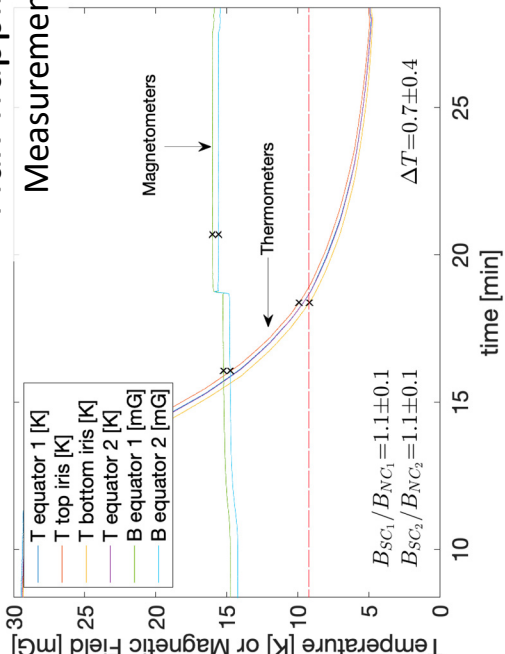
**Fluxgate
magnetometers**
(3 around cell
of cavity)



Flux Expulsion

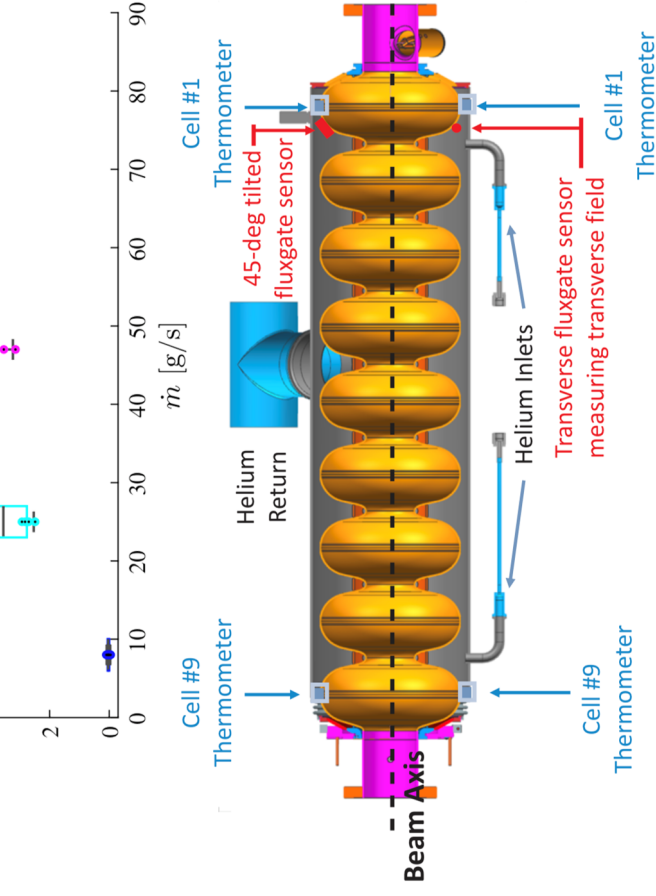
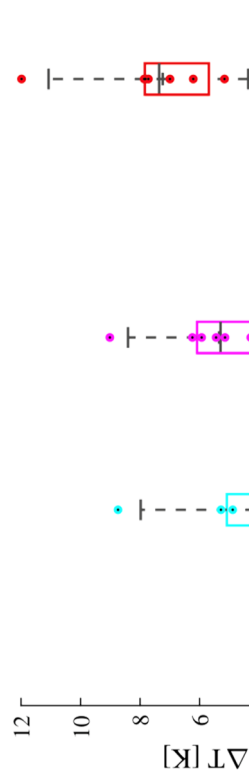
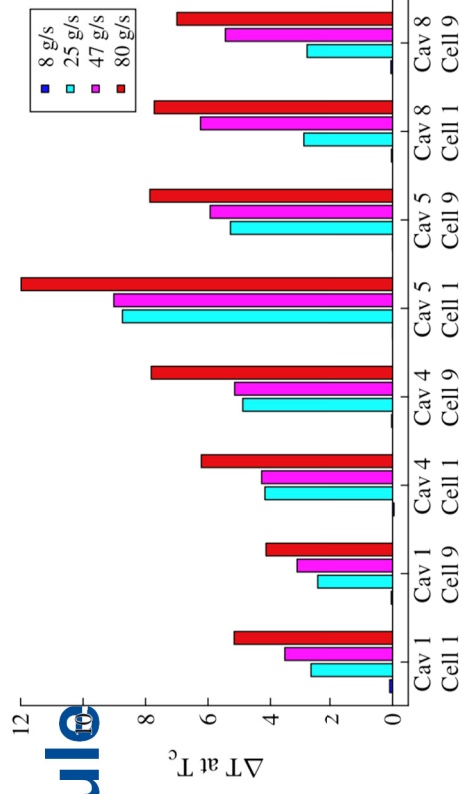


Flux Trapping



Achieving dT/dx in Cryomodule

- Cryo feeds on every CM for individual cooldown
- Cavities fed with two inlets
- Excellent dT/dx observed in prototype CMs (extra T sensors)



Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high Q_0 applications

Cite as: J. Appl. Phys. 119, 213903 (2016); <https://doi.org/10.1063/1.4953087>

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S. Posen, M. Checchin, A. C. Crawford , A. Grassellino, M. Martinello, O. S. Melnychuk, A. Romanenko, D. A. Sergatskov , and Y. Trenikhina



- **Significant variation** in flux expulsion behavior for high RRR niobium given 800 C furnace treatment
- **Developed “cure”** for poorly expelling material – heat treatment at 900-1000 C

