Introduction to Magnetic Flux Expulsion in Bulk Niobium Cavities

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TTC Topical Workshop on Flux
9 November 2018
CERN
Experiments to Probe the Physics of Flux Expulsion
N doped 1.3 GHz

Exactly the same setup – only difference is fast/slow cooldown

Field Enhancement from Magnetic Probe on Cavity Surface

Several factors influence $Q_0$-degradation from magnetic flux:

- Ambient magnetic field
  - Local value of Earth’s field, shielding, demagnetization, magnetic components, thermocurrents (static & dynamic), active compensation, etc. [discussed earlier this morning]

- Flux expulsion
  - Fraction of ambient flux is expelled out of superconductor vs becoming trapped in it during cooldown [the rest of today]

- Sensitivity
  - For a given amount of trapped flux, what is the added surface resistance [several presentations on this subject tomorrow]
1) Cooldown matters: cooldown can determine if ambient flux is trapped or expelled

Same cavity, just cooled differently through 9.2K

- #1: First fast from 300K
- #2: Slow from 15K
- #3: Fast from 15K

Flux expelled efficiently

Flux mostly trapped

2K, 1.3 GHz

Systematic Method for 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. Measurements are performed as a function of $dT/dx$.
  
  - Complete trapping: $B_{SC}/B_{NC} = 1$
  - Complete expulsion: $B_{SC}/B_{NC} \approx 1.7$

2) 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**

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**Graphs and Tables**

- **Left Graph:**
  - Title: Onset of strong increase in trapping
  - X-axis: $T_1-T_2$ (K)
  - Y-axis: Expulsion ratio $B_{sc}/B_{tc}$
  - Data points:
    - Black squares: N doped
    - Red circles: EP+120C

- **Right Graphs:**
  - Two graphs showing $R_{res}$ vs $T_1-T_2$ (K)
  - Graphs for different $E_{ac}$ values:
    - $E_{ac} = 4$ MV/m
    - $E_{ac} = 16$ MV/m
  - Legend:
    - Black squares: $E_{ac} = 4$ MV/m
    - Red circles: $E_{ac} = 16$ MV/m
  - Data points:
    - Black squares: $Q$ at 1.5K
    - Red circles: $Q$ at 3x10^-11, 2x10^-11, 1x10^-11

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**References**

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Top of cavity

Bottom of cavity
2) Large thermal gradients at $T_c$ promote expulsion of flux
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2) Large thermal gradients at $T_c$ promote expulsion of flux
3) Slow, uniform cooldown tends towards trapping all flux – even if cavity expels well at large $dT/dx$.

- **Fast cool-down** lead to **large thermal gradients** which promote efficient flux expulsion.
- **Slow cool-down** $\rightarrow$ poor flux expulsion.

As middle hits $T_c$,

Measure temp at top of cavity

Helium cooling from below

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3) Slow, uniform cooldown tends towards trapping all flux
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4) Surface treatments have insignificant impact

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

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)
4) Surface treatments have insignificant impact

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

Depends on **bulk treatment, not surface**

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)
Several factors influence $Q_0$-degradation from magnetic flux:

- Ambient magnetic field
  - Local value of Earth’s field, shielding, demagnetization, magnetic components, thermocurrents (static & dynamic), active compensation, etc. [discussed earlier this morning]

- Flux expulsion
  - Major influence from bulk of superconductor
  - Fraction of ambient flux is expelled out of superconductor vs becoming trapped in it during cooldown [the rest of today]

- Sensitivity
  - Major influence from surface of superconductor
  - For a given amount of trapped flux, what is the added surface resistance [several presentations on this subject tomorrow]
5) Some niobium production runs have very poor expulsion – even with large $\Delta T$ 

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

![Graph showing niobium production runs with variability in expulsion](image)
5) Some niobium production runs have very poor expulsion – even with large $\Delta T$

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

![Graph showing variability in niobium production runs](image)
6) High temperature treatment can make poorly expelling material expel well even with small $\Delta T$

- 900°C – 1000°C furnace treatment *improves* expulsion
6) High temperature treatment can make poorly expelling material expel well even with small ΔT.

- 900°C furnace treatment improves expulsion.

- High temperature treatment can make poorly expelling material expel well even with small ΔT.

- 900°C-1000°C treatment improves expulsion.

- 1.3 GHz 1-cell cavities

- AES017 800°C doping
- AES017 +1000°C 4h + 800°C doping
- AES018 EP +800°C 6h
- AES018 +1000°C 1h
- AES022 +6hr 800°C
- AES022 +3hr 900°C

- B_{ext} < 1 mG
- B_{ext} : 5 mG
- B_{ext} : 5 mG

- E_{acc} = 0, 5, 10, 15, 20, 25, 30

- Q_0 = 10^{10}, 10^{11}

- Full trapping

- Fermilab

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)
7) 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
7) Improvement in expulsion is correlated with grain growth

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

Impurities/RRR? Dislocations?

800 C only

Tokyo Denkai

Wah Chang

1000 C 4 hrs
7) Improvement in expulsion is correlated with grain growth.
8) Heavy deformation degrades expulsion behavior

Influence of stress/dislocations?

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Full expulsion

Heavy tuning

Full trapping

- AES020 5 day 800 C
- AES020 bake in H
- AES020 +/-1 MHz tuning
- AES020 +/-10 MHz tuning
- AES020 +900C 3h
- AES020 +/-1 MHz tuning
9) Geometry affects expulsion

- Geometry can affect the location and intensity of trapped flux
- Trapping in the high magnetic field region can lead to substantial heating

Comparison of Theoretical Models
Model for Flux Expulsion – Competition Between Forces

- Competition between two forces:
  - Pinning force from pinning sites
  - Depinning force from thermal gradient


See also M. Checchin, SRF 2017
As $dT/dx$ increases, the probability of having a flux line interact with a pinning site decreases.

and $\xi^*$. The existence of the factor $|T'|^{-1}$ in Eq. (13) can be understood as follows. As a temperature gradient increases, a thickness of the vortex state domain decreases [see Eq. (17)], and a number of vortices contained in the vortex state domain decreases. Then a reaction probability decreases, and a number of trapped vortices, $N_{\text{trap}}$, decreases. Note that, when

See T. Kubo, PTEP 2016 053G01
As $dT/dx$ increases, the **probability** of having a flux line interact with a pinning site decreases.
Very Slow/Uniform Cooldown

(a) Normal conducting \((T>T_c)\)
(b) Superconducting \((T<T_c)\)

Large Thermal Gradient

Slow/Uniform Cooldown

Identifying the Features Responsible for Pinning Flux During Cooldown in SRF-Grade Bulk Niobium
Criteria for Features

- It is dominated by **bulk** properties - not impacted by standard surface treatment
- Pinning is made weaker by **heat treatment** for several hours in temperature range of 900±100 C, and the temperature depends on the material
- Pinning is made stronger by **cold work** of material
Criteria for Features

- It is dominated by **bulk** properties - not impacted by standard surface treatment
- Pinning is made weaker by **heat treatment** for several hours in temperature range of $900 \pm 100$ C, and the temperature depends on the material
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Some Possible Candidates

- Grain boundaries
- Impurities (possibly segregated at grain boundaries)
- Dislocations (possibly congregated as tangles or walls)
Grain Boundaries

Non-rolled

Rolled sheets

Calculated full expulsion

TE1RILG001 (not rolled) as received
TE1RILG001+EP+600 C 3 h
TE1RILG002 (rolled) as received
TE1RILG002+EP+600 C 3 h

$B_{SC}/B_{NC}$

$\Delta T$ During Cooldown [K]

S. Posen (FNAL), TTC Riken 2018

J. Koszegi (HZB), J. App. Phys

J. Koszegi (HZB), J. App. Phys
**Impurities**

Legend: Red line: hot spot, Blue line: cold spot

- NbH-
- O-
- C-
- NbN
- C_2-
- F

Interlaced

M. Martinello (FNAL), TTC Riken 2018
Dislocations

Local Misorientation Histogram

- Cold spot 1
- Cold spot 2
- Hot spot 1
- Hot spot 2

Low angle GBs

High angle GBs

M. Martinello (FNAL), TTC Riken 2018

S. Balachandran (ASC), TTC Riken 2018

High angle Grain boundary (>15°)

Low angle Grain boundary (3-4°)

LAGB (8°)

T. Konomi (KEK), TTC Riken 2018
Criteria for Features

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- Pinning is made stronger by **cold work** of material

Some Possible Candidates

- **Grain boundaries**
  - Grain boundaries unlikely to be dominant factor based on LG cavities, Magneto-optics
- **Impurities** (possibly segregated at grain boundaries)
  - Impurities unlikely to be dominant factor based on SIMS studies
- **Dislocations** (possibly congregated as tangles or walls)
  - Dislocations under intense study with EBSD, ECCI
Conclusion
Flux Expulsion R&D Outcome: Strong $Q_0$ Improvement in CM

- LCLS-II production cavities in Fermilab cryomodules
- Red – early cavity processing procedure
- Blue – processing procedure modified for flux expulsion

More details this afternoon
Crucial Questions

• What microscopic phenomena make different niobium production runs have such different flux expulsion behavior? (including different heat treatment temperatures required)
• What practical measurable quantities can we use to specify flux expulsion behavior in niobium?
• Can we modify specifications to give predictable flux expulsion behavior for a given heat treatment without compromising mechanical properties?
Red magnetic field lines are expelled from SC wall.

SC/NC front passing over wall during transition.

Simulation courtesy E. Cenni, CEA.