Breakthrough Technology for Very High Quality Factors in SRF Cavities

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27th Linear Accelerator Conference (LINAC'2014)
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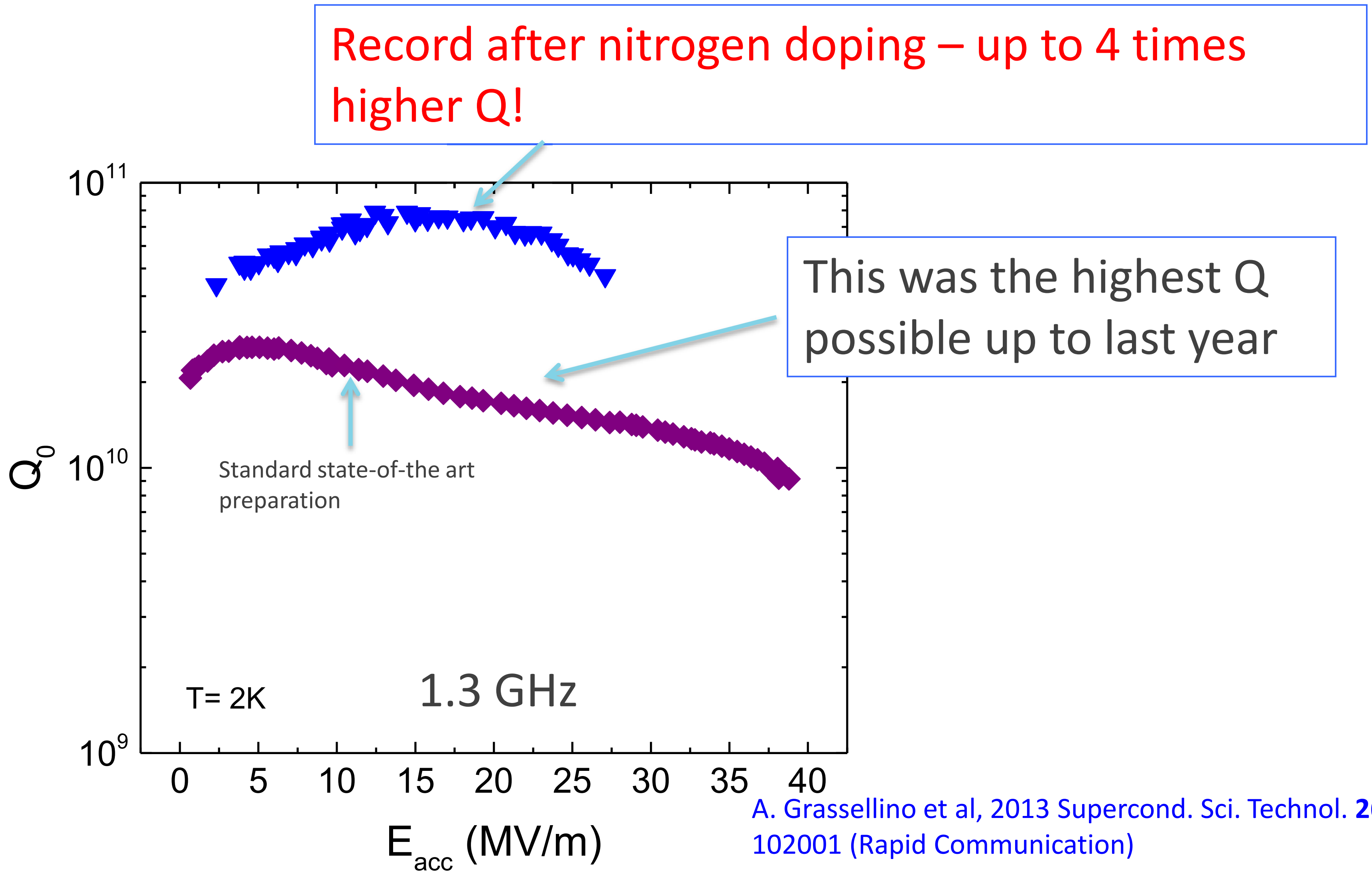
Outline

- Two major discoveries at Fermilab
  - Nitrogen doping to lower the BCS surface resistance
    - Lower than the previously perceived "theoretical limit"
    - Example at 16 MV/m: $Q > 3 \times 10^{10}$ by doping vs. $Q \sim 1.5 \times 10^{10}$ with the standard ILC/XFEL cavity processing
    - Also lowers residual
  - Effective magnetic flux expulsion by fast/high thermal gradient cooldown to achieve record low residual resistances
    - Example: $Q = 2.7 \times 10^{11}$ in 27 mG ambient field
- Immediate implications
  - LCLS-II
- Future perspectives

- First breakthrough at Fermilab: Nitrogen doping can drastically lower “fundamental” BCS losses in cavity walls and increase Q several times

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication) – selected for highlights of 2013

Nitrogen doping: a breakthrough in Q



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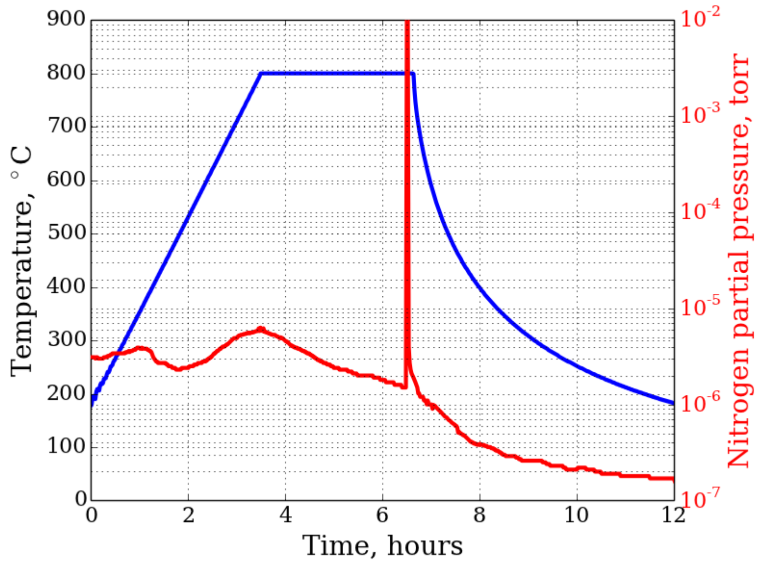
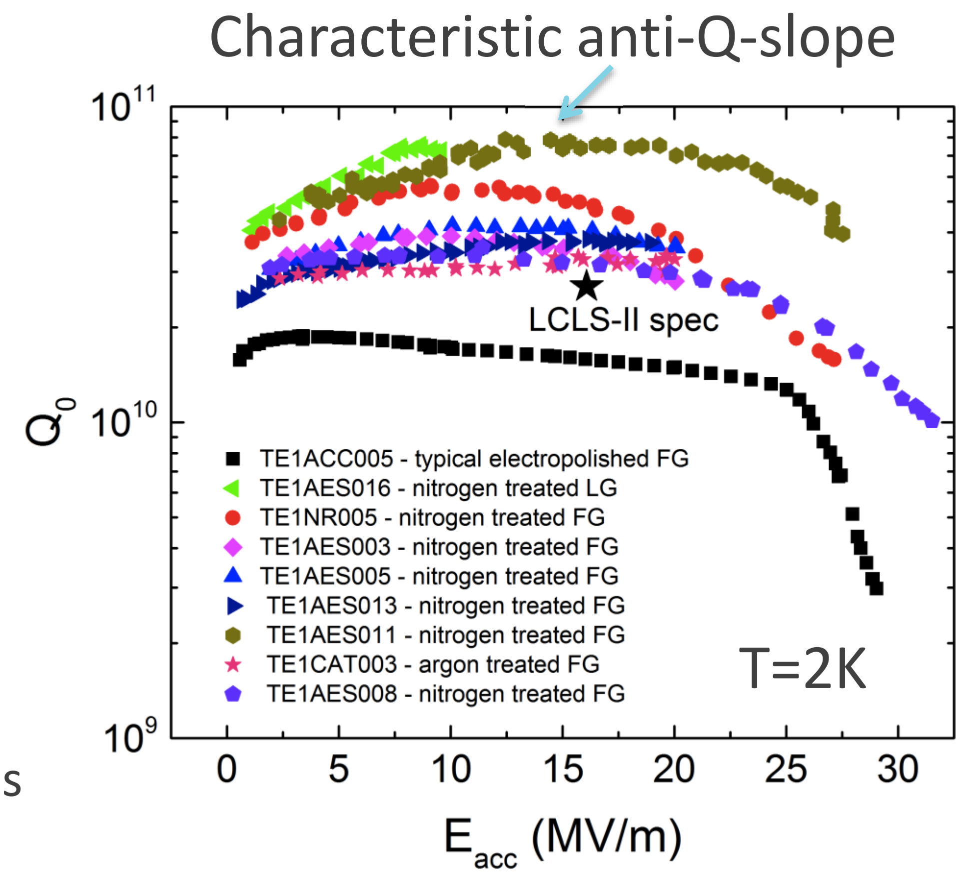
Breakthrough in quality factor: nitrogen doping



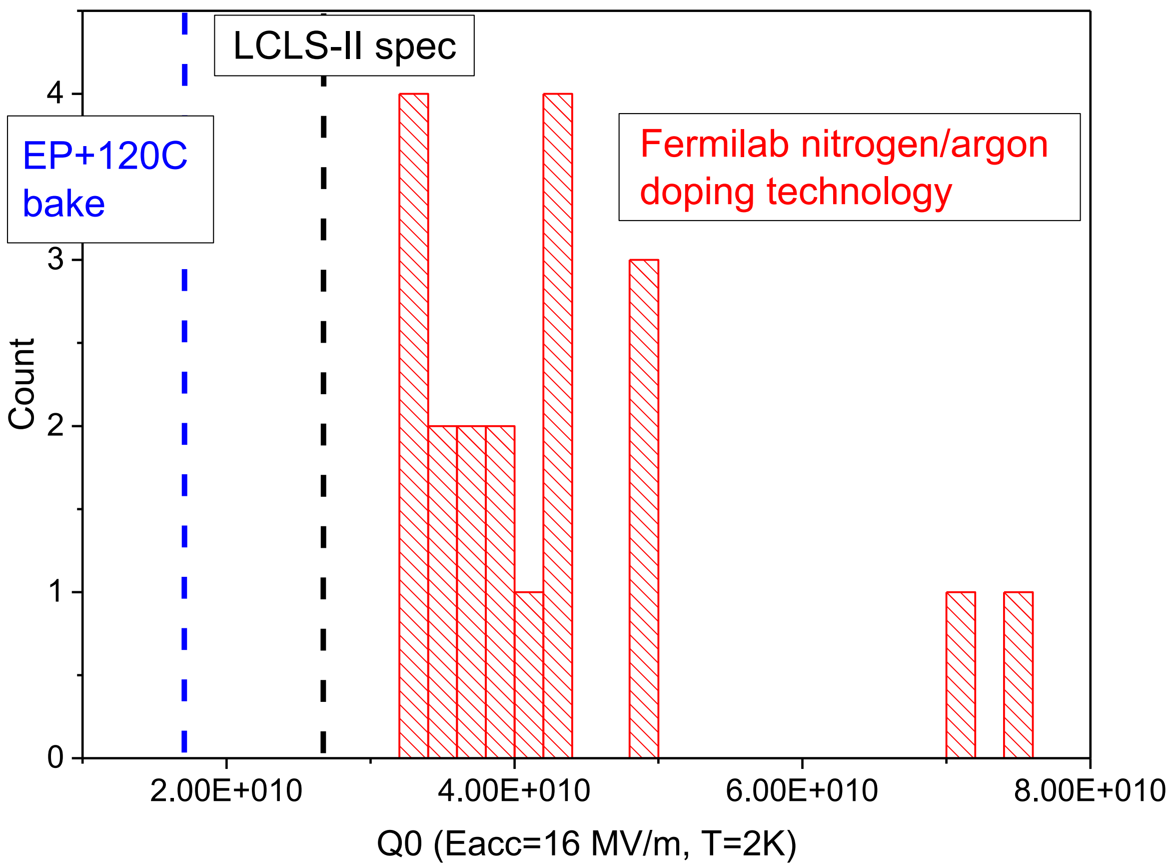


- Injection of small nitrogen partial pressure at the end of 800C degassing followed by several ums of EP-> drastic increase in Q
- Reproduced on tens of 1- and 9-cell cavities at FNAL

