Vertical and Horizontal High Q Testing – Lessons Learned for LCLS-II

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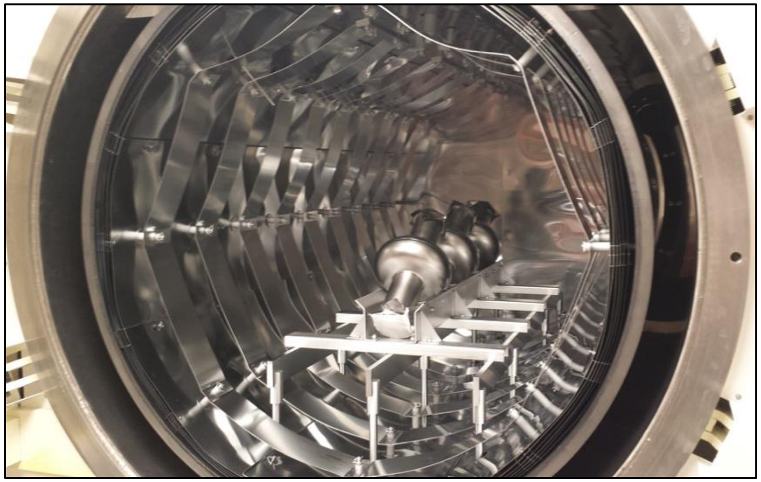
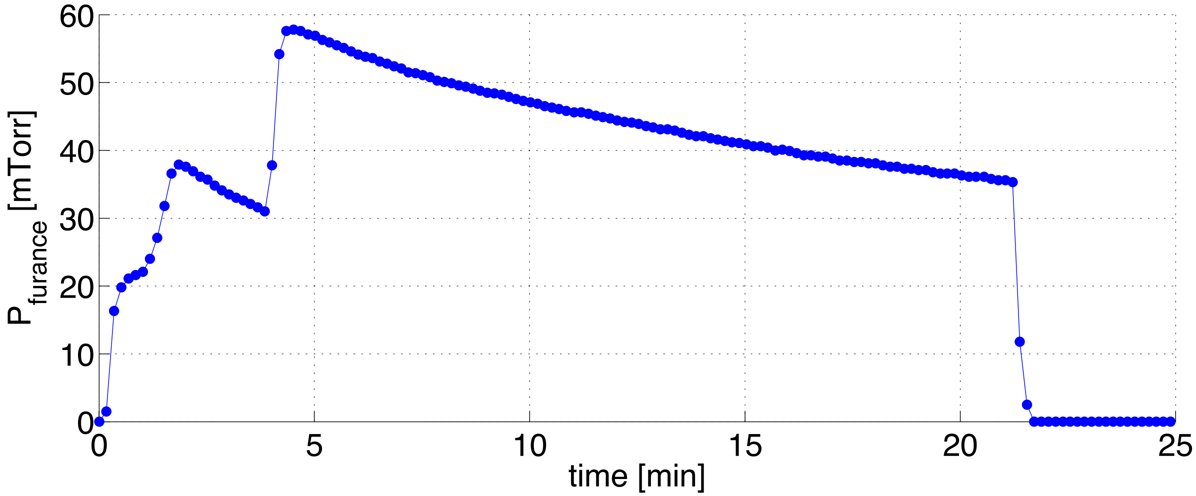
LCLS-II High Q R&D

- 3 Labs participated in R&D on High Q: Cornell, Fermilab, and JLab
- This R&D consisted of:
  - Design of N-Doping recipe for Single and 9-Cell cavities
  - Testing of cavities vertically
  - Testing of fully dressed cavities horizontally
- This work was meant to demonstrate feasibility and repeatability of N-doping for LCLS-II

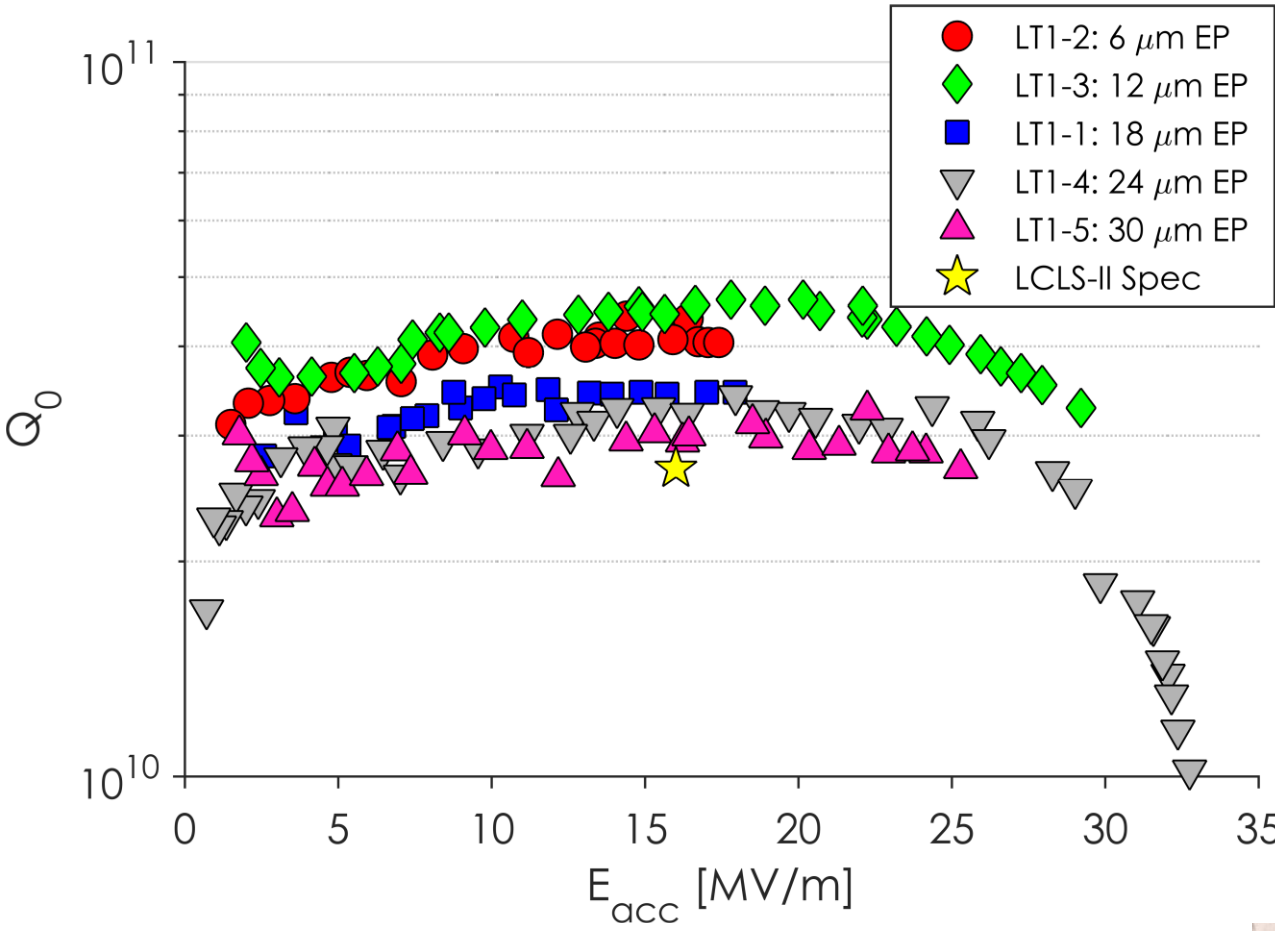
Cornell Results: Single-Cells

- 5 single-cells given same doping: 800°C, ~60 mTorr N_2, 20 minutes + 30 minute anneal, followed by different EP (6-30 μm)





