Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Flux expulsion efficiency for different cavity materials and treatments

Sam Posen

TTC Meeting, SLAC

2 December 2015

Maintaining High Q_0 in Presence of External B Fields

- High Q_0 can reduce cryogenic costs in high duty factor SRF linacs by tens of millions of dollars
- High Q_0 in vertical test must be preserved to cryomodule
- Significant source of Q_0 degradation: flux losses

B_{ext}
- Use of non-magnetic components
- Magnetic shielding/active compensation

B_{trap}
- Cool through transition with dT/dy (bulk Nb)
- Minimize pinning centers

R_s
- Optimize mean free path

Maintaining High Q_0 in Presence of External B Fields

- High Q_0 can reduce cryogenic costs in high duty factor SRF linacs by tens of millions of dollars
- High Q_0 in vertical test must be preserved to cryomodule
- Significant source of Q_0 degradation: flux losses

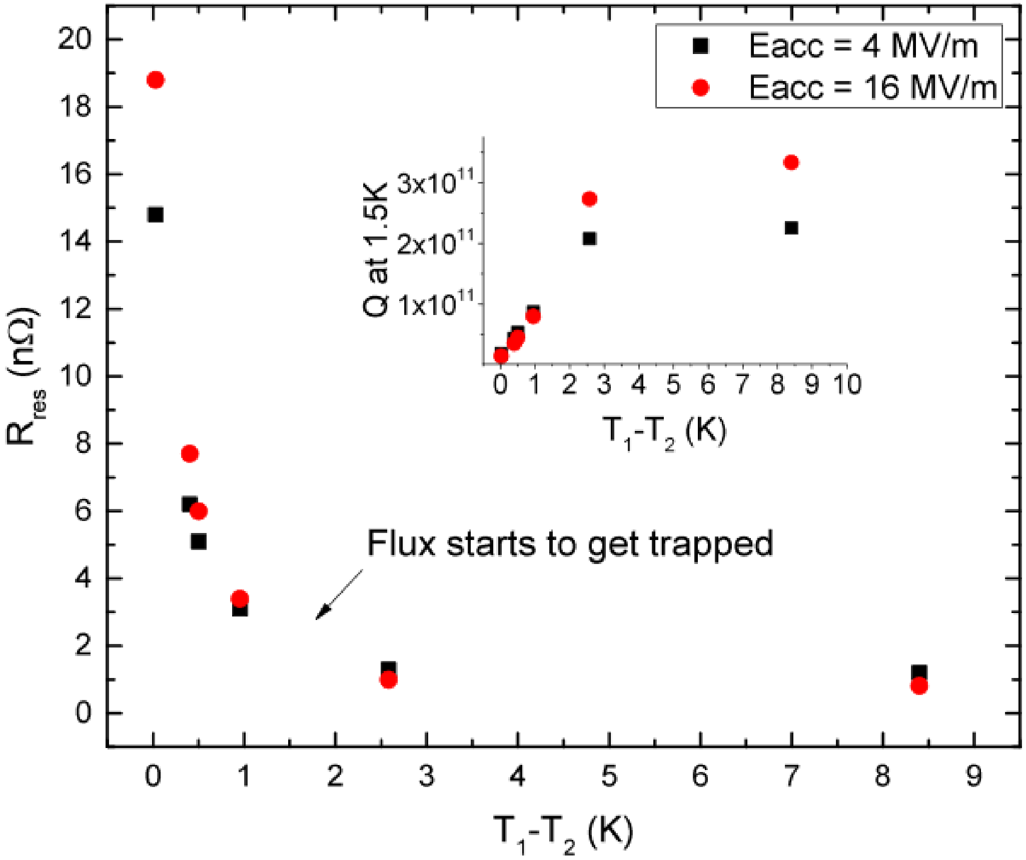
B_{ext}
- Use of non-magnetic components
- Magnetic shielding/active compensation

B_{trap}
- **Cool through transition with dT/dy (bulk Nb)**
- **Minimize pinning centers**

R_s
- Optimize mean free path

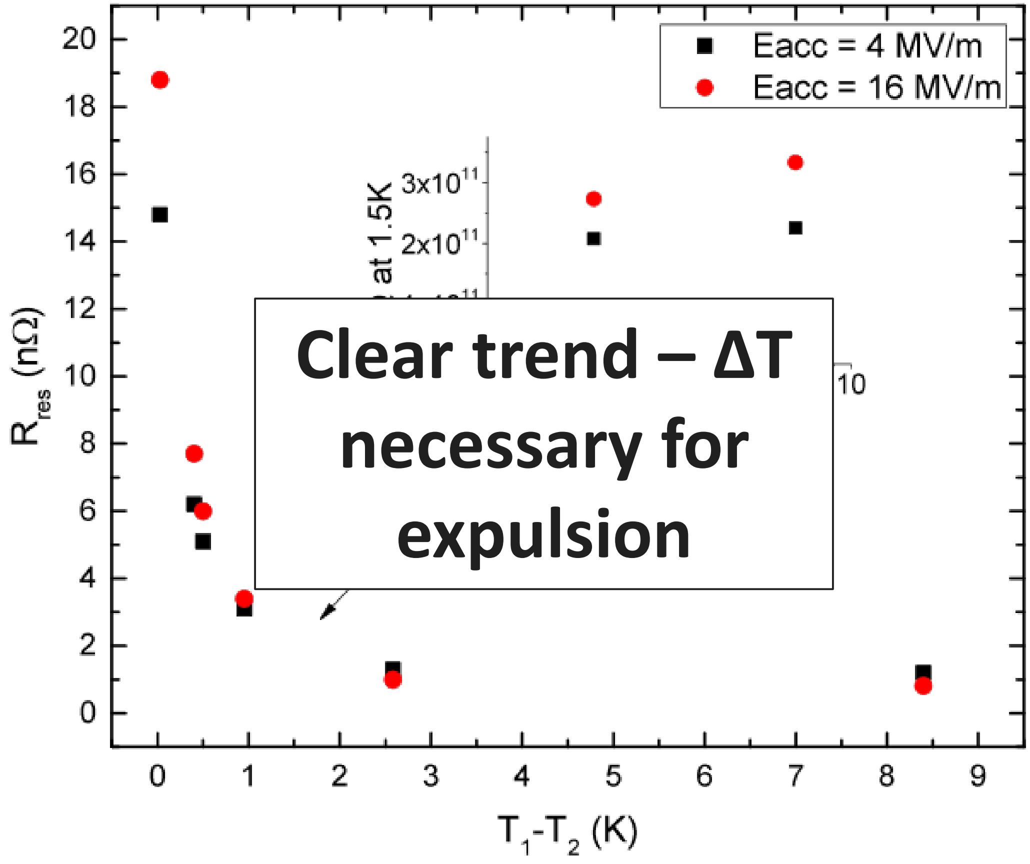
Fermilab

Minimize Trapping 1: Cool through T_c with dT/dy (bulk Nb)



A. Romanenko et al., *Appl. Phys. Lett.* 105, 234103 (2014).

Minimize Trapping 1: Cool through T_c with dT/dy (bulk Nb)

