Magnetic Flux Expulsion Studies on Niobium

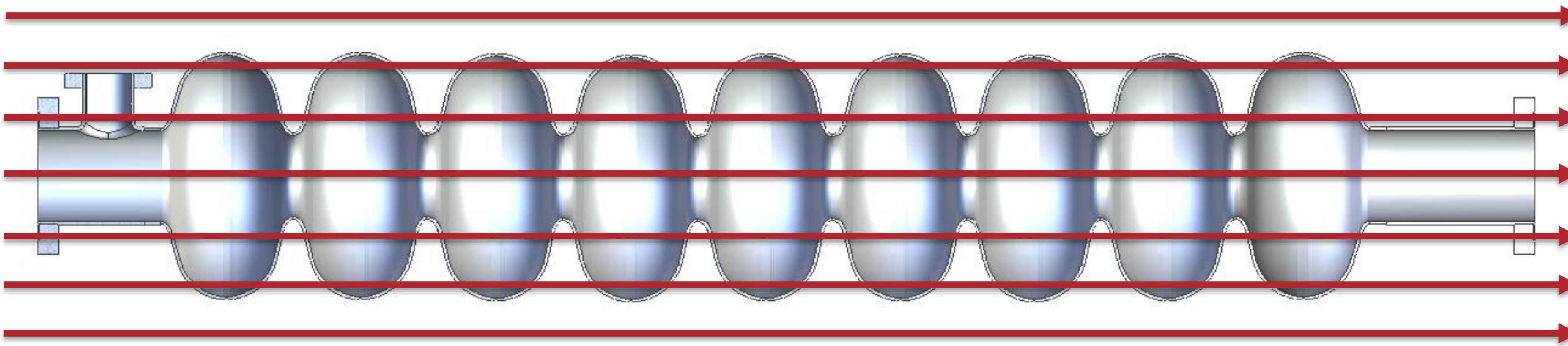
Sam Posen & Fermilab SRF Team

SRF Conference 2017

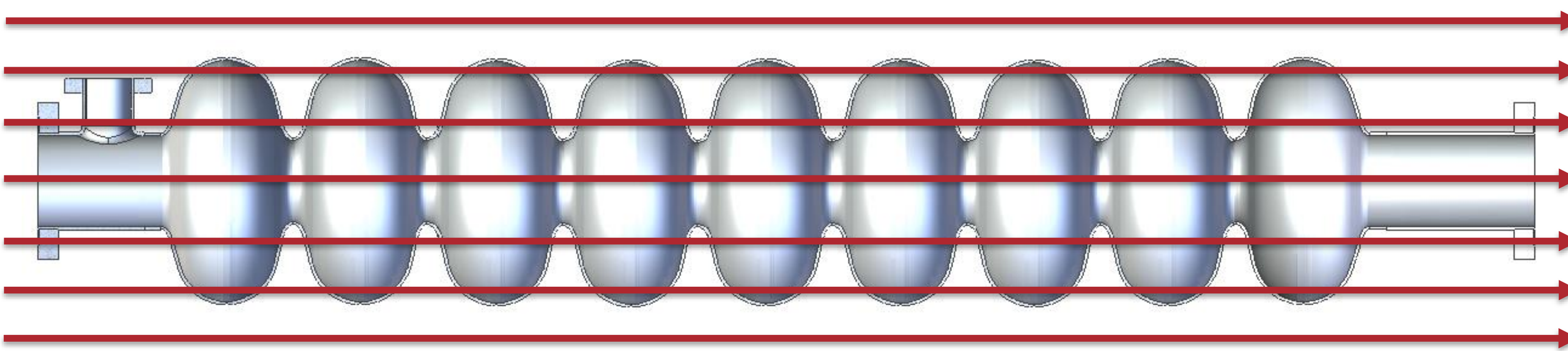
18 July 2017

Live from Batavia, USA!

Why Flux Expulsion is Important

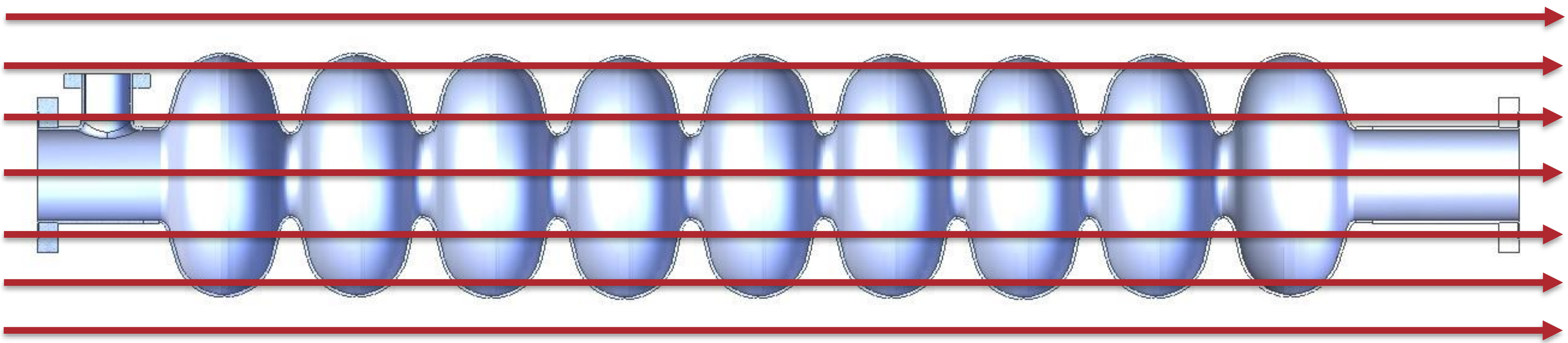


LCLS-II CAV0007 – fabricated and prepared by RI, TD material

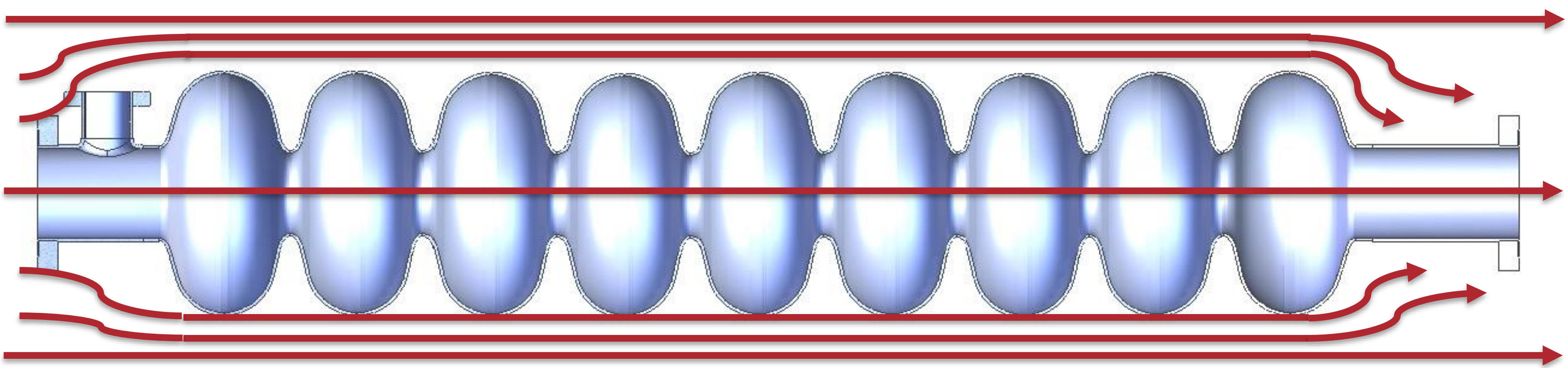


LCLS-II CAV0019 – fabricated and prepared by RI, TD material

Why Flux Expulsion is Important



LCLS-II CAV0007 – fabricated and prepared by vendor B, TD material



LCLS-II CAV0019 – fabricated and prepared by vendor B, TD material

Why Flux Expulsion is Important

Cavity	Usable Gradient* [MV/m]	Q0 @ 16 MV/m (or useable gradient) 2 K
CAV0008	20.5	2.0E+10
CAV0003	21.0	2.5E+10
CAV0006	21.0	2.0E+10
CAV0007	21.0	2.2E+10
CAV0016	18.2	1.8E+10
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CAV0011	20.5	2.3E+10
CAV0015	21.0	2.3E+10
Average	**20.0**	**2.1E+10**
Total Voltage	**166 MV**	

Cavity	Usable Gradient* [MV/m]	Q0 @ 16 MV/m (or useable gradient) 2 K
CAV0034	21.0	3.4E+10
CAV0039	21.0	4.2E+10
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CAV0026	9.2	3.2E+10
CAV0027	21.0	3.2E+10
CAV0029	21.0	4.4E+10
CAV0042	16.8	2.8E+10
CAV0032	21.0	3.0E+10
Average	**17.6**	**3.5E+10**
Total Voltage	**146 MV**	

Fermilab CM-2
Cavities treated with baseline recipe

Fermilab CM-3
Treatment modified to improve flux expulsion

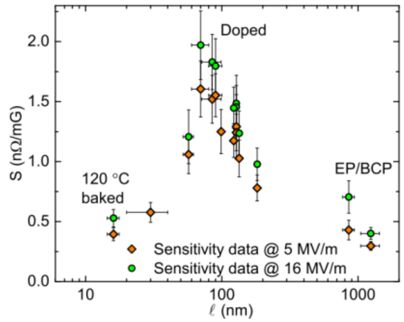
Total voltage Spec: 133 MV Q_0 Spec: 2.7×10^{10}

Magnetic Flux Expulsion

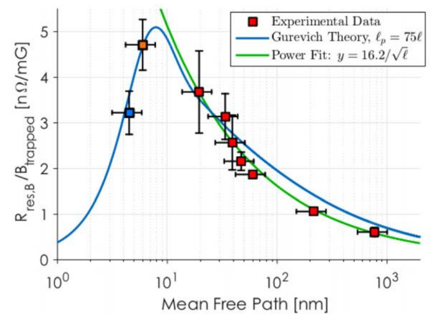
Background

Expulsion is an Important Factor in Flux Losses

- Determines what fraction of ambient flux becomes trapped
- Other factors:
  - Sensitivity to trapped flux

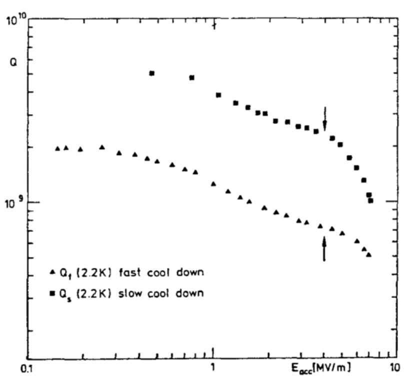


M. Martinello et al. Appl. Phys. Lett. 109, 062601 (2016)

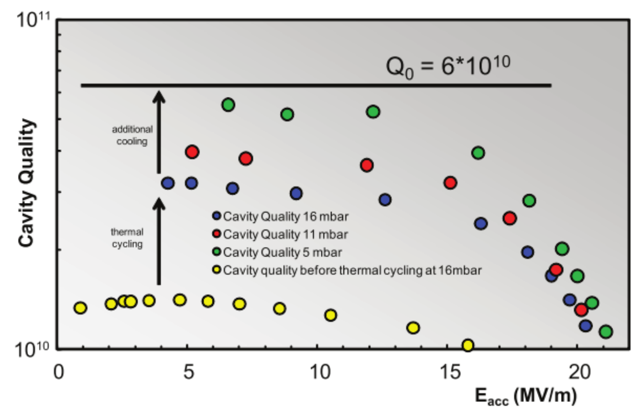


D. Gonnella et al. Appl. Phys. Lett. 119, 073904 (2016)

  - Thermocurrents due to connections near cavity (e.g. He vessel)
  - Thermocurrents due to bilayers (e.g. Nb_3Sn/Nb)