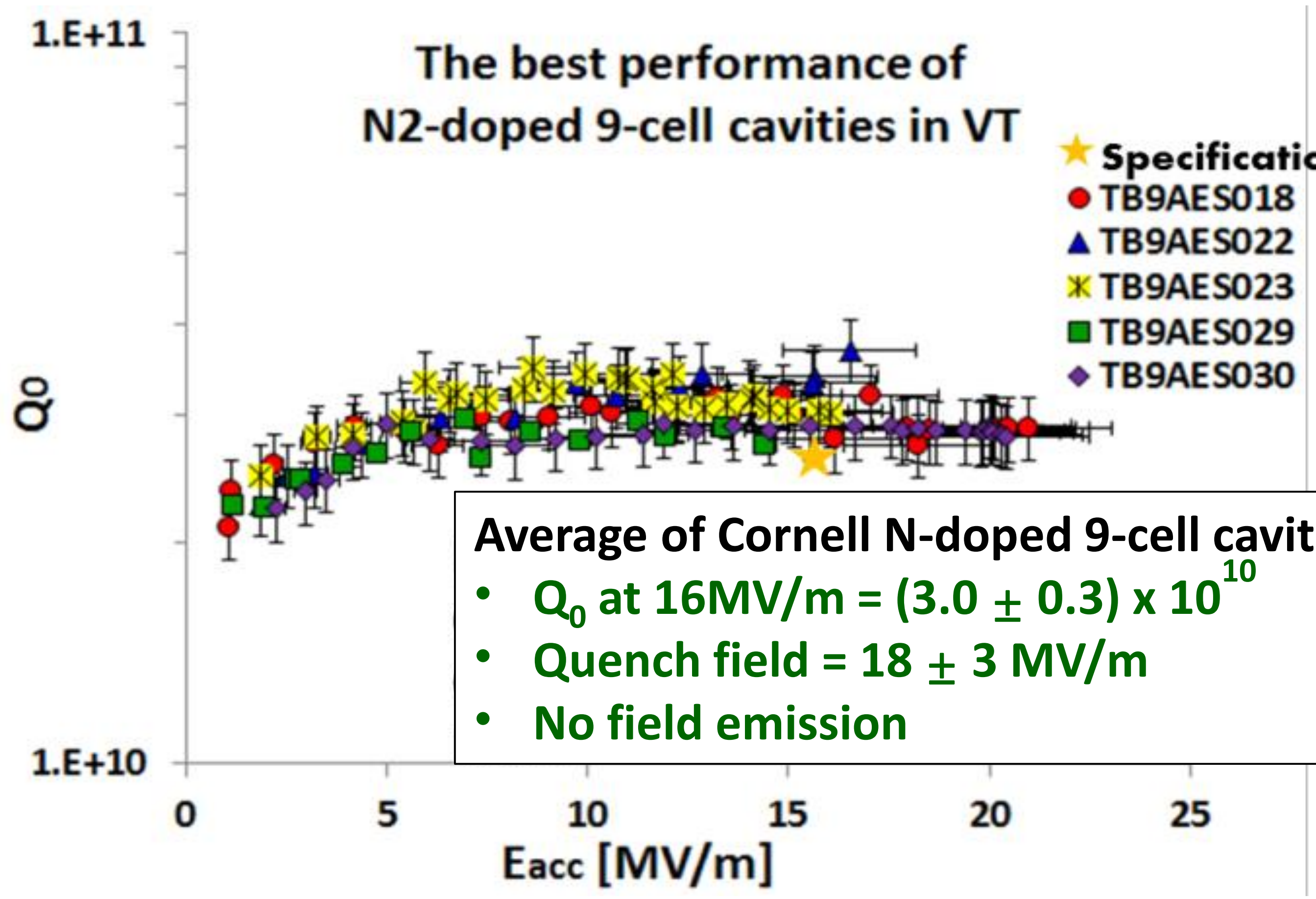
Cornell Results: Single-Cells



- Average Q_0 at **2K**: **3.6 x 10^{10}** at 16 MV/m
- Average max field: **27 MV/m**
- Far exceeding LCLS-II specs

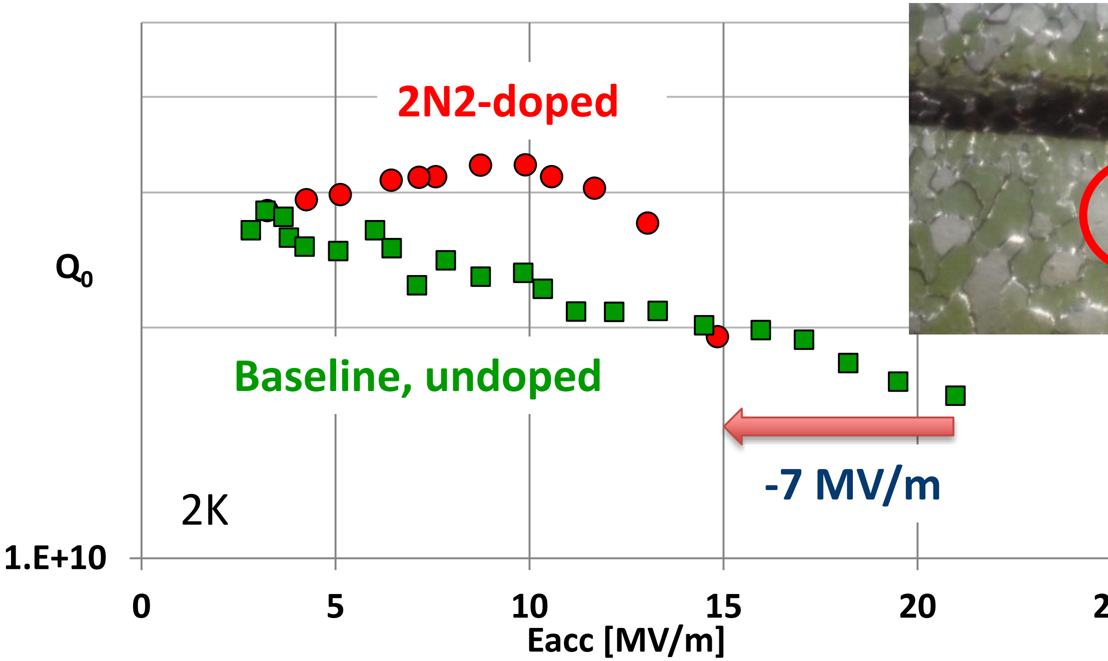
Cornell Results: 9 Cells

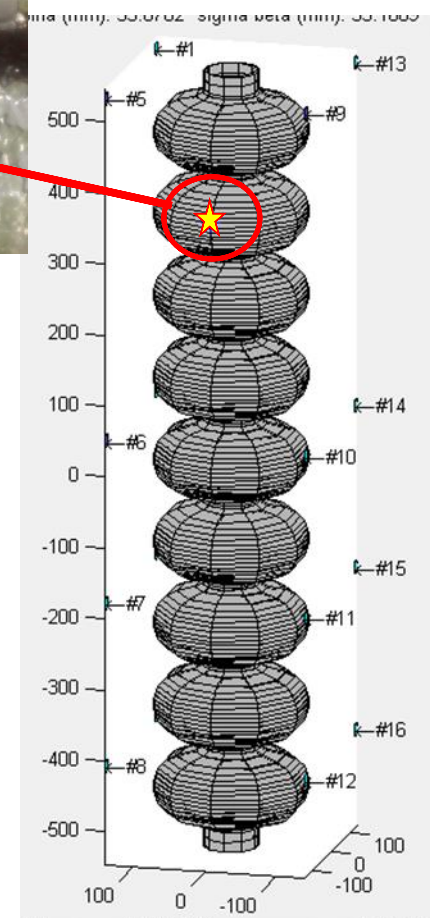
20N30 doping: 20 min N-doping + 30 min anneal at 800C
6N6 doping: 6 min N-doping + 6 min anneal at 800C



Average of Cornell N-doped 9-cell cavities
- Q_0 at 16MV/m = $(3.0 \pm 0.3) \times 10^{10}$
- Quench field = 18 ± 3 MV/m
- No field emission

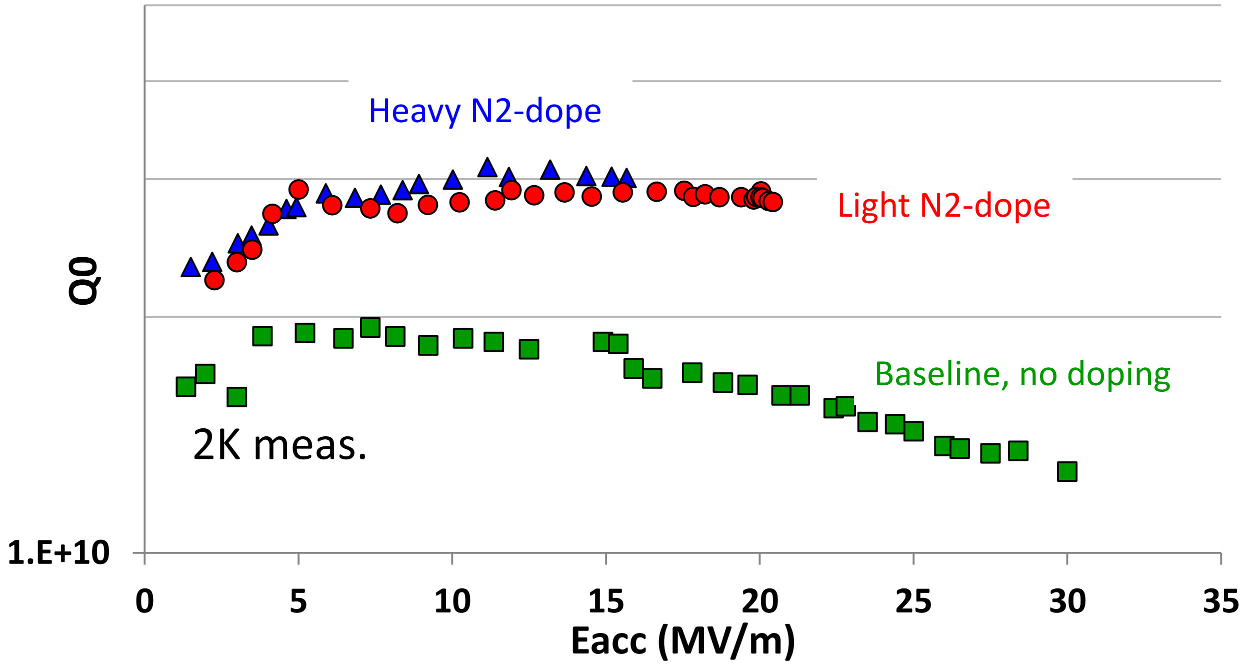
Effect of N-Doping on Quench Field



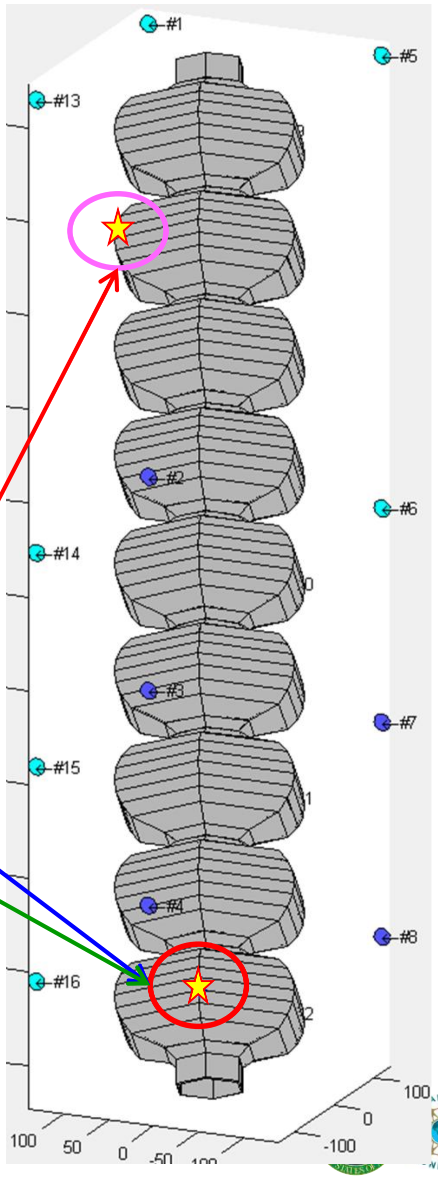


- Same quench location before and after doping
- 30% drop in quench field after doping
- Doping model predicts 30% drop in lower critical field after doping (~130 mT => ~90 mT)!
- Should expect: 32 MV/m XFEL quench field average
  => 22 MV/m LCLS-II doped cavity average