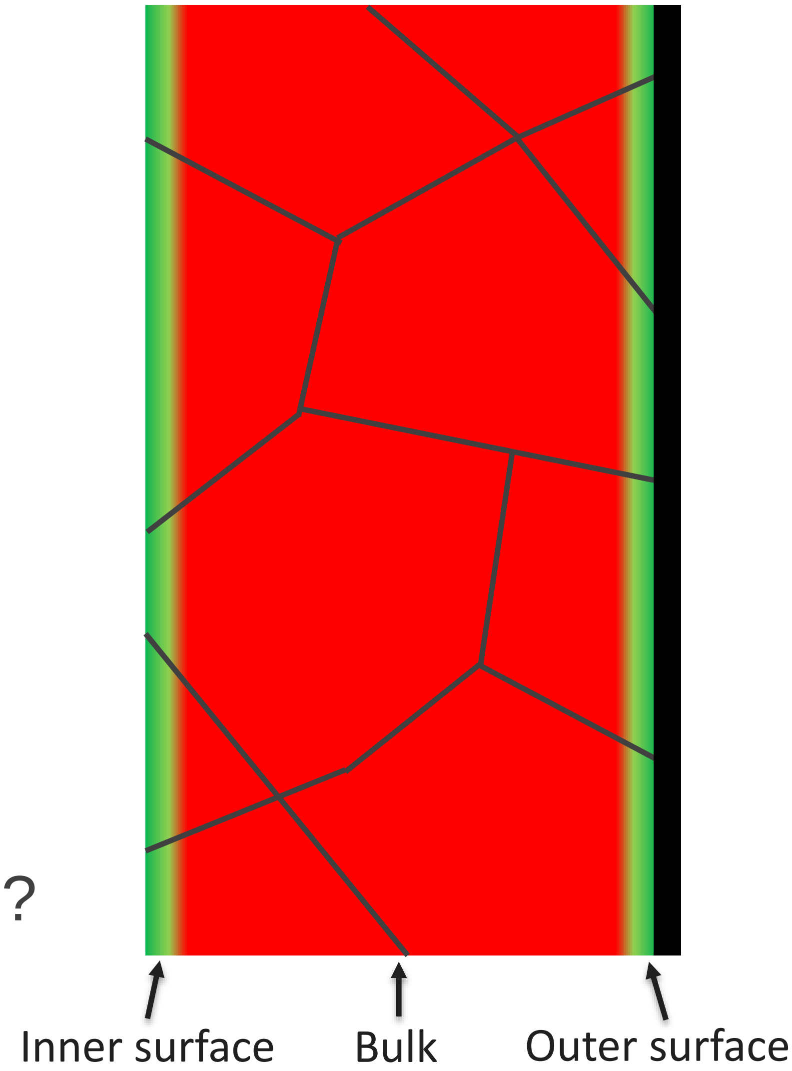


Clear trend – ΔT necessary for expulsion

A. Romanenko et al., *Appl. Phys. Lett.* 105, 234103 (2014).

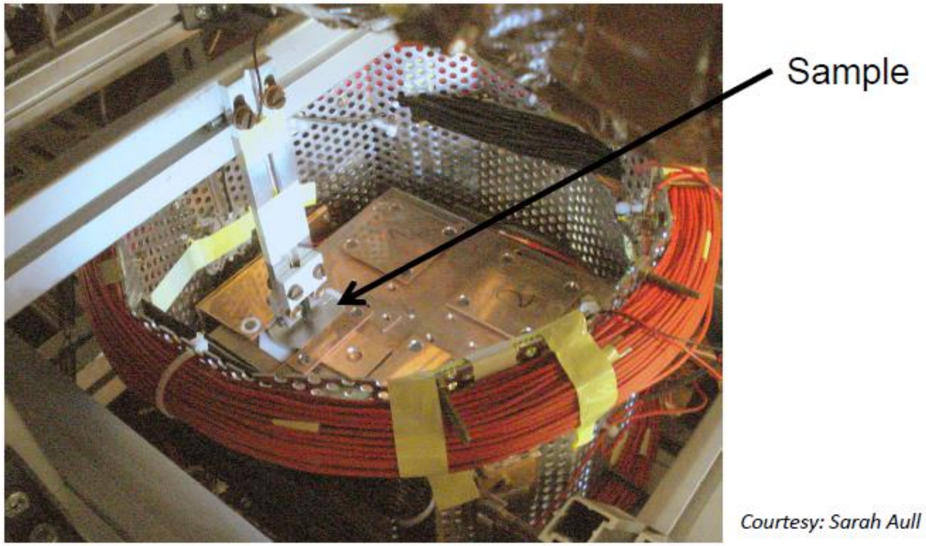
Minimize Trapping 2: Minimize Pinning in SRF-Treated Nb

- Surface features:
  - Oxides
  - Nitrides
  - N- or O-rich niobium
  - Mechanical damage
  - Contamination
- Bulk features:
  - Grain boundaries
  - Dislocations
  - Impurities
- How important are these to pinning?



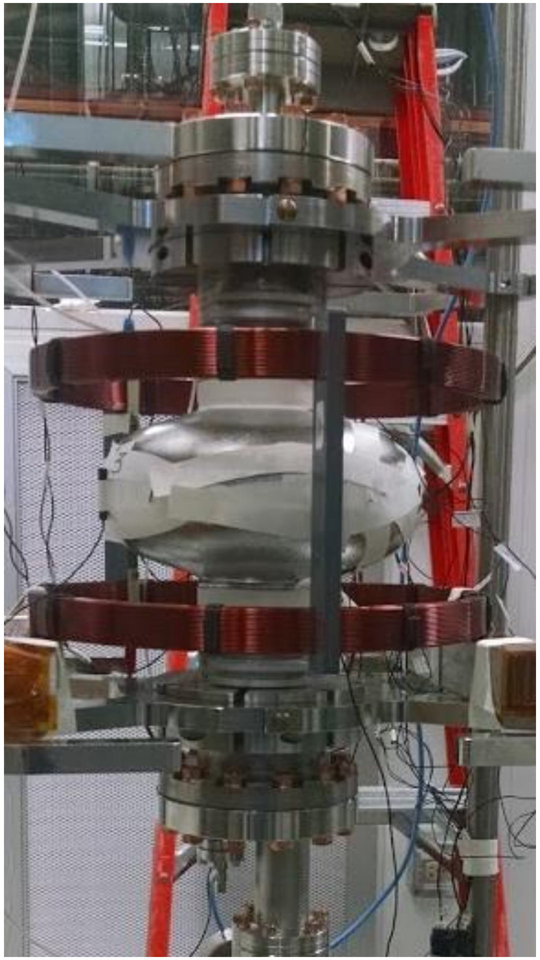
Previous Studies

- Previous studies, e.g.
  - Aull, Kugeler and Knobloch, *PRSTAB* 15, 062001 (2012)
  - A. Dhavale et al, *Supercond. Sci. Tech*., 25, 065014 (2012)
  - G. Ciovati, and A. Gurevich, Proc. SRF 2007, TUP13 (2007)
- Qualitative trends, but no measurement as a function of thermal gradient, which is **crucial**



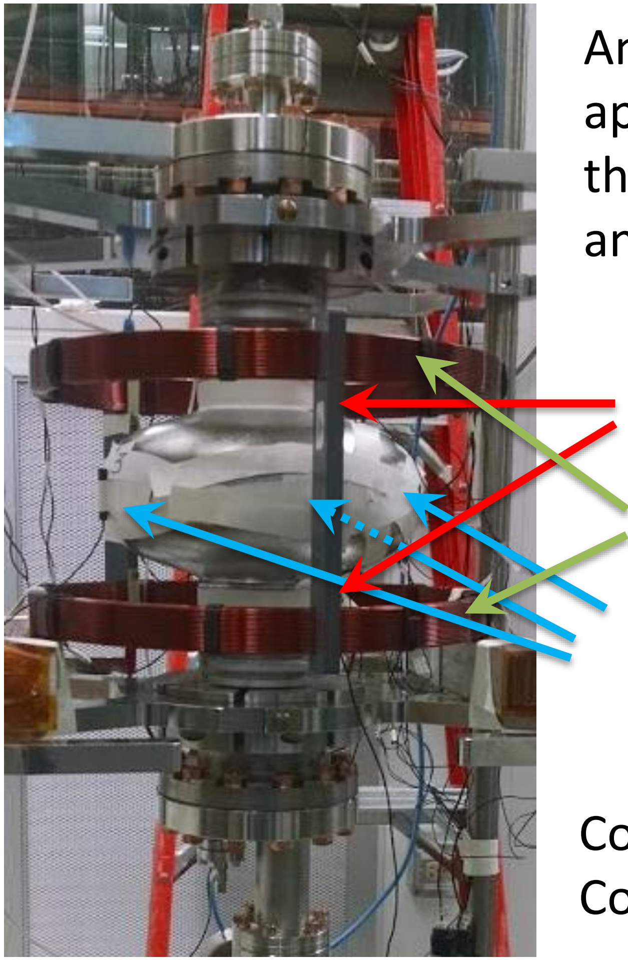
Courtesy: Sarah Aull

Experimental Considerations



- Goal: measure flux trapping as a function of **thermal gradient** and **material treatment**
- Connection to R_{res} – Performing study on cavities directly determines required conditions to avoid severely degraded RF performance

Measuring Flux Expulsion During Transition

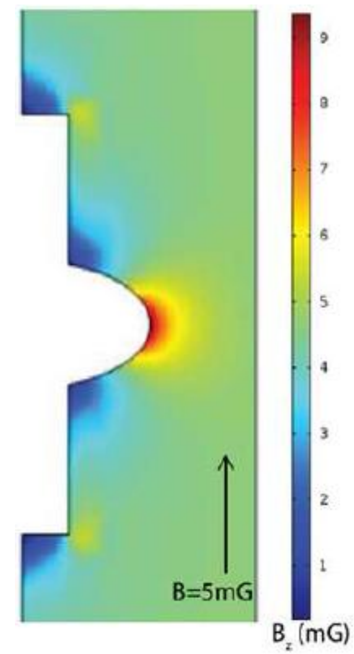


An axial magnetic field on the order of 10 mG is applied during cooldown. Fluxgate magnetometers at the equator measured the magnetic field before B_{NC} and after B_{SC} superconducting transition.

