Magnetic Flux Expulsion Studies on Niobium

Sam Posen & Fermilab SRF Team
SRF Conference 2017
18 July 2017
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

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Fermilab CM-2 Cavities treated with baseline recipe

Fermilab CM-3 Treatment modified to improve flux expulsion

Total voltage Spec: 133 MV  Q₀ Spec: 2.7x10^10
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
  - Thermocurrents due to connections near cavity (e.g. He vessel)
  - Thermocurrents due to bilayers (e.g. $\text{Nb}_3\text{Sn}/\text{Nb}$)


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

O. Kugeler et al. SRF Conference (2009).
Expulsion is an Important Factor in Flux Losses

- Determines what fraction of ambient flux becomes trapped
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  - Thermocurrents due to bilayers (e.g. Nb, Sn/Nb)

\[ R_{fl} = S \cdot \eta \cdot B_{ext} \]

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

![Diagram showing thermal gradients and flux expulsion](image)

**Graphs:**
- **Expulsion ratio $B_{sc}/B_{sc}^{\text{ref}}$**
  - Onset of strong increase in trapping
  - N doped (black squares)
  - EP+120C (red circles)

- **Residual resistance $R_{\text{res}}$ (nΩ)**
  - Flux starts to get trapped
  - $E_{\text{acc}} = 4 \text{ MV/m}$ (black squares)
  - $E_{\text{acc}} = 16 \text{ MV/m}$ (red circles)

Measure temp at top of cavity
As middle hits $T_c$
Helium cooling from below

2) Surface treatments have insignificant impact

Different surface conditions in cavities with similar bulk history: similar expulsion
2) Surface treatments have insignificant impact

Different surface conditions in cavities with similar bulk history: similar expulsion depends on bulk treatment, not surface.
3) 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 the relationship between $B_{SC}/B_{NC}$ and $\Delta T$ during cooldown for niobium production runs.]

Niobium vendor: Tokyo Denkai

Niobium vendor: Wah Chang

1.3 GHz 1-cell cavities

S. Posen et al., J. Appl. Phys. 119, 213903 (2016)
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- Variability from batches even within a single vendor

Niobium vendor: Tokyo Denkai

JLab cavities: Strong expulsion with TD material

Niobium vendor: Tokyo Denkai
4) High temperature treatment can make poorly expelling material expel well even with small $\Delta T$

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

- 900°C treatment improves expulsion.

1.3 GHz 1-cell cavities

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

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

Impurities/RRR? Dislocations?

800 C only

1000 C 4 hrs

Tokyo Denkai

Wah Chang
5) 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?

1000 C 4 hrs

Tokyo Denkai

Tokyo Denkai
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

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

1.3 GHz 1-cell cavities

Data measured by Jefferson Lab

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

Full expulsion

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)

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

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

After 900°C treatment: much improved.

1.3 GHz 1-cell cavities

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

Data measured by Jefferson Lab

Data measured by Fermilab
As-received niobium material for LCLS-II production:

- Very poor expulsion

LCLS-II Preproduction

1.3 GHz 1-cell cavities

Data measured by Jefferson Lab

After 900°C treatment:

- Much improved

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

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

Cavity $Q_0$ Performance in VT

- 800/140 in Low $B_{amb}$
- 900/200 in 5-10 mG

Data from both JLab and Fermilab

See D. Gonnella’s talk on Thursday
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**Fermilab CM-2**
- Baseline recipe: 800 C degas, 140 μm bulk EP
- Fast cooldown

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

Total voltage Spec: 133 MV  
Q₀ Spec: 2.7x₁₀⁻¹⁰

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 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

Cut 2 slices, 5 mm thick

Roll to 3 mm thickness

Cut down to disc size

1-cell 1.3 GHz cavity fabrication (now)

Large Grain Experiment

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

- Intellectual and experimental contributions to this experimental endeavor from Sebastian Aderhold, Mattia Checchin, Curtis Crawford, Anna Grassellino, Martina Martinello, Alex Melnychuk, Hasan Padamsee, Roman Pilipenko, Alexandr Romanenko, Dmitri Sergatskov, Yulia Trenikhina
- Special thanks to Fermilab VTS teams
- Special thanks to LCLS-II, Jefferson Lab, SLAC for data and niobium samples relevant to LCLS-II
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 $\Delta T$)
  4. High temperature treatment can make poorly expelling material expel well (even with small $\Delta T$)
  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