Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Intro to the flux expulsion problem for LCLS-2

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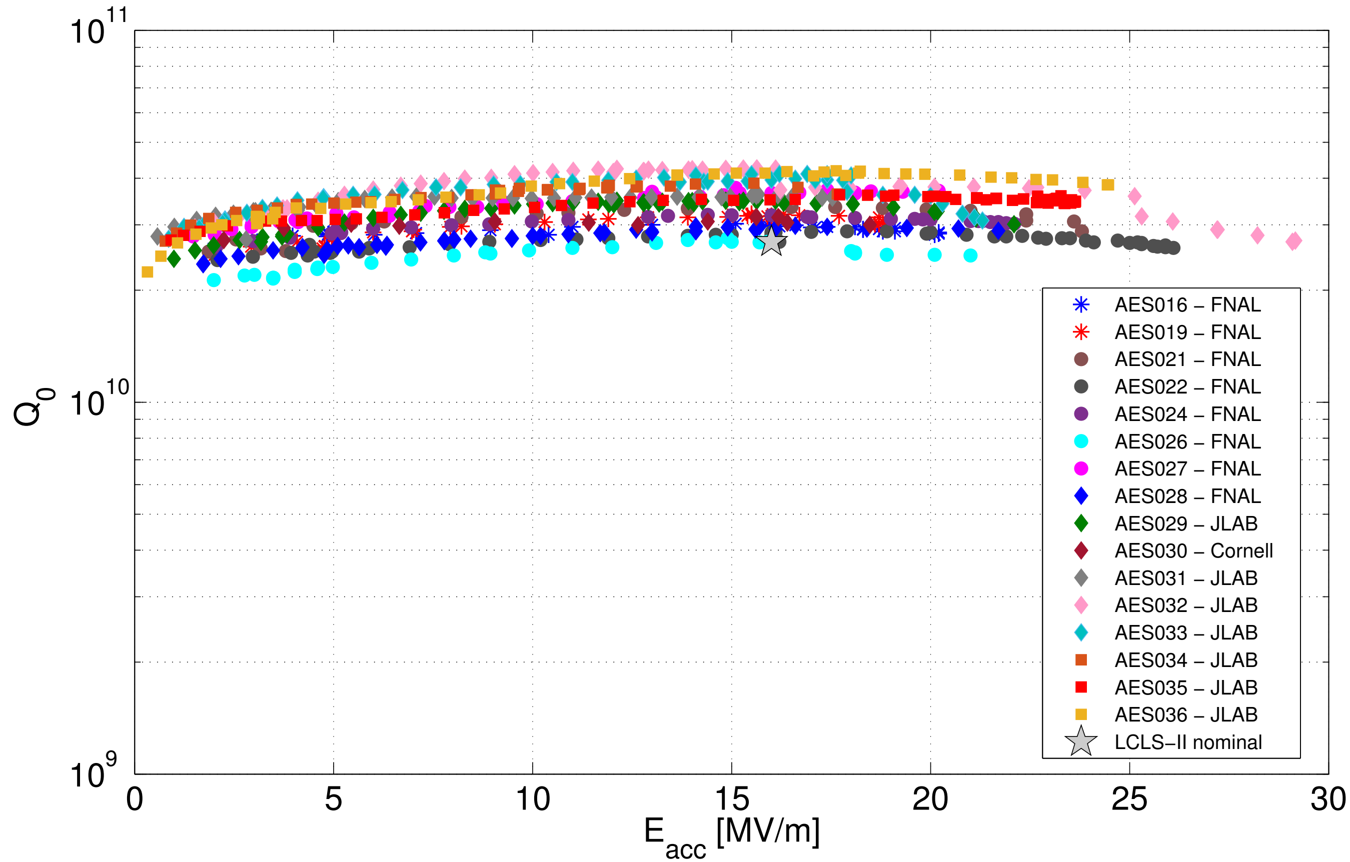
Flux Expulsion review

June 29th 2016

Timeline of High Q activities for LCLS-2

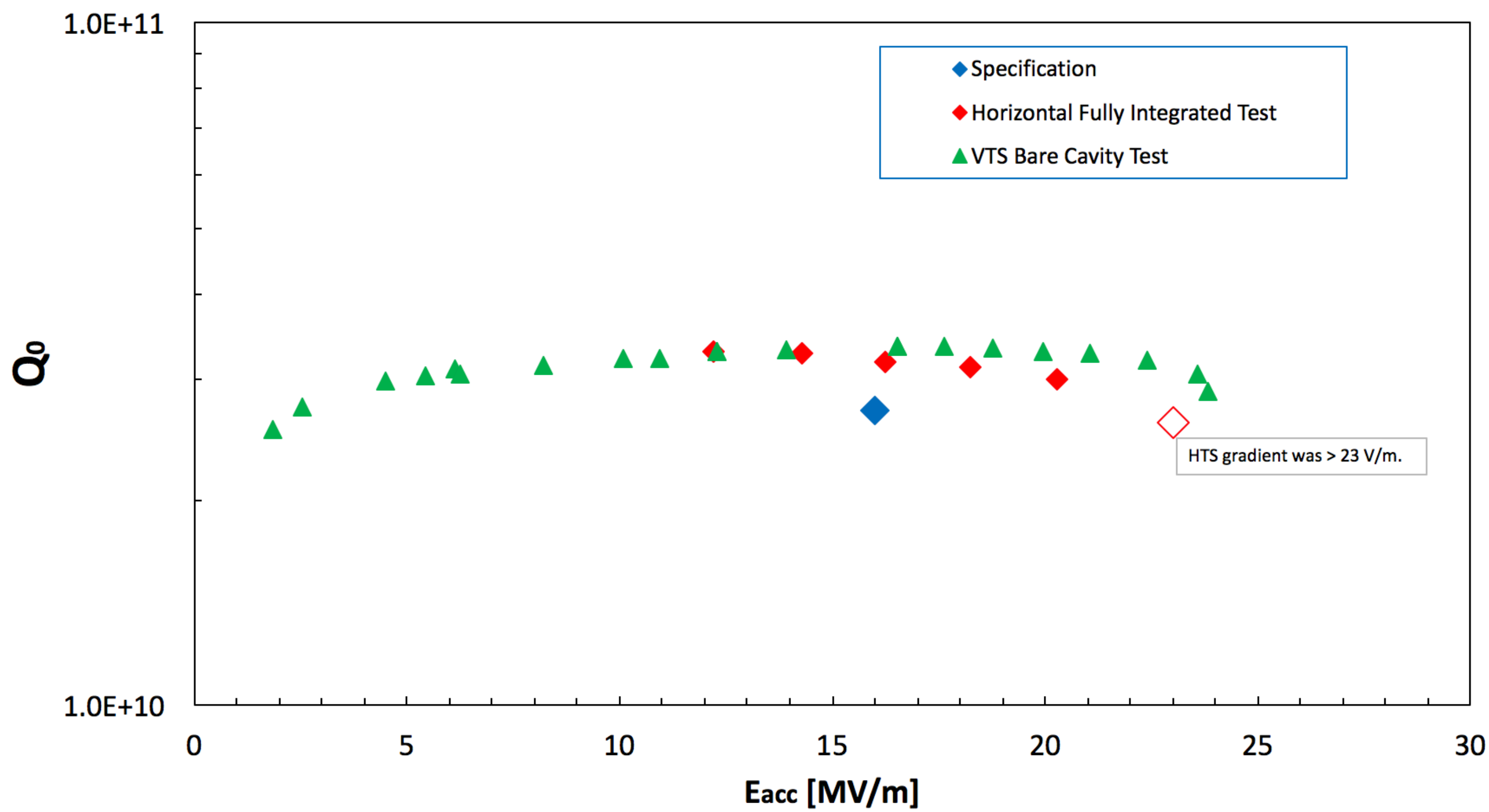
- 2014: LCLS-2 choice of doping surface processing as only pathway to Q>2.7e10 at 2K, 16 MV/m, to attempt to fit linac refrigeration need in one 4KW @ 2K cryoplant
- 2014-15: High Q collaboration FNAL-SLAC-Jlab-Cornell established to transfer/ validate doping recipe, and verify high Q in dressed nine cell in horizontal test stands
- Early 2014, FNAL finds that slow/homogeneous cooling through Tc causes full flux trapping, and that larger thermogradients can help drive magnetic flux out of Nb
- 2014-15: High collaboration plus doping transfer to vendor proves very successful at demonstrating repeatably Q>2.7e10 on single and nine cells
- 2015: But risk of degradation due to magnetic field trapping due to non ideal cooldown drives the choice of a second cryoplant to mitigate risk of insufficient refrigeration
- However, fast cooldown and obtaining Q>2.7e10 remains LCLS-2 goal
- 2015 – FNAL observation that bulk material of different vendor batches respond differently to flux expulsion capability as a function of thermogradient
- 2016 – Following CD2/3 recommendation LCLS-2 launches assessment of flux expulsion capability of production material – TD and Ningxia