Effect of N-Doping on Quench Field

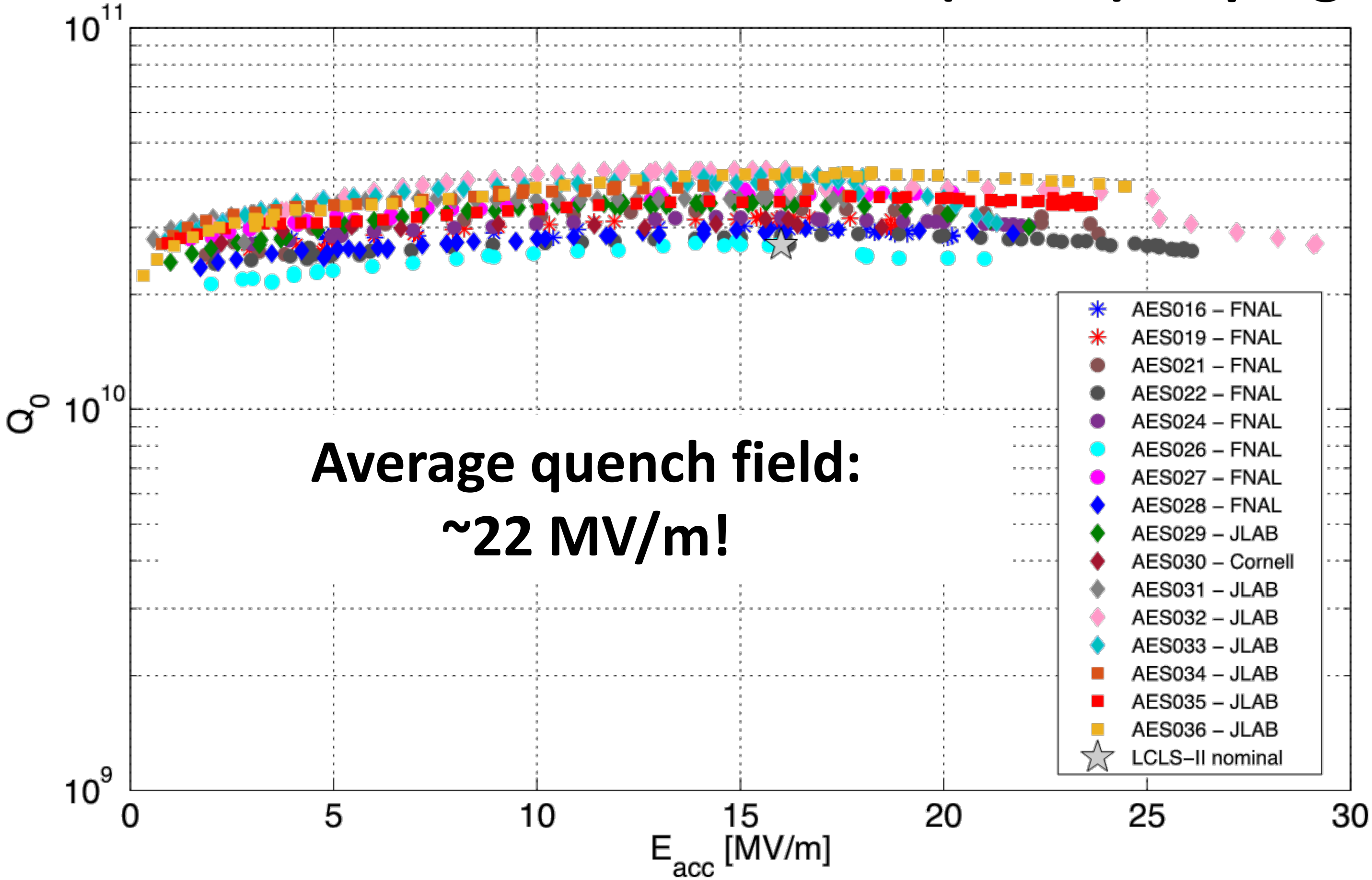


RF surface	Qo at 16MV/m	Pi-mode limit
Heavy N2 dope (20/30)	3.0e10	Quench, 17MV/m
Baseline, no doping	1.7e10	Quench, 30MV/m
Light N2 dope (6/6)	2.9e10	Quench, 20MV/m



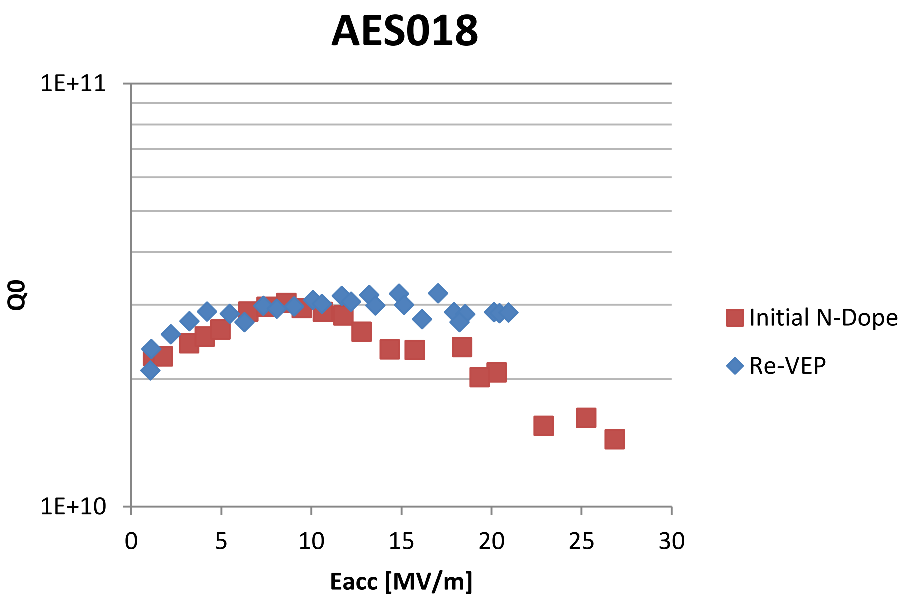
Cornell, FNAL, Jlab 9 Cell Results

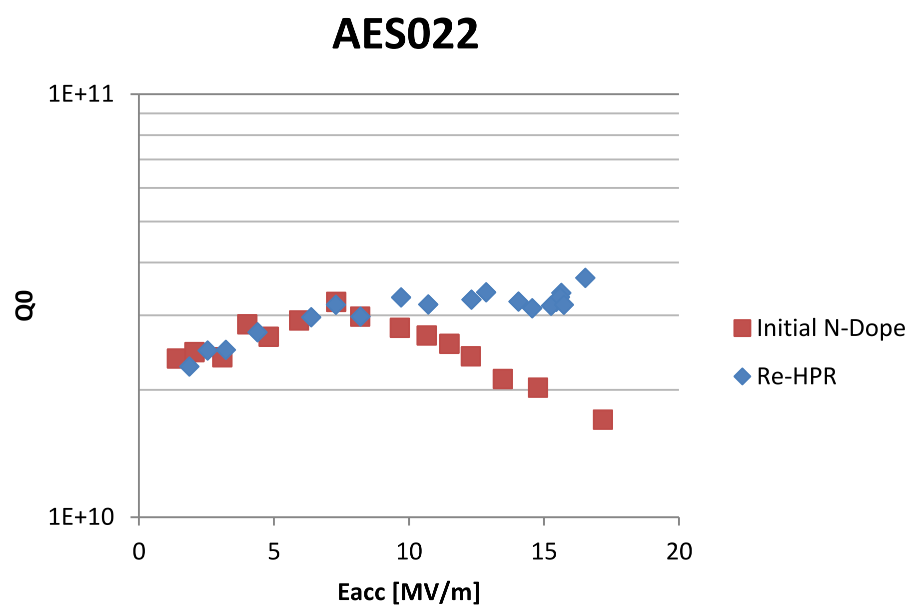
9-Cell Performance after Short (2 min) Doping



Conclusion: Reduced lower critical field H_{c1} in N-doped cavities => earlier vortex penetration at defects => lower average quench field.

Field Emission





- Two of Cornell's 9-cell cavities were limited by FE after doping
- One was fixed with just an additional HPR, the other with additional VEP (which did not change Q_0 performance)

Conclusion: Re-HPR and additional chemistry can be used if cavities are limited by field emission

Lessons for LCLS-II

- **Lesson 1: Nitrogen-Doping is sufficient to reach High Q – performance can be achieved reliably at the three labs**
- Lesson 2: We can expect an increase of 1 to 3 nΩ of residual resistance from VT to HT
- Lesson 3: Large ΔT_{trans} and small ΔT_{long} are necessary to reach High Q in N-doped cavities
- Lesson 4: Pressure in the furnace does significantly not affect nitrogen uptake in cavities
- Lesson 5: Great care needs to be taken with auxiliary parts such as HOM couplers, input couplers, etc.

