Niobium Impurity-Doping Studies at Cornell

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On behalf of: P. Bishop, B. Clasby, H. Conklin, R. Eichhorn, B. Elmore, F. Furuta, G.M. Ge, ***D. Gonnella****, T. Gruber, G. Kulina, D. Hall, G. Hoffstaetter, J. Kaufman, P. Koufalis, J. Maniscalco, T. O'Connel, P. Quigley, D. Sabol, J. Sears, E. Smith, V. Veshcherevich*

U.S. DEPARTMENT OF ENERGY
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Outline

- Single-cell N-doping studies
- Multicell N-doped cavity performance
- Cryomodule testing of N-doped cavities
- Conclusions

Single-cell N-doping studies

For more information, see posters MOPB004 and MOPB042

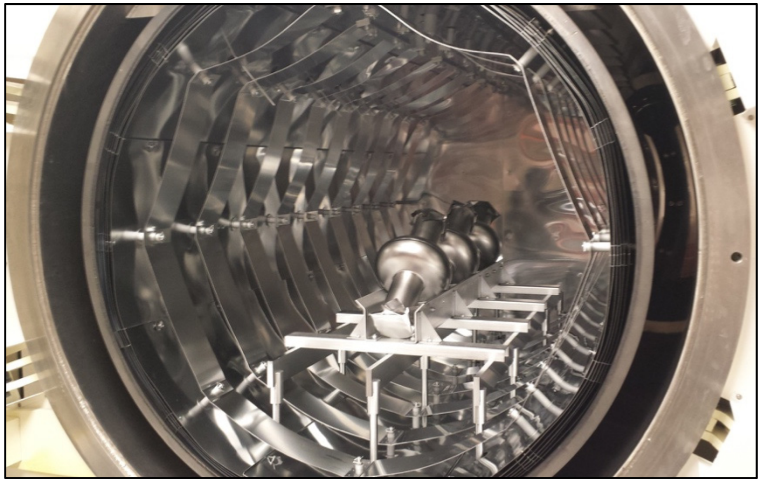
Single-cell N-Doping Studies

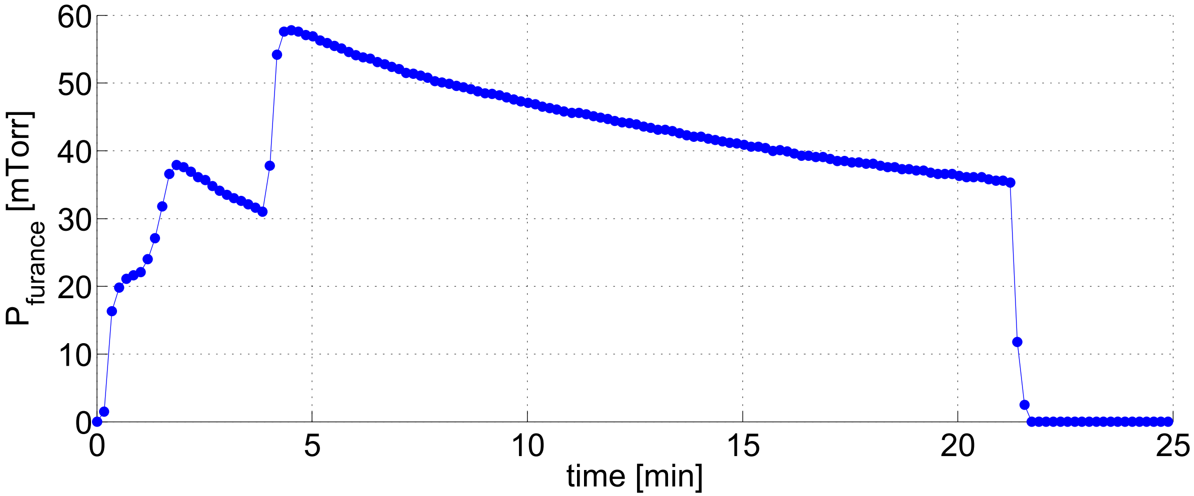
Study #1 (5 cavities):

- **20 min N-doping at 800C + 30 min anneal at 800C**
- **Different final VEP amounts**

Study #2 (1 cavity):

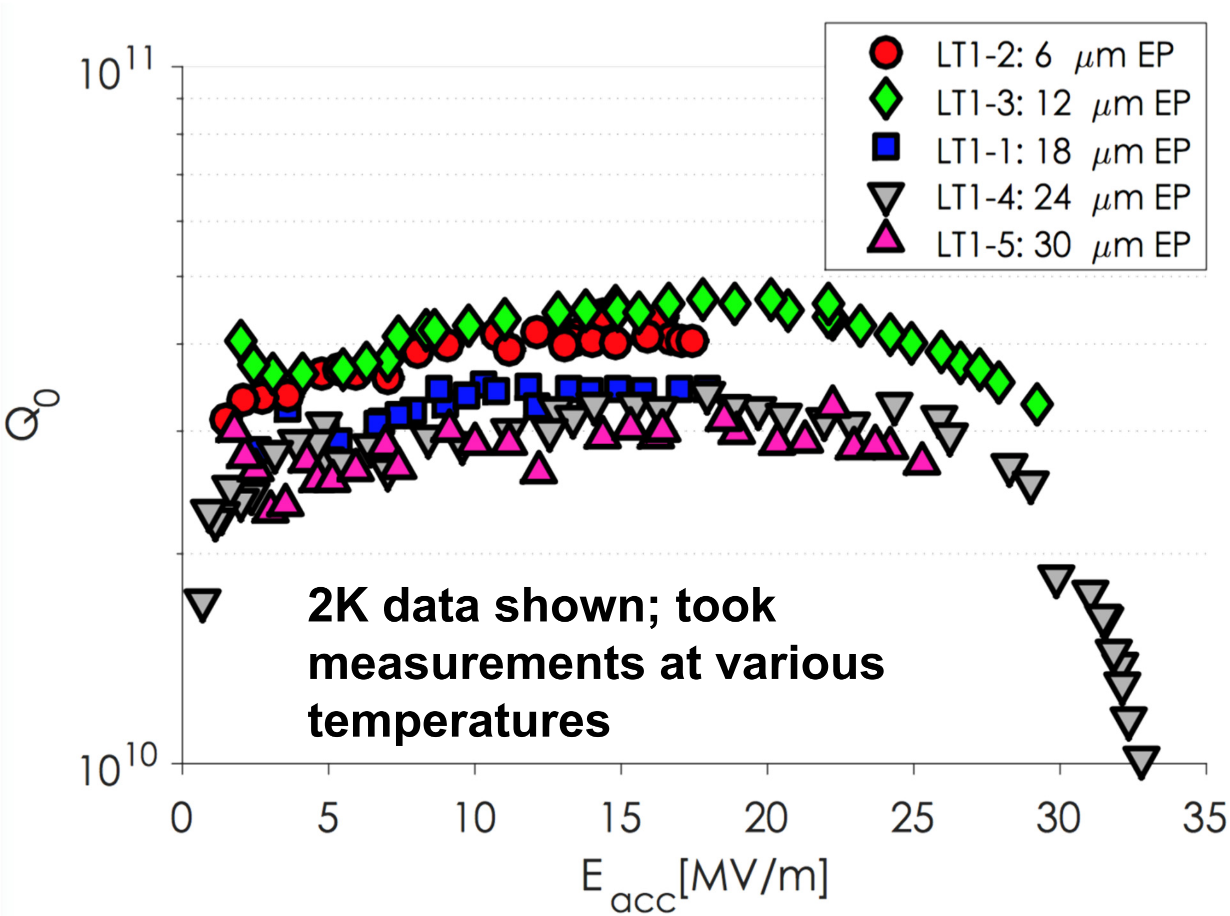
- **20 min N-doping at 900C + 30 min anneal at 900C**





Study #1: 20N30 N-Doping at 800C

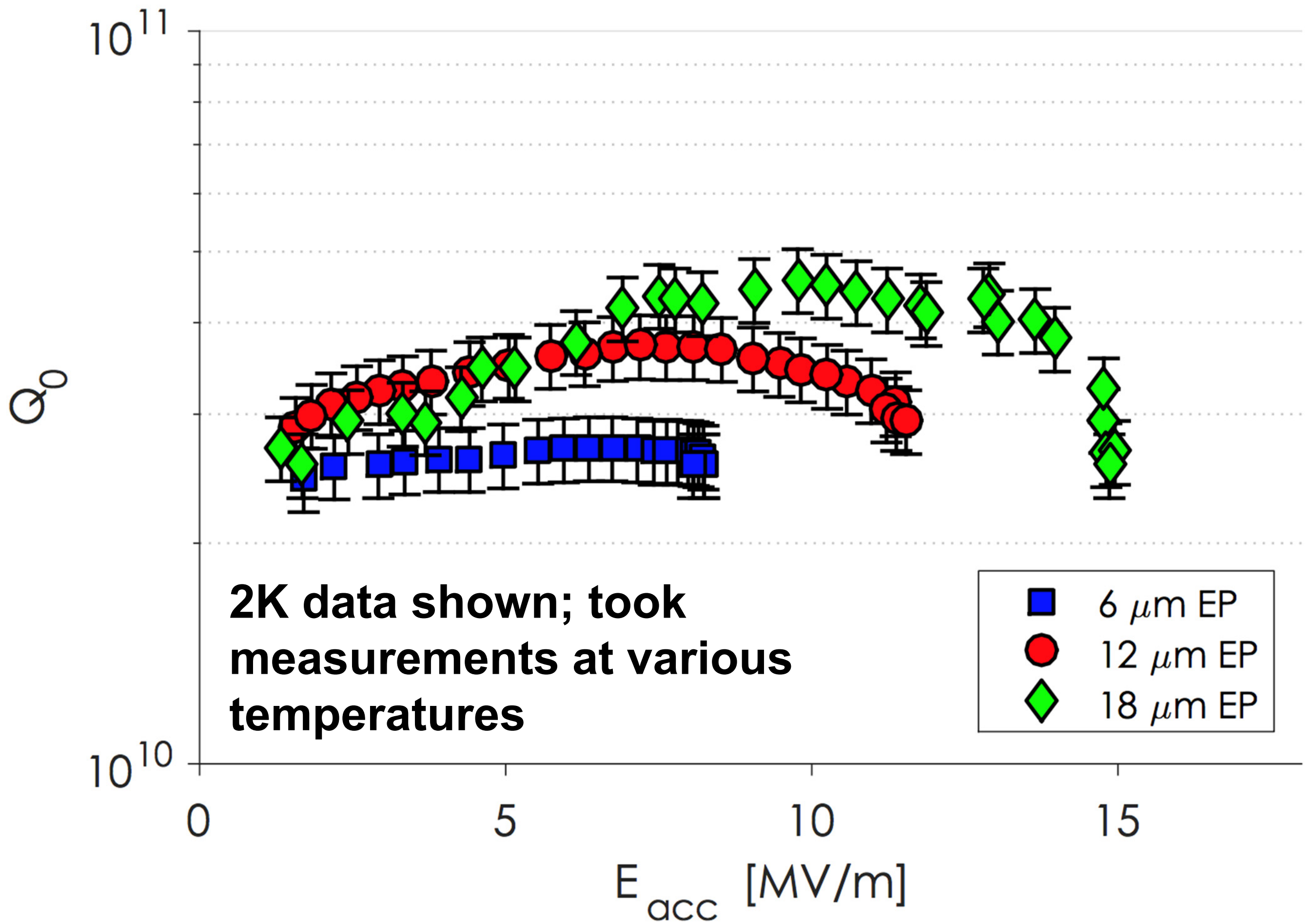
Doping at "nominal" LCLS-II doping temperature