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

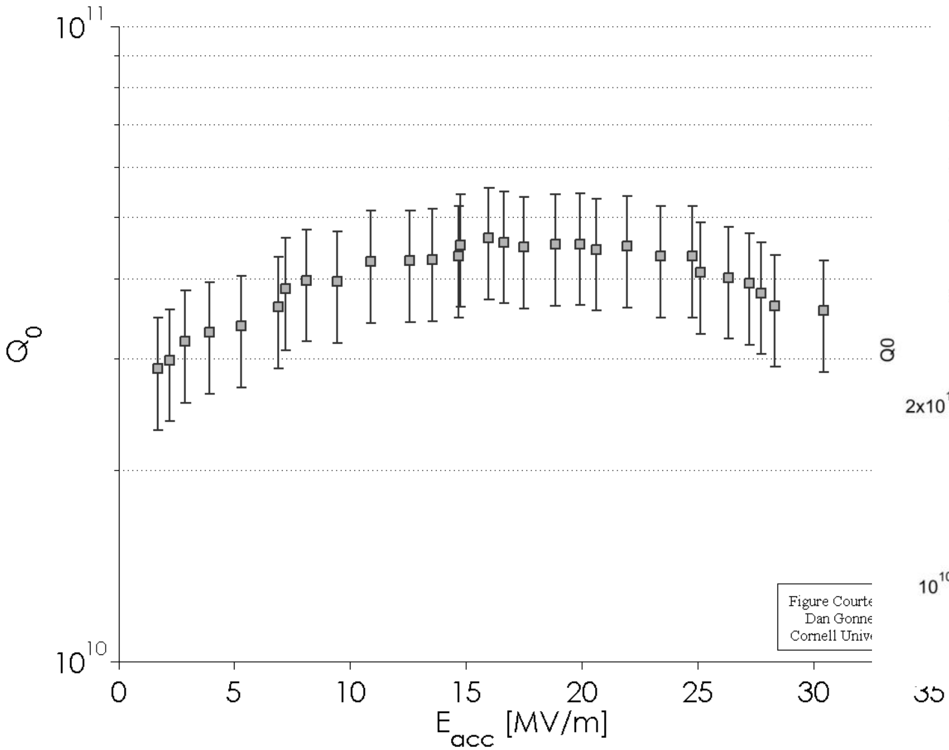
Doping is easily reproducible process

	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Q0	20	**4.3e10**	1.2e10	3.2e10	**4.0e10**	7.4e10

