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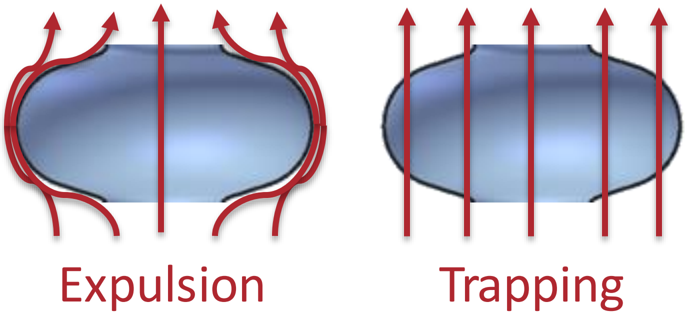
Flux Expulsion Studies

Sam Posen

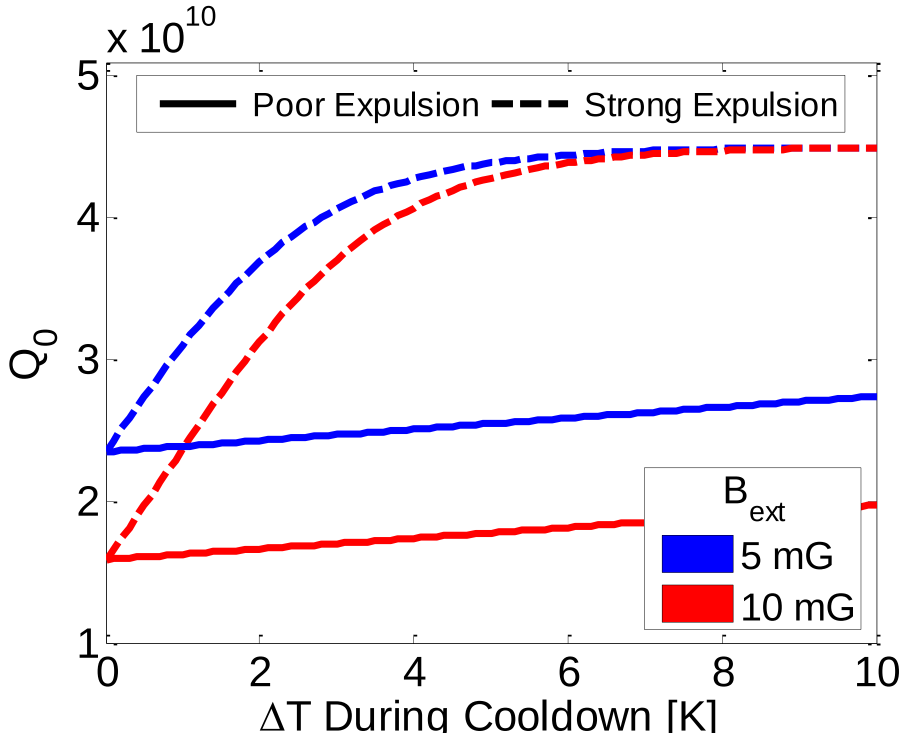
1 March 2016

Flux Expulsion

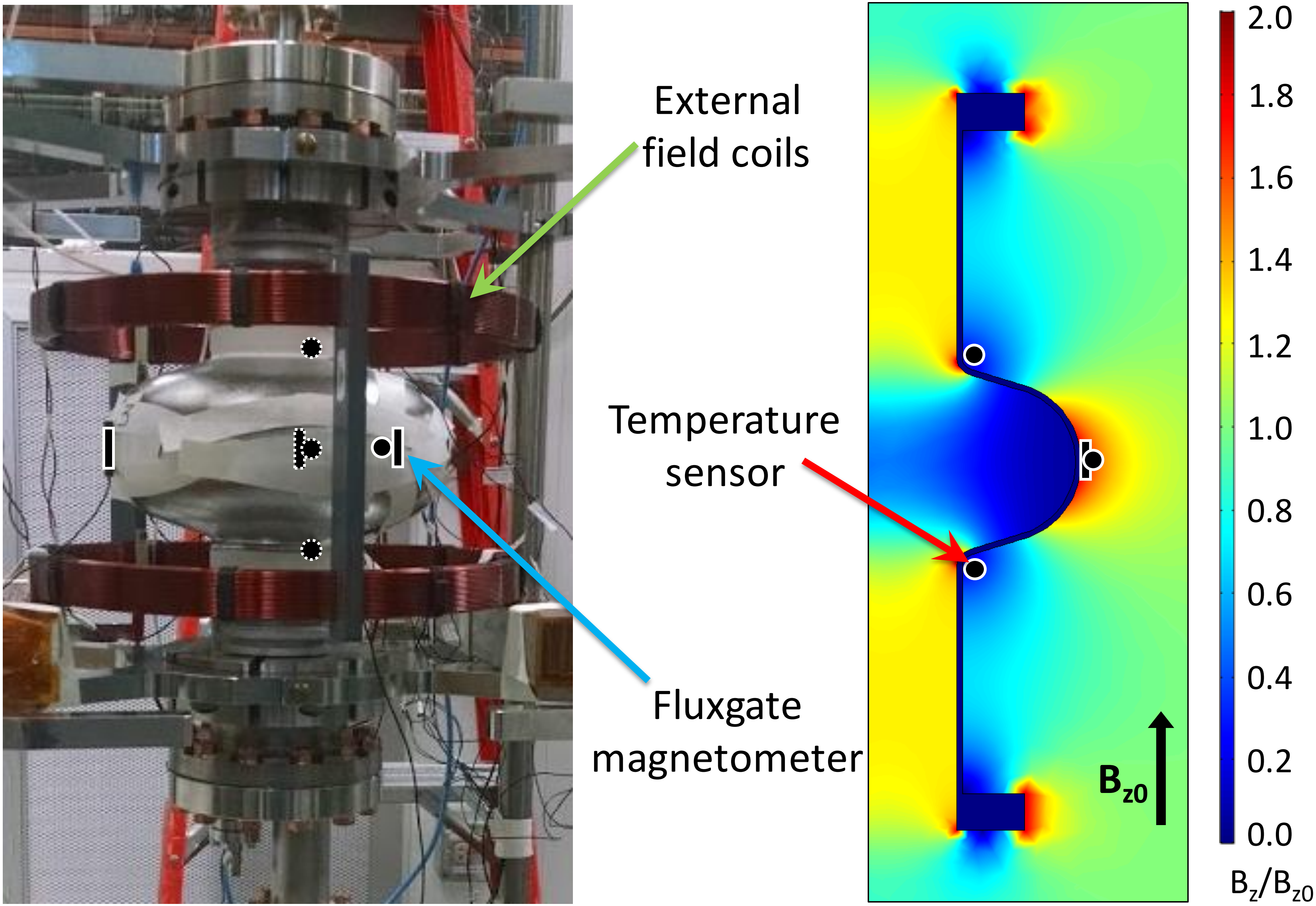
- Why push to increase Q_0 by improving flux expulsion of cavities? Benefits to project:
  - **Higher energy** operation
  - Lower **operational costs**
  - Cryogenic overhead for **LCLS II upgrade**
  - High Q_0 has been focus: great to achieve goal



High Q_0:
- Low background fields
- Cooldown with ΔT
- Good expulsion

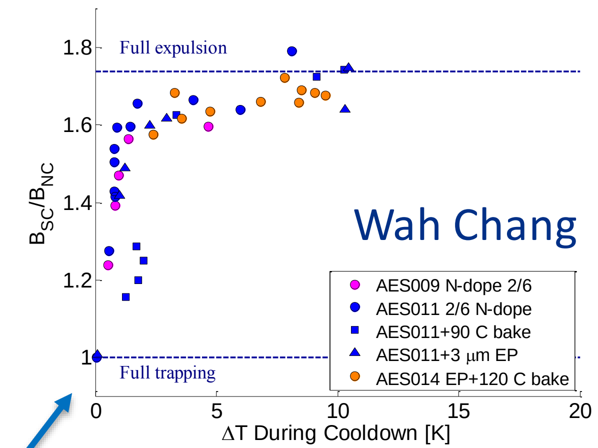


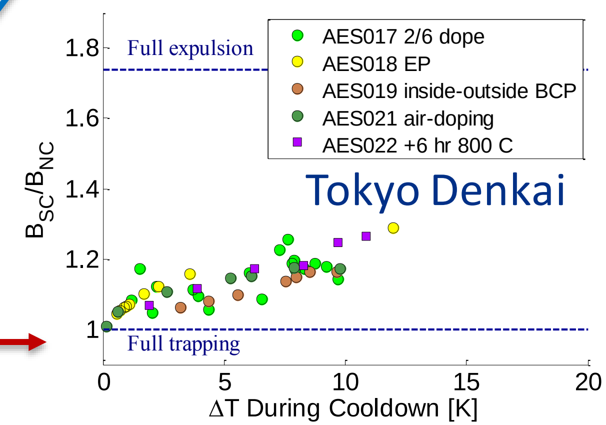
Fermilab

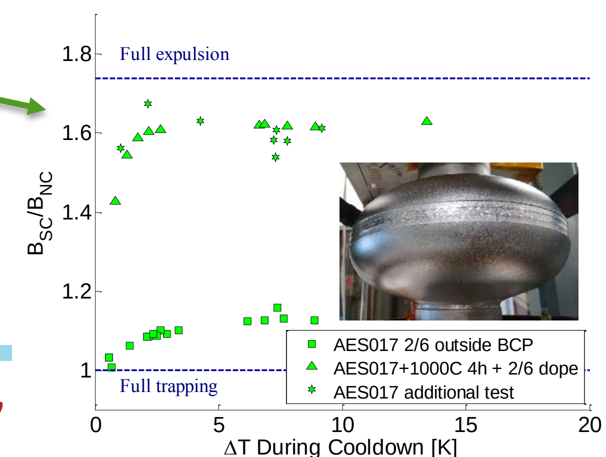

External field coils
Temperature sensor
Fluxgate magnetometer
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B_z/B_{z0}
B_{z0}

Previous Studies

- Previous observations from FNAL studies:
  - Flux expulsion depends on **thermal gradient** during cooldown and **material history**
  - Some cavities expel nearly all flux for ΔT>2K while others show <50% even for ΔT~10K
  - Seems to be consistency within batches: found one set of cavities with Wah Chang material expelled well and another with Tokyo Denkai did not
  - Can cure poor expulsion! Great improvement in one cavity after 1000 C 4 h



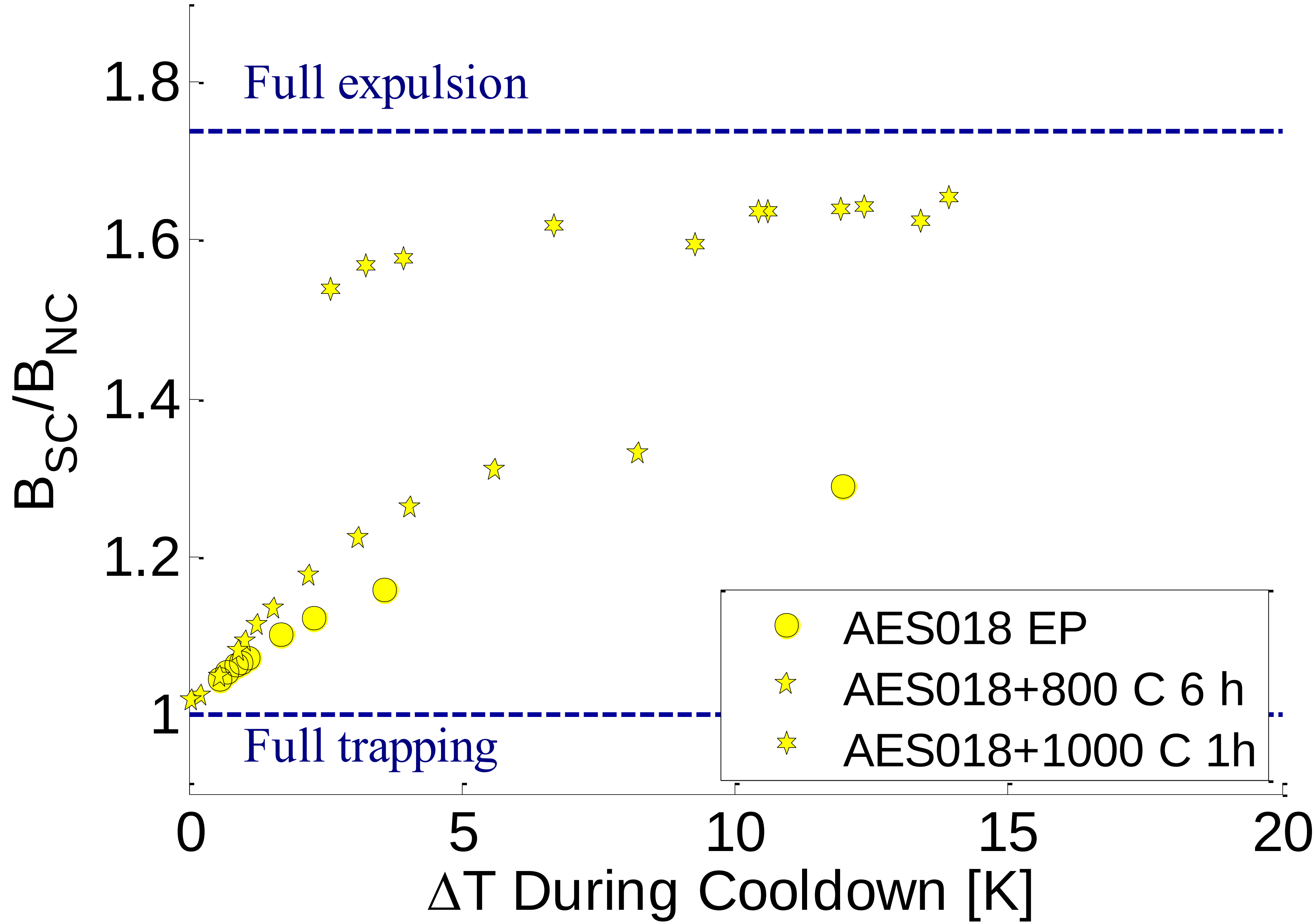


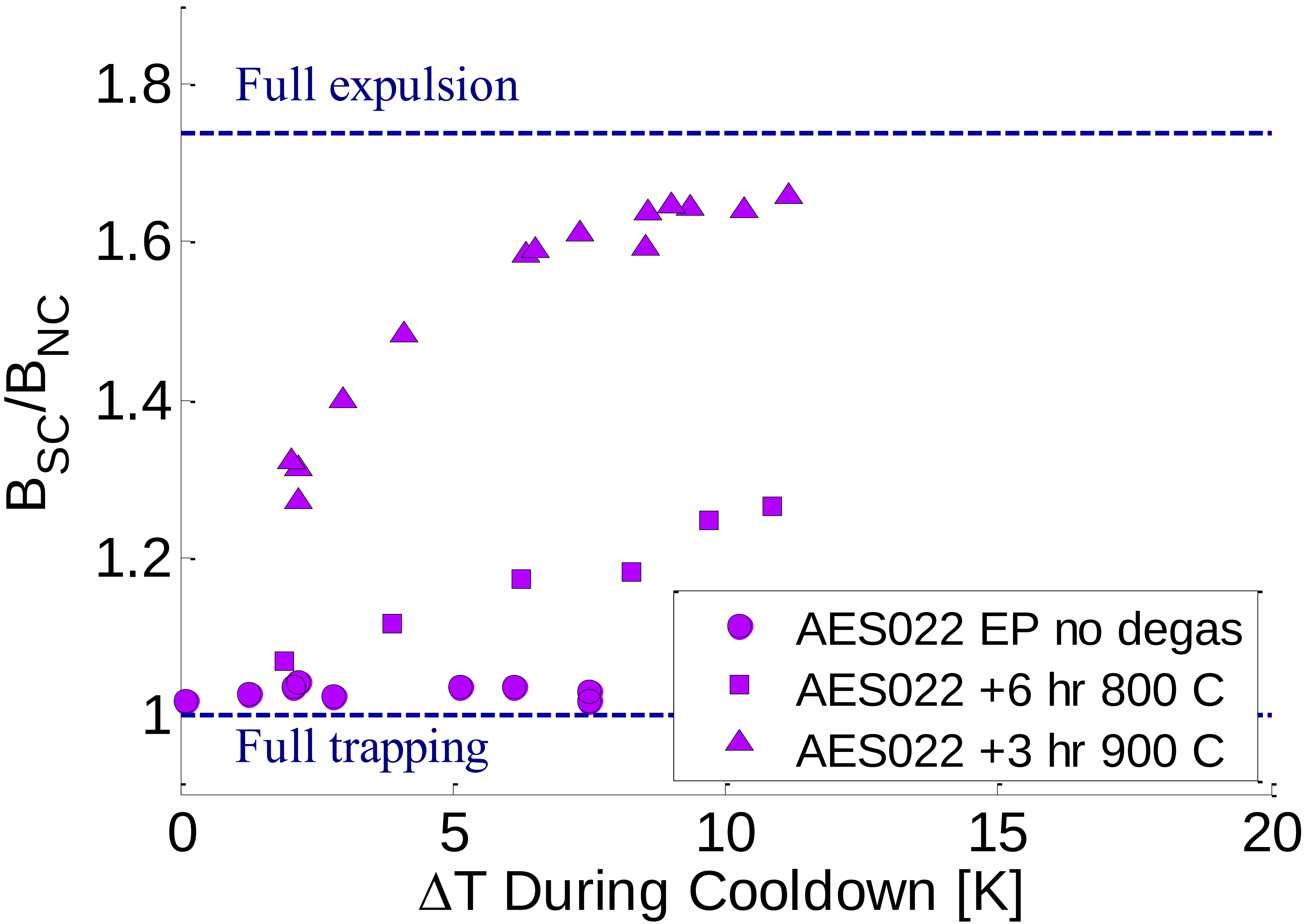


Next steps were:

- Determine if niobium vendors consistently have similar expulsion
- See how lower temp/less time changes expulsion

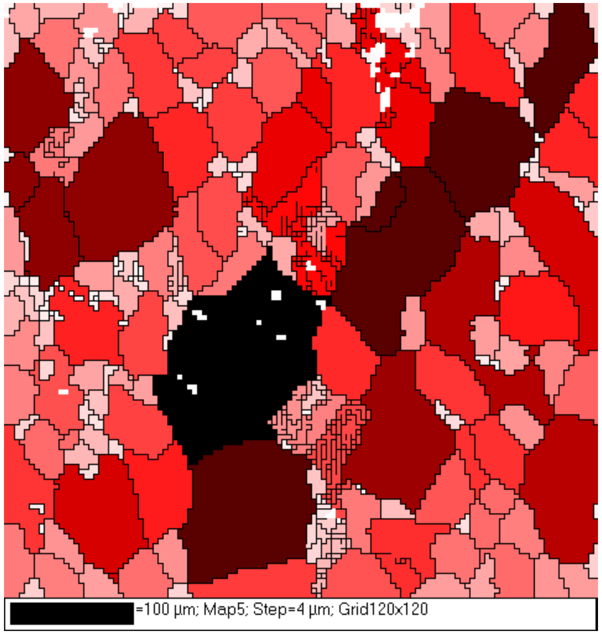
arXiv:1509.03957


Full expulsion
Full trapping
B_{SC}/B_{NC}
1.8
1.6
1.4
1.2
1
0
5
10
15
20
ΔT During Cooldown [K]
AES018 EP
AES018+800 C 6 h
AES018+1000 C 1h

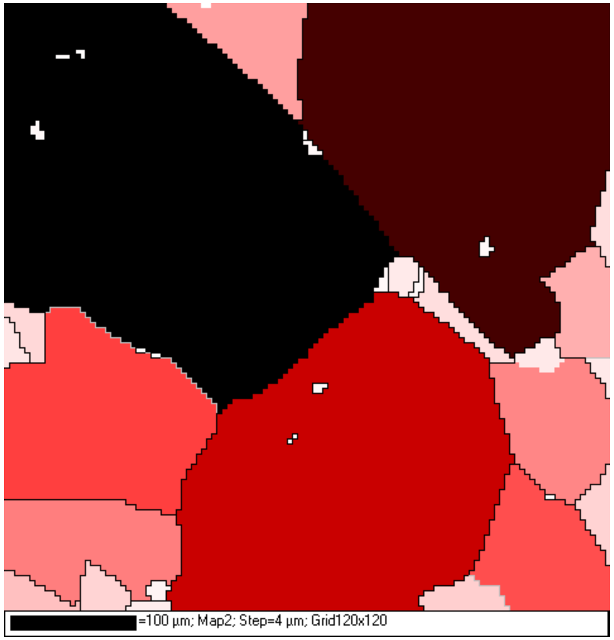

Full expulsion
Full trapping
B_{SC}/B_{NC}
1.8
1.6
1.4
1.2
1
0
5
10
15
20
ΔT During Cooldown [K]
AES022 EP no degas
AES022 +6 hr 800 C
AES022 +3 hr 900 C

Heat Treatment Effect on Grain Size

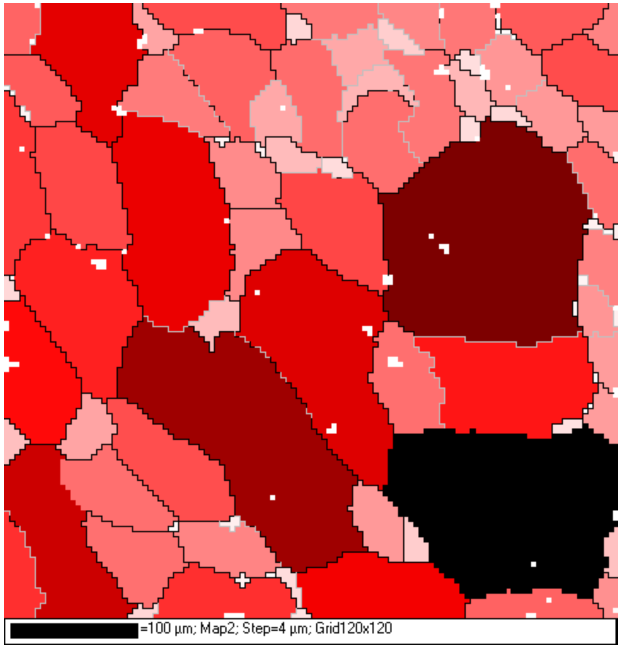
Tokyo Denkai – No Bake
Sample 7828



Tokyo Denkai – 1000 C, 1 hr
Sample 7826

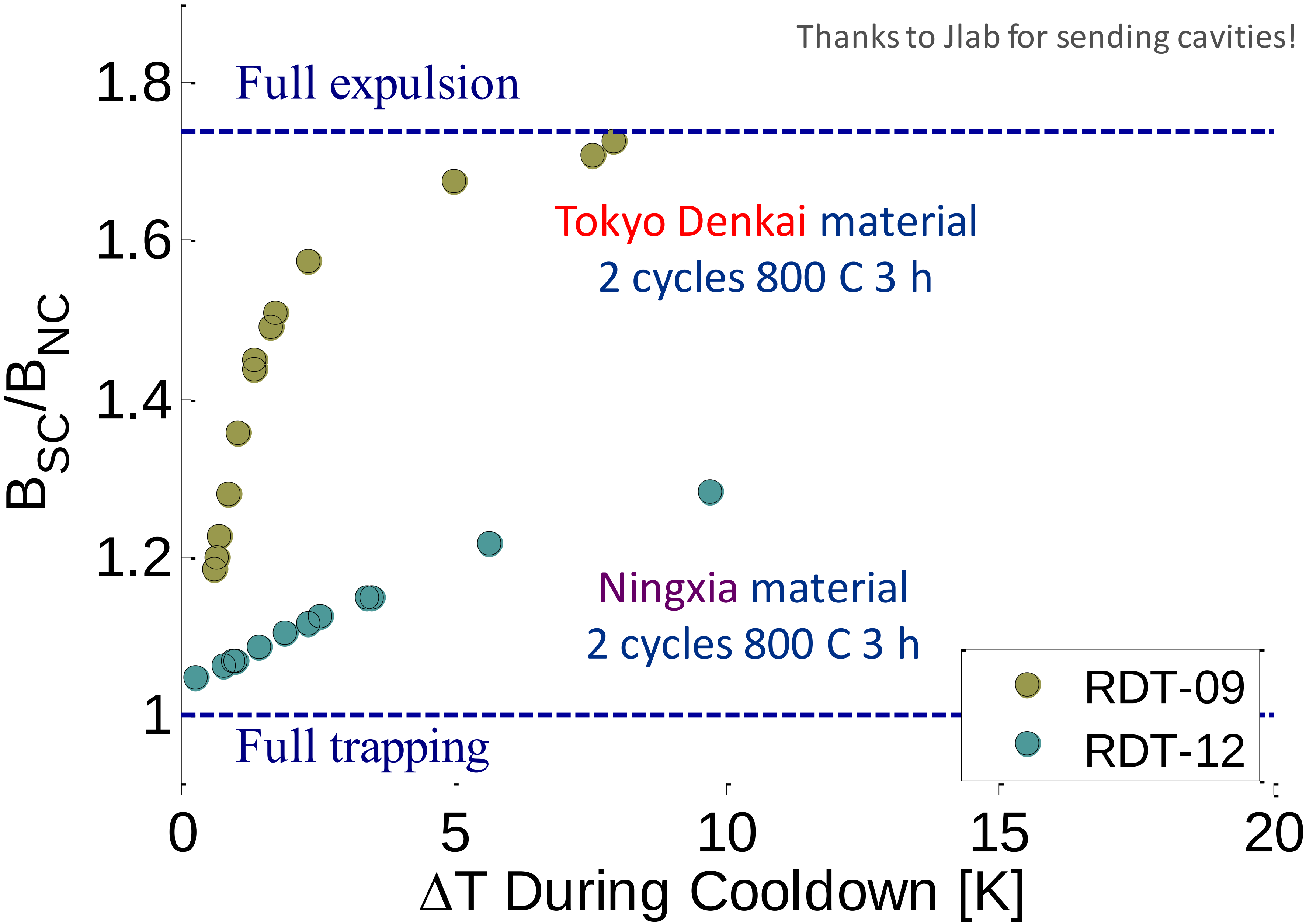


Tokyo Denkai – 900C, 3 hr
Sample 7818



Lighter = smaller grain / Darker = larger grain

Thanks to Jlab for sending cavities!



Observations

- 900 C 3 h improved expulsion significantly compared to 800 C 6 h, though did not bring expulsion as strong as 1000 C 4 h
- 1000 C 1 h showed stronger expulsion than 900 C 3 h cavity
- 2 cavities sent to us by JLab show
  - 1 cavity with Ningxia – poor expulsion
  - 1 cavity with Tokyo Denkai – strong expulsion
- Seems to show that there is variability even within a single material vendor (Tokyo Denkai) depending on batch

Possible Actions for LCLS II Project

- Course of action discussed with JLab to assess flux expulsion capability of material and qualify remediation if necessary (in parallel w/ production, as early as possible):
  - Set aside material from each of two LCLS II material vendors, Tokyo Denkai and Ningxia
  - JLab builds single cell from each vendor, and both JLab and FNAL will measure expulsion/RF (hopefully both expel well!)
  - If expulsion should be improved, labs will implement remediation furnace treatment, then remeasure
  - Could then study single cells made from raw material that was heat treated before fabrication
  - Could use results to evaluate if worthwhile applying to subsequent production cavities
- Both insurance and potential improvement

Overview

When cavities are cooled below their superconducting transition temperature in a magnetic field, flux may become trapped in the material (see Figure 1). Trapped flux dissipated under RF fields, lowering the Q_0 of the cavity. Even relatively small residual magnetic fields, if trapped, can substantially affect the Q_0. Early studies of nitrogen doping [1-2] showed that flux could be expelled by cooling the cavity with a spatial temperature gradient. Even large fields could be fully expelled with a sufficient temperature gradient [2]. This important lesson was applied to the design of the LCLS-II cryomodules, installing additional cryogenic valves to encourage temperature gradients, as well as extra magnetic shielding to reduce residual fields.

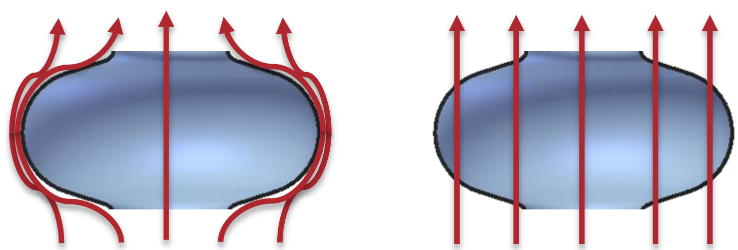


Figure 1: Cooling a cavity cell in a magnetic field may result in expulsion (left) or trapping (right) of magnetic field lines.

Later SRF R&D activities [3] revealed a potential risk for achieving high Q_0 in the LCLS-II production cavities. Experiments showed that there is variability in the tendency of niobium cavity material to trap magnetic flux during cooldown. The material used in early studies of nitrogen doping expelled particularly strongly, but other materials studied showed considerably weaker performance.

For LCLS-II, there is a substantial risk of reduced Q_0 if:

1) The cavity material used for LCLS-II production cavities expels poorly
2) There is significant residual magnetic fields for some cavities (even if the 5 mG specification is met, if the field is mostly trapped, it can cause substantial degradation, as shown in Figure 2)
3) The temperature gradient achieved during cooldown is not large enough to expel flux to a satisfactory degree

SRF R&D studies also showed that that flux expulsion behavior depends on the bulk material (not the surface) and that high temperature furnace treatment could be used to modify the bulk niobium, converting cavities from weak to strong flux expulsion behavior [3-4].

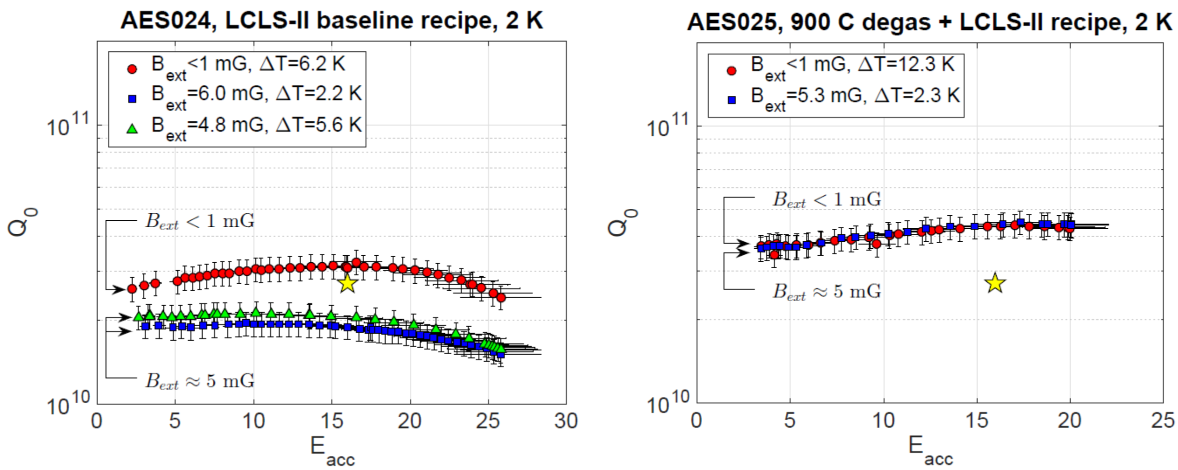


Figure 2: Cavity performance after cooling in a magnetic field [4]. Left: substantial Q_0 degradation is observed when cooling a single cell cavity given the LCLS-II baseline treatment in a 5 mG field. Right: no degradation is observed in a similar cavity given an additional 900 C furnace treatment. The star represents the LCLS-II specification. Both cavities were made from Ningxia material, but from a different fabrication run than the LCLS-II production material.

To evaluate the risk and to plan a course of action if necessary, the following plan was formulated:

1) Evaluate risk of substantial flux trapping through measurement of single cell cavities made from niobium material from production
2) Evaluate risk of substantial degradation due to trapped flux through measurement of the first prototype cryomodule
3) Project decision: if risk is worthwhile, continue—otherwise continue production as planned
4) Qualify high temperature treatment process on 9-cell cavities
5) If satisfactory, implement in production

The plan is sketched in the flowchart of Figure 4, and details of each step are given below.