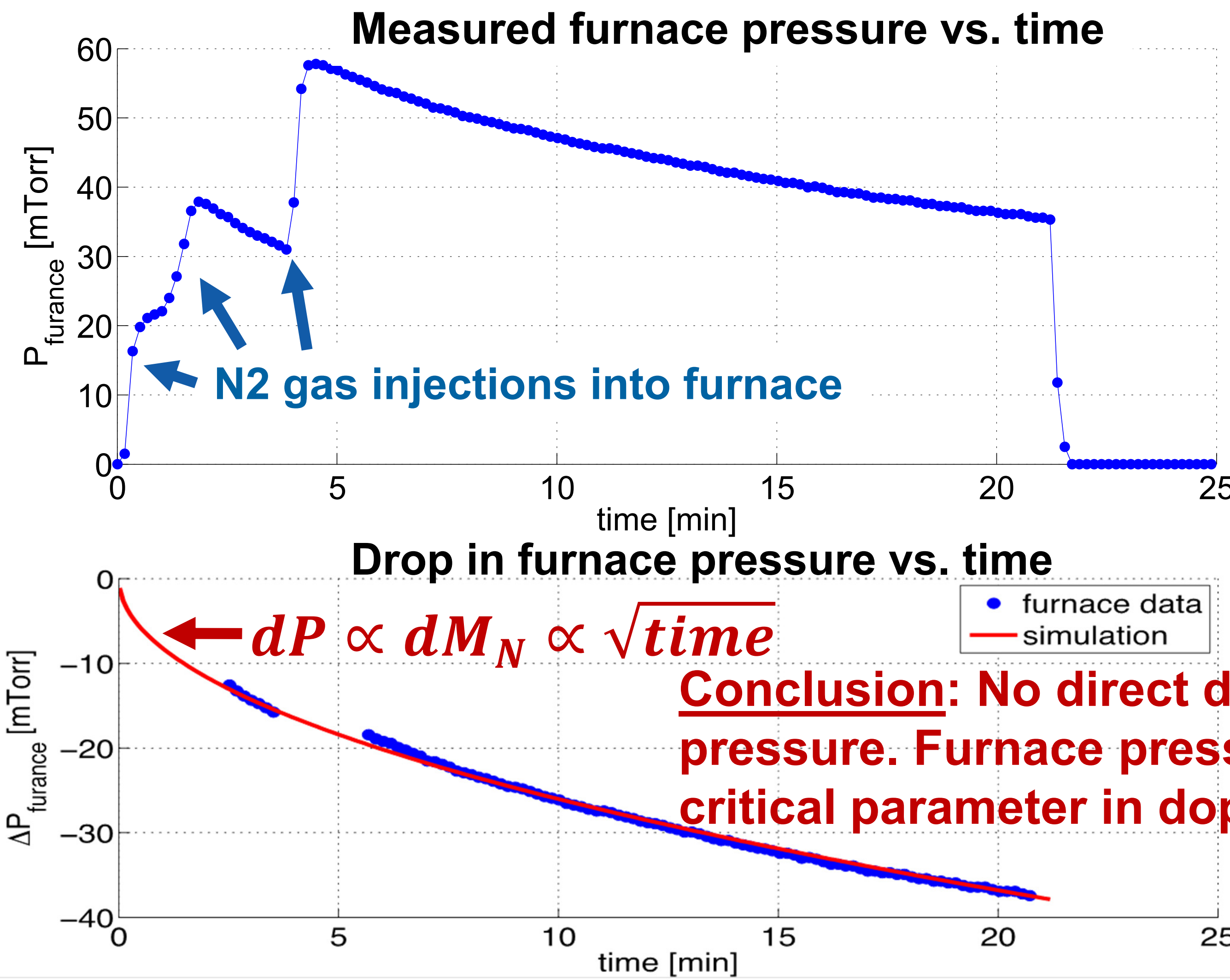
- Average Q_0 at **2K**: **3.6 x 10^{10}** at 16 MV/m
- Average max field: **27 MV/m**
- Far exceeding LCLS-II specs

Study #2: 20N30 N-Doping at 900C

Doping at elevated temperature ("over-doping")

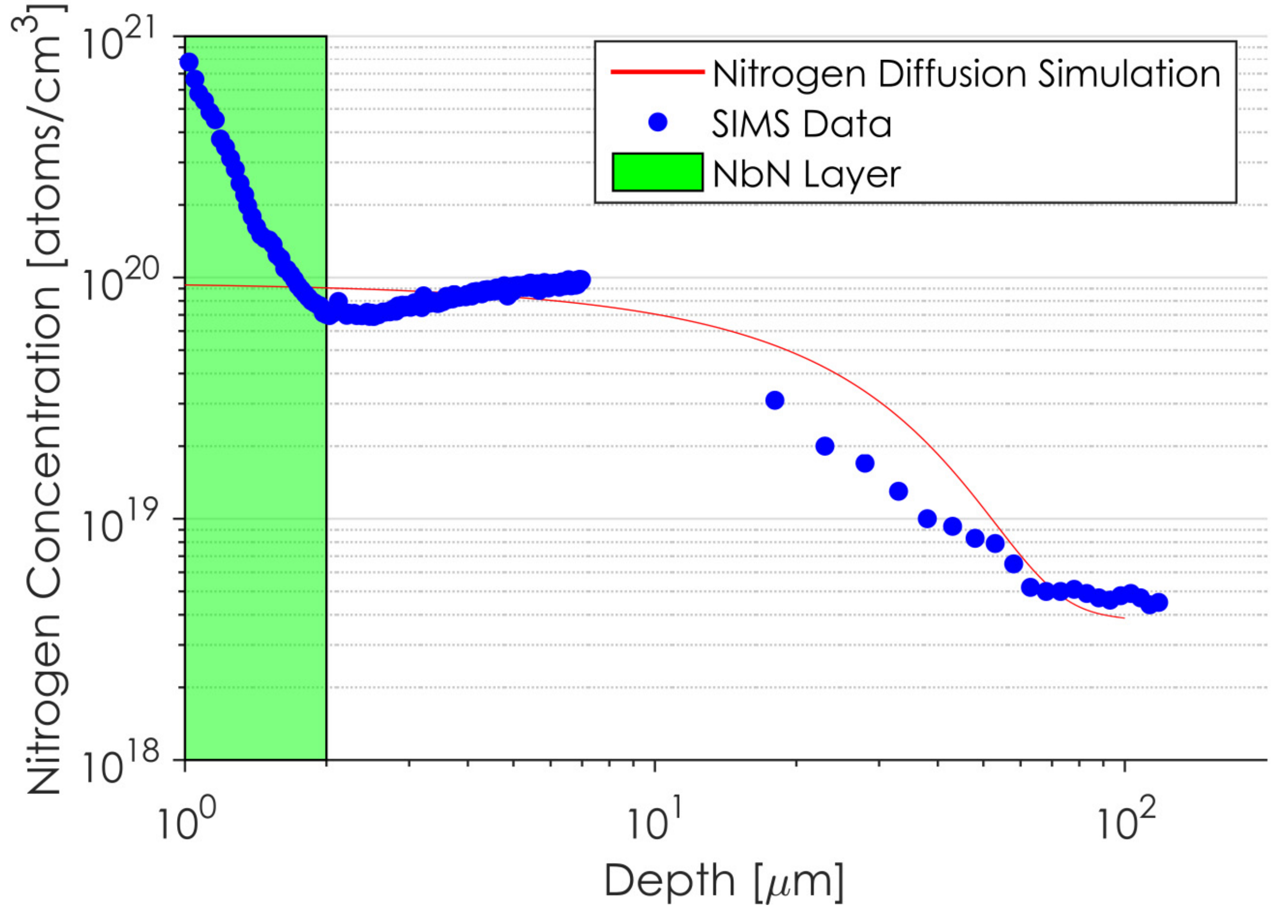


N-Doping Model Development: N-Uptake



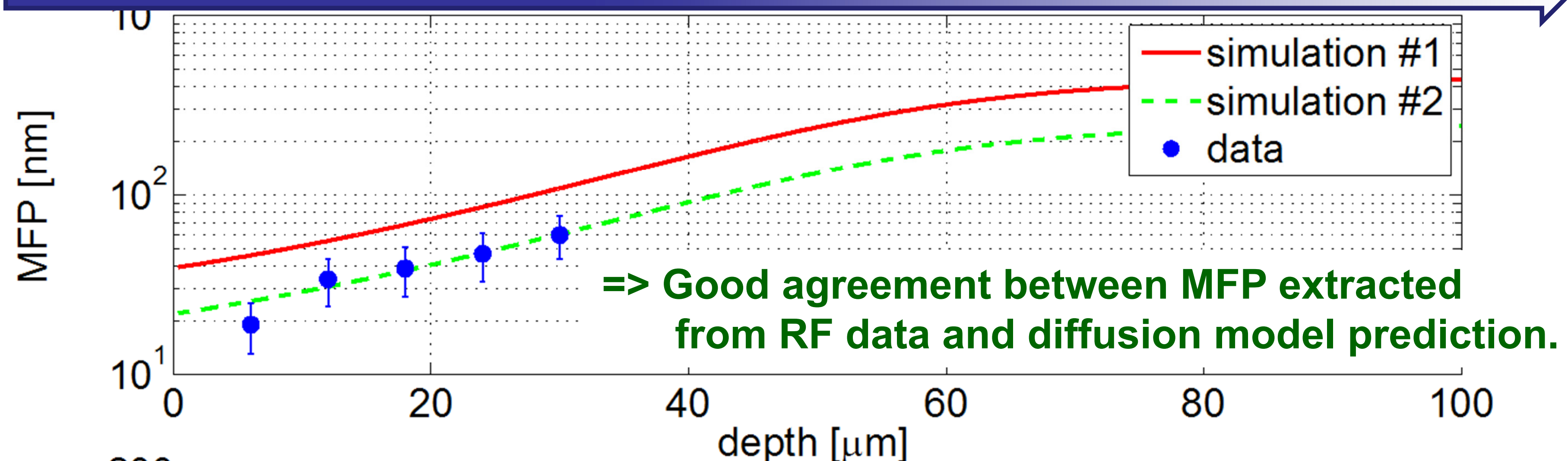
<u>Conclusion</u>: No direct dependence on pressure. Furnace pressure is not a critical parameter in doping process.

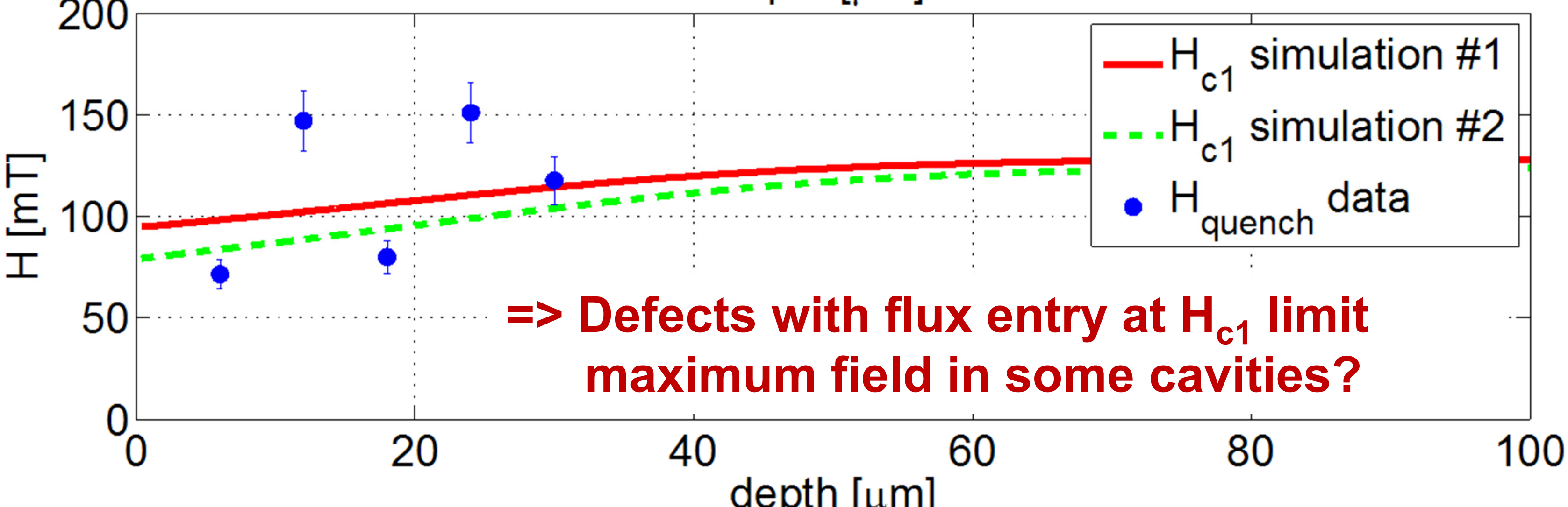
N-Doping Model Development: Doping Depth Profile