Vertical Test Procedures

- Q_0 vs E_{acc} is measured at multiple temperatures:
  - Cornell measures each cavity from 1.6 to 2.1 K in 0.1 K increments
  - FNAL measures each cavity at 1.5 and 2.0 K
  - This allows one to decompose surface resistance in to residual and BCS portions
- Cornell typically measured each cavity in a variety of cool downs with different cool down rates and external magnetic fields

Vertical Test Procedures

- Cavities are assembled with high Q input couplers – this gives an easy and accurate measurement of the Q_0
  - Cornell uses variable couplers, FNAL and JLab use fixed couplers
- Vertical test dewars have ~1 mG ambient magnetic field at all three labs
- Cavities are typically cooled by dumping in liquid, resulting in very fast cool downs with large temperature gradients

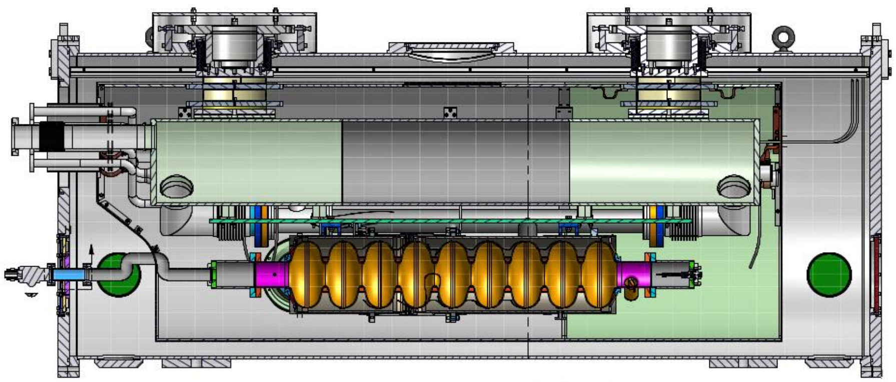
Instrumentation and VT Summary

Item	Details
Temperature Sensors	At least 3 Cernox sensors on cavity cells
Fluxgate Magnetometers	At least two, one transverse, one longitudinal
Ambient magnetic field	<1 mG
Radiation Monitors	1 outside the dewar under the shielding block (at Cornell)
Q_0 vs E measured at	1.6, 1.7, 1.8, 1.9, 2.0, 2.1 K (Cornell)
Other items measured	Q_0 vs T, f vs T (Cornell)
Additional details	Multiple cool downs with different cooling rates and external magnetic fields (Cornell)

In Production

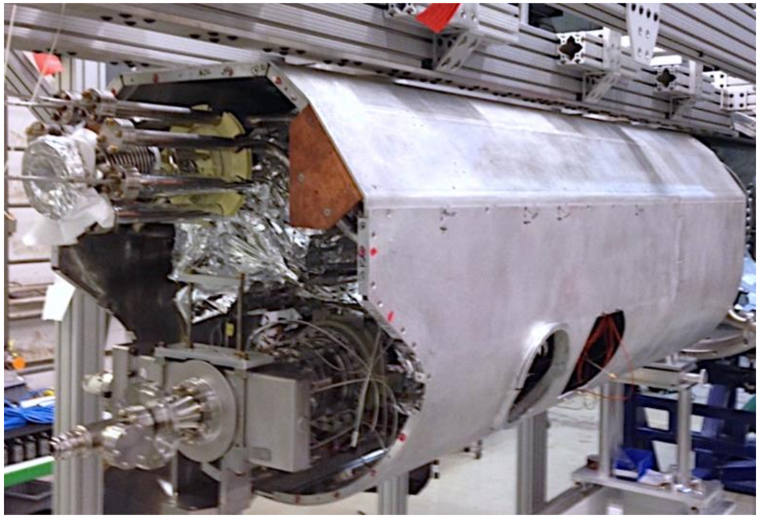
Item	Details
Temperature Sensors	At least 3 Cernox sensors on cavity cells **Need at least 1**
Fluxgate Magnetometers	At least two, one transverse, one longitudinal
Ambient magnetic field	~~<1 mG~~ **5 mG?**
Radiation Monitors	1 outside the dewar under the shielding block (at Cornell) **Do we need more?**
Q_0 vs E measured at	1.6, ~~1.7, 1.8, 1.9,~~ 2.0~~, 2.1 K~~ (Cornell)
Other items measured	~~Q_0 vs T, f vs T (Cornell)~~
Additional details	~~Multiple cool downs with different cooling rates and external magnetic fields (Cornell)~~

Cornell HTC Results



One-cavity test cryomodule

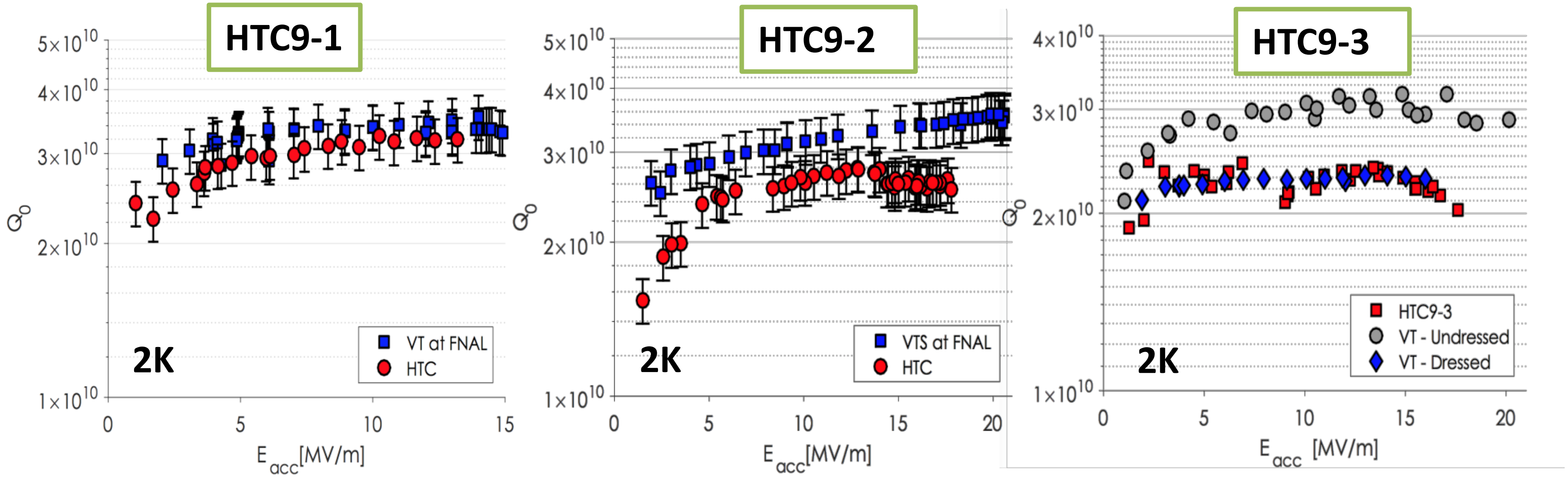
- Short version of a main linac cryomodule
- Same module construction (magnetic shields, cryogenic system…)
- Dedicated to high Q_0 studies



Cornell HTC Results

Test	Cavity	Prepared By	RF Coupler	Helium Vessel	Other
HTC9-1	ACC012	FNAL	High Q	ILC	
HTC9-2	AES011	FNAL	High Q	ILC	
HTC9-3	AES018	Cornell	High Q	LCLS-II	
HTC9-4	AES018	Cornell	LCLS-II	LCLS-II	
HTC9-5	AES030	JLab	LCLS-II	LCLS-II	Tuner, HOM Couplers

Cornell HTC Results



Cavity	Lhe Tank	HTC Test	VT Result	HT Result	$\Delta R_{VT\text{->}HT}$ [nΩ]
TB9ACC012	ILC	HTC9-1	$(3.5\pm0.4)\times10^{10}$	$(3.2\pm0.3)\times10^{10}$	1 ± 2
TB9AES011	ILC	HTC9-2	$(3.4\pm0.3)\times10^{10}$	$(2.7\pm0.3)\times10^{10}$	2 ± 2
TB9AES018	LCLS-II	HTC9-3	$(2.2\pm0.3)\times10^{10}$	$(2.2\pm0.2)\times10^{10}$	0 ± 2

Conclusion: No significant change in performance when cavity is installed in cryomodule.