M. Peiniger et al. SRF Workshop (1988).



O. Kugeler et al. SRF Conference (2009).

Expulsion is an Important Factor in Flux Losses

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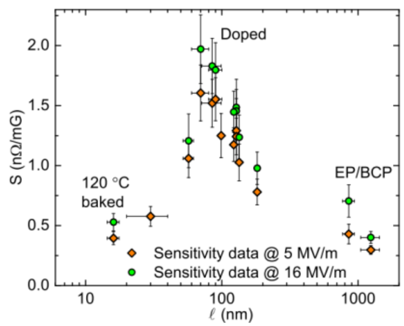
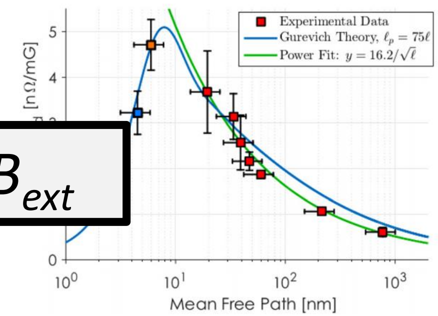


M. Martinello et al.
Appl. Phy
109, 062

$$R_{fl} = S \cdot \eta \cdot B_{ext}$$



D. Gonnella et al.
Appl. Phys. Lett.
119, 073904 (2016)

  - Thermocurrents due to connections near cavity (e.g. He vessel)
  - Thermocurrents due to bilayers (e.g. Nb Sn/Nb)

S depends on surface treatment (e.g. N-doping vs EP)
B_{ext} depends on shielding, hygiene, thermocurrents
What about *η*? Recent experimental evidence: thermal gradient during cooldown & **bulk structure**

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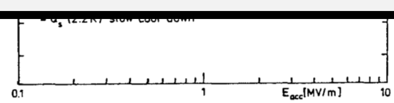
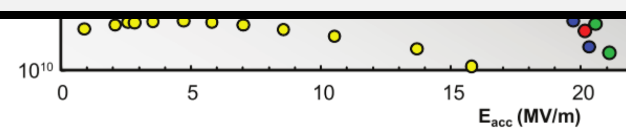


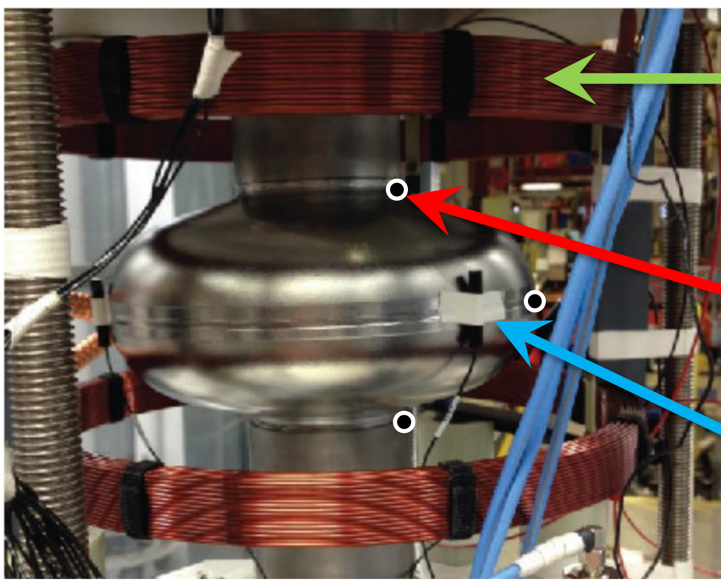


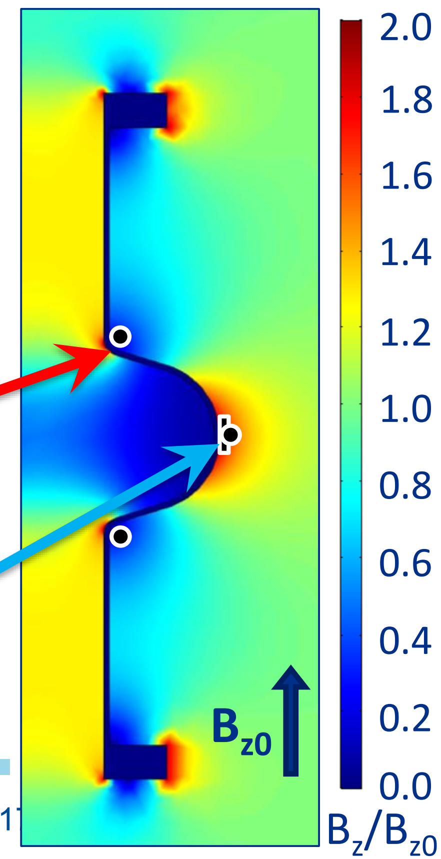
Fermilab

A. Romanenko et al., Appl. Phys. Lett. 105, 234103 (2014)
A. Romanenko et al., J. Appl. Phys. 115, 184903 (2014)

Measuring Flux Expulsion

- An axial magnetic field is applied during cooldown. Fluxgate magnetometers at the equator measured the magnetic field before B_{NC} and after B_{SC} superconducting transition.
  - Complete trapping: $B_{SC}/B_{NC} = 1$
  - Complete expulsion: $B_{SC}/B_{NC} \sim 1.7$



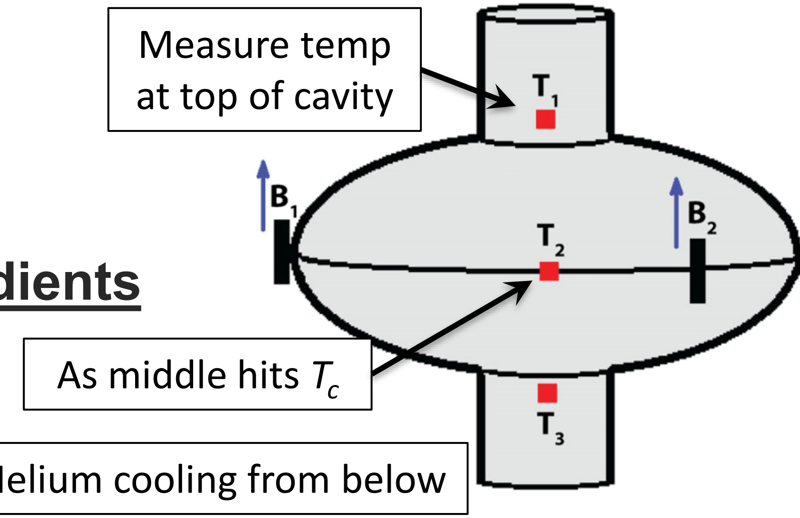


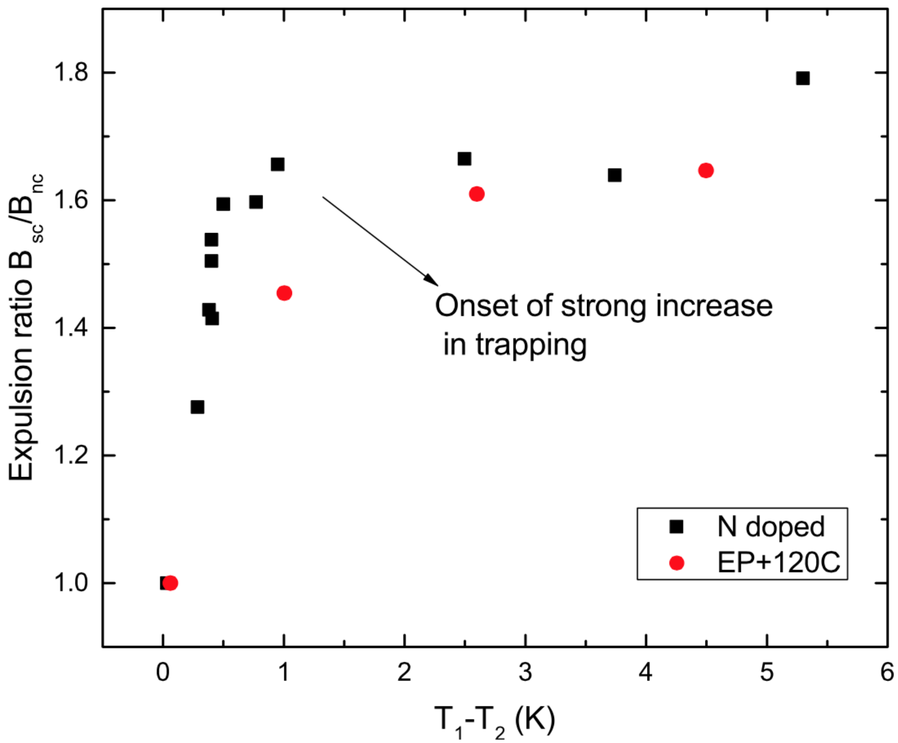
Magnetic Flux Expulsion

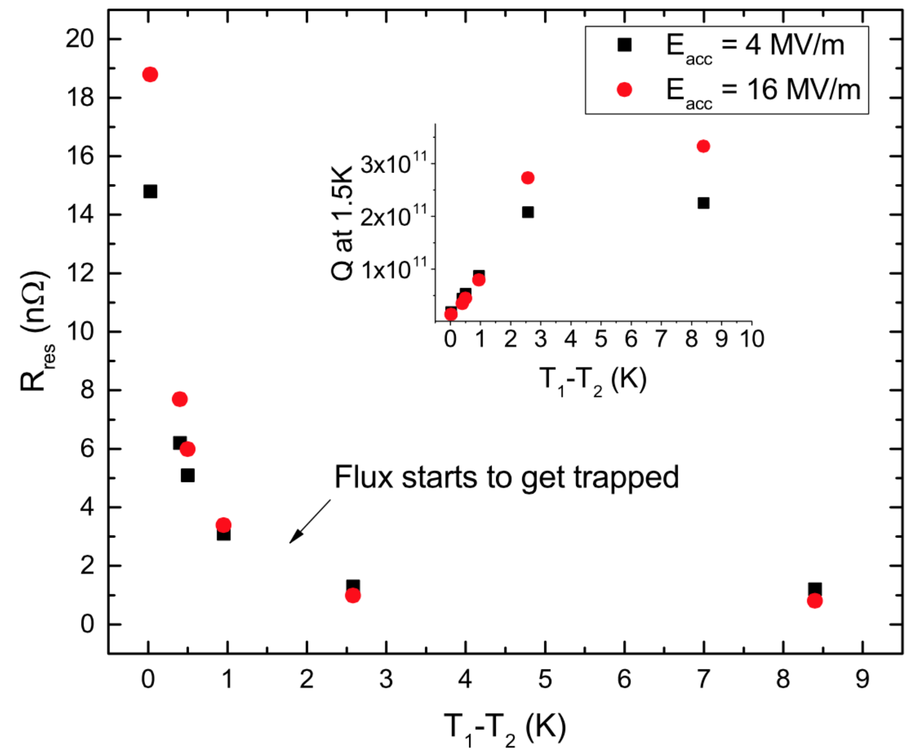
Results of Experiments to Probe the Physics of Flux Expulsion

1) Large thermal gradients at T_c promote expulsion of flux

- **Fast cool-down** lead to **large thermal gradients** which promote efficient flux expulsion
- Slow cool-down → poor flux expulsion