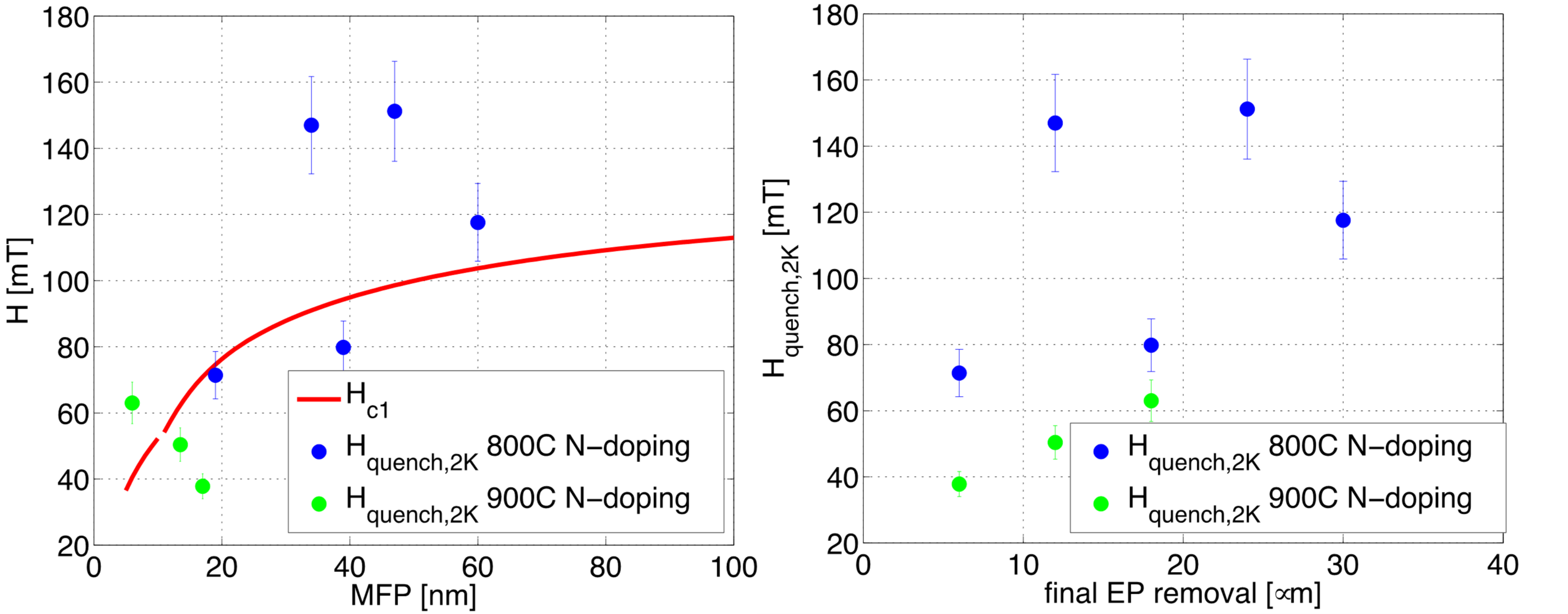
=> Good agreement between measures interstitial nitrogen doping profile and diffusion model prediction.

N-Doping Model Development: MFP and H_{c1} vs. Depth



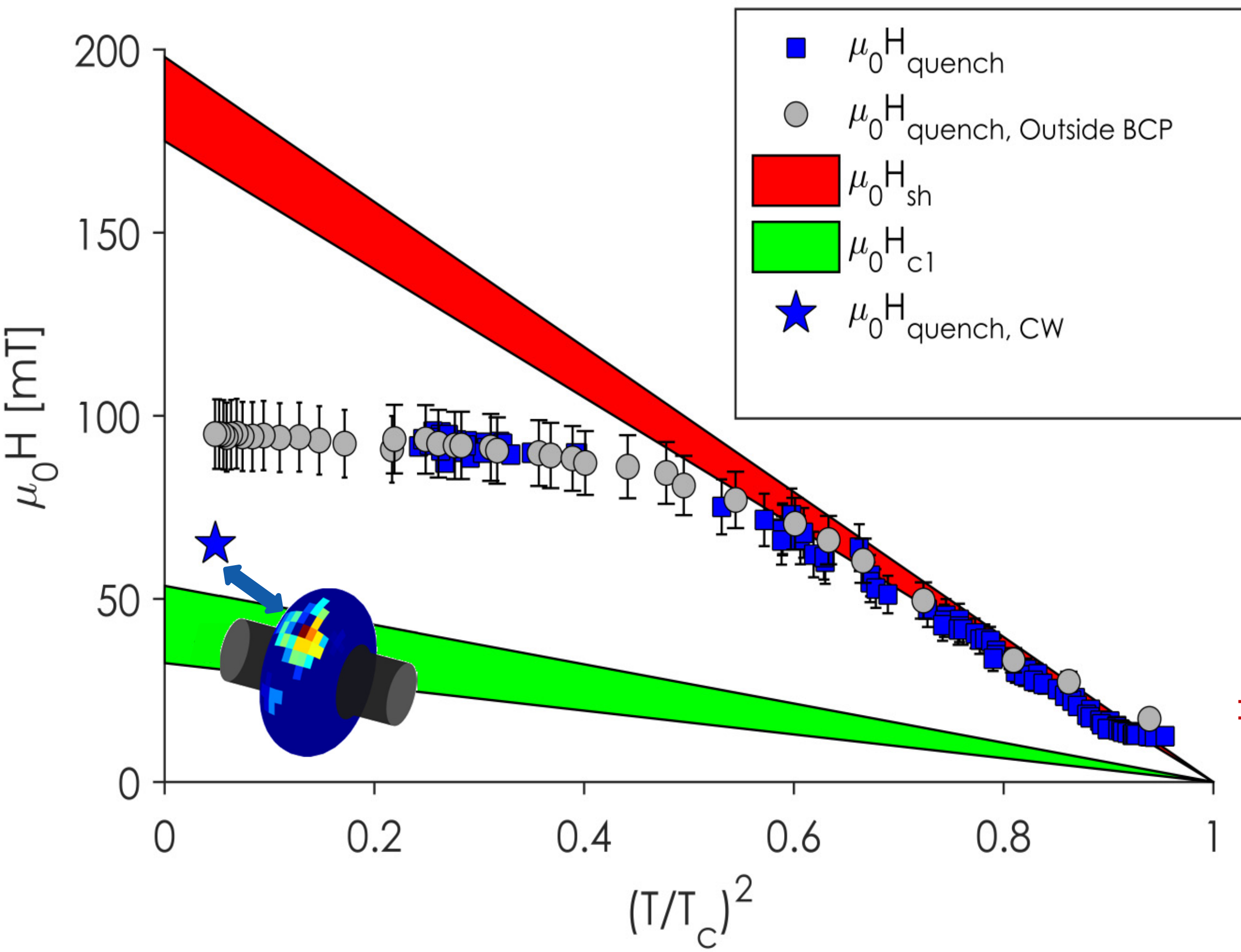


N-Doping and Quench Studies



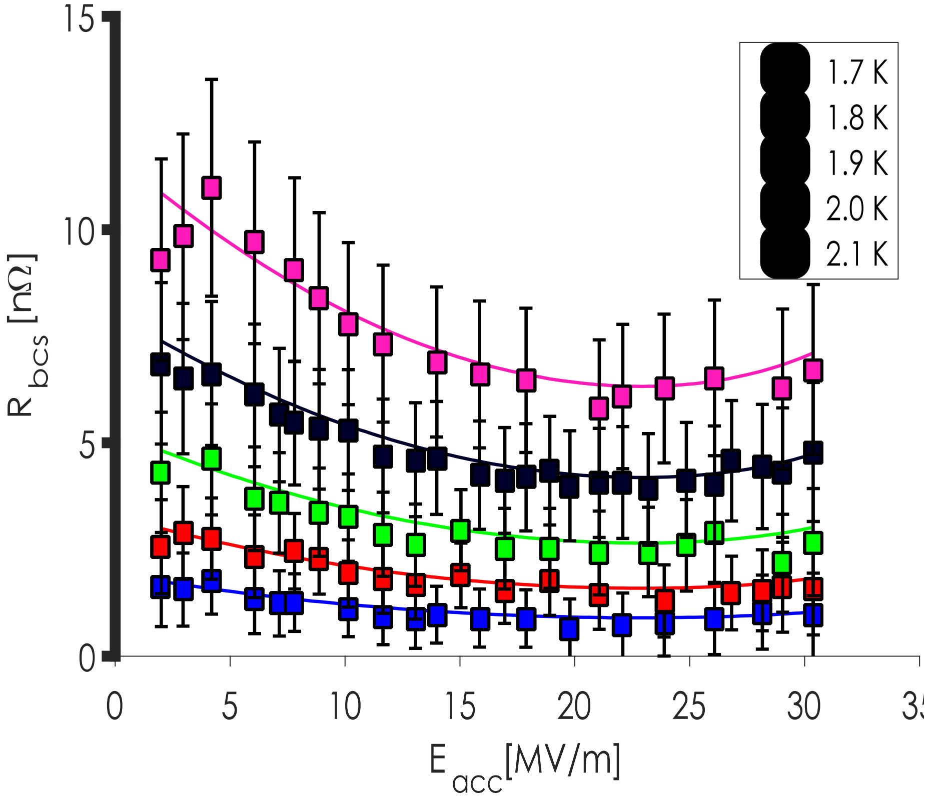
- ⇒ **Defects with flux entry at ~H_{c1} limit maximum field in some cavities?**
- ⇒ **Note: 800C doping reduces H_{c1} by ~30%**
- ⇒ **Minimum of few μm EP needed to remove all surface NbN?**

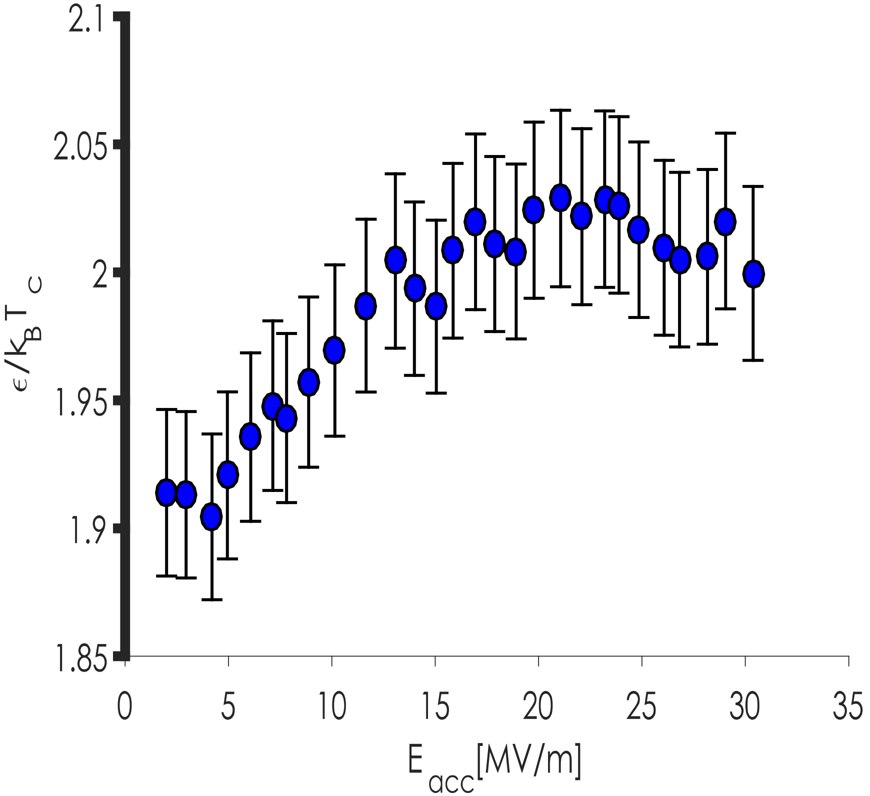
Pulsed High-Power Quench Studies on 900C "overdoped" Cavity