Temperature sensors

External field coils

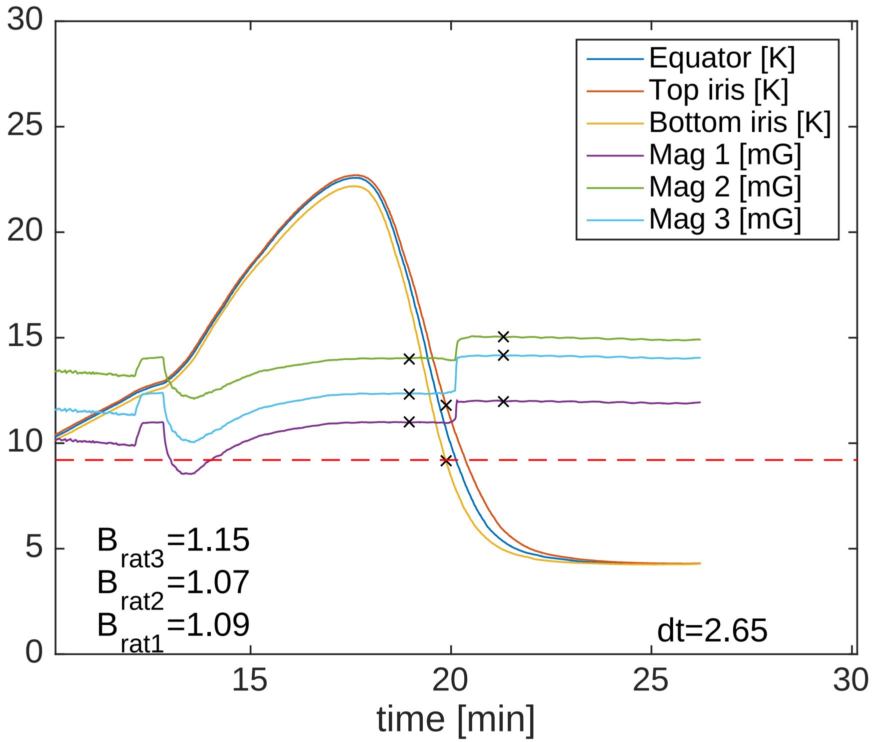
Fluxgate magnetometers



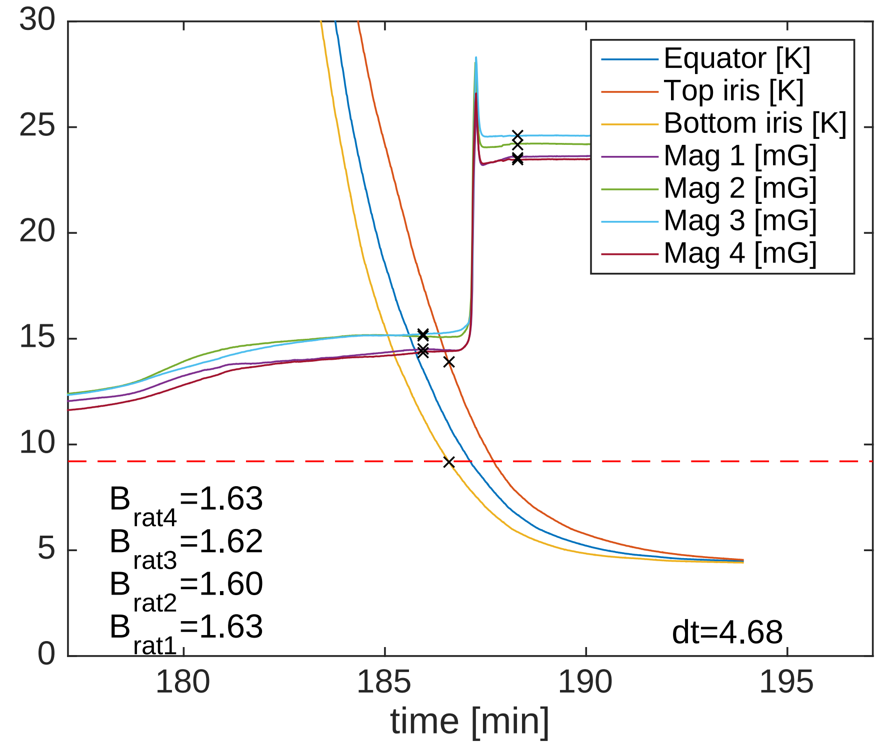
Complete trapping: $B_{SC}/B_{NC} = 1$
Complete expulsion: $B_{SC}/B_{NC} \sim 1.8$

Measurement technique from A. Romanenko et al., *Appl. Phys. Lett.* 105, 234103 (2014).