A. Romanenko et al., Appl. Phys. Lett. 105, 234103 (2014)
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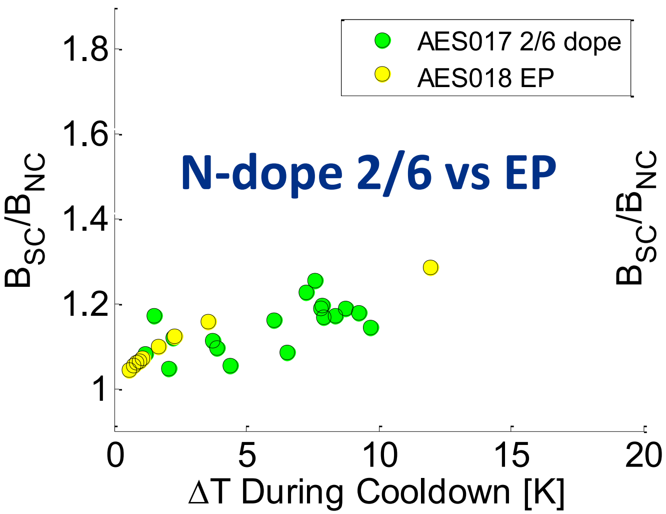
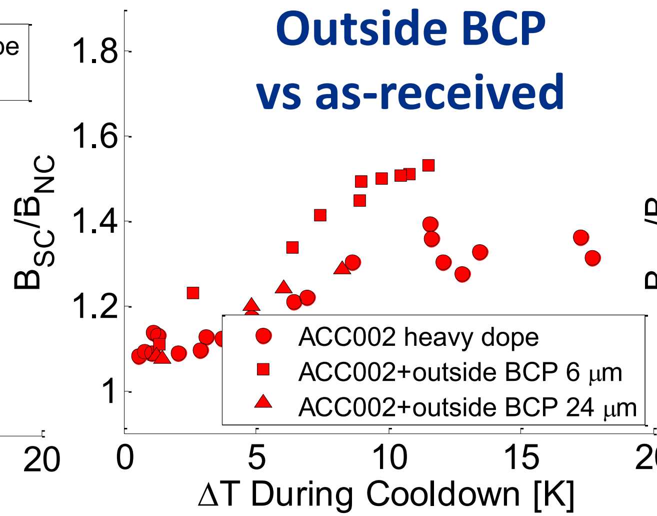
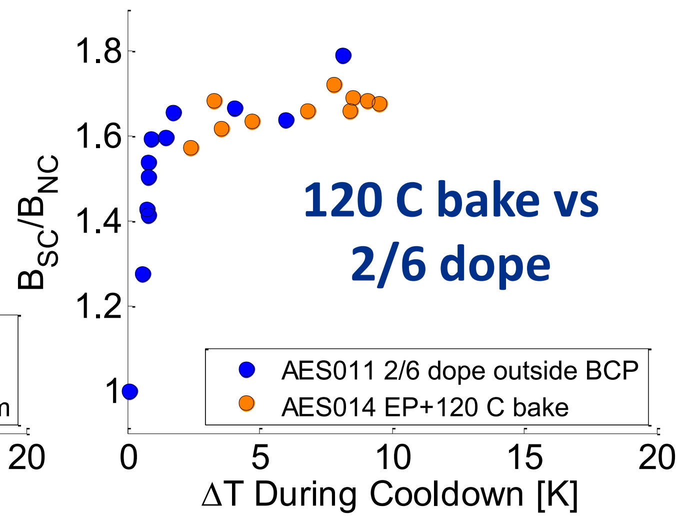
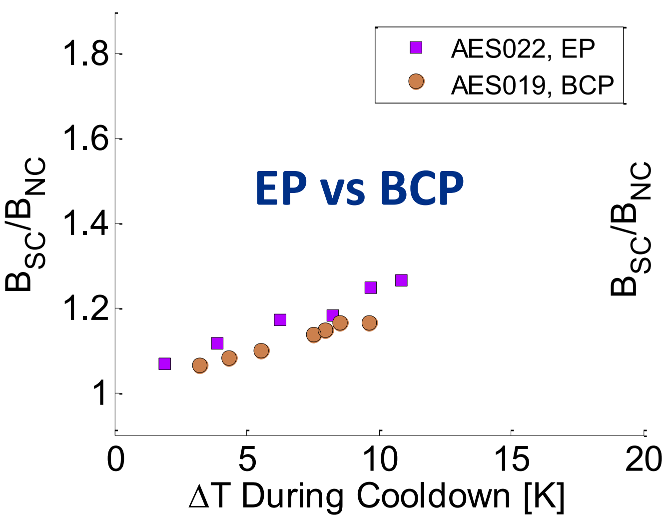
2) Surface treatments have insignificant impact

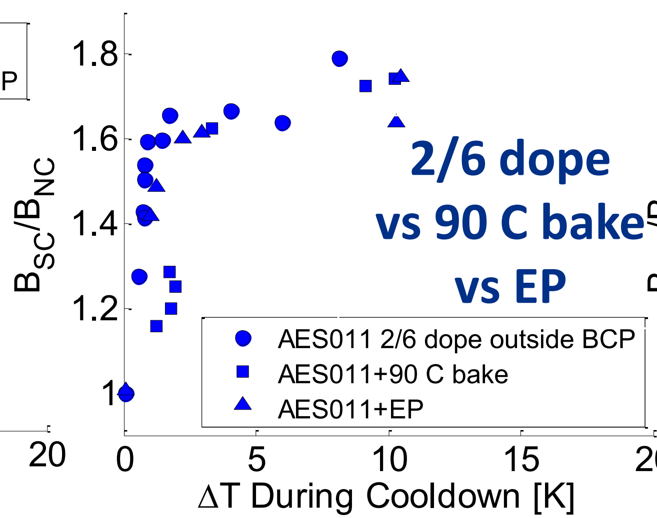


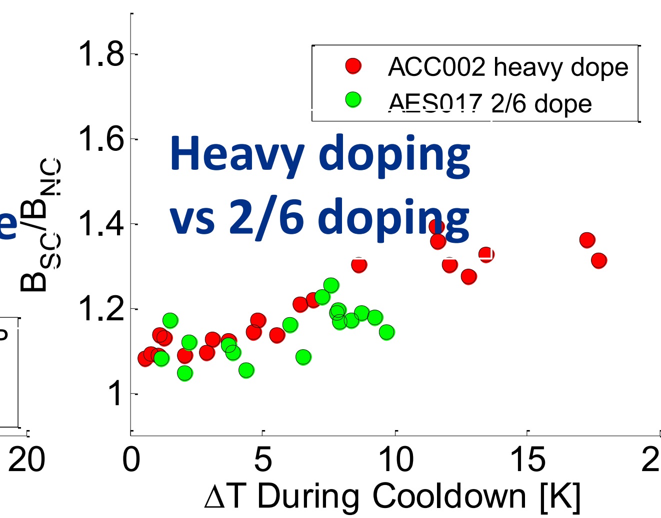




Different surface conditions in cavities with similar bulk history: similar expulsion







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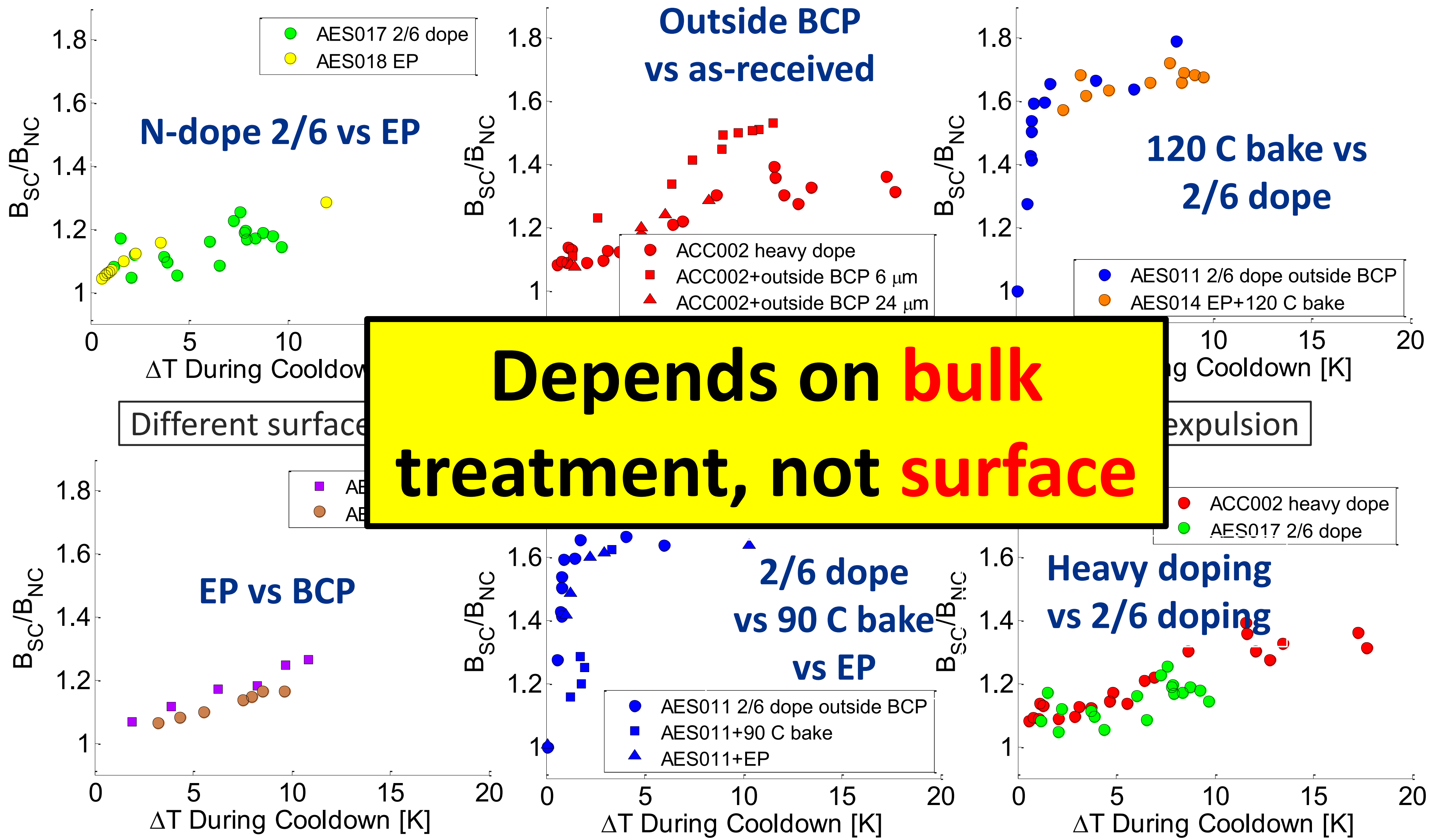
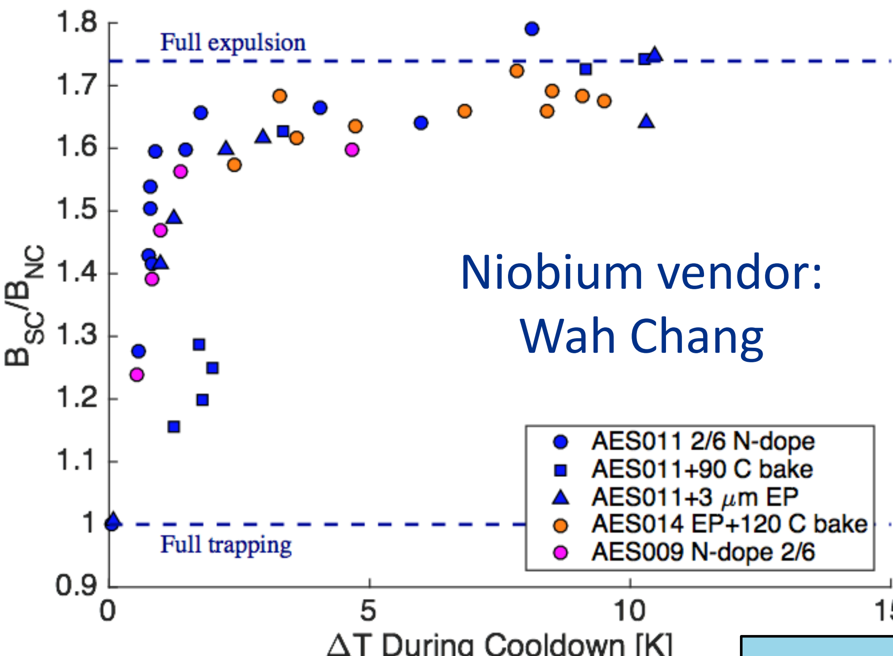
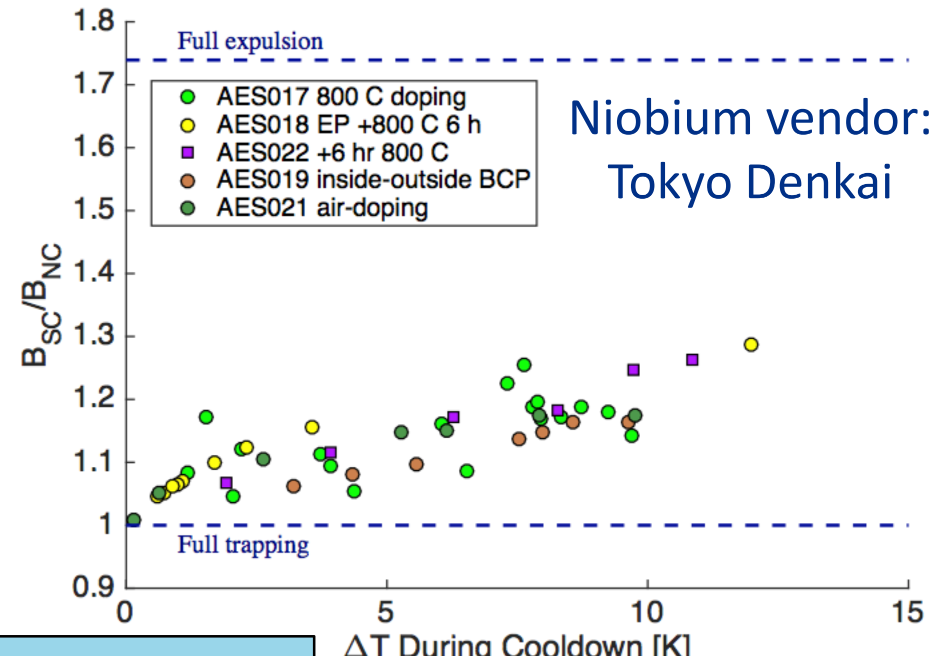