⇒ **Defect limited at lower temperatures!**

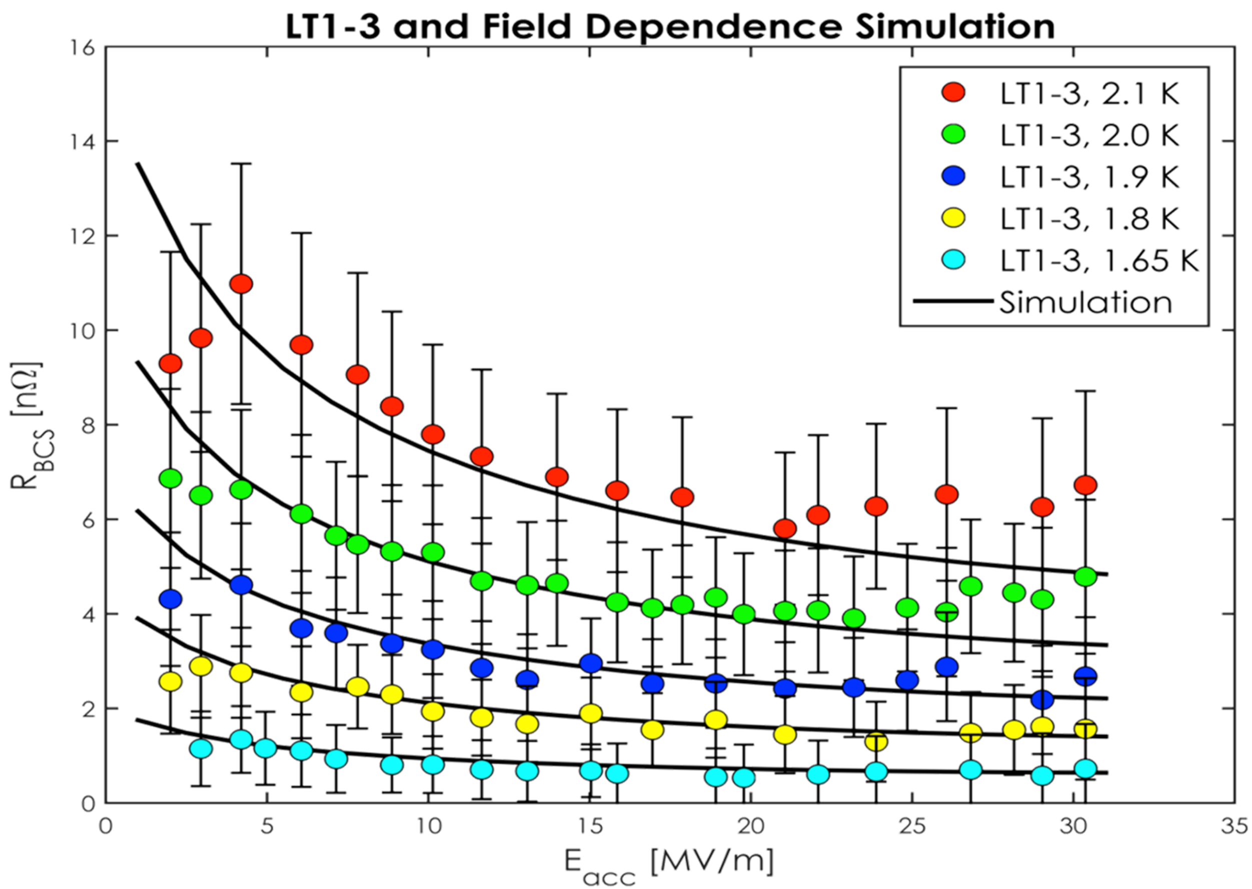
N-Doping Effect on Q_0: $R_{BCS}(E_{acc})$ Studies





<u>Conclusion</u>: Observed field dependency of temperature depended part of surface resistance well described by assuming field dependent effective spectral gap.

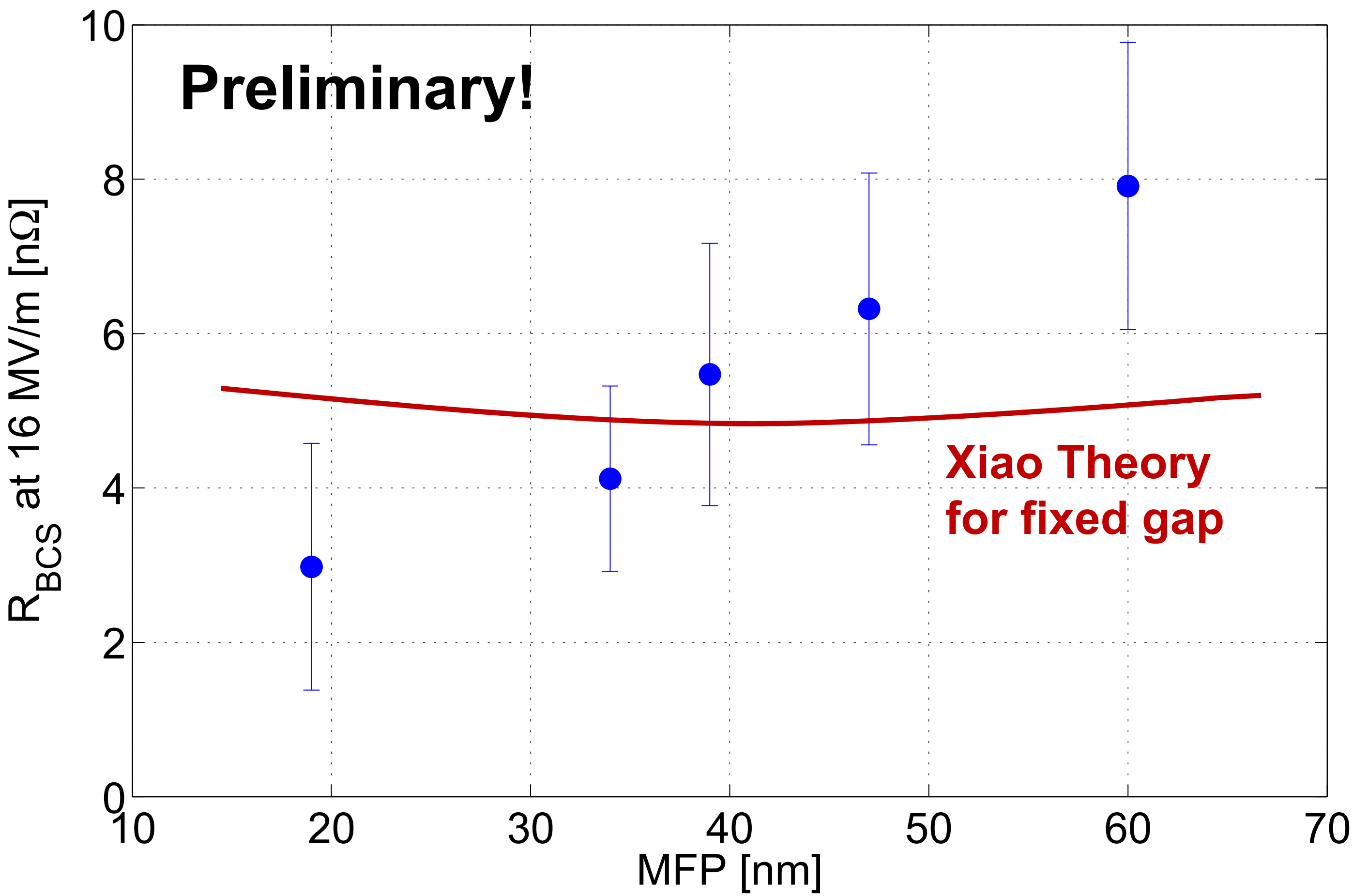
N-Doping Effect on Q_0: Comparison with Moving Cooper Pair Theory (B.P Xiao)



B.P. Xiao, C.E. Reece, and M.J. Kelley, Superconducting surface impedance under radiofrequency field. Physica C: Superconductivity, 2013. 490(0): p. 26-31.

Acknowledgements to Binping Xiao for providing this simulation code.

N-Doping Effect on Q_0: Dependence on MFP

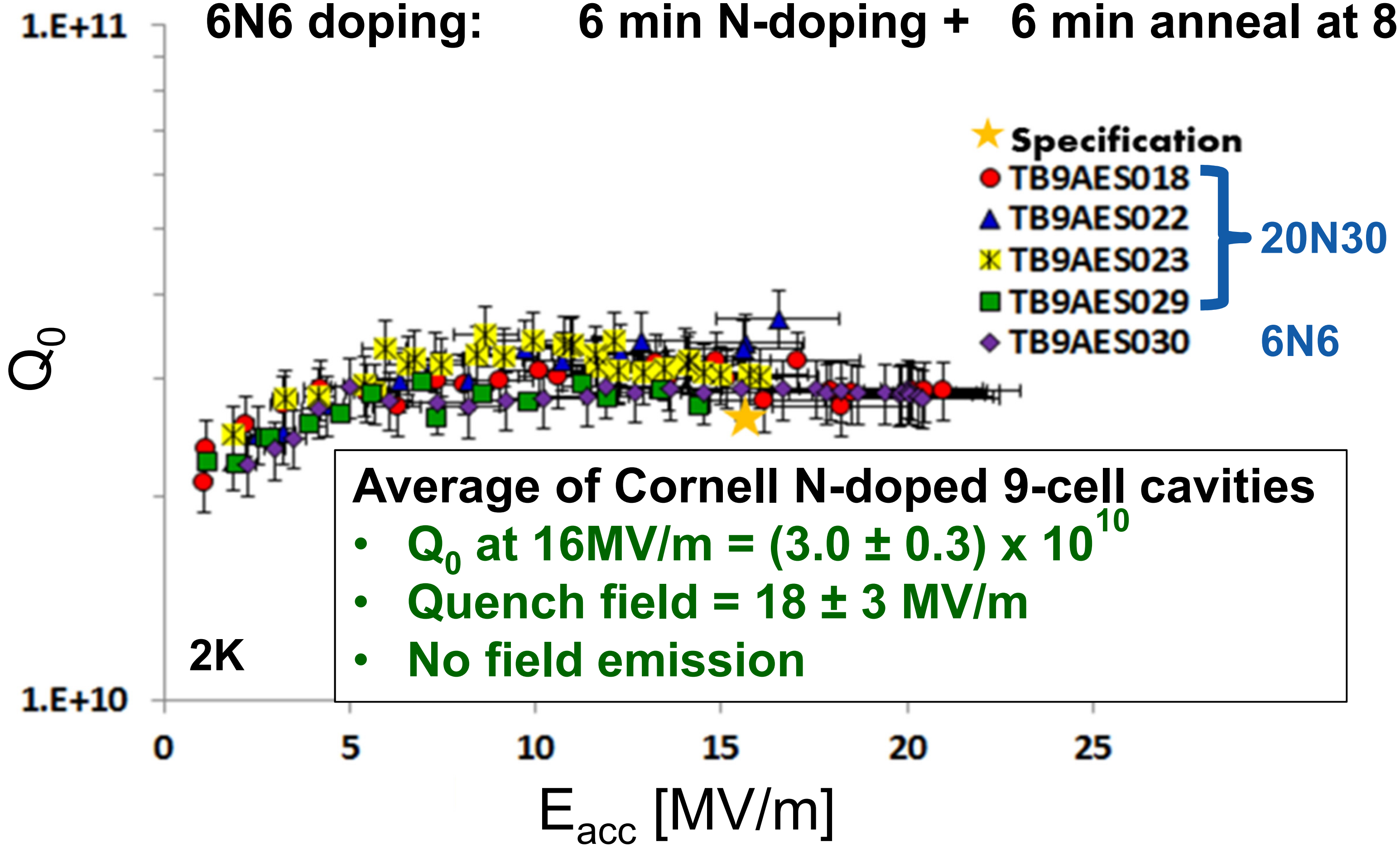


Multicell N-doped cavity performance

For more information, see poster MOPB084

9-cell N-Doped Cavity Performance

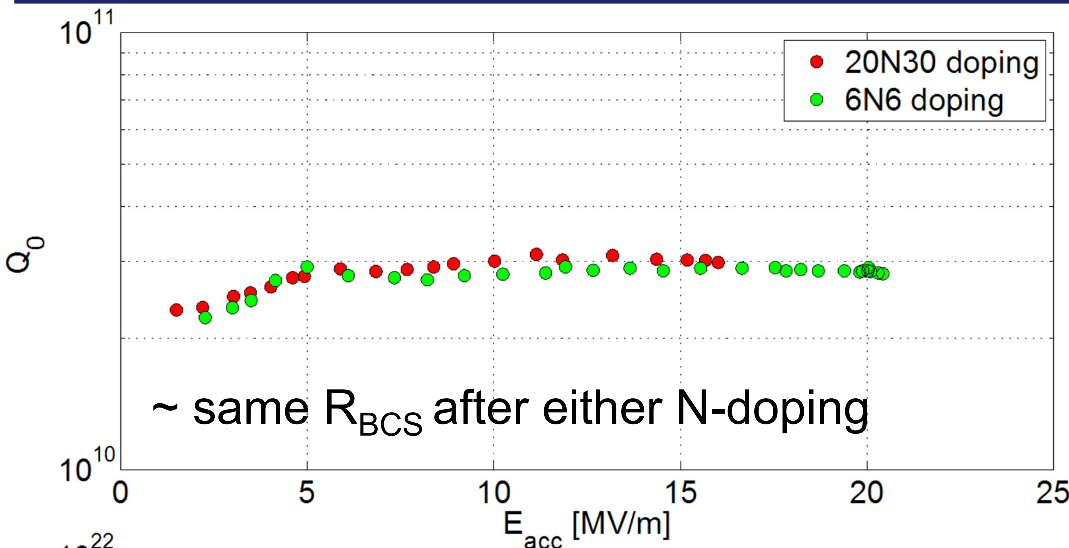
20N30 doping: 20 min N-doping + 30 min anneal at 800C
6N6 doping: 6 min N-doping + 6 min anneal at 800C