Measuring Flux Expulsion During Transition

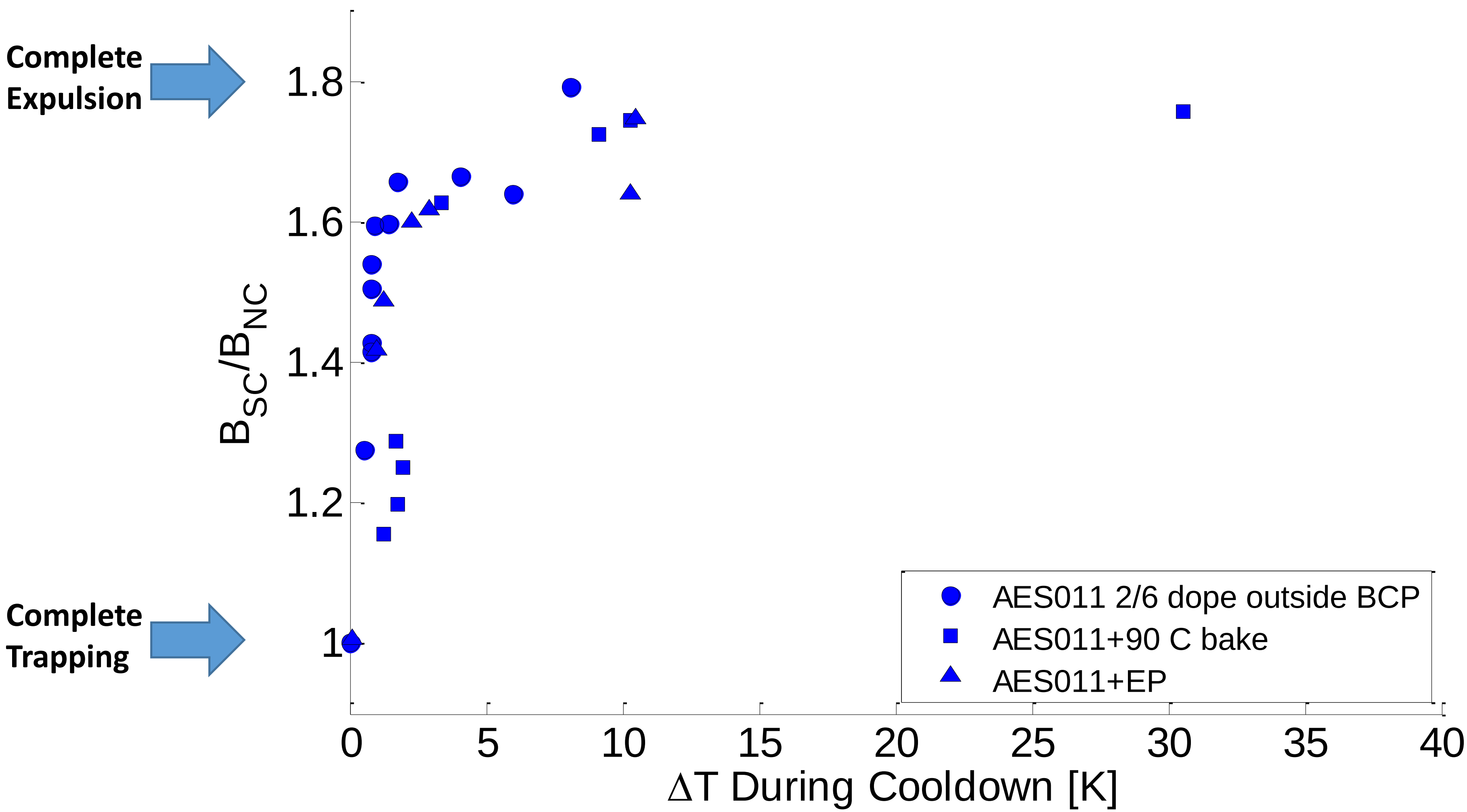


Poor expulsion: $B_{SC}/B_{NC} \sim 1.1$

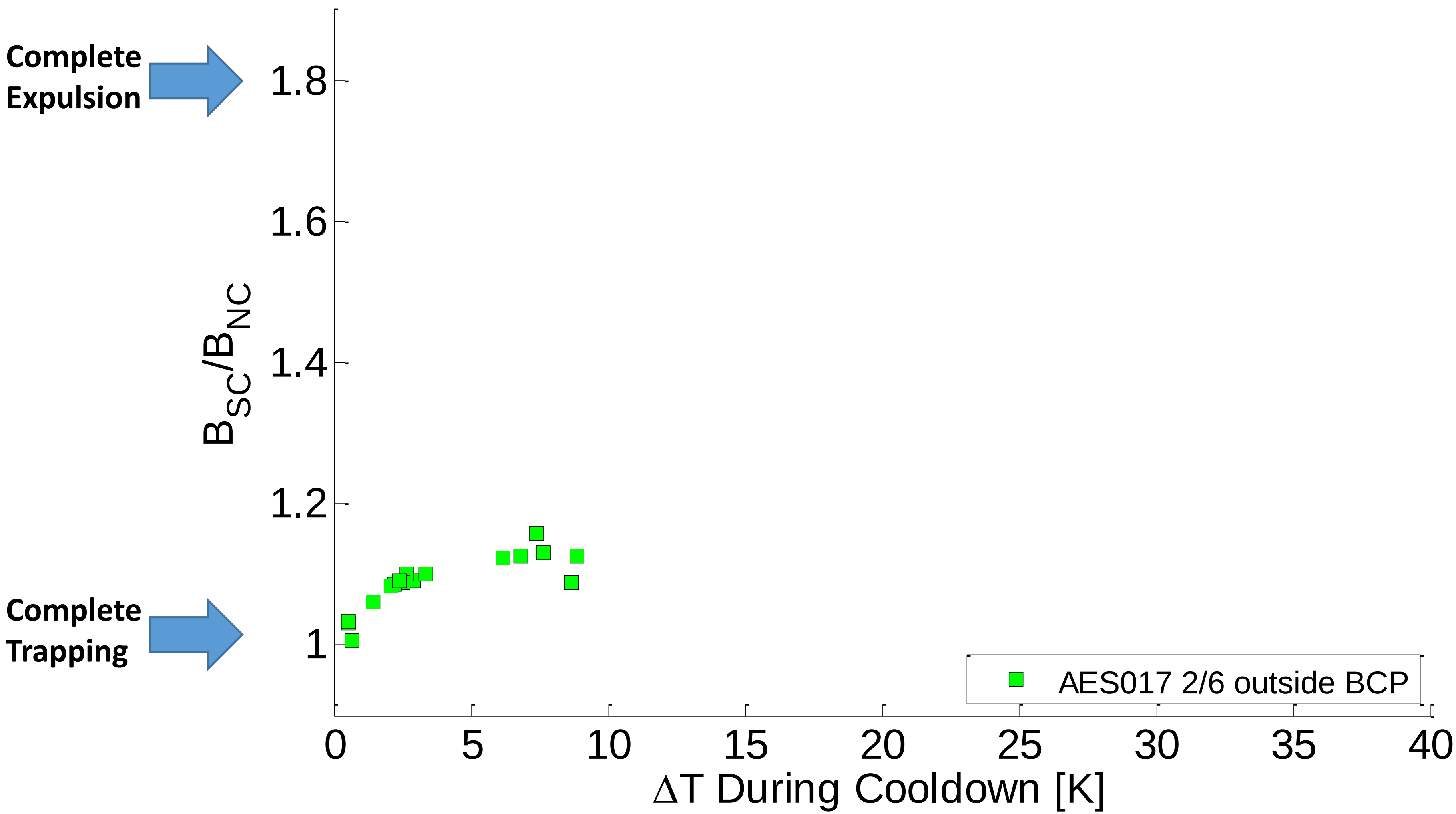


Good expulsion: $B_{SC}/B_{NC} \sim 1.6$

Example of Cavity that Expels Flux Well



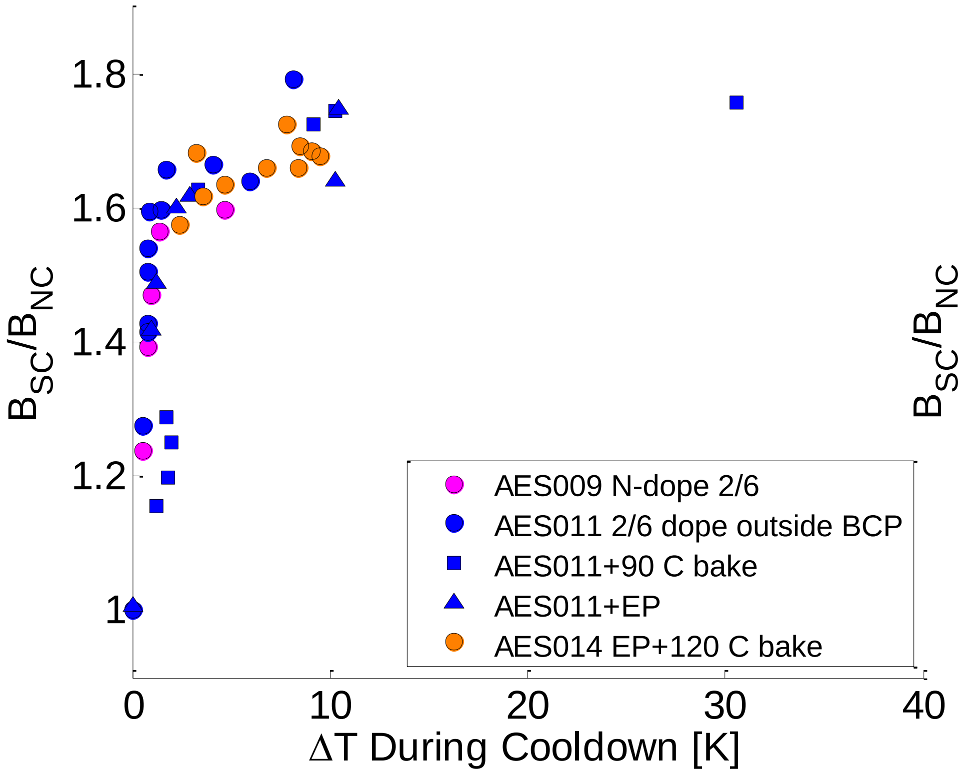
Example of Cavity that Expels Flux Poorly (Large Trapping)



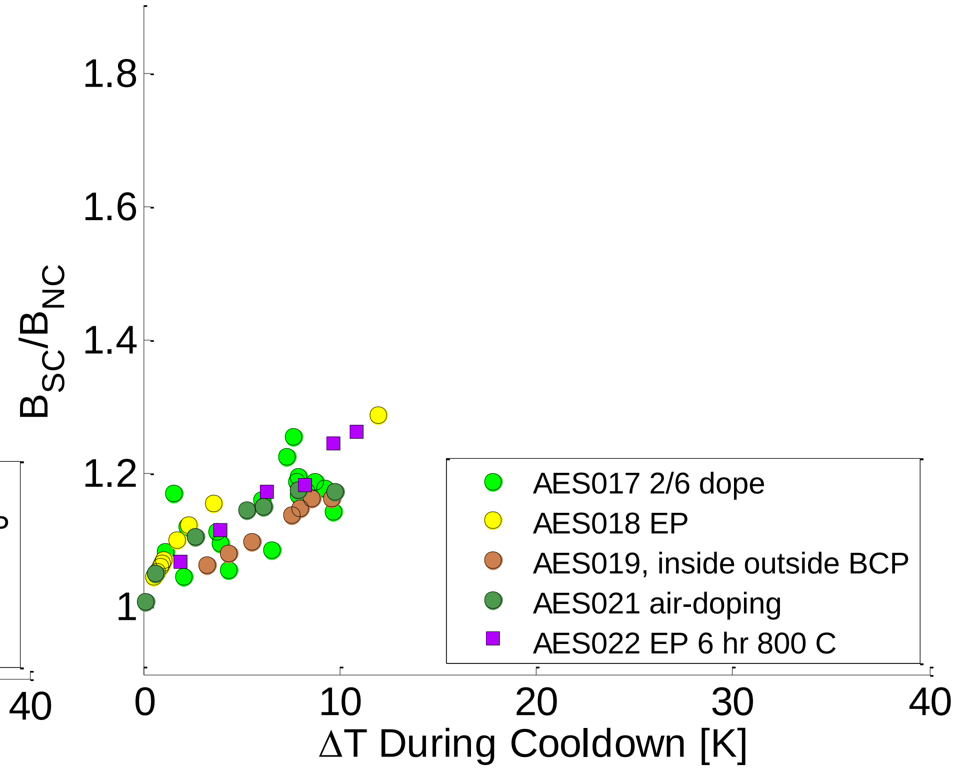
Large Survey

- Measured many single cell 1.3 GHz cavities
- Thermal cycles – start from 15-100 K, cool down to 7 K, warm up
- Parasitic measurements on other experiments
- 22 datasets measured (i.e. treatment then into dewar)