2014: Vertical Test Bare Nine Cell 2.0K Results, doping recipe 2/6



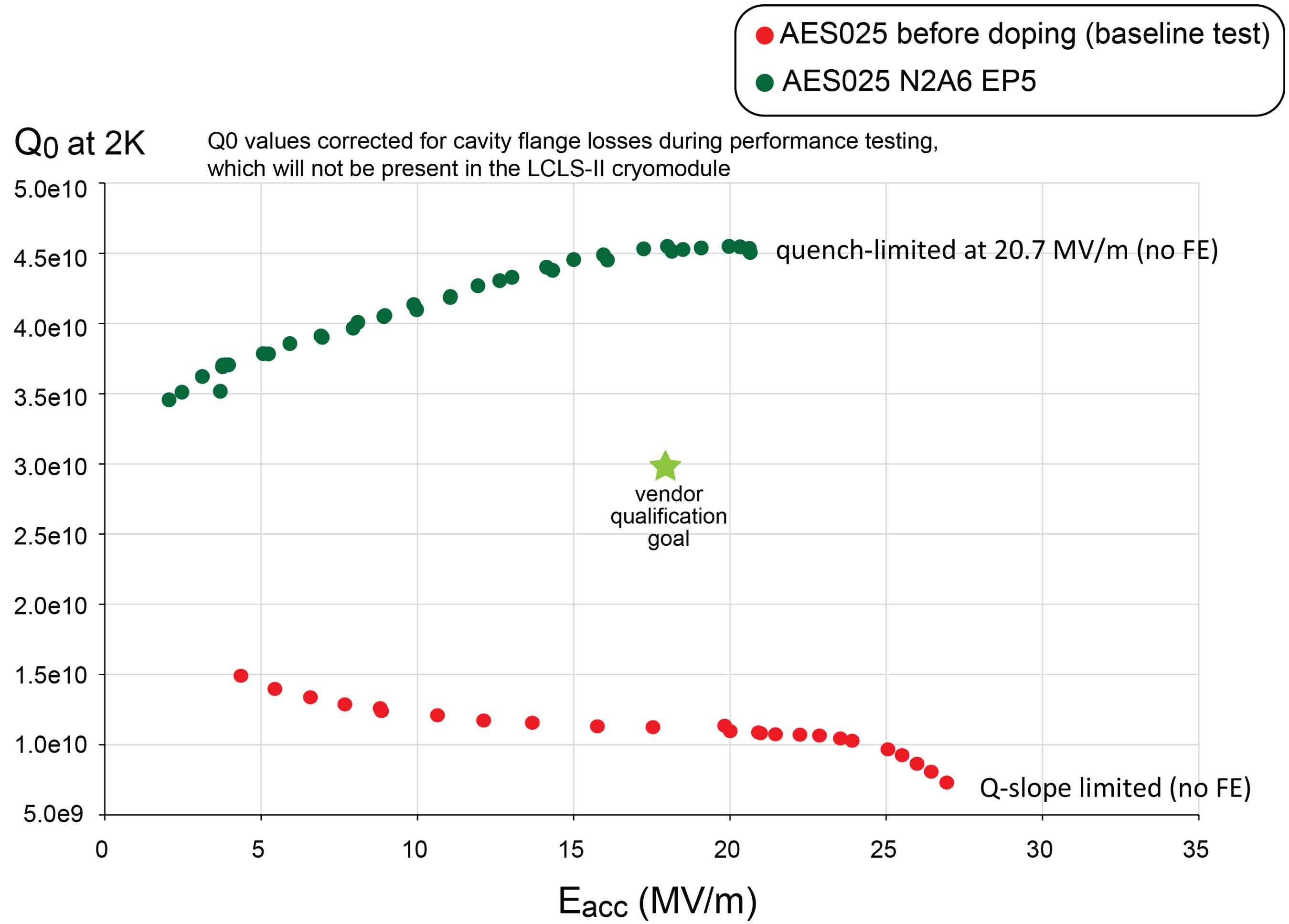
Record values: Avg Q (16 MV/m, 2K)= 3.5e10, Avg Quench field ~ 22 MV/m

2014-15: Record Q > 3e10 at 2K, 16 MV/m in cryomodule environment for LCLS-II cavity