3) Some niobium production runs have very poor expulsion – even with large ΔT

- Seems to be a great deal of variability in as-received material
- Variability from batches even within a single vendor





1.3 GHz 1-cell cavities

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

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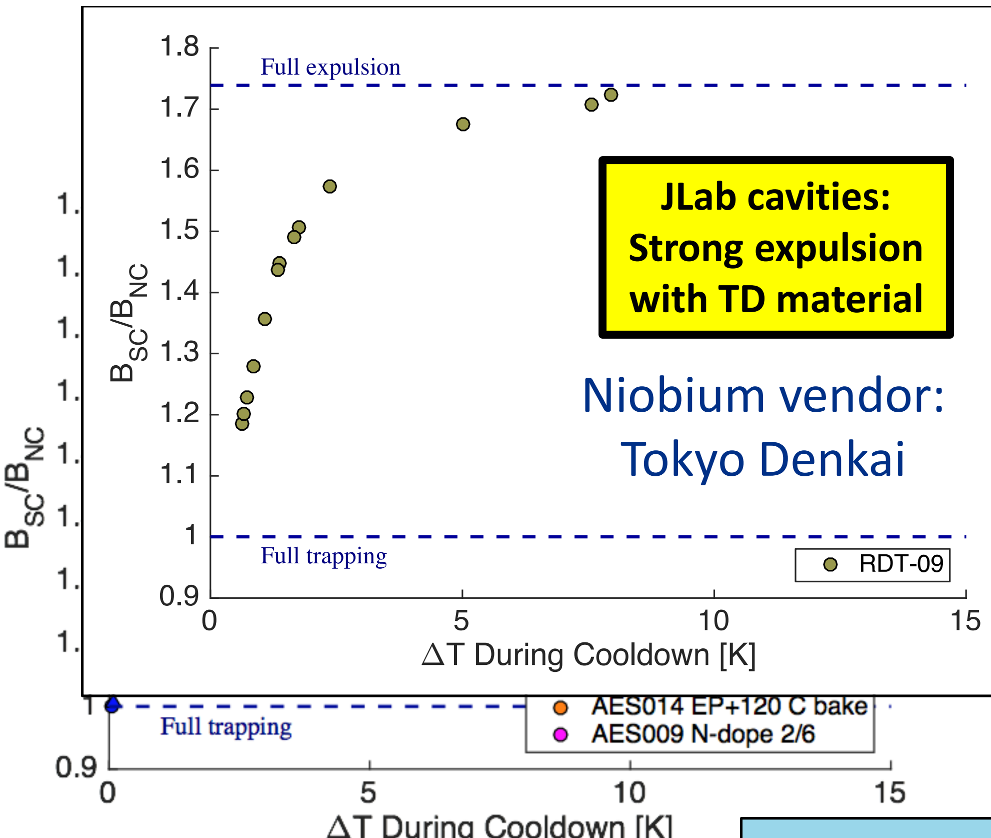
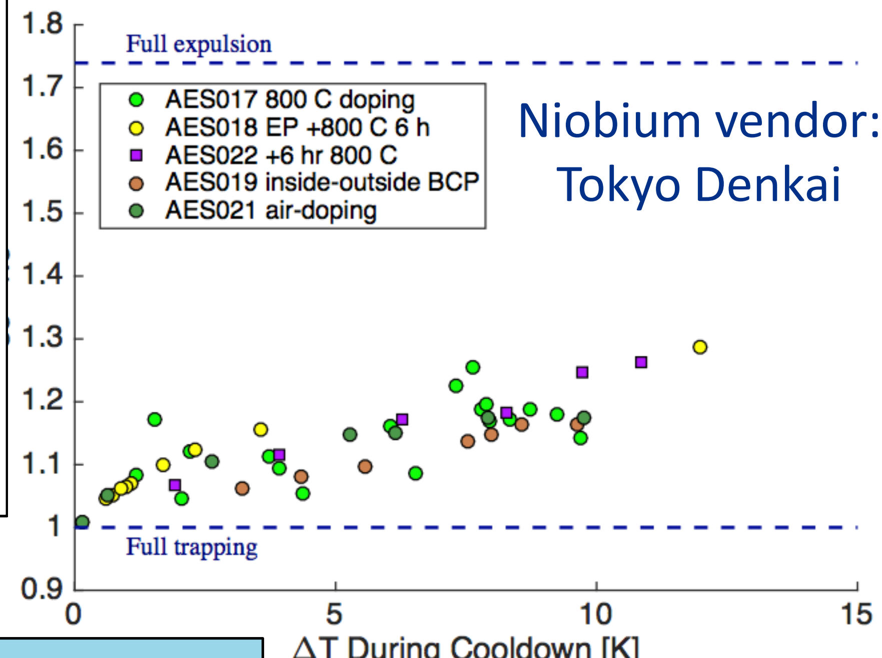