Quickly Apparent Trend With Batches of AES Cavities



AES Single Cells Batch 1



AES Single Cells Batch 2

Quickly Apparent Trend With Batch of AES Cavities

AES Single Cells Batch 1

AES Single Cells Batch 2

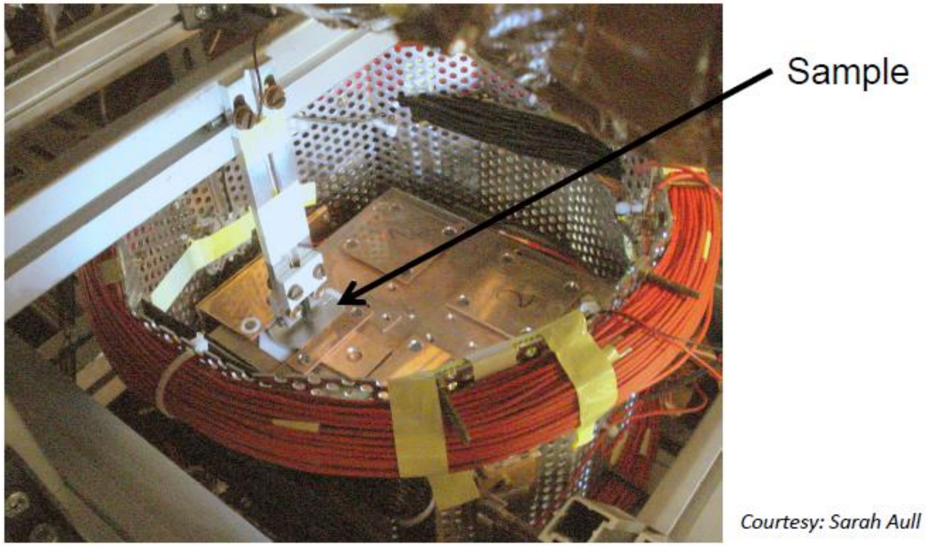
Quickly Apparent Trend With Batch of AES Cavities

AES Single Cells Batch 1

AES Single Cells Batch 2

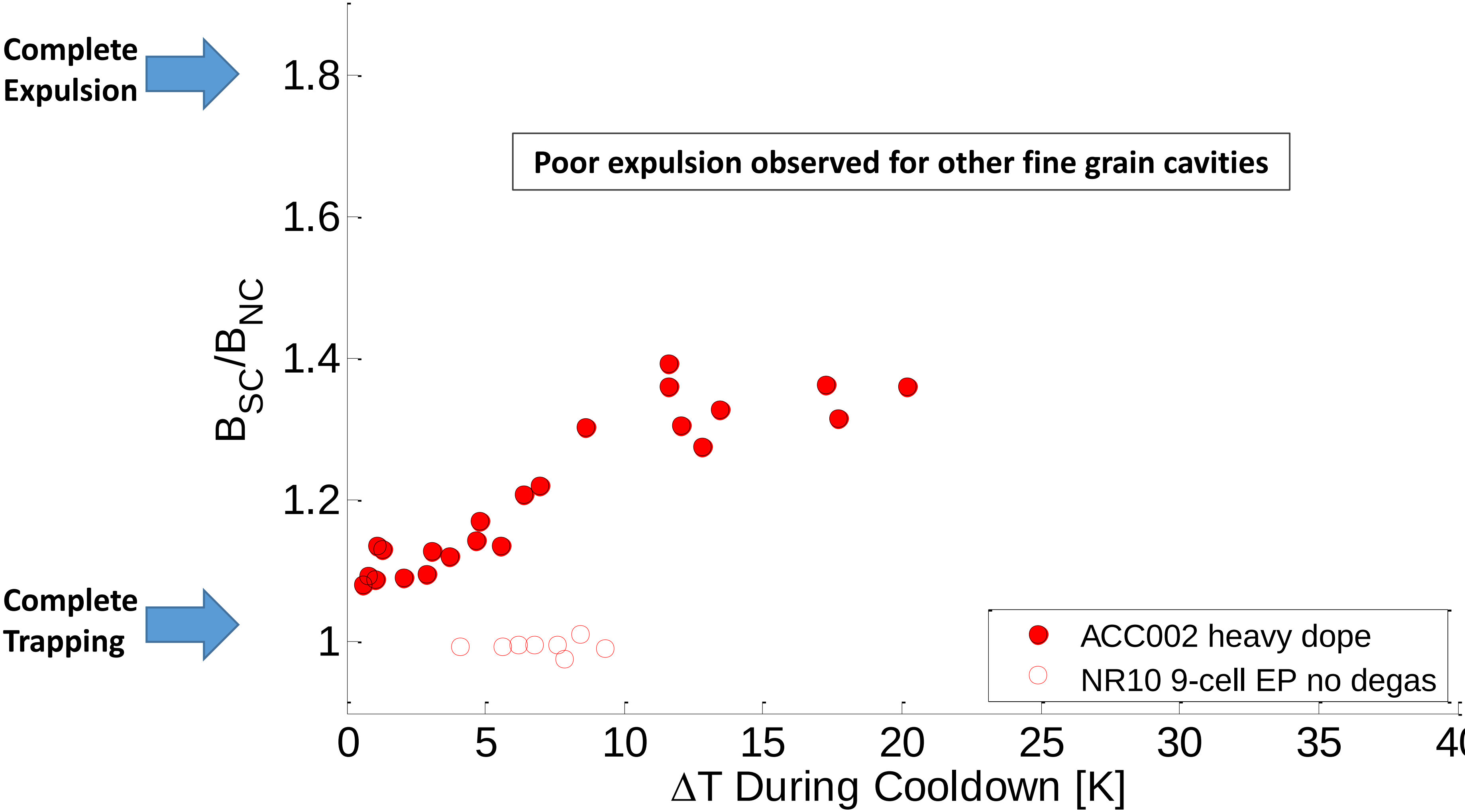
Previous Studies

- Previous sample studies, e.g.
  - Aull, Kugeler and Knobloch, *PRSTAB* 15, 062001 (2012)
  - A. Dhavale et al, *Supercond. Sci. Tech*., 25, 065014 (2012)
- No measurement as a function of thermal gradient, but qualitative trend: larger grain material seems to expel better



Courtesy: Sarah Aull

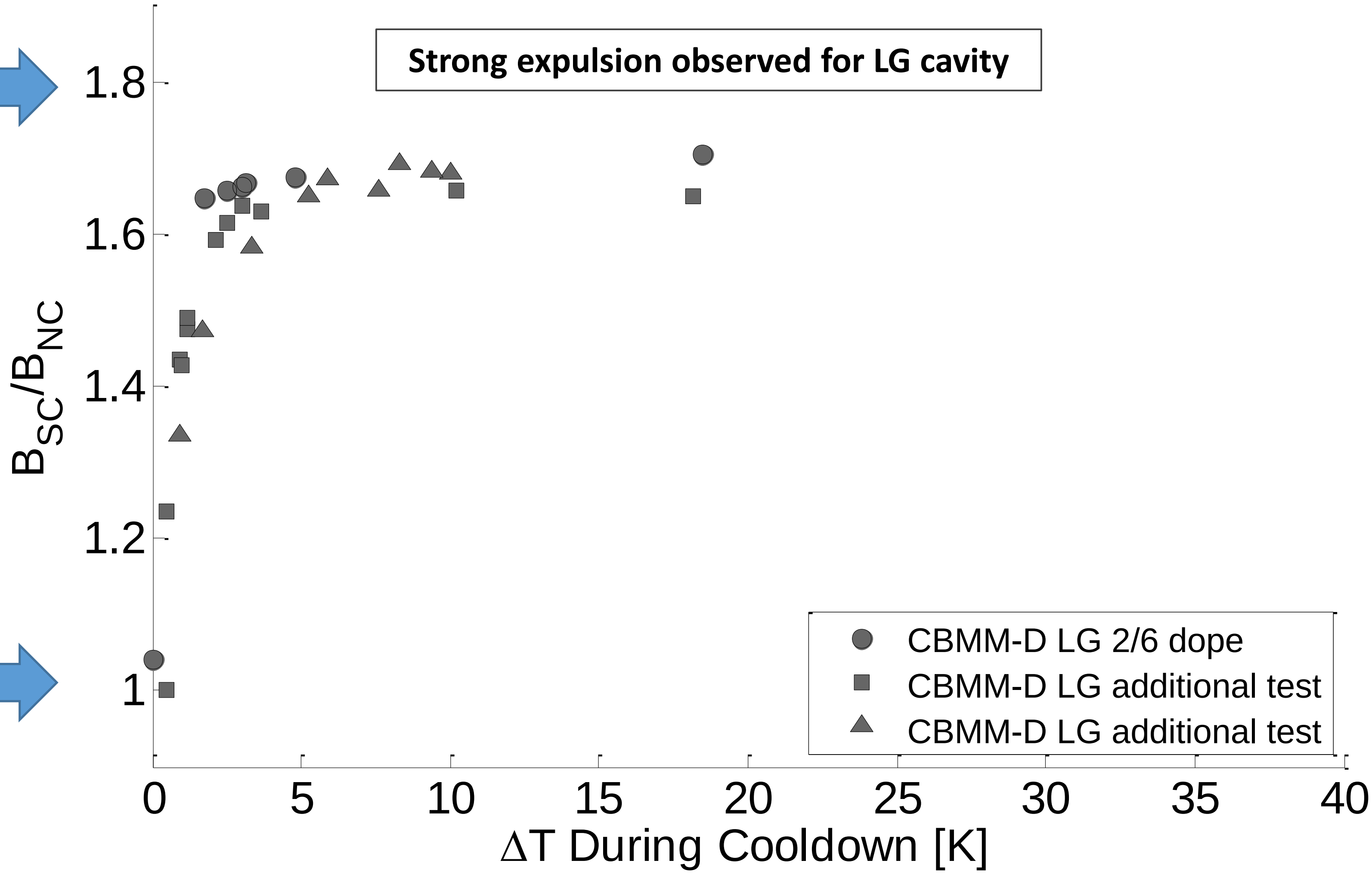
Other Fine Grain Cavities – Poor Expulsion