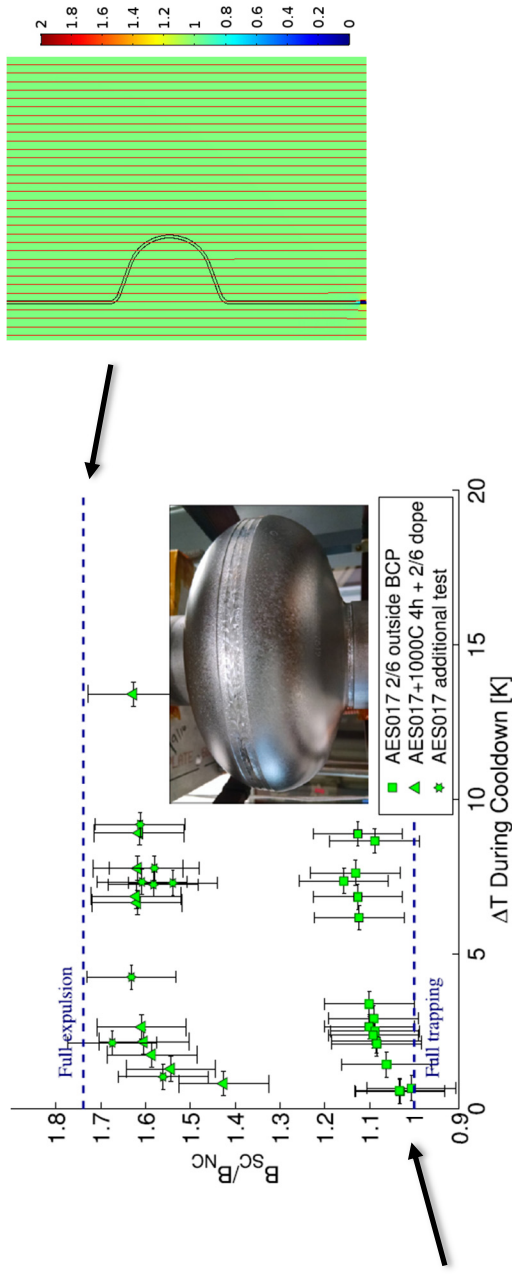
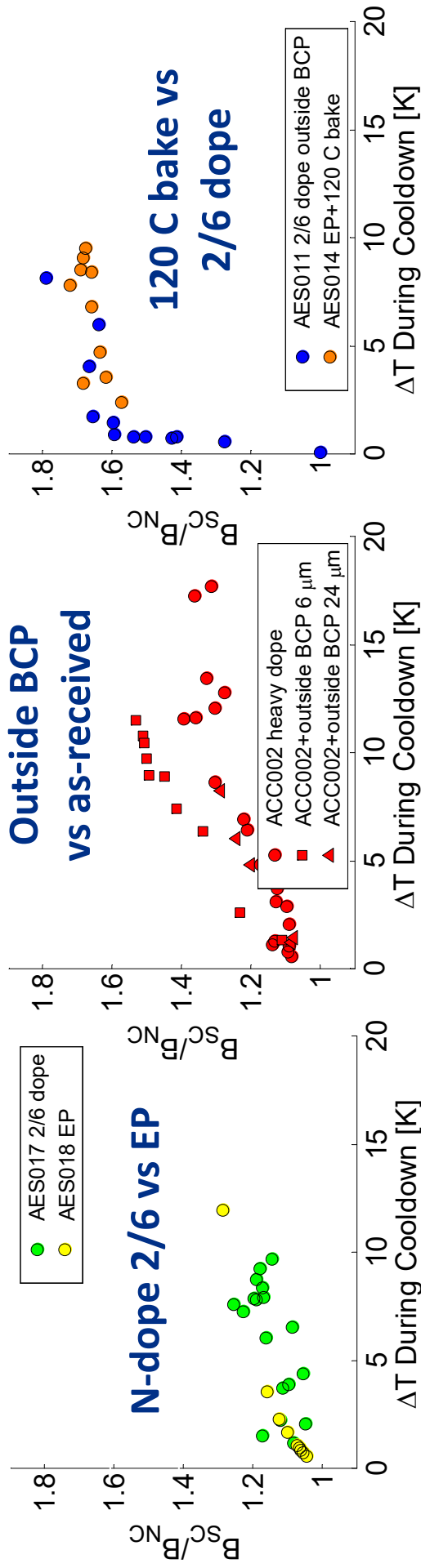
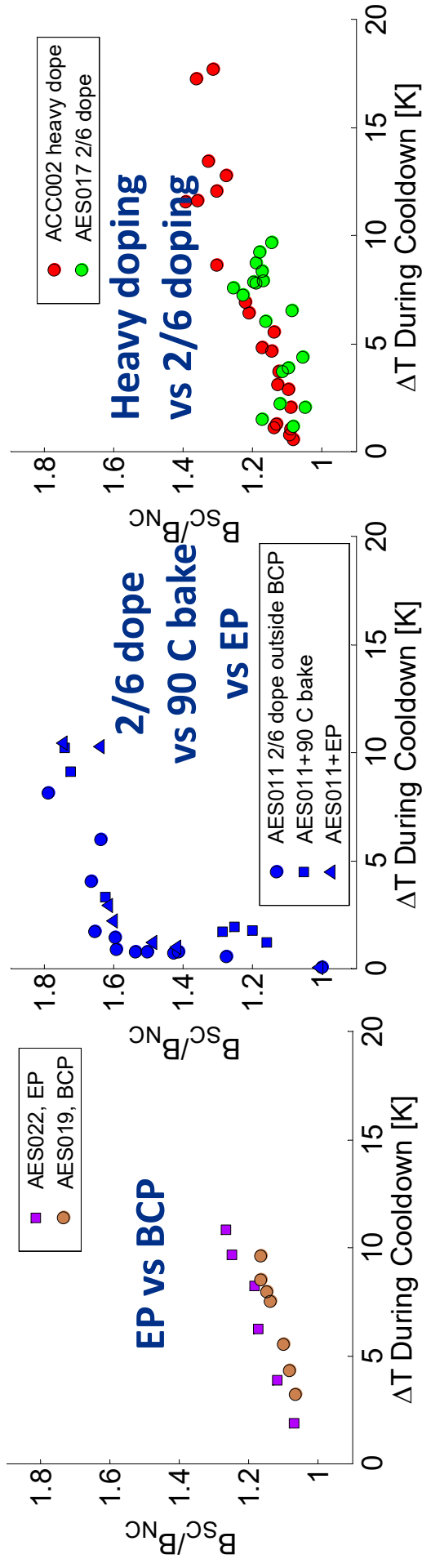


FIG. 6. AES017, a cavity from production group 2 that showed strong flux trapping behavior, was converted to expel strongly after a 1000 °C 4 h furnace treatment. The inset image shows the grain growth after treatment.

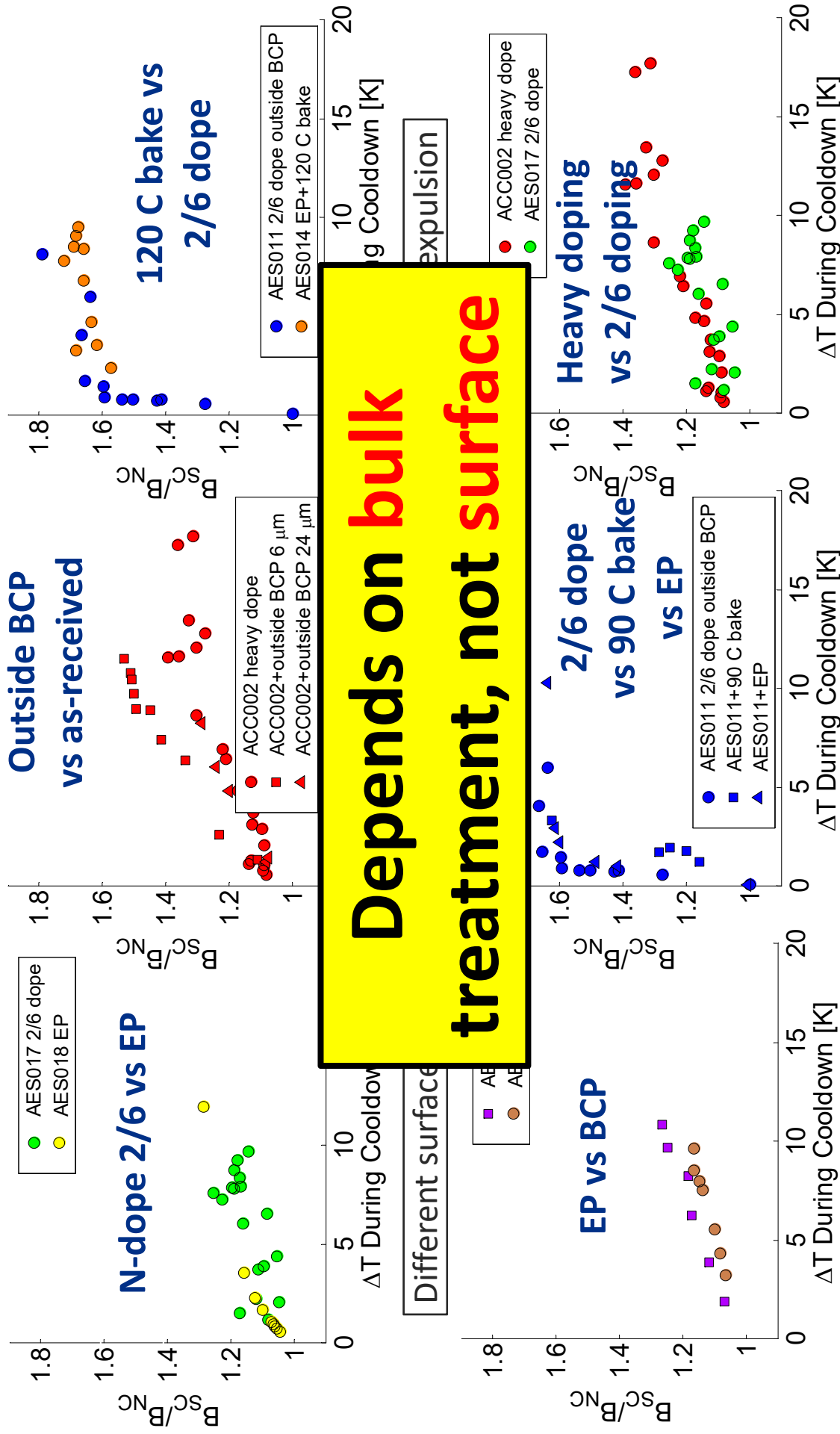
1) Surface treatments have insignificant impact



Different surface conditions in cavities with similar bulk history: similar expulsion