Single Cell Measurement

The goal of the single cell cavity measurements is to evaluate the flux expulsion behavior of the LCLS-II high RRR cavity material. Two cavities were made from the Ningxia material and two were made from the Tokyo Denkai material. Experiments will study if the material expels flux efficiently when the material is treated with the LCLS-II baseline recipe, and they will study if a 900 C furnace treatment improves the expulsion in this material to a worthwhile extent.

The primary method for evaluating flux expulsion is to measure the step change in magnetic field at the cavity surface as the niobium is cooled below its superconducting transition temperature of 9 K. This method, shown in Figure 3, has been shown to be reliable in previous experiments [1-4]. The secondary method for evaluating flux expulsion is RF measurement. Previous experiments have used the change in quality factor after cooldown in a magnetic field to confirm the fraction of flux trapped.

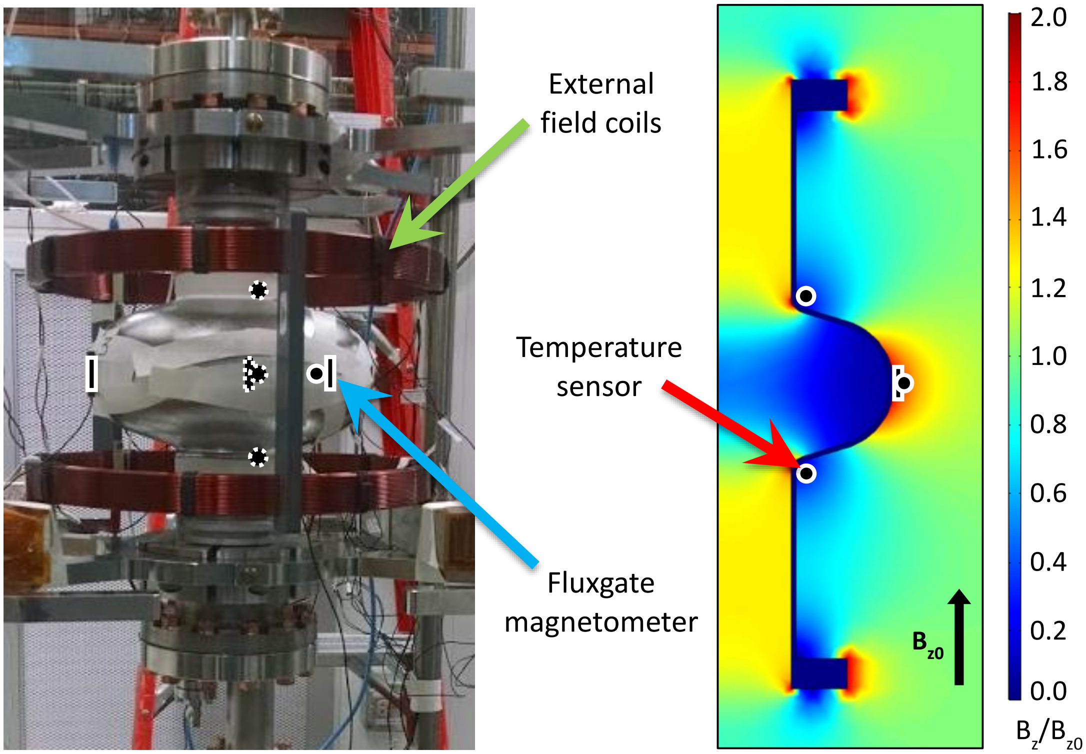


Figure 3: Magnetic measurement of flux expulsion

Researchers at JLab have tested the two single cavities made from Ningxia material and found, based on magnetic measurements, that the expulsion is poor. They will remove the cavities from the testing apparatus and perform optical inspection with a cavity borescope. Based on their findings, they may attempt to retreat to address the unusually low quality factors and unusually low quench fields observed. These Ningxia cavities will then be sent to Fermilab, where they will be evaluated for flux expulsion, then given 900 C furnace treatment and evaluated again. Concurrent to these activities on the Ningxia cavities, the two Tokyo Denkai cavities will begin the same process of evaluation, furnace treatment, and post-treatment evaluation.

Timeline of single cell measurement: to be completed by end of June

Cryomodule Measurement

While these single cell cavities are being evaluated, first experiments are planned for Fermilab's prototype cryomodule. Three important measurements will be performed: 1) residual magnetic field at the cavities, 2) vertical temperature gradient during cooldown, and 3) residual resistance compared to vertical test. These measurements will inform the risk of degradation due to trapped flux with the baseline recipe. For example, if the residual magnetic fields during superconducting transition are very small, then even full flux trapping is expected to have little effect on performance.

<u>DECISION 1</u>: If a worthwhile improvement to flux expulsion is observed in the LCLS-II production material after furnace treatment, AND if cryomodule measurements suggest substantial risk of degradation due to trapped flux in cavities made from production material, then proceed. Otherwise, stop.

9-Cell Measurement

Different strategies are offered for measurement of 9-cell cavities.

Strategy A
Each vendor will produce a 9-cell cavity modified according to a high temperature furnace treatment process that will be chosen based on single cell measurements and impact to cost and schedule. The two cavities will be fully processed and dressed by the vendors, to fully qualify the modified treatment. Additionally, fluxgate magnetometers will be installed inside the helium vessels to help to evaluate flux expulsion. The cavities will then be tested as usual at the partner labs. If the performance is acceptable, these two cavities can be used in production. Otherwise, they will count as reimbursement for the two Fermilab cavities that were consumed during early LCLS-II studies of nitrogen-doping recipes.

Strategy B
Each vendor will produce four 9-cell cavities modified according to a high temperature furnace treatment process that will be chosen based on single cell measurements and impact to cost and schedule. The eight cavities will be fully processed and dressed by the vendors. The cavities will be tested as usual at one of the partner labs and installed in a production cryomodule.

Strategy C
Strategy A will be implemented, and if the results are satisfactory, it will be followed by strategy B.

The choice of strategy will have to be determined by a cost-benefit analysis informed by measurements made on single cells and the prototype cryomodules.

DECISION 2: If the performance of the 9-cell cavities is determined to be superior as a result of the modified process, then it will be implemented on all future production cavities.

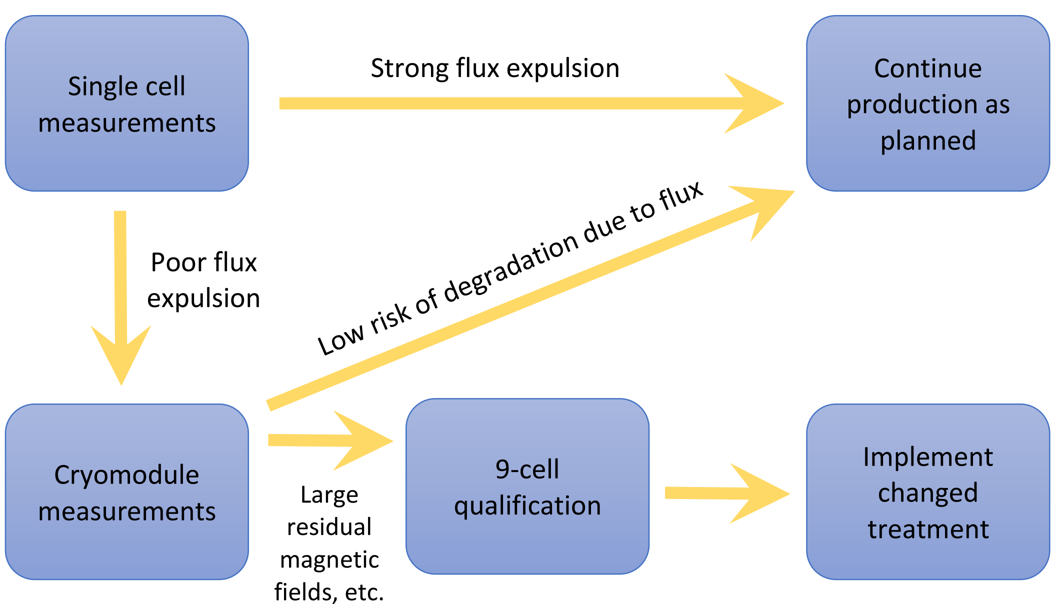


Figure 4: Flowchart of activities.

References

[1] A. Romanenko, A. Grassellino, O. Melnychuk, and D. A. Sergatskov, *J. Appl. Phys.* 115, 184903 (2014).

[2] A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. 105, 234103 (2014).

[3] S. Posen, A. Grassellino, A. Romanenko, O. Melnychuk, D. A. Sergatskov, M. Martinello, M. Checchin, and A. C. Crawford. arXiv:1509.03957 (2015).

[4] Posen, S., M. Checchin, A. C. Crawford, A. Grassellino, M. Martinello, O. Melnychuk, A. Romanenko, D. A. Sergatskov, and Yulia Trenikhina. Proc. International Particle Accel. Conf. WEPMR009 (2016).

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Magnetic field and expulsion needed to achieve specifications?

A. Grassellino, S. Chandrasekaran, M. Martinello, S. Posen, D.A. Sergatskov

Tuesday SRF meeting – LCLS-II

June 7th 2016

Question from Dave Schultz:

- <u>“What level of flux expulsion is needed to achieve the LCLS-II specifications in cryomodules?”</u>

- Answer depends on the average magnetic field that cavities will see in cryomodule at transition temperature

$$Q = G/ Rs \quad \text{where } R_S = R_{BCS} + R_0 + R_{TF}$$

Intrinsic residual (R_0)

Trapped magnetic flux residual (R_{TF})

Btrap ($\eta * B_{amb}$)

$$R_{TF} = s * \eta * B_{amb}$$

Sensitivity to mag field (s)

Flux expulsion efficiency (η)

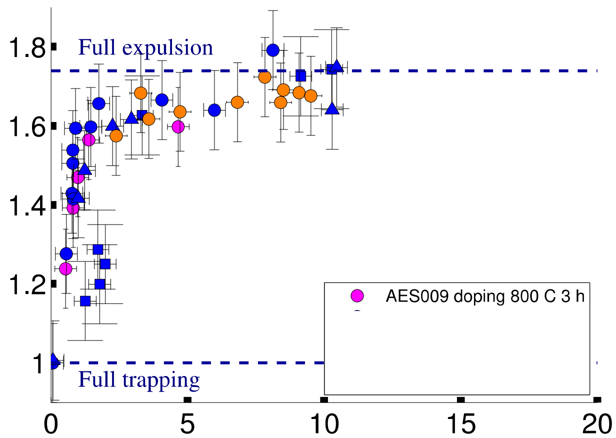
Ambient field in CM (B_{amb})

Fermilab

Flux expulsion efficiency and trapped flux sensitivity: two different things (bulk vs surface treatment property)

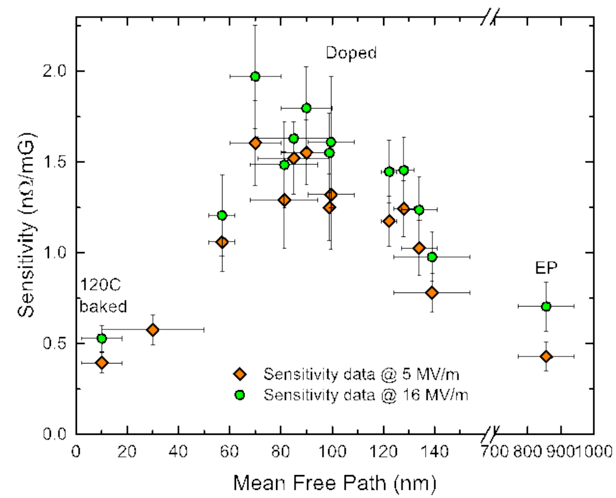
1) Flux expulsion efficiency: bulk

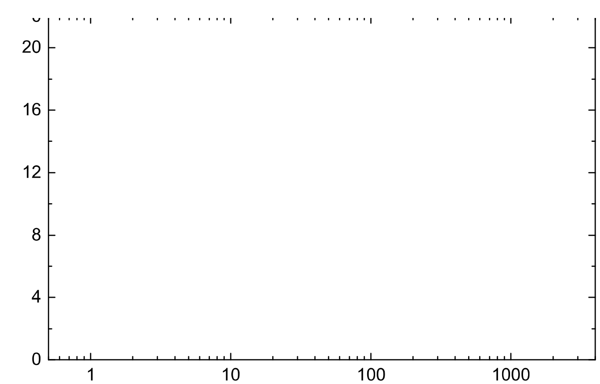
S. Posen et al, J. Appl. Phys. **119**, 213903 (2016)



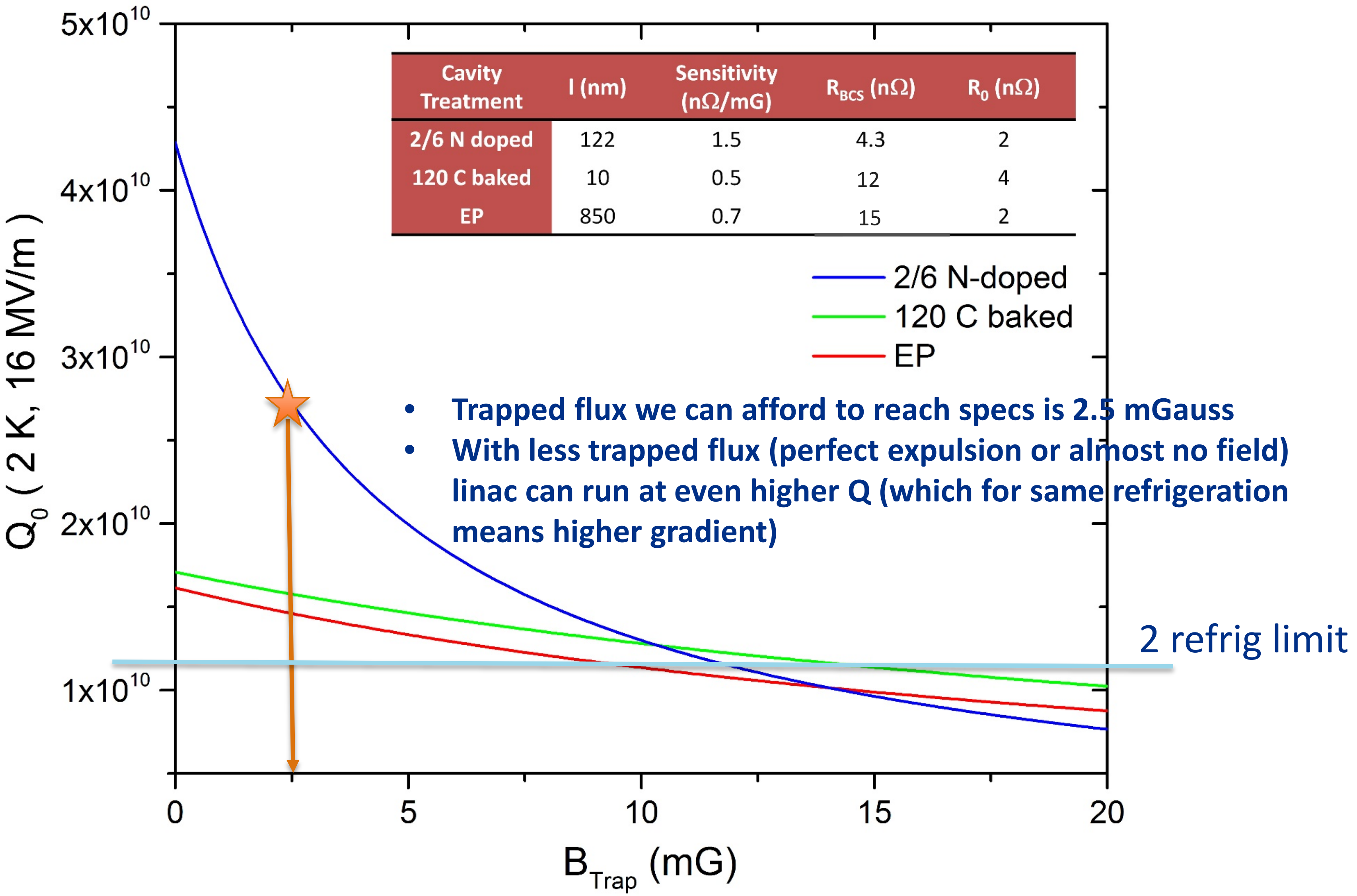
2) Trapped flux sensitivity: surface

M. Martinello et al, Proceedings of IPAC16





Q-factor vs Trapped Flux for different surface processing, as a function of trapped magnetic field



Cavity Treatment	l (nm)	Sensitivity (nΩ/mG)	R_{BCS} (nΩ)	R_0 (nΩ)
2/6 N doped	122	1.5	4.3	2
120 C baked	10	0.5	12	4
EP	850	0.7	15	2

- **Trapped flux we can afford to reach specs is 2.5 mGauss**
- **With less trapped flux (perfect expulsion or almost no field) linac can run at even higher Q (which for same refrigeration means higher gradient)**

Fermilab

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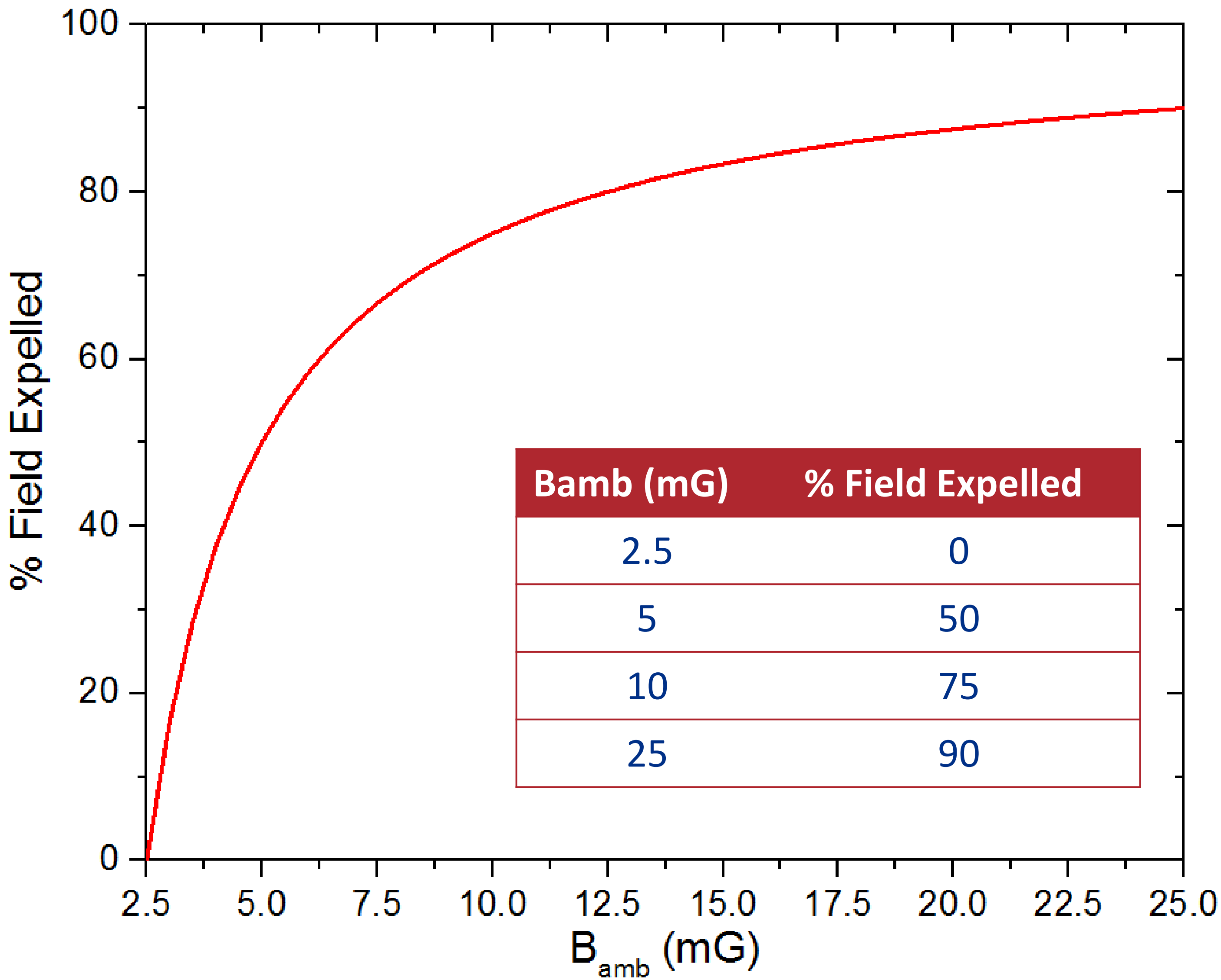
To reach specification: Q=2.7e10 → Btrap=2.5mG
→ percentage of expulsion needed as a function of ambient B:



Bamb (mG)	% Field Expelled
2.5	0
5	50
10	75
25	90

What level of magnetic fields to expect for the CM? Preliminary measurements on pCM (so far)

Fluxgates							Coldmass on Big Bertha w/o vessel on it - 20160519		Coldmass on Big Bertha w/ vessel on it - 20160526			CM at WS5 - 20160601		
	Cavity #		Longitudinal or Perpendicular to cavity axis?	Top or bottom of cavity?	Angle (degrees)	Upstream or downstream on cavity?	Magnetic field		Magnetic field		Δ from previous	Magnetic field		Δ from previous
Serial #	Serial	On string					µT	mG	µT	mG	%	µT	mG	%
Inside cavity helium vessel														
1295	TB9AES021	1	L/P	T	45	-	0.202	2.020	-0.054	-0.540	-126.73	-0.068	-0.680	25.93
1296			P	B	90	-	0.141	1.410	0.120	1.200	-14.89	0.155	1.550	29.17
1381	TB9AES024	4	L/P	T	45	-	0.001	0.010	0.186	1.860	18500.00	0.233	2.330	25.27
1378			P	B	90	-	2.495	24.950	2.600	26.000	4.21	2.594	25.940	-0.23
1366	TB9AES028	5	L/P	T	45	-	0.044	0.440	0.094	0.940	113.64	0.073	0.730	-22.34
1365			P	B	90	-	0.133	1.330	0.084	0.840	-36.84	0.056	0.560	-33.33
1287	TB9AES027	8	L/P	T	45	-	0.970	9.700	1.042	10.420	7.42	1.011	10.110	-2.98
1290			P	B	90	-	0.140	1.400	0.104	1.040	-25.71	0.015	0.150	-85.58
Between magnetic shield layers 1 and 2														
1397	TB9AES021	1	L	Ext	-	US	0.144	1.440	0.023	0.230	-84.03	0.157	1.570	582.61
1396	TB9AES019	2	L	Ext	-	US	0.047	0.470	-0.075	-0.750	-259.57	0.060	0.600	-180.00
1395	TB9AES028	5	L	Ext	-	DS	-0.139	-1.390	0.159	1.590	-214.39	0.282	2.820	77.36
1398	TB9AES022	7	L	Ext	-	DS	-0.067	-0.670	0.050	0.500	-174.63	0.228	2.280	356.00
1400	TB9AES027	8	L	Ext	-	DS	0.578	5.780	0.659	6.590	14.01	0.370	3.700	-43.85

File updated: June 6, 2016.
Saravan K. Chandrasekaran

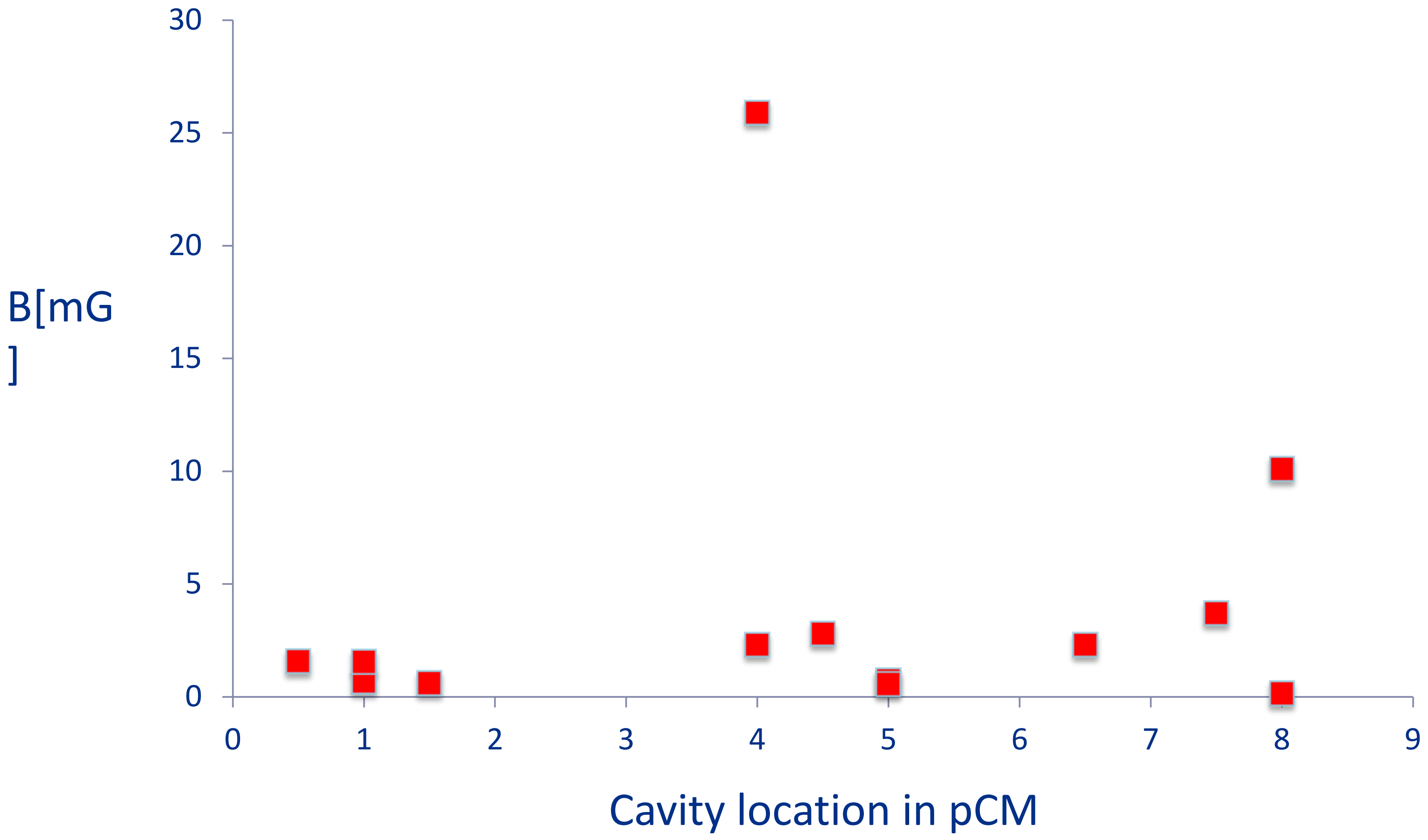
→ Median @ WS5: 1.57 mGauss

→ Average @ WS5: 4.07 mGauss

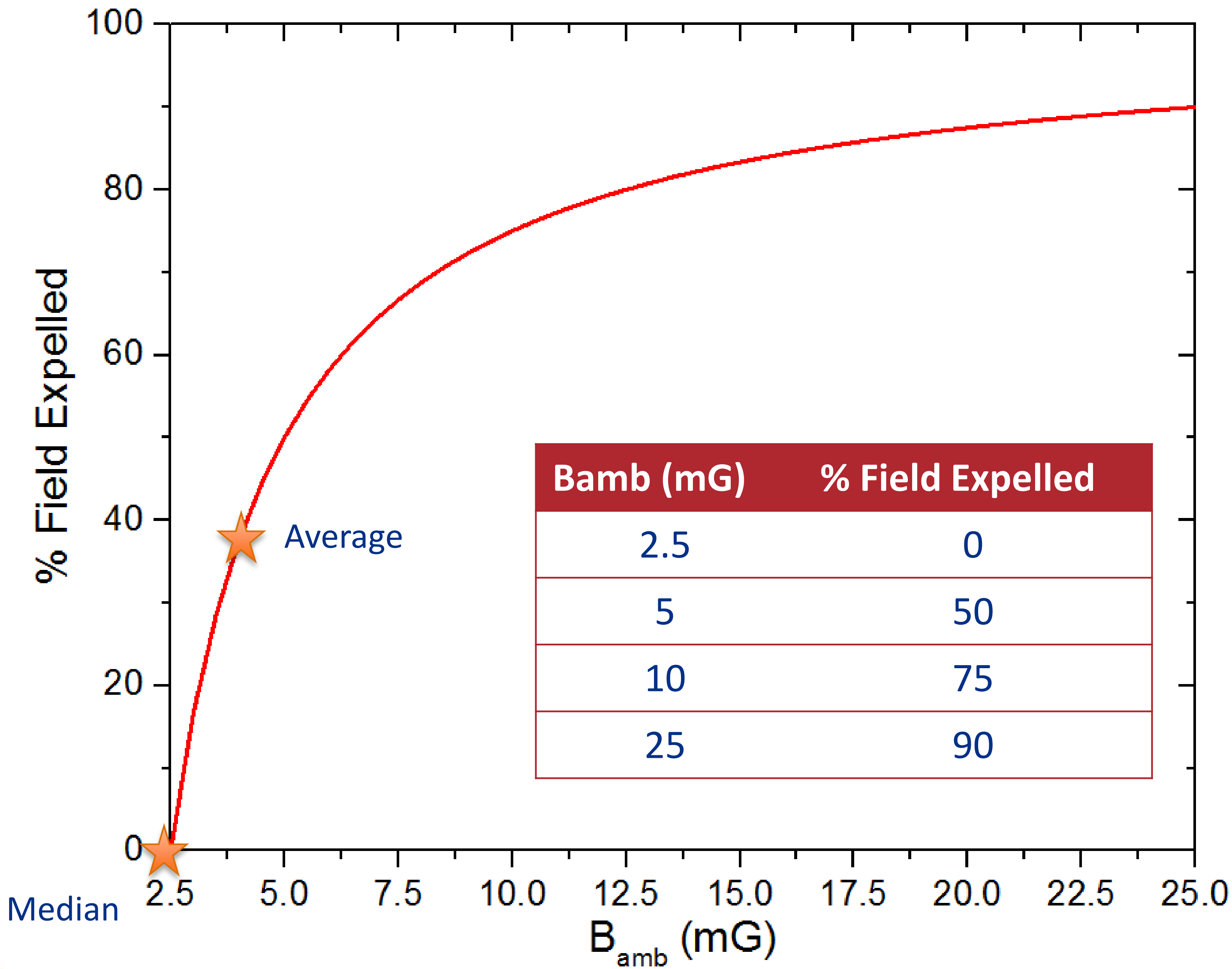
This is for warm and particular direction – need more data

Fermilab

Magnetic field @ WS5 in pCM (as a function of cavity position)



To reach specification: Q=2.7e10 → Btrap=2.5mG:
< 40% expulsion needed to reach specs