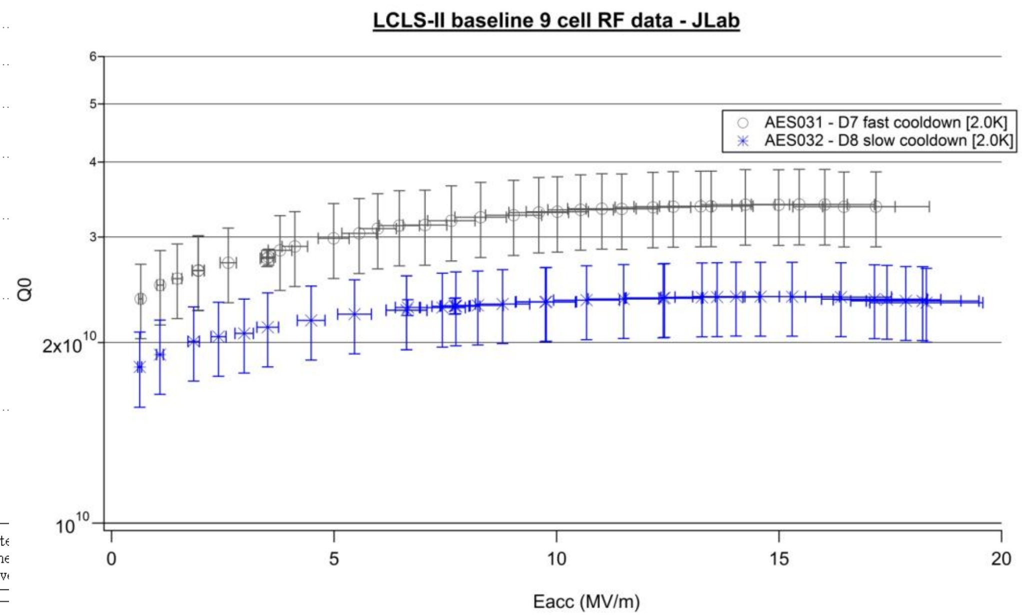


Obtained Q several times above state-of-the-art

Reproduced at other labs in 1- and 9-cells

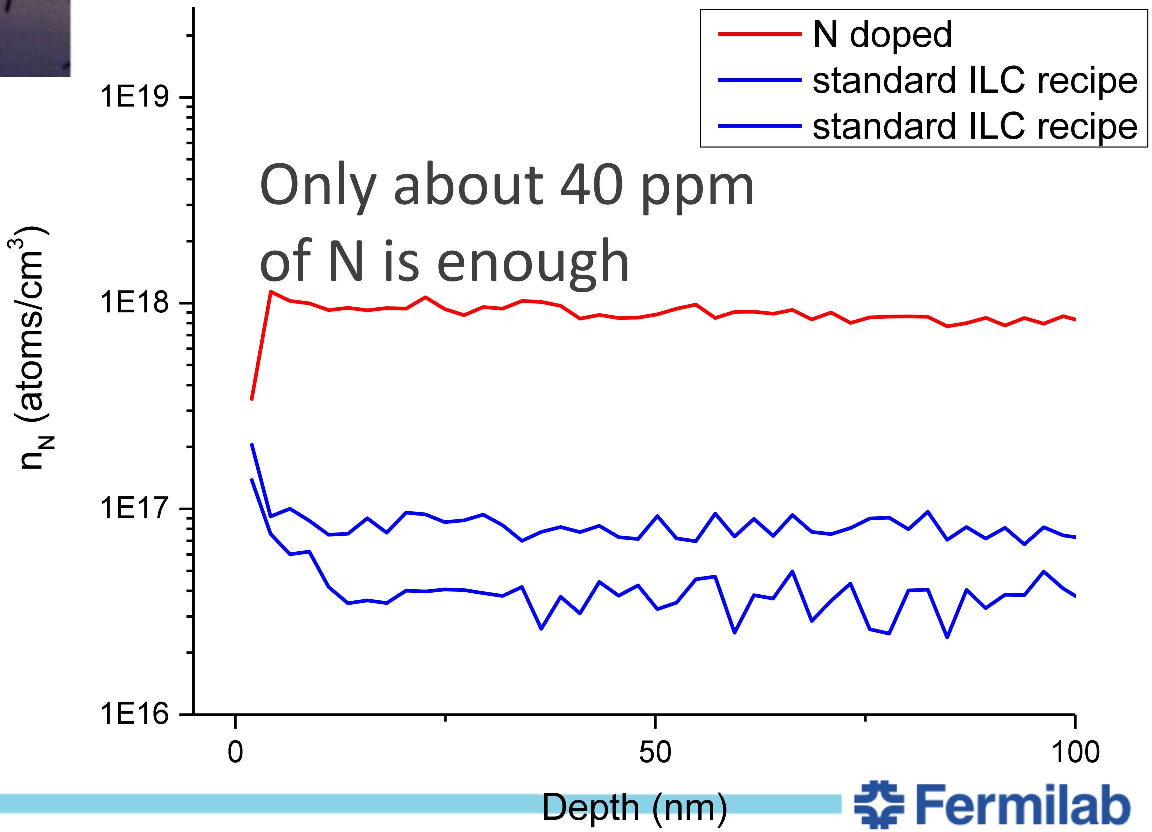


Cornell

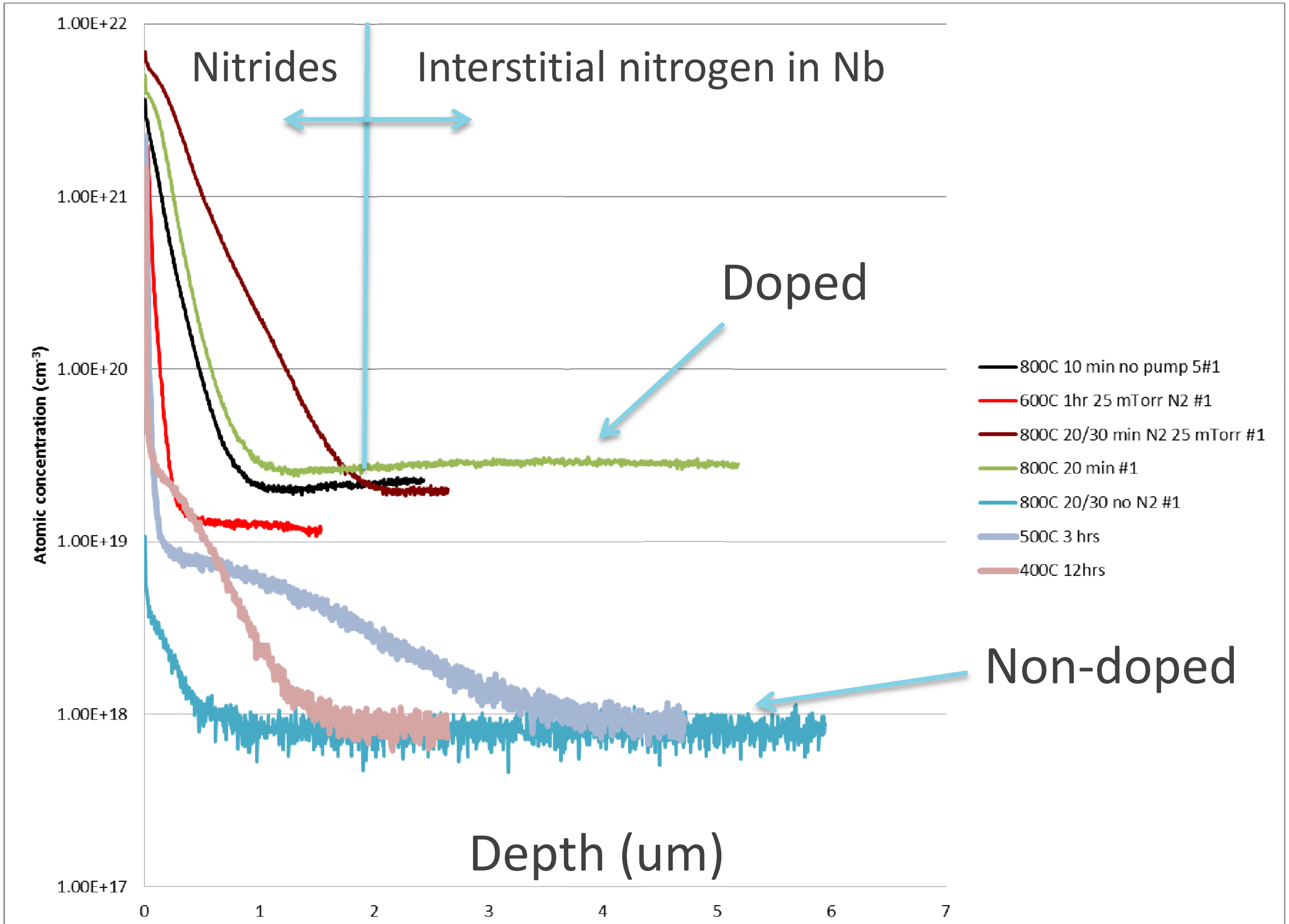


JLab

Cutouts from N doped cavities - SIMS



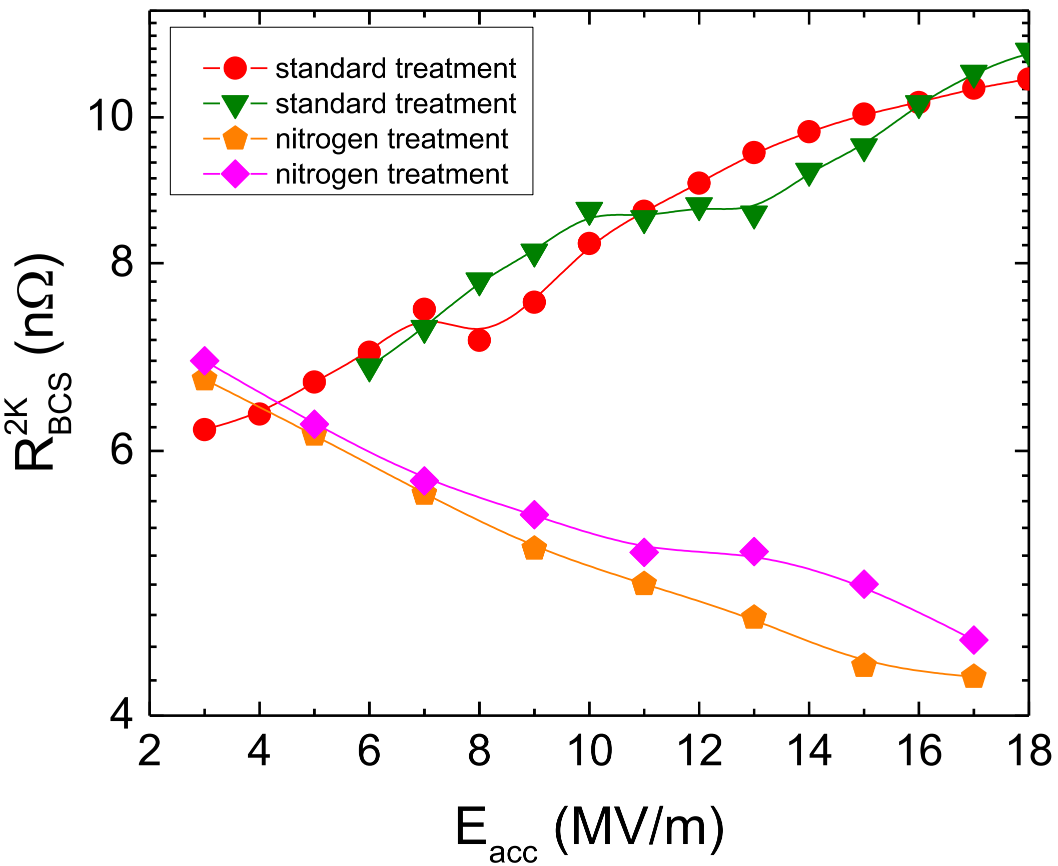
What does N treatment do? N depth profiles by SIMS



Fermilab

Physics – origin of the effect

$$R_s(T) = R_{BCS}(T) + R_{residual}$$



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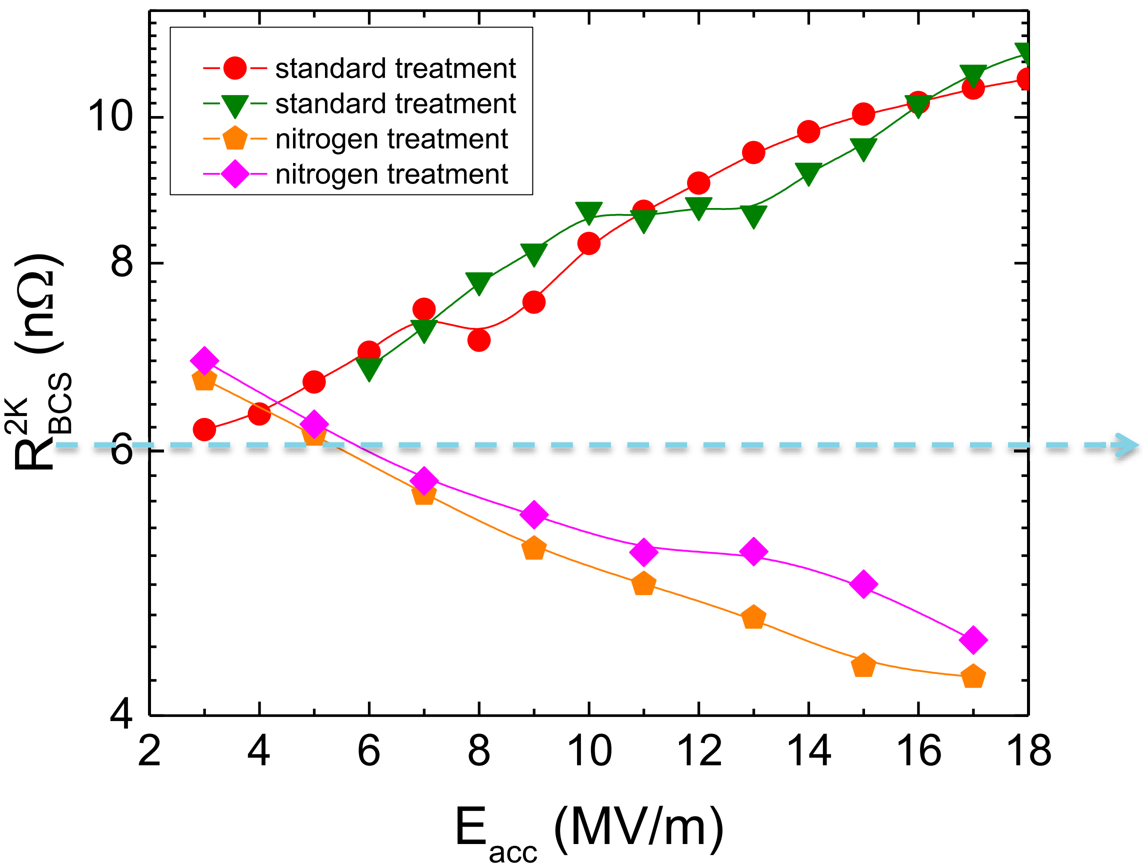

This is what Mattis-Bardeen theory predicted to be the lowest possible surface resistance for Nb -> we breached it!

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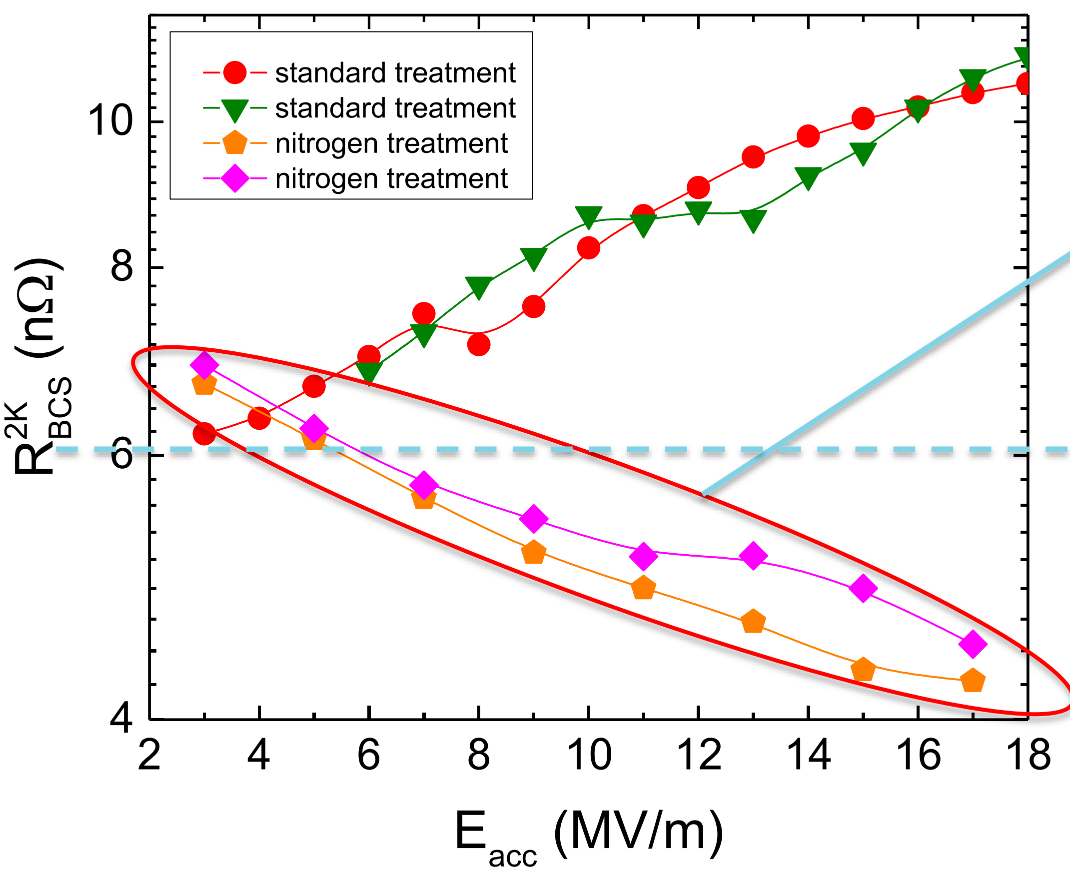

Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

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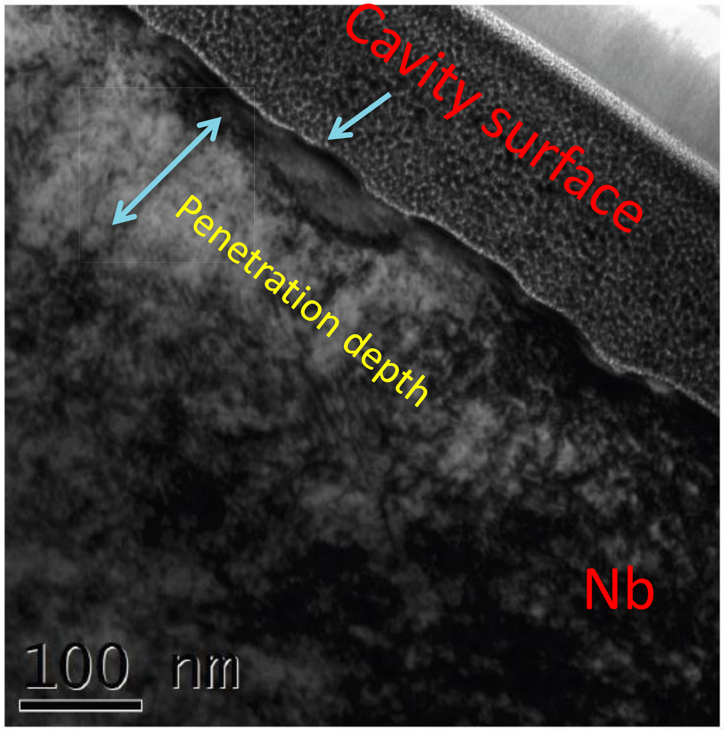
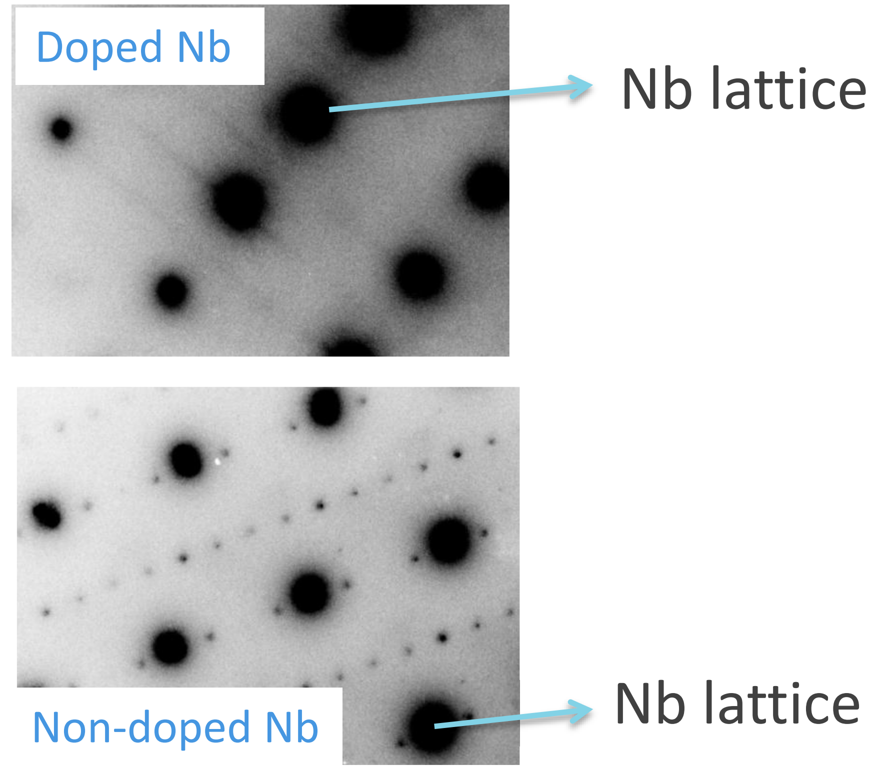
Nanostructural studies provide first clues

Y. Trenikhina (IIT/FNAL), A. Romanenko – to be published

TEM on FIB-prepared cutouts



Electron diffraction patterns from the penetration depth taken at 94K reveal the difference



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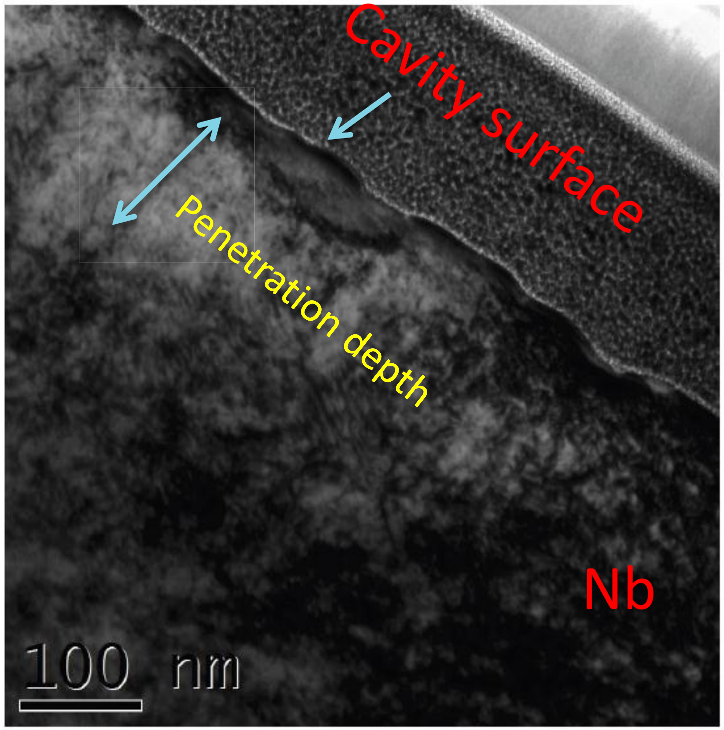

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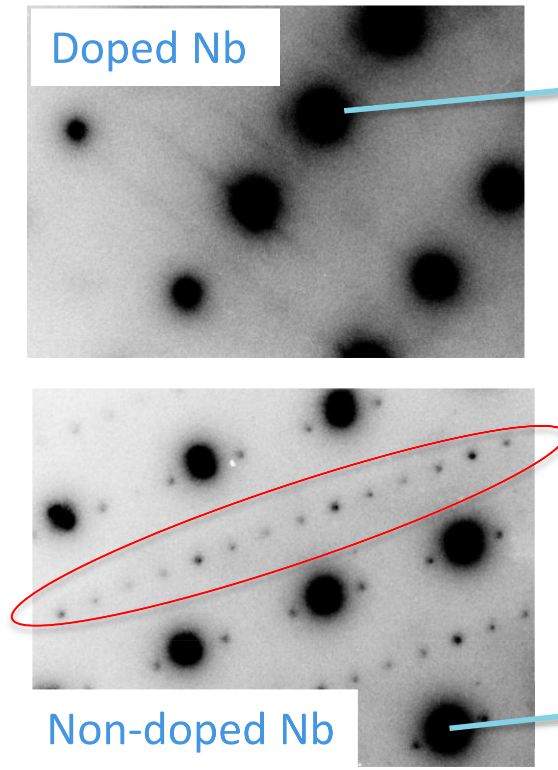

Nb lattice

Secondary diffraction peaks appear signalling the formation of lossy niobium hydrides

Nb lattice

Fermilab

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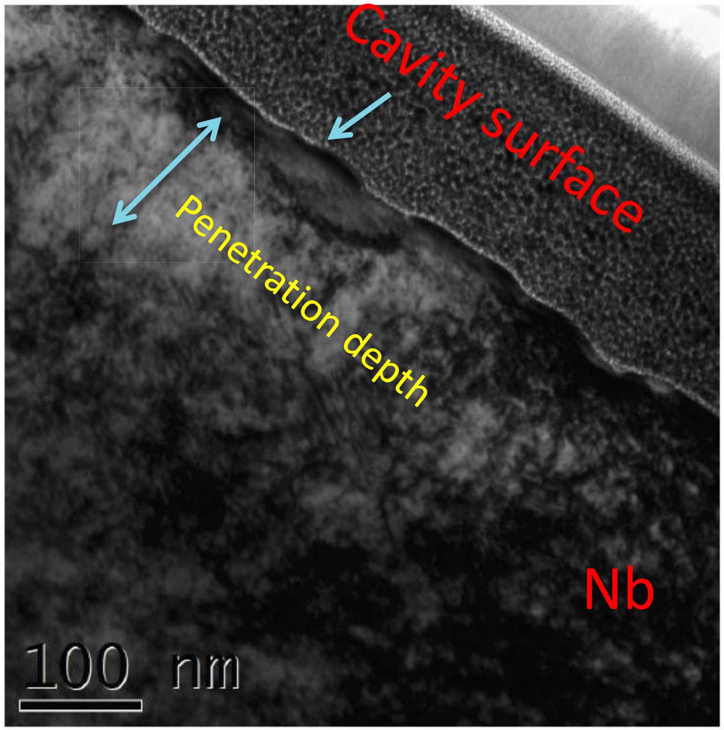

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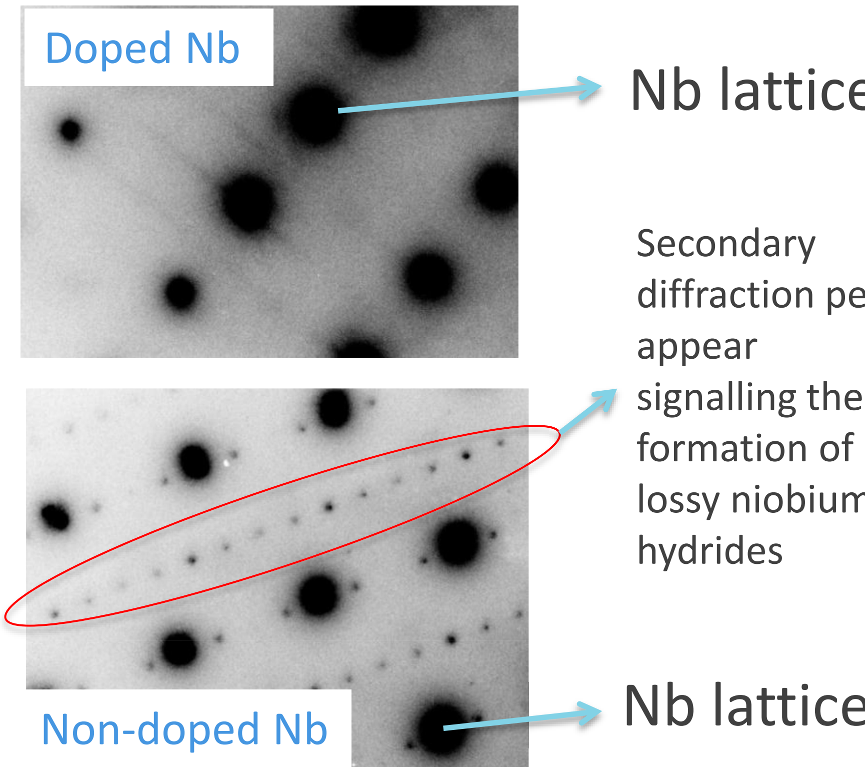


- Hydrides may be the cause of the medium and high field Q slopes [see A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, 2013 Supercond. Sci. Technol. 26 035003]
- Nitrogen doping may fully trap hydrogen => only intrinsic Nb behavior is then manifested?