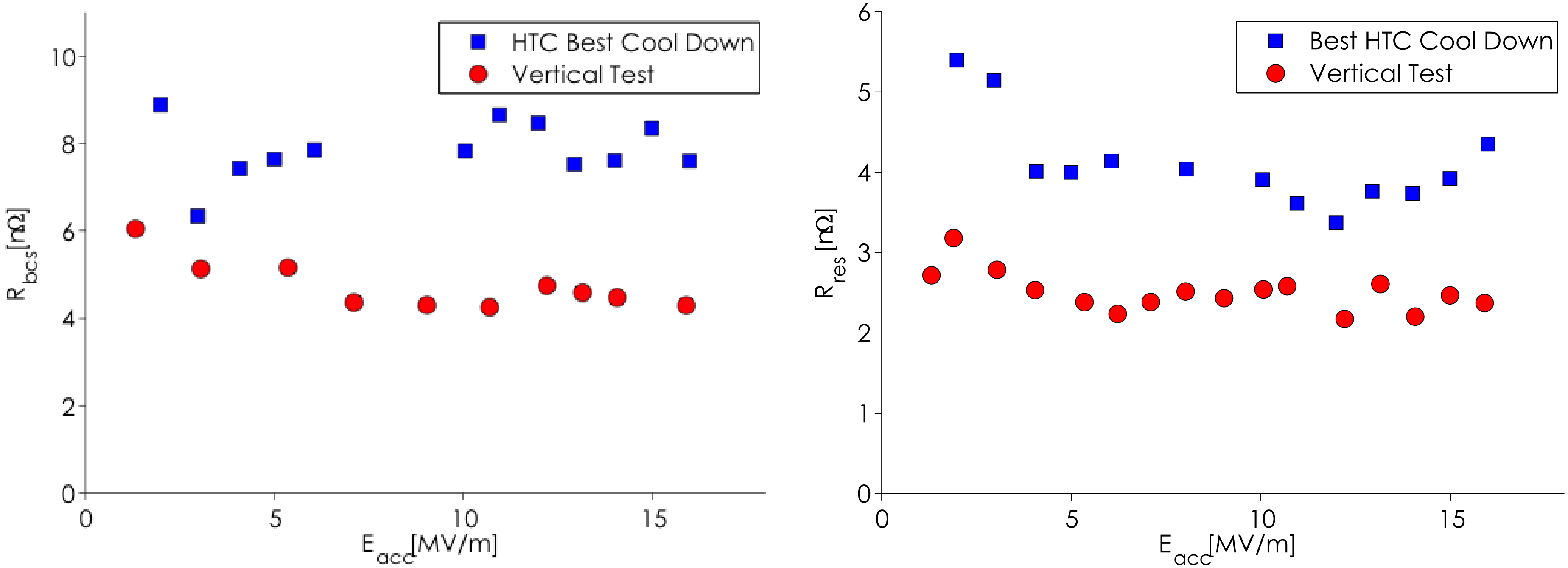
Cornell, FNAL, Jlab 9 Cell Results

Cavity ID#	2K Q0 at 16 MV/m - vertical test, bare cavity [1E10]	2K Q0 at 16 MV/m - vertical test, dressed cavity [1E10]	2K Q0 at 16 MV/m - horizontal test [1E10]	Maximum accelerating field, latest test [MV/m]	ΔR - vertical bare to vertical dressed [nΩ]	ΔR - vertical dressed to horizontal dressed [nΩ]
ACC015	3.5			24.0		
AES016	3.0			20.2		
AES019	3.2	3.1		18.8	0.3	
AES021	3.4	2.8	3.1	23.0	1.7	-0.9
AES022	3.1			26.2		
AES024	3.2	3.2		22.0	0.0	
AES026	2.8	2.8		21.4	0.0	
AES027	3.6	2.7	2.8	22.8	2.5	-0.4
AES028	3.5	3.0		23.0	1.3	
AES029	3.6	3.6		23.7	0.0	
AES030	2.9	2.5		18.2	1.5	
AES031	3.5		2.4 at 8 MV/m	19.4		
AES032	4.2	2.8		23.0 (admin limit)	3.2	
AES033	3.9	3.6		21.3	0.6	
AES034	3.9	3.5		22.5	0.8	
AES035	3.6	2.9	3.0	17.5	1.8	-0.3
AES036	4.1	3.7		19.0 (admin limit)	0.7	
Average	**3.5**	**3.1**	**3.0**	**21.6**	**1.1**	**-0.5**

Conclusion: We see a 1 to 3 nΩ increase in residual resistance from bare VT to dressed HT

Should we increase the spec to 3.4×10^{10} in VT to meet 2.7×10^{10} in CM?

Decomposition of R_s



- In HTC9-3, both BCS resistance and residual resistance changed from VT to HT
- Should we be taking 1.6 and 2 K curves during production to identify which component of R_s potential issues are coming from?

HT Procedures

- Q_0 vs E_{acc} is measured cryogenically due to low Q_{ext}, which is very time consuming
- Cool downs are typically done by dumping in helium gas, which results in fast cool downs but with smaller temperature gradients than can be achieved in vertical test
- Multiple cool downs completed to optimize flux expulsion and reach high Q_0

Instrumentation and HT Summary

Item	Details
Temperature Sensors	Cernox sensors distributed on the cavity cells, beam tubes, coupler, and HOM cans
Fluxgate Magnetometers	At least two, one transverse, one longitudinal
Ambient magnetic field	<3 mG
Radiation Monitors	On either side of the cryomodule
Q_0 vs E measured at	1.6, 2.0 K
Other items measured	Q_0 vs T, f vs T (Cornell)
Additional details	Multiple cool downs with different cooling rates and external magnetic fields (Cornell)

In Production

- Many Cernox sensors are impractical from a cost perspective – how many should we have?
- Fluxgates are also expensive but we need at least one to measure magnetic fields
- 1.6 K and 2.0 K curves should be measured in order to better understand poor performance
  - Some cavities will not meet spec, understanding why is very important to solving that problem in future cavities
- Temperature sensors on the HOM cans are highly recommended – will be discussed in detail later

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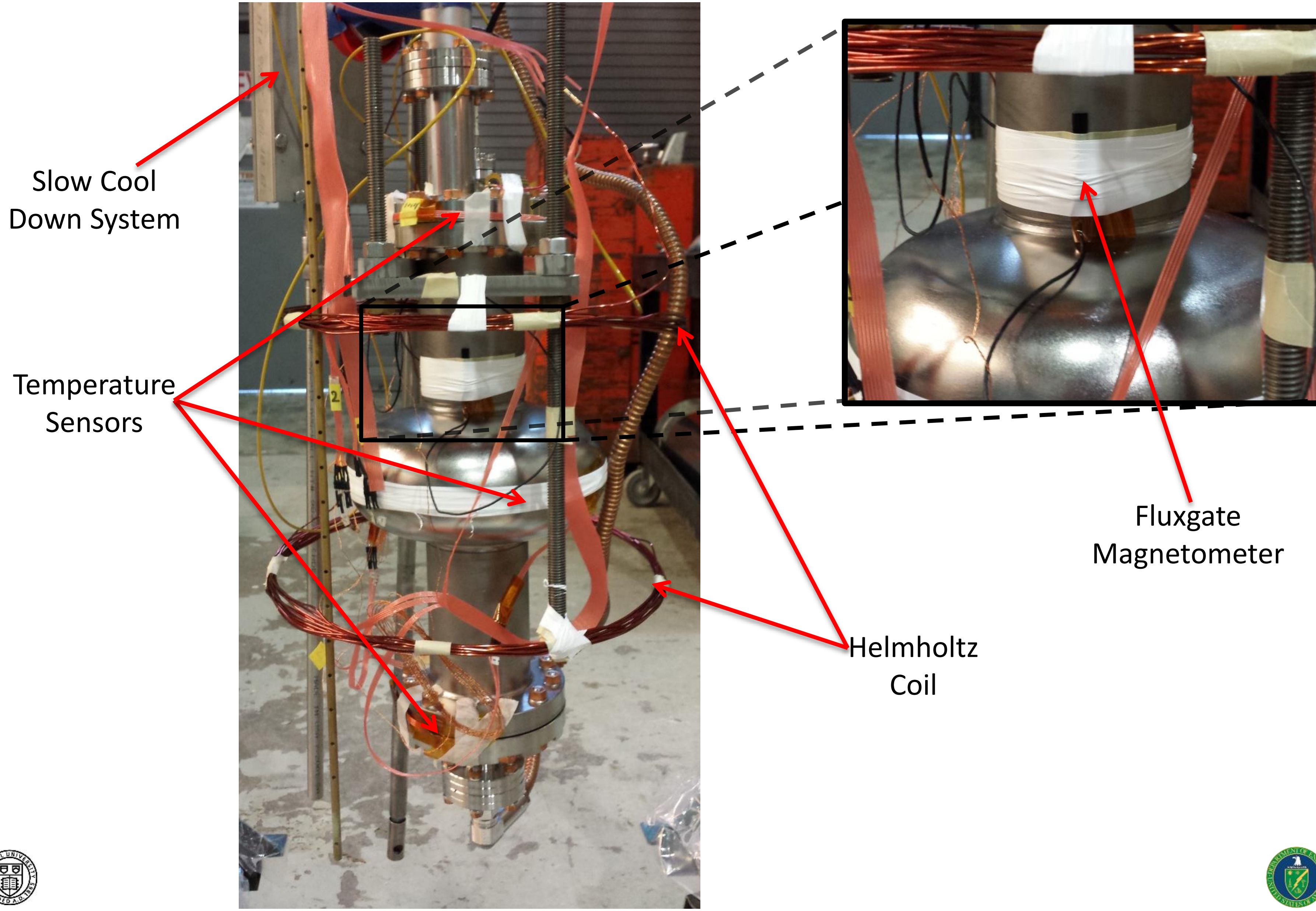
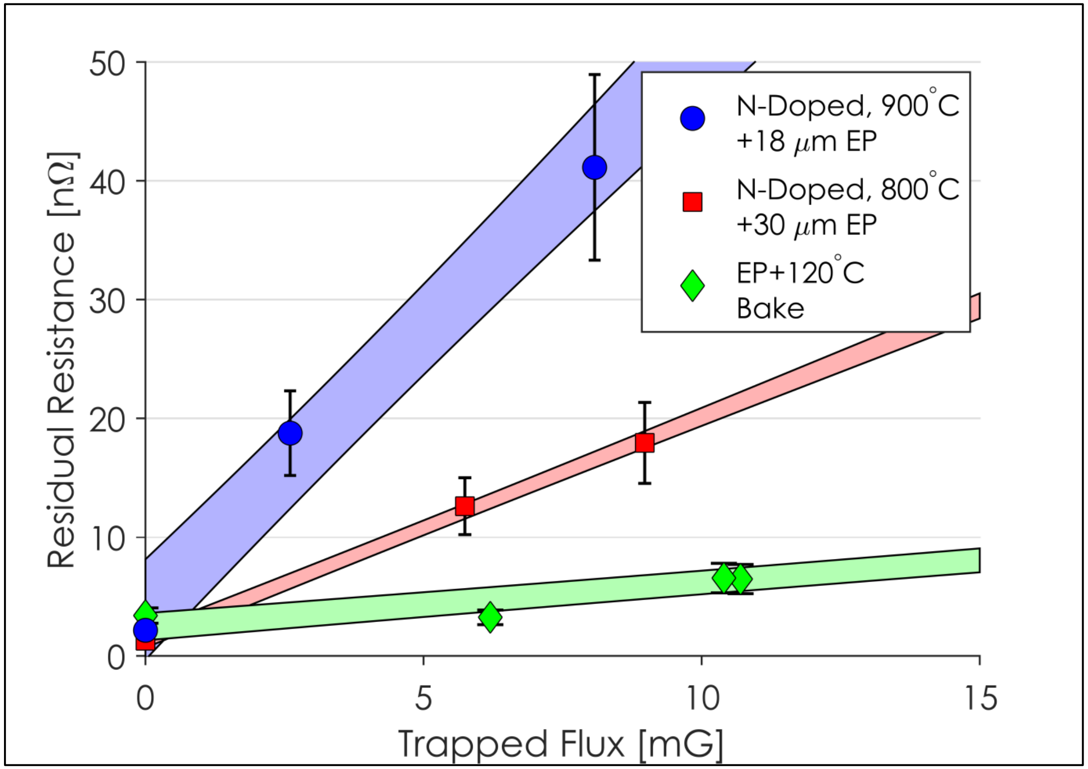
Magnetic Field Studies