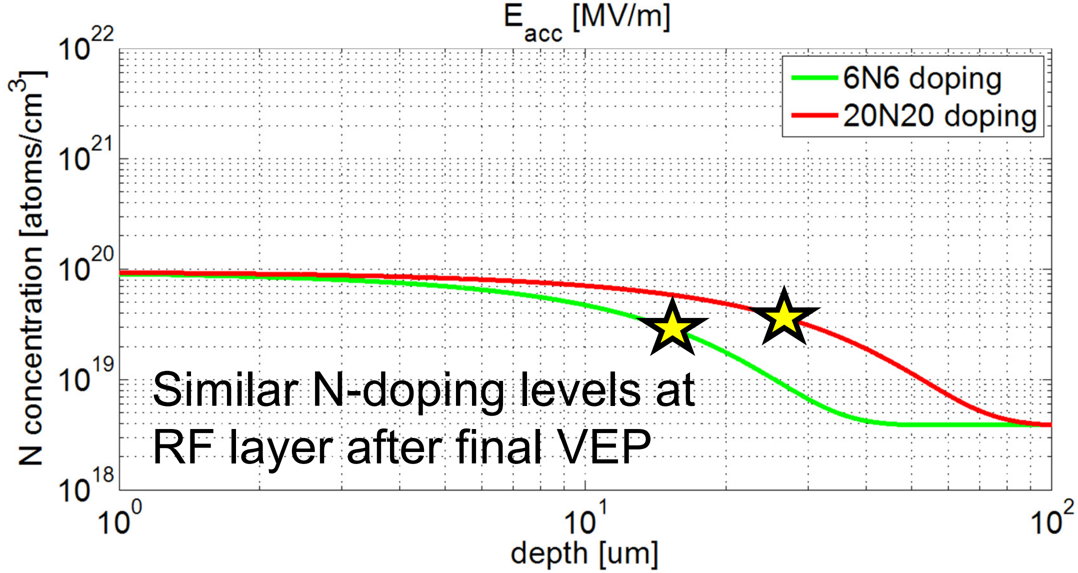


Average of Cornell N-doped 9-cell cavities

- Q_0 at 16MV/m = $(3.0 \pm 0.3) \times 10^{10}$
- Quench field = 18 ± 3 MV/m
- No field emission

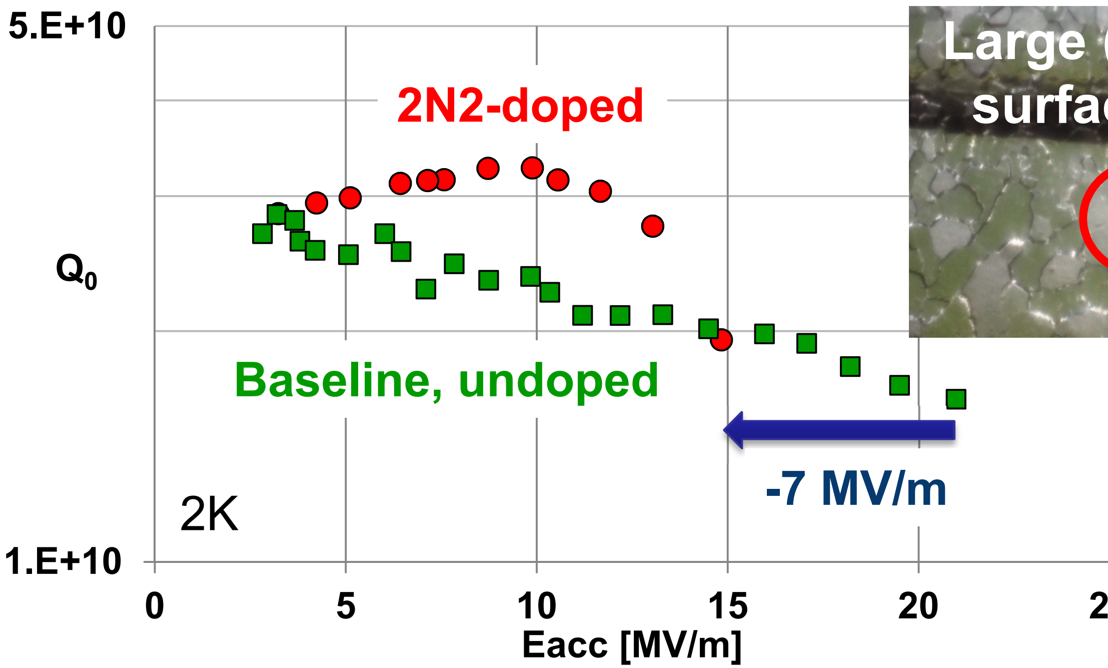
Short vs. Long N-Doping: TB9AES030

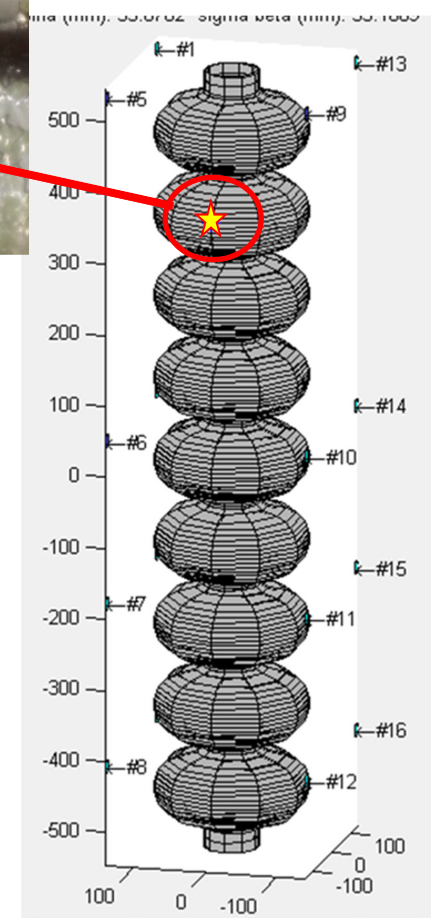




- **Preparation #1 (20N30)**
  - 20 min N-doping + 30 min anneal
  - 26 μm final VEP
- **Preparation #2 (6N6):**
  - Surface reset VEP (40 μm)
  - 6 min N-doping + 6 min anneal
  - 14 μm final VEP
- **Higher quench field after short N-doping due to:**
  - More total chemistry?
  - Thinner doping layer (has very poor thermal conductivity with RRR~10)?
  - Somewhat lower N-doping level (higher H_{c1})?

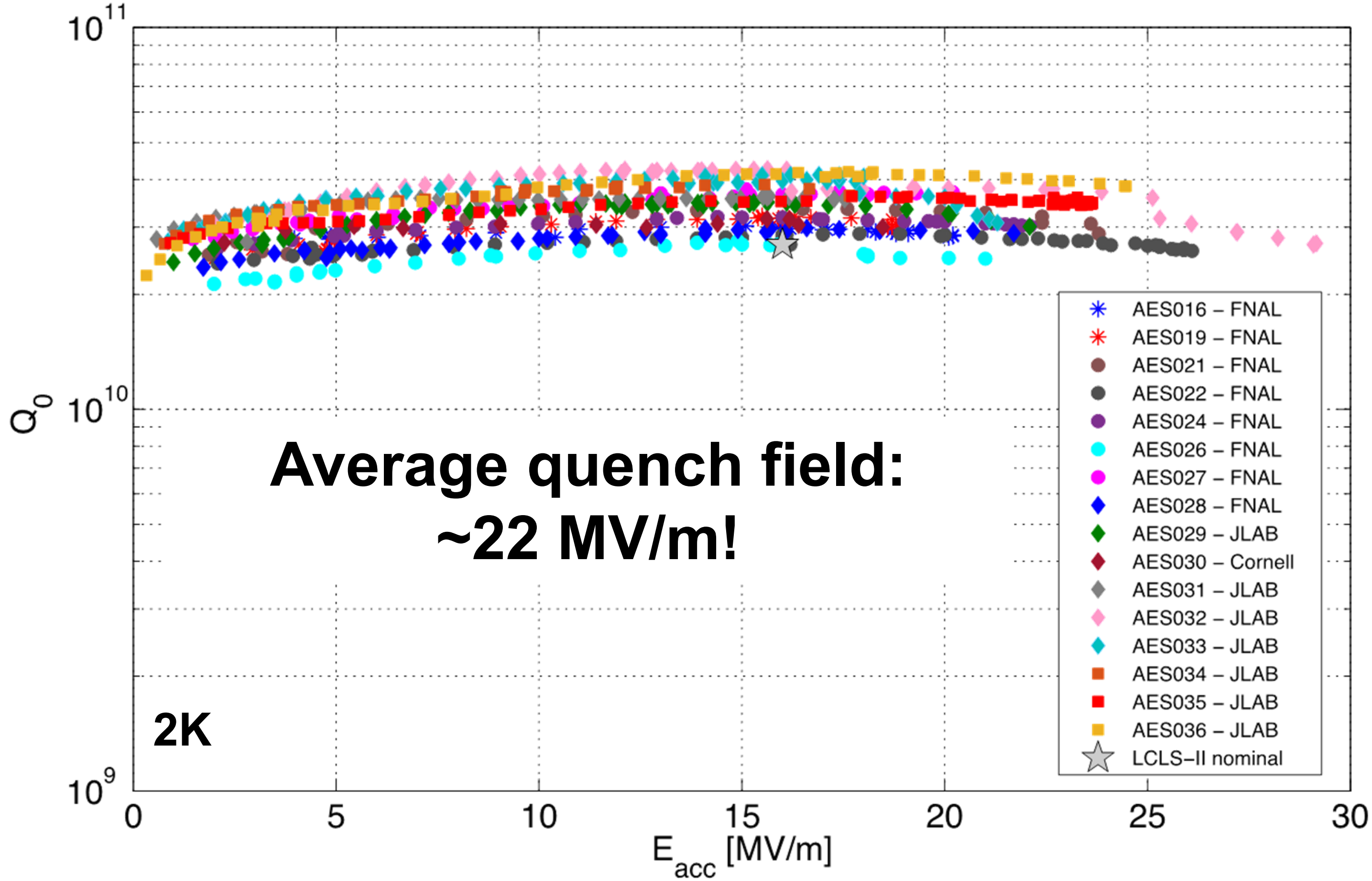
9-cell N-Doped Cavity Quench: TB9AES22





- **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

Combined JLAB, FNAL, Cornell Cavity Performance after Short N-Doping

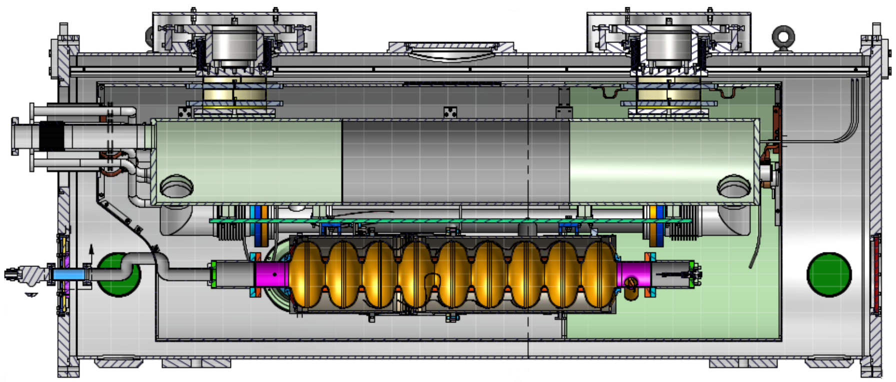


Conclusion: Reduced lower critical field H_{c1} in N-doped cavities => earlier vortex penetration at defects => lower average quench field.