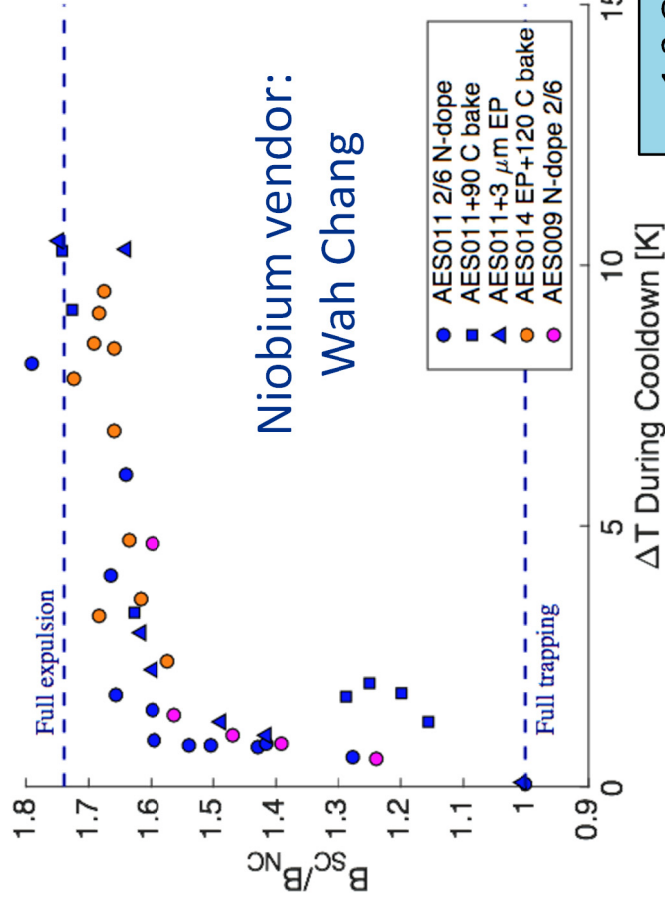


1) Surface treatments have insignificant impact

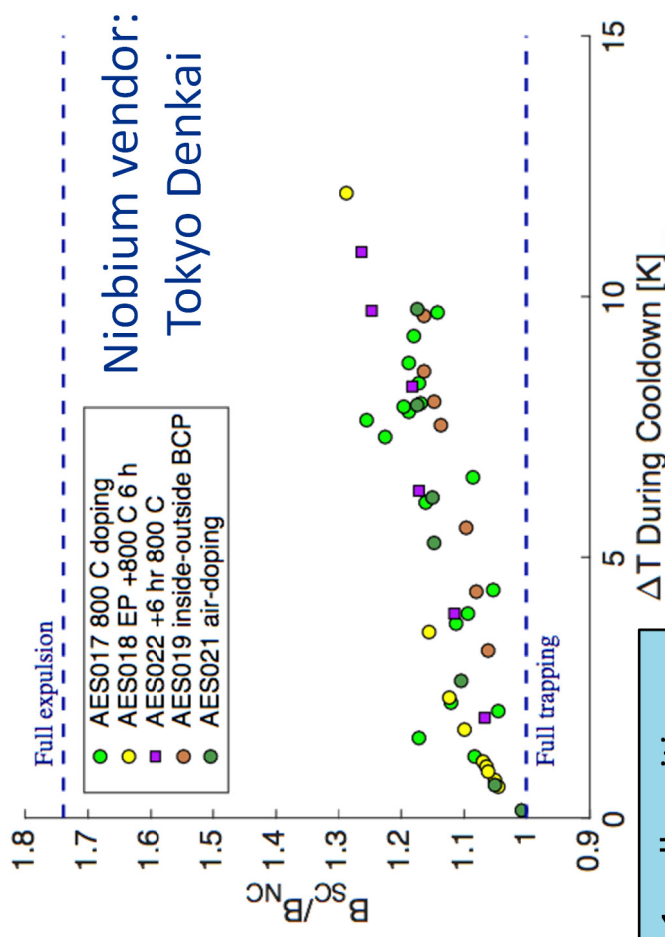


2) Some niobium production runs have very poor expulsion – even with large ΔT

- Seems to be a great deal of variability in as-received material
- All cavities below given 800 C heat treatment

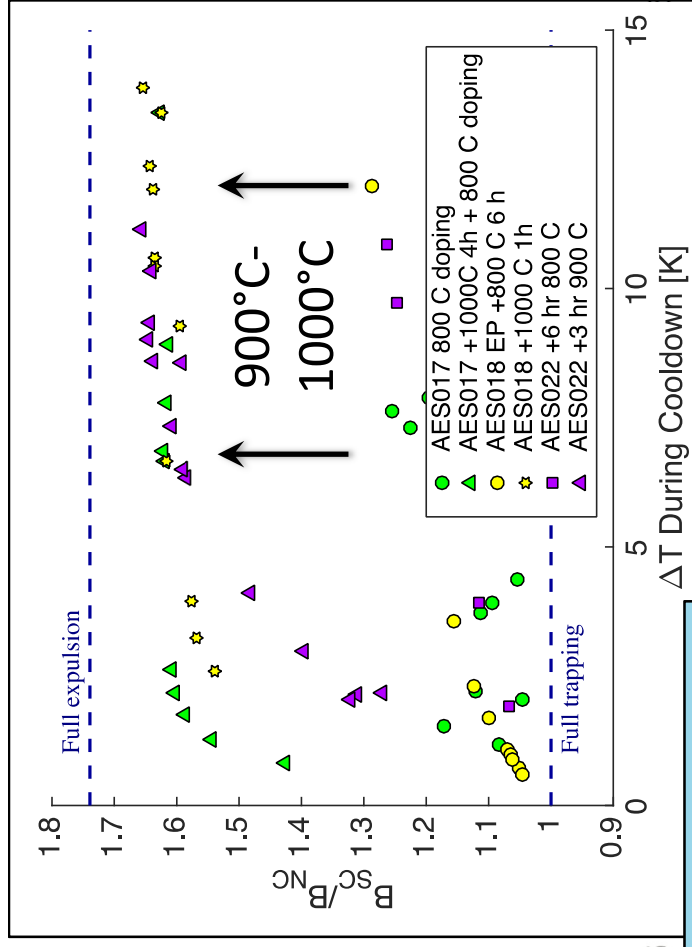
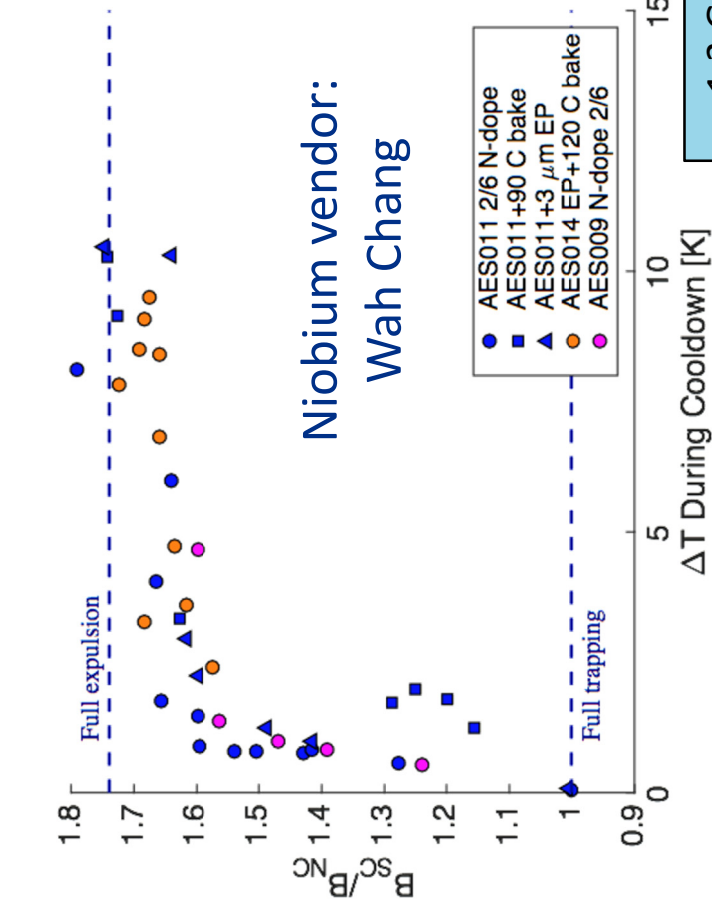


1.3 GHz 1-cell cavities



3) High temperature treatment can make poorly expelling material expel well even with small ΔT

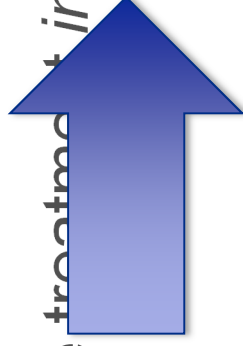
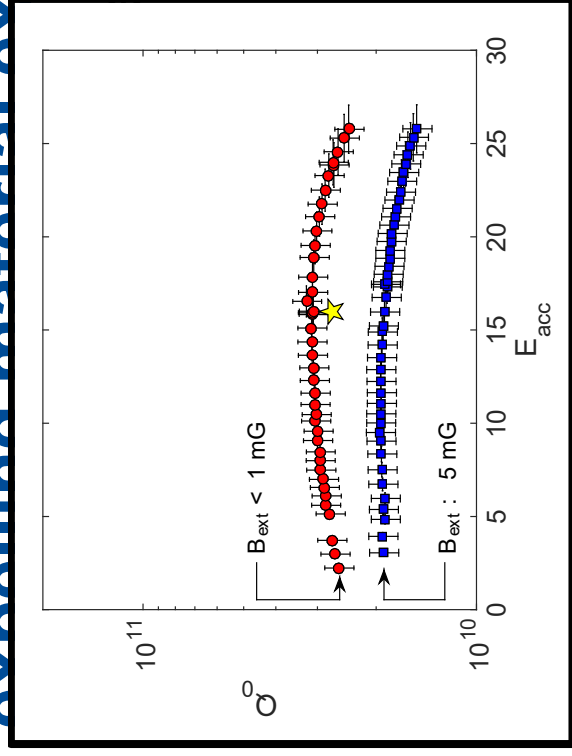
- 900 C – 1000 C furnace treatment *improves* expulsion