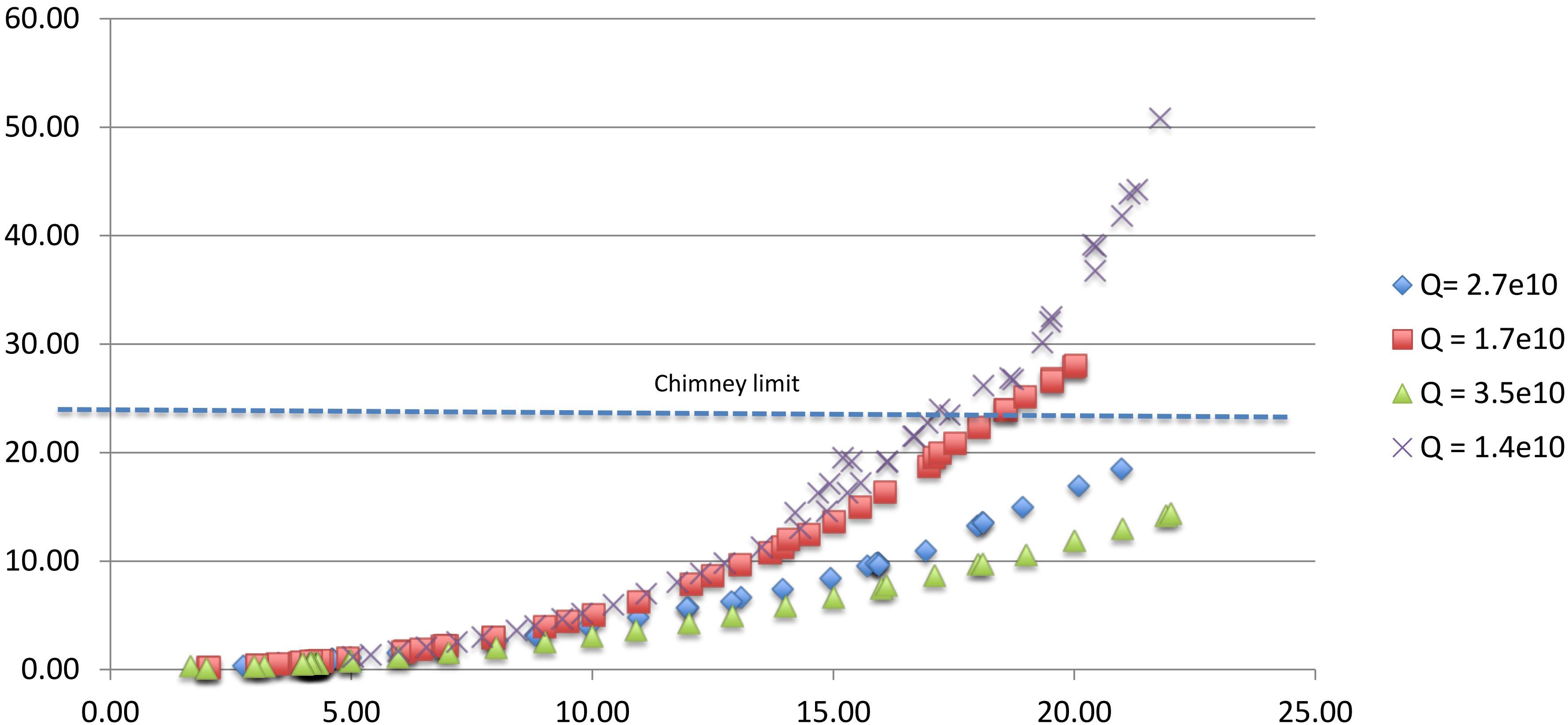


Bamb (mG)	% Field Expelled
2.5	0
5	50
10	75
25	90

Conclusions

- Given the current magnetic field measurements in pCM, percentage of flux expulsion efficiency needed to reach Q of 2.7e10 goes from 40% to even full trapping being acceptable; (depends if take average or median as most indicative value)
  - Slow cooldown measurements in pCM testing can tell us more about average field seen by cavities
- Given the preliminary assessment of flux expulsion capability in the production material (close to none), if no corrective action is taken (eg 900C) with current magnetic field levels we would obtain ~ 2e10 in CM, versus potentially up to 4e10
  - Moreover, if things worsen with mag field (eg mag hygiene, shielding quality), Q could lower further
- What does this mean practically? See next slide

Power dissipation of nine cell cavity with Q at 3.5e10 vs 2.7e10 vs 1.7e10



<u>Fix 15 W per cavity:</u>

1. 1.7e10 → 15 MV/m → 4.2 GeV
2. 2.7e10 → 19 MV/m → 5.3 GeV
3. 3.5e10 → 22 MV/m → 6.1 GeV

We should estimate what it means based on total refrigeration available, chimney limit, for potential energy upgrades

LCLS-II material qualification - expulsion ratio and RF tests

Ari Palczewski
Jefferson National laboratory
6/21/2016

Overall Plan – Three Basic Steps

- Evaluate existing materials using single cells to identify problem (JLab)
- Using single cells, develop possible recipe modifications and test (FNAL)
- Develop and validate modified recipe on 9-cells (FNAL with JLab supoprt) – details TBD
  - Considering options that include work at Partner Labs and vendors

- M. Ross requested review with SRF experts of current status and discussion of possible remediation (30-June)

Flux expulsion and RF scope (now) – LCLS-II Material Evaluation

- Build 4 single cell cavities out of actual stock from LCLS-II (8 sheets), using reclaimed flanges/beam-pipes from high Q0 R&D.
- 2 single cell from each Vendor, one from each ingot (OTIC/Ningxia – ingot ENT-132 & ENT-134 and Tokyo Denkai - ingot 1991 & 2022)
- Process all 4 cavities with baseline recipe (Bulk BCP/EP, 800C 3h 2N6, EP 5) @ JLab (including sample coupons with same processing)
- Test 4 cavities - @ JLab and send to FNAL
  - RF – low magnetic field (0-2mGauss field) qualification
  - flux expulsion thermal cycles - high magnetic field (10 mGauss)
  - RF - high magnetic field (5 mGauss)
- Sample analysis - crystal structure and hardness at FNAL before and after processing. (no complete as far as I know of)
- Report on results – How susceptible are the batches to flux trapping? Do we think this will be an issue for the project?

Current status – completion dates

	RDTNX-01	RDTNX-02	RDTTD-01	RDTTD-02
Baseline RF	5/24	5/23	6/6	6/3
5mG RF	NA	NA	6/10	6/9
Flux expulsion	5/25	5/30	6/6	6/4
Ship to FNAL	6/29	6/29	06/14	06/14
Surface reset	85-100μm	90-100μm	NA	NA
Reset RF	26MV/m	Not tested	NA	NA
Baseline RF #2	6/21	6/22	NA	NA
5mG RF #2	6/23	6/24	NA	NA

Re-test needed due to quality issues with single cell manufacturing

Material by vendor – Ningxia 6 Ingots

OTIC	Ninxia				
batch	SN – sample	RRR	HV Min	HV MAX	grain size ASTM
ENT-132	321414	380	44.6	56.6	5.5-6.0
	321211	412	35.7	39.3	5.0-5.5
ENT-133	332408	378	47.8	54.9	6.5-7.0
	333322	416	37.4	39.4	6.0-6.5
ENT- 134	343104	315	50.8	58.4	8.0-8.0
	341409	301	37.6	43.2	7.0-7.5
ENT-130	301306	339	50.1	51.2	7.5-8
	301420	365	37.3	39	7.0-7.5
ENT-128	283422	394	48.1	54.8	6.0-6.5
	281420	350	37.9	39.6	6.0-6.5
ENT-131	312114	392	46.2	58.8	6.0-6.0
	312218	**393**	**34.6**	**39.2**	**6.5-7.0**

Yellow is 2 batches, 4 sheet each for Single cell studies

Material by vendor – Tokyo Denkai 18 Ingots

Lot/heat treatment	ingot	RRR - nom	crystal size astm sample	crystal size astm sample	Hv max by HT	HV min by HT	# of sheet from Ht lot
67	1950	371	6		53.1	38.1	7
68	1973	351	6		48.9	37.4	99
	1992	361	6				
69	1990	374	na		42.5	36.4	144
	1991	468	5	5			
70	1994	351	6	5	46.7	37.1	67
71	1995	483	7	5	48.3	37.8	143
	2010	364	na				
72	2012	378	6		47.8	37.8	136
	2013	395					
73	2014	381	6		51.4	38.4	142
	2015	418	6				
74	2016	399	6		48.7	39.6	137
	2017	373	7				
75	2018	387	na		49.8	39.2	139
	2022	365	7	6			
76	2023	405	na		49.8	39.6	141
	2024	428	7	6			
77	2025	373	na		48.7	38.8	140
	2026	398	6	6			
78	2027	404	6		47.4	37.8	60
	2032	362	7				

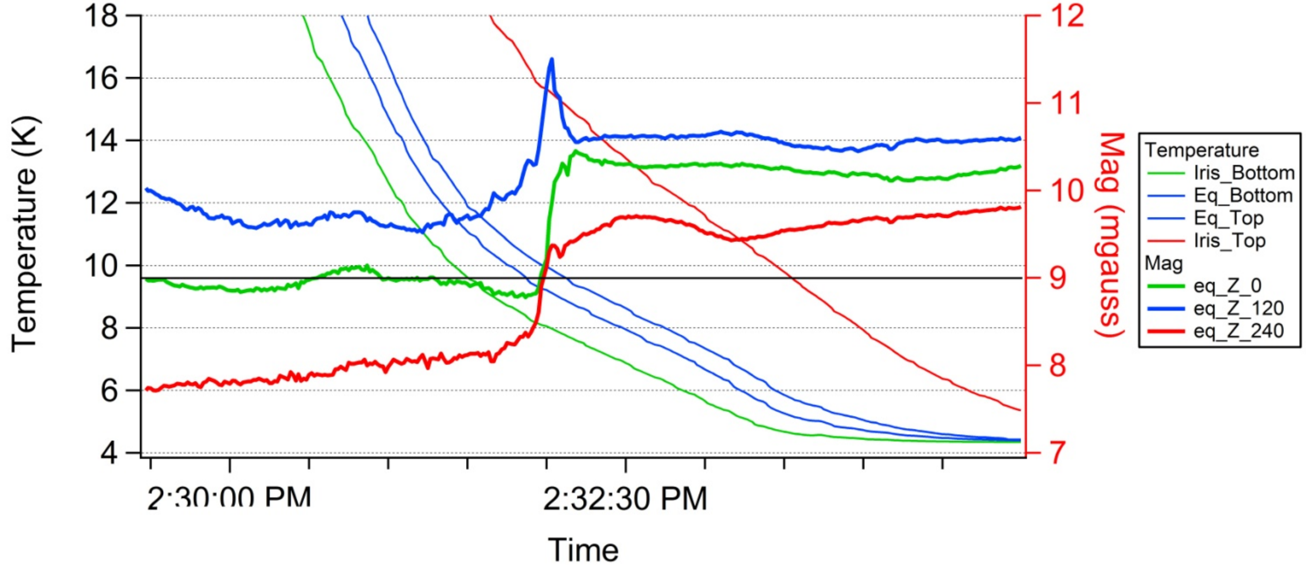
Yellow is 2 batches, 4 sheet each for Single cell studies

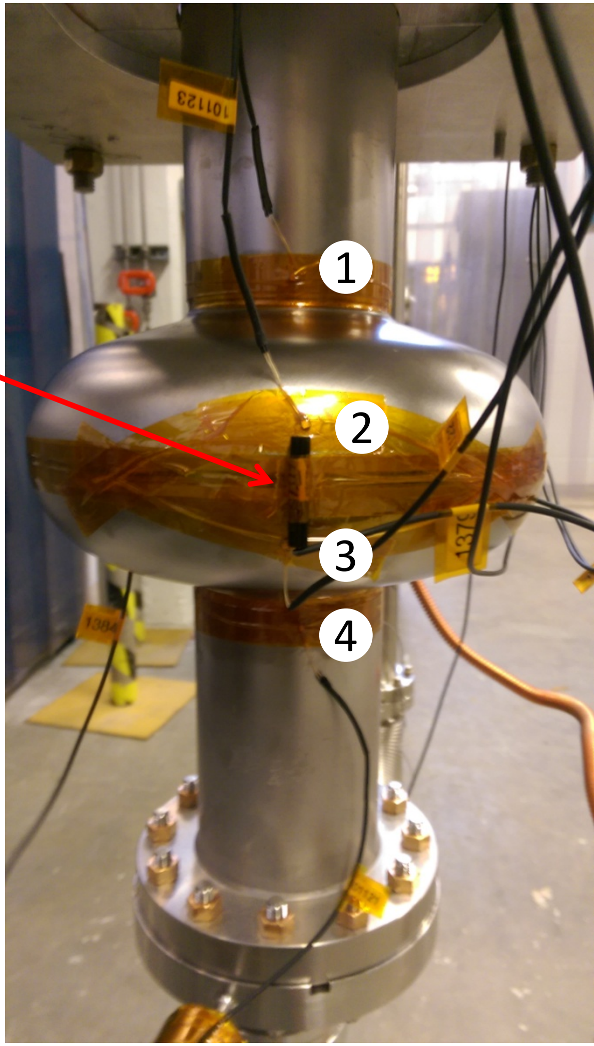
JLab setup

Comp coils integrated into dewar at JLab → Evaluates flux expulsion in same manner as at FNAL/Cornell

1 - Cernox 1cm above iris
2 - Cernox 2cm above equator
3 - Cernox 2cm below equator
4 - Cernox 1cm below iris

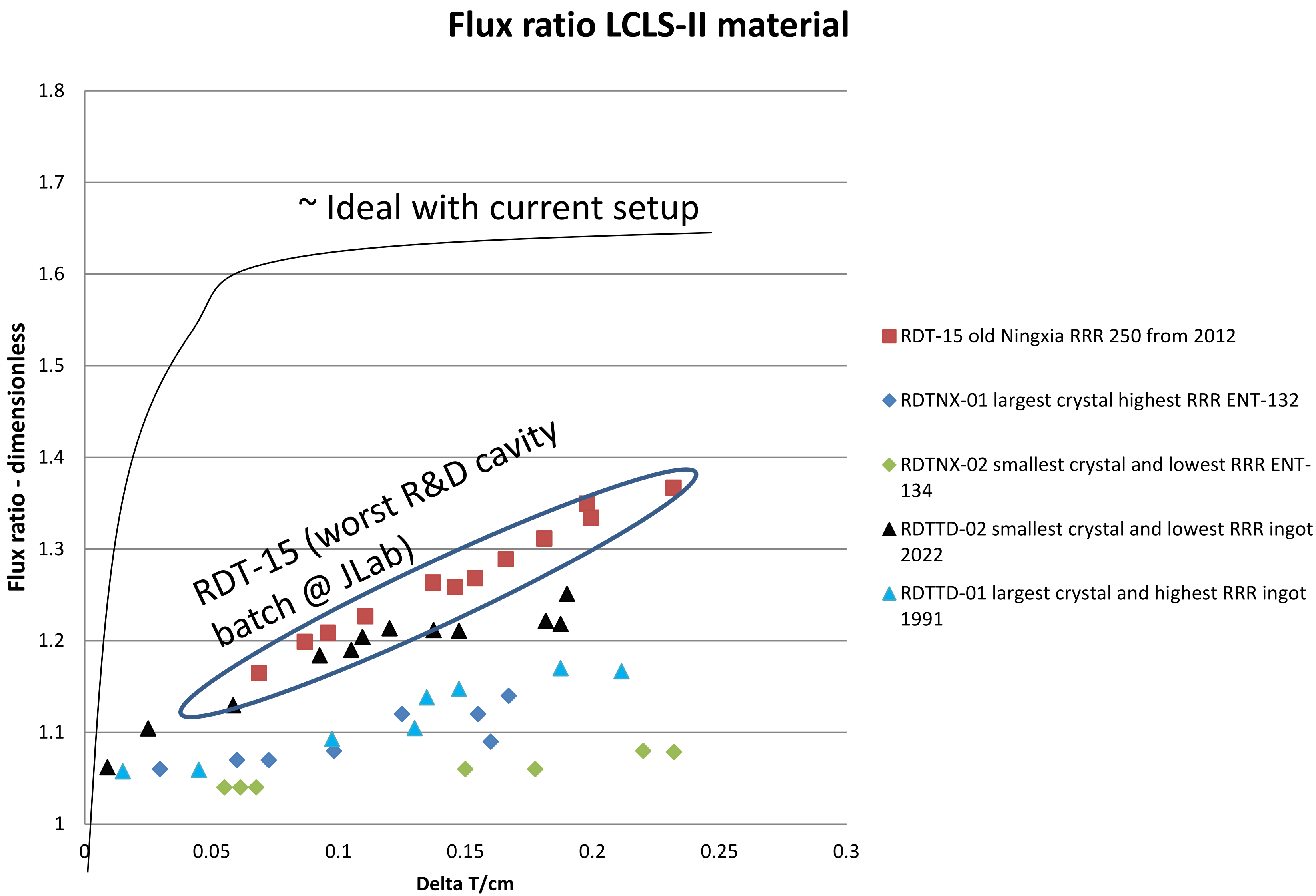
Flux gate (3X @ 0, 120 and 240°) all axial

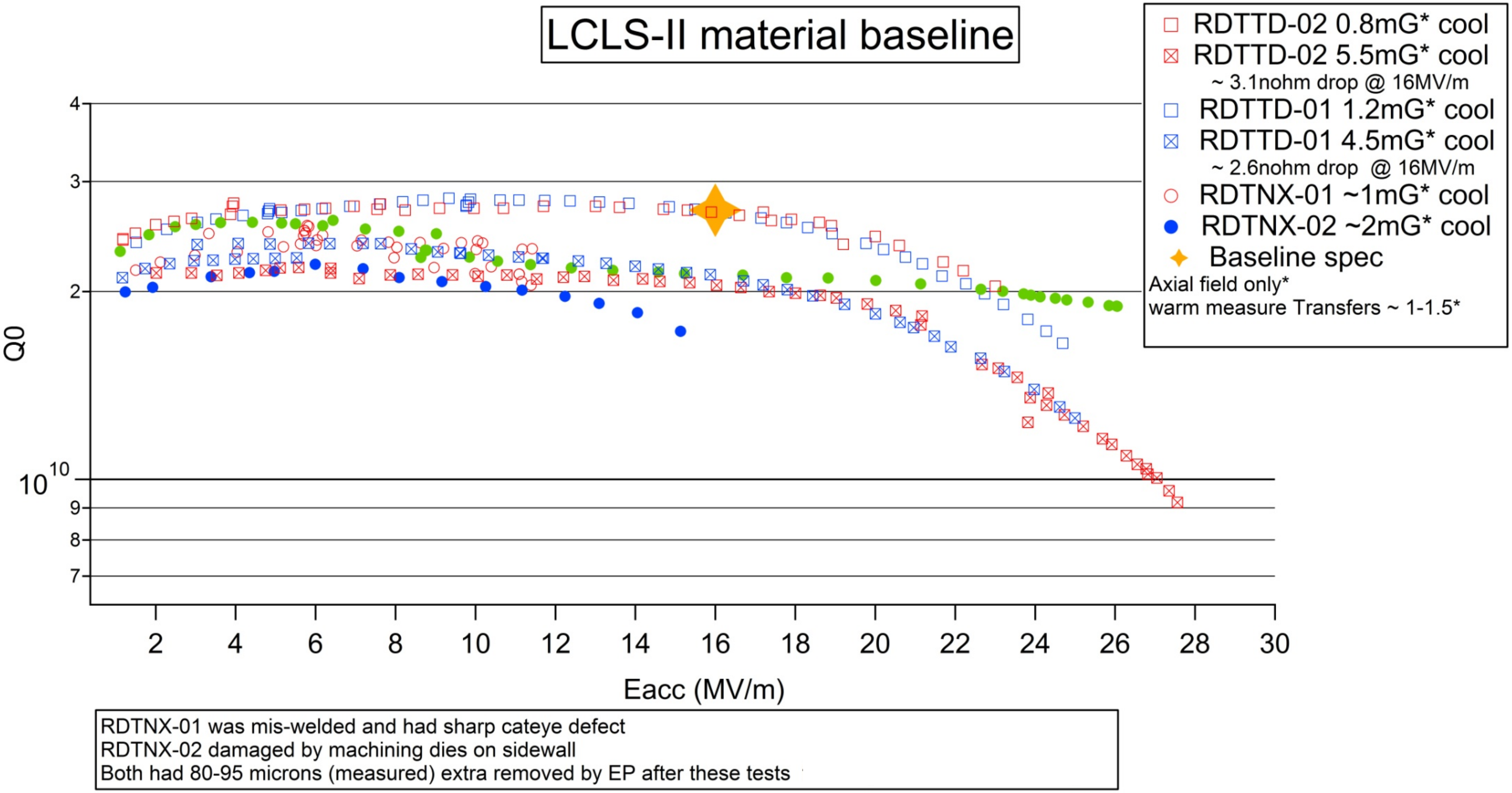




Large iris-iris asymmetry for large gradients in Jlab dewar – use 2 equator sensors for temperature gradient rather than iris to iris (qualitatively the same)

This is flux ratio as a function of temperature difference per cm about equator, there are 2 sensors on the equator, each 20mm away from equator at flux gate location



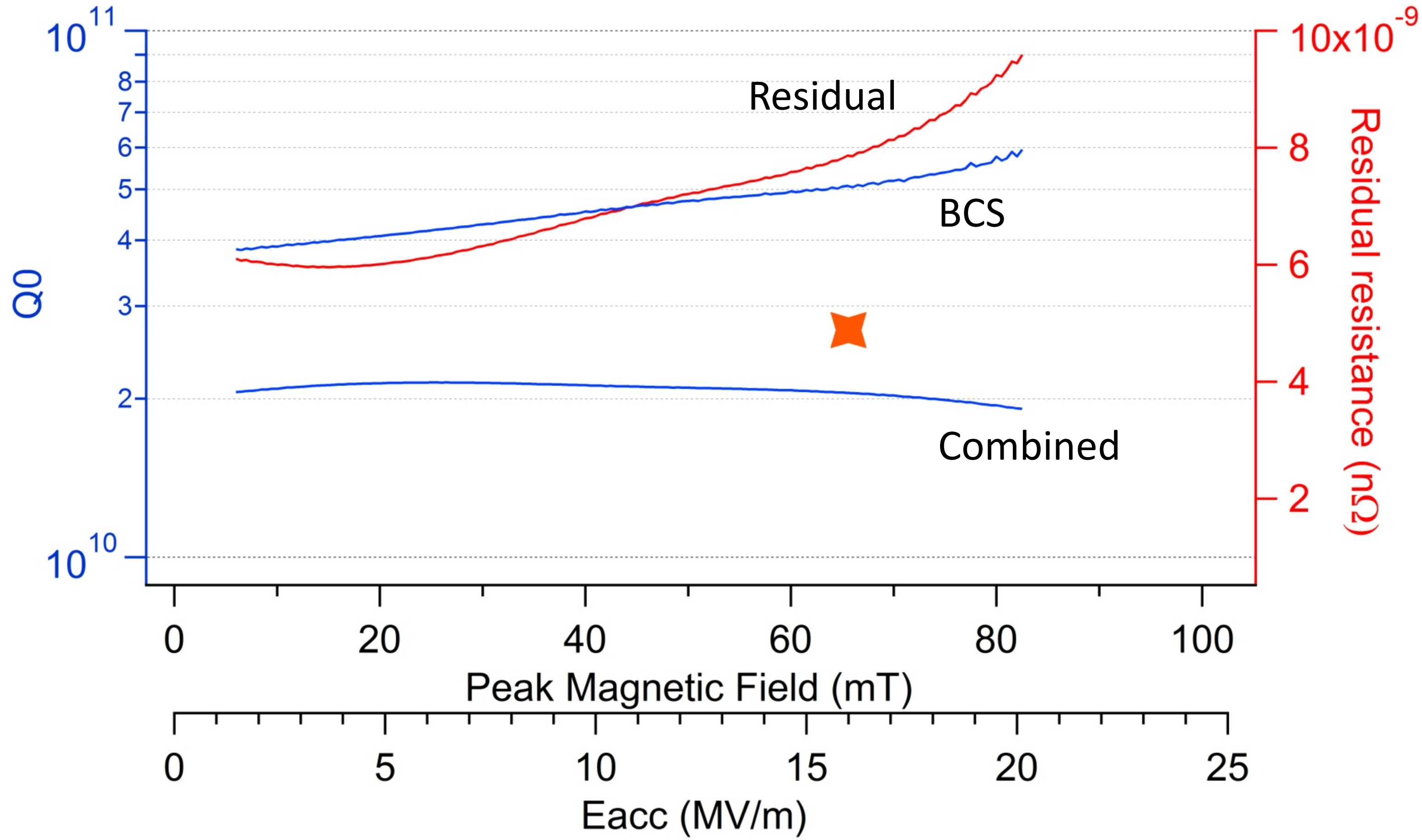


RDTNX-02 will not be re-baselined and has been re-doped and EP'ed, currently cooling for test tomorrow
RDTTD-02 was MP limited in first test, was gone after thermal cycle and 5mG test
Green circles in figure is from RDTNX-01 reset, no bake, no heat treatment only EP

What flux trapping is acceptable?

- High flux trapping = high fundamental RS
- High flux trapping = High fundamental RS field dependence – slope on RS
- **All data from FNAL and JLab suggest to get 2.7e10 @ 16MV/m in 5mG field you must have “good flux expulsion” from the LCLS-II material; for 0-2mG you can meet spec as material is “ok” (as long as Ningxia is same as Tokyo Denkai RF wise)**
  - There is no current data which hits an intermediate region between LCLS-II material and “good flux expulsion” on any tested cavities.

Flux expulsion vs. residual resistance – RDTTD-01 5mG field



Reminder – spec of 2.7e10 @ 16MV/m is 10 nΩ
BCS resistance is 5-5.5nΩ – 2N6 EP 5 baseline recipe
Magnetic field should contribute ~0.6 nΩ/mG trapped flux
@ 16MV/m Total 5.5nΩ+0.6nΩ/mG*6mG(approx X_Y_Z)+background 4-5 nΩ ~ 13nano ohms

My answers to scope questions

- How susceptible are the batches of LCLS-II material to flux trapping? - Probably couldn't have been worse.
- Do we think this will be an issue for the project? – Depends on what the Q0 spec is – next slide.
- Should there be more work done?
  - Depends on what Q0 spec is – next slide.

Current expectations if we do nothing

Assumptions

- Total field in module **is** 5mguass all directions combined.
- RDTNX cavities do not perform much worse than RDTTD cavities.
- Cool-down in module can meet spec defined by FNAL/Cornell ~ 5K top to bottom.
- End cavities in cryomodule do not have higher than expected magnetic field – this would cause an even larger drop (~ 1.5e10 @ 12-15mG)

9 cell in cryomodule

2.0e10 @ 16MV/m and 1.8e10 @ 19MV/m

What should be done moving forward if a “fix” is deemed necessary

1. Retest 4 cavities @ FNAL to verify results – underway.
2. Re-dope 4 cavities with “new recipe” – currently @ 900C and test performance. 2 @ FNAL and 2 @ JLab, especially after last nights test of 900c recipe.
3. Perform tensile strength and crystal growth analysis on current and purposed new recipe. – will the cavities be too soft? What would be acceptable in terms of cavity softening.

9 cell possible path forward - if tensile strength and single cell work pans out.

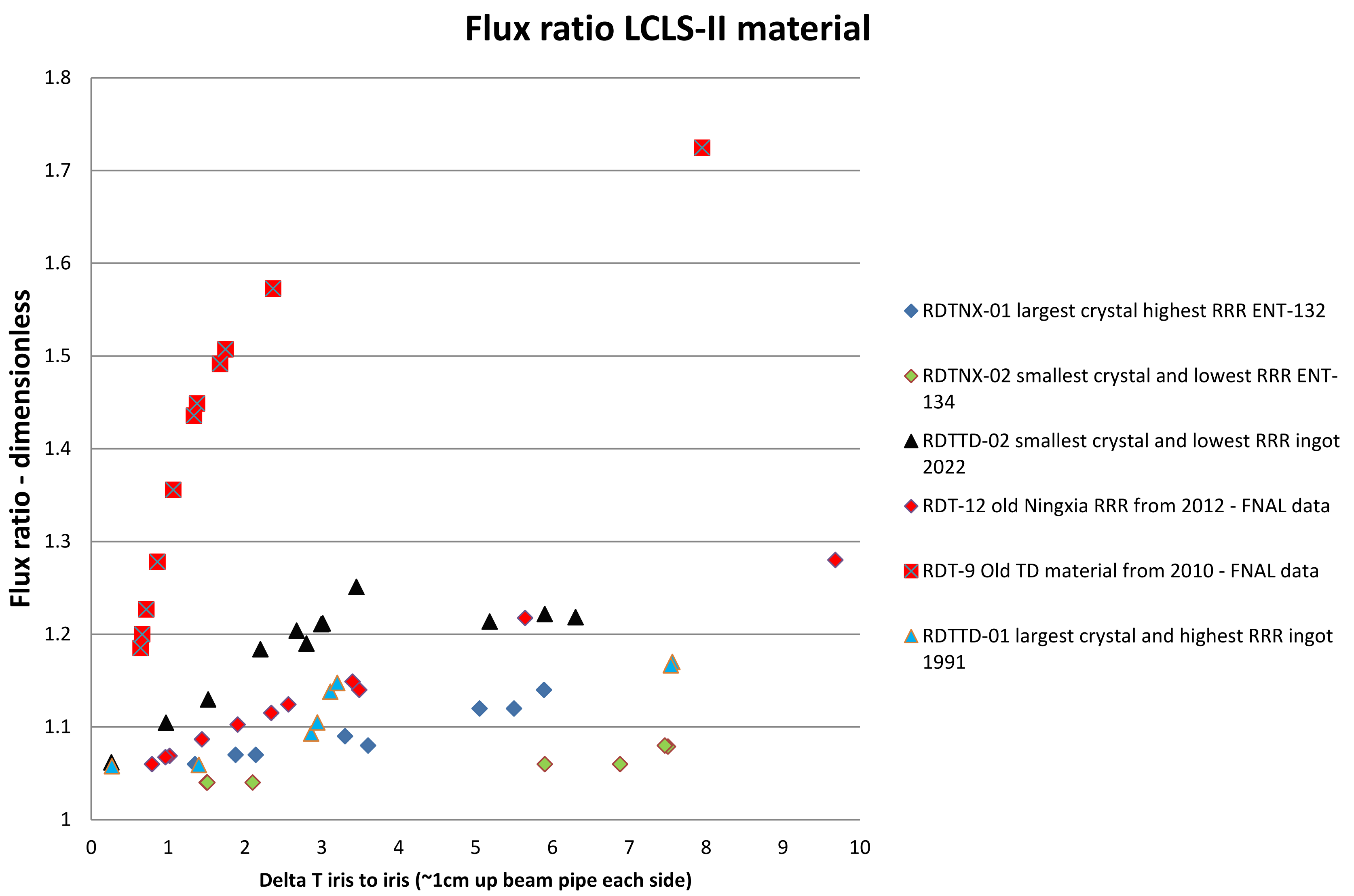
- Dope 9 cells ASAP at venders (I suggest module worth, 4 from each vender), this would include validation for furnace runs before.
- Ship the new recipe cavities ASAP to validate handling.
- Move them to head of line for vertical RF and handling tests.
- Perform horizontal test @ FNAL with baseline and modified recipe cavities ASAP.
- Hold production at vendor @ doping until HTB tests are done?

backup

9 cell possible path forward - if tensile strength and single cell work pans out.

- Aggressive and very risky
  - First articles (8 cavities) from Zanon are doped with new recipe, and second articles from RI (8-16 cavities), hold production for single cell work and accept outcome after without holding up production any further with new recipe, you can only switch back after new recipe module tested
- Aggressive and less risky
  - Second articles (9-16 cavities) from Zanon are doped with new recipe, and second articles from RI (8-16 cavities), test through module before deciding to change any other cavities.
- Less Aggressive and less risky
  - Dope the next 2 cavities each from each vender with New recipe and let flow through system. And wait til they are tested in module to decide to change back half of production.

This is flux ratio as a function of temperature difference between the iris, the sensors are actually on the beam pipe about 1cm above and below the cell.