Cryomodule testing of N-doped cavities

For more information, see poster MOPB041

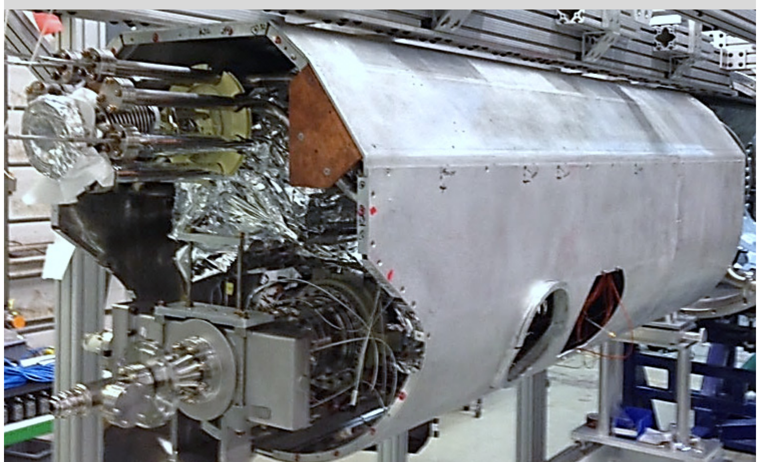
Cornell Horizontal Test Cryomodule (HTC)



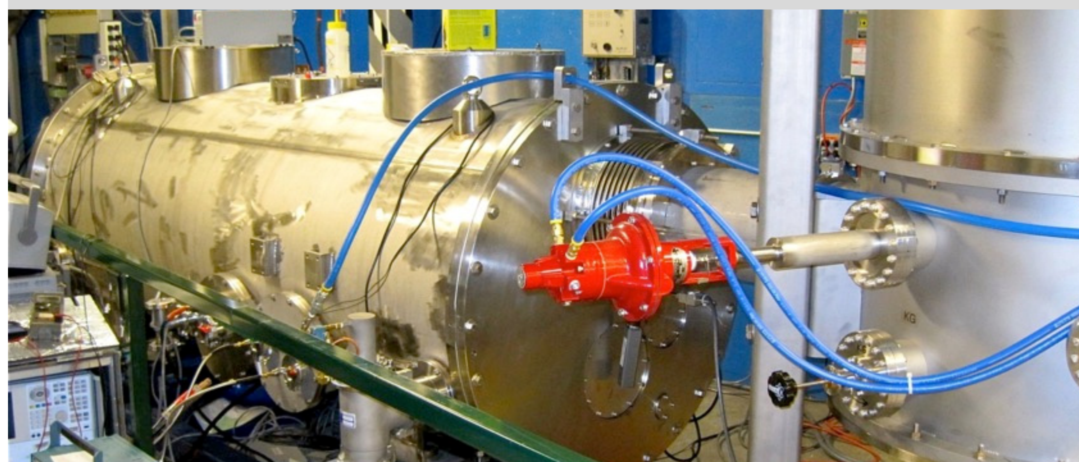
One-cavity test cryomodule

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

Module assembly



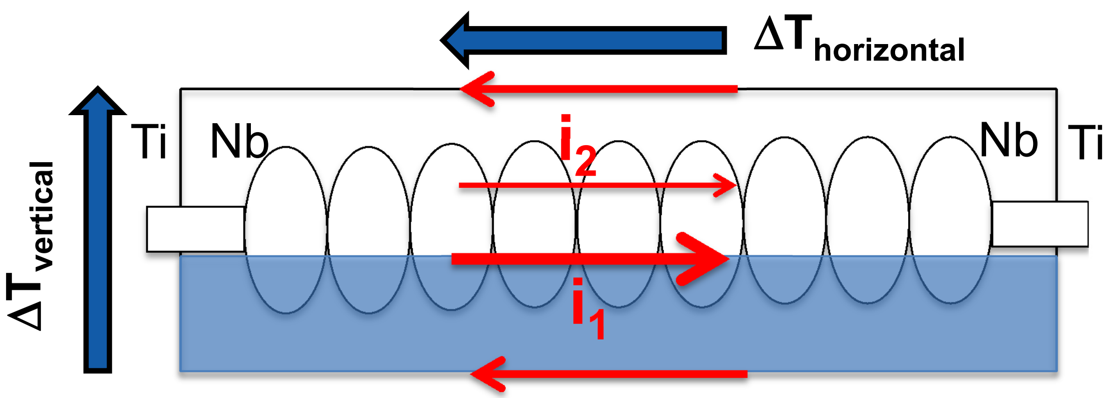
Test cryomodule installed in test area

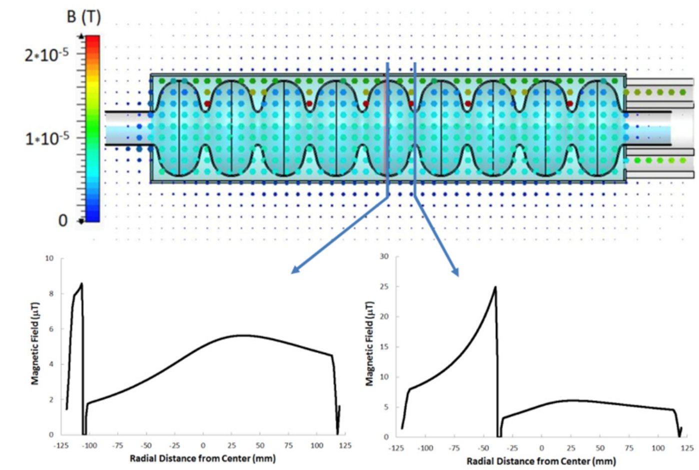


HTC Testing of LCLS-II N-Doped Cavities

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

Cool-down and Thermal Currents in Horizontal Tests





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

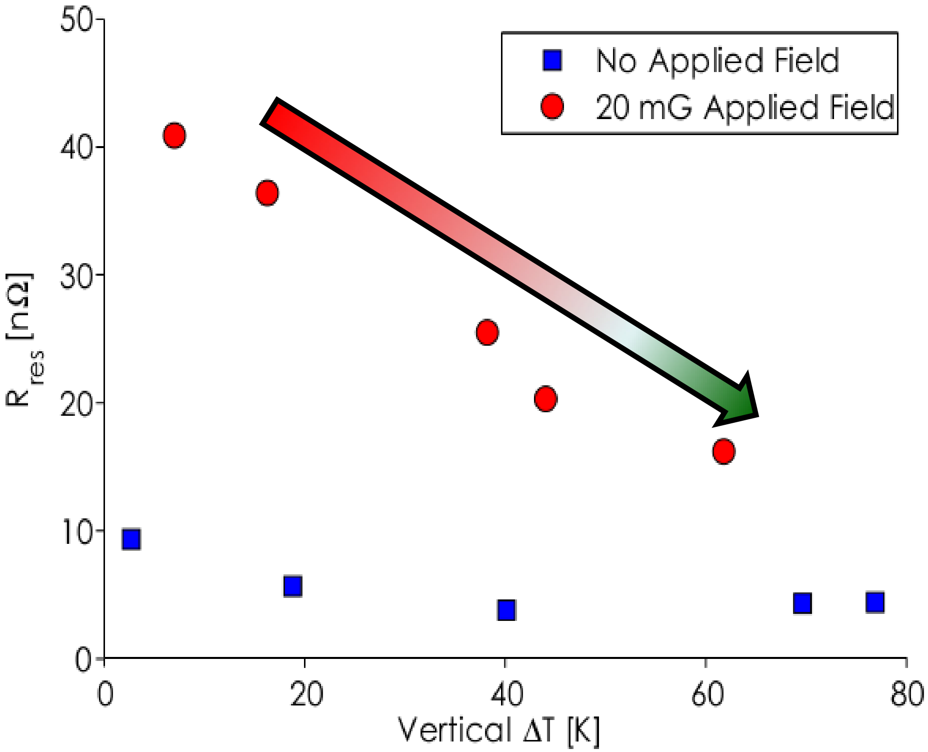
- **Good for efficient magnetic field expulsion**
- **But: conductivity $\sigma = \sigma(T)$ => Cylindrical symmetry is broken!**
  - $\Rightarrow$ **Finite $\Delta T_{horizontal}$ will drive thermal-electric currents with preferential flow through the bottom of the cavity**
  - $\Rightarrow$ **Non-zero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

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

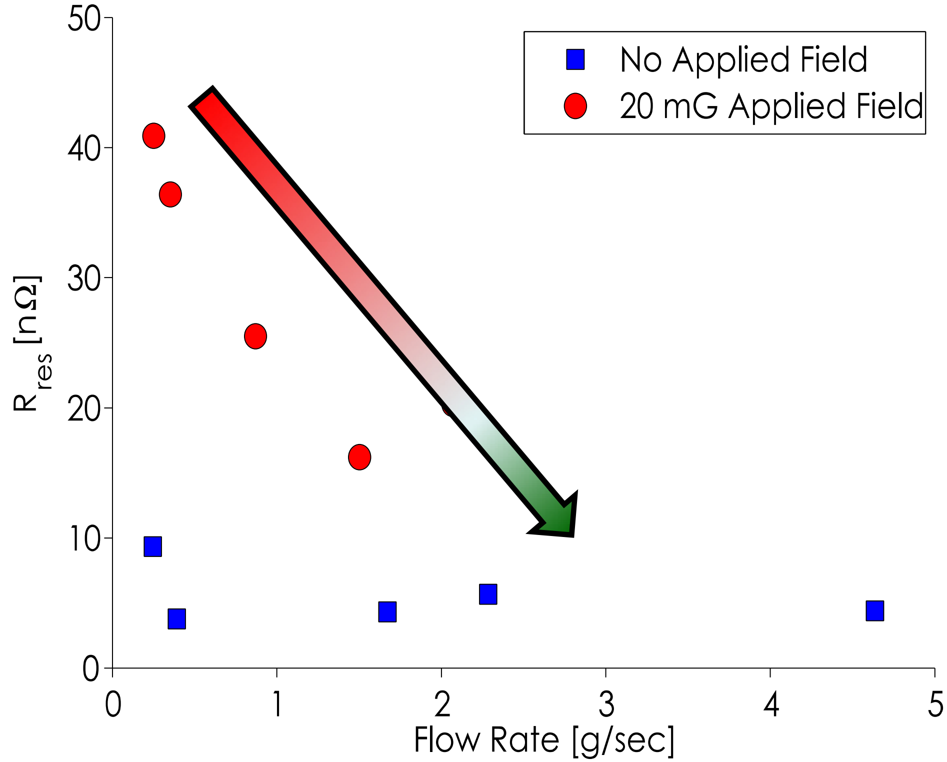
D. Gonnella et al., J. Appl. Phys. 117 , 023908 (2015)
R. Eichhorn, arXiv:1411.5285 [physics.acc-ph] (2014)
J.-M. Vogt et al., Phys. Rev. ST Accel. Beams 18, 042001 (2015)