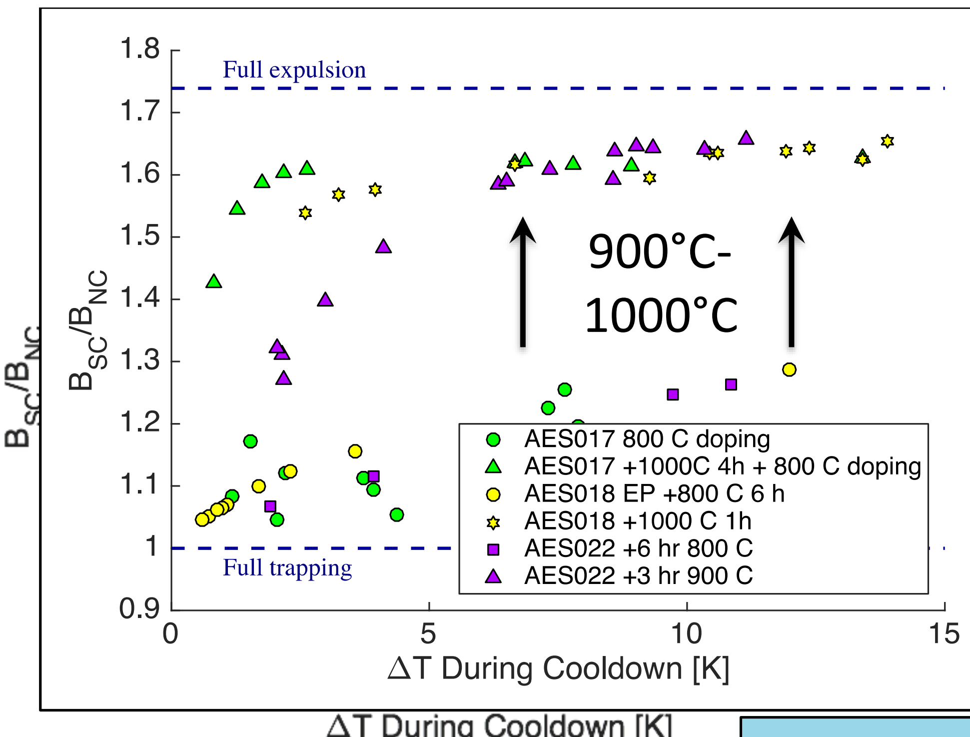


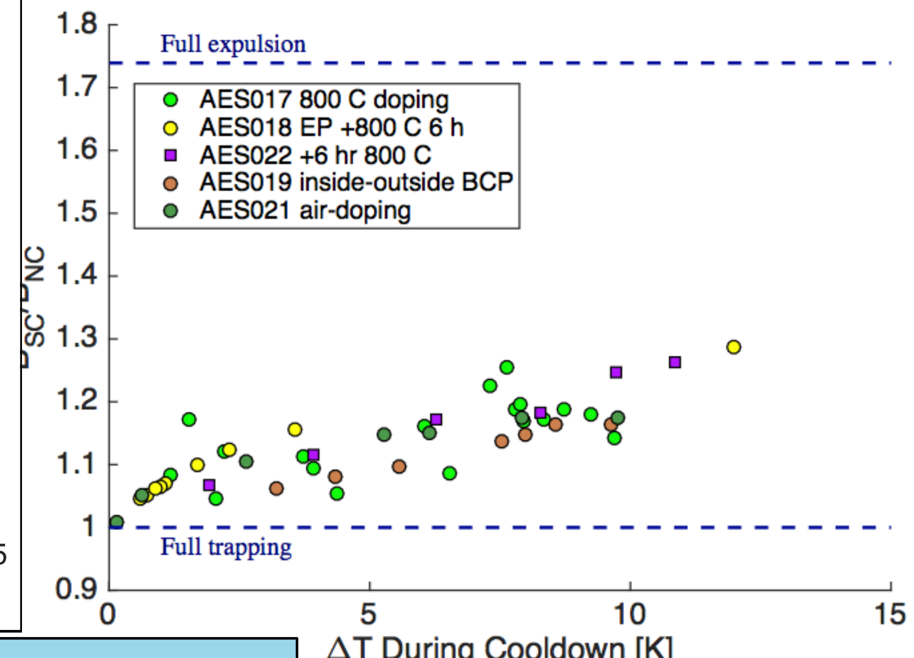
1.3 GHz 1-cell cavities

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

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

- 900 C – 1000 C furnace treatment improves expulsion





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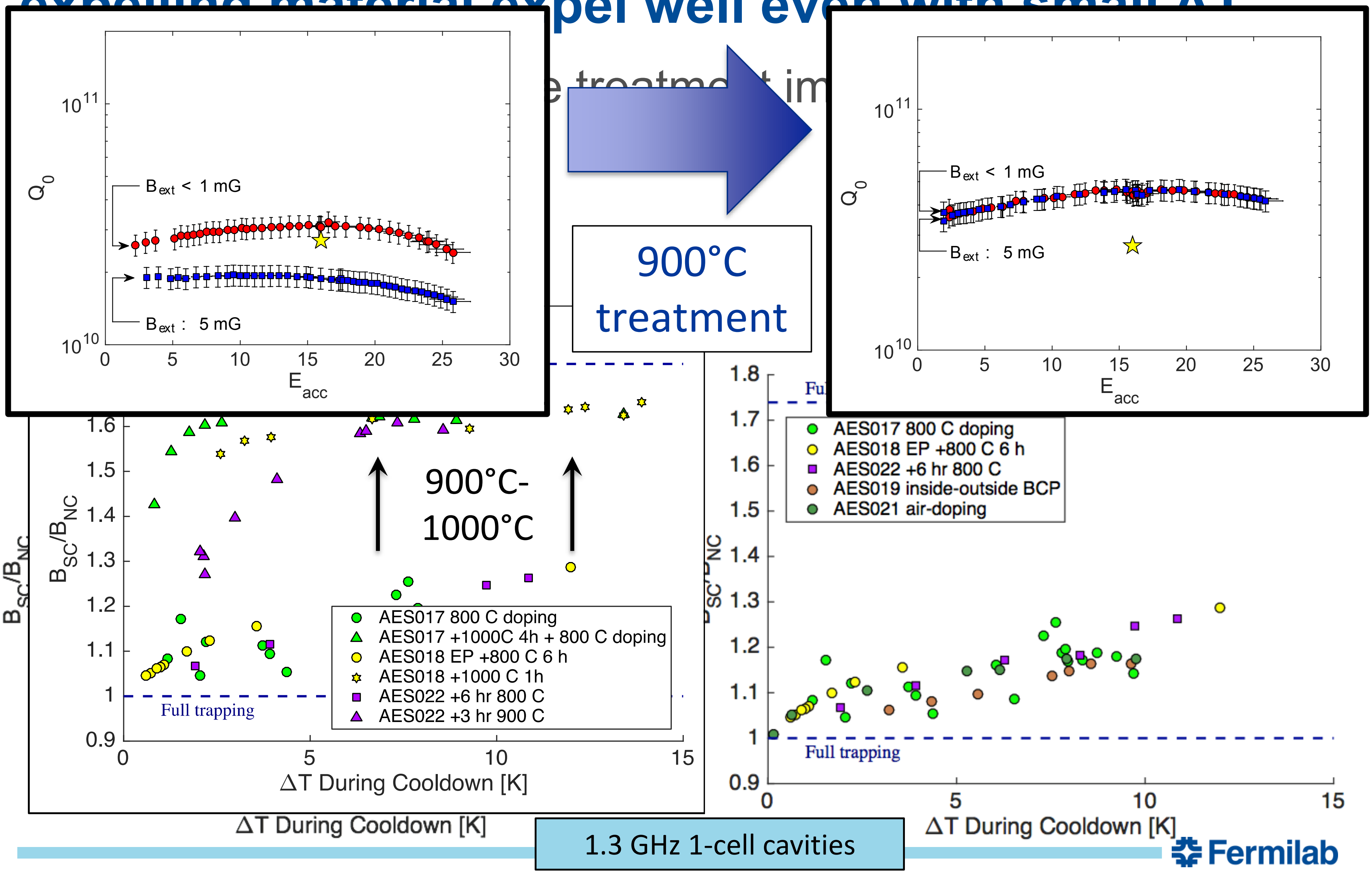
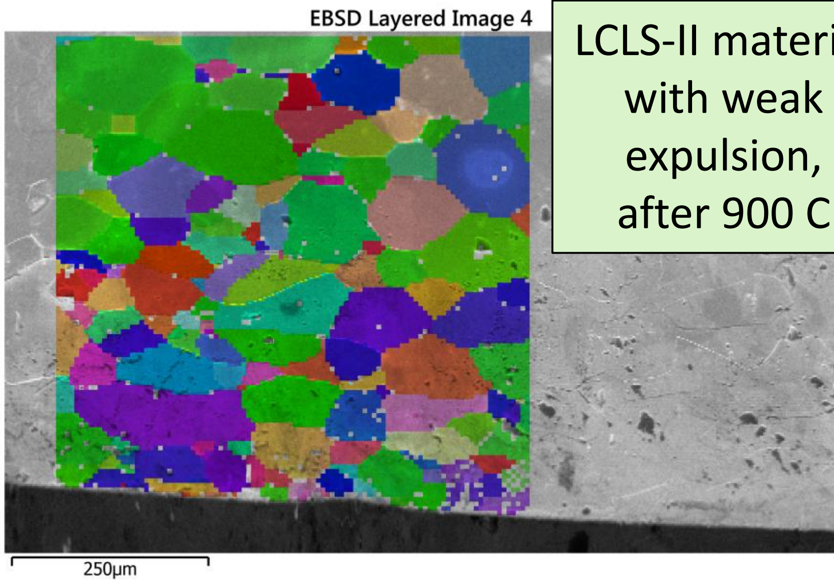
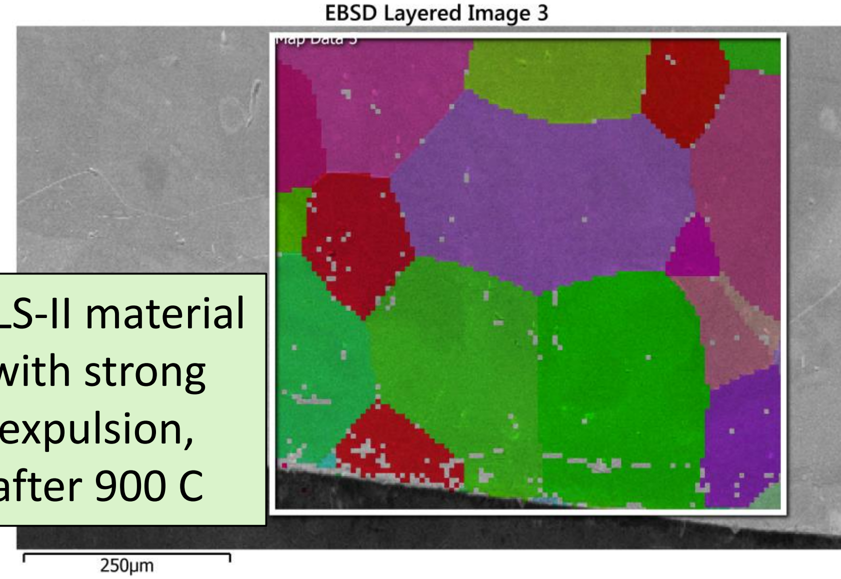


S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

5) Improvement in expulsion is correlated with grain growth



LCLS-II material with weak expulsion, after 900 C



LCLS-II material with strong expulsion, after 900 C

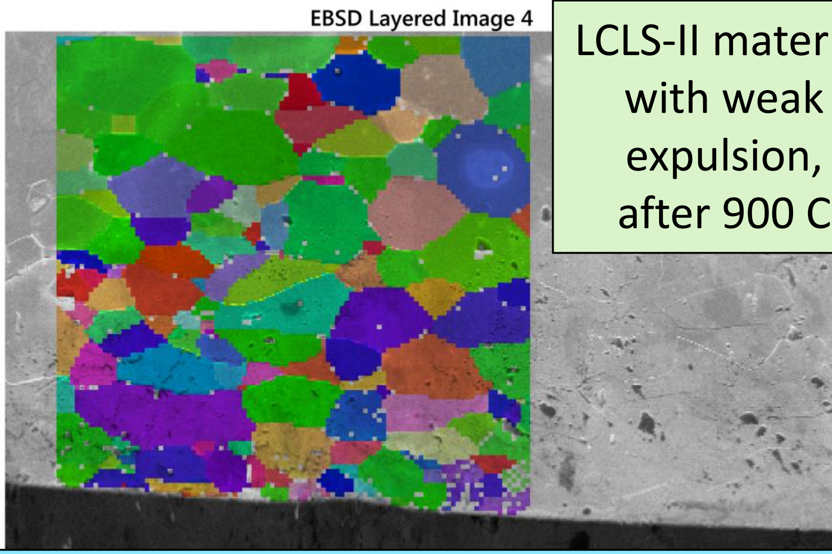
1000 C 4 hrs

Tokyo Denkai

800 C only

Wah Chang

5) Improvement in expulsion is correlated with grain growth



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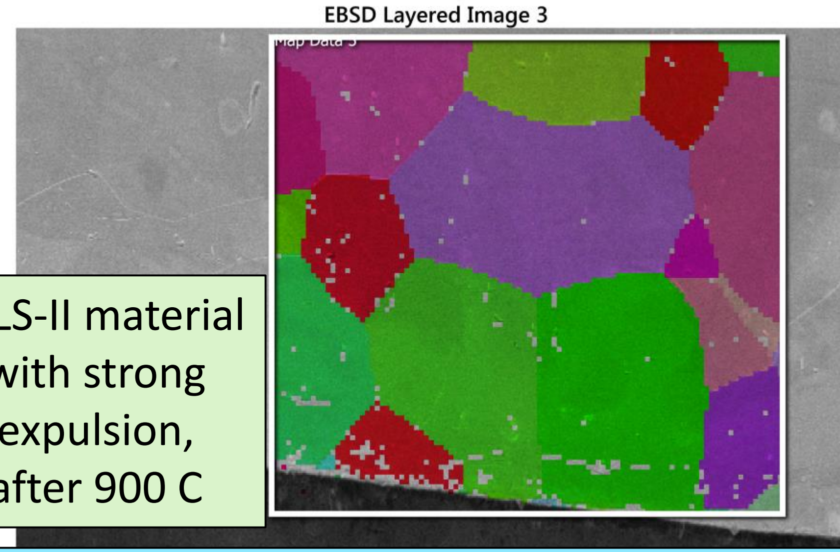


Why is 800 C enough to grow giant grains in some Nb but 1000 C required for others?

Impurities/RRR? Dislocations?