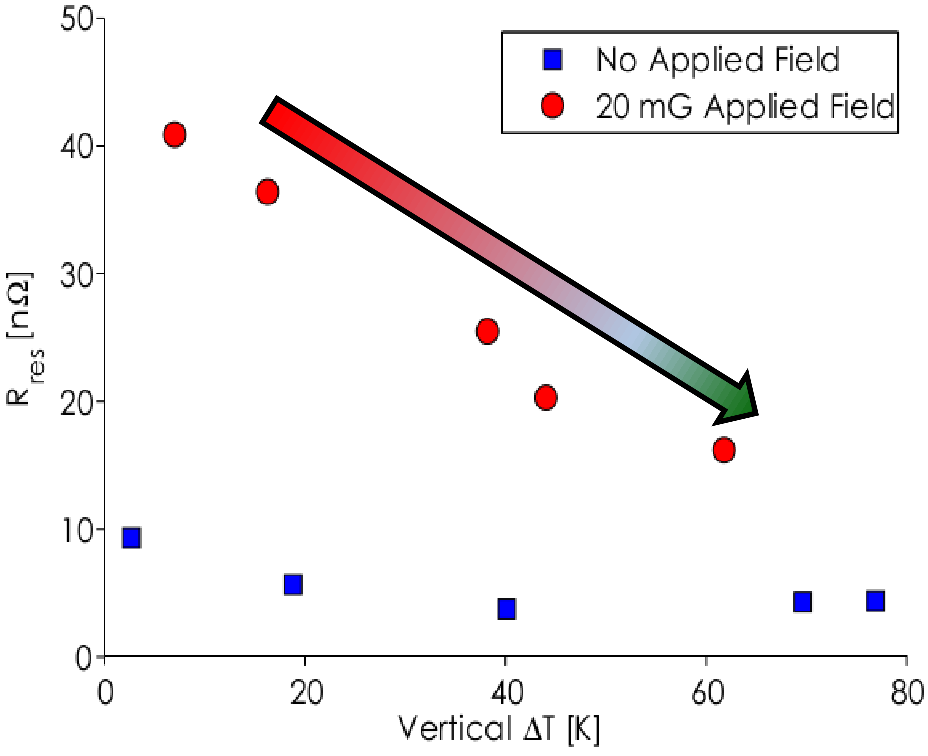
Magnetic Field Studies



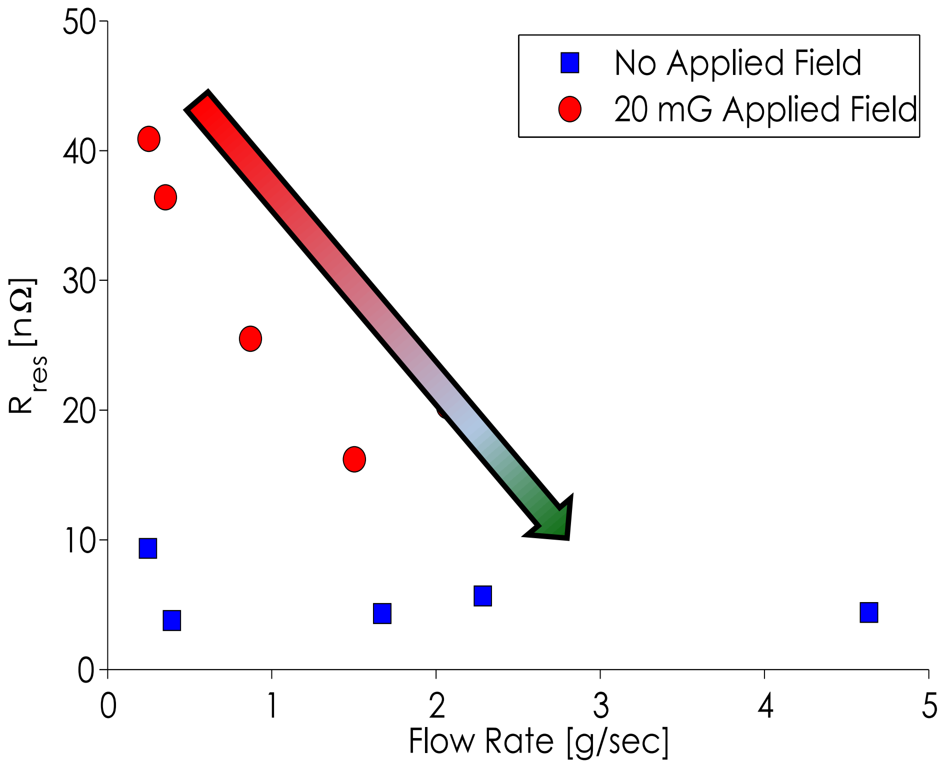
- Stronger doping results in a higher sensitivity to trapped flux.
- Nitrogen-doped cavities showed a higher sensitivity than EP and EP+120°C baked cavities.

Cool Down Studies

R_{res} vs ΔT_{vert}

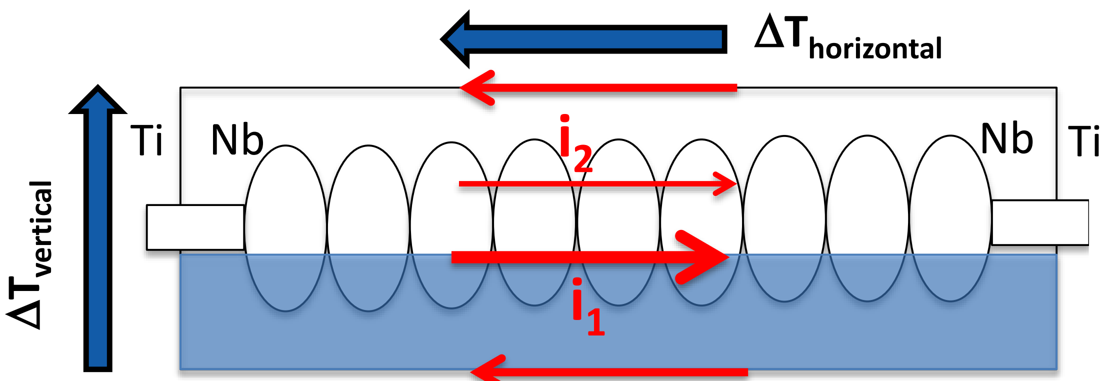


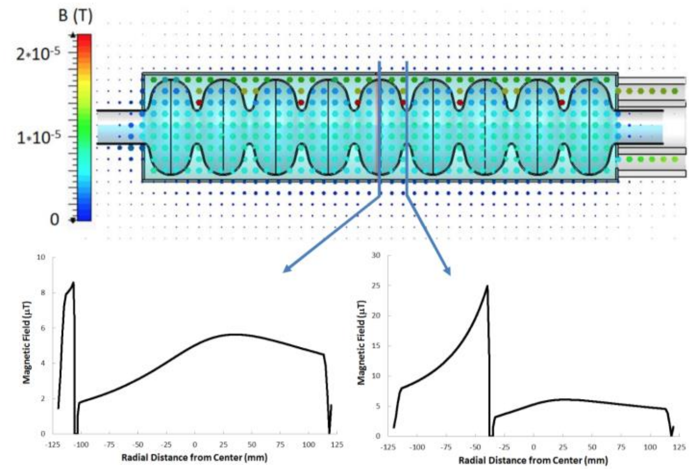
R_{res} vs Helium Mass Flow Rate



Conclusion: Helium flow rates of >2 g/s needed for efficient magnetic field expulsion by vertical temperature gradients.

Cool Down Studies





Cavity primarily cools from bottom to top => large $\Delta T_{vertical}$ in fast cool down

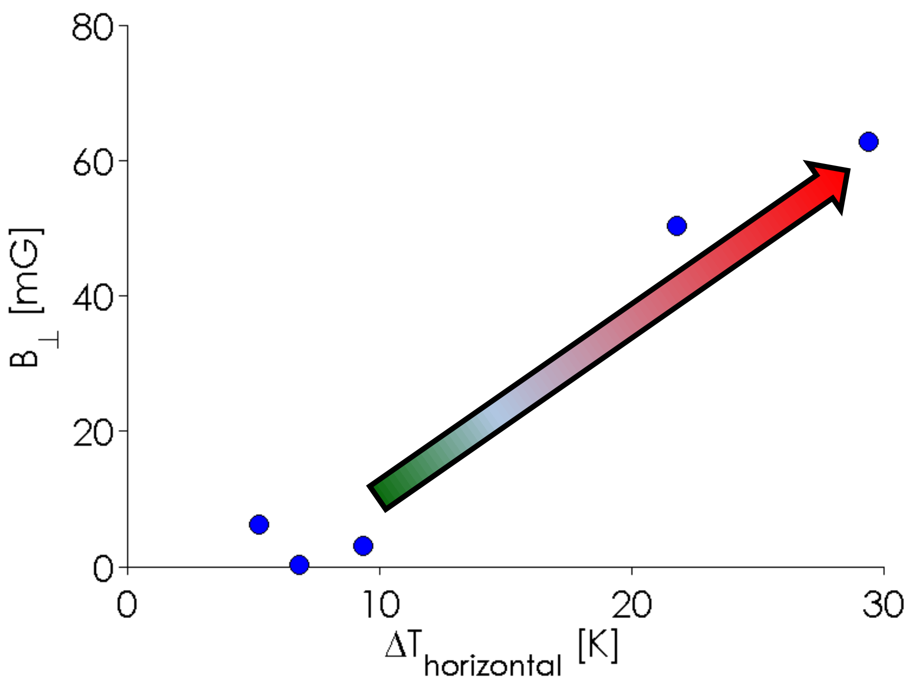
- **Good for efficient magnetic field expulsion**
- **But: conductivity $\sigma = \sigma(T)$ => Cylindrical symmetry is broken!**
  - **$\Rightarrow$ Finite $\Delta T_{horizontal}$ will drive thermal-electric currents with preferential flow through the bottom of the cavity**
  - **$\Rightarrow$ Non-zero magnetic field at the cavity inner surface**