Preliminary Single Cell Flux Expulsion Results from Modified Recipe at FNAL

Sam Posen

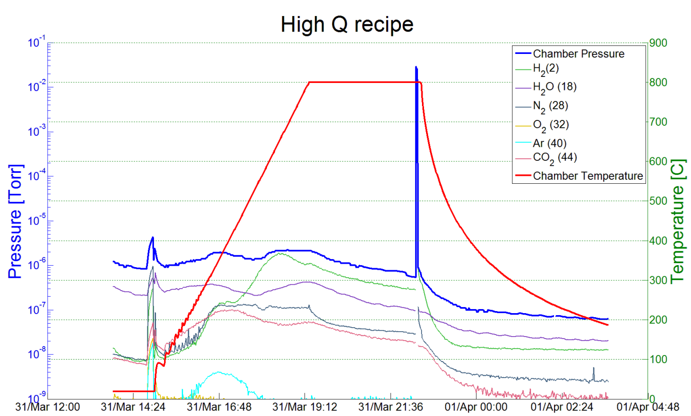
LCLS II SRF Meeting

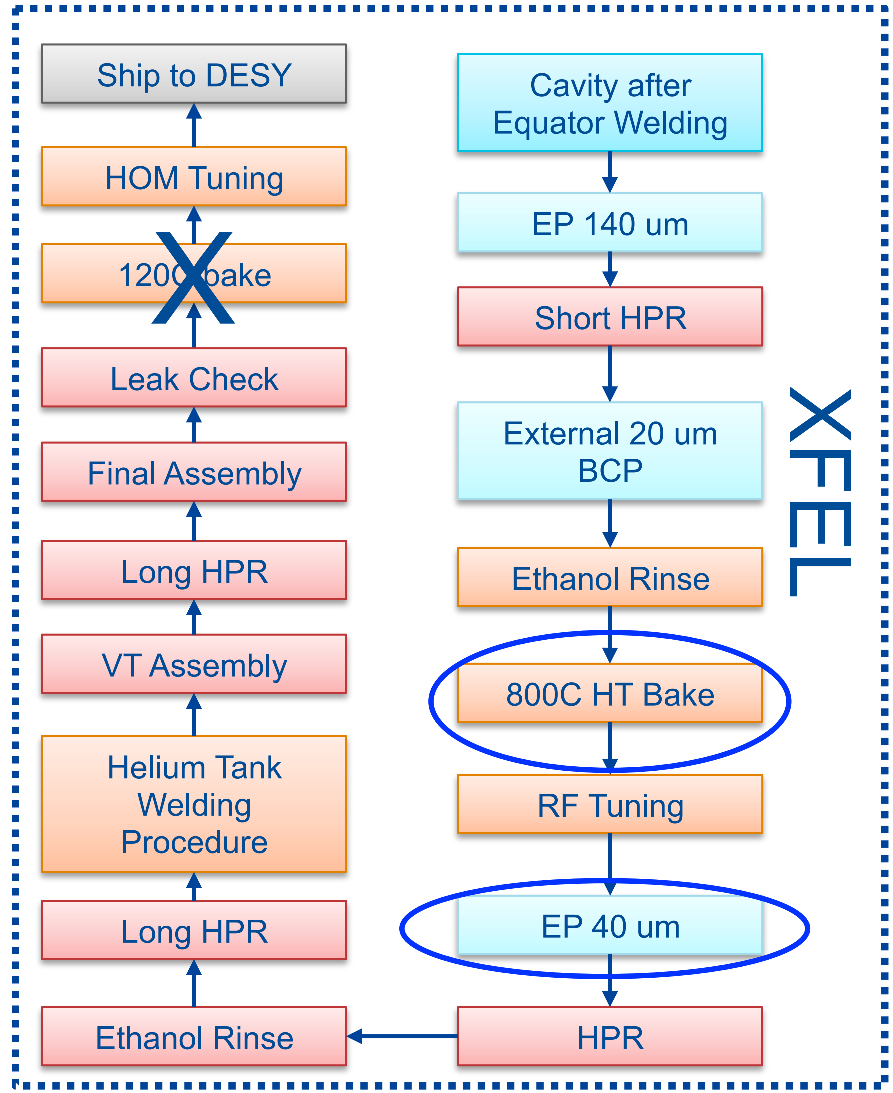
21 June 2016

Flux Expulsion Improvement

Cavity Treatment:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP





Flux Expulsion Improvement

Option 1: 900 C treatment before bulk EP

Cavity Treatment:

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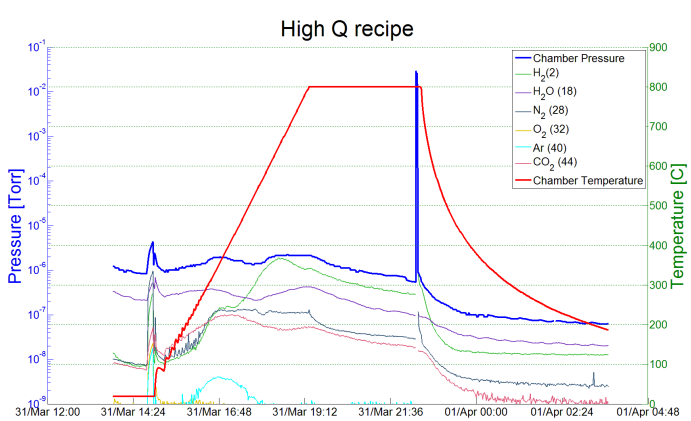
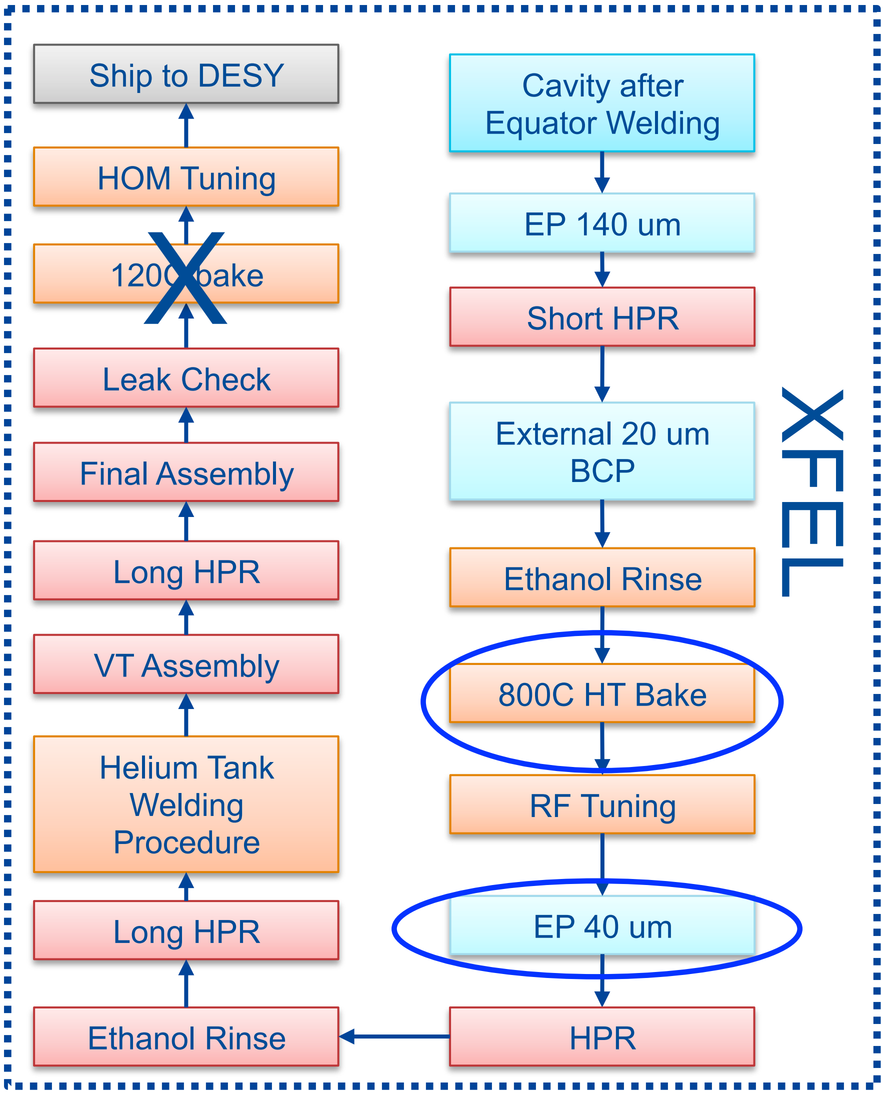
- 5 microns EP





Fermilab

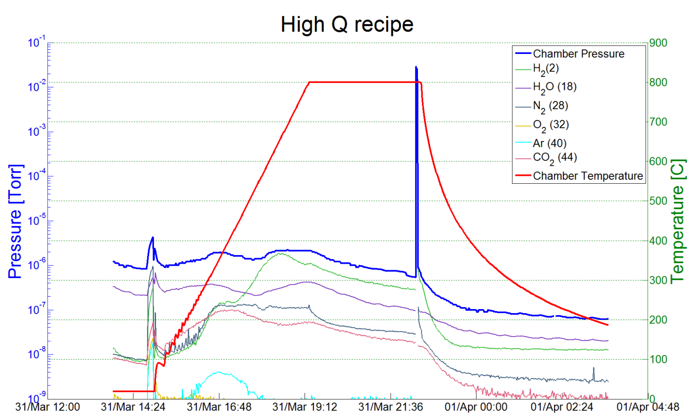
Flux Expulsion Improvement

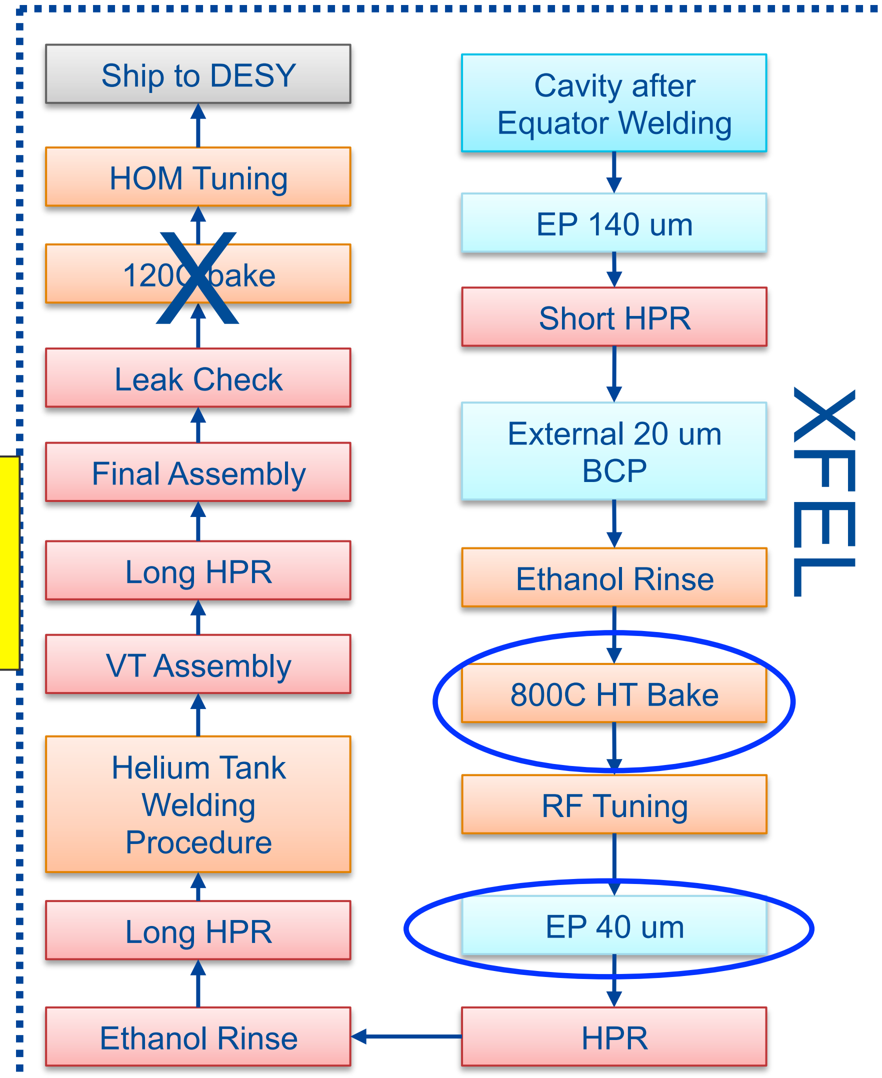
Cavity Treatment:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP

Option 1: 900 C treatment before bulk EP

Option 2: Change degas temp to 900 C (800 C for doping)





Previously…

Two single cell 1.3 GHz cavities for this study – fabricated by AES with RRR Nb from Ningxia:

TE1AES024 – LCLS II baseline recipe: bulk EP, degas and nitrogen-dope 2/6 at 800 C, 5 micron EP

TE1AES025 – Modified LCLS II recipe: **900 C furnace treatment**, bulk EP, degas and nitrogen-dope 2/6 at 800 C, 5 micron EP

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- We wanted to study effects of:
  - 5 mG field on Q_0 for baseline LCLS II recipe
  - Modification 1: 900 C treatment before bulk EP (TE1AES025)
  - Modification 2: 900 C treatment just prior to doping (TE1AES024)

Previously…

New data: TE1AES024 after 30 micron EP + furnace 900 C 3 h + doping at 800 C + 5 micron EP

Two single cell 1.3 GHz cavities for this study – fabricated by AES with RRR Nb from Ningxia:

TE1AES024 – LCLS II baseline recipe: bulk EP, degas and nitrogen-dope 2/6 at 800 C, 5 micron EP

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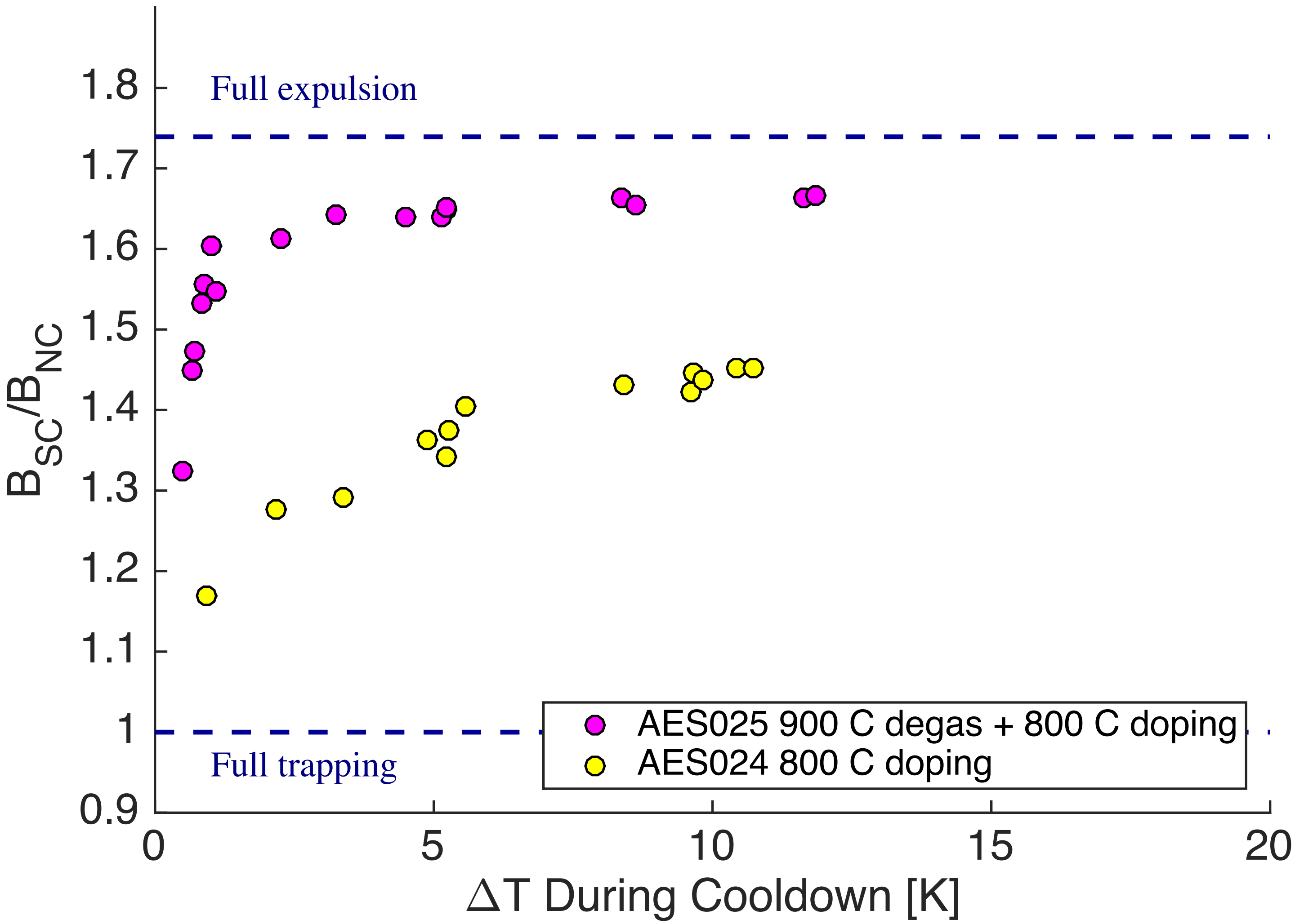
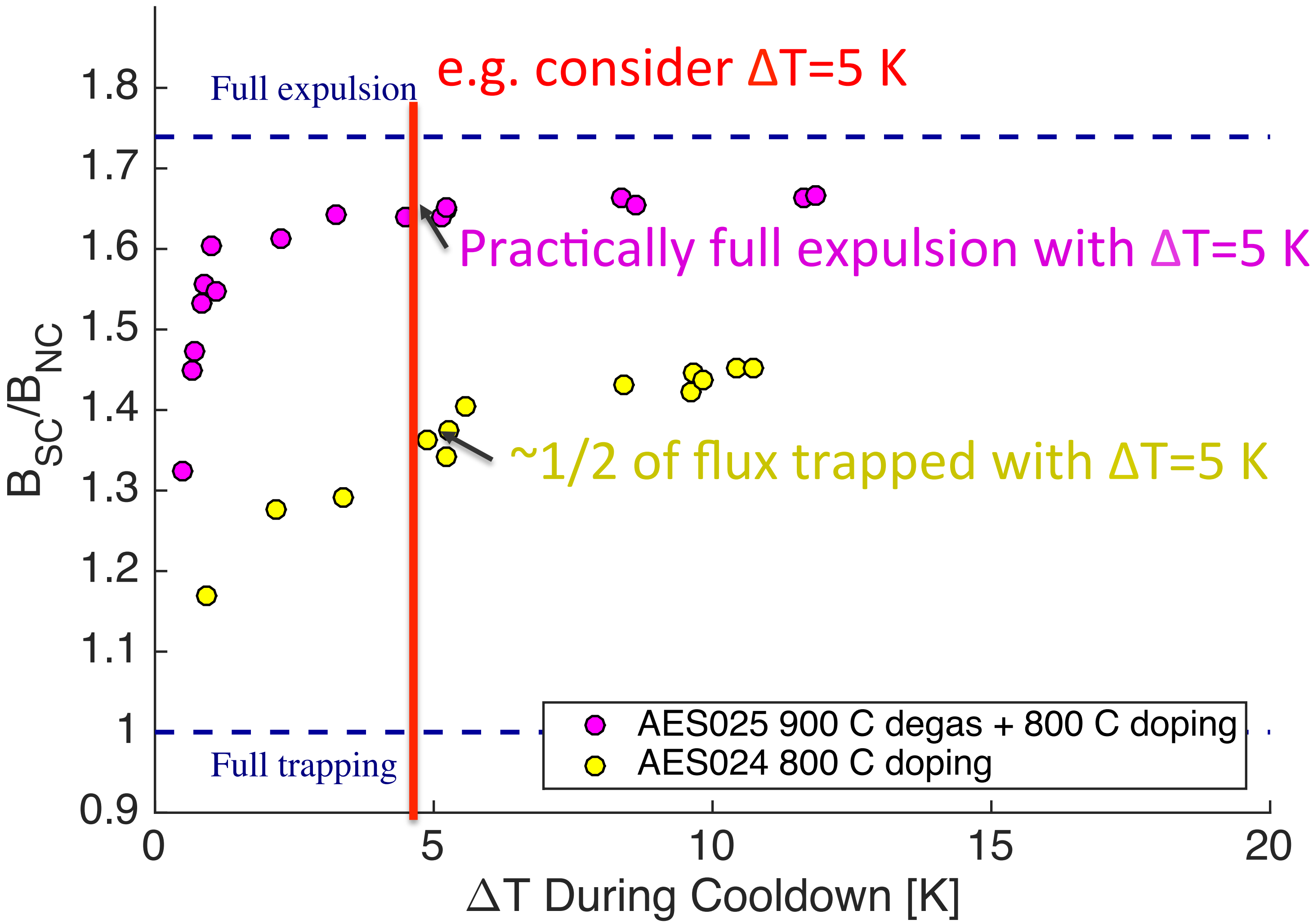
Previously: Flux Expulsion Results



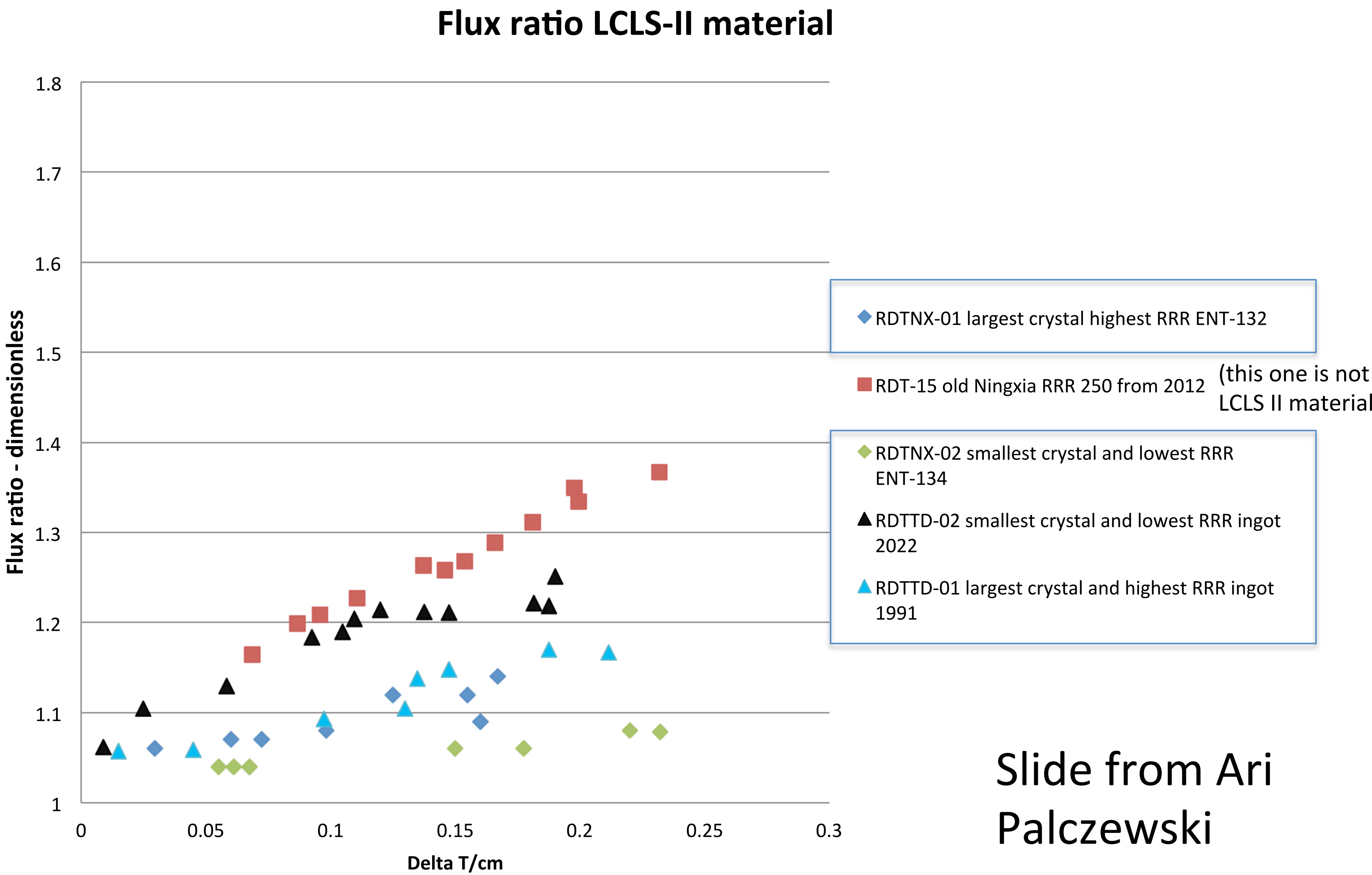
Fermilab

Previously: Flux Expulsion Results



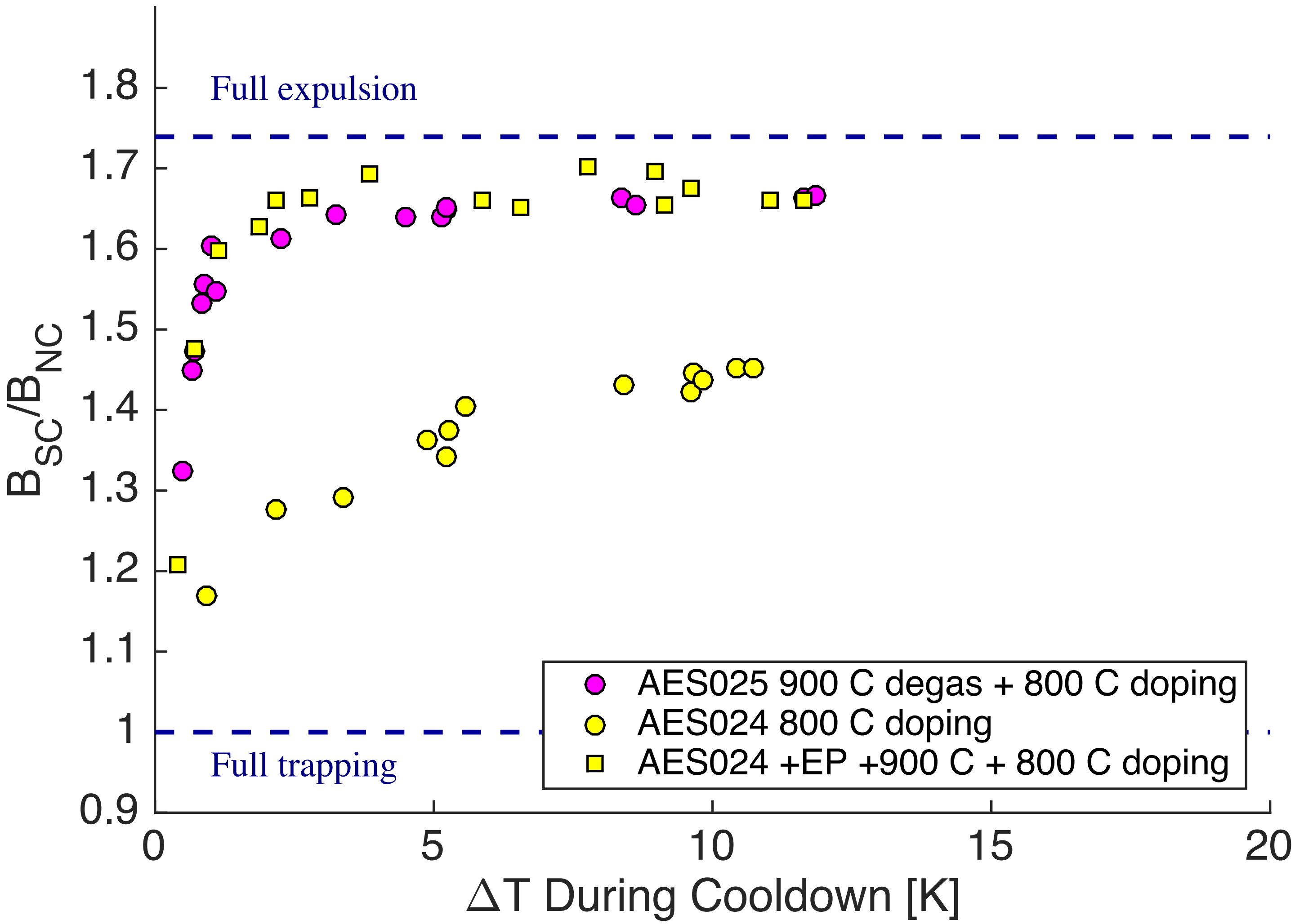
Fermilab

This is flux ratio as a function of temperature difference per cm about equator, there are 2 sensors on the equator, each 20mm away from equator at flux gate location – I also have the data for RDT-15 which I used to baseline cooldown cycles as well.