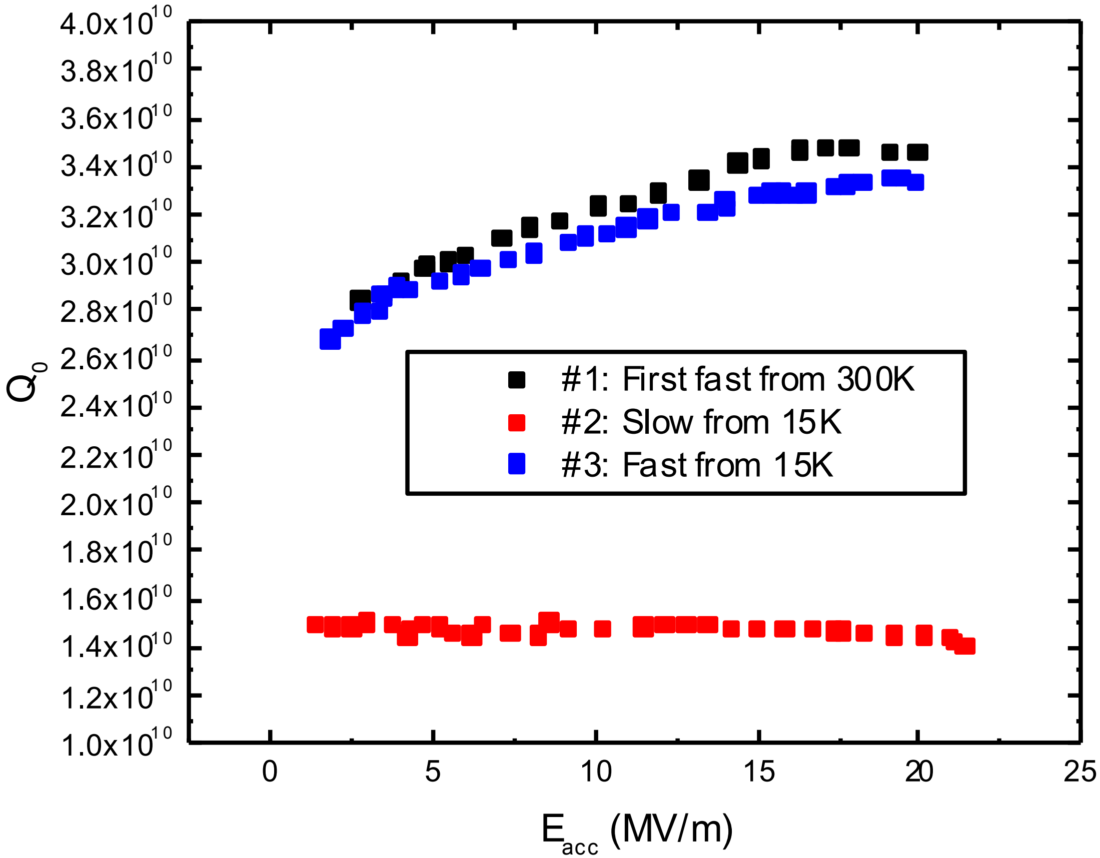
No Q degradation from vertical test to "accelerator conditions" with fast cooldown procedure through critical temperature, improved HOMs/high power coupler thermal strapping, and magnetic shielding

2015: Successful nitrogen doping technology transfer to industry for LCLS-II production



– Four times higher Q (cavity efficiency) at LCLS-II operating gradient

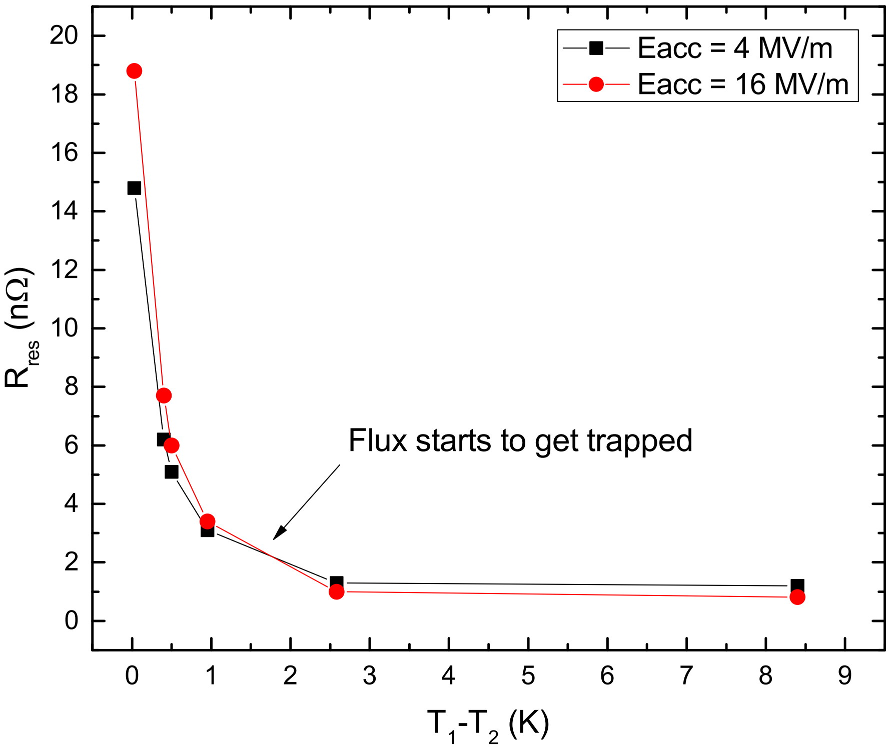
2014: Discovery of slow cooldown trapping all flux

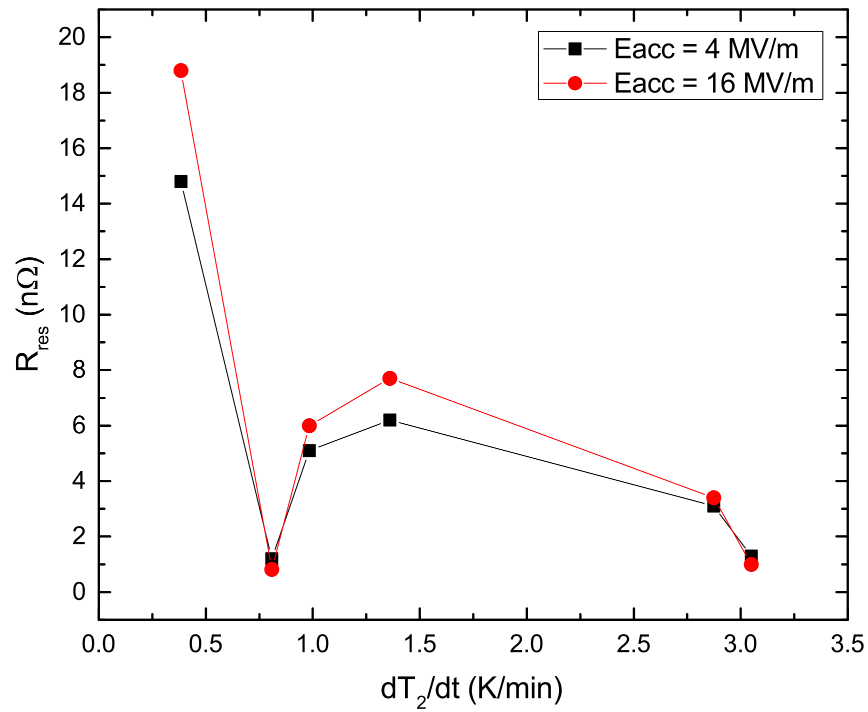


- Dressed N doped nine cell cavity vertical test at T=2K
- Sensitivity Tests conducted

A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. ***115****, 184903 (2014)*
A. Romanenko, A. Grassellino, A.Crawford, D. A. Sergatskov, Appl. Phys. Lett. 105, 234103 (2014)
D. Gonnella et al, J. Appl. Phys. ***117****, 023908 (2015)*
M. Martinello, M. Checchin, A. Grassellino, A. Romanenko, A. Crawford, D. A. Sergatskov, O. Melnychuk, J. Appl. Phys. ***118****, 044505 (2015)*

2014: It's a matter of thermogradient along the cell (at the phase front)