Large Grain Cavity – Strong Expulsion

Complete Expulsion

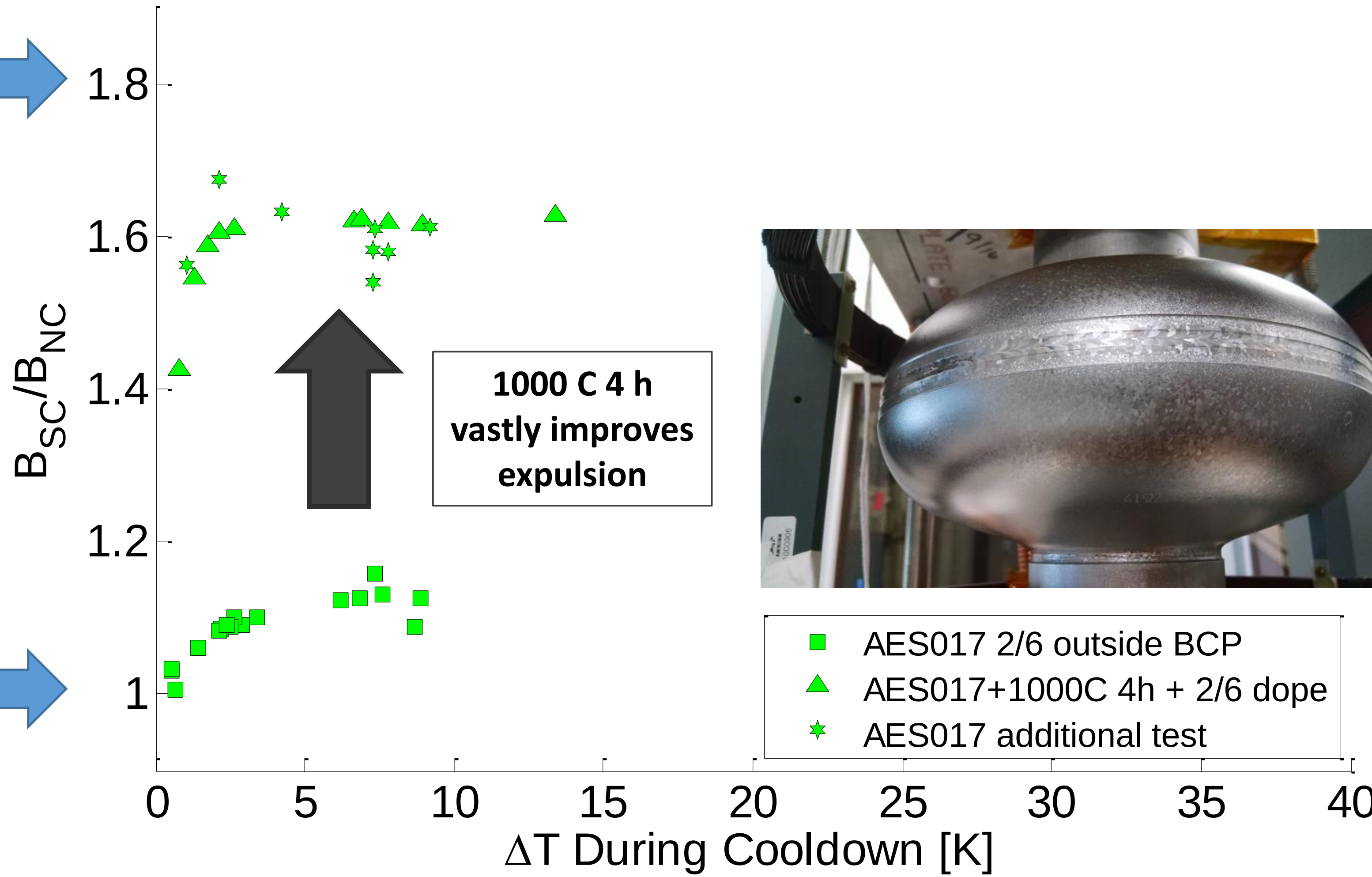
Complete Trapping



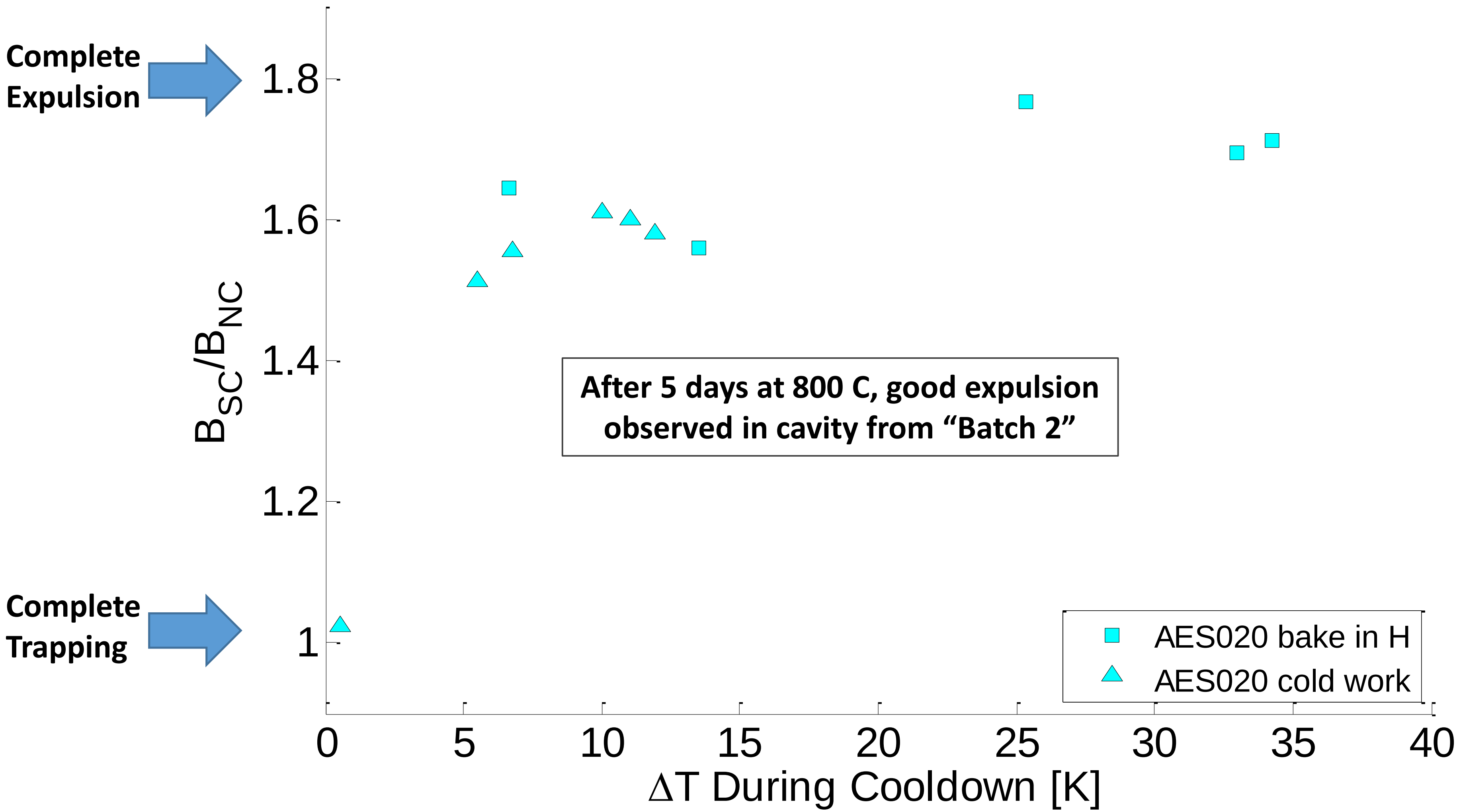
Conversion to From Poor to Strong Expulsion