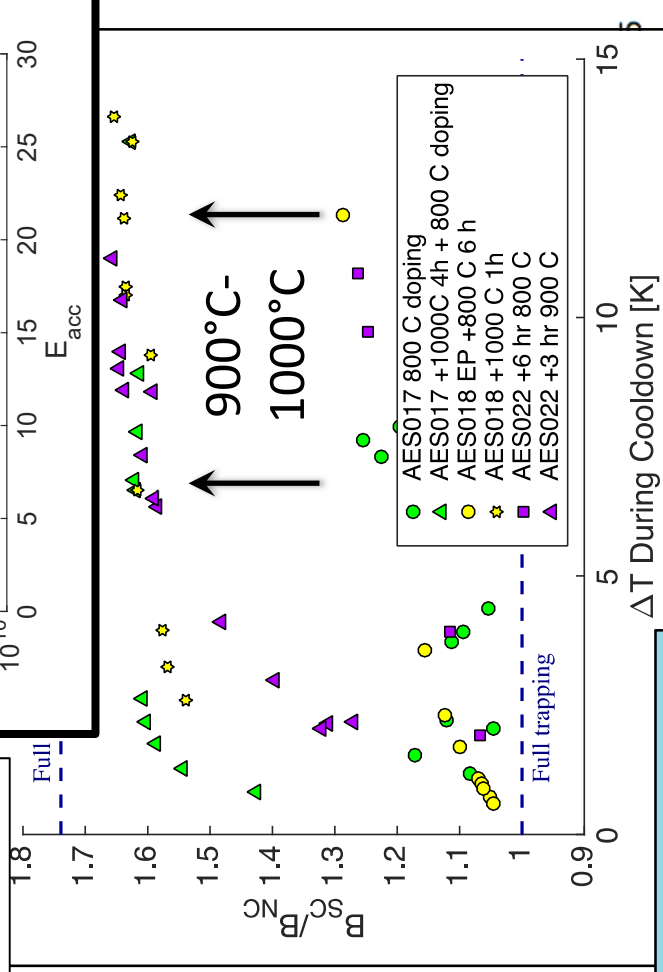
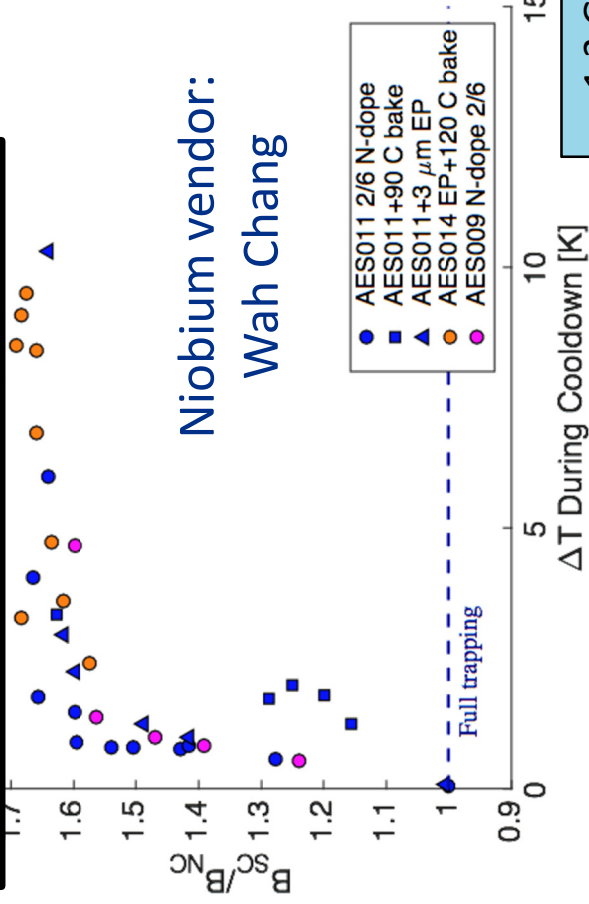
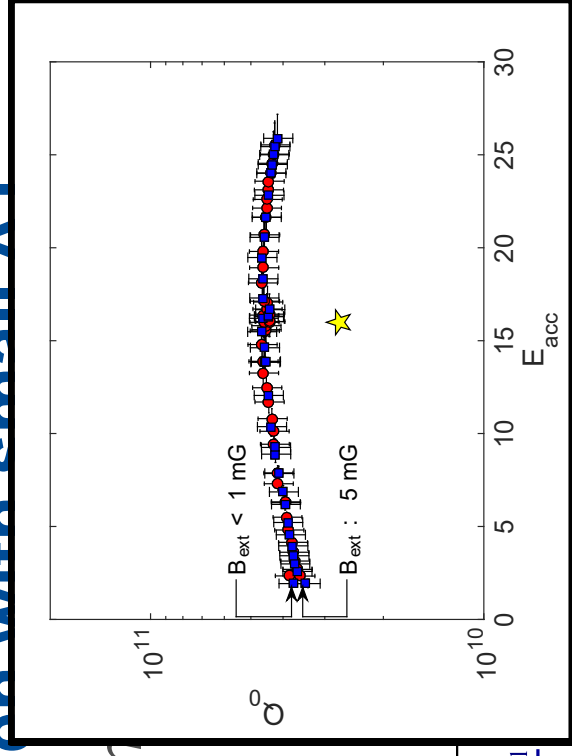
1.3 GHz 1-cell cavities



3) High temperature treatment can make poorly expelling material expel well even with small ΔT



