Progress in “High Q” Program

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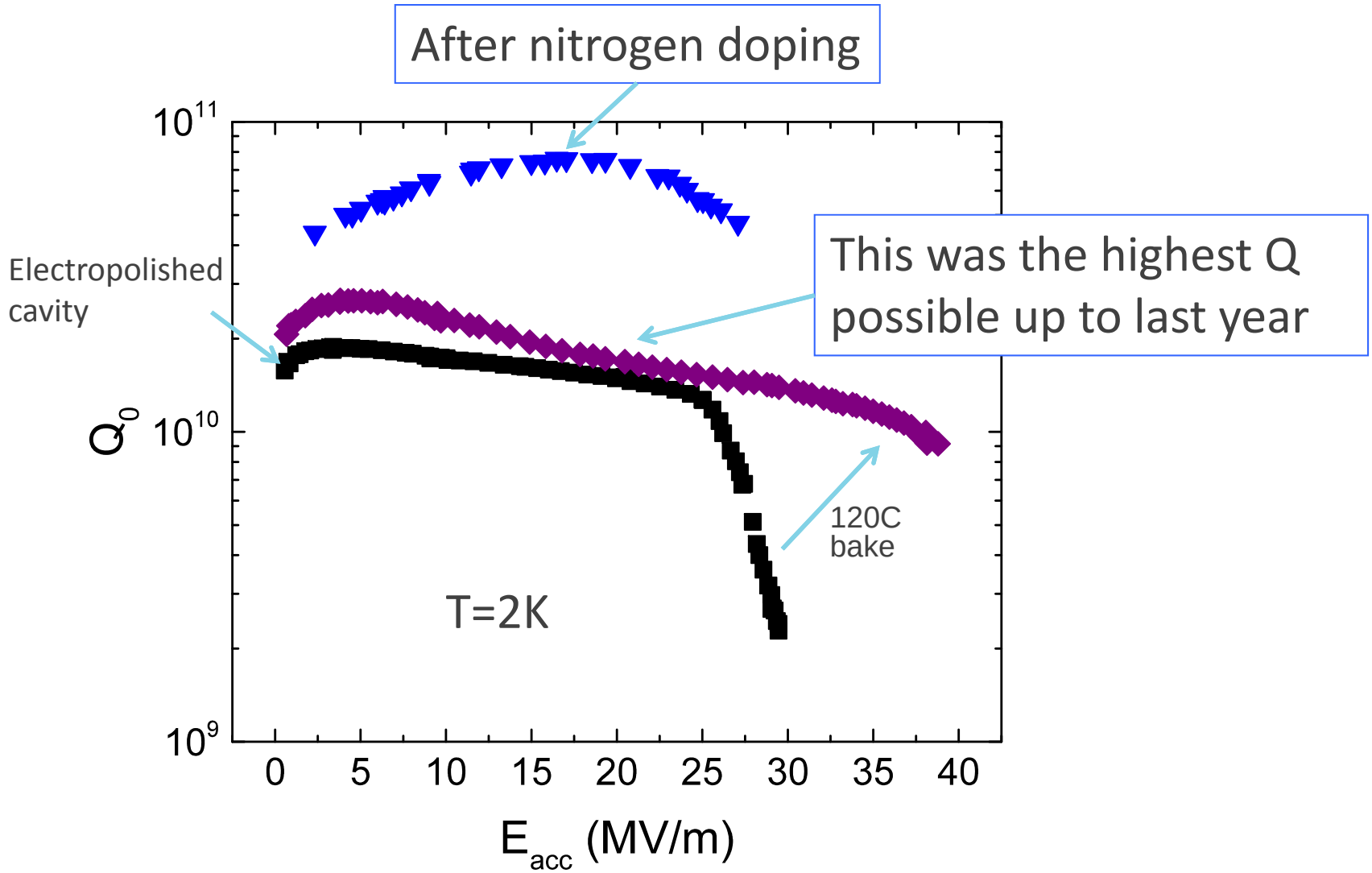
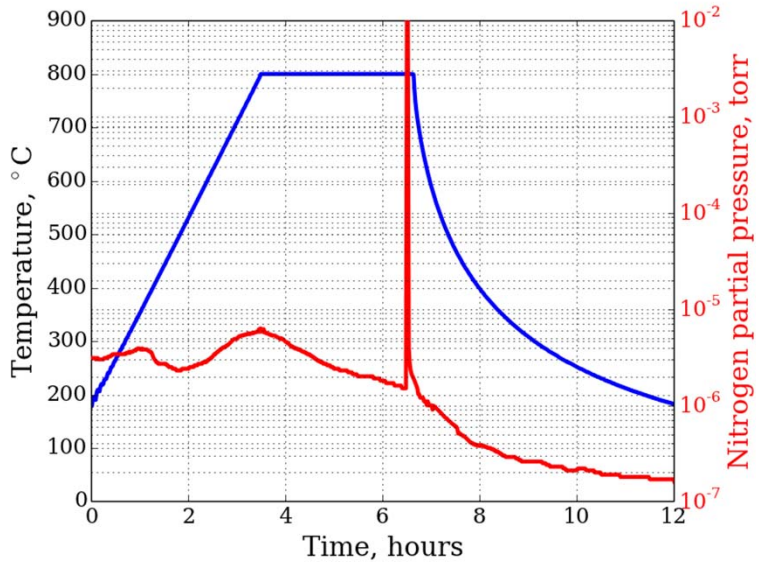
PIP-II Meeting

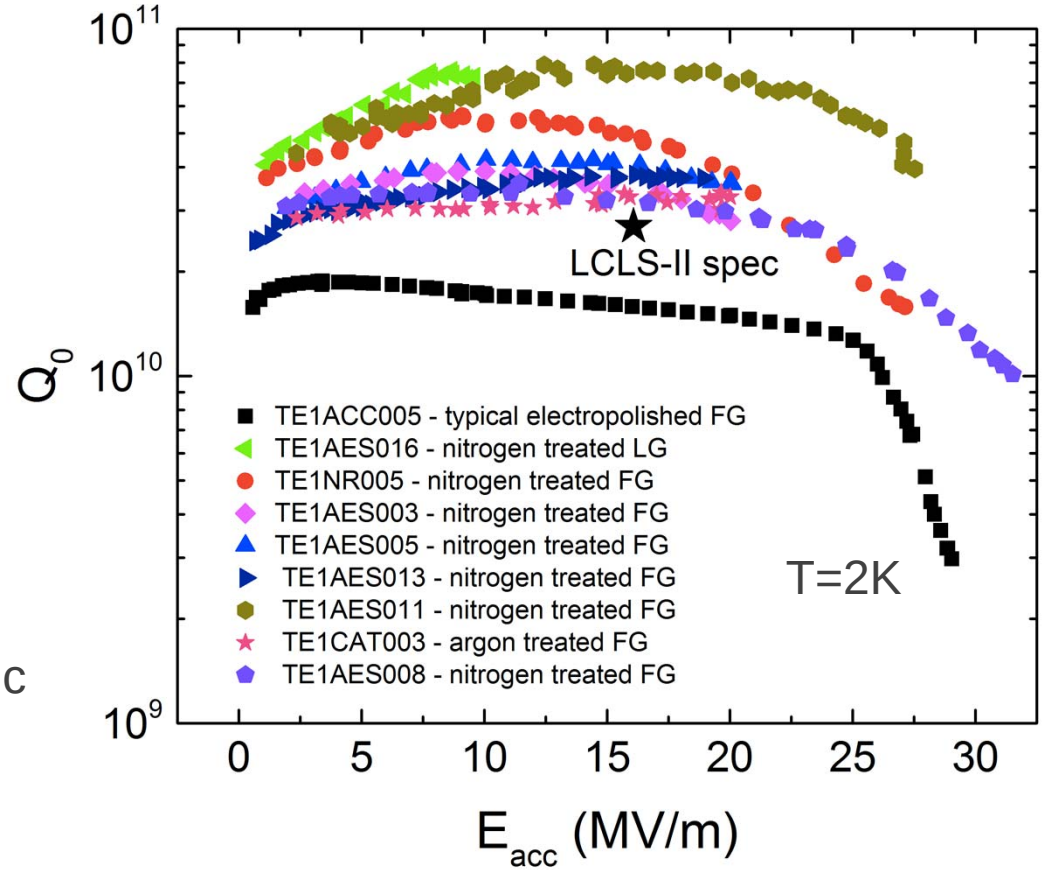
10 June 2014

Nitrogen doping: a breakthrough in Q



Nitrogen doping



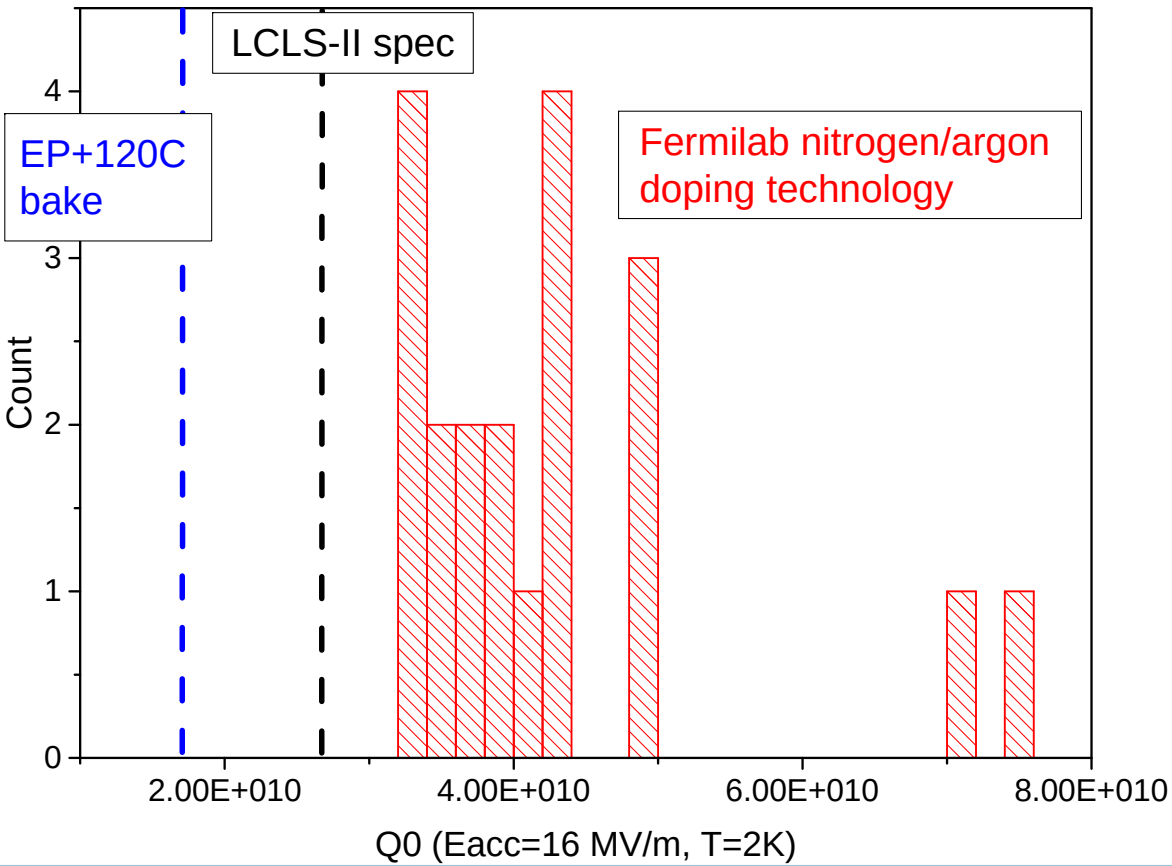


- Injection of small nitrogen partial pressure at the end of 800C degassing, followed by EP-> drastic increase in Q
- At present more than 40 cavities treated
- R&D program ongoing for LCLS-II with the goal of validating Q=2.7e10@2K, 16MV/m in

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

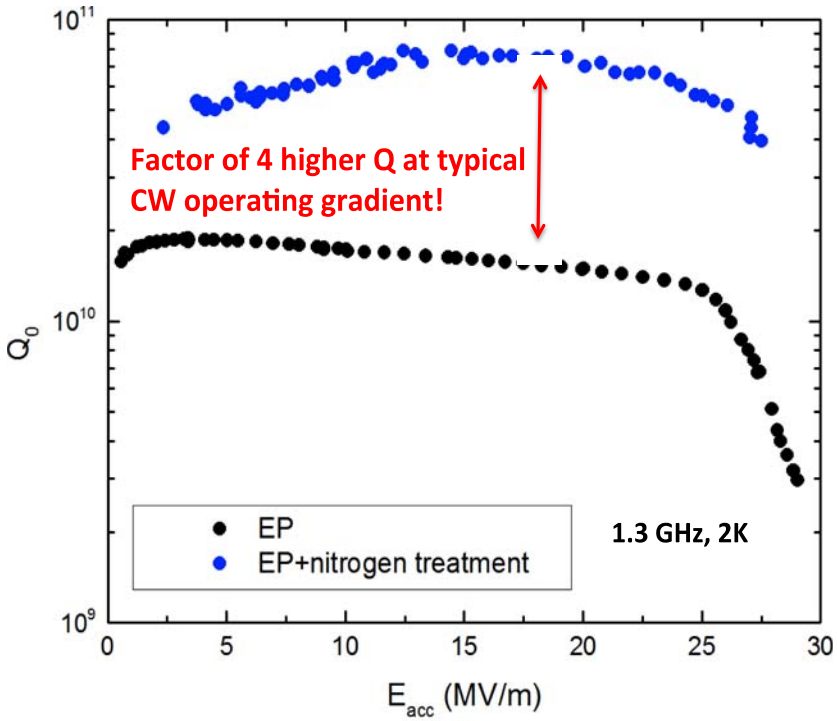
Statistics of Q values obtained by doping

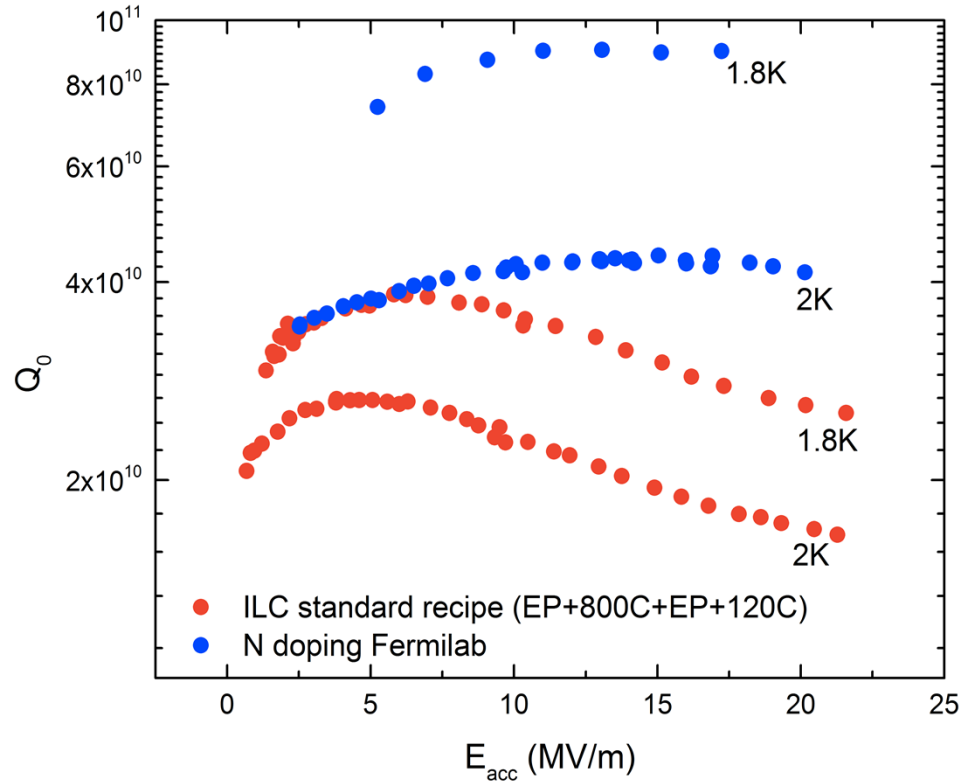
	N total	Mean	Standard Deviation	Minimum	Median	Maximum
Q0	20	**4.3e10**	1.2e10	3.2e10	**4.0e10**	7.4e10



- Q several times above state-of-the-art
- Improvement in both R_{BCS} (B) and R_0(B)

Comparing to standard treatments