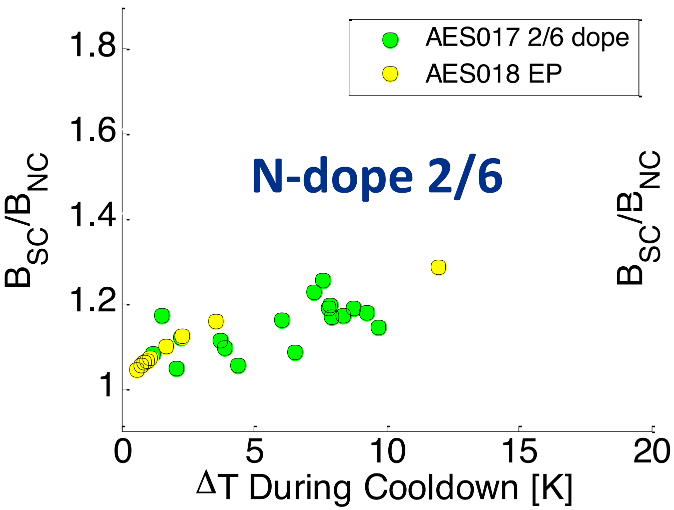


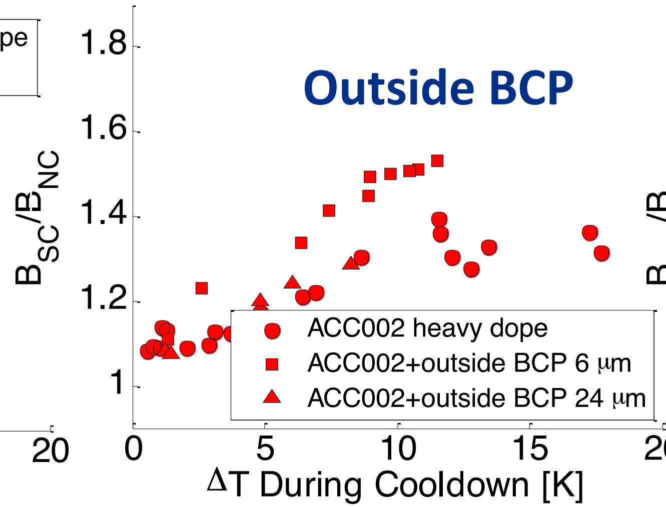
A. Romanenko, A. Grassellino, A.Crawford, D. A. Sergatskov, Appl. Phys. Lett. 105, 234103 (2014)

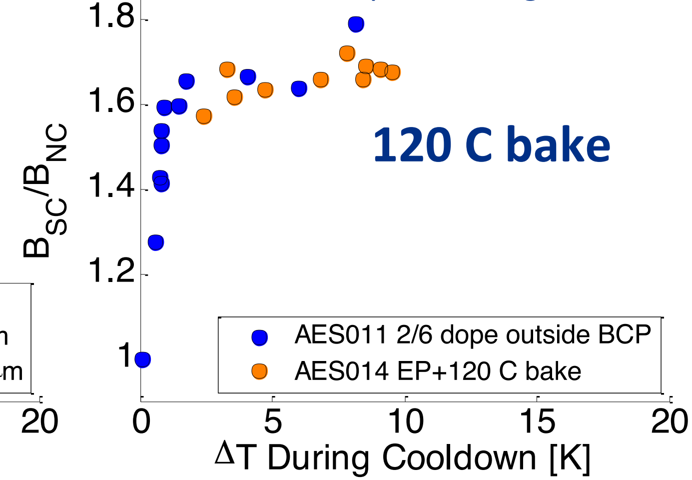
M. Martinello et al, J. Appl. Phys. **118**, 044505 (2015)

2015: Do inner or outer surface conditions affect expulsion?
Surface Alteration has No Significant Effect on Expulsion

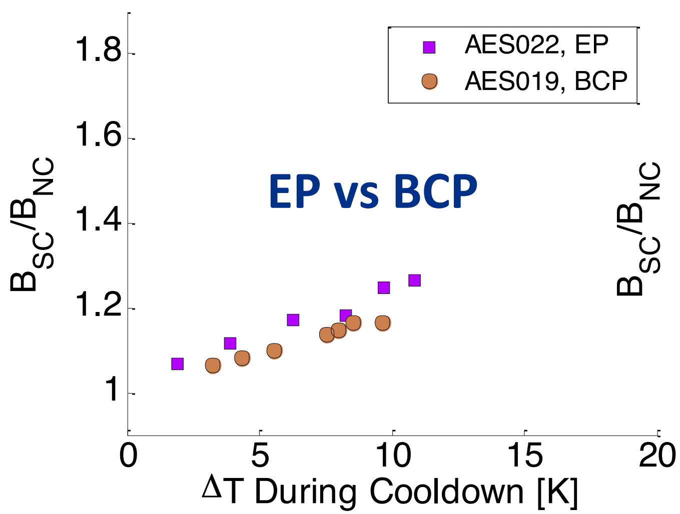
S. Posen et al, proceedings of SRF15

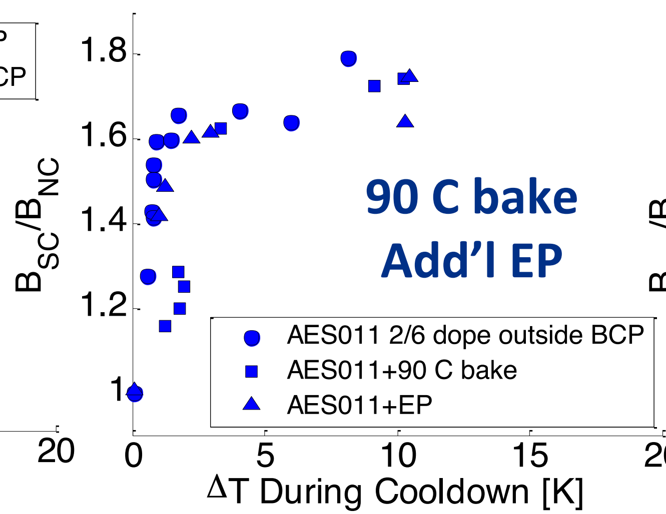


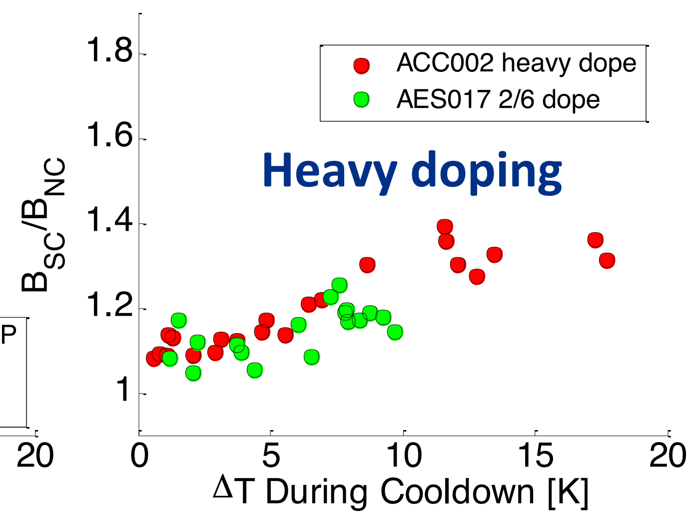




Different surface conditions in cavities with similar bulk history: similar expulsion