Slide from Ari Palczewski

New Results: AES024 after reset + 900 + dope



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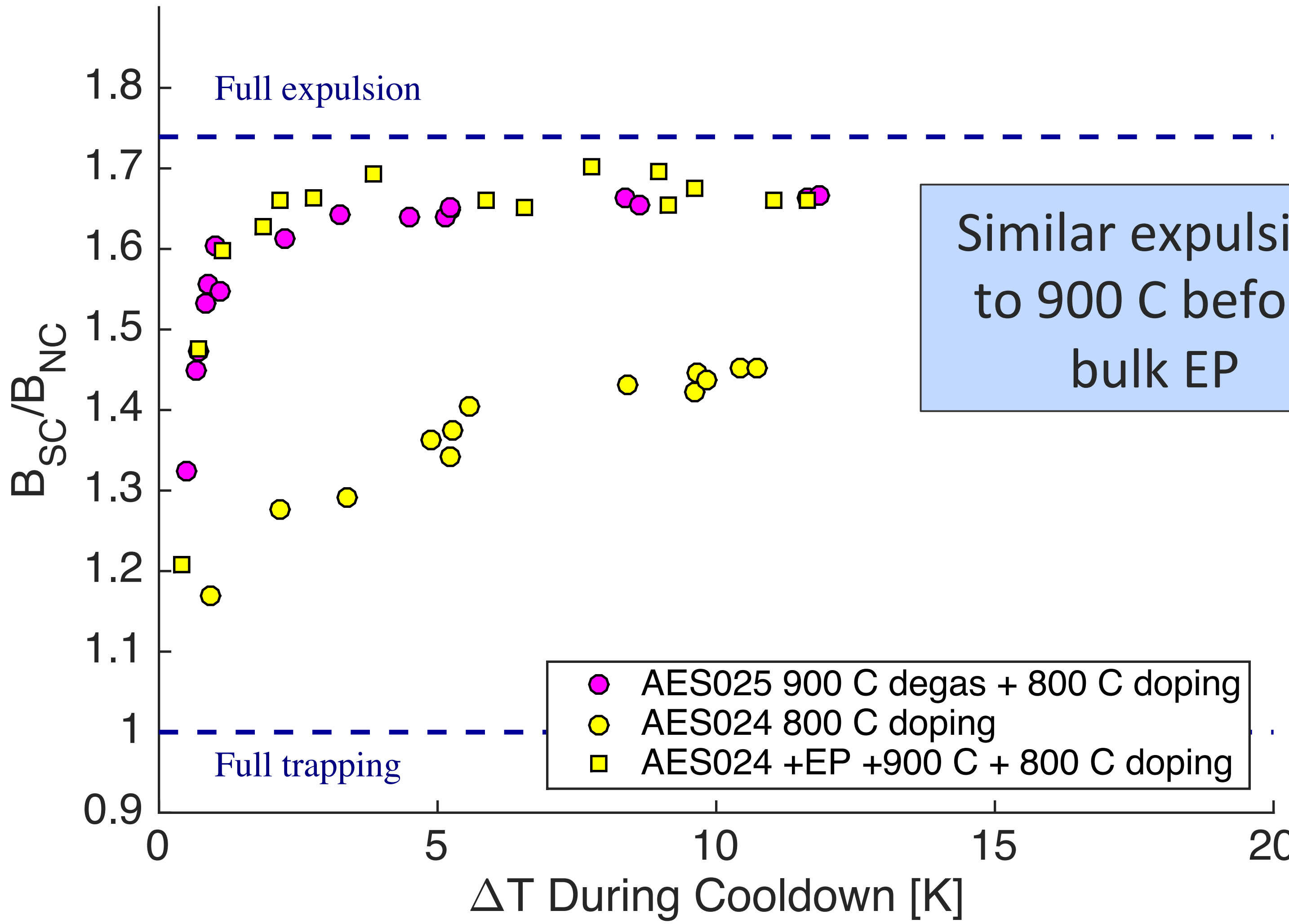
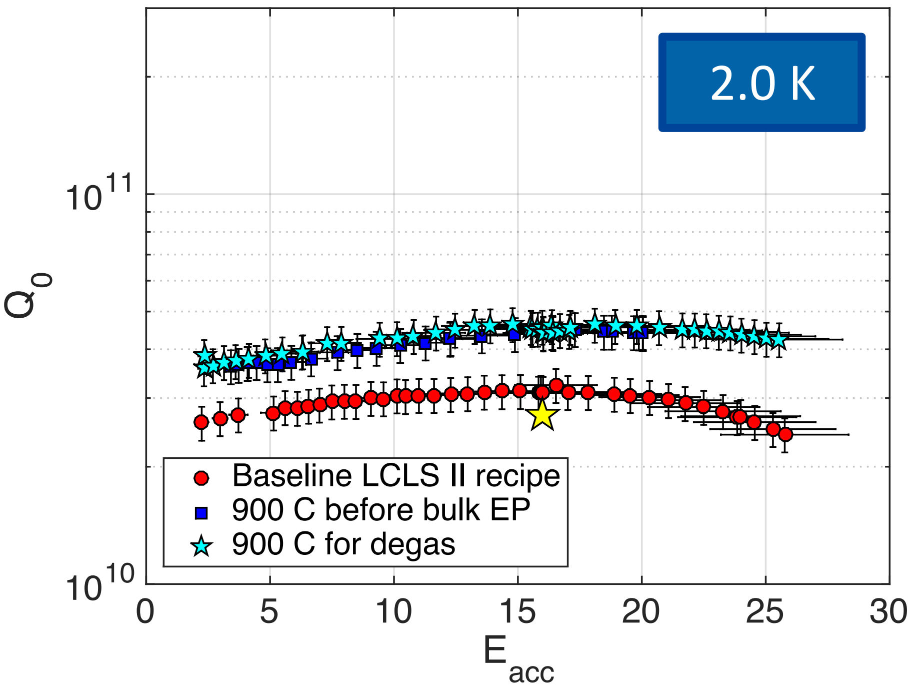
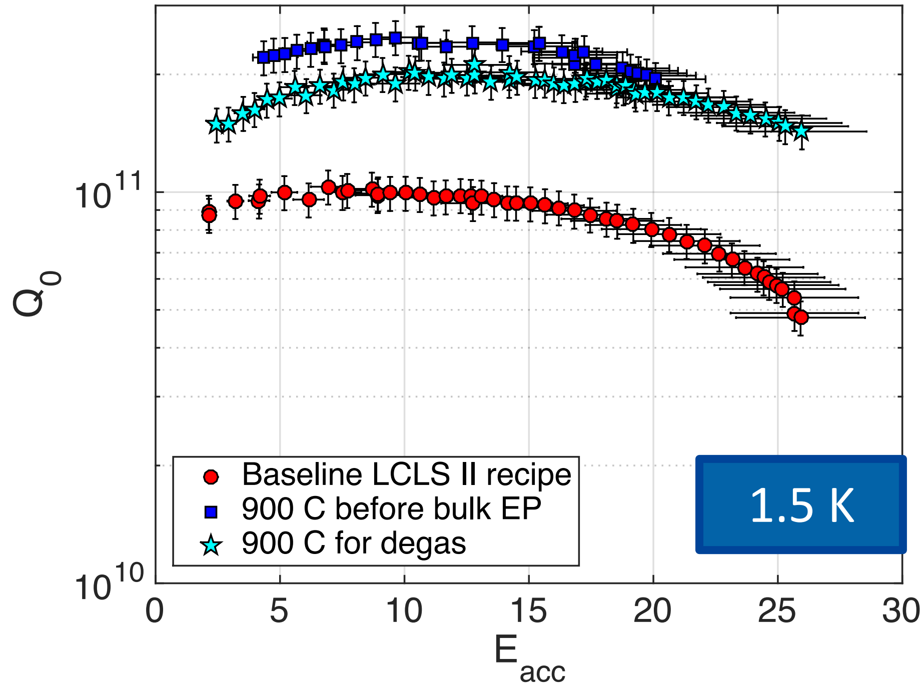


Similar expulsion to 900 C before bulk EP

RF Results

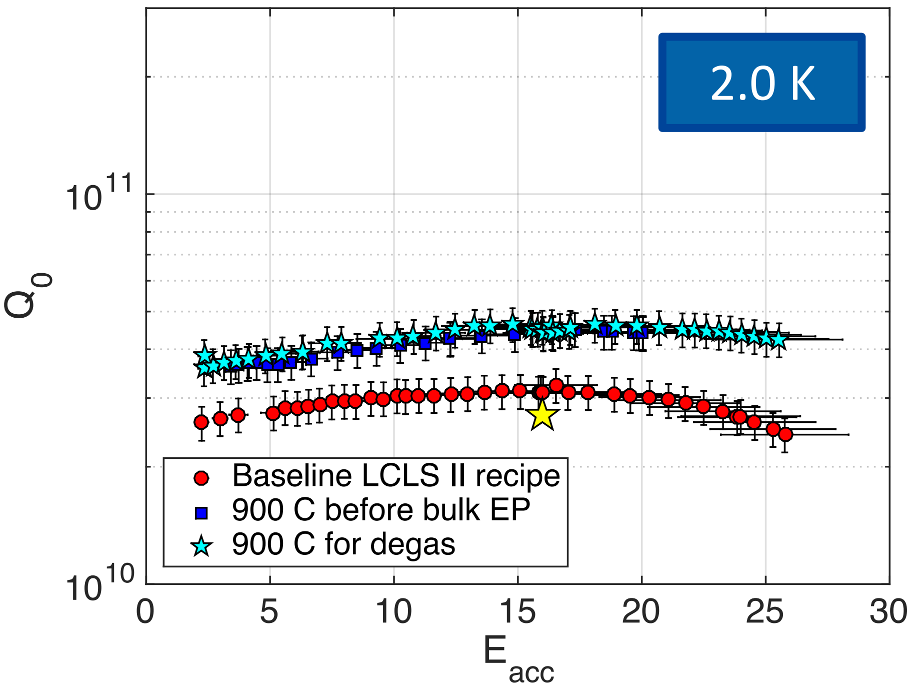


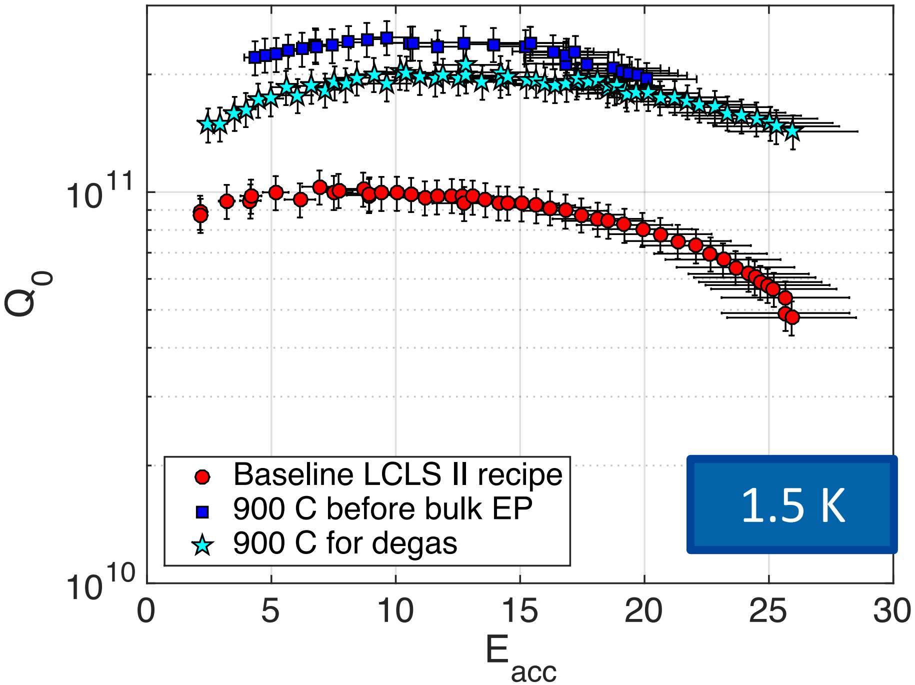
2.0 K
Q0
Eacc
10^11
10^10
0
5
10
15
20
25
30
Baseline LCLS II recipe
900 C before bulk EP
900 C for degas



1.5 K
Q0
Eacc
10^11
10^10
0
5
10
15
20
25
30
Baseline LCLS II recipe
900 C before bulk EP
900 C for degas

RF Results





Similar quench field, no field emission observed, higher Q_0 than before

Next Steps

- TE1AES024: Measure after cooldown in 5 mG field: from expulsion measurements we expect minimal impact on Q_0
- 1-cell cavities: Afterwards can study impact of 900 C 3 h + 800 C doping on 1-cell cavities made from LCLS II material
- 9-cell cavities: Ideal next step is to have a 9-cell cavity treated at vendor to evaluate in full-scale test

From: Anna Grassellino <annag@fnal.gov>
Sent: Tuesday, June 21, 2016 11:53
To: Schultz, David C.; Ross, Marc C.; Richard P Stanek; Camille M Ginsburg; Edward Daly; joe preble
Subject: discussion on Q today

Dear Dave,

I just wanted to comment/clarify few things about these studies being presented. I think the main message is that we are highlighting the opportunity for the project to get more, not less. Remember that flux trapping was found to be a risk two years ago due to unknown cooling in CM, so second refrigerator was added to mitigate this risk. So on the risk front, of Q degradation due to trapped flux, there is nothing new.

In answer to your question “what went wrong with the recipe we had established”: the answer is nothing went wrong. The doping recipe is the same and will remain the same, it is 800C doping 2min/6min. It is still the surface treatment that produces cavity surfaces with the lowest intrinsic surface resistance.

The risk being brought up with these studies is about the effect of trapped magnetic flux, which as we highlighted during the high Q collaboration work, can degrade Q. On the trapped flux, during the high Q collaboration we showed:

-that fast cooling with large thermogradients helps expelling flux
-that slow cooling traps all

Given the risk of unknown cooling obtainable in cryomodule, to mitigate trapped flux losses, a second refrigerator was added.

After the R&D phase was over, at FNAL we continued studies on flux trapping/detrapping on our own research funds. What we found at FNAL about a year ago, and brought up to the project right away, is:

-some material expels flux more stubbornly even with large themrogradients
-but if you treat it at 900C instead of 800C it expels flux perfectly with small thermogradients

This is why we suggested the project should assess production material so we could know what to expect.

Somehow the cavities in our pCM ended up lucky with material that expels well with 800C, while material for production end up unlucky with stubborn flux expelling material.

Bu the good and important message to take away is that we have sufficient data to know how to cure it. And we have an option to cure it with minimal impact to cost and schedule. We need to just decide how to proceed quickly, and Marc has been very focused on this.

Notice that this work on finding and curing the flux trapping was funded externally to the project, but we kept working on it keeping LCLS-2 and its success in mind. It is a bonus to the project from motivated researchers.

If you’d like further clarifications, we could speak over the phone.

Best,

Anna

Anna Grassellino
Scientist I
Cavity Performance and Test Group Leader, SRF Department
Cavity Measurements Lead Scientist, SRF Program

Technical Division
Fermi National Accelerator Laboratory
P.O. Box 500, MS 316
Batavia, Illinois 60510
USA

630 840 2458 office
www.fnal.gov
annag@fnal.gov

From: Anna Grassellino
To: Schultz, David C.
Cc: Anna Grassellino; Ross, Marc C.; Richard P Stanek; Camille M Ginsburg; Edward Daly; joe preble
Subject: Re: discussion on Q today
Date: Tuesday, June 21, 2016 18:07:46

Dear Dave,

this is a good question and we are currently actively pursuing the understanding via samples and cavity analysis. So far two main candidates have been suggested:

- grain size

- defects content (dislocations etc)

Both grain boundaries and defects will act as pinning centers for flux lines. This means effectively traps for the dissipative magnetic fluxoids. The higher the density of these pinning centers in the material, the higher the force required to dislodge these flux lines from the material, hence larger thermal force is required to win the pinning force. But if pinning is weak, even a small thermogradient wave is enough to sweep effectively all the flux out.

Based on the information I have so far from all the experiments we have run, I tend to think it is defects content rather than grain boundaries. We can summarize these results in some presentation if you like. As you may know, niobium material vendors apply several steps to the material in order to produce sheets. Some of these steps like rolling will cause lots of damage at the first hundred or more microns of the sheets. Re-annealing and/or chemical etching is also applied by the vendors, which should help remove the layer with high density of defects. So perhaps variation in processes like amount of chemical etching and/or annealing temperature post rolling at the different material vendors may ultimately give a niobium sheet with more or less defects, hence more or less flux trapping.

We can address this hypothesis with a simple experiment on the single cells made of the production material: we can etch them heavily inside and outside so to eliminate external and internal layer rich of defects and retest flux expulsion capability, to see if indeed the problem is localized in the external “damage” layer.

Hope this helps

Anna

> On Jun 21, 2016, at 4:14 PM, Schultz, David C. <dcs@slac.stanford.edu> wrote:
>
> Somehow the cavities in our pCM ended up lucky with material that expels well with 800C, while material for production end up unlucky with stubborn flux expelling material.
>
> What’s the difference?
>
> ---

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Sent: Tuesday, June 21, 2016 9:53 AM
To: Schultz, David C.; Ross, Marc C.; Richard P Stanek; Camille M Ginsburg; Edward Daly; joe preble
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LCLS-II Flux Expulsion – Proposed path forward

Marc Ross

Saturday, June 25, 2016

1) Complete an assessment of the data taken up to present, including single-cell, nine-cell (a few), and ambient magnetic-field suppression studies.
    a. Collect heat-treatment records of 16 prototype cryomodule cavities. N.b. at least one has been heat-treated above the nominal 800C.
    b. Collect mechanical tuning-stability records for these cavities.
    c. Develop technique (to be used during production) to measure flux expulsion in 9-cell bare and dressed cavities.
2) Prepare to modify the cavity de-gas/doping heat-treatment recipe so that the cavity weldment is pre-annealed, i.e. the oven temperature is raised above the baseline temperature.
    a. Fix recipe-modification details using single-cell test results
    b. Evaluate associated risks, (most of which are mechanical), and develop counter-measures and test them.
3) Assuming the associated risks are properly addressed namely 1) and 2) above are complete, identify (at both cavity vendors) which cavity in the planned production cycle should be the first to receive the modified recipe.
4) Trigger this step to be taken following a review of 1) to 3).

	Engineering Note	
	Title: Flux Expulsion in LCLS-II Cavities	
	Note Number: LCLSII-4.5-EN-0607	
	Author(s): A. Grassellino	Page 1 of 4

Document Approval:	**Date Approved**
Approver: John Corlett, LBNL Senior Team Lead	
Approver: Marc Ross, Cryogenic System Manager	

Revision History:

Revision	Date Released	Description of Change
R0	February 29, 2016	Original release.

Introduction

Recently FNAL extended the studies that had highlighted the importance of cooling SRF bulk niobium cavities with large thermal gradients to expel magnetic flux lines [1], by adding the effect of bulk treatment together with cooldown conditions on the tendency to trap flux in single cell 1.3 GHz cavities [2]. The first studies had demonstrated that cooling bulk niobium cavities through transition with a spatial temperature gradient reduces residual resistance from external magnetic fields, independently from surface treatments, and that slow and homogeneous cooling through critical temperature is to be avoided as it consistently leads to full flux trapping. This has been shown both in vertical test and in horizontal test environments. The exact mechanism is not fully understood, but it is likely that thermal forces on pinned vortices play an important role. During cooldown, a temperature gradient will be present not just from the bottom to top of the cavity, but also from outside wall to inside. It has been shown that spatial temperature gradients create a force on vortices, pushing them towards cooler regions, away from the RF surface and out of the cavity. If the force is large enough, it can depin flux and expel it. The required depinning force—and hence the required thermal gradient—would depend on the strength with which magnetic field lines were pinned. Sample studies suggest that grain boundaries and dislocations act as pinning centers.

While this flux trapping effect may act to significantly reduce the achievable Q_0, several mitigations are possible to recover a high Q_0, and result in LCLS-II cryogenic heat load well within the capacity of the installed refrigeration systems.

Experimental Results

One of the goals of the recent FNAL study was to determine the effec
treatment histories on flux expulsion efficiency as a function of thermogradient. More than ten different single cells have been studied, and each sequentially as a function of thermal treatments and surface treatments like doping, 120C bake, BCP etc. An interesting finding is summarized in Figure 1, where a noticeable difference in expulsion trend was found for cavities of similar bulk and surface treatment, but from different niobium material vendors – first from

Wah Chang showing full flux expulsion with very small thermogradients across the cavity, and second from Tokyo Denkai showing poor flux expulsion ~ 30% maximum, even for large thermogradients. Some cavities with poor flux expulsion were treated then with a high temperature bake ~1000C for 4 hours which brought then the cavity to full flux expulsion, as shown in Figure 2. Another cavity was treated at 800C for ~20 hours and also showed full flux expulsion. So a trend was found in length of bulk annealing with efficiency of flux expulsion.

These findings triggered the importance of investigating the capability of flux expulsion of the material that will be used for the LCLS-II production. All prototype cryomodule cavities were made from material vendor Wah Chang, while LCLS-II production material is from Tokyo Denkai (shown at FNAL to have poor flux expulsion capability) and Ningxia (unknown). Table 1 summarizes different Q scenarios for realistic flux detrapping efficiency – as measured on prototype cryomodule cavities – and for a conservative flux detrapping scenario, which assumes 100% flux trapping. The two cases are then evaluated for different, and conservative, remnant magnetic field conditions, in particular with and without compensation coils. In the worst possible case of complete flux trapping and highest measured remnant magnetic field at the cavities, we see that a Q_0 as low as ~1.1e10 at 2K, 16 MV/m, could be achieved. This would correspond to a total heat load of 7.7 kW at the 2.0 K temperature level, at the limit for the two planned cryogenic plants. This worst case scenario can be mitigated by several approaches, outlined below, and is not expected for LCLS-II if at least one of these approaches is implemented.

Mitigations

To develop a cure to improve the flux expulsion of the procured niobium material, two single cell cavities will be built, one from the LCLS-II production Tokyo Denkai material and one from Ningxia material. Each will be treated with the LCLS-II baseline protocol, and flux expulsion evaluated in a vertical test dewar. If the detrapping efficiency as a function thermal gradient appears poor, then two more single cells would be built, one out of high temperature annealed material and one will be annealed post forming. The flux expulsion would then be evaluated on the two single cells, and if significantly improved, then one of the two pathways (pre-anneal of the material or anneal post forming) could be chosen as an alternative baseline for the LCLS-II production cavity processing protocol. The single cell fabrication and evaluation plan would be carried out by Jlab and FNAL and should not interfere with cavity production at the vendor sites, which would proceed as per project schedule.

Additionally, active cancellation of the dominant longitudinal magnetic field at the cavities has been developed and may be implemented to provide a magnetic environment significantly enhancing the achievable Q_0, as can be seen in the data in Table 1 [6].

The plan for future production cavities will be developed after test results from single-cell cavities are available, and will involve evaluation of the risks associated with this effect including impact on performance, cost, and schedule.

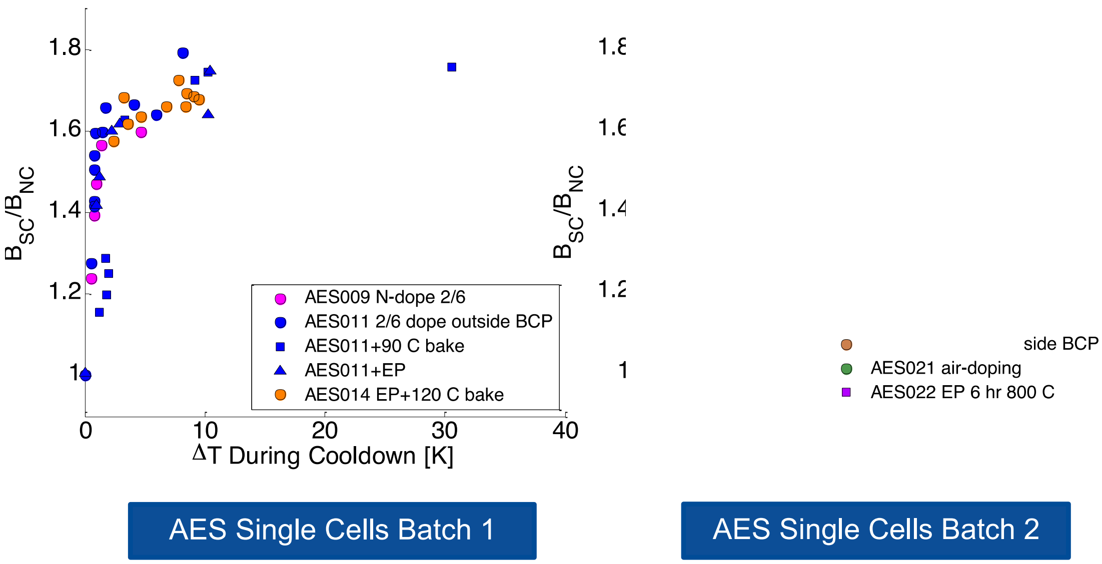

Figure 1 – Comparison of flux expulsion efficiency for Wah Chang (left) and Tokyo Denkai (right) single cells, of similar bulk annealing history (3-6 hours at 800C).

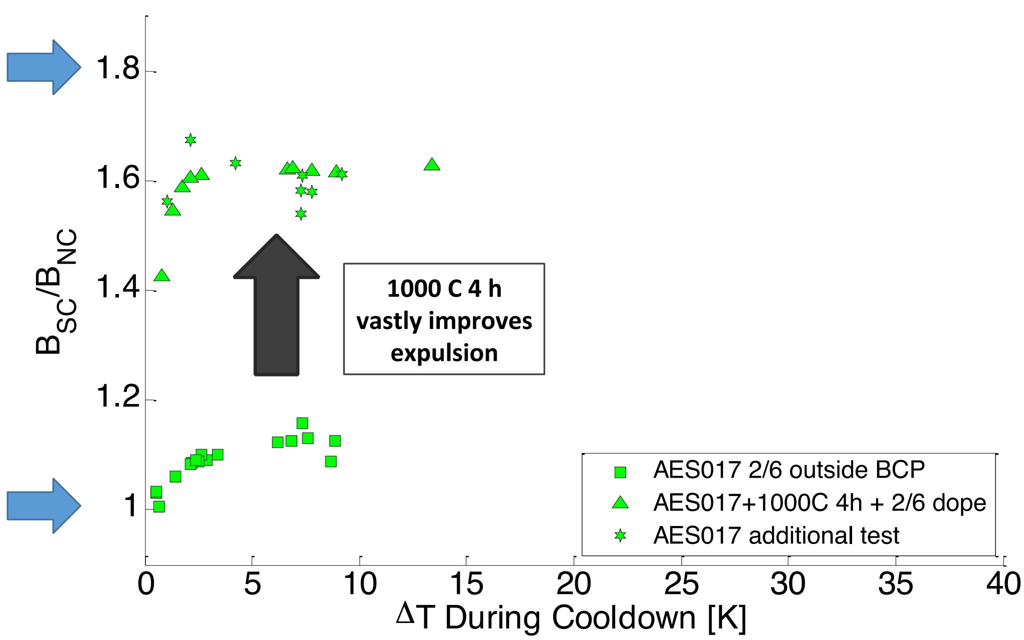

Figure 2- Improved flux expulsion for originally poor performing Tokyo Denkai cavity, post 1000C anneal.

Table 1- Summary of Q obtainable for different flux expulsion and remnant magnetic fields scenarios.

Scenario	Flux expulsion efficiency (nΩ/mG)	Comp. coil?	B_{avg} (mG)	R_s (nΩ)	Q ($x10^{10}$)
Realistic	0.5 [3,4]	No	15	13.5	2
		Yes	3	7.5	3.5
Conservative (100% trapping)	1.2 [5]	No	15	24	1.1
		Yes	3	9.6	2.8

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FLUX EXPULSION VARIATION IN SRF CAVITIES *

S. Posen†, A. Grassellino, A. Romanenko, O. Melnychuk,
D. A. Sergatskov, M. Martinello, M. Checchin, and A. C. Crawford
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

Treating a cavity with nitrogen doping significantly increases Q_0 at medium fields, reducing cryogenic costs for high duty factor linear accelerators such as LCLS II. N-doping also makes cavities more sensitive to increased residual resistance due to trapped magnetic flux, making it critical to either have extremely effective magnetic shielding, or to prevent flux from being trapped in the cavity during cooldown. In this paper, we report on results of a study of flux expulsion. We discuss possible ways in which flux can be pinned in the inner surface, outer surface, or bulk of a cavity, and we present experimental results studying these mechanisms. We show that grain structure appears to play a key role and that a cavity that expelled flux poorly changed to expelling flux well after a high temperature furnace treatment. We further show that after furnace treatment, this cavity exhibited a significant improvement in quality factor when cooled in an external magnetic field. We conclude with implications for SRF accelerators with high Q_0 requirements.

BACKGROUND

In the last several years, there has been rapid progress in technology for high Q_0 applications. Nitrogen doping was discovered and recipes were developed to dramatically reduce both BCS and residual surface resistances (R_{BCS} and R_{res}) at peak fields on the order of 70 mT [1]. Furthermore, researchers observed the importance of cooldown on residual resistance in the bulk dressed niobium cavity prepared by BCP [2], attributing the effect to additional magnetic fields generated by thermocurrents [3]. Subsequently, the importance of the cooldown conditions on the amount of trapped flux even for the same ambient field was discovered in bare cavities of various surface treatments [4] showing the dramatic impact of spatial temperature gradient at transition on the residual resistance. Studies showed that N-doping increases the sensitivity of the residual resistance to trapped magnetic flux [5]. In addition, the effect of material preparation on tendency to trap flux (i.e. percent of external flux not expelled during cooldown) was studied in bulk niobium samples [6, 7].

Building on these studies, in this paper we study the effect of preparation and cooldown conditions on the tendency to trap flux in single cell 1.3 GHz cavities.

* This work was supported by the US Department of Energy
† sposen@fnal.gov

FLUX EXPULSION

Cooling N-doped bulk niobium cavities through transition with a spatial temperature gradient reduces residual resistance from external magnetic fields. This has been shown both in vertical test [4] and in horizontal test [8]. The exact mechanism is not well understood, but it is likely that thermal forces on pinned vortices play an important role. We offer a picture of how this could work in Fig. 1.

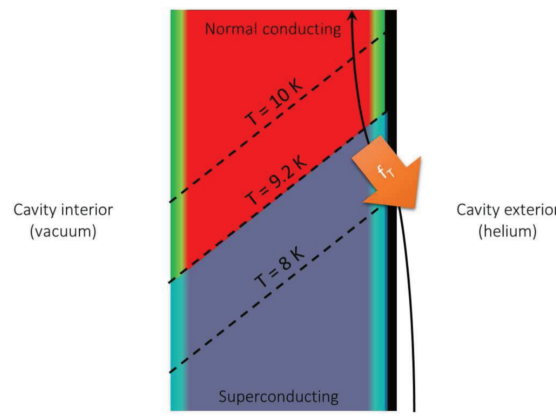

Figure 1: Schematic of a cross section of a bulk N-doped cavity wall, showing layers of different materials: N-doped niobium at the inner surface, high purity niobium in the bulk, N-doped niobium at the outer surface, and NbN compounds at the outer surface. Isotherms during cooldown are also indicated schematically, along with the corresponding thermal force f_T on a vortex.

During cooldown, a temperature gradient will be present not just from the bottom to top of the cavity, but also from outside wall to inside. It has been shown that spatial temperature gradients create a force on vortices, pushing them towards cooler regions [9] (see [10] for another SRF cavity application of this). In the geometry from Fig. 1, there is a component of the force pushing the vortices away from the RF surface and out of the cavity. If the force is large enough, it can depin flux and expel it.

The required depinning force—and hence the required thermal gradient—would depend on the strength with which magnetic field lines were pinned. Sample studies suggest that grain boundaries and dislocations act as pinning centers [6, 7]. In addition to these bulk properties, surface properties may play a role. A N-doped cavity will have a thin layer of nitrogen-rich material at its interior and exterior surfaces. Immediately after doping, it can also have a layer of poorly superconducting niobium nitride phases on its interior and exterior surfaces, though the interior nitrides

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are generally removed with electropolishing (EP). A cavity treated with 120°C baking will have oxygen-rich material on its inner and outer surfaces.

If grain boundaries and dislocations act as pinning centers, it should be possible to change flux expulsion in a cavity by treating it with high temperature baking. If the interior or exterior layers act as strong pinning sites, it should be possible to change flux expulsion with chemical removal. One of the goals of this study was to determine the effect of these two treatments on flux expulsion.

If flux expulsion could be improved, it could be possible to reduce the requirements on magnetic shielding and on thermal gradient during cooldown for cavities in high Q_0 machines. For example, in [8], it was found that vertical gradients on the order of 20 K were required to minimize R_{res}, even with a double layer of magnetic shields.

APPARATUS

For this study, flux expulsion and surface resistance were measured for a number of cavities prepared in various ways, under different cooldown conditions. Flux expulsion was measured using the method from [11]. An axial magnetic field on the order of 10 mG was applied to the cavities using external field coils. A number of fluxgate magnetometers (generally three) were spaced around the equator of the cavities, parallel to the axis, as shown in Fig. 2. The magnetic field was measured before (B_{NC}) and after (B_{SC}) transition to the superconducting state, as shown in Fig. 3. When the external field was completely trapped in the superconductor, the field distribution remained approximately the same (predicted ratio $B_{SC}/B_{NC} = 1$). When the external field was completely expelled by the superconductor, the fields outside the superconductor are enhanced by approximately 80% (predicted ratio $B_{SC}/B_{NC} = 1.8$).

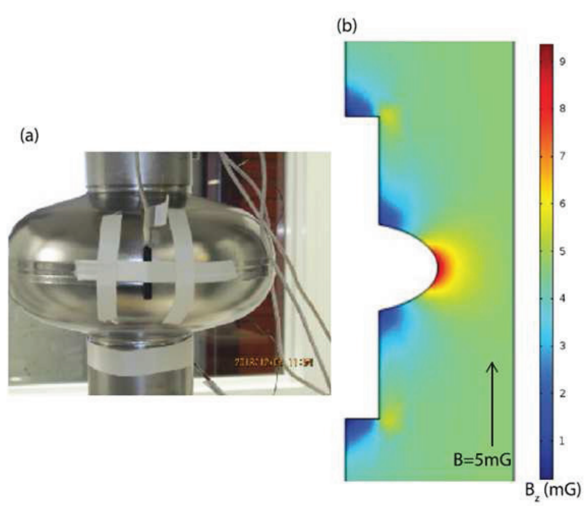

Figure 2: Method for measuring flux trapping: a) fluxgate magnetometer placed on the cavity equator; b) simulation of an externally applied magnetic field when it is fully expelled from the superconducting cavity.

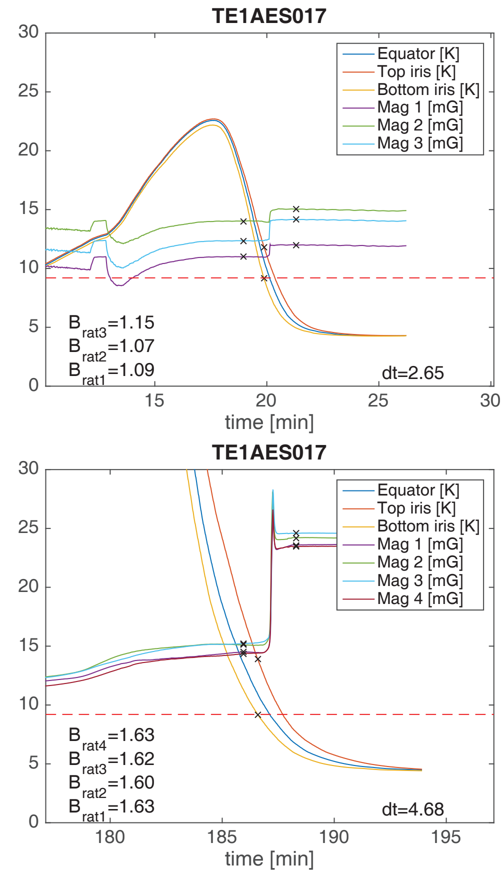

Figure 3: Example measurements of flux expulsion during cooldown. ΔT is measured from iris-to-iris when the bottom iris reaches 9.2 K. B_{NC} and B_{SC} are measured before and after transition. The x's mark which values are used. The magnetic field ratios show that in the top example, flux is largely trapped, and in the bottom, flux is largely expelled.