Some possible mechanisms for intrinsic Nb behavior leading to increasing Q with field

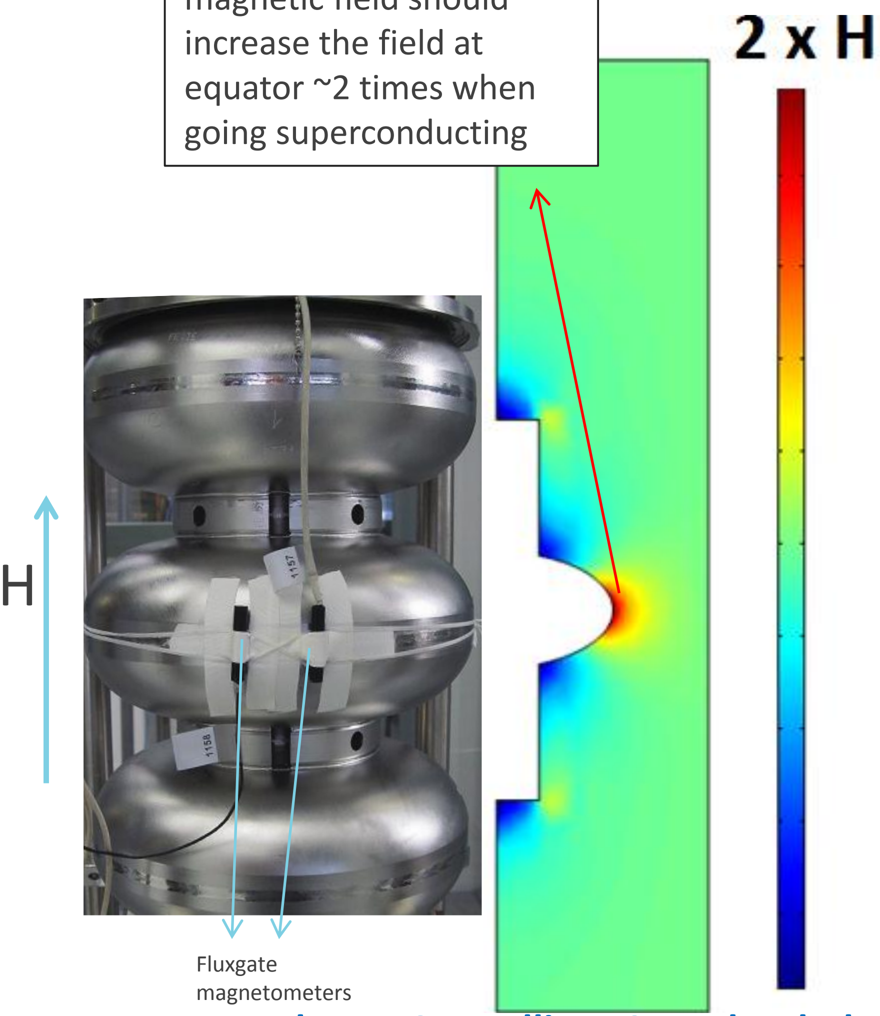
- Momentum of Cooper pairs changes the DoS
  - B. P. Xiao et al, Physica C **490** (2013) 26-31
- Quasiparticle energy distribution deviates from thermal equilibrium
  - P. J. de Visser et al, Phys. Rev. Lett. **112**, 047004 (2014)
- Time-dependent DoS
  - A. Gurevich, Phys. Rev. Lett. 113, 087001 (2014)

- Second breakthrough at Fermilab: cooldown rate and thermal gradients around Tc drastically affect the Meissner effect and can be used to achieve ultra-low residual resistances even in high ambient fields

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

Magnetic probes reveal the new physics

Full expulsion of the magnetic field should increase the field at equator ~2 times when going superconducting



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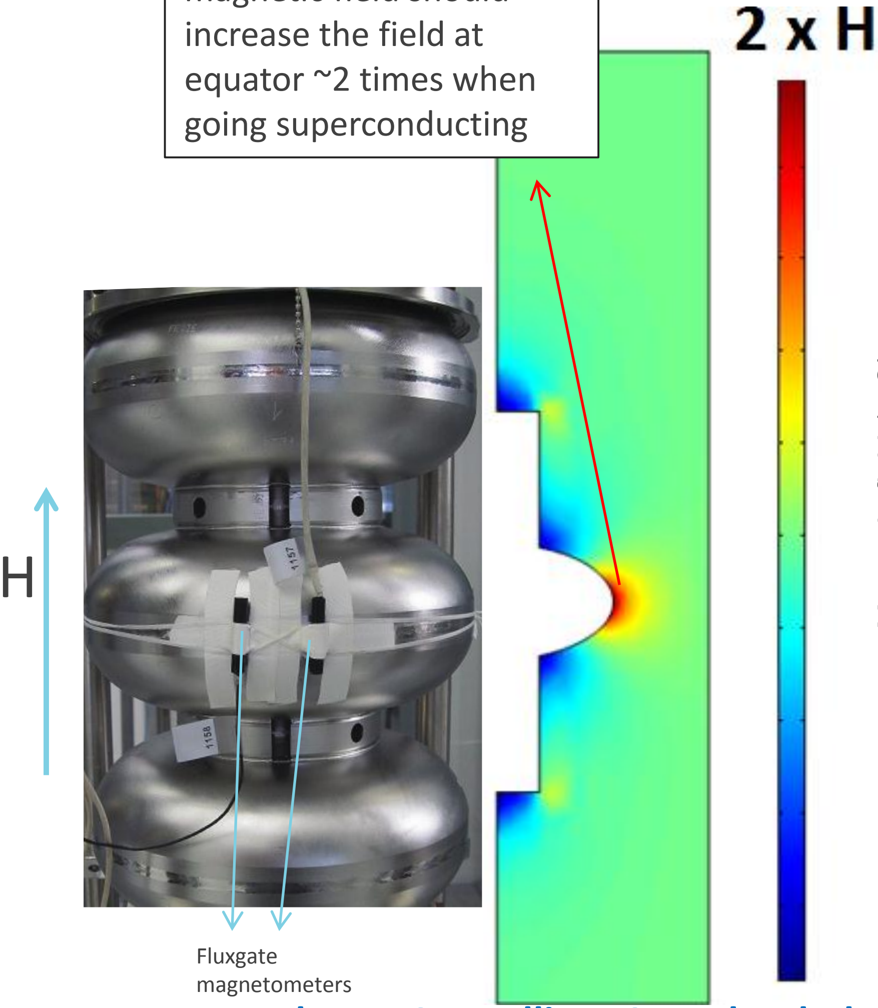
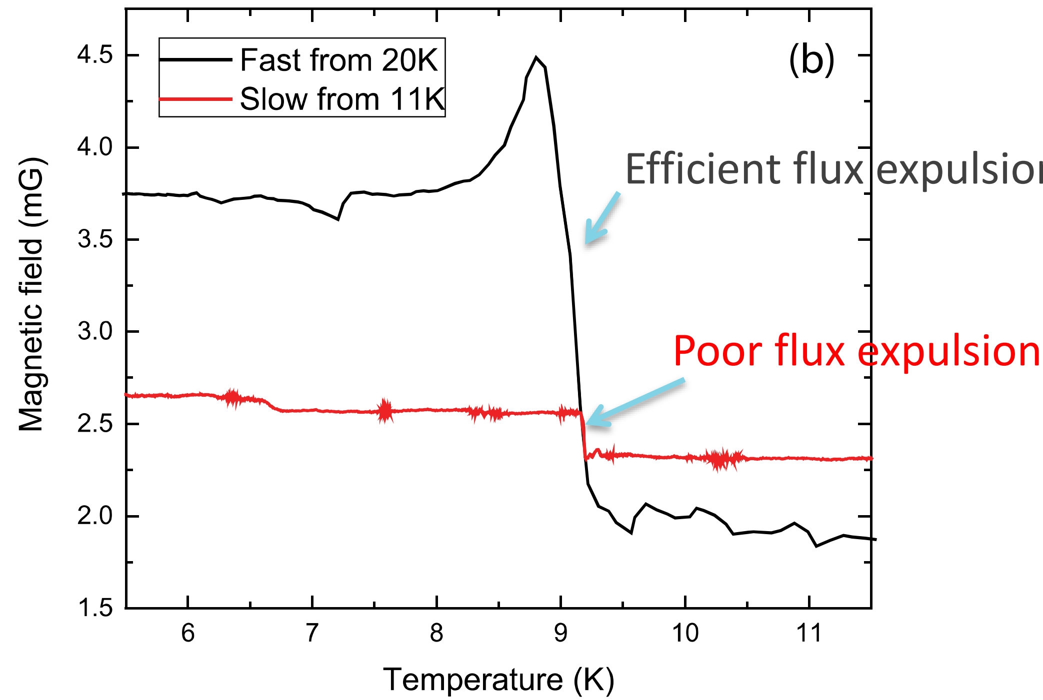