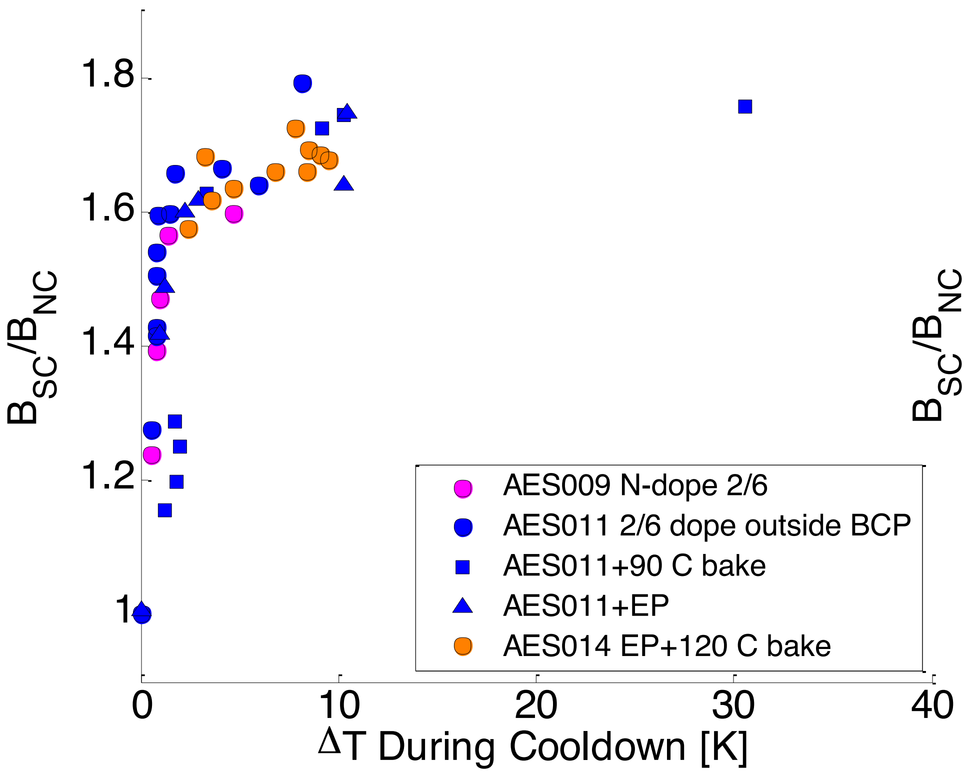




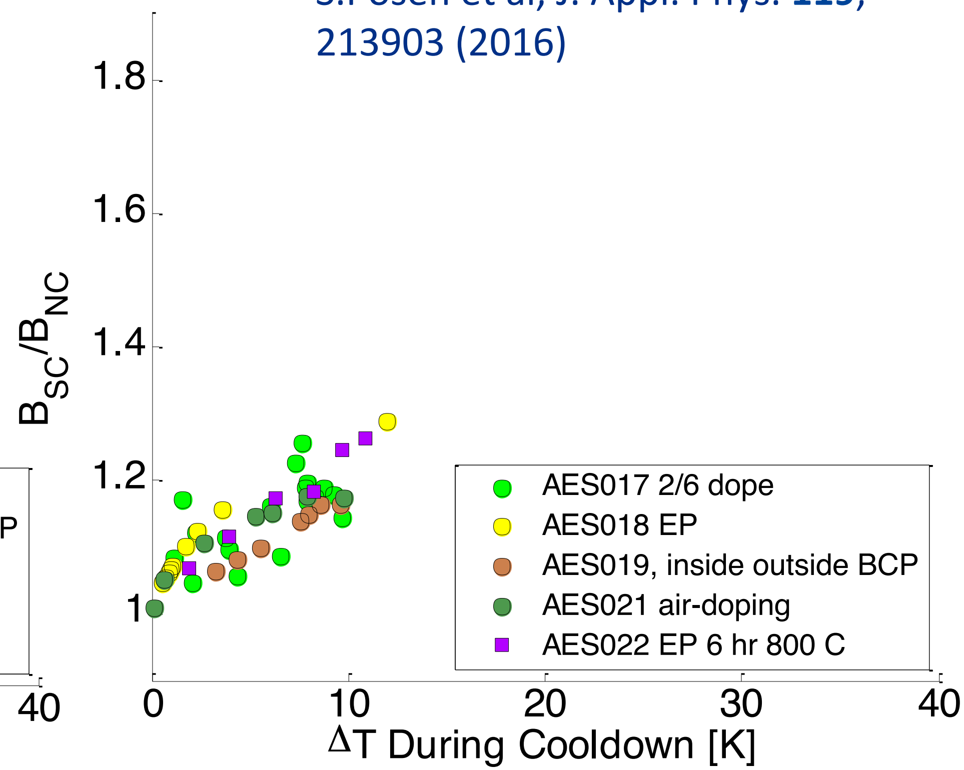


2015: But the bulk does : Clear Trend With Batches of AES Cavities

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



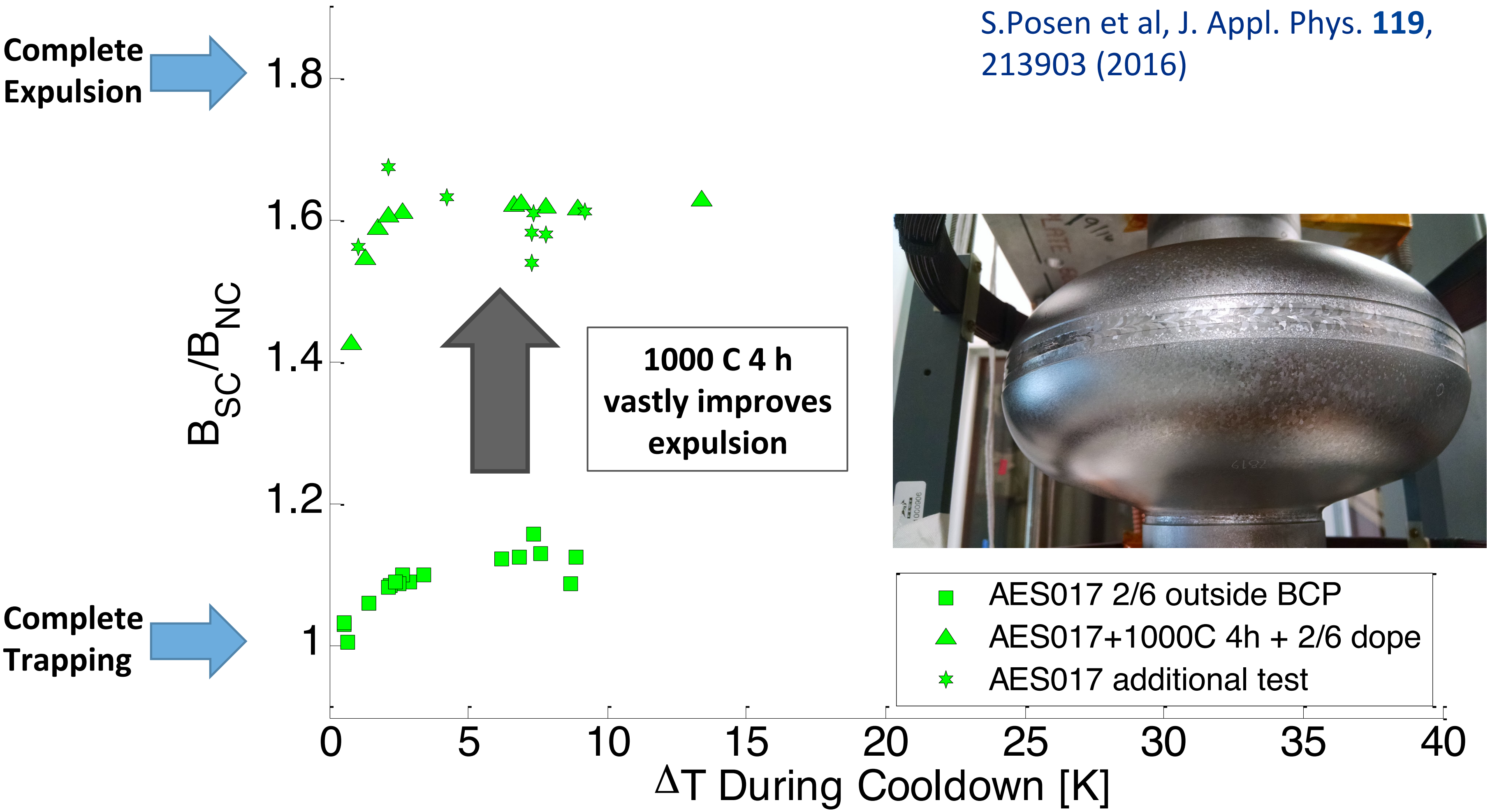
AES Single Cells Batch 1



AES Single Cells Batch 2

2015: We can convert to from poor to strong expulsion – to hear more from Sam

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



So, how to preserve Q > 2.7e10 at 16 MV/m, 2K?