Complete Expulsion

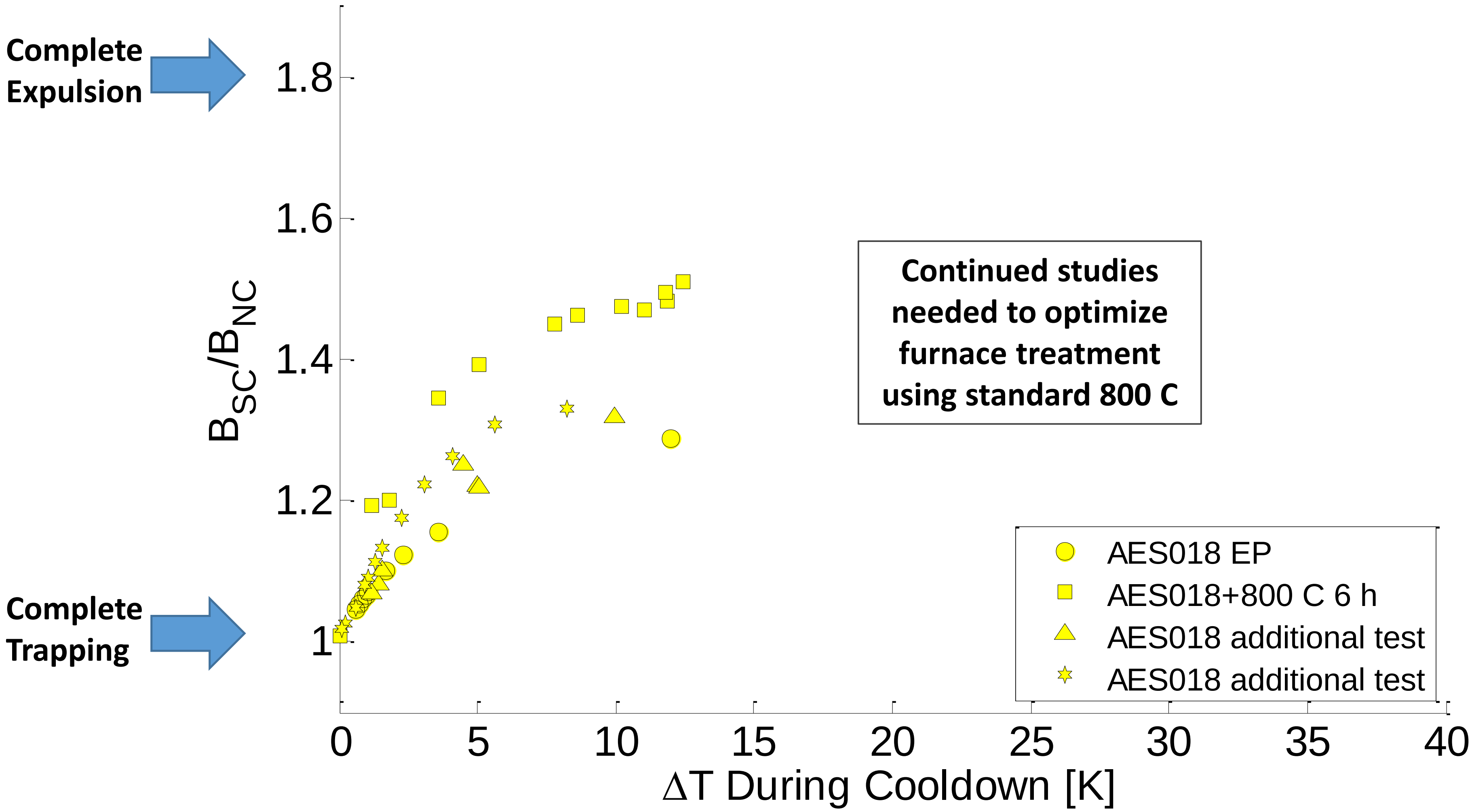
Complete Trapping



Long Treatment at 800 C

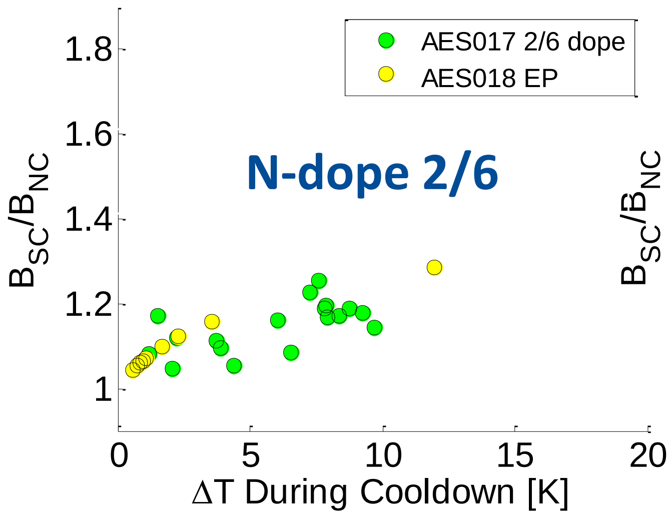


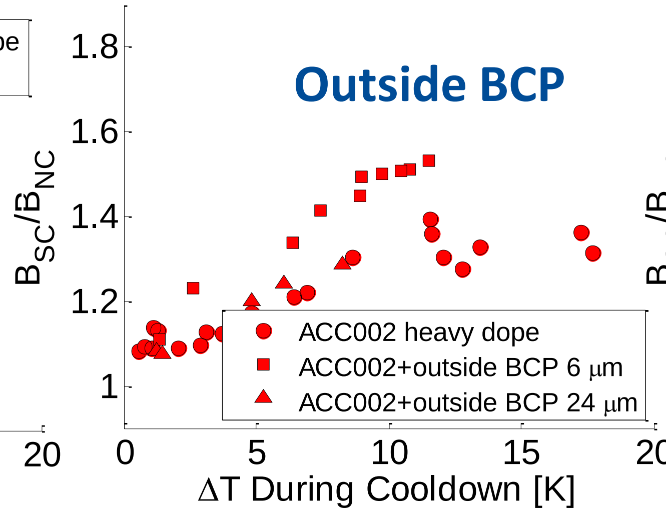
Long Treatment at 800 C

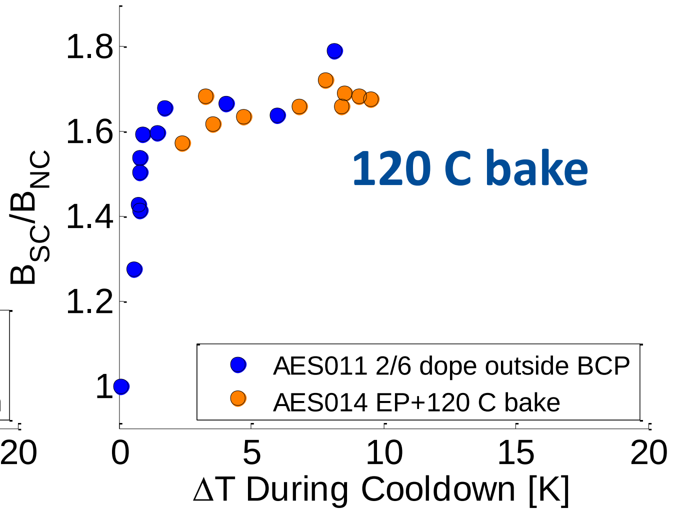


Continued studies needed to optimize furnace treatment using standard 800 C

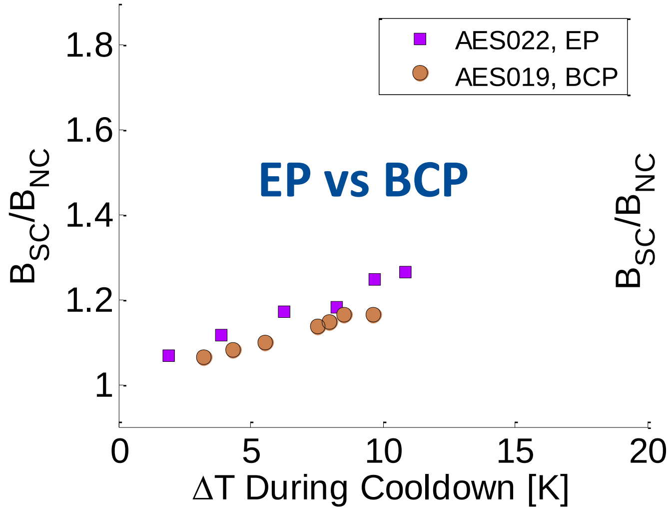
Surface Alteration With No Significant Effect on Expulsion