Cryomodule Cavity Cool-Down and Vertical Temperature Gradients

Residual resistance vs. vertical temperature gradient over LHe vessel



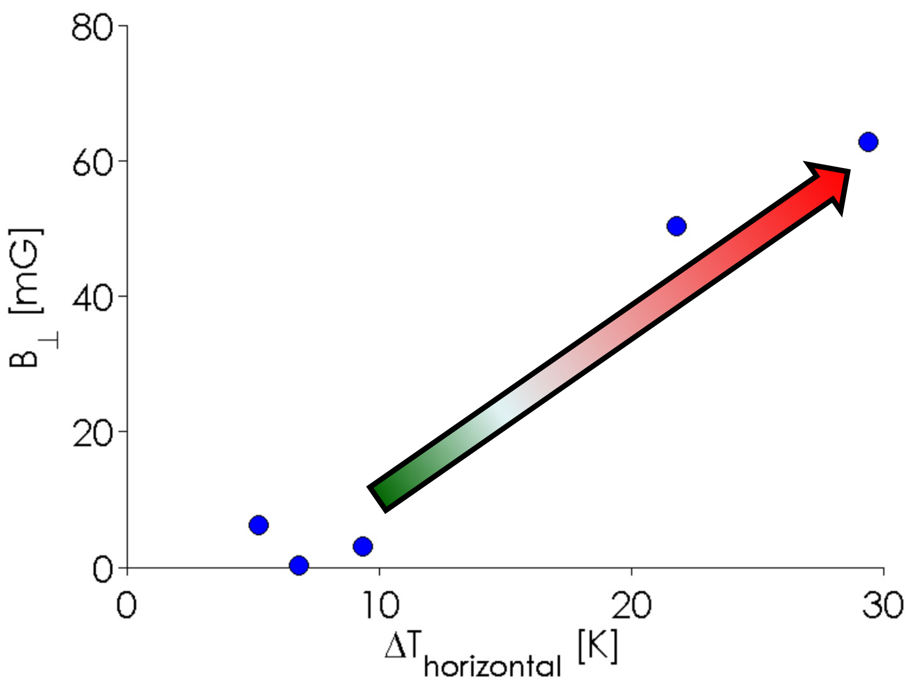
Residual resistance vs. helium mass flow during cool down



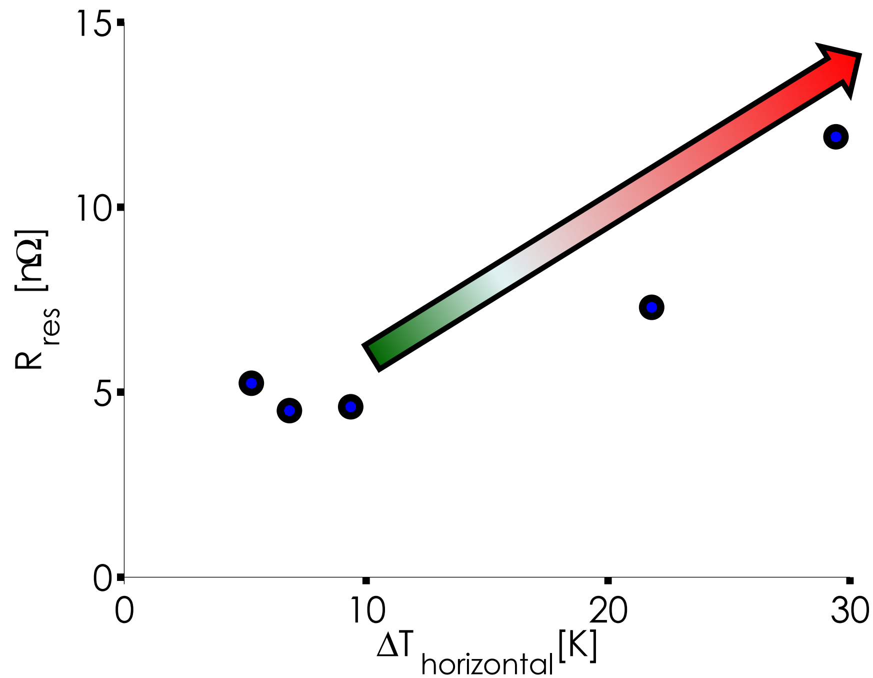
Conclusion: Helium flow rates of >2 g/s needed for efficient magnetic field expulsion by vertical temperature gradients.

Cryomodule Cavity Cool-Down and Horizontal Temperature Gradients

Transverse magnetic field vs. horizontal temperature gradient over LHe vessel in fast cool down



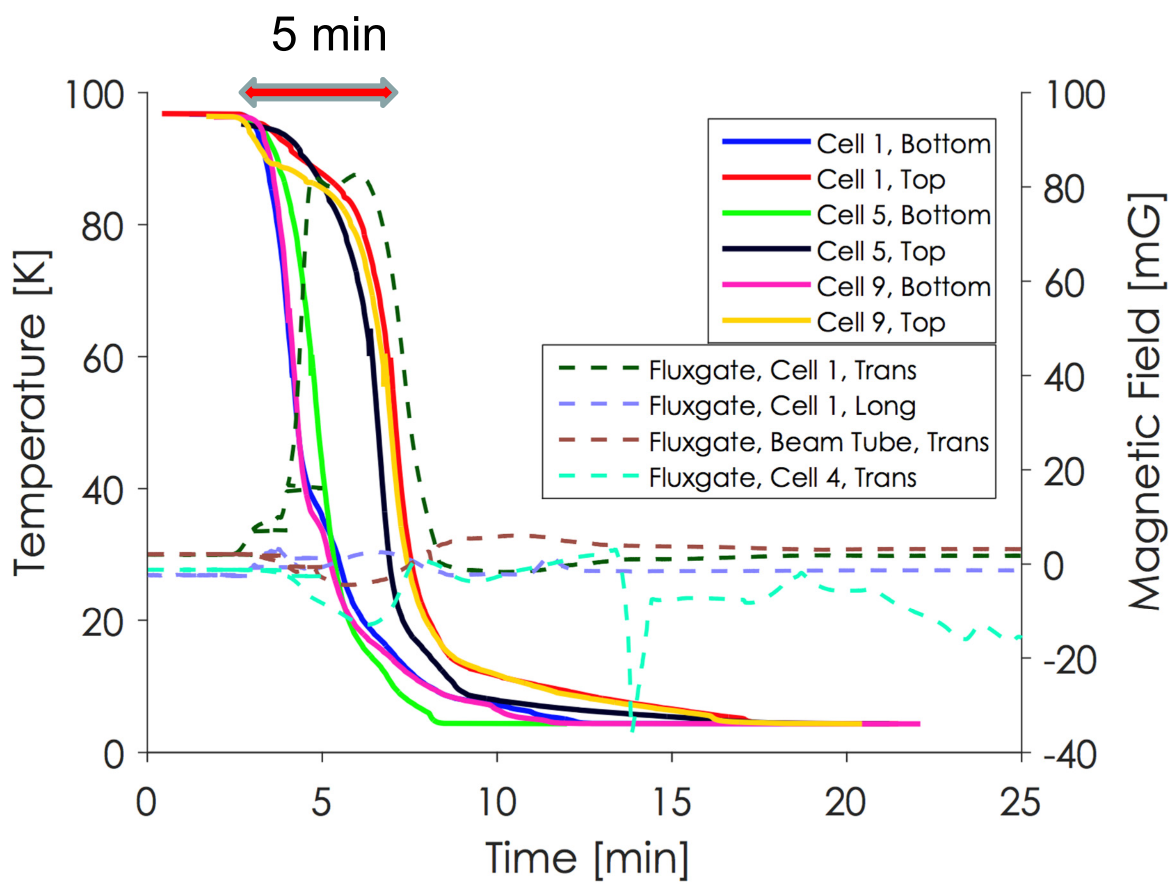
Residual resistance vs. horizontal temperature gradient over LHe vessel in fast cool down



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

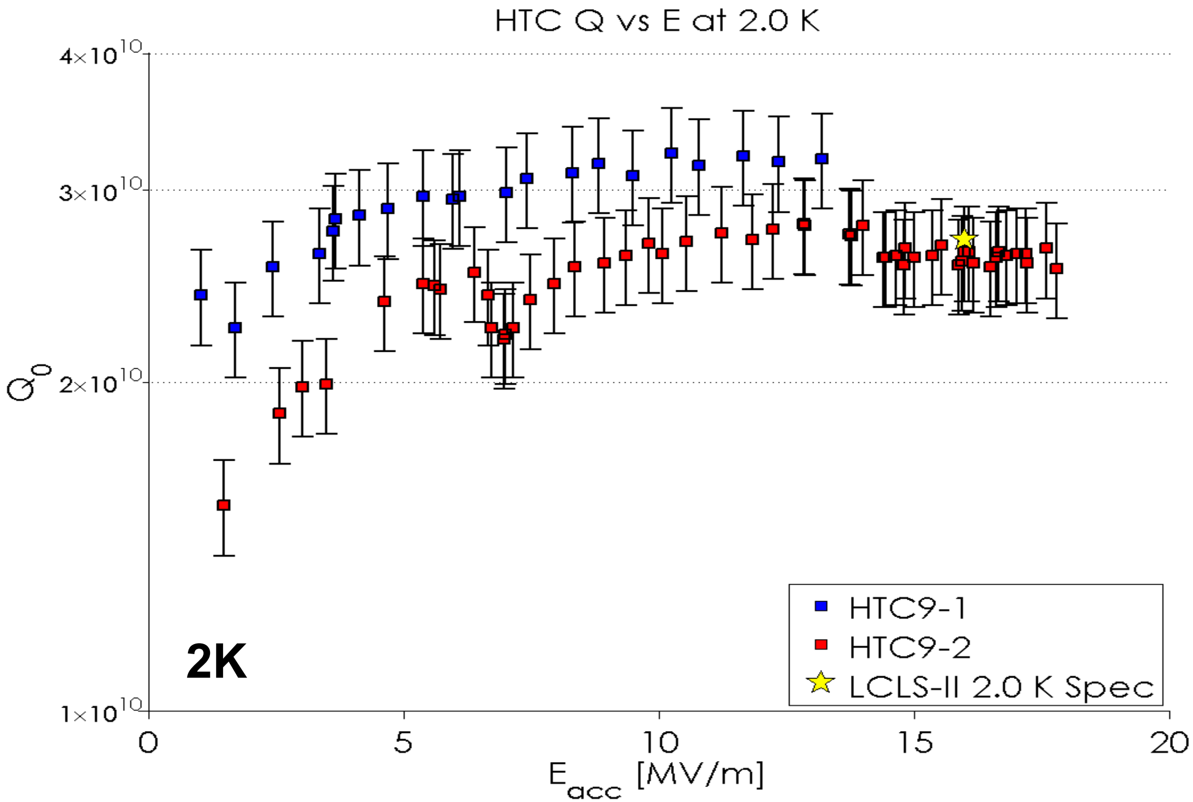
Cool-down Dynamics In Fast Cool-Down

For LCLS-II LHe Vessel with symmetric cryo-connections



- ✓ **Fast cool down in few minutes**
- ✓ **Large vertical temperature gradients (10 to 30 K) when transitioning from nc to sc**
- ✓ **Small horizontal temperature gradients <10K**
- ✓ **Small thermo-electric magnetic fields when transitioning from nc to sc**

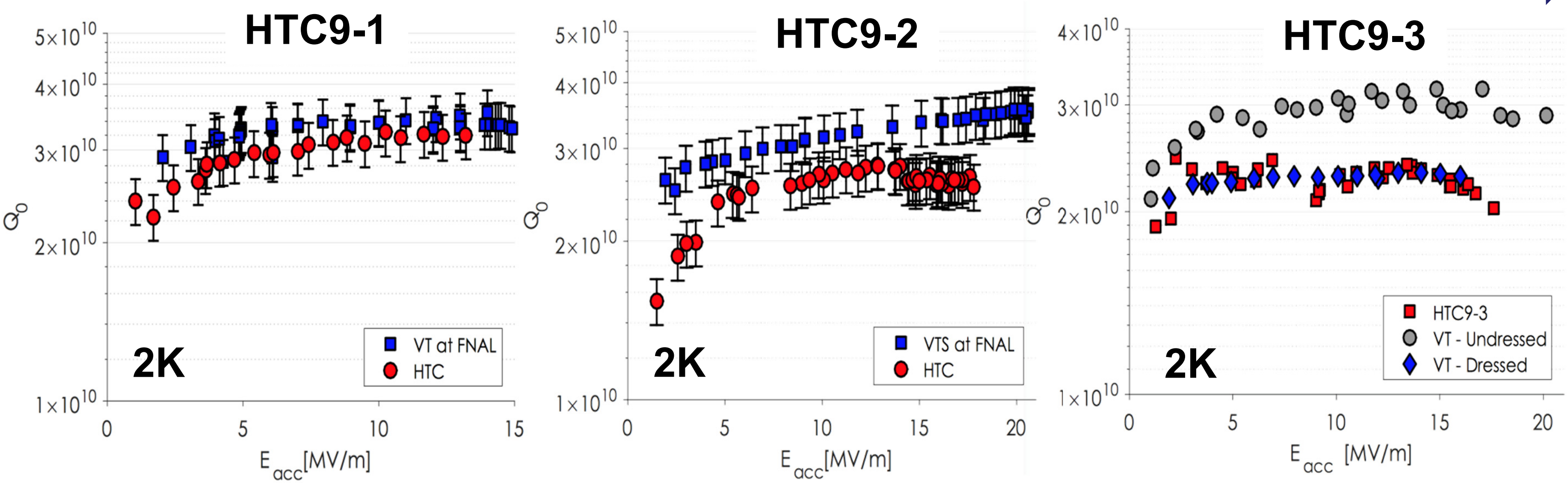
1st Cryomodule Test of a N-Doped LCLS-II Cavity



First cavity to meet LCLS-II specs in a cryomodule!