- <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

Trapped magnetic flux residual

$$R_{TF} = s * \overbrace{\eta * B_{amb}}^{\text{Btrap}}$$

Ambient field in CM

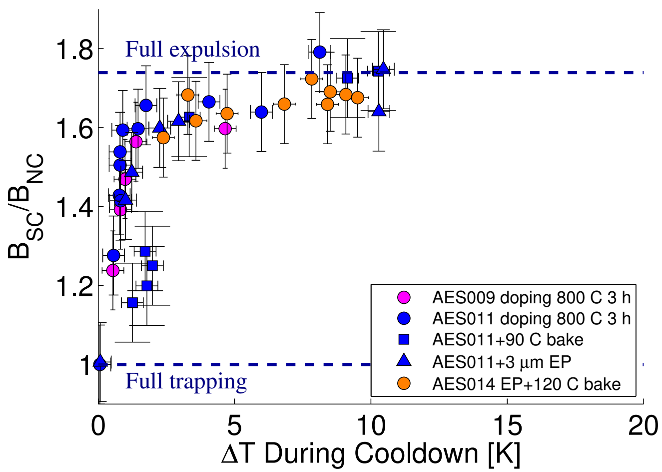
Sensitivity to mag field

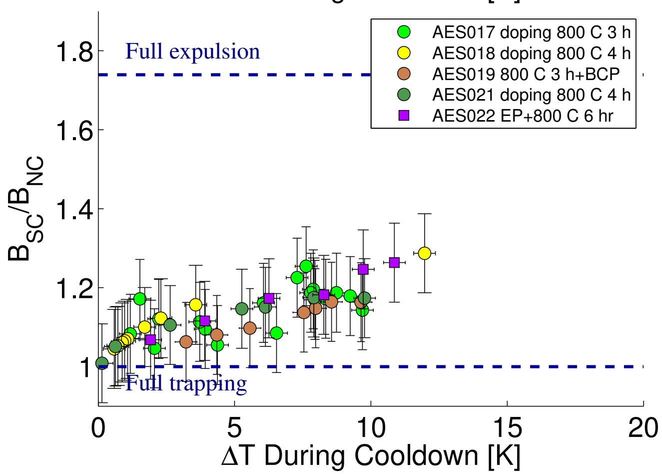
Flux expulsion efficiency

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

1) Flux expulsion efficiency: bulk

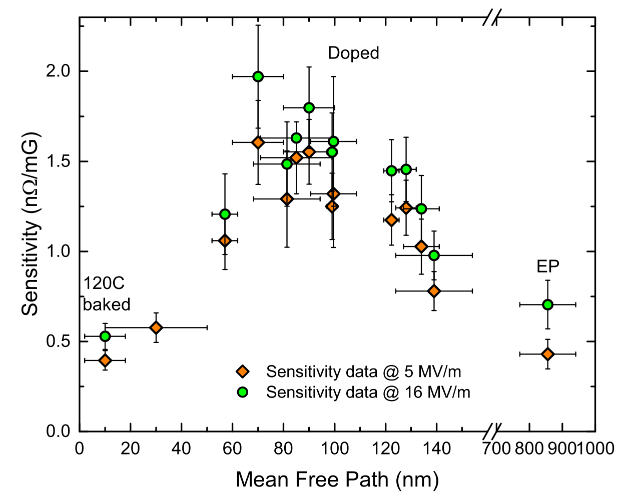
S. Posen et al, J. Appl. Phys. **119**, 213903 (2016)