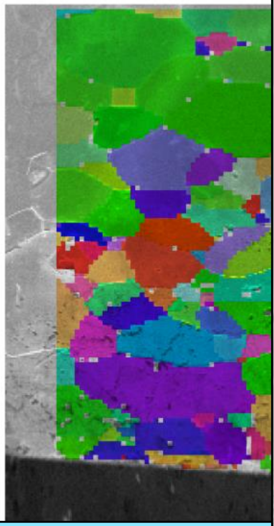
1000 C 4 hrs

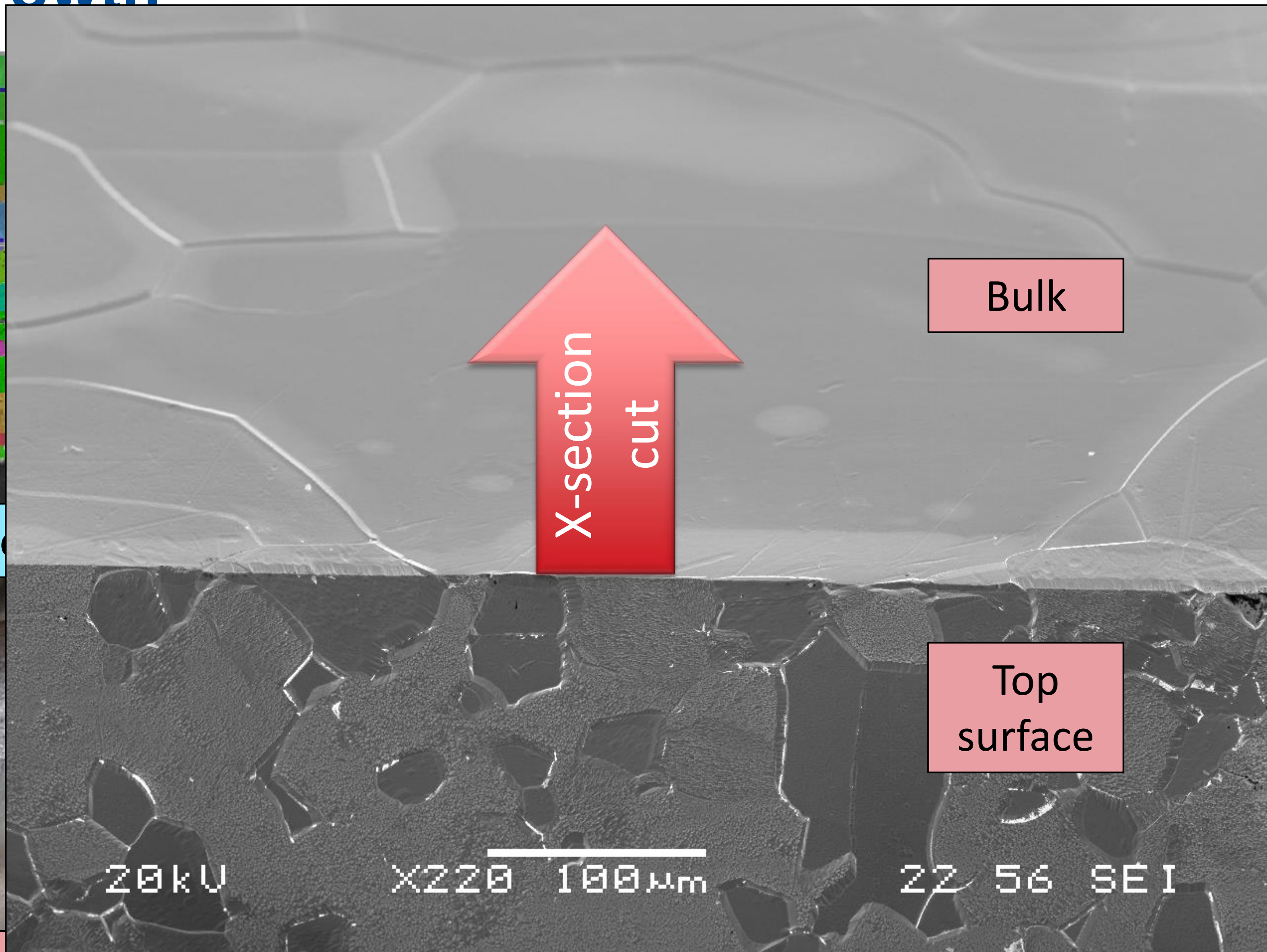
Tokyo Denkai

800 C only

Wah Chang

5) Improvement in expulsion is correlated with grain growth





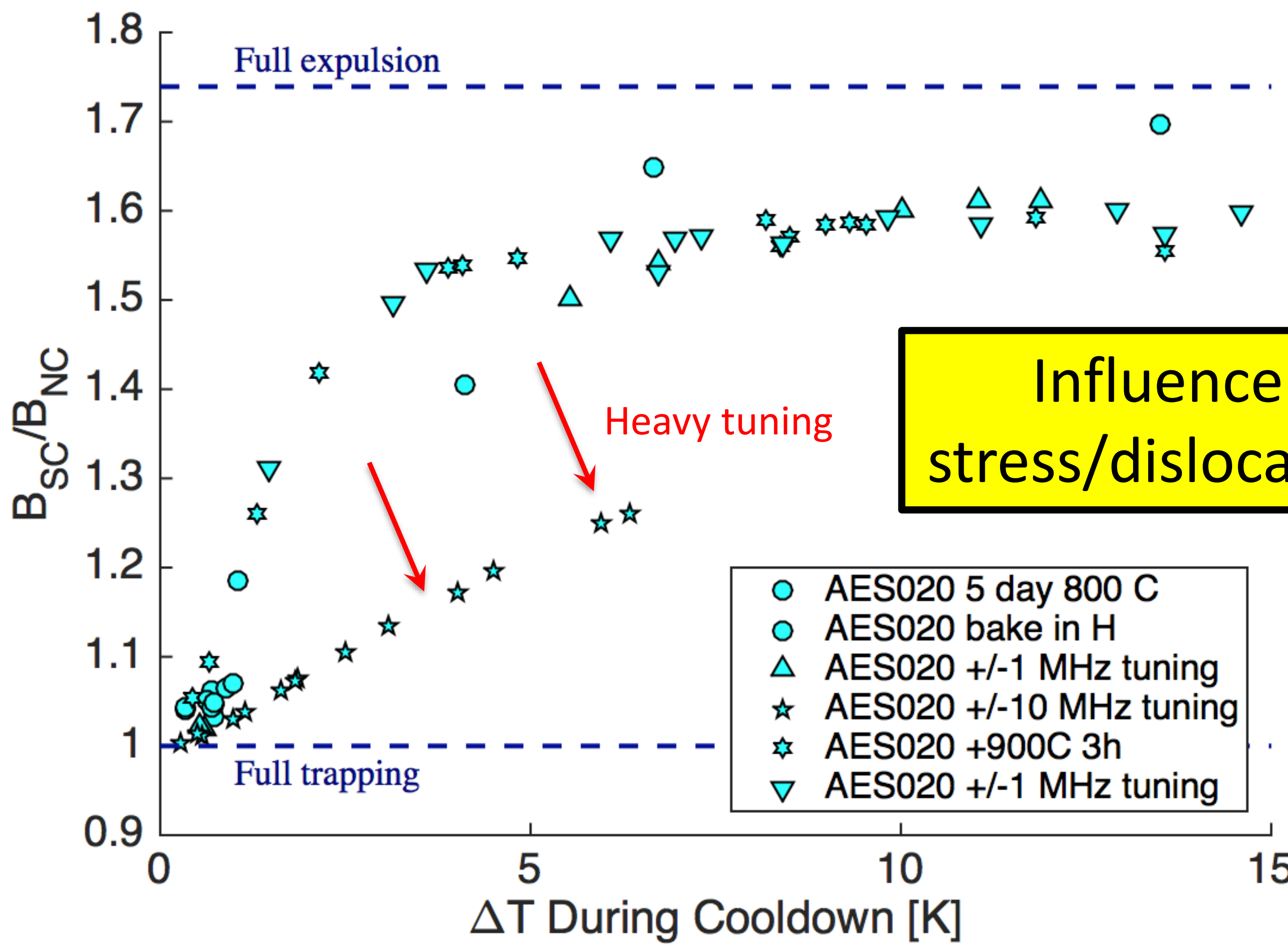
Why is 800 C ... hers?

1000 C 4 hrs

Tokyo Denkai

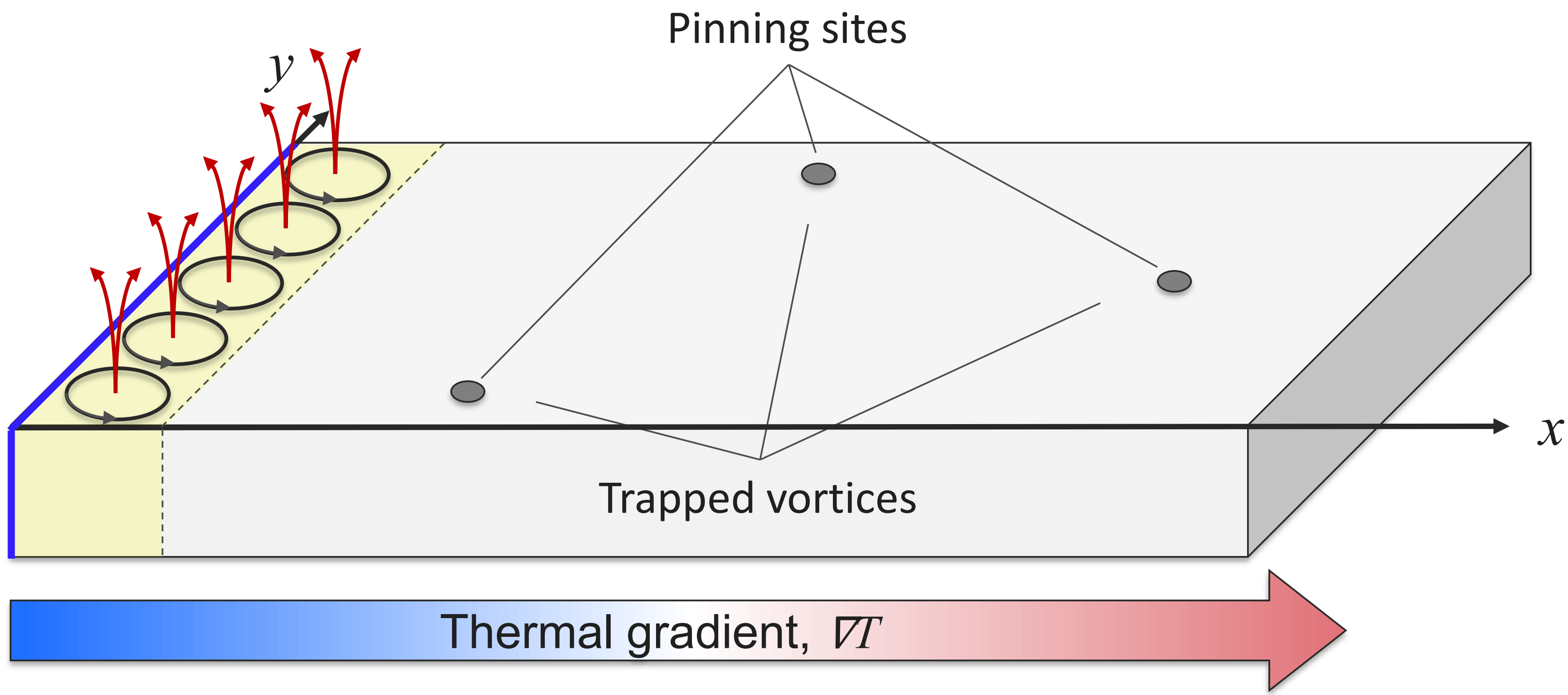
Wah hang

6) Heavy deformation degrades expulsion behavior

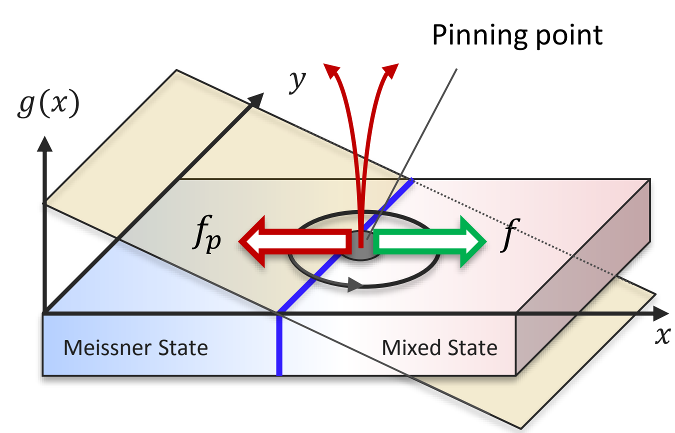


Influence of stress/dislocations?

Model for Flux Expulsion Consistent with 1)-6) Above



- What types of pinning sites are the dominant mechanism for trapping?
- Grain/crystal boundaries? Intragrain dislocations from deformation?