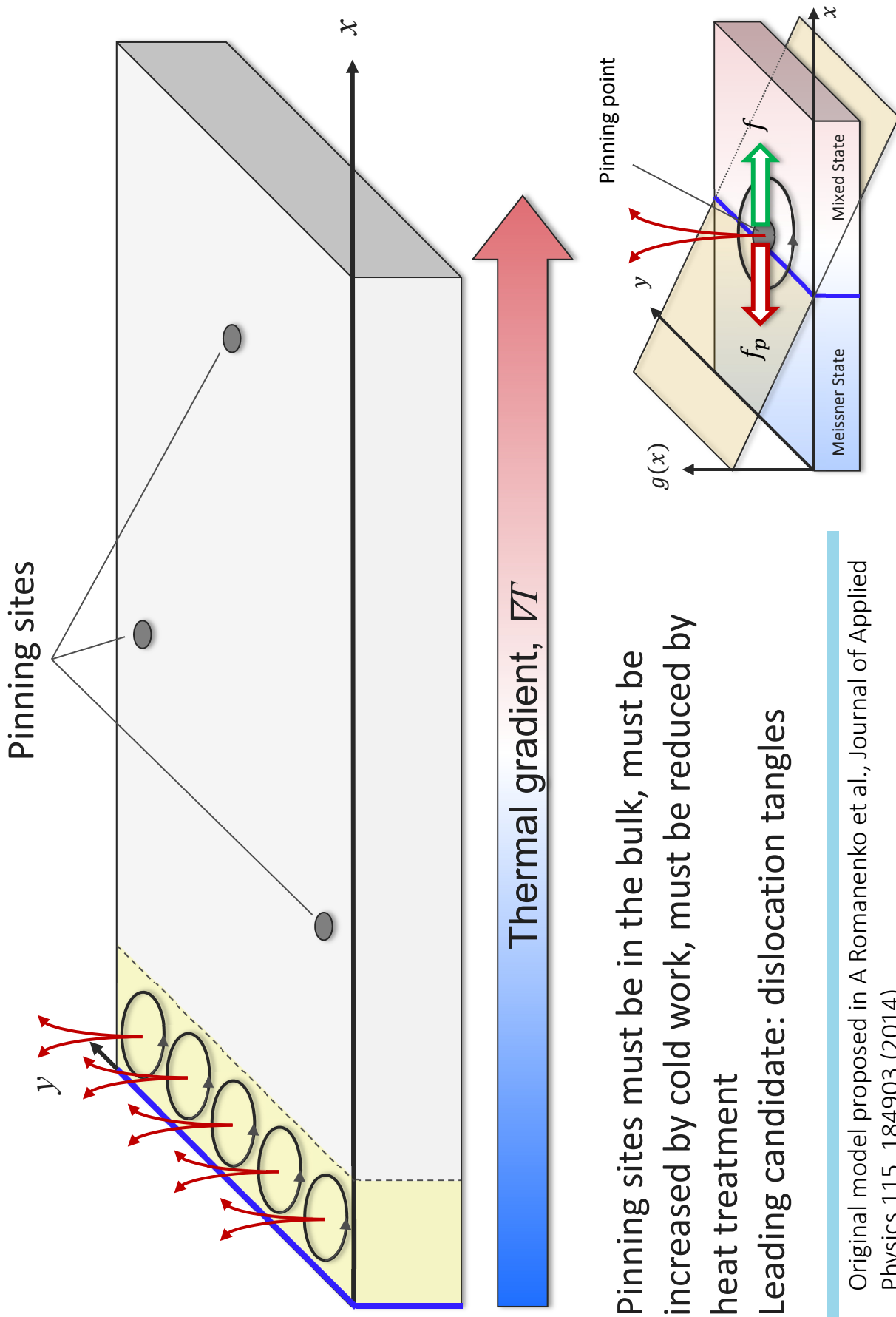
900°C
treatment



1.3 GHz 1-cell cavities

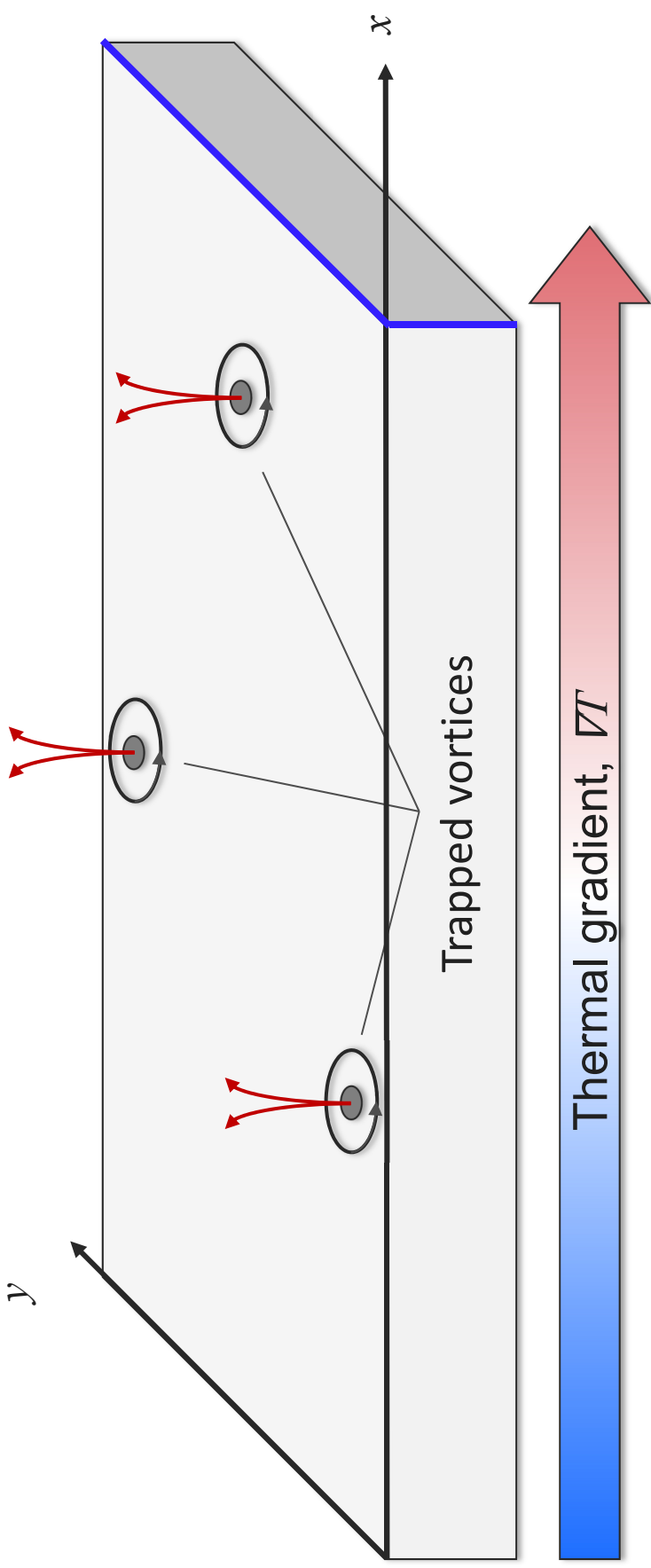


Model for Flux Expulsion Consistent with Observations

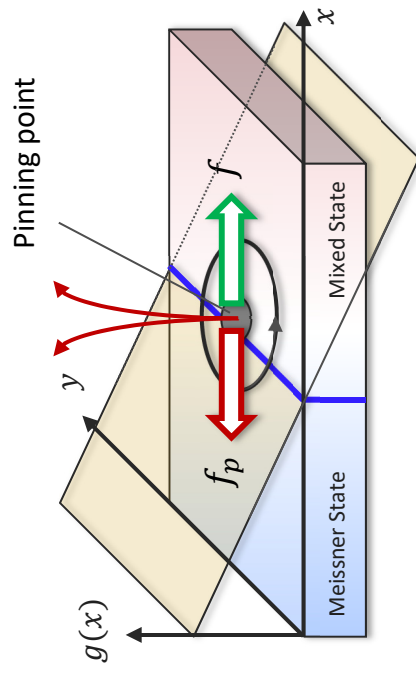


- Pinning sites must be in the bulk, must be increased by cold work, must be reduced by heat treatment
- Leading candidate: dislocation tangles

Model for Flux Expulsion Consistent with Observations

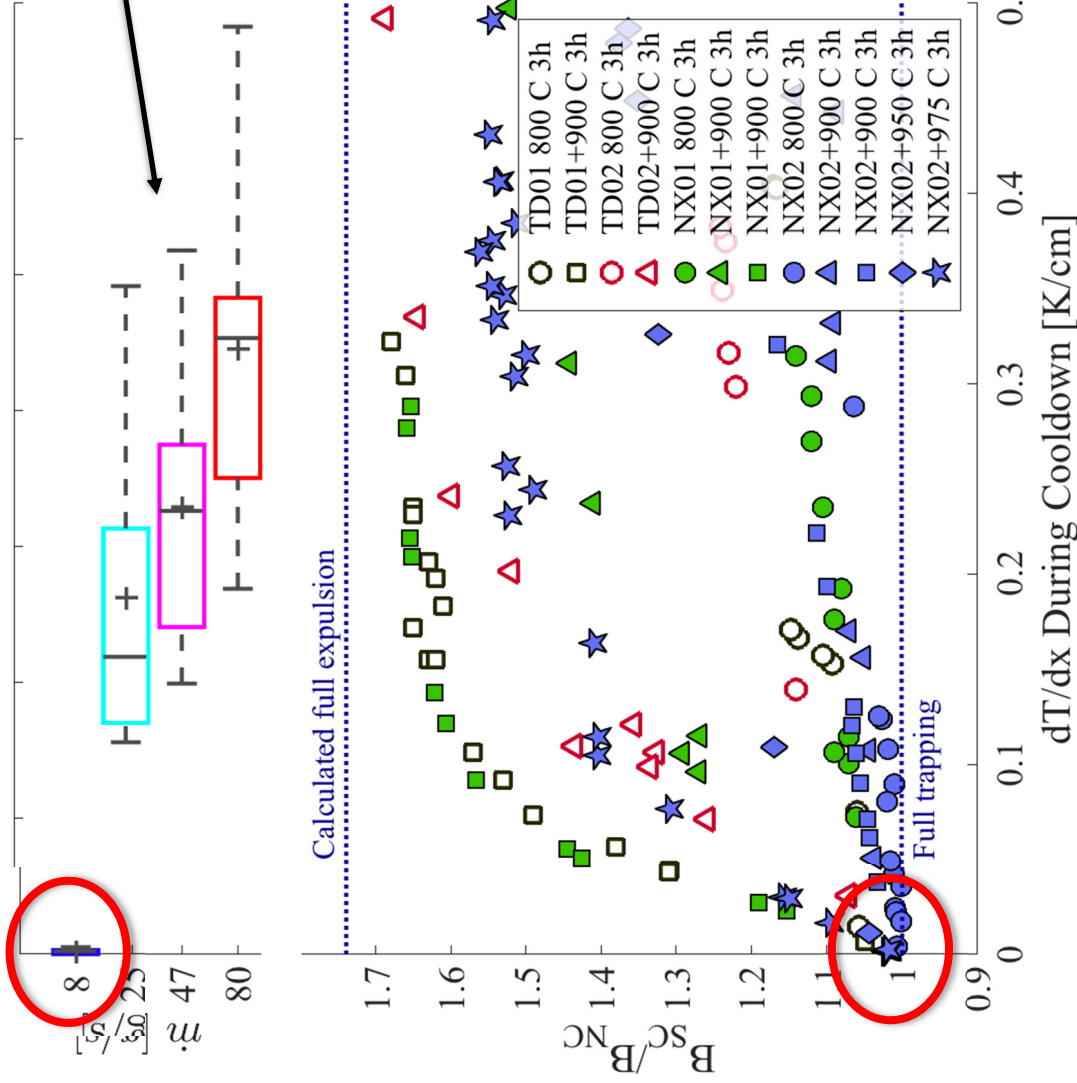


- Pinning sites must be in the bulk, must be increased by cold work, must be reduced by heat treatment
- Leading candidate: dislocation tangles



Original LCLS-II Production Material

Low massflow/slow cooldown traps all flux regardless of the heat treatment!