D. Gonnella et al., J. Appl. Phys. 117 , 023908 (2015)

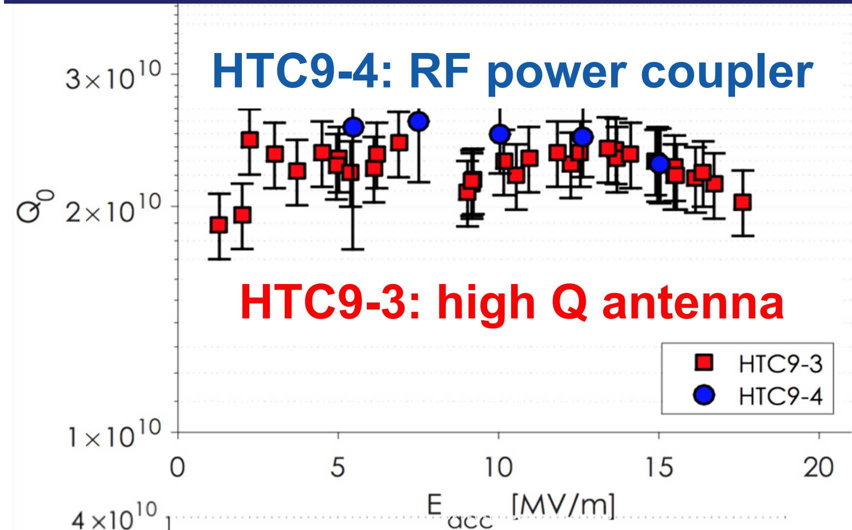
Performance Change from Vertical to Horizontal Test



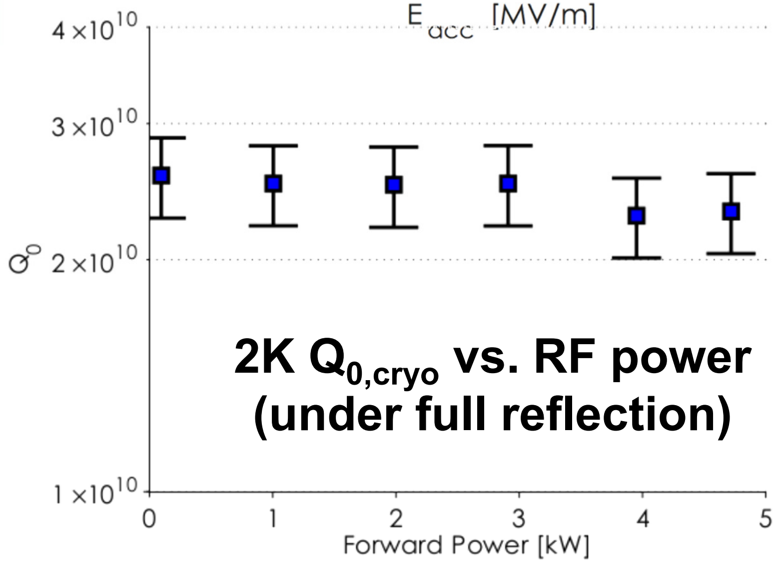
Cavity	Lhe Tank	HTC Test	VT Result	HT Result	$\Delta R_{VT\text{->}HT}$ [nΩ]
TB9ACC012	ILC	HTC9-1	$(3.5 \pm 0.4) \times 10^{10}$	$(3.2 \pm 0.3) \times 10^{10}$	1 ± 2
TB9AES011	ILC	HTC9-2	$(3.4 \pm 0.3) \times 10^{10}$	$(2.7 \pm 0.3) \times 10^{10}$	2 ± 2
TB9AES018	LCLS-II	HTC9-3	$(2.2 \pm 0.3) \times 10^{10}$	$(2.2 \pm 0.2) \times 10^{10}$	0 ± 2

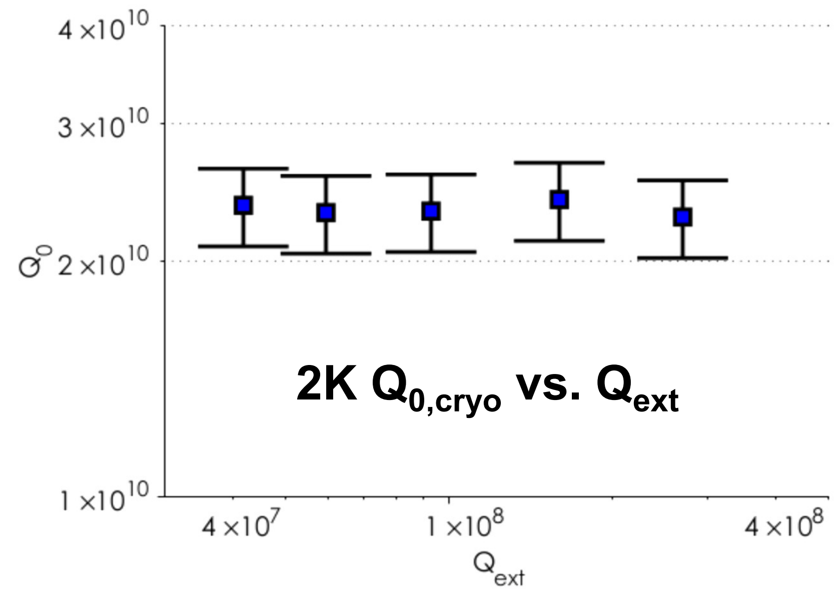
Conclusion: No significant change in performance when cavity is installed in cryomodule. Fast cool-down is reliable in expelling flux.

Impact of the RF Input Coupler on Cavity Performance (TB9AES018)

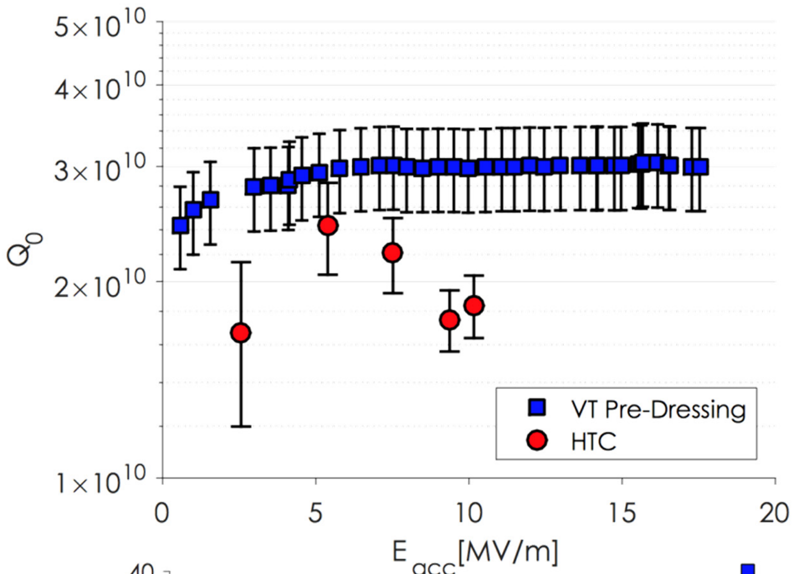


Conclusion: No significant increase in 2K cryogenic load or cavity performance degradation from RF input coupler.

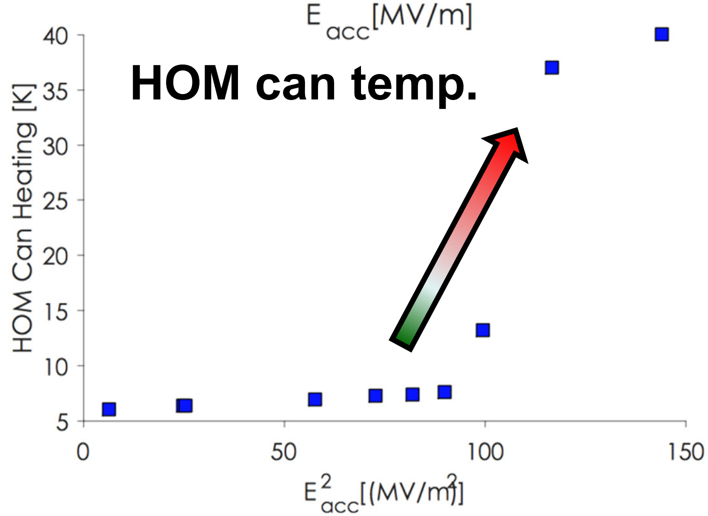


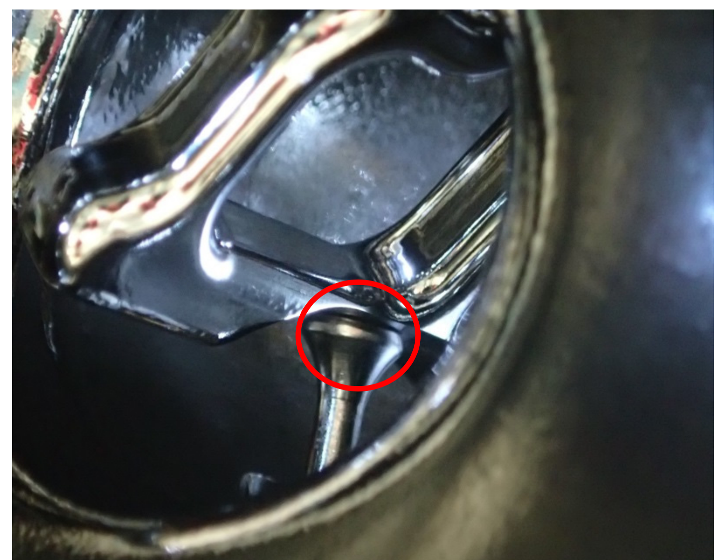


Full System Test in HTC9-5: HOM Coupler Issues



- **Short (due to HOM can fabrication error) and <u>multipacting</u> in one HOM coupler resulted in significant heating and Q-slope**
- **Important tuner and microphonics studies with FNAL team (see poster TUPB095)**





Conclusions

Conclusions

- N-doping very robust and well controlled way to increase 2K Q_0
- Furnace pressure is not a critical parameter in doping process.
- Observed field dependency of R_{BCS} is well described by assuming a field dependent effective spectral gap.
- Reduced lower critical field H_{c1} in N-doped cavities => earlier vortex penetration at defects => lower average quench field.
- Helium flow rates of >2 g/s needed for efficient magnetic field expulsion in cryomodule test.
- Small horizontal temperature gradients <10K critical to keep impact of thermal-electric currents on R_{res} small.
- No significant change in performance when cavity is installed in cryomodule. Fast cool-down is reliable in expelling flux.
- No significant increase in 2K cryogenic load or cavity performance degradation from RF input coupler.

Thank you for your attention!