Details in talk by Mattia Checchin

Magnetic Flux Expulsion

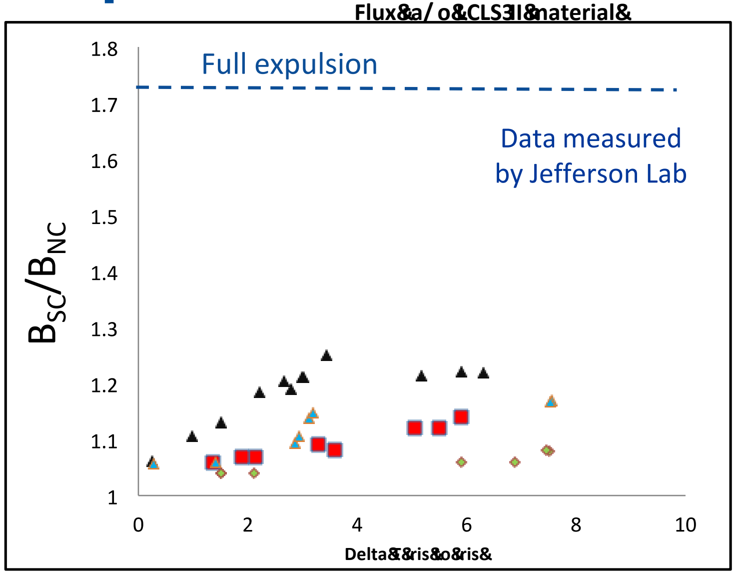
Material for LCLS-II

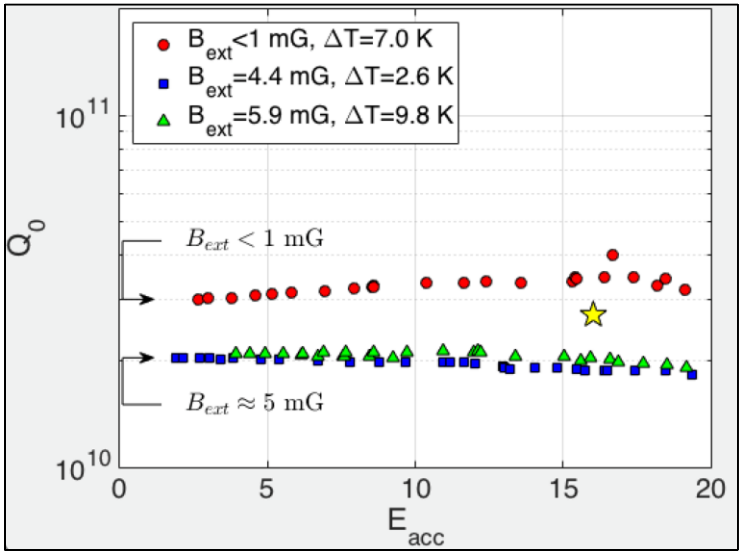
LCLS-II - Preproduction

1.3 GHz 1-cell cavities

Cooling in 5 mG applied field (spec for background field in module)

As-received niobium material for LCLS-II production: very poor expulsion

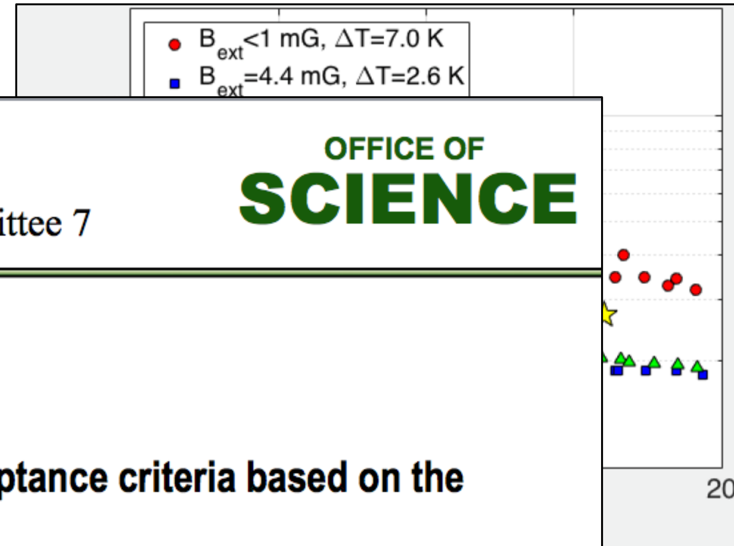




LCLS-II - Preproduction

1.3 GHz 1-cell cavities

Cooling in 5 mG applied field (spec for background field in module)



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U.S. DEPARTMENT OF ENERGY

2.7 Cryomodules

D. Stout, MSU / Subcommittee 7

OFFICE OF SCIENCE

Recommendations

1. **The Project is ready to proceed to CD-2/3**
2. **Finalize cavity and cryomodule minimum acceptance criteria based on the current project baseline – by 3/2016**
3. **Conduct a supply chain risk assessment of critical cryomodule assembly components to identify items needing second sources or other mitigations – by 3/2016**
4. **Develop a cure to improve the flux expulsion of the procured niobium material and implement before cavity production.**
5. **Conduct an independent peer review of the detailed assembly methods for connecting cryomodules – prior to first connection in 2017**

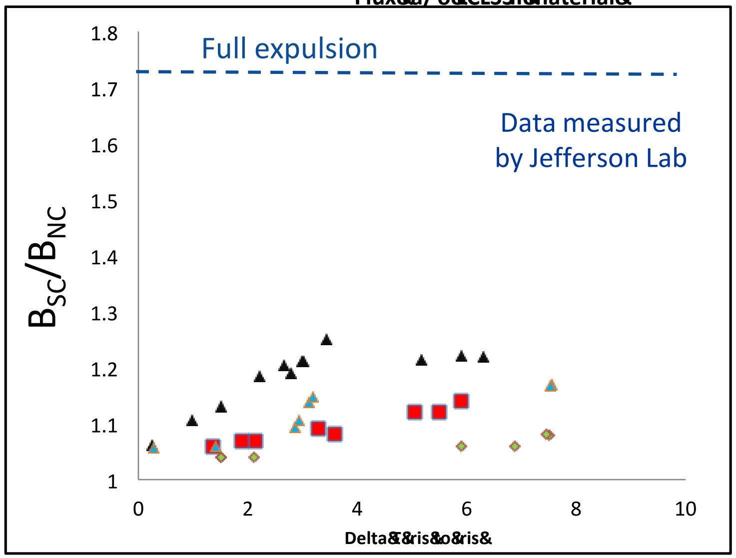
LCLS-II CD2/3 Review Closeout, Dec 2015

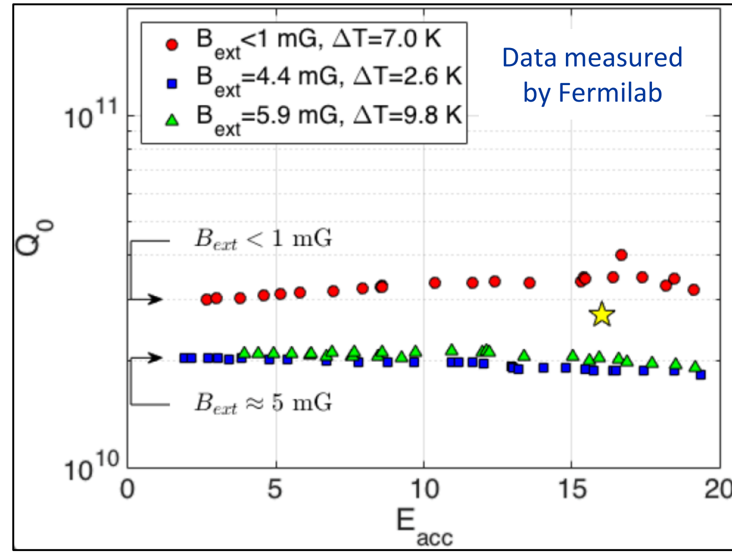
LCLS-II - Preproduction

1.3 GHz 1-cell cavities

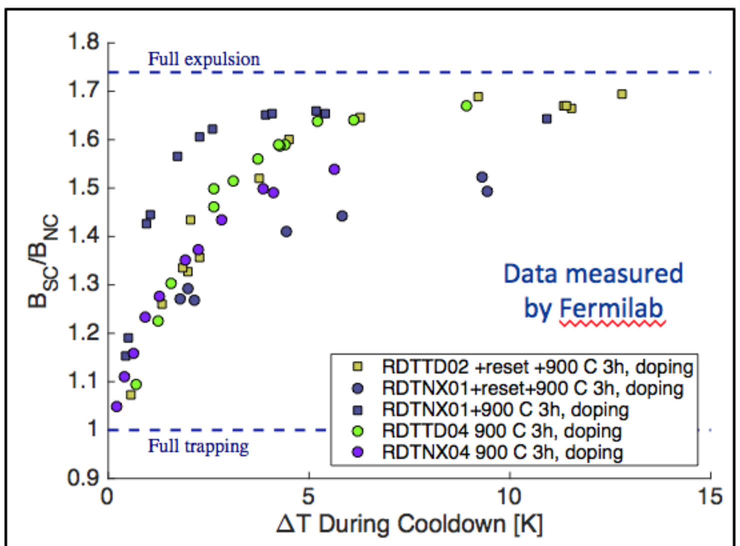
Cooling in 5 mG applied field (spec for background field in module)

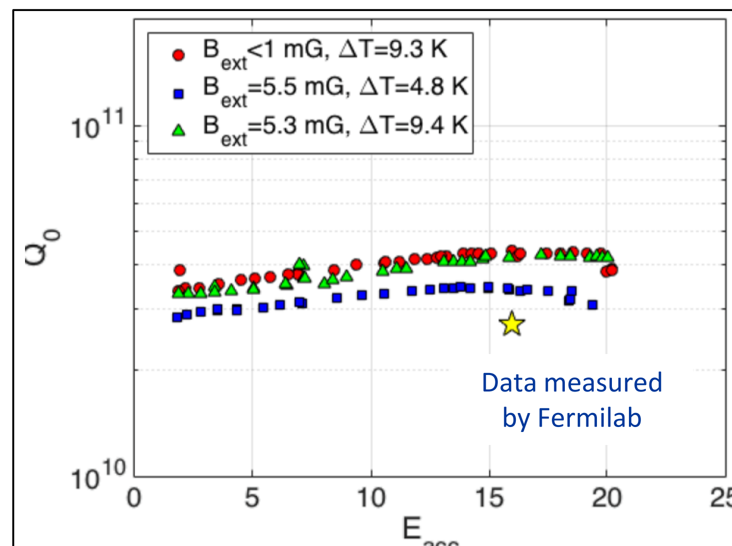
Flux&a/ o&CLS3II&material&





As-received niobium material for LCLS-II production: very poor expulsion





After 900°C treatment: much improved

LCLS-II

1.3 GHz 1-cell cavities

Cooling in 5 mG applied field (spec for background field in module)