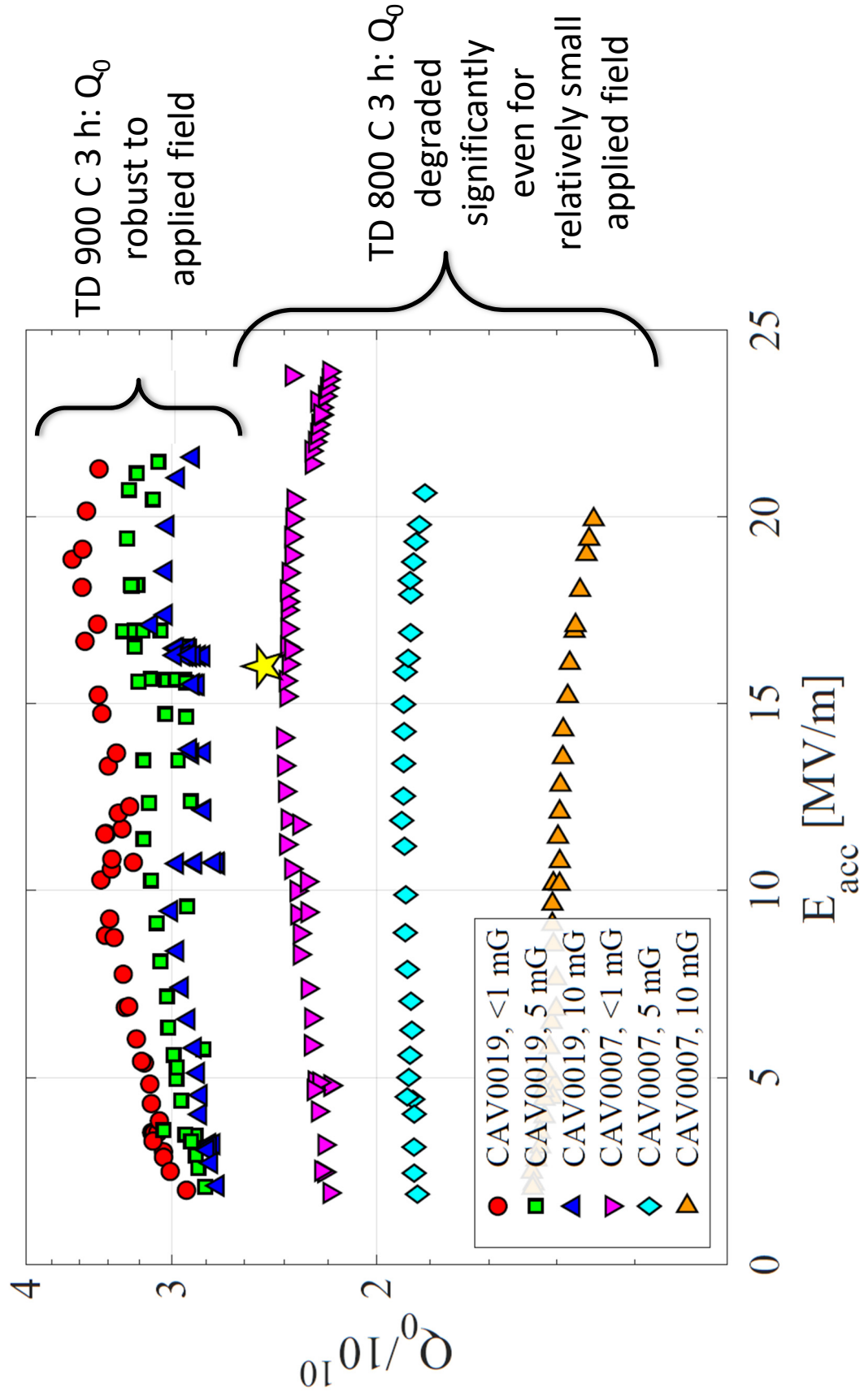


Fermilab pCM data shows importance of high massflow – of 4 cooldowns, only those with massflow >25 g/s extend into acceptable expulsion range; more g/s expected to achieve better expulsion

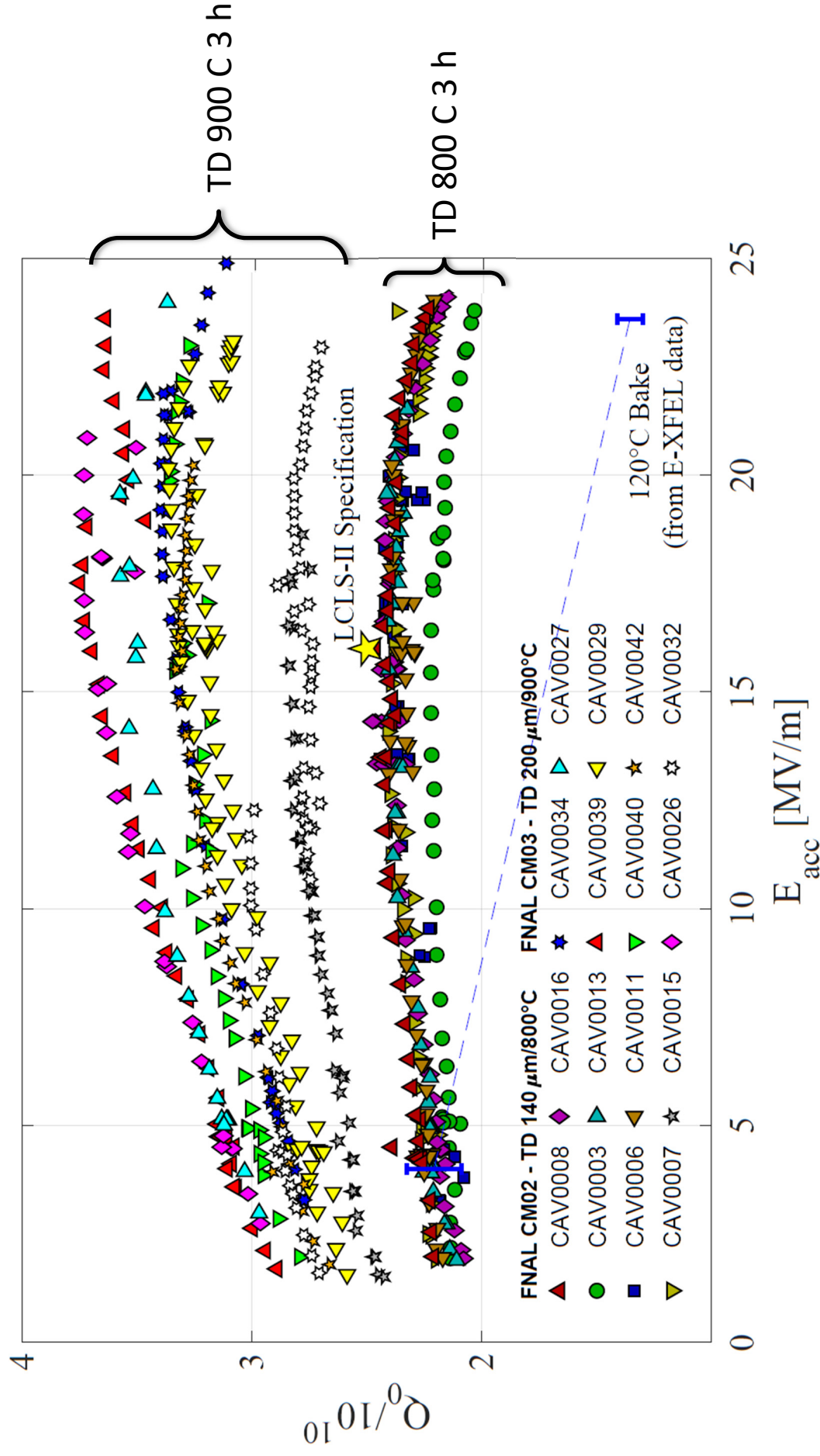
Conclusion about original LCLS-II Nb:

- Very poor expulsion with only 800 C 3 h
- **TD needs 900 C 3h** (both cavities)
- **NX needs 950 C – 975 C** (NX2 more stubborn than NX1)

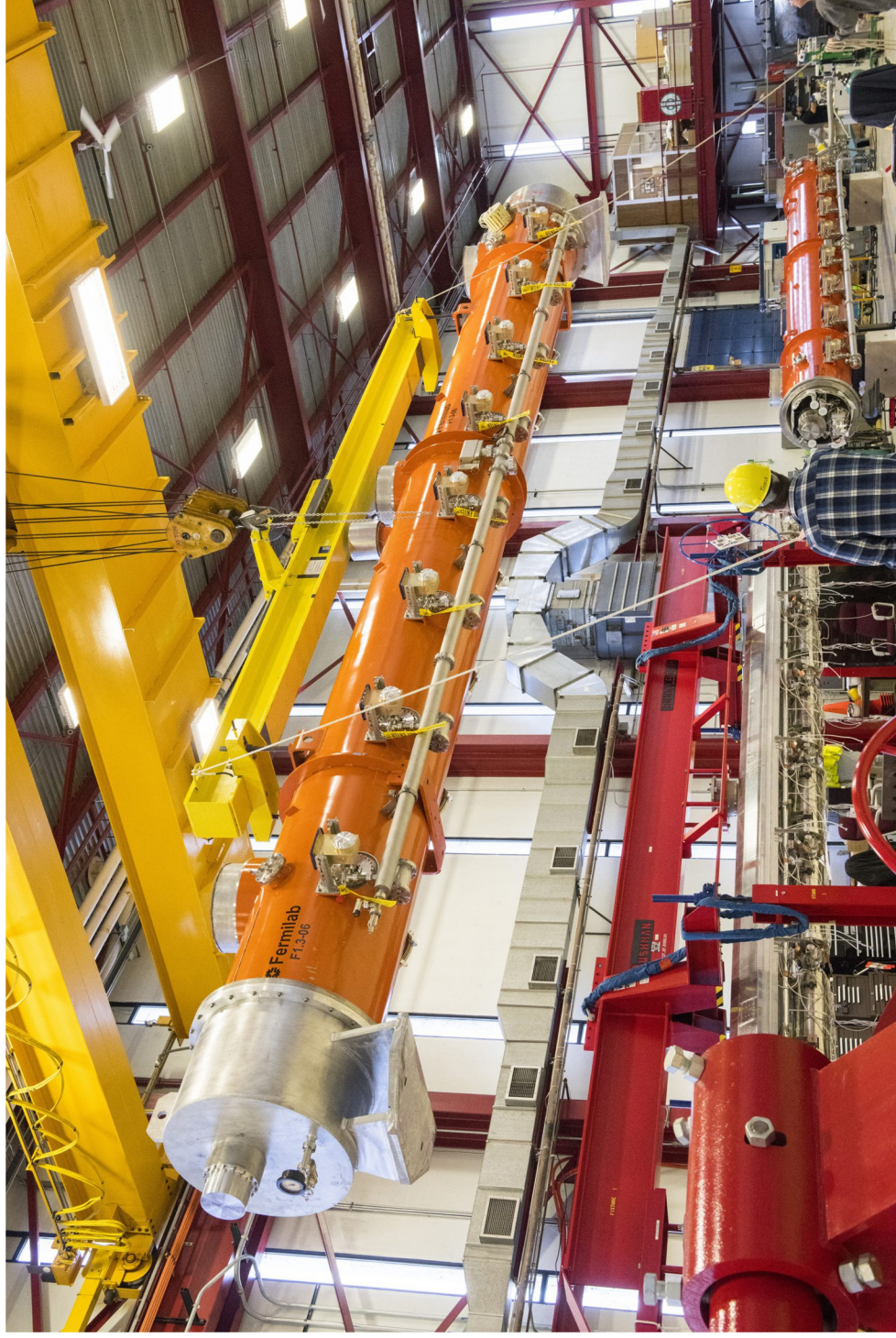
Effect of Heat Treatment in Vertical Test



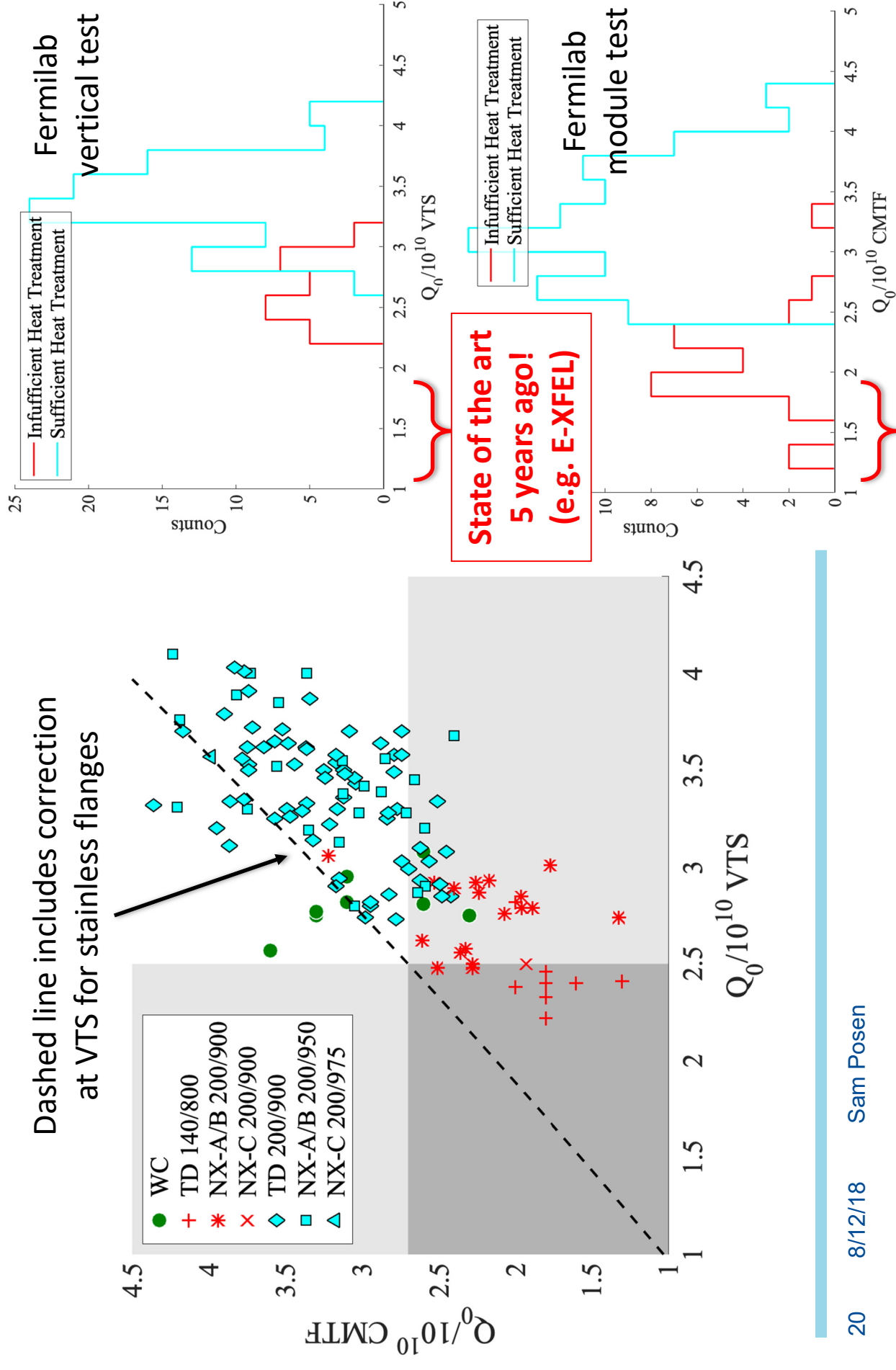
Effect of Heat Treatment in Vertical Test