The fine grain 1.3 GHz single cell cavities used in this study were prepared in various ways, sometimes for other studies, from which parasitic flux expulsion measurements were made. The cavities were cooled in a vertical test dewar with liquid helium filling from the bottom. Temperature sensors were placed at the top and bottom iris and at the equator. The spatial temperature gradient was measured from the bottom to the top iris when the bottom iris reached 9.2 K. The temperature gradient was varied by beginning the cooldown at different starting temperatures. If RF results were to be measured during cooldown, liquid would continue to be added to the dewar—otherwise, once all sensors read 5 K, the helium flow was stopped and the dewar was warmed up. By performing a series of warmup-cooldown cycles to only 5 K, flux expulsion could be characterized for a cavity with modest helium usage.

RESULTS

The results of the flux expulsion measurements are overviewed in Fig. 4.

The first measurement was performed on cavity AES011, which received a 5 micron external BCP after nitrogen dop-

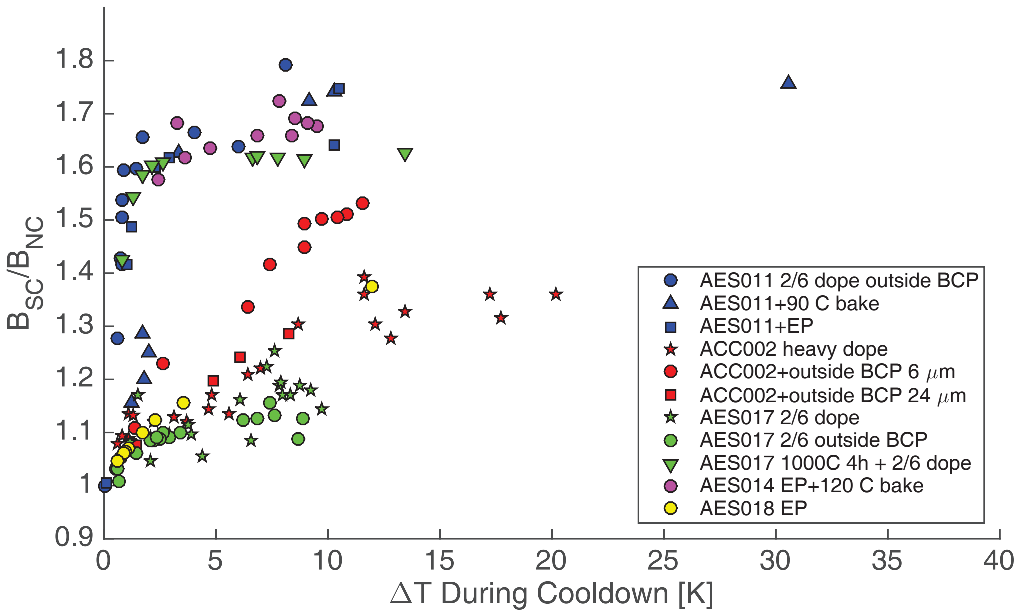

Figure 4: Flux expulsion ratio B_{SC}/B_{NC} of cavities prepared in various ways as a function of iris-to-iris temperature difference during cooldown. A ratio of 1.8 represents perfect flux expulsion, while a ratio of 1.0 represents full flux trapping. Some cavities fail to expel flux even for ΔT on the order of 10 K, and they show enhanced surface resistance in RF measurements. Uncertainty in expulsion ratio is approximately 0.1 and in ΔT, it is approximately 1 K.

ing with the 2/6 recipe (2 minutes in N_2 gas at 800°C with 6 minute anneal and EP). These results were presented in [11]. This cavity expelled flux fairly well, achieving close to full expulsion for $\Delta T \gtrsim 2$ K. In subsequent tests, it received a 90°C bake and a 3 micron electropolish. Neither treatment affected the expulsion appreciably.

The next cavity that was tested was ACC002. This cavity was heavily doped (20 minutes in nitrogen at 800°C), and its flux expulsion was characterized before any external chemistry (AES011 was RF tested before its external BCP treatment, but the procedure for flux expulsion measurement was developed later). It showed considerably smaller flux expulsion as a function of thermal gradient than AES011. After external BCP of 6 microns to remove the NbN phases, it seemed to show somewhat improved expulsion. Additional BCP of 24 microns seemed to result in similar expulsion to before the first round of BCP.

AES017, which was doped with a 2/6 recipe, also showed relatively poor expulsion. It showed no appreciable change after outside BCP of 5 microns. After the outside BCP, the cavity should have had a very similar inner and outer surface as AES011. Both received 2/6 doping followed by a light external BCP. The fact that they have strongly different behavior suggests that the inner and outer surface treatment is not a dominating factor determining flux expulsion in these cavities. This is supported by the relatively small effect of the outside BCP on ACC002, as well as it having an expulsion characteristic intermediate to that of AES011 and AES017 in spite of having a heavier level of N-doping.

One interesting feature of AES011 is that in spite of being fabricated from material with grain size on the order of 50 microns, its surface shows very large grains, as shown in Fig. 5, suggesting significant grain growth over its history. However, logs of the treatment of this cavity show furnace treatments at 800°C, but not at higher temperatures. One possible reason for significant grain growth at such low temperatures would be a high RRR value of the material [12]. Material reports from these cavities show that the material had RRR values of approximately 480. Other cavities from this batch of cavities also seemed to expel flux well, such as AES014. On the other hand, the material from the batch with AES017 came from a different vendor, with reported RRR values of approximately 350. AES018, also from this batch, showed relatively poor expulsion as well.

The hypothesis that flux expulsion characteristic is strongly related to the lattice of the bulk material is supported by the last test of AES017. In this test, the cavity was given a heat treatment at 1000°C for 4 hours before reducing the temperature to 800°C and doping the cavity again with 2/6 recipe (to make up for nitrogen diffused into the bulk). After this treatment, the cavity appeared to have millimeter-sized grains, and it showed greatly enhanced flux expulsion, similar to that of AES011 and AES014.

DISCUSSION

The results suggest that there are two factors that significantly contribute to good flux expulsion: thermal gradients and heat treatment to affect crystal structure. The results do not distinguish between the effects of grain growth (re-

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Figure 5: Significant grain growth observed in AES011.

duction in total number of grain boundaries) and the effects of recrystallization and dislocations. However, sample studies suggest both play a role: improved flux expulsion is observed both when going from polycrystalline samples to single crystal samples and when going from single crystal samples without heat treatment to ones with heat treatment at 800 and 1200°C [6].

The positive impact of larger grains would also be consistent with previously reported results suggesting improved quality factors in large grain cavities compared to fine grain cavities [13].

In Fig. 6, we show that the factors being studied in these experiments have a significant impact on cavity performance. Both sets of Q vs E curves come from AES017, one before furnace treatment at 1000°C, and one after. In both cases, the cavity was treated with a 2/6 N-doping, giving it a low-field Q_0 of approximately 3×10^{10} at 2 K when the cavity is cooled in the absence of magnetic fields. However, when cooled in an external magnetic field of ~10 mG with a modest thermal gradient, the values are starkly different. The cooldowns for these curves are shown in Fig. 3. Before furnace treatment, the cavity shows a low field Q_0 on the order of 1.5×10^{10} at 2 K, while after, it is on the order of 3×10^{10}. These measurements show that the improvement in flux expulsion directly translates to an improvement in Q_0 in the presence of an external field.

Note that the Q-slope observed in the Q vs E curve post 1000°C treatment is characteristic of an overdoped cavity. It is suspected that the N-content in the cavity surface is higher than desired, possibly due to leftover nitrogen from the first 2/6 doping before doping again after the 1000°C treatment. The cavity will next be retested after a 3 micron EP. Heavy doping is not expected to strongly influence flux expulsion based on the results of ACC002.

Preliminary measurements of a cavity manufactured from large grain material also show very good flux expulsion.

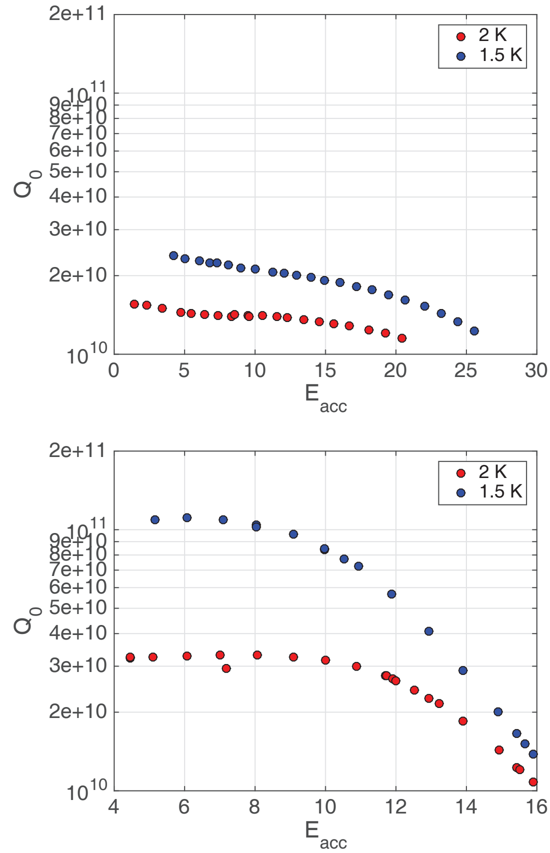

Figure 6: Q vs E curves of AES017 cooled with thermal gradients on the order of 4 K in a ~10 mG external field. Before 1000°C furnace treatment (top), the cavity expels poorly and the Q_0 is strongly suppressed relative to the zero-external-field value. After 1000°C treatment (bottom), the cavity expels well and the Q_0 is close to the ideal value. The corresponding cooldowns for these Q vs E curves are shown in Fig. 3.

CONCLUSIONS

In this paper, we presented results from a study of tendency to trap magnetic flux in 1.3 GHz single cell niobium cavities. It was found that expulsion of magnetic flux was significantly enhanced after furnace treatments at high temperatures and a modest spatial temperature gradient during cooldown through transition—on the other hand, various surface treatments of the cavity had little impact. This agrees with previous sample studies, but additional experiments should be performed to study the connection between furnace treatment and improvement in flux expulsion. If additional experiments confirm this connection, then these results may be important for high Q_0 machines such as LCLS II. Before production begins, representative quality control cavities could be fabricated using the planned material and production method. The cavities may show good expulsion as-manufactured. However, if poor expulsion is observed, the study presented here suggests that the addition of a high temperature furnace treatment could prevent sig-

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nificant residual resistance due to trapped flux. This may represent a simpler solution than additional magnetic shielding, larger thermal gradients, or additional cryogenic capacity.

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MAGNETIC FLUX EXPULSION STUDIES IN NIOBIUM SRF CAVITIES *

S. Posen†, M. Checchin, A. C. Crawford, A. Grassellino, M. Martinello,
O. Melnychuk, A. Romanenko, D. A. Sergatskov, and Yulia Trenikhina,
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract

With the recent discovery of nitrogen doping treatment for SRF cavities, ultra-high quality factors at medium accelerating fields are regularly achieved in vertical RF tests. To preserve these quality factors into the cryomodule, it is important to consider background magnetic fields, which can become trapped in the surface of the cavity during cooldown and cause Q_0 degradation. Building on the recent discovery that spatial thermal gradients during cooldown can significantly improve expulsion of magnetic flux, a detailed study was performed of flux expulsion on two cavities with different furnace treatments that are cooled in magnetic fields amplitudes representative of what is expected in a realistic cryomodule. In this contribution, we summarize these cavity results, in order to improve understanding of the impact of flux expulsion on cavity performance.

INTRODUCTION

How strong is the impact of residual magnetic fields on the Q_0 of a superconducting RF cavity? Trapped flux degrades Q_0 and necessitates additional cryogenic capacity for cooling at a given accelerating gradient. With magnetic shielding and active compensation to reduce the residual axial field to ~5 mG, what will the impact on Q_0 be? Recent discoveries have shown that:

- Spatial thermal gradients during cooldown can significantly improve expulsion of magnetic flux [1]
- Flux expulsion behavior can be substantially enhanced through UHV furnace treatment [2]

In this contribution, we study two newly fabricated cavities produced using high RRR niobium from the same production group. Only one of these cavities is given high temperature furnace treatment at temperatures higher than 800 C. The impact on flux expulsion behavior is measured, as is the impact on Q_0 in a magnetic field that is of similar strength to what would be expected in an accelerator cryomodule.

MEASUREMENT TECHNIQUE

The setup for measuring flux expulsion, after the method in [3], is shown in Fig. 1. An axial magnetic field is applied to a cavity during cooldown, and fluxgate magnetometers at the middle of the cell measure the magnetic field before B_{NC} and after B_{SC} the superconducting transition. Thermometers measure the temperature at the top, bottom, and middle of the cavity cell. The temperature difference between the top and bottom of the cell is used to represent the thermal gradient. If the applied field is fully trapped in the cavity wall when the cavity passes through the superconducting transition temperature, the field should not change (B_{SC}/B_{NC}=1). If the field is fully expelled by the superconductor, simulations show that the field should be enhanced by a factor of approximately 70% (B_{SC}/B_{NC}=1.7). An uncertainty of 0.1 was assumed for B_{SC}/B_{NC} due to the exact distance of the fluxgate probe from the cavity surface, its alignment relative to the applied field and non-uniformities in the field. An uncertainty of 0.2 K was assumed for the temperature measurement in each probe, due to thermal impedance between cavity and thermometer and non-uniformity in temperature around the cavity.

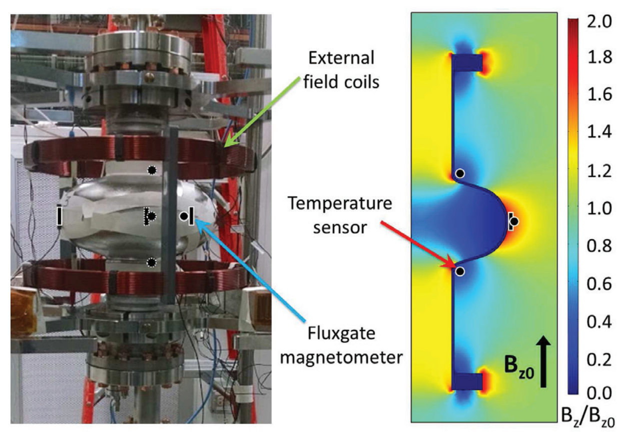

Figure 1: Apparatus used to measure flux expulsion (left) and simulation used to determine the magnetic field enhancement factor for full expulsion.

Two fine grain 1.3 GHz single cell cavities, AES024 and AES025, were fabricated by the same vendor using high RRR niobium from the same production run. Only AES025 was given 900 C furnace treatment for 3 hours. Then both received bulk EP, 800 C degas, and ‘2/6’ nitrogen doping with 5 micron EP (which is the baseline recipe for the cavities for the LCLS-II project [4]). During cooldown in vertical test, spatial temperature gradient was measured from the bottom to the top iris when the bottom iris reached 9.2 K. For each cavity, many cooldown-warmup cycles were run. Unless RF data was taken, cooldown was stopped at 6 K.

* This work was supported by the US Department of Energy
† sposen@fnal.gov

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FLUX EXPULSION RESULTS

Figure 2 shows example measurements of flux expulsion during cooldown from AES024 and AES025. Figure 3 shows a survey of many measurements, which together illustrate the significant difference in the expulsion characteristic of the two cavities. AES025, which received 900 C treatment for 3 hours, shows substantially stronger expulsion than AES024, which did not. Even for ΔT∼1 K, nearly all flux is expelled from AES025, while ΔT∼5 K gives only B_{SC}/B_{NC} ∼1.3 for AES024. In fact, in later testing, AES025 was subjected to slow cooling in an attempt to trap as much flux as possible, but even with this procedure, approximately 70% of the flux was expelled due to its strong expulsion behavior.

RF MEASUREMENTS

In addition to the survey of flux expulsion data, RF data was measured for both cavities[1], after cooling them under carefully controlled thermal and magnetic conditions. In various tests, shown in Figs. 4 and 5, both cavities were cooled in a field <1 mG and in a field of 5 mG, which is the maximum tolerance for background field in LCLS-II cryomodules [4] [2]. For AES024, which showed weaker expulsion behavior, RF measurements showed substantial vulnerability to Q_0 degradation due to trapped flux. Even with a ΔT of 5 K across the cavity during cooldown, the Q_0 was degraded in the 5 mG field to below the specification of 2.7×10^{10}. However, for AES025, which showed strong expulsion, even with ΔT of of 2 K, no Q_0 degradation was observed relative to cooling in <1 mG field.

CONCLUSIONS

The results indicate that as-received high-RRR niobium material can be vulnerable to flux trapping that substantially degrades performance. For high Q_0 machines such as LCLS-II, achieving the highest Q_0 possible can allow for lower operating costs and the possibility of higher gradient operation. As a result, depending on the properties of the niobium material, it may be worthwhile to apply additional treatment steps to enhance flux expulsion. Placing a cavity in a UHV furnace at 900 C for 3 hours prior to bulk EP was shown to be effective for improving expulsion and preventing Q_0 degradation with a modest temperature gradient during cooldown.

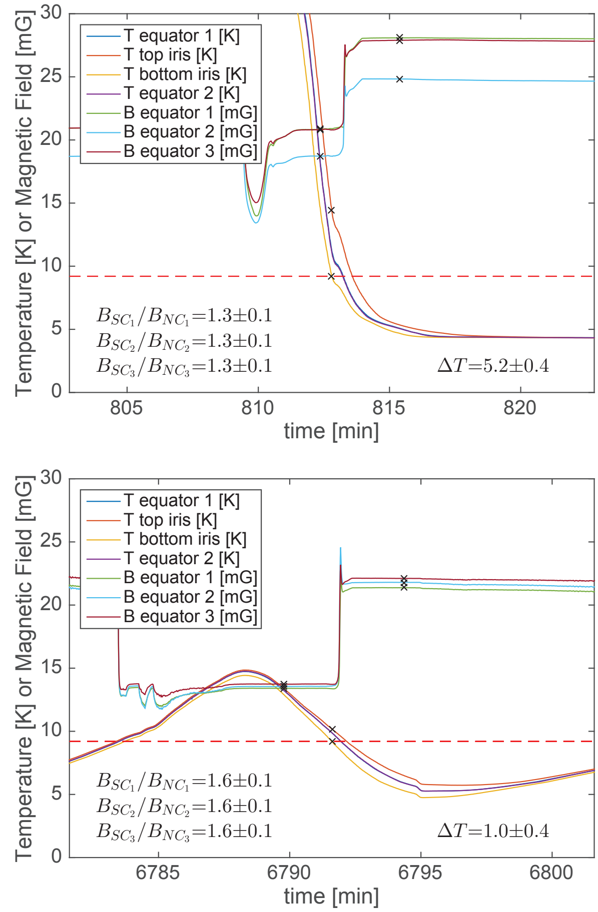

Figure 2: Example measurements of flux expulsion during cooldown from AES024 (top) and AES025 (bottom). The x's mark the values that are used to calculate ΔT and B_{SC}/B_{NC}.

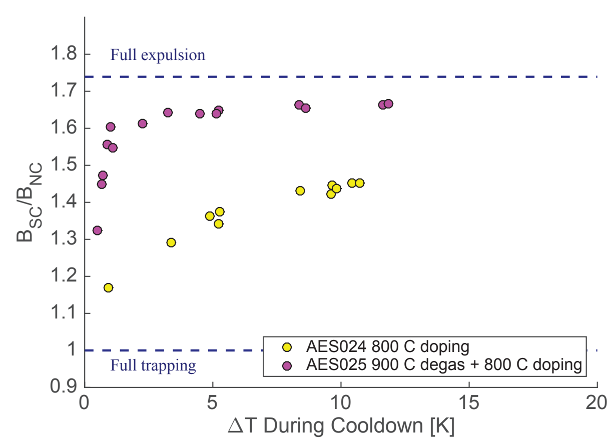

Figure 3: Survey of flux expulsion measurements for AES024 and AES025. AES025, which received 900 C furnace treatment, shows substantially stronger expulsion.

[1] It should be noted that a cable used in these tests showed inconsistent Q_{ext2} values in other measurements. This may have introduced some systematic error. In addition, since relatively low fields ∼5 mG were applied in the RF measurements, small background fields in perpendicular directions may have a significant impact relative to the applied field.

[2] Note that even if 5 mG were trapped, nitrogen doping would still have a significant advantage compared to non-doped niobium [5].

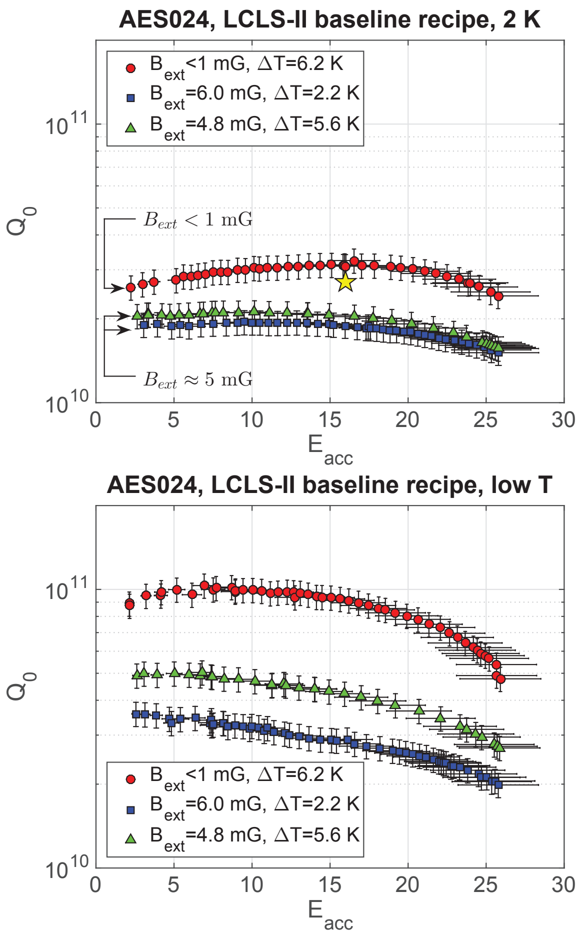

Figure 4: AES024 exhibits a substantial impact of a small background field on the Q_0. When the cavity is cooled in 5 mG, even with a ΔT of 5 K across the cavity, it shows substantial degradation compared to cooling in a <1 mG field. Measurements are shown for a bath temperature of 2.0 K (top) and ~1.5 K (bottom).

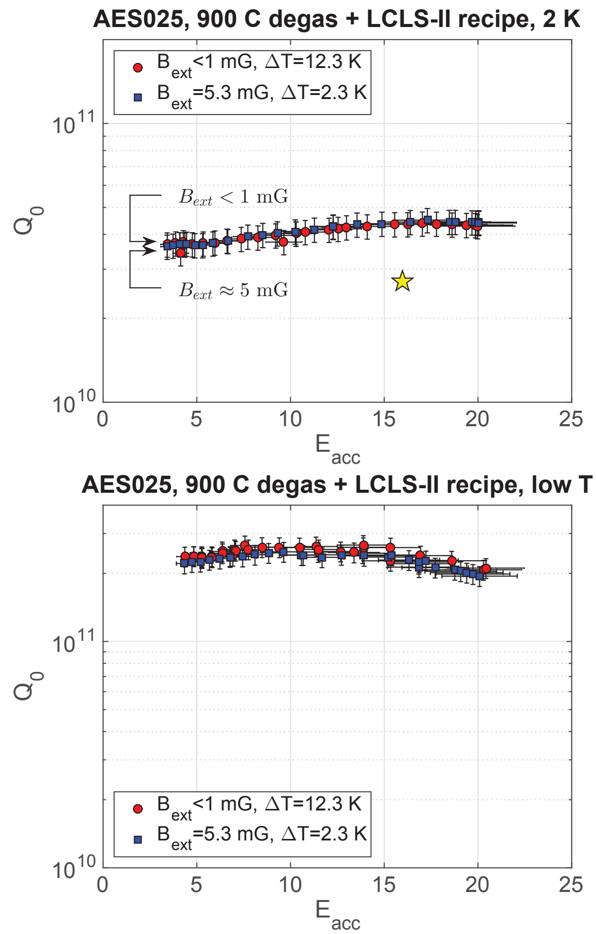

Figure 5: AES025 exhibits minimal impact of a small background magnetic field on the Q_0. When the cavity is cooled in 5 mG with ΔT of only 2 K, the Q_0 appears unchanged relative to cooling in a field <1 mG. Measurements are shown for a bath temperature of 2.0 K (top) and ~1.5 K (bottom).

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

S. Posen,* M. Checchin, A. C. Crawford, A. Grassellino, M. Martinello, O. Melnychuk, A. Romanenko, and D. Sergatskov
Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA.
(Dated: February 17, 2016)

Even when cooled through its transition temperature in the presence of an external magnetic field, a superconductor can expel nearly all external magnetic flux. This Letter presents an experimental study to identify the parameters that most strongly influence flux trapping in high purity niobium during cooldown. This is critical to the operation of superconducting radiofrequency cavities, in which trapped flux degrades the quality factor and therefore cryogenic efficiency. Flux expulsion was measured on a large survey of 1.3 GHz cavities prepared in various ways. It is shown that both spatial thermal gradient and high temperature treatment are critical to expelling external magnetic fields, while surface treatment has minimal effect. For the first time, it is shown that a cavity can be converted from poor expulsion behavior to strong expulsion behavior after furnace treatment, resulting in a substantial improvement in quality factor. Future plans are described to build on this result in order to optimize treatment for future cavities.

PACS numbers: 74.25.Wx, 74.70.Ad, 29.20.Ej

Recently, concentrated research effort has been devoted to obtaining high quality factors (Q_0) in superconducting radiofrequency (SRF) cavities, structures that transfer energy to beams in particle accelerators. High Q_0 reduces the considerable costs for cryogenics—both infrastructure and AC wall power for the cryogenic plant—required to cool cavities operating with high duty factor. Treatments such as nitrogen-doping [1] have been invented to substantially improve nominal quality factors, but Q_0 can be strongly degraded by trapped magnetic flux.

Q_0 degradation by trapped flux can be considered as a three step process: 1) the cavity is cooled in a finite external magnetic field environment B_{ext}; 2) some of that field, B_{trap}, is trapped in the surface of the cavity; and 3) the surface resistance R_s of the cavity (Q_0 is inversely proportional to R_s) is increased by an amount R_{fl} due to the trapped field. Preparation can be optimized to reduce the impact of each of these steps. Use of non-magnetic components, magnetic shielding, and active field cancellation can reduce B_{ext} in step 1 (see e.g. Ref. 2). The mean free path can be optimized to reduce R_{fl} for a given B_{trap} in step 3 (see e.g. Refs. 3 and 4). For step 2, the amount of external field trapped in the cavity during cooldown can be reduced, and recent experiments have shown that even full expulsion is possible (previous experimental results [5, 6] had reported full trapping—$B_{trap} \sim B_{ext}$). These recent experiments include the discovery that the fraction of external field that is trapped in the surface of a niobium cavity during cooldown is strongly dependent on the thermal gradient over its surface [7, 8], which may be explained by thermal forces [9] or other mechanisms [10]. In this Letter, we present an experimental study that further develops the understanding of flux expulsion in niobium cavities. For the first time, expulsion is studied as a function of both thermal gradient and cavity preparation. The goal of the study was to determine whether flux trapping behavior is determined by bulk properties (e.g. grain boundaries, as in [11, 12]) or surface properties (e.g. nitrides from the nitrogen-doping process) and then to find a treatment that improves expulsion.

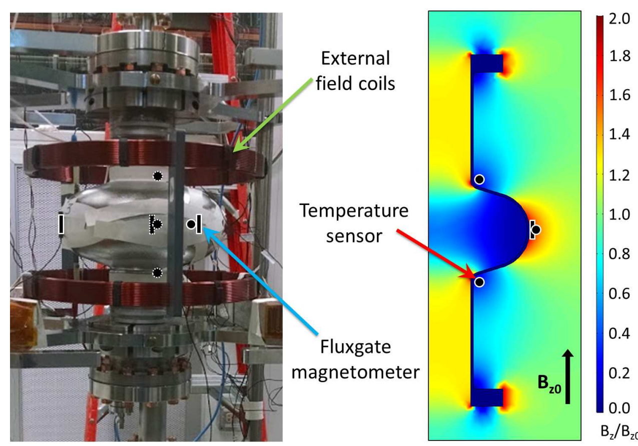

FIG. 1. Apparatus for measuring magnetic flux expulsion in a 1.3 GHz single cell SRF cavity (left), and simulation of axial field component resulting from the complete expulsion of an external field parallel to the cavity axis, normalized to the external field (right).

The arrangement for measuring flux expulsion in a single cell cavity is shown in Figure 1 (measurement technique from Ref. 7). Magnetic field coils are arranged around the cavity, and a current is applied to create a field of 10 mG at the surface. Fluxgate magnetometers are attached to the middle, oriented in the same direction as the applied field. Thermometers measure the temperature at the top and bottom of the cavity cell and the middle. During cooldown, as the temperature falls below the transition temperature T_c and the cavity goes from the normal conducting (NC) state to the superconducting (SC) state, a step change is observed in the magnetic field sensors. The magnitude of this change corresponds to the amount of flux expelled. If B_{ext} is fully trapped, the field measured above T_c, B_{NC}, is the same as the field measured below T_c, B_{SC} (B_{SC}/B_{NC}=1). When B_{ext} is completely expelled, calculations of the full Meissner expulsion show that the expected ratio of B_{SC}/B_{NC} should be 1.7 [13]. In this way, the measurement of B_{SC}/B_{NC} reveals what fraction of flux is trapped during cooldown instead of being expelled. The temperature difference between the top and bottom thermometer at T_c gives a measure of the spatial temperature gradient across the cavity. Typical measurements of flux expulsion are shown in Figure 2 [14].

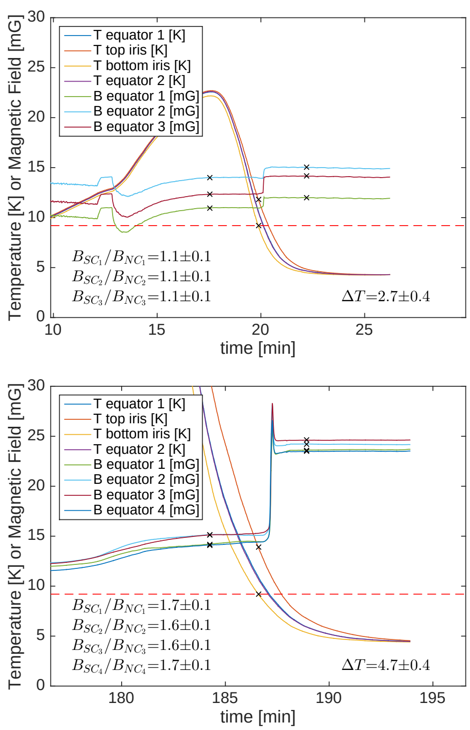

FIG. 2. Typical flux expulsion measurements. As the cavity passes through T_c during cooldown (dashed line), temperature and magnetic field are recorded (illustrated with 'x' symbols). Some cavity preparations can result in strong flux trapping behavior, showing B_{SC}/B_{NC} ratios close to 1 for modest ΔT (e.g. top) and others result in efficient flux expulsion, with ratios close to 1.7 under similar conditions (e.g. bottom).

Several single cell 1.3 GHz cavities were measured over several cooldown cycles to show the trend with spatial temperature gradient for a given cavity preparation. A total of 22 datasets were measured, each for a different treatment. Each dataset consists of many cooldowns to 7 K, varying ΔT [15]. A trend in the data quickly became apparent, as shown in Figure 3. Two production groups of cavities from the same vendor had consistently different trapping behavior: the cavities from production group 1 expelled well while those in production group 2 expelled poorly. For the cavities that expel flux well, ΔT as low as 2 K over the cavity cell are sufficient to expel the majority of the external field. For the cavities that expel poorly, the majority of the flux is trapped even for ΔT close to 10 K.