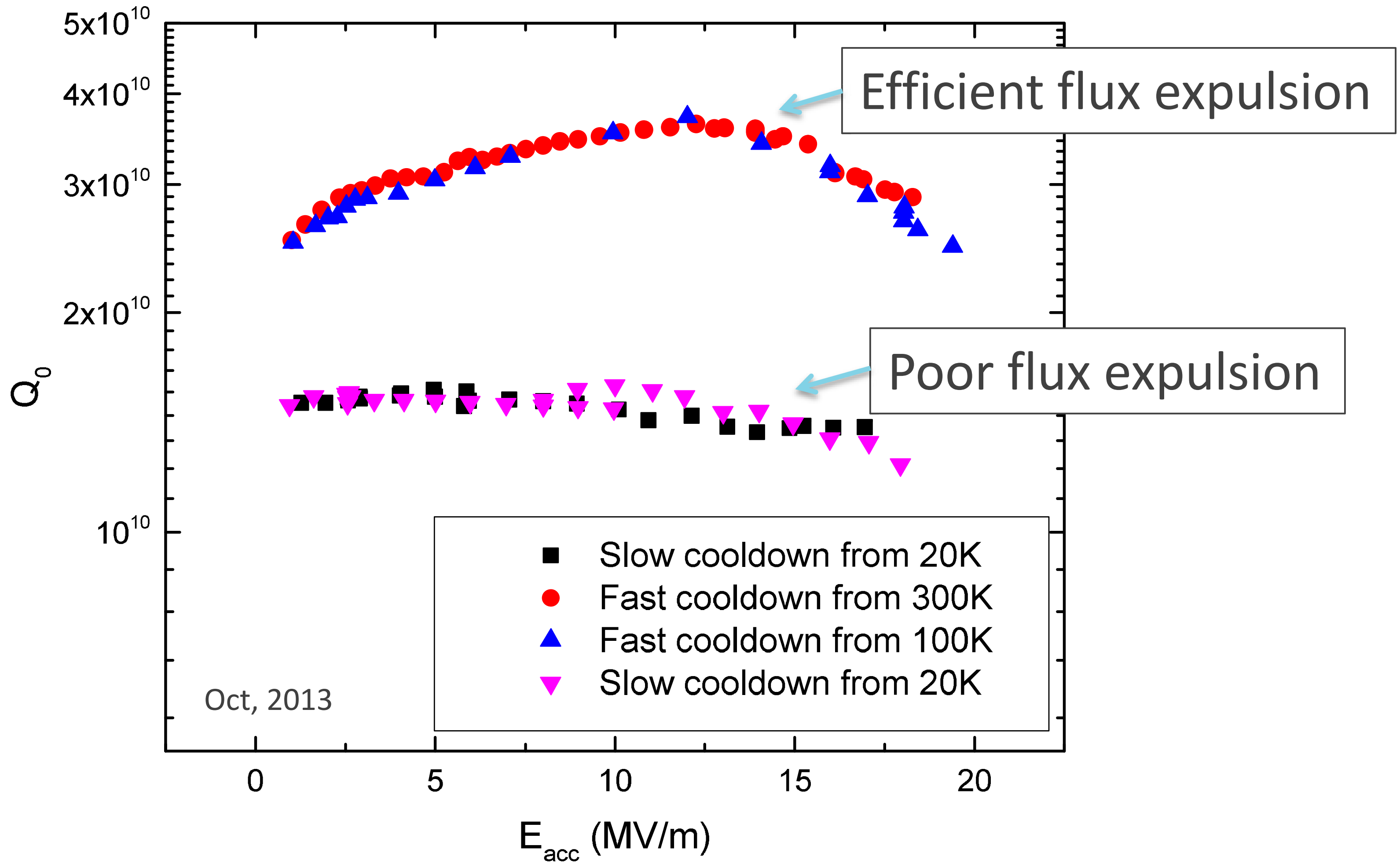
It turns out the expulsion efficiency can be controlled by the cooldown procedure through Tc=9.2K (fast/slow, uniform or not)



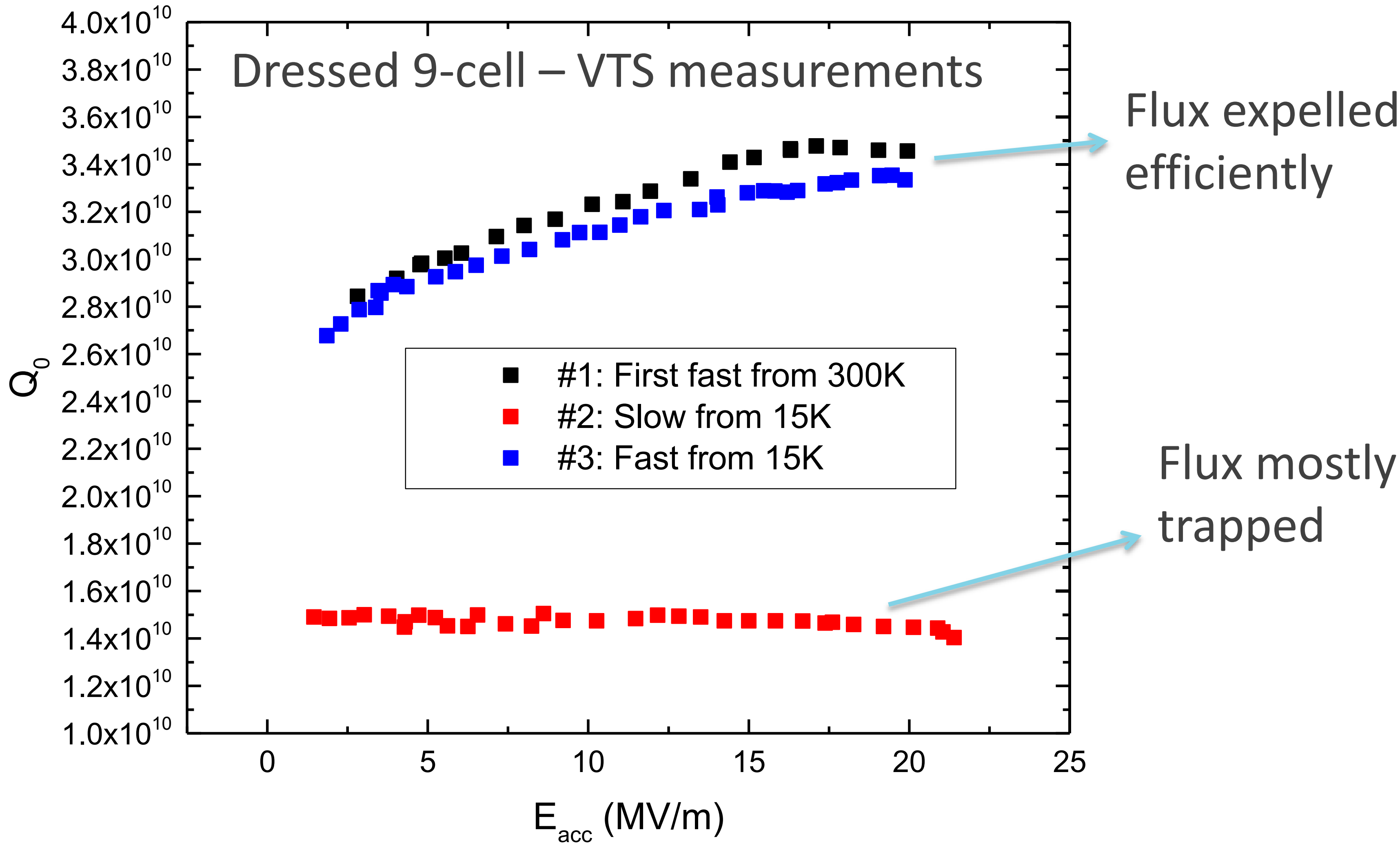
Same Meissner behavior for EP, EP+120C, N doping, fine/single grain, cooling is what matters