LCLS-II Cryomodule Production at Fermilab



Fermilab CMTF and VTS Data F1.3-01 through 016

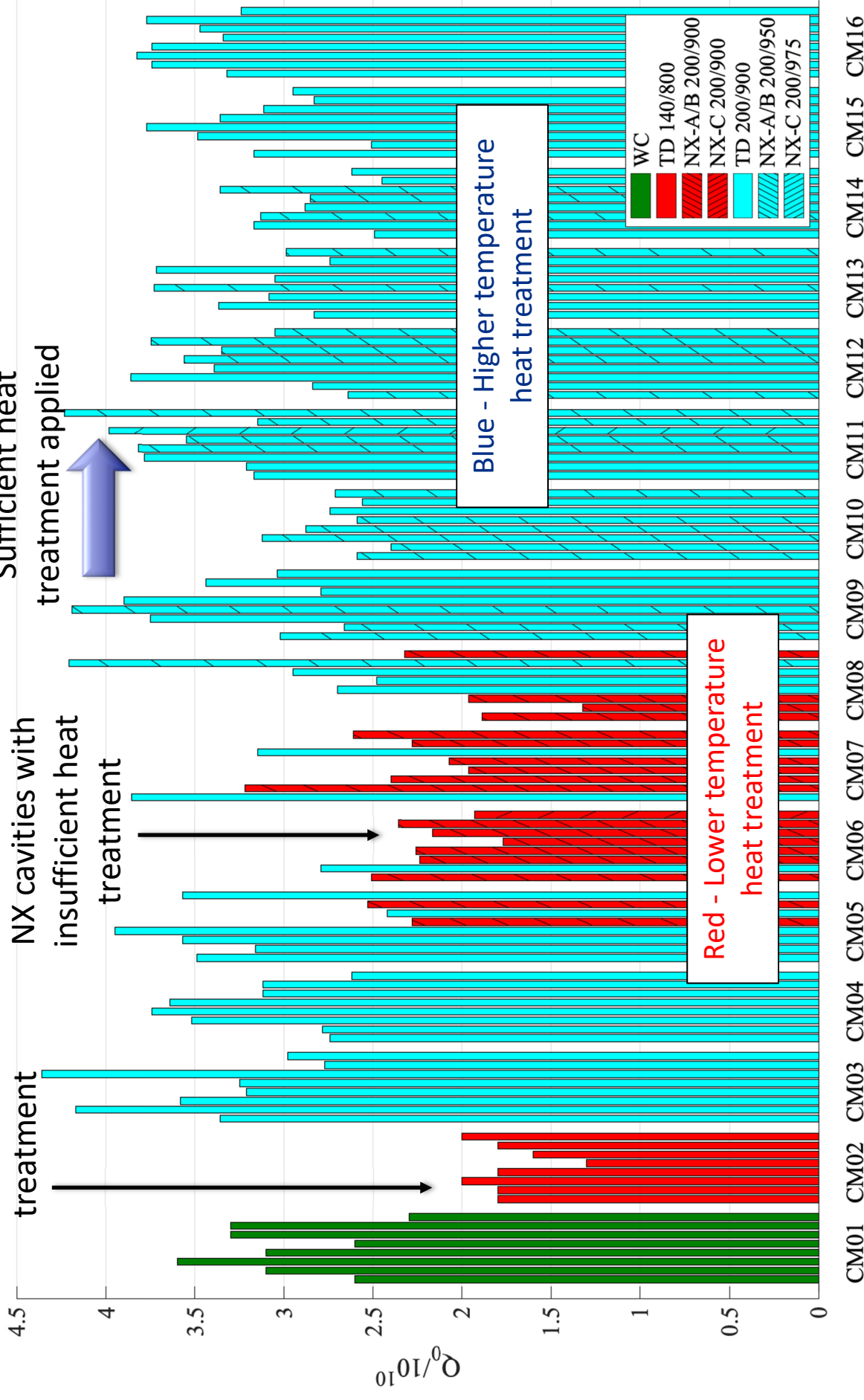


Fast cooldown at CMTF, $E_{acc} \sim 16$ MV/m, 2.0 K

TD cavities with
insufficient heat
treatment

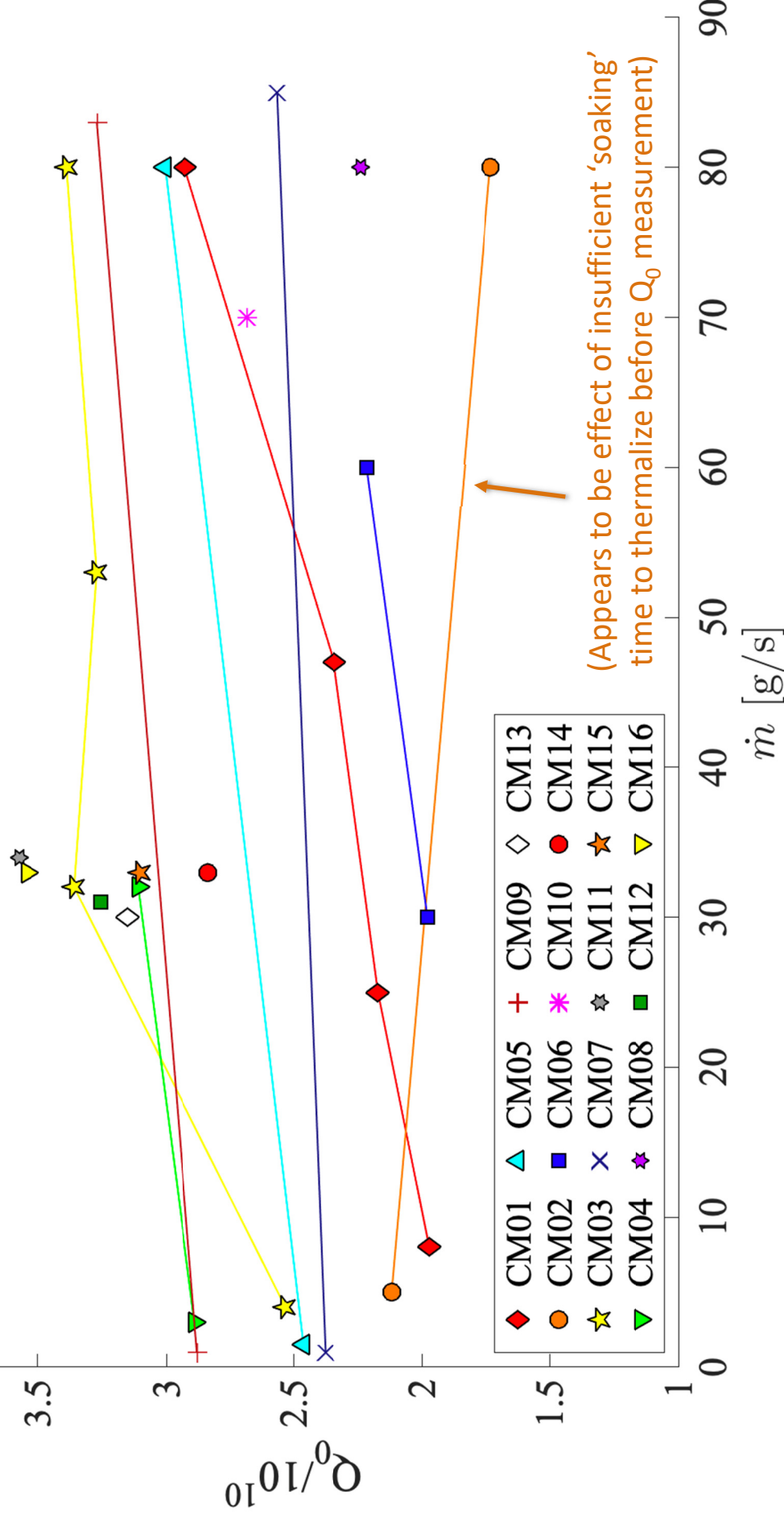
NX cavities with
insufficient heat
treatment

Sufficient heat
treatment applied



Effect of Massflow on Q_0

Expected trend is observed – higher massflow ->
improved expulsion -> higher Q_0



Summary

- Poor flux expulsion created a risk of low Q_0 for LCLS-II production material with baseline recipe. This was mitigated via high massflow and a 900-1000 C heat treatment developed in timely R&D
- $Q_0 \sim 3 \times 10^{10}$ is regularly being achieved in LCLS-II cryomodules with modified heat treatment
- Temperature required was found to depend on niobium production run, but material from both vendors was made to satisfy the stringent requirements of LCLS-II
- We are actively working on R&D to guide modifications to material specifications for future high Q_0 SRF cavity production
- Use flux expulsion to significantly raise Q_0 for LCLS-II HE, PIP-II, ILC, and beyond

Acknowledgements

- LCLS-II cryomodule production in partnership with teams at FNAL, JLab, and SLAC
- All cryomodule measurements shown here are by FNAL LCLS-II team
- Major thanks to Genfa Wu, Anna Grassellino, Elvin Harms, Nikolay Solyak