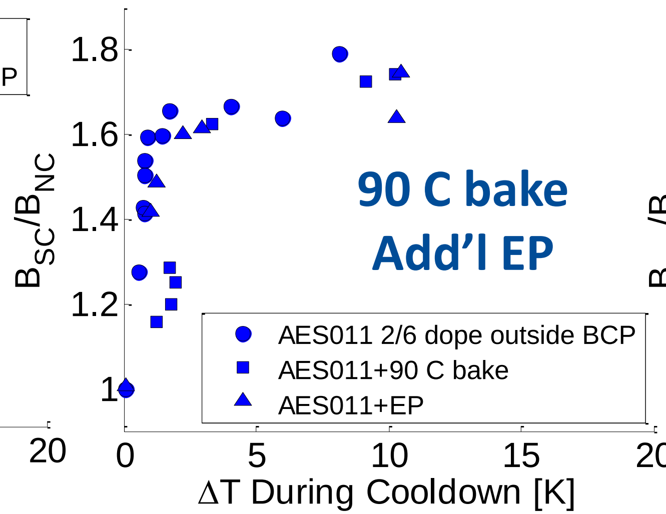


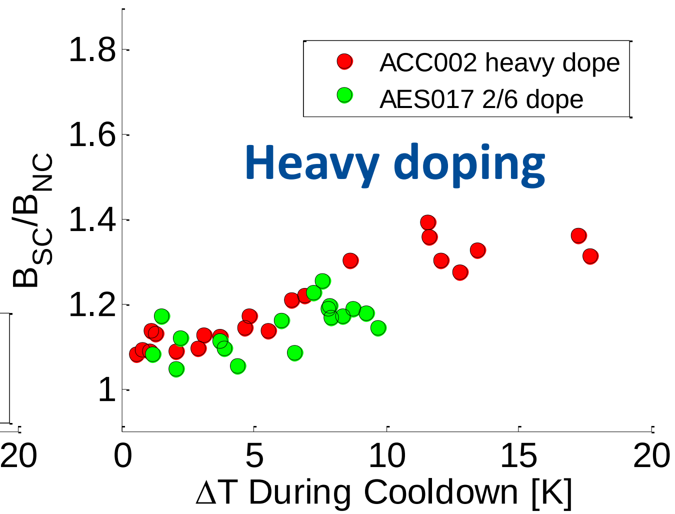




Different surface conditions in cavities with similar bulk history: similar expulsion

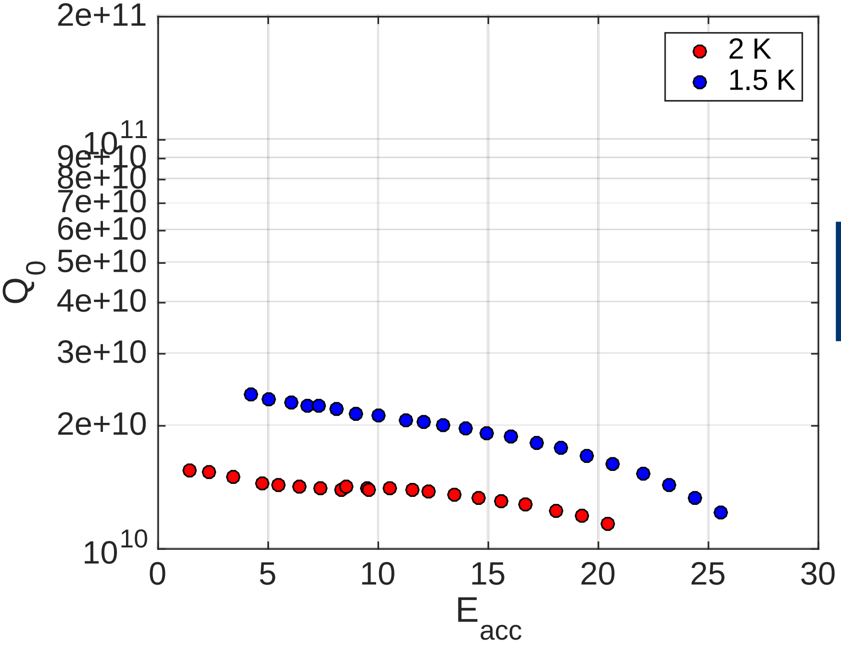




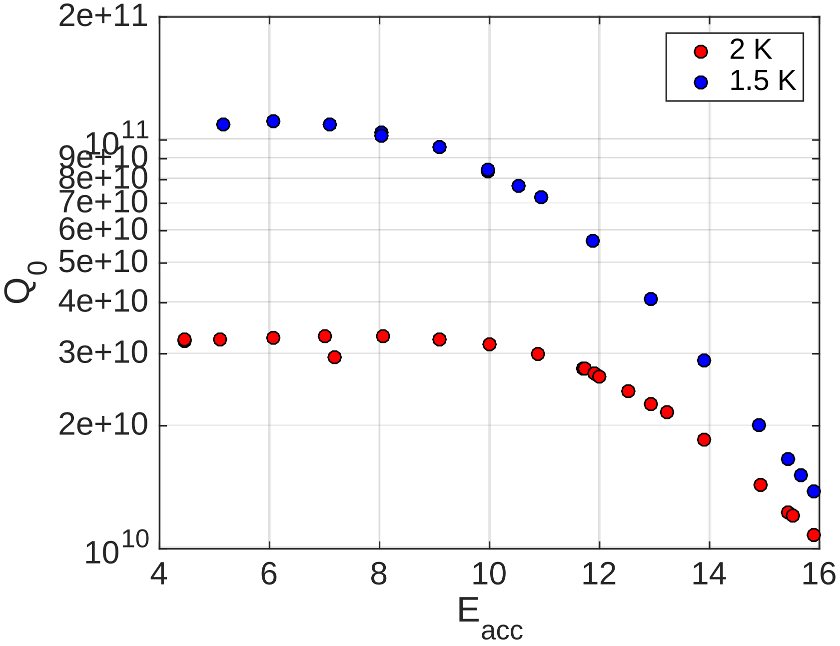


Effect on Q vs E

AES017 cooled in 10 mG



1000 C Bake



Poor expulsion: $B_{SC}/B_{NC} \sim 1.1$

Good expulsion: $B_{SC}/B_{NC} \sim 1.6$

Summary

- Treating for strong expulsion can reduce requirements for:
  - Shielding/active compensation of external fields – B_{ext}
  - Sensitivity to trapped flux – $R_s(B_{trap})$
  - Cryogenic plant size and power consumption
- Experiment: Measure trapped flux as a function of treatment and spatial temperature gradient
- **Thermal gradient** at transition critical for all preparations
- Modification of **bulk structure** through furnace treatment shows trend of **improved** flux expulsion
- Modification of **surface structure** shows **minimal influence** on flux expulsion
- Additional studies are required to determine reproducible conditions for strong expulsion of flux (try at 800 C)

Implications for Achieving High Q_0 in Cryomodules

- If reduced **grain boundary density** improves expulsion, path to optimize preparation – furnace treatment, larger ASTM spec for half-cell sheets, ingot LG Nb for sheets
- Consistent with high Q_0 in LG studies, e.g. W. Singer et al., Phys. Rev. ST-AB, 16, 012003 (2013)
- N-doping discovery made on cavity with strong expulsion

Outlook

- Cavity studies – Progressive measurements with 6 hr 800 C furnace treatments
- Sample studies – with progressive steps of 6 hr at 800 C, measure:
  - Grain size and dislocation content (SEM-EBSD)
  - Mechanical properties (tensile test)
  - Flux expulsion (small dewar)