A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

Bare N doped 9-cell in vertical test



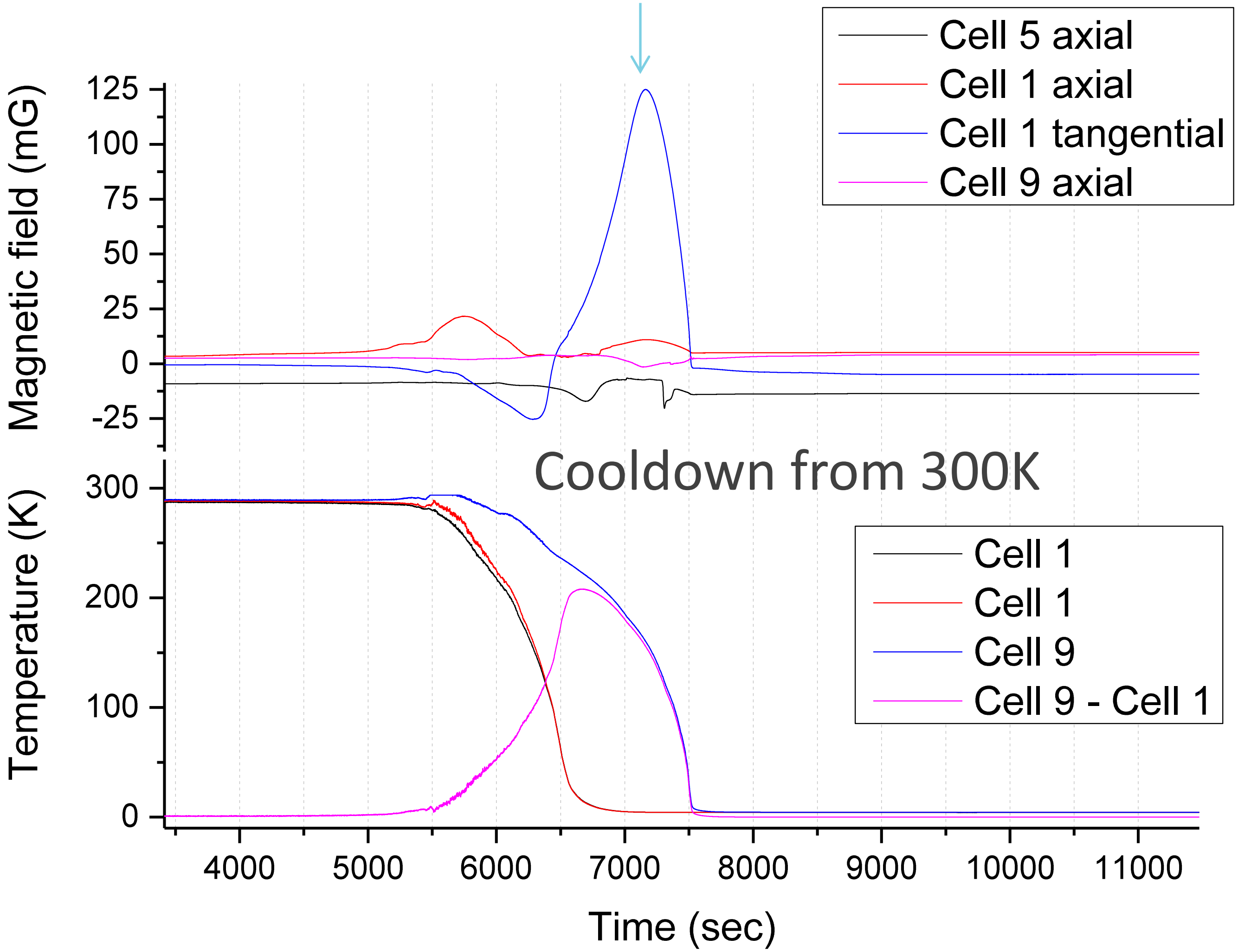
Bare/dressed cavities behave identical



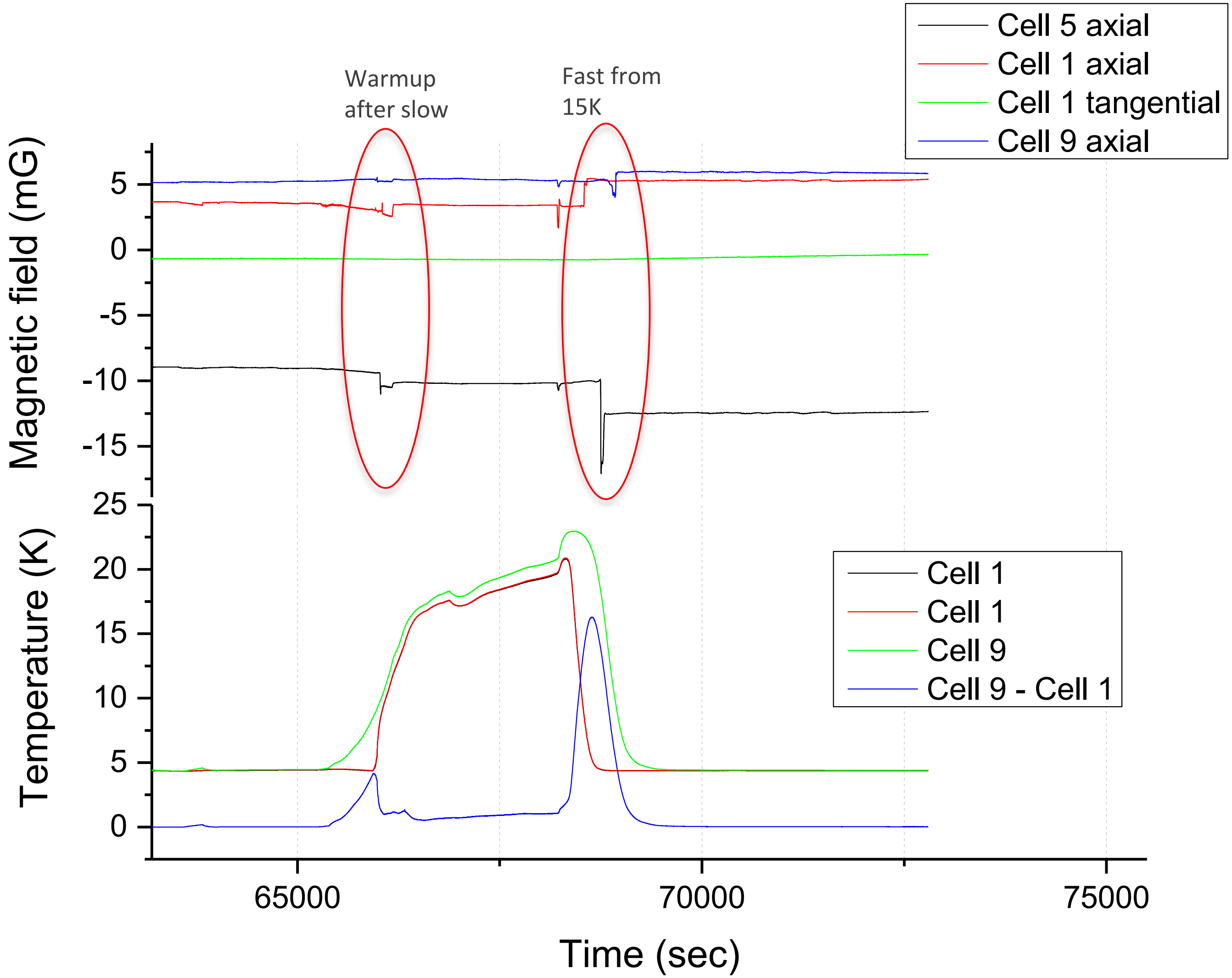
Thermal currents are present but have no effect

No effect of thermal currents in VTS of dressed cavities

Large (125 mG) magnetic fields generated by thermal currents, no effect on Q

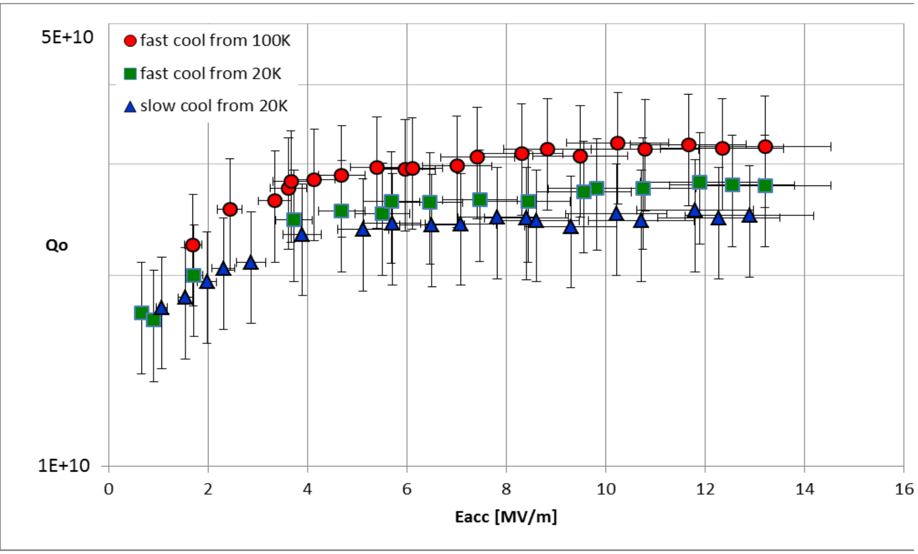


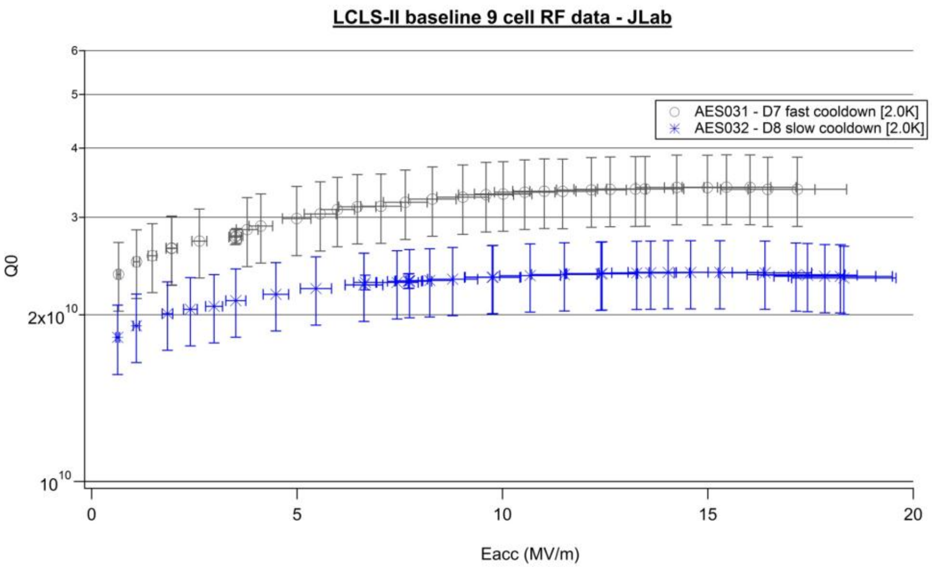
Dressed cavities behave exactly the same as bare



Everything the same as in our J. Appl. Phys. **115**, 184903 (2014)

Confirmed at Cornell and Jlab – VTS and HTS



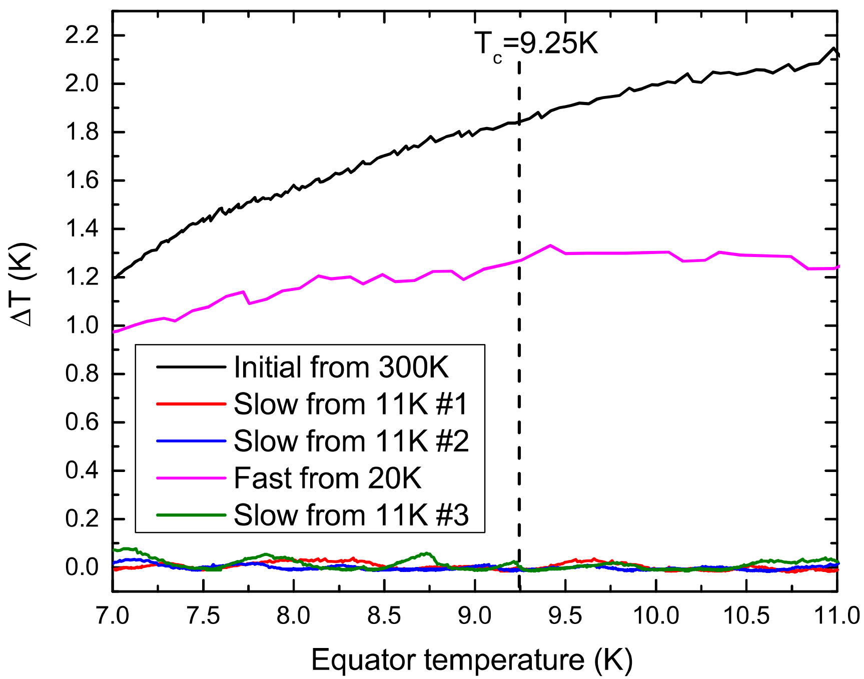


Cornell HTS measurements of the Fermilab N-doped 9-cell [See MOPP018]

JLab VTS data on a 9-cell [See TUPP138]