$\Rightarrow$ Ideal cool-down: large $\Delta T_{vertical}$ by fast cool down with small $\Delta T_{horizontal}$

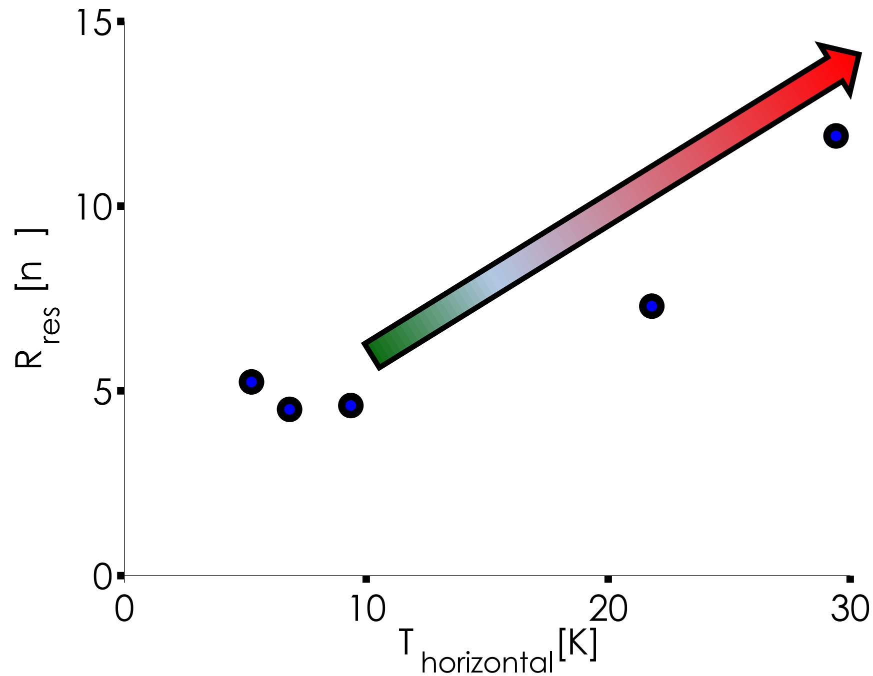
D. Gonnella et al., J. Appl. Phys. 117 , 023908 (2015)
R. Eichhorn, arXiv:1411.5285 [physics.acc-ph] (2014)
J.-M. Vogt et al., Phys. Rev. ST Accel. Beams 18, 042001 (2015)

Cool Down Studies

B_{trans} vs ΔT_{horiz}



R_{res} vs ΔT_{horiz}



<u>Conclusion</u>: Small horizontal temperature gradients <10K critical to keep impact of thermal-electric currents on R_{res} small.

The LCLS-II Helium vessel helps to minimize ΔT_{horiz}

Lessons for LCLS-II

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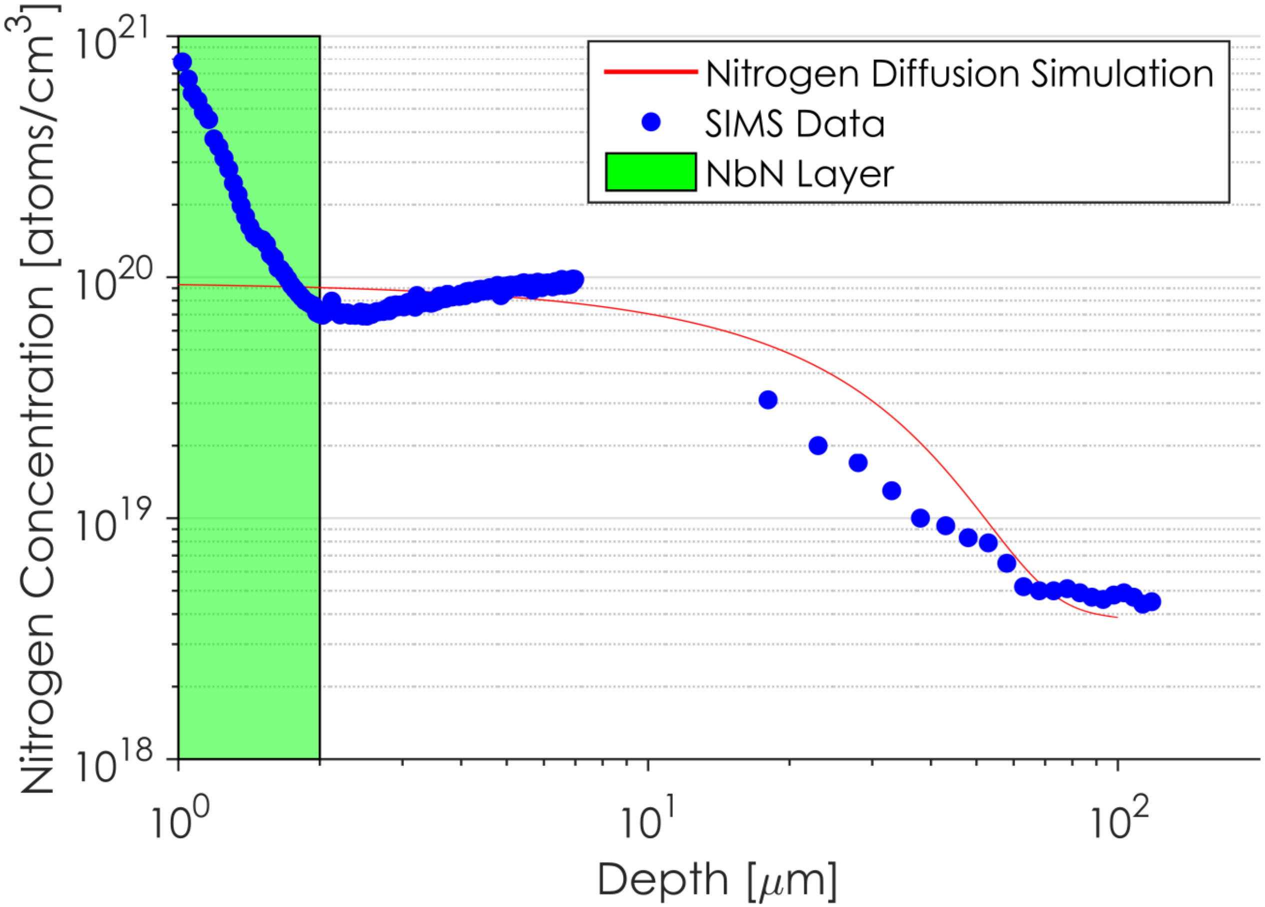
- Lesson 5: Great care needs to be taken with auxiliary parts such as HOM couplers, input couplers, etc.

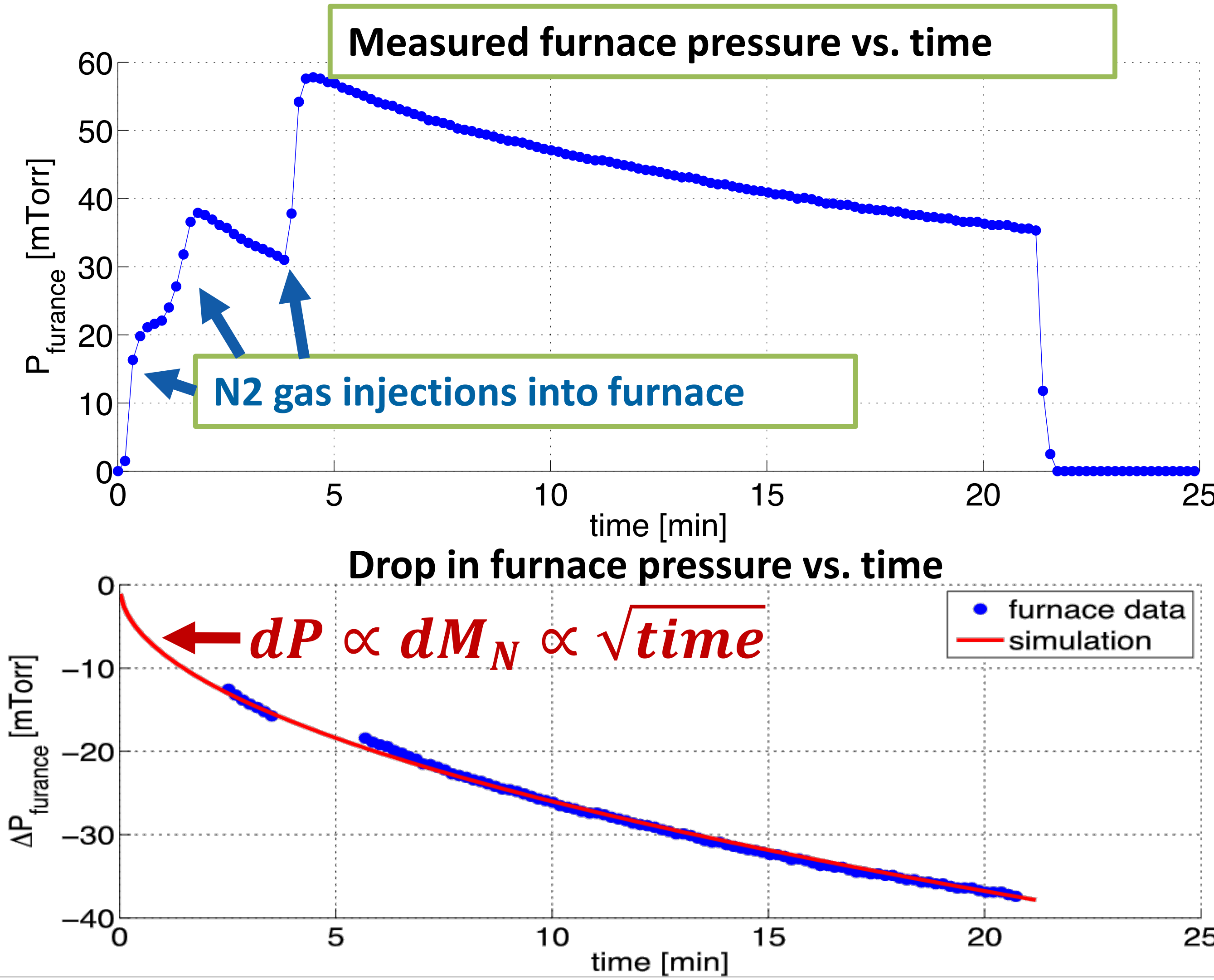
Diffusion Simulation

We have developed a diffusion simulation code that predicts nitrogen concentration in niobium based on doping parameters



Good agreement between measures interstitial nitrogen doping profile and diffusion model prediction.