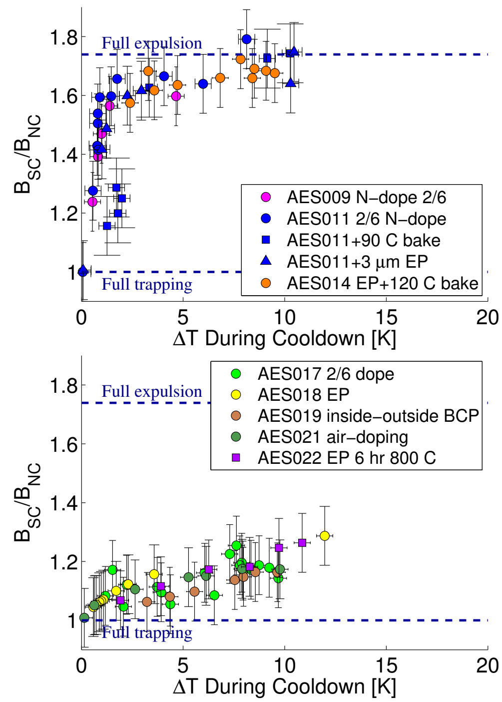

FIG. 3. Measured curves of flux expulsion as a function of temperature difference ΔT from bottom to top of the cavity cell as the cavity passes through T_c during cooldown. The cavities measured from production group 1 (AES007-AES016) showed strong expulsion behavior (top) while those from production group 2 (AES017-AES022) showed strong trapping (bottom).

The cavities in production group 1 were acquired earlier and had previously undergone several rounds of processing, and they showed another notable behavior. After a few cycles of ultra-high-vacuum (UHV) furnace treatment at 800°C for up to 3 hours, the cavities in this production group, which initially had grain size ∼100 µm, showed strong grain growth. This is shown in Figure 4.

Previous experiments on niobium samples studied the difference between fine grain and large grain material in fraction of flux trapped during cooldown [16, 17]. These studies were performed before it was recognized that it was important to control for thermal gradient, making it difficult to extract quantitative data, but qualitative

FIG. 4. Grain growth in AES011. The cavity was fabricated from material with ∼100 µm sized grains, some of which grew to the few mm-scale after only a few UHV furnace cycles at 800°C that were each 3 hours long or shorter.

trends were demonstrated. Material with larger grains appeared to have higher expulsion, suggesting that grain boundaries may act as pinning sites for flux, giving an advantage to cavities with fewer grain boundaries. This is consistent with the results in Figure 3, as well as with previous studies of high field pinning [11, 12]. However, even in single crystal niobium samples, heat treatment appeared to improve expulsion, suggesting that e.g. dislocation content plays an important role [16].

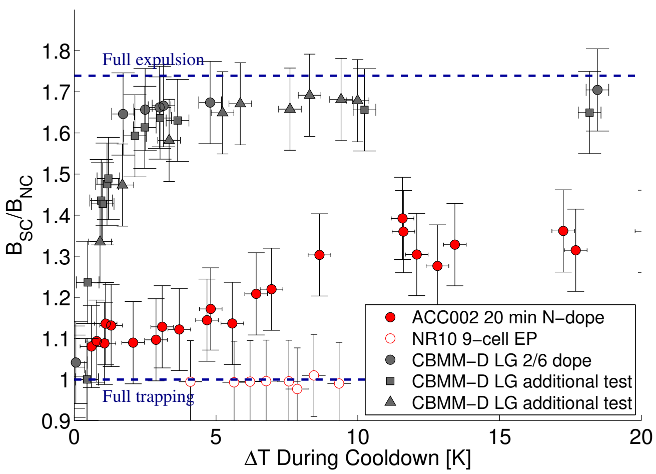

FIG. 5. Flux expulsion measurement in two 1.3 GHz fine grain cavities, single cell ACC002 and 9-cell NR010, and one large grain 1.3 GHz single cell, CBMM-D. It should be noted that CBMM-D received more furnace cycles than ACC002 or NR010.

Cavities from other production groups also show results consistent with this. Figure 5 shows two fine grain cavities that expel poorly and one large grain cavity that expels well. To confirm the effect of bulk characteristics such as grain size and dislocation content in flux trapping, one of the cavities from production group 2 was heated at 1000°C for 4 hours in a UHV furnace. The grain size was visibly increased and the expulsion improved substantially, as shown in Figure 6. This strongly supports the hypothesis that bulk properties determine flux expulsion behavior.

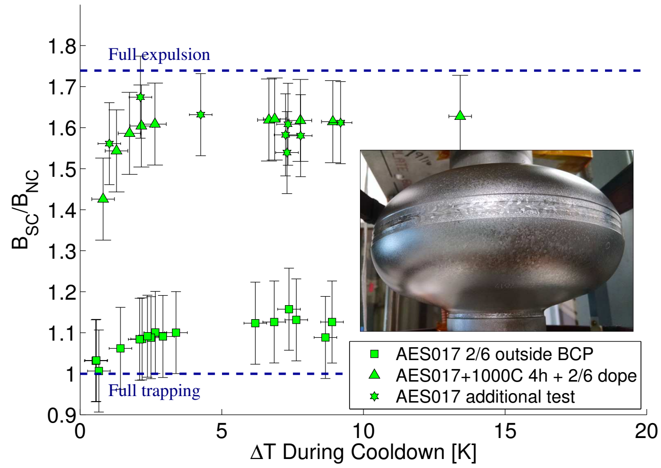

FIG. 6. AES017, a cavity from production group 2 that showed strong flux trapping behavior, was converted to expel strongly after a 1000°C 4 h furnace treatment. The inset image shows the grain growth after treatment.

The cavities measured in the survey had been treated with a wide variety of surface processing techniques. By comparing cavities from the same production group, with similar furnace treatment history but different surface processing, we can study the effect of the surface on flux expulsion. We can also study the effect of a given surface treatment by comparing flux expulsion on a single cavity before and after treatment. Figure 7 shows a number of such comparisons, such as electropolished (EP) surface vs buffered chemical polish (BCP) surface, N-doping with 2/6 recipe [1] vs EP, and as-treated outside surface vs outside BCP. In each case, the flux expulsion is nearly the same for cavities with similar bulk history regardless of surface conditions.

To show that flux expulsion significantly affects Q_0, RF measurements were performed on the cavity from Figure 6 before and after 1000°C furnace treatment. Each time, the cavity was cooled down in a 10 mG field with a modest ΔT of 2-4 K. The B_{SC}/B_{NC} ratio measured before heat treatment was 1.1, showing that most of the external flux was trapped, while the ratio measured after was 1.6, showing strong expulsion (these cooldowns are shown in Figure 2). Figure 8 shows the corresponding substantial improvement in Q_0 at 1.5 K and 2 K [18].

In this Letter, we have presented new results measuring expulsion of magnetic flux during cooldown through T_c in niobium SRF cavities. It was found that efficient flux expulsion is strongly influenced not only by spatial thermal gradient but also by treatment. Cavities that showed

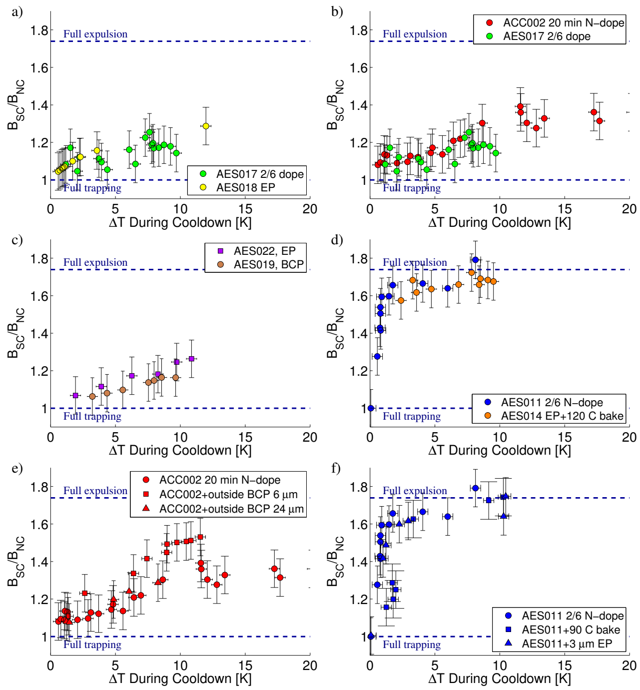

FIG. 7. Flux expulsion vs ΔT, comparing a variety of different surface treatments with similar bulk history. Each graph compares curves for 2 or 3 treatments that produce very different surfaces but show similar expulsion behavior: a) EP vs N-doped; b) 'light' N-dope (20 minutes in N at 800°C) vs 'heavy' N-dope (2 minutes in N at 800°C + 6 minute anneal); c) EP vs BCP; d) light doping + external BCP vs EP + 120°C bake; e) effect of light and heavy BCP of external surface f) effect of 90°C bake and additional EP.

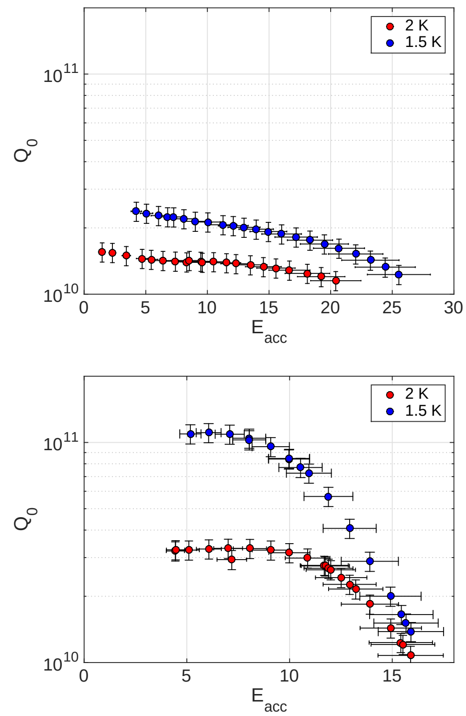

FIG. 8. Q_0 vs accelerating gradient E_{acc} for AES017 after cooldown in a 10 mG field with a modest ΔT ~2-4 K. Before 1000°C heat treatment (top), the cavity traps most of the flux and resulting in a low field Q_0 at 1.5 K of $\sim 2 \times 10^{10}$. After the heat treatment to improve flux expulsion (bottom), this value improves to $\sim 1 \times 10^{11}$.

signs of modified bulk structure after high temperature furnace treatment exhibited significantly stronger flux expulsion as a function of temperature than those that did not. The surface preparation showed no significant effect. Using these results, a procedure was designed that was shown to substantially improve flux expulsion behavior by UHV furnace treatment at 1000 C for 4 h. A 1.3 GHz cavity was evaluated before and after this procedure by cooling in a field ~10 mG with a modest temperature gradient ~2-4 K. After 1000 C treatment, RF measurements showed that Q_0 at 1.5 K improved by a factor of ~5. Future studies will focus on determining what specific properties determine expulsion behavior—e.g. grain boundary density or dislocation content—and optimizing treatment for improving flux expulsion without compromising mechanical properties. For example, if grain boundary density is important to expulsion behavior, future cavities could be manufactured from material with larger grain size, or cavities could be given an optimized furnace treatment after manufacture to ensure that high Q_0 can be maintained in a cryomodule environment with a realistic background magnetic field. The experimental results presented here may be useful in other applications where magnetic field isolation is important, such as in quantum computing.

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* sposen@fnal.gov

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[14] Sources of measurement uncertainty in ΔT include thermal impedance between cavity and thermometer, assumed to result in overall uncertainty of 0.4 K. Sources of measurement uncertainty in B_{SC}/B_{NC} include radial background fields and misalignment of fluxgate probe, assumed to result in overall uncertainty of 0.1.

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

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk

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APPLIED PHYSICS LETTERS **105**, 234103 (2014)

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

A. Romanenko,[a)] A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

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Ambient magnetic field, if trapped in the penetration depth, leads to the residual resistance and therefore sets the limit for the achievable quality factors in superconducting niobium resonators for particle accelerators. Here, we show that a complete expulsion of the magnetic flux can be performed and leads to: (1) record quality factors $Q > 2 \times 10^{11}$ up to accelerating gradient of 22 MV/m; (2) $Q \sim 3 \times 10^{10}$ at 2 K and 16 MV/m in up to 190 mG magnetic fields. This is achieved by large thermal gradients at the normal/superconducting phase front during the cooldown. Our findings open up a way to ultra-high quality factors at low temperatures and show an alternative to the sophisticated magnetic shielding implemented in modern superconducting accelerators. [http://dx.doi.org/10.1063/1.4903808]

The microwave surface resistance R_s of superconducting radio frequency (SRF) cavities can be represented as a sum of the strongly temperature dependent $R_{BCS}(T)$ caused by thermally excited quasiparticles,[1] and a temperature independent residual resistance R_{res}. Trapped magnetic flux increases R_s by contributing to R_{res}, and the contribution is thought to come from the normal conducting cores of the trapped fluxoids.[2] Since $R_{BCS}(T) \propto \exp\{-\Delta/kT\}$—where Δ is the superconducting gap—is exponentially vanishing at lower temperatures, the minimum achievable value of R_s remains limited by R_{res}, thereby setting the limit on the achievable quality factor $Q \propto 1/R_s$. For fine grain ($\sim$50 μm) size niobium used to manufacture the majority of SRF cavities, the previous understanding was that close to 100% of the ambient magnetic field gets trapped during the transition to superconducting state. Magnetic shielding to lower the magnetic field amplitude at cavity walls was considered the only option to avoid the increased R_{res} and increased wall dissipation, and has therefore been implemented as the essential part of all SRF accelerators.

It was discovered at Helmholtz Zentrum Berlin (HZB) that the residual resistance of niobium cavities can be affected by the cooling dynamics during normal/superconducting transition,[3,4] which takes place for niobium at the critical temperature $T_c = 9.25$ K.

The cavity used for HZB studies was dressed—meaning that it had titanium vessel welded around it, which gets filled with liquid helium in order to cool the cavity down to temperatures of 2 K or below (see Fig. 1 in Ref. 4 for a schematic). This is a typical cooling design for cavities in accelerators, whereas bare cavities without titanium vessels are typically submerged in liquid helium in a vertical test cryostat for measurements. Based on the readings of the temperature sensors on the beam tubes outside of titanium vessel, the effect found at HZB was attributed to the additional magnetic field generated by thermal currents, which gets trapped during the cooldown through T_c. Such thermal currents in the thermocouple loop created by the cavity and titanium vessel are generated if the temperatures at the niobium-titanium junctions on both sides are different. Theoretical analysis showed[5] that broken current flow symmetry is required in order for this contribution to be non-negligible.

A different physical mechanism was subsequently discovered at Fermilab[6] by mounting the fluxgate magnetometers and temperature sensors directly on the walls of both bare and dressed cavities. The residual resistance was demonstrated to be tracking the changes in the trapped fraction of the ambient magnetic field, and the better expulsion/lower R_{res} to correspond to the larger temperature gradients at the normal/superconducting transition front during the cooling through T_c. This new effect suggested that much higher fields than previously thought could, in principle, be expelled using high enough thermal gradients at T_c.

In this paper, we report the discoveries of: (1) full flux expulsion leading to record Q values of $>2 \times 10^{11}$ up to accelerating gradient $E_{acc} = 22$ MV/m; (2) almost complete flux expulsion leading to $Q \sim 3 \times 10^{10}$ at 2 K and $E_{acc} = 16$ MV/m even in high magnetic fields of $B \leq 190$ mG attainable with little or no magnetic shielding. Detailed temperature and magnetic field measurements show that the determining parameter is the temperature gradient dT/dx at the normal/superconducting phase front and reveal its threshold values required for efficient flux expulsion of about 0.1–0.2 K/cm.

We used a 1.3 GHz single cell TESLA shaped cavity for our studies, which was prepared by nitrogen doping.[7] Among the cavity preparation procedures, nitrogen doped cavities possess highest quality factors and are the most sensitive to the trapped flux, thus making them the ideal tool to study the flux expulsion. All the measurements were performed at Fermilab vertical testing facility, which has magnetic shielding with the ambient fields typically reduced down to <5 mG values.

In order to control the magnetic field, Helmholtz coils were assembled around the cavity. Three single-axis

[a)]E-mail: aroman@fnal.gov

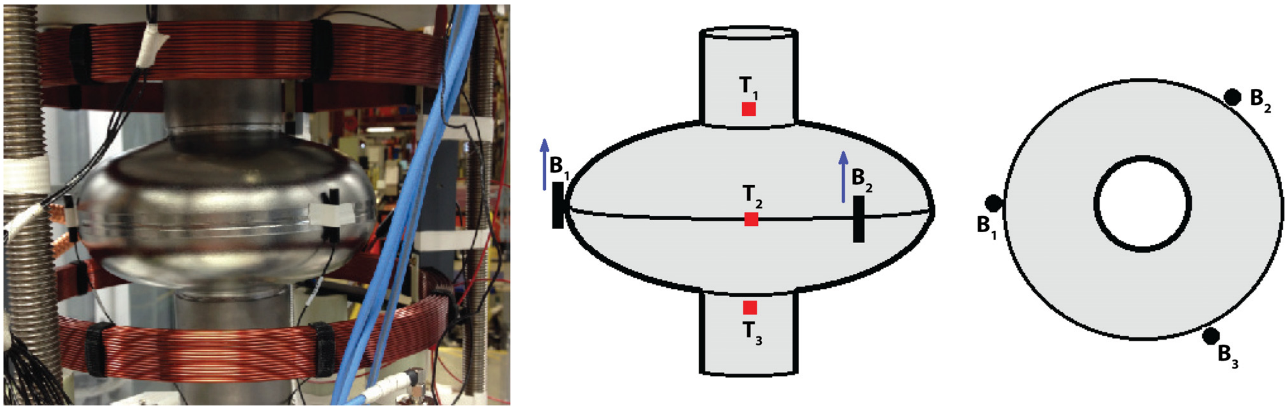

FIG. 1. Picture of the setup and schematic of the magnetic and temperature probes mounting used for the measurements.

Bartington Mag-01H cryogenic fluxgate magnetometers were mounted around the equator with $\sim 120^\circ$ spacing to measure the magnetic field along the cavity axis (vertical) direction. Transverse components of the Earth magnetic field are also present in the test cryostat, but they are lower than the vertical one due to the geometry of the magnetic shield (vertical cylinder) and are not varied by the Helmholtz coils. Three Cernox temperature sensors were mounted as follows: one at the top iris, one at the equator, and one at the bottom iris. The picture of the setup and the schematic of the probe mounting are shown in Fig. 1. We define $B_{avg} = (B_1 + B_2 + B_3)/3$.

The cooldowns were performed under different ambient magnetic fields ranging between 2 mG and 190 mG and from different starting temperatures ranging from 300 K to 12 K. The cavity quality factor Q was measured as a function of the accelerating gradient E_{acc} at 2 K and—for most of the measurements—at the lowest achievable temperature of 1.5 K.

First set of results is shown in Fig. 2 with Q of the cavity reaching above 2×10^{11} up to the accelerating field of 22 MV/m for three different cooldowns in three different $B_{avg} = 2$ mG; 10 mG; and 23 mG. We select 4 MV/m and 16 MV/m as representative gradients to compare with the previous literature data and to provide direct information for medium gradient accelerators such as LCLS-II. No degradation in Q with increasing ambient magnetic fields suggests that the fields are fully expelled. Furthermore, it shows that full expulsion can be achieved by cooling from different starting temperatures.

The second result, which was obtained after cooling from 300~K in $B_{avg} = 190$ mG, is shown in Fig. 3. Despite the very high magnetic field, which is within a factor of two from the Earth's magnetic field, the measured $Q = 2.9 \times 10^{10}$ at 2 K and 16 MV/m is still high enough to satisfy the requirements of the LCLS-II project ($Q = 2.7 \times 10^{10}$ at 16 MV/m), which has the highest Q specification out of all SRF-based accelerators ever proposed or built.

In order to pinpoint the required thermal conditions for efficient flux expulsion, we have fixed the ambient field to 10 mG and varied temperature distribution along the cavity during cooling cycles by changing the starting temperature and helium flow rate. Obtained values of R_{res} were calculated from measured Q at 1.5 K using $R_{res} = G/Q$, where $G = 270$ is the cavity geometry factor. The results are shown in Fig. 4 (and Q values in the inset) as a function of temperature difference between the top iris (T_1) and equator (T_2), and in Fig. 5 as a function of the cooling rate $dT_2/dt|_{T_2=T_c}$. As it can be clearly seen, temperature difference at the phase front is the main factor for flux expulsion, while cooling rate

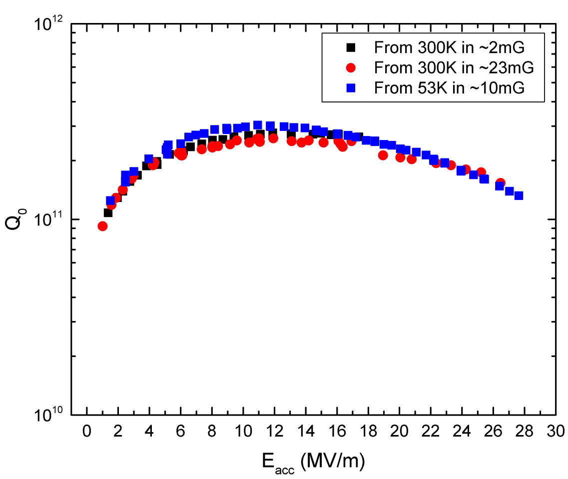

FIG. 2. $Q(E_{acc})$ curves at $T_1 = T_2 = T_3 = 2$ K for three different cooldowns in different B_{avg}.

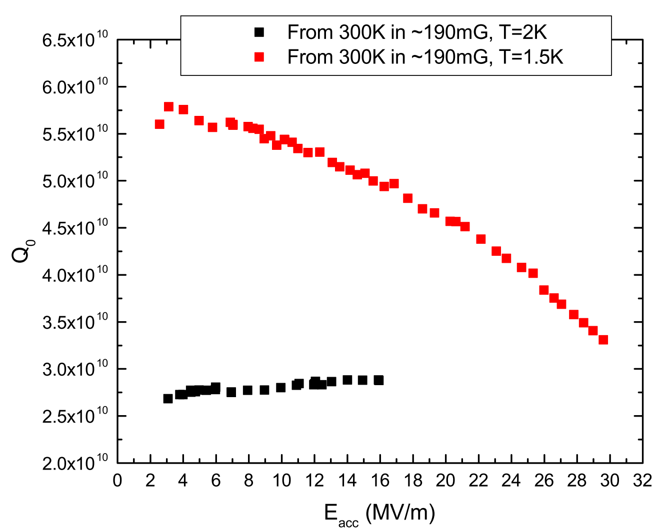

FIG. 3. $Q(E_{acc})$ curves at $T_1 = T_2 = T_3 = 2$ K (black) and $T_1 = T_2 = T_3 = 1.5$ K (red) measured after cooldown from 300 K in $B_{avg} \approx 190$ mG.

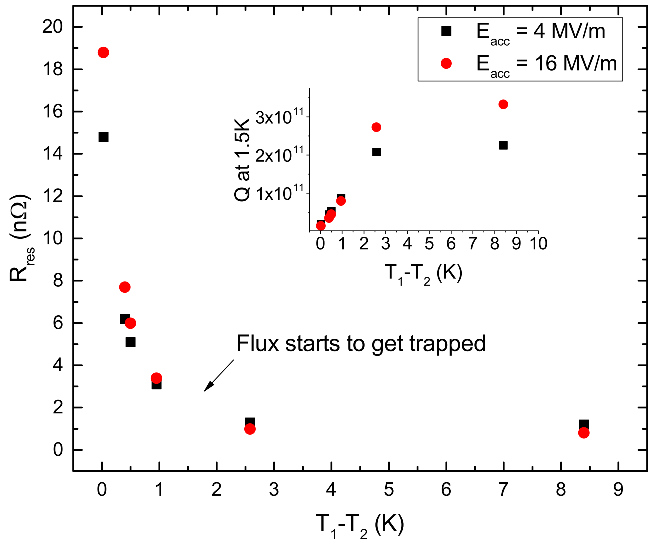

FIG. 4. Residual resistance at 1.5 K as a function of the temperature gradient present at the normal/superconducting front as measured when equator reaches T_c. Inset shows the corresponding Q values.

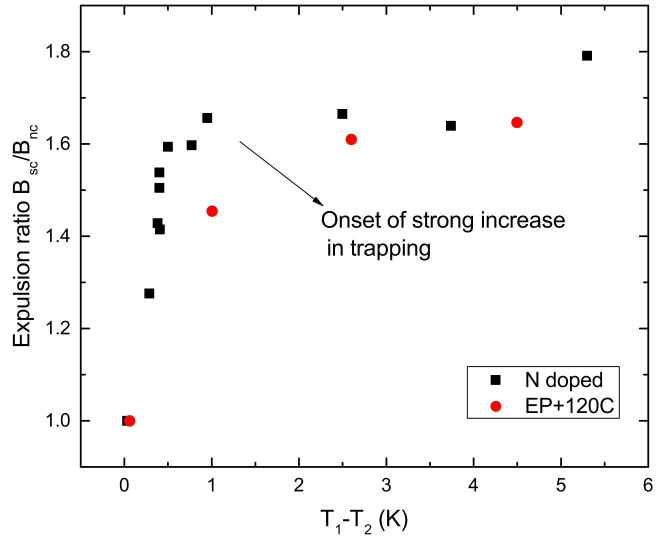

FIG. 6. Ratio of the magnetic field at the equator in superconducting state (B_{sc}) to that in the normal state (B_{nc}).

itself has no clear effect. This finding is consistent with one of our proposed interpretations in Ref. 6 and may also be related to the thermal depinning work of Huebener and Seher.[8]

In our previous work,[6] we have shown via magnetostatic simulations that if the magnetic flux is fully expelled, the vertical component of the magnetic field at the equator should be increased by close to a factor of 1.8. Therefore, a ratio of the flux magnetometer readings before and right after the transition provides a measure of the amount of the flux expelled. In Fig. 6, a summary plot for all the cooling procedures in various magnetic fields is shown. Fast increase in the trapped fraction (decrease in the expulsion ratio) is clearly observed as soon as the temperature difference across the top half-cell drops below ∼1–2 K, which corresponds to the gradient of 0.1–0.2 K/cm along the cavity surface. This increase in trapping causes the increase in R_{res} shown in Fig. 5.

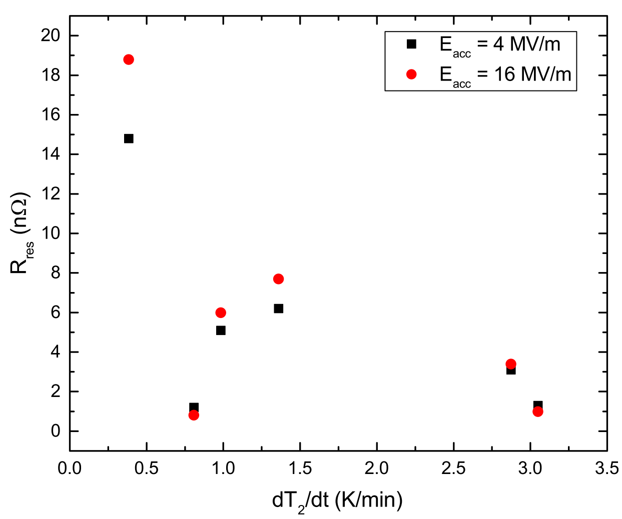

FIG. 5. Residual resistance at 1.5 K as a function of the cooling rate measured when equator reaches T_c.

An identical TESLA shape cavity but prepared by electropolishing/120 °C baking was measured in some cooldowns as well and exhibited a very similar qualitative behavior (red circles in Fig. 6). This suggests that the expulsion efficiency is not determined by surface pinning properties, as 120 °C baked cavities have a drastically lower electron mean free path ℓ at the surface (and therefore different pinning strength).[9]

In this paper, we have shown that optimized Meissner expulsion procedure allows to completely eliminate the magnetic flux contribution and results in ultralow residual resistances even in high magnetic fields of up to 190 mG. If coupled with the ultralow BCS and non-flux residual resistance achieved via nitrogen doping, record quality factors of $>2 \times 10^{11}$ emerge up to high fields. As one of the immediate practical implications, a variety of large-scale SRF-based projects, i.e., LCLS-II at SLAC and PIP-II at FNAL, can have a significantly lower operational power even with poor magnetic shielding.

The implications also extend to any other superconducting devices involving trapped flux, where changing the temperature gradient during the transition through T_c can allow to tune the trapped flux amount for the fixed applied magnetic field.

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

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

A. Romanenko,[a] A. Grassellino,[b] O. Melnychuk, and D. A. Sergatskov
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

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We report a strong effect of the cooling dynamics through T_c on the amount of trapped external magnetic flux in superconducting niobium cavities. The effect is similar for fine grain and single crystal niobium and all surface treatments including electropolishing with and without 120 °C baking and nitrogen doping. Direct magnetic field measurements on the cavity walls show that the effect stems from changes in the flux trapping efficiency: slow cooling leads to almost complete flux trapping and higher residual resistance, while fast cooling leads to the much more efficient flux expulsion and lower residual resistance.
[http://dx.doi.org/10.1063/1.4875655]

I. INTRODUCTION

Trapped magnetic flux represents one of the known contributors to the residual resistance R_{res} of superconducting radio frequency (SRF) niobium cavities.[1] Experiments showed that R_{res} due to trapped flux also increases with the magnitude of the RF field on the cavity surface[2] and can therefore have a significantly negative impact on the intrinsic cavity quality factor Q_0 at medium accelerating fields.

For this reason, minimization of trapped flux in niobium cavities has recently been a topic of particular interest, especially in light of its potential impact on cryogenic costs of high duty factor accelerators, i.e., Linac Coherent Lights Source upgrade at SLAC National Accelerator Laboratory (LCLS-II), Energy Recovery Linacs, and a potential upgrade of the European X-ray Free Electron Laser (XFEL). Studies at Helmholtz-Zentrum Berlin (HZB) showed that the details of the cooling procedure affect the amount of trapped flux and thus its associated additional residual surface resistance.[3,4] Based on the possible interpretation of the results, two main mechanisms of improvement of cavity performance (due to reduction of the amount of trapped magnetic flux) have been suggested: (1) slow cooling through transition temperature;[3,4] (2) reduction of thermocurrents, which are enabled by bimetal titanium-niobium junctions in dressed cavities, by minimizing temperature gradients.[4] Following HZB results, Cornell has also recommended a slow cooldown procedure based on the interpretation of their horizontal test results.[5] However, the physical mechanism of the effect has not been clearly established.

To illuminate the mechanism, it is very important to understand if the effect is specific to dressed cavities, or if it is a generic effect present also in bare niobium cavities. Furthermore, the effect of different surface treatments has to be understood as well. To do so, it is crucial to perform direct magnetic field measurements on the cavity in the cryostat to correspond with the RF measurements, which is the key component of our work.

In this paper, we present a set of systematic vertical test stand measurements on *bare* single and nine cell 1.3 GHz TESLA elliptical shape SRF cavities made of fine grain ($\sim$50 μm) and single crystal RRR $\sim$300 niobium, which reveal a strong effect of cooling protocol through T_c on the residual resistance: a slow cooling leads to higher residual resistance than the fast cooling. Meissner effect measurements directly on cavity walls show that the increase in the residual resistance is due to the smaller flux expulsion (larger flux trapping) at slow cooling rates, which provides an alternative explanation for the findings in Ref. 4.

II. EXPERIMENTAL PROCEDURE

We have performed all our measurements at the vertical test stand at Fermilab. Temperature during the experiments was continuously monitored at several locations in the cryostat by four Cernox thermometers attached to the outside cavity walls. RF measurements were performed using the standard phase-lock technique in the temperature range between 2 K and 1.5 K. Surface resistance R_s measured at the lowest temperature $T \sim 1.5$ K was very close to the residual resistance R_{res} as was reconfirmed by the explicit deconvolution following our original procedure.[6] Thus, in what follows, we use terms R_{res} and $R_s(T \leq 1.5\ \text{K})$ interchangeably.

In order to prevent the possible occurrence of thermal currents, we used additional measures to improve the electrical insulation of cavities from the supporting fixtures, e.g., kapton tape between the cavity and stainless steel holding fixtures or G10 holding fixtures instead of metal. Thus, our work is not designed to address the effect of thermal currents but rather any intrinsic effects of the cooling dynamics itself.

Typical fast and slow cooling procedures we used are shown in Fig. 1. In the case of the fast cooling, various temperature differences up to 200 K can be present across the cavity (maximum depends on the starting temperature), and cooling rates through T_c are of the order of 30–40 mK/s. Slow

[a]Electronic mail: aroman@fnal.gov
[b]Electronic mail: annag@fnal.gov

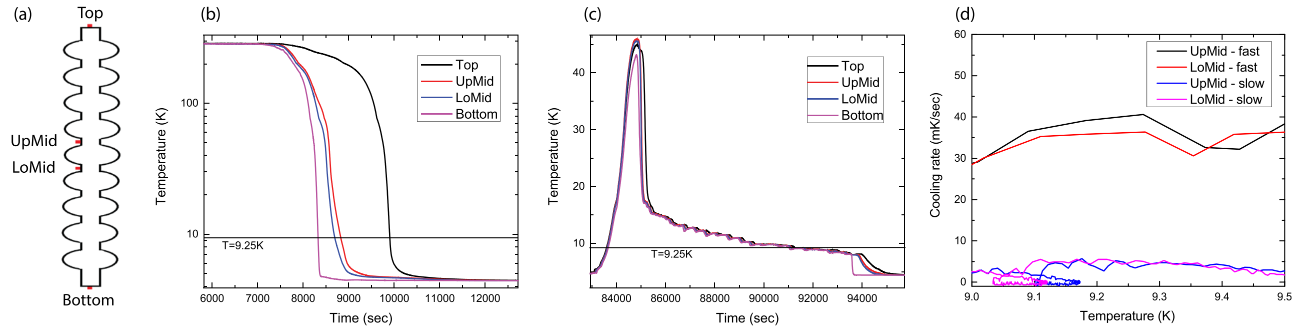

FIG. 1. Example of (a) temperature sensors positions and readings for: (b) fast and (c) slow cooling procedures corresponding to one of the nine cell tests; (d) corresponding cooling rates around T_c for UpMid and LoMid sensors.

cooling is very uniform with temperature differences on the order of 0.1 K and cooling rate through T_c of 2–5 mK/s.

For magnetic field measurements, we used Bartington cryogenic Mag-01H single-axis fluxgate magnetometers attached to the outside cavity walls. Similar approach was originally implemented in Ref. 2 but using Hall probes. Fluxgate magnetometers were mounted in the vertical orientation to measure the magnetic field component parallel to the vertical symmetry axis of the cryostat unless specified otherwise in the text. An example of the magnetic probe placement on a 1-cell cavity is shown in Fig. 2(a). Depending on the flux trapping efficiency, the transition to the Meissner state should lead to the expulsion of the magnetic flux from cavity walls and thus to an increase in the magnetic field amplitude measured right outside. If some of the flux remains trapped, the expulsion is smaller and the field outside changes less. COMSOL simulations assuming remnant field of $B = 5$ mG in the axial direction are shown in Figs. 2(b) and 2(c) and demonstrate that for the case of no trapping the magnetic field at the equator should be enhanced by about a factor of 2 when cavity is fully superconducting. Magnetic field measurements were taken upon both cool-down and warm-up through T_c, providing full information regarding the magnetic field environment and the efficiency of flux expulsion.

III. RESULTS

We have investigated cavities prepared by different state-of-the-art processing methods as described below.

A. Electropolishing (EP) without 120 °C baking

In this experiment, we used fine and single crystal 1-cell cavities after bulk electropolishing with about 120 μm of material removed. Cavities were mounted on the same test stand and magnetic probes were mounted on the equator of each cavity. Initial fast cooling from 300 K was followed by two cycles of warm-up to 11 K and slow cooling back to 4.2 K, warm-up to 20 K and a fast cooling to 4.2 K, and finally a warm-up and slow cooling from 11 K down to 4.2 K. Each of the cool-downs was followed by a full RF test.

Residual resistance R_{res} of the single crystal cavity as a function of E_{acc} measured at $T < 1.5$ K is shown in Fig. 3(a). The value of R_{res} was clearly and reprodicibly dependent upon if the fast or slow cool-down had been performed. In particular, fast cool-downs from 300 K to 20 K (black squares and blue triangles) lead to similar R_{res} about 2 nΩ *lower* than that after all slow cool-downs from 11 K (red circles, green triangles, and magenta diamonds). The value of the strongly temperature dependent BCS surface resistance remained approximately the same for all the RF tests.

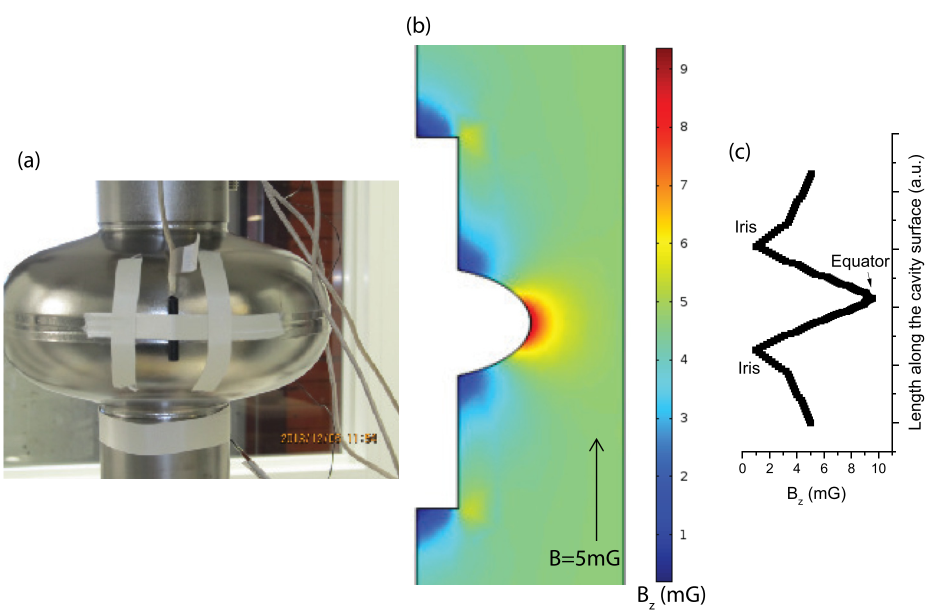

FIG. 2. (a) Fluxgate magnetometer placement at the 1-cell cavity equator; (b) simulated distribution of the magnetic field after field cooling in the remnant field of 5 mG in vertical direction; and (c) magnetic field amplitude over the cavity surface.

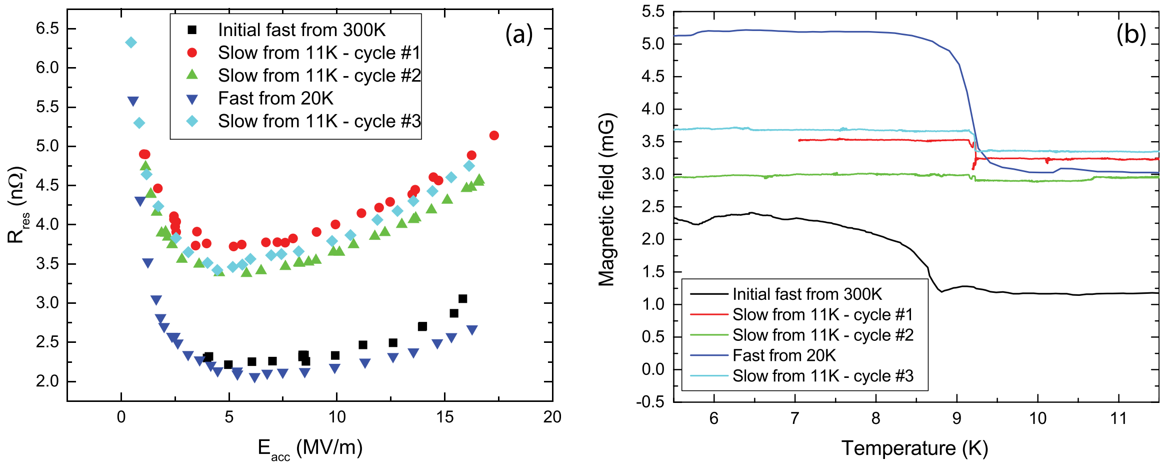

FIG. 3. (a) Residual resistance of the single crystal 1-cell electropolished cavity after different cooling cycles and (b) corresponding magnetic field data at the equator during cool-down.

The magnetic probe readings around T_c are shown in Fig. 3(b). The magnitude of the ambient field at transition was similar for fast and slow cool-downs confirming no impact of thermal currents. In all cases, it was possible to observe a jump at $T_c = 9.25$ K, which signals the transition into Meissner state and represents the flux expulsion from the cavity walls [see Fig. 2]. The primary difference found was that fast cooling leads to a significant increase in the magnetic field right outside of the cavity walls, while slow cooling leads to a much smaller change. This indicates that slow cool-down procedure seems to prevent flux from being expelled, leading to almost complete flux trapping, while a fast cool-down through T_c helps pushing efficiently the flux out of the superconductor. Higher amount of trapped flux correlated strongly with the observed higher residual resistance values for slow cooling.

Exactly, similar RF behavior was observed for the fine grain cavity with R_{res} (E_{acc}) curves shown in Fig. 4. The magnetic field probe readings were also fully similar to those shown in Fig. 3(b).

B. Nitrogen doping

We used 9-cell and 1-cell cavities prepared by the nitrogen doping procedure[7] with the previously measured "anti Q slope" performance after regular fast cooling.

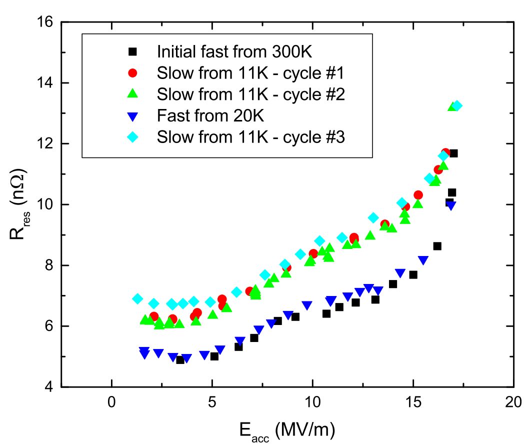

FIG. 4. (a) Residual resistance of the fine grain 1-cell electropolished cavity after fast and slow cooling cycles.

No magnetic sensors were mounted in the 9-cell cavity experiment and only RF measurements were performed. We sequentially investigated fast and slow cooling procedures with the drastically different cooling rates and thermal gradients across the cavity described above with the results of the $Q_0(E_{acc})$ measurements at $T = 2$ K shown in Fig. 5(a).

A strong decrease in Q_0 was found in the case of the slow cooling procedure versus the fast. As in the case of EP, $Q_0(T)$ measurements at different E_{acc} revealed that the change in Q_0 arose from the increase in residual resistance as shown in Fig. 5(b), while the BCS component remained unchanged. The low field residual resistance increased by about 8 nΩ, and a stronger field dependence appeared, which led to a total increase of $\gtrsim$10 nΩ in residual resistance at medium fields.

In detail, the sequence of the tests was the following. The first RF test was performed after a typical fast cool-down from 300 K to 4.2 K. Second test followed a warm up to 20 K and slow cooldown through transition temperature similar to that in Fig. 1(c). This resulted in a large residual resistance as shown in Fig. 5(b) and a mediocre Q_0 vs. E_{acc} performance as illustrated in Fig. 5(a). The cavity was then warmed up to 300 K and cooled down fast, similar to the cycle shown in Fig. 1(b). As a result, the performance recovered reaching a residual resistance of $\sim$4 nΩ and a $Q_0 \sim 3 \times 10^{10}$ at medium fields at 2 K. The cavity was then warmed up to 100 K and held at 100 K for 8 h to rule out the potential presence of hydrogen and Q-disease. From 100 K, the cavity was then cooled down rapidly through T_c. This resulted again in the good performance similar to the one after previous fast cool-down from 300 K. Cavity was then again warmed up to 20 K and the slow cool-down procedure was repeated, yielding again identical poor performance as in the previous slow cool-down.

Next, we studied the performance of a 1-cell nitrogen doped cavity with the 2 K results of $Q_0(E_{acc})$ shown in Fig. 6(a). Similar to the 9-cell cavity, slow cooling led to a significantly lower Q_0, again due to an increase in the residual resistance as was confirmed by lower temperature measurements.

Magnetic field probes mounted on the cavity equator showed that ambient field at T_c was unaffected by the speed

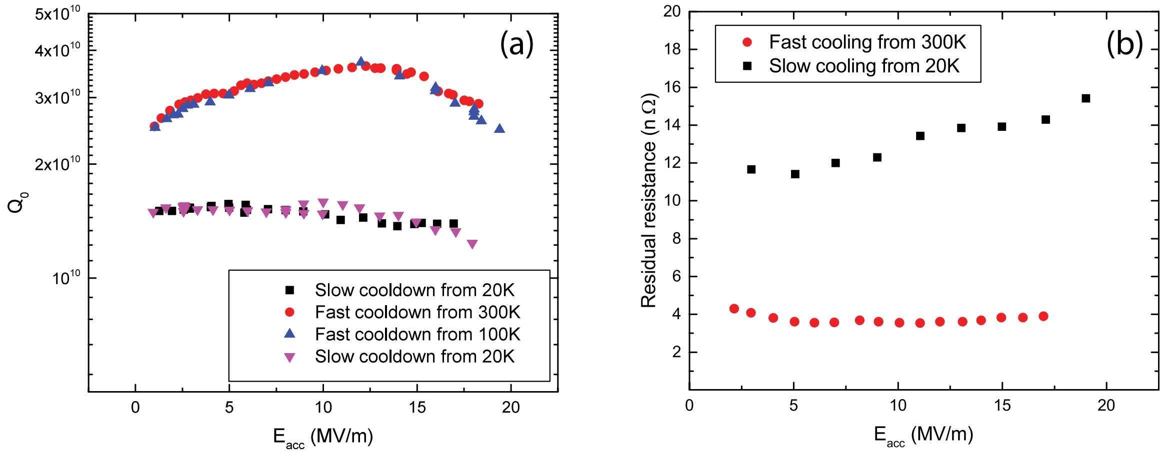

FIG. 5. (a) $Q_0(E_{acc})$ curves at 2 K for different cooling speeds measured on the 9-cell nitrogen doped cavity and (b) residual resistance for fast and slow cooling rates.

of the cool-down, but the drastic difference in the trapping efficiency between the slow and fast cooling was again observed—see Fig. 6(b), where the warm-up data are shown for clarity. Also in this case, the higher amount of trapped flux correlated well with the increase in R_{res} after slow cooling.

Notice that the increase in R_{res} for the 9-cell cavity is significantly higher than that for the 1-cell cavity. However, it may be simply a manifestation of the higher average magnetic fields sampled by the 9-cell in dewar with multiple potentially magnetic components. Indeed, later investigations showed that some of the holding fixtures possessed higher magnetic moments and could have led to the observed difference.

The magnitude of the R_{res} increase was nevertheless higher for nitrogen doped cavities as compared with the EP case. We will further discuss this point below.

C. Electropolishing followed by 120 °C baking

In these experiments, we investigated 9-cell and 1-cell cavities prepared by the standard ILC recipe, which consists of EP 120 μm + 800 °C baking for 3 h + EP 20 μm + 120 °C baking for 48 h.

The RF performance of the 9-cell was consistent with the previous findings, as shown in Fig. 7(a): fast cool-down led at 2 K and medium fields to $Q_0 \sim 1.5 \times 10^{10}$, and slow to a lower $Q_0 \sim 1.2 \times 10^{10}$, again due to the residual resistance change. The same behavior was observed for the 1-cell cavity, for which the R_{res} (E_{acc}) is shown in Fig. 8(a) after fast cooling from 20 K and after a slow cooling from 11 K. The additional residual resistance of about 1–2 nΩ emerged after a slow cooling.

Magnetic probes were mounted on the equator of the second cell from the top for the 9-cell test. The magnetic field (~3.5 mG) recorded by the probes [see Fig. 7(b)] right before transition was the same for both slow and fast cooling, while the suppression of the flux expulsion by slow cooling was again the only apparent difference correlating with the change in Q_0 of the cavity. Similar behavior was registered also by the magnetic probe placed on the equator of the 1-cell during the corresponding test as shown in Fig. 8(b), which was again correlating with the observed change in R_{res} of the cavity. These data reconfirm that the mechanism behind the increase in residual resistance with slow cooling is lack of flux expulsion in contrast to strong and efficient flux expulsion obtained with fast cooling.

Compared to the nitrogen doped and electropolished cavities, the effect on the residual resistance is smallest in the 120 °C bake case, which will be further discussed below.

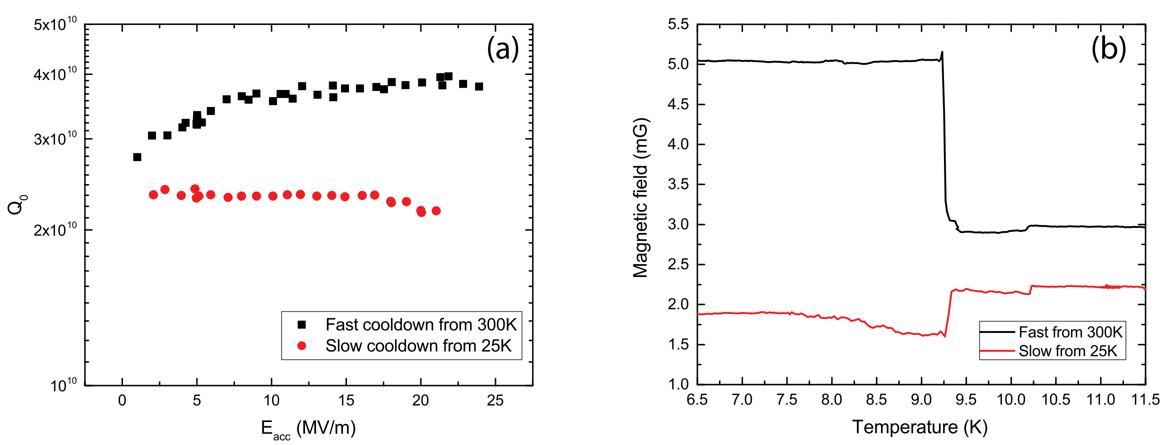

FIG. 6. (a) $Q_0(E_{acc})$ curves at 2 K for different cooling rates measured on the 1-cell nitrogen doped cavity and (b) corresponding magnetic field measurements around T_c (warm-up).

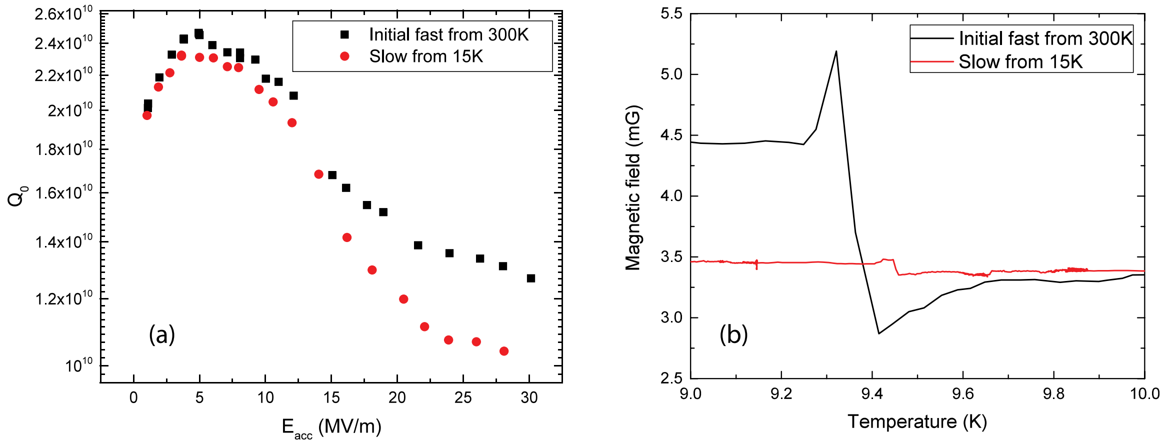

FIG. 7. (a) $Q_0(E_{acc})$ curves at 2 K measured on the 9-cell cavity treated by the EP + 120 °C baking process for fast and slow cooling procedures and (b) magnetic field at the equator recorded during cooling.

D. Effect of starting temperature on fast cooldown

While cavity results above shown the same efficient flux expulsion upon fast cooling from 300, 100, and 20 K, it is important to understand if there exists a minimal starting temperature $T > T_c$, which is required to maintain this efficiency.

To address this, we used another 9-cell nitrogen doped cavity and varied starting temperature of the cavity (and hence maximum temperature gradients) followed by multiple fast coolings through T_c recording the magnetic fields only (no RF test). In this experiment, the ambient magnetic field at the probe location was also slightly higher (∼12 mG). We found that the efficiency of flux expulsion was similar for starting temperatures of 300, 50, 35, 15, and 11 K—see Fig. 9, for example, of the magnetic field data taken during the warm-up. Temperature recording was interrupted during warm-ups after 15 K and 11 K cooling cycles but magnetic field recordings still showed the same jump at transition. This experiment suggests that cooling rate through T_c is what matters the most for an efficient expulsion rather than a starting temperature.

IV. DISCUSSION

In our experiments, flux magnetometers placed directly on cavity walls clearly showed that while the ambient field on the cavity surface was unaffected, the resulting residual resistance was strongly dependent upon the speed of the cool-down. Change in the field outside of the cavity allowed us to conclude that slow (≲2–5 mK/s) cooling through T_c leads to a much stronger external flux trapping in SRF niobium cavities than fast (≳30 mK/s) cooling, which allows for much more efficient flux expulsion. This effect appears to be universal and independent on the surface treatment and grain size.

However, the same amount of trapped flux translated differently into RF losses for different surface treatments. This difference can be qualitatively understood based on the simplified model of the vortex dissipation P_{diss} under applied RF field, in which P_{diss} is proportional to the normal core surface area $A \propto \xi^2$ and the normal state resistivity ρ_n. Since both the coherence length ξ and ρ_n depend on the electron mean free path ℓ so does the P_{diss}. It has been measured that $\ell \sim 2$ nm at the surface of a 120 °C baked cavity, $\ell \sim 40$ nm for nitrogen doped cavities,[8,9] and $\ell \leq 100$ nm for unbaked EP cavities, hence the possible difference.

Cooling down a cavity is a complicated process and it is quite possible that the cooling rate is not an explicit parameter that determines amount of the trapped flux, but rather the parameter that determines a type of the cooling process

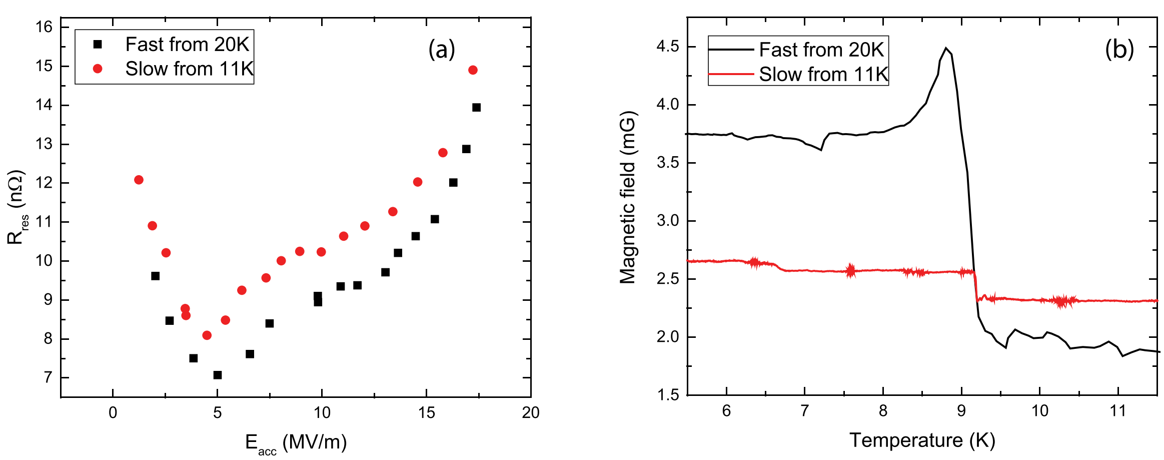

FIG. 8. (a) Residual resistance of the fine grain 1-cell EP + 120 °C baked cavity after fast and slow cooling cycles and (b) corresponding magnetic field data at the equator (cool-down).

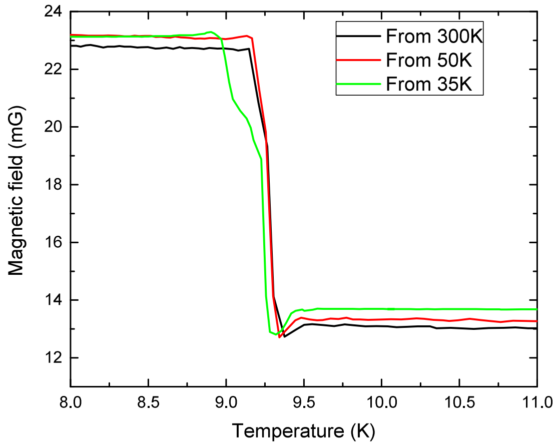

FIG. 9. Trapped flux in the 9-cell nitrogen doped cavity after fast cooling from different starting temperatures.

which, in turn, changes the amount of flux trapped in the cavity. Changing the cooling rate would also change a few other parameters, most importantly evolution of the temperature distribution around the cavity.

Nevertheless, based on our results, the cooling through T_c has to be fast in order to avoid the increase of the residual resistance due to trapped flux. Recent heat load measurements[10] in a cryomodule populated with 120 °C baked large grain 1.3 GHz dressed cavities seem to agree with these findings: the original fast cool-down led to a high Q_0 (low heat load), then a slow cool-down through transition led to significantly larger heat loads (lower Q_0), and finally the low heat load (high Q_0) was recovered after warming up above and fast cooling back down through T_c.

It should be emphasized that our findings do not contradict and may actually provide an alternative explanation/interpretation for the measurements on dressed cavities presented in Ref. 4. Indeed, in the HZB study, the original cooling, which led to the largest residual resistance, was by far the longest (18 h) corresponding to the slowest rate of transition through T_c. Thus, the magnetic flux expulsion should have been the least efficient, hence the increase in residual resistance. Corroborating this alternative interpretation of the experimental data is the fact that multiple vertical tests of dressed cavities performed at DESY[11] showed no difference in the quality factors between bare and dressed cavities.

Other important experiments at Cornell University[5,12] showed that the residual resistance of the dressed cavity in the horizontal cryostat can be decreased by warming above T_c and slowly cooling back down, however the comparison is made with respect to the original cool-down, which is slow as well. Nevertheless, lack of increase in the surface resistance after fastest possible cooling from 100 K clearly suggests that the role of thermal gradients in those experiments is secondary (if any) and the same trapping efficiency dependence may be the main underlying mechanism of the observed changes. Measurements of the magnetic field at T_c and instantaneous (rather than average) cooling rate may provide further insight into the mechanisms at work.

To further clarify these physical mechanisms, we plan studies similar to ours but on dressed cavities. If thermocurrents will not be ruled out and actually do also play a role in dressed cavities, then the optimal cool-down procedure would be to cool down fast though transition but from a lower temperature, e.g., 20 K.

If thermocurrents will be excluded, then attention should be paid exclusively to the rate of cooling through T_c from any starting temperature.

At the moment, we offer two speculative interpretations for the observed trapping efficiency difference between fast and slow cool-downs.

The first one is the following. During a fast cool-down, liquid helium is being poured to the bottom of the warm dewar. Rising boiled-off helium gas sets a well defined temperature stratification around the cavity. In this situation, the superconducting phase emerges at the bottom of the cavity and proceeds to sweep the cavity from the bottom to the top as shown in Fig. 10(a). It looks plausible that the propagating phase boundary efficiently sweeps out the magnetic flux. During a slow cool-down the dewar and the cavity is cooled down by a cold gas produced by mixing in warm helium to the liquid helium inside the supply line. The temperature of this mixture is carefully controlled by varying the amount of the added warm gas. In a rough approximation, the cavity can be considered to be isothermal and in thermal equilibrium with the cooling gas. In this scenario, the superconducting phase would nucleate at multiple locations throughout the cavity. During the further cooling those interfaces can encircle some areas of normal phase as schematically shown in Fig. 10(b). The magnetic flux contained in those "islands," to get expelled, would need to pass through superconducting

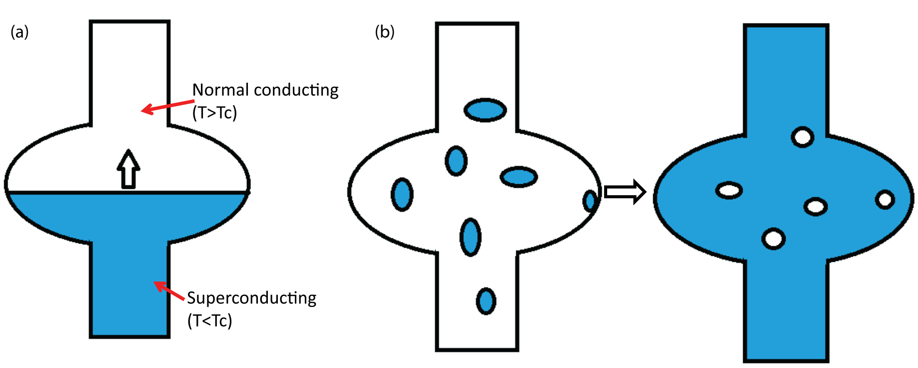

FIG. 10. Schematic of the difference between the superconducting phase nucleation dynamics between the: (a) fast cool-down and (b) slow cool-downs

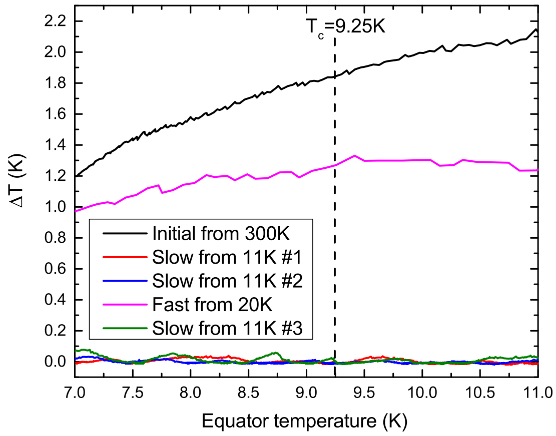

FIG. 11. Temperature difference between the equator and lower iris of the 1-cell cavity during different cooling procedures.

areas which is energetically unfavorable. This impediment would increase the amount of flux that gets trapped inside the superconductor. The same qualitative behavior in single crystal and fine grain cavities despite the difference in bulk pinning seems to be in favor of this model as well.

The second speculative possibility is that thermal gradients present during fast cooldown may exert a depinning force on the vortices, which counteracts trapping and helps pushing the flux out of the superconductor. In Fig. 11, a temperature difference between the lower iris and equator of a fine grain 1-cell EP cavity is shown as a function of the equator temperature, which shows that temperature differences of the order of 1–2 K are present during the fast cooling. This translates into local temperature gradients of $\lesssim 0.4$ K/cm, which may be high enough for fluxoid depinning around T_c leading to the more efficient flux expulsion in the case of fast cooling. During a very slow cool-down temperature gradients are unavoidably very small, no thermal depinning force is aiding the expulsion, and the efficiency of flux expulsion may decrease.

We plan on addressing these models in further detail and explore other possibilities in future studies.

V. CONCLUSION

We have discovered a strong systematic effect of the cool-down rate through T_c on the ambient flux trapping efficiency of SRF niobium cavities. While the trapping effect itself is universal among surface treatments, the magnitude of the resulting changes in the residual resistance appears to be dependent on the surface treatment.

The reported findings are of primary importance for all the proposed high duty cycle accelerators based on SRF technology since preserving the low residual resistance allows to minimize their required operational power. The recommended operational cooling procedure in a cryomodule that currently emerges from these studies to minimize flux trapping is therefore to pass the 9.25 K transition temperature with a cooling rate $\gtrsim 30$ mK/s. The lowest acceptable cooling rate may be lower and will be established by further investigations. Furthermore, since the effect is based on the trapping of the ambient magnetic field, increased magnetic shielding is an easy additional way to avoid the degradation in cases where only slow cooling can be performed. Possible effects of thermal currents in dressed cavities will also be studied next and may put an additional restriction on the starting temperature of the recommended fast cool-down.

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