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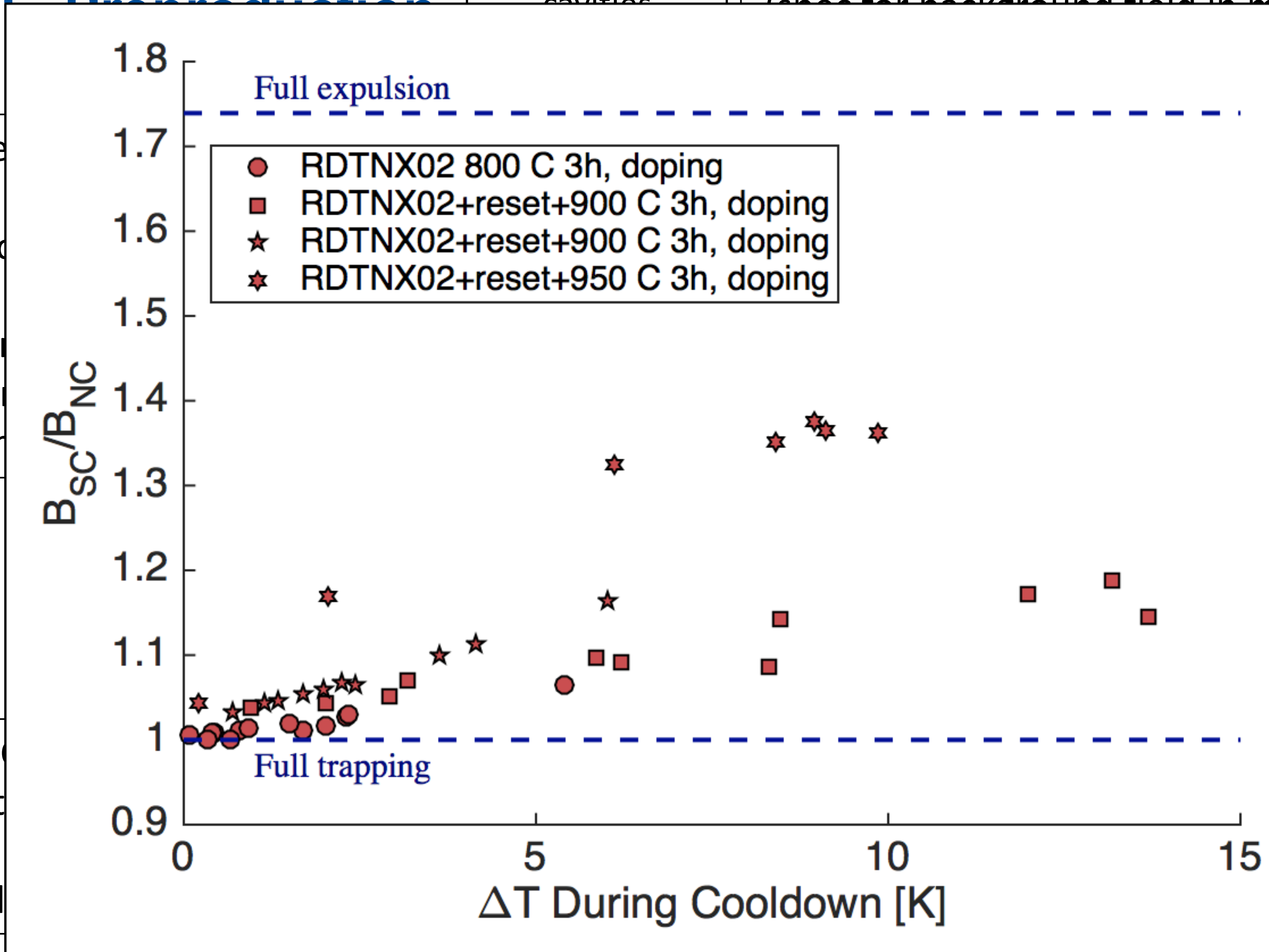
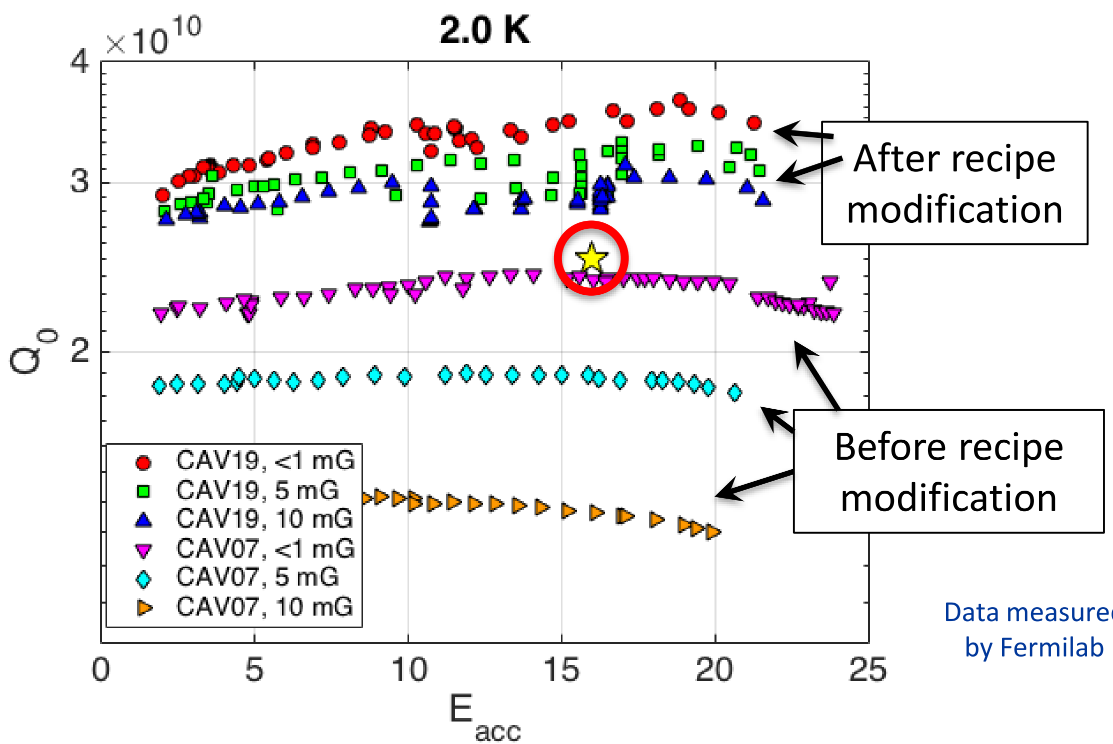


After 900° treatment much improved

"Lot C" material – lower RRR, smaller grains (details in talk from Ari Palczewski)

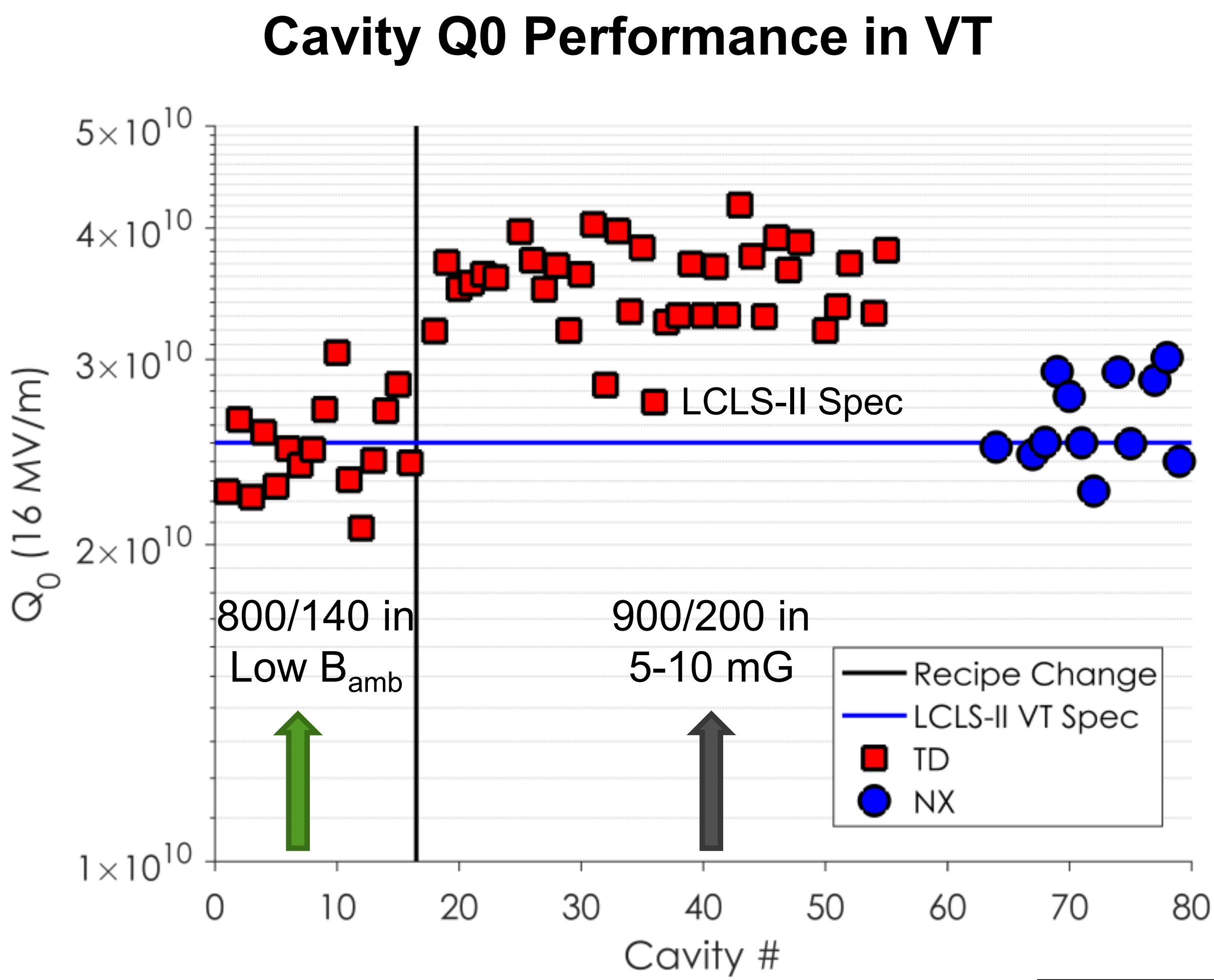
LCLS-II - Production

- See below difference between flux trapping in baseline 800 C recipe compared to 900 C modification
- These are production 9-cell cavities that are now in cryomodules for LCLS-II



Data measured by Fermilab

LCLS-II Production Cavity Q_0 Before/After Recipe Change



Data from both JLab and Fermilab

See D. Gonnella's talk on Thursday

Why Flux Expulsion is Important

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CAV0008	20.5	2.0E+10
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CAV0015	21.0	2.3E+10
Average	**20.0**	**2.1E+10**
Total Voltage	**166 MV**	

Fermilab CM-2
Baseline recipe: 800 C degas, 140 µm bulk EP
Fast cooldown

Cavity	Usable Gradient* [MV/m]	Q0 @ 16 MV/m (or useable gradient) 2 K
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CAV0026	9.2	3.2E+10
CAV0027	21.0	3.2E+10
CAV0029	21.0	4.4E+10
CAV0042	16.8	2.8E+10
CAV0032	21.0	3.0E+10
Average	**17.6**	**3.5E+10**
Total Voltage	**146.4**	

Fermilab CM-3
Modified recipe: 900 C degas, 200 µm bulk EP
Fast cooldown

Total voltage Spec: 133 MV Q_0 Spec: 2.7×10^{10}

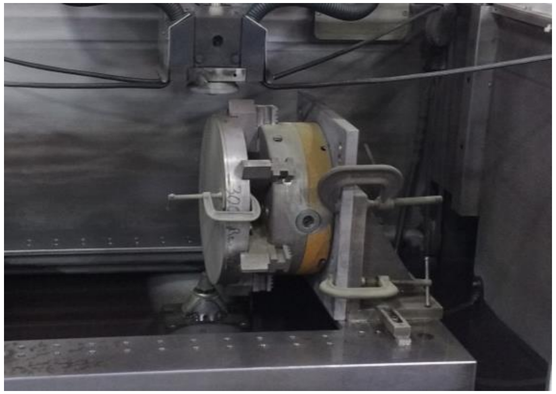
See Genfa Wu's talk on Friday

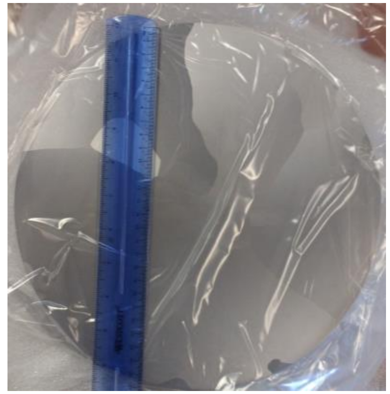
Magnetic Flux Expulsion

Additional Experiments

Future High Q_0 Cavity Production

- The activity to ‘cure’ the flux expulsion in LCLS-II cavities put a strain on the project
- For future procurement of niobium for high Q_0 cavity production, it is **crucial to understand how to improve specifications**
- In parallel: experiments to further develop understanding of physical mechanisms that control trapping/expulsion during cooldown





Large Grain Experiment

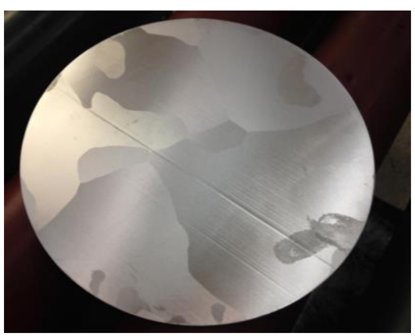
Experiment designed to distinguish effects of dislocations independent of grain size: does LG material inherently expel strongly?

Large Grain Ingot → Cut 2 slices, **3 mm** thick → 1-cell 1.3 GHz cavity fabrication (now)

Large grains, low dislocation content

Large grains, high dislocation content

Large Grain Ingot → Cut 2 slices, **5 mm** thick → Roll to 3 mm thickness → Cut down to disc size → 1-cell 1.3 GHz cavity fabrication (now)



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Summary

- Flux expulsion experiment handbook:

1. Large thermal gradients at T_c promote expulsion of flux
2. Surface treatments have insignificant impact
3. Some niobium production runs have very poor expulsion (even with large ΔT)
4. High temperature treatment can make poorly expelling material expel well (even with small ΔT)
5. Improvement in expulsion is correlated with grain growth
6. Heavy deformation degrades expulsion behavior

- Experiments continue to boost understanding of flux expulsion physics and improve material specifications for future projects