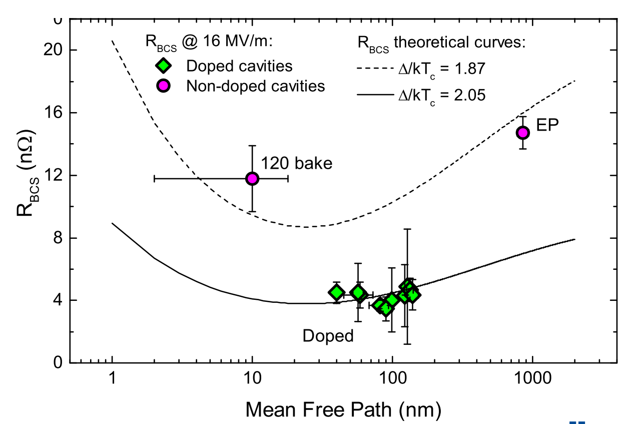




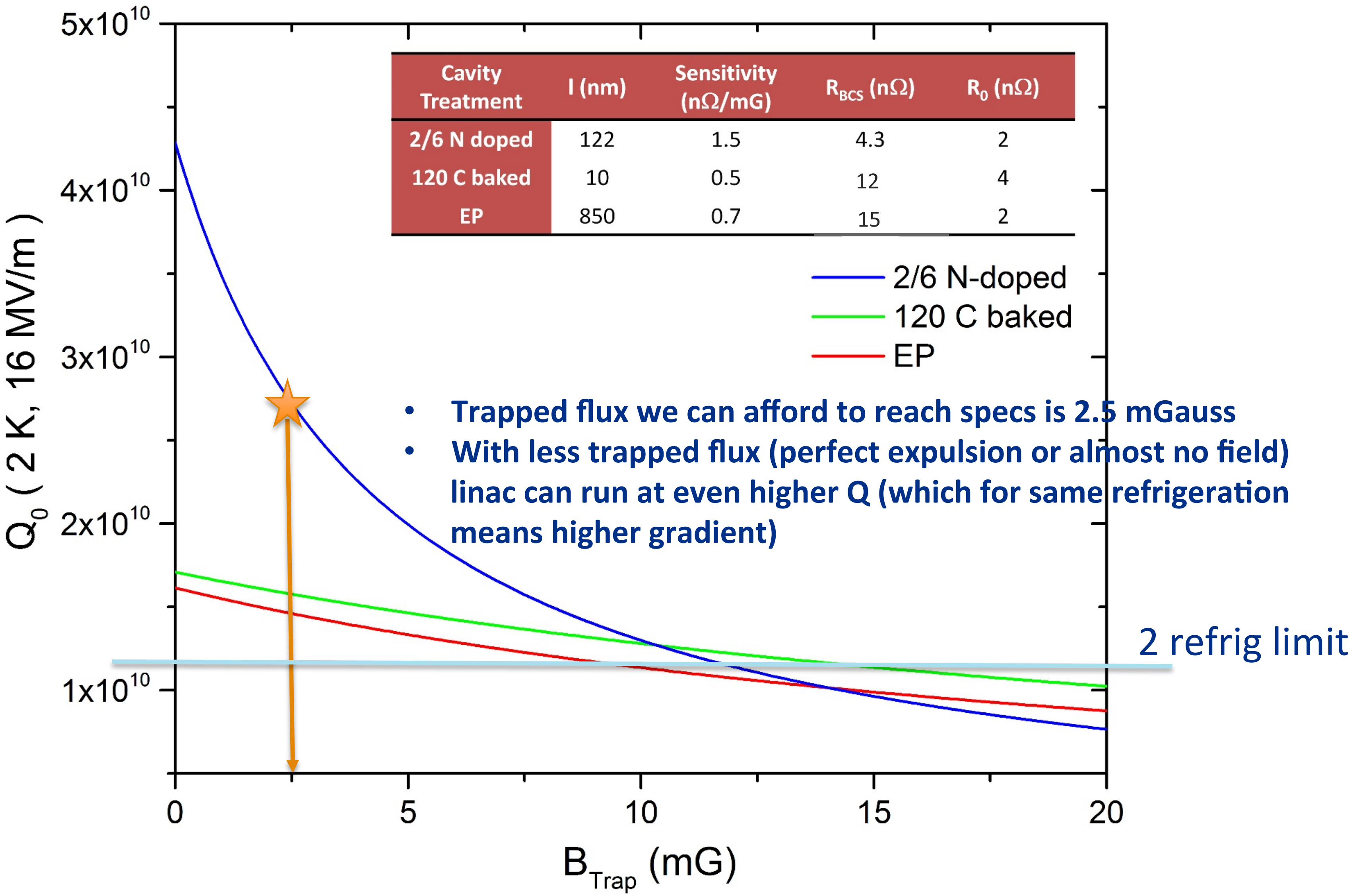
2) Trapped flux sensitivity: surface

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)**

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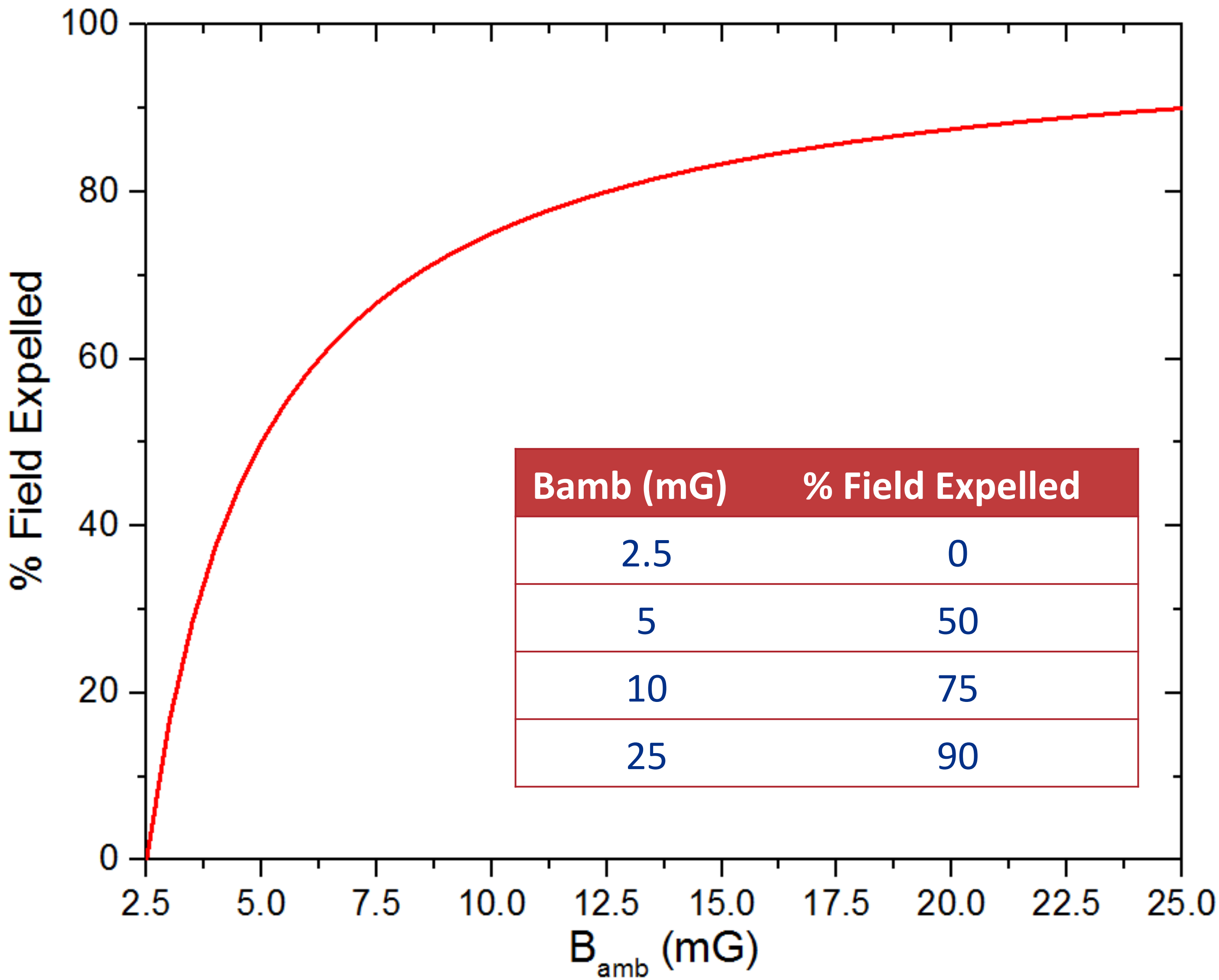
To reach specification: Q=2.7e10 → Btrap=2.5mG
→ percentage of expulsion needed as a function of ambient B:



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

May 29, 2016

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

Fluxgates							Coldmass on Big Bertha w/o vessel on it - 20160519		Coldmass on Big Bertha w/ vessel on it - 20160526			CM at WS5 - 20160601			CM at WS5 - 20160623			CM at WS5 - 20160627		
	Cavity #		Longitudinal or Transverse 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	Magnetic field		Δ from previous	Magnetic field		Δ from previous
Serial #	Serial	On string					µT	mG	µT	mG	%	µT	mG	%	µT	mG	%	µT	mG	%
Inside cavity helium vessel																				
1295	TB9AES021	1	L/T	T	45	-	0.202	2.020	-0.054	-0.540	-126.73	-0.068	-0.680	25.93	-0.072	-0.720	5.88	-0.064	-0.640	-11.11
1296			T	B	90	-	0.141	1.410	0.120	1.200	-14.89	0.155	1.550	29.17	-0.295	-2.950	-290.32	-0.273	-2.730	-7.46
1381	TB9AES024	4	L/T	T	45	-	0.001	0.010	0.186	1.860	18500.00	0.233	2.330	25.27	0.660	6.600	183.26	0.015	0.150	-97.73
1378			T	B	90	-	2.495	24.950	2.600	26.000	4.21	2.594	25.940	-0.23	-4.567	-45.670	-276.06	-4.509	-45.090	-1.27
1366	TB9AES028	5	L/T	T	45	-	0.044	0.440	0.094	0.940	113.64	0.073	0.730	-22.34	-0.183	-1.830	-350.68	-0.124	-1.240	-32.24
1365			T	B	90	-	0.133	1.330	0.084	0.840	-36.84	0.056	0.560	-33.33	2.736	27.360	4785.71	2.660	26.600	-2.78
1287	TB9AES027	8	L/T	T	45	-	0.970	9.700	1.042	10.420	7.42	1.011	10.110	-2.98	0.157	1.570	-84.47	0.159	1.590	1.27
1290			T	B	90	-	0.140	1.400	0.104	1.040	-25.71	0.015	0.150	-85.58	-4.130	-41.300	-27633.33	-4.139	-41.390	0.22
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	-0.254	-2.540	-261.78	-0.214	-2.140	-15.75
1396	TB9AES019	2	L	Ext	-	US	0.047	0.470	-0.075	-0.750	-259.57	0.060	0.600	-180.00	-0.076	-0.760	-226.67	-0.095	-0.950	25.00
1395	TB9AES028	5	L	Ext	-	DS	-0.139	-1.390	0.159	1.590	-214.39	0.282	2.820	77.36	0.066	0.660	-76.60	0.182	1.820	175.76
1398	TB9AES022	7	L	Ext	-	DS	-0.067	-0.670	0.050	0.500	-174.63	0.228	2.280	356.00	0.016	0.160	-92.98	0.058	0.580	262.50
1400	TB9AES027	8	L	Ext	-	DS	0.578	5.780	0.659	6.590	14.01	0.370	3.700	-43.85	-0.288	-2.880	-177.84	0.370	3.700	-228.47
Work done on the pCM since last measurement									Vacuum vessel was slid over the coldmass.			CM moved to WS5.			Cryogenic lines were welded on; welds were X-rayed twice; inside cavity FGs were soldered to CF flange; coupler warm ends were installed.			FG 1395 to 1397 were soldered to flange.		

File updated: June 27, 2016.
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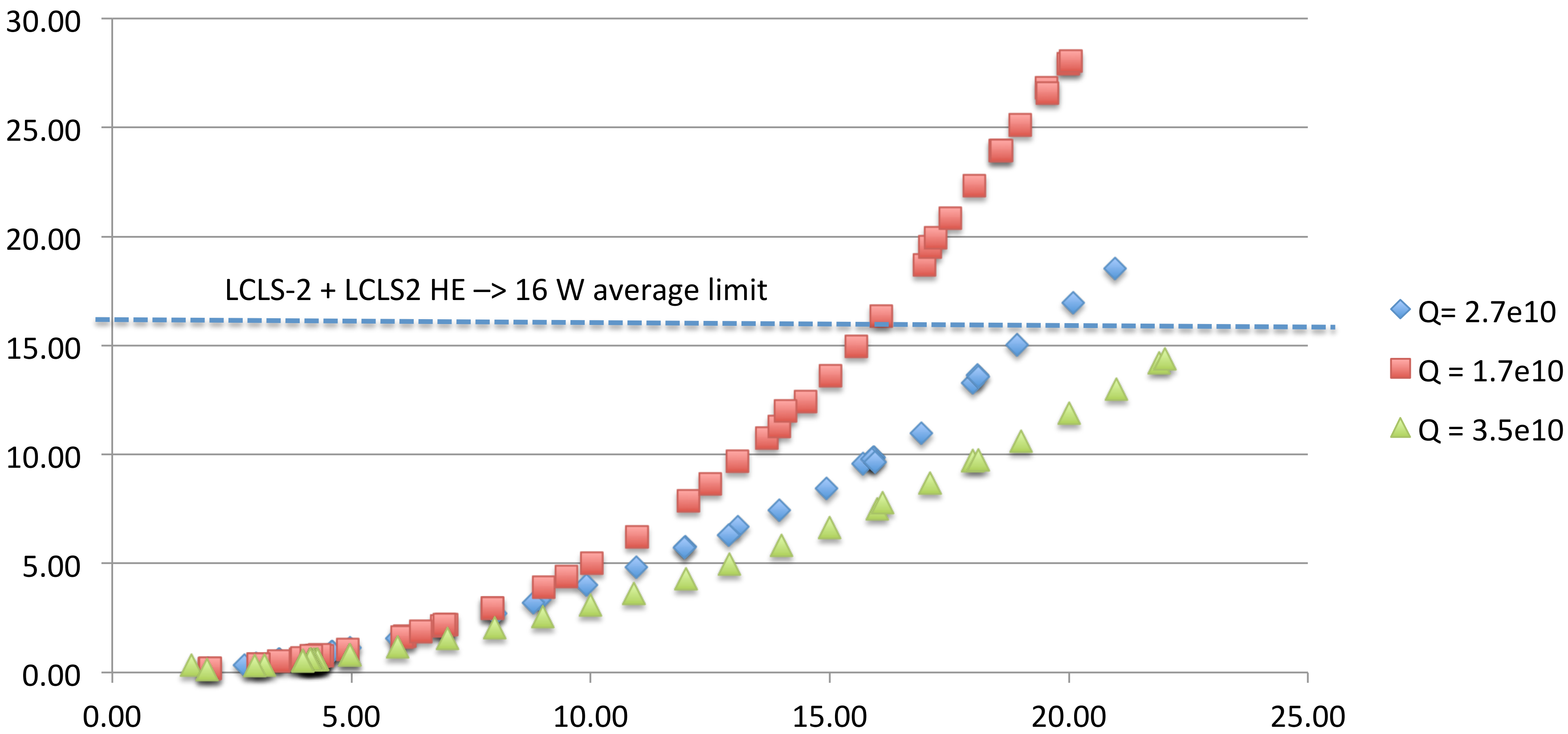
Conclusions

- Given the current magnetic field measurements in pCM, percentage of flux expulsion efficiency needed to reach Q of 2.7e10 goes from 60% to even full trapping being acceptable;
  - Slow cooldown measurements in pCM testing will tell us more about real average field seen by cavities
  - If fields in CM can be kept at ~ 2mGauss average it is not a problem, but we still need to verify that
- Given the preliminary assessment of flux expulsion capability in the production material (close to none), if no corrective action is taken (eg 900C) we could 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? Second cryoplant mitigates this risk. Why worry? See next slide

LCLS-2 –HE→ 8GeV
Power diss of nine cell cavity, Q at 3.5e10 vs 2.7e10 vs 1.7e10



Two refrigerators pose a limit of 16 W per cavity:

1. 1.7e10 → 16 MV/m → 6.9 GeV
2. 2.7e10 → 19.5 MV/m → 8.4 GeV
3. 3.5e10 → 23 MV/m → 10 GeV