Possible mechanism #1

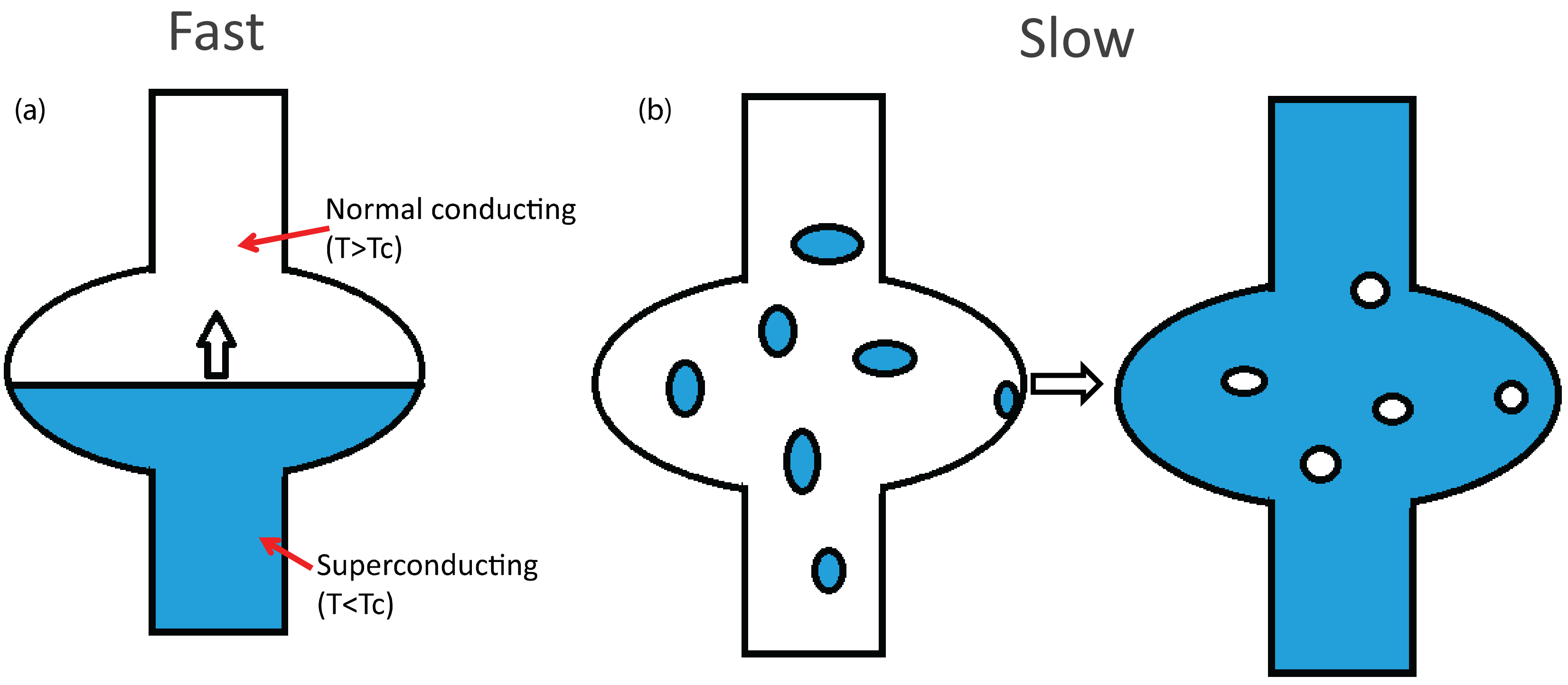
- Thermal gradient at the superconducting/normal conducting boundary is <u>aiding</u> the flux expulsion => the higher dT/dx the better (fast and from higher temperature preferred)
- See [**J. Appl. Phys. 115, 184903 (2014)**] for details



Example of thermal difference across the 1-cell cavity

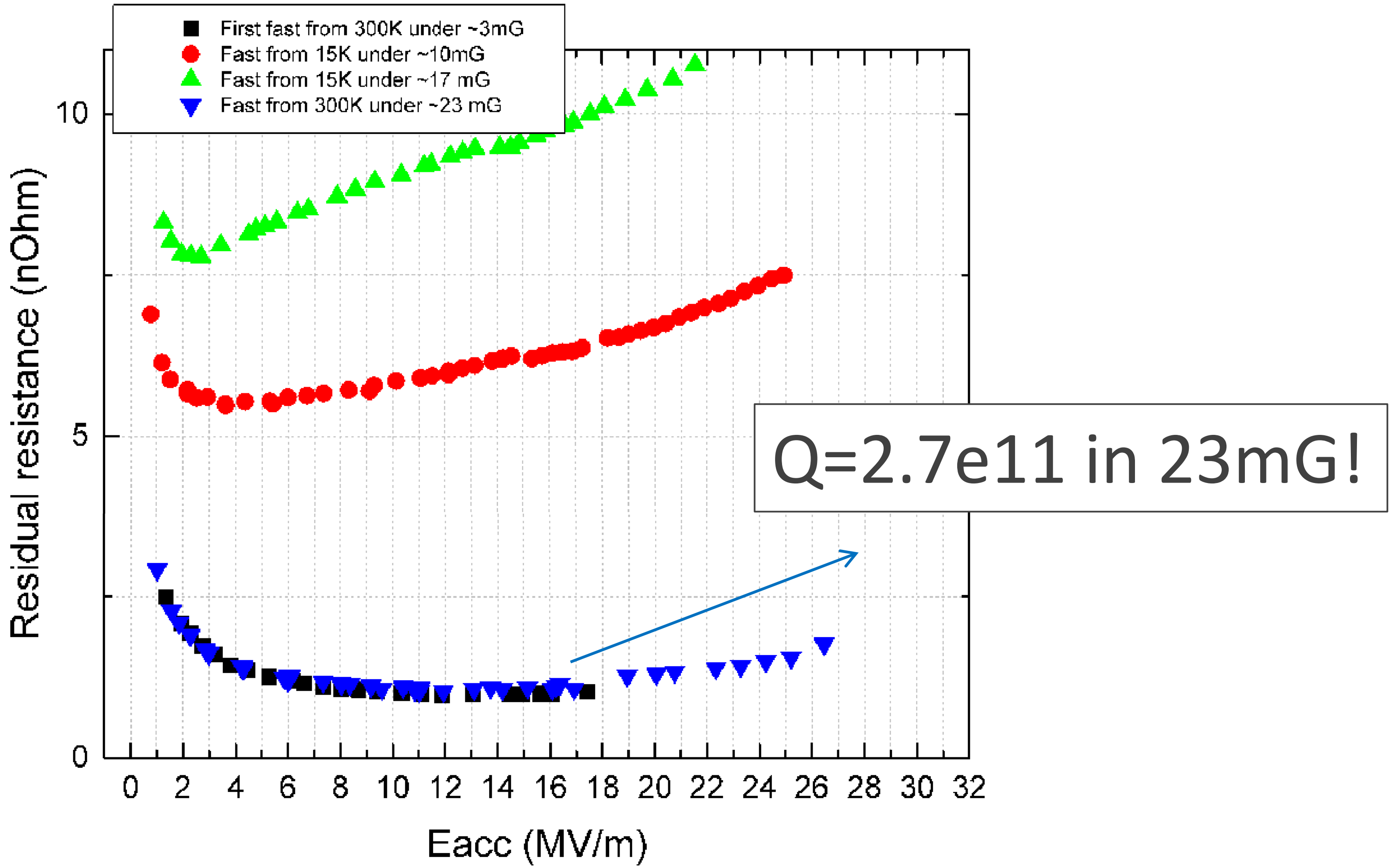
Possible mechanism #2

- See [**J. Appl. Phys. 115, 184903 (2014)**] for details



For this mechanism uniformity is “bad” -> leads to islands

Optimal cooling conditions produce record high Qs even when ambient fields are large



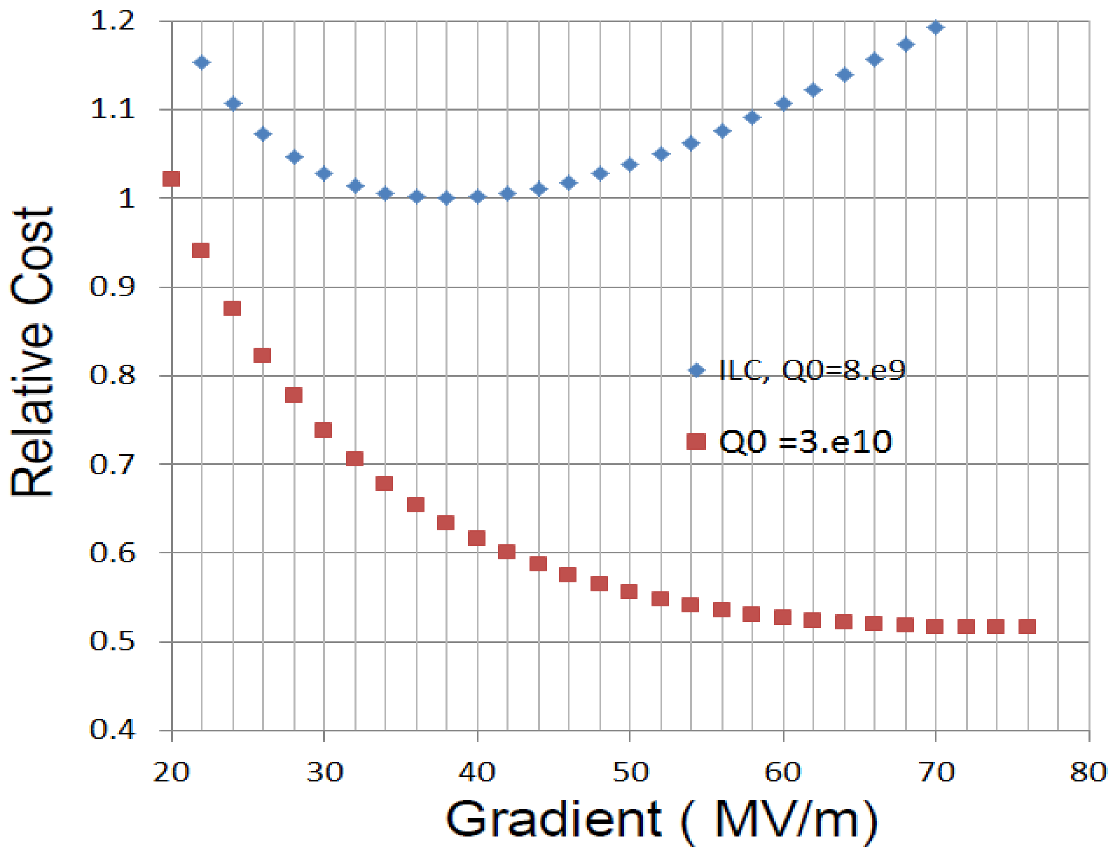
Also means that magnetic shielding requirements may be relaxed

Implications

- CW operation becomes possible for short-pulse machines
- LCLS-II at SLAC
  - Adopted N doping as a baseline
    - 2x higher Q leads to a factor of 2 decrease in required refrigeration => 1 cryoplant less = savings of ~50-100M$ in capital costs + 10s of M$ in operational costs
- PIP-II at FNAL
  - Increase of duty factor from 5% to 30% desired by Mu2e becomes possible with doubling the Q
- Q can be preserved/improved and the magnetic shielding requirements relaxed if the optimal cooling is mastered in the cryomodule
  - Looks straightforward, no show stoppers here
- High gradient/high Q becomes possible => future e+e- machines at drastically reduced costs

Impact of Increasing Q on optimal Gradient

- **ILC requirements:** Eacc > 35 MV/m/ Q0 > $8x10^9$
- **Improving Q_0 from $8x10^9$ to $3x10^{10}$ has a big impact on machine cost**
- **Optimal gradient moves to ~ (70 - 80) MV/m**



Fermilab

Conclusions

- We have two new breakthroughs increasing the Q
  - Nitrogen doping
    - Doped cavities become even more efficient at higher fields
  - Efficient flux expulsion
    - Opens up the route to minimize the residual resistance even in poorly shielded realistic environment
      - May allow to relax the specs on magnetic shielding
- Exciting time in SRF
  - We will follow the science of these discoveries further and see where it leads us

THANK YOU