Diffusion Simulation



- Nitrogen uptake during doping is not dependent on pressure
- Conclusion: Exact pressure in the furnace **does not matter** to achieve the same doping level

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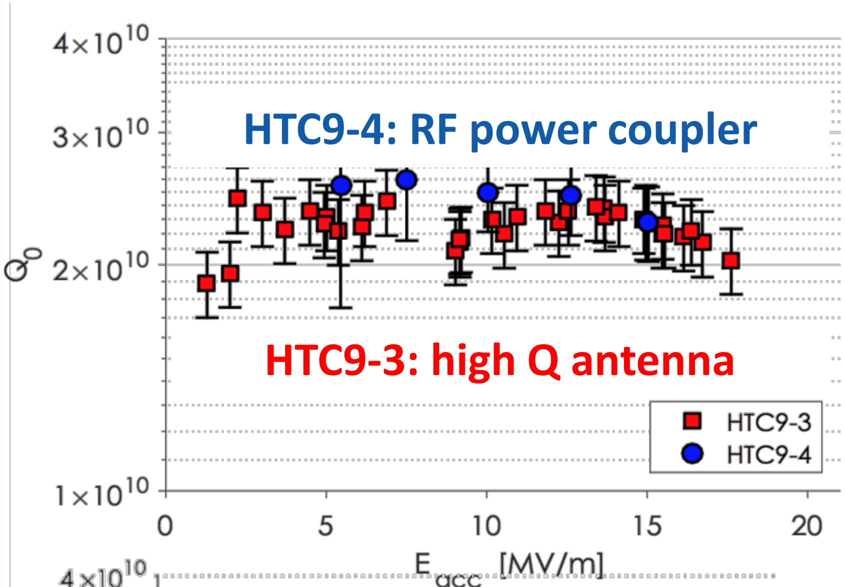
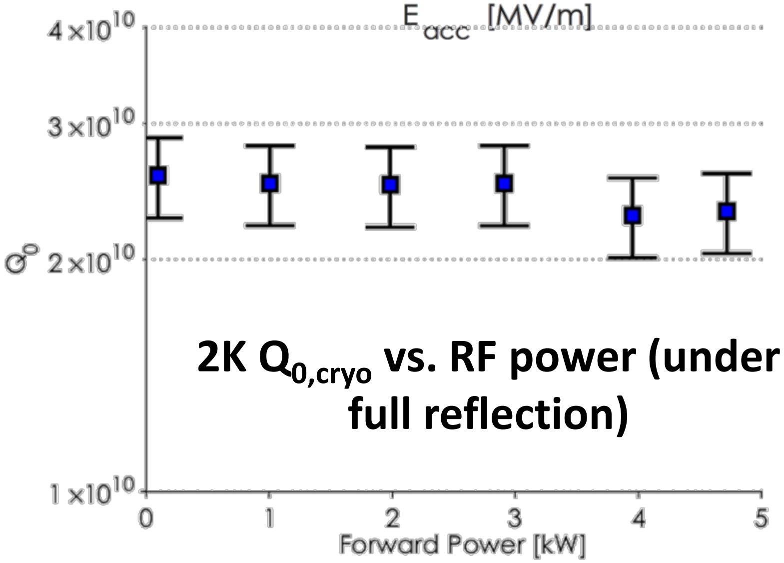
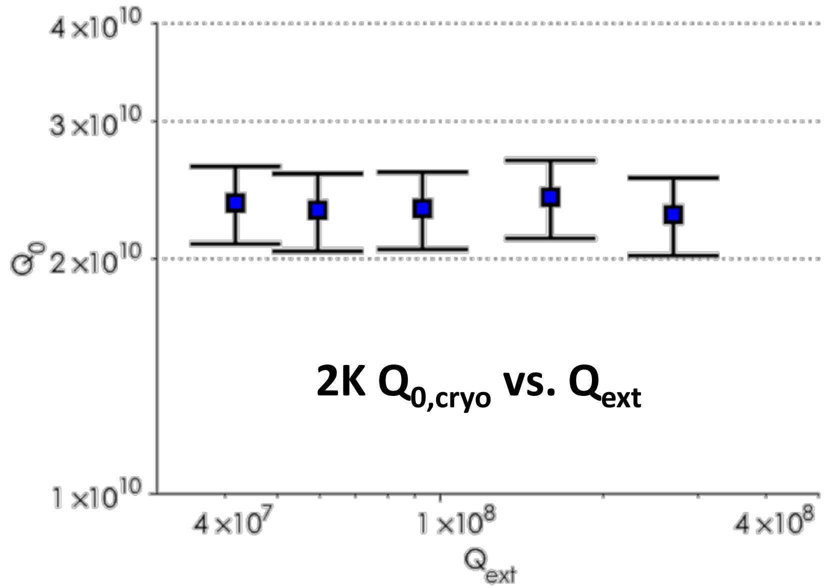
Impact of HPC on Q_0

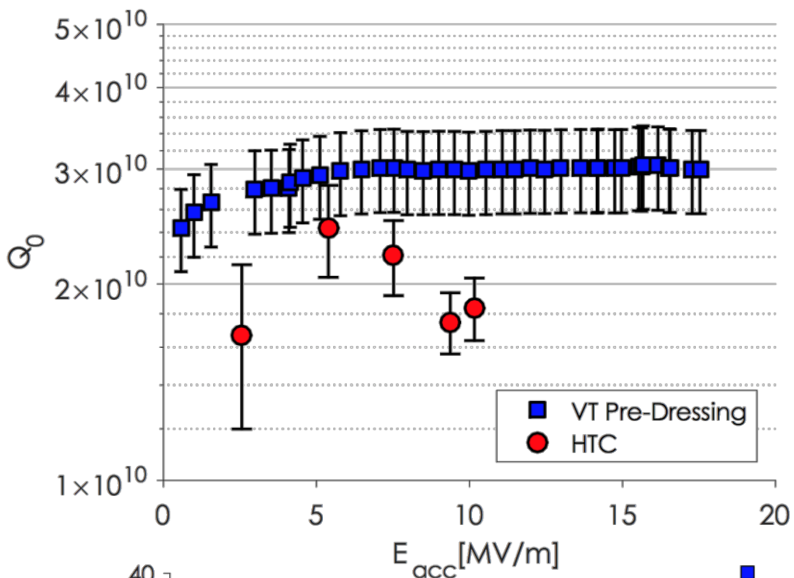


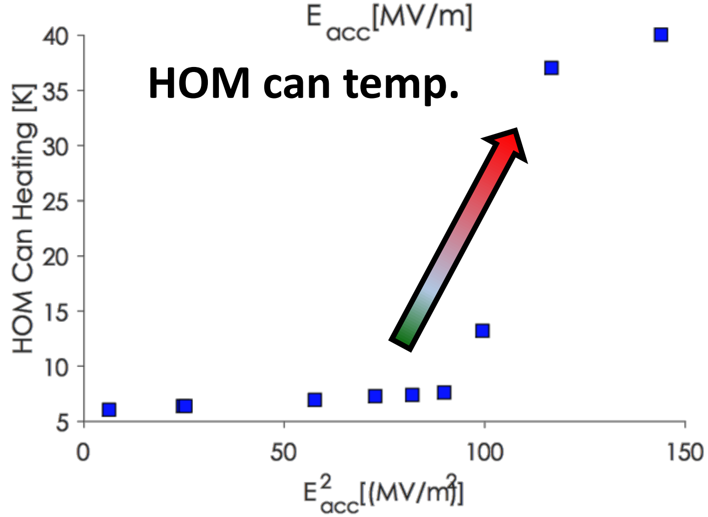
<u>Conclusion</u>: No significant increase in 2K cryogenic load or cavity performance degradation from RF input coupler.



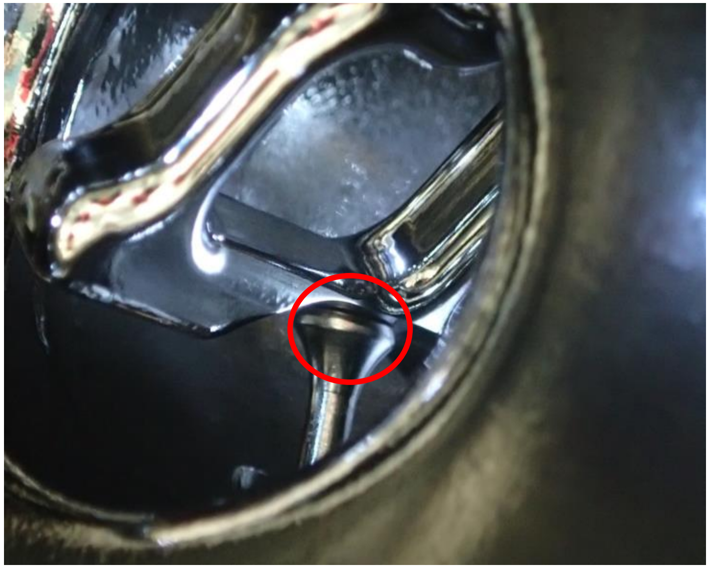


HOM Can Multipacting





Short (due to HOM can fabrication error) and <u>multipacting</u> in one HOM coupler resulted in significant heating and Q-slope



FNAL also observed this behavior but was able to condition it away

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Main Takeaway

In every vertical and horizontal test, we encountered something unexpected – it is reasonable to assume that we will continue to experience this at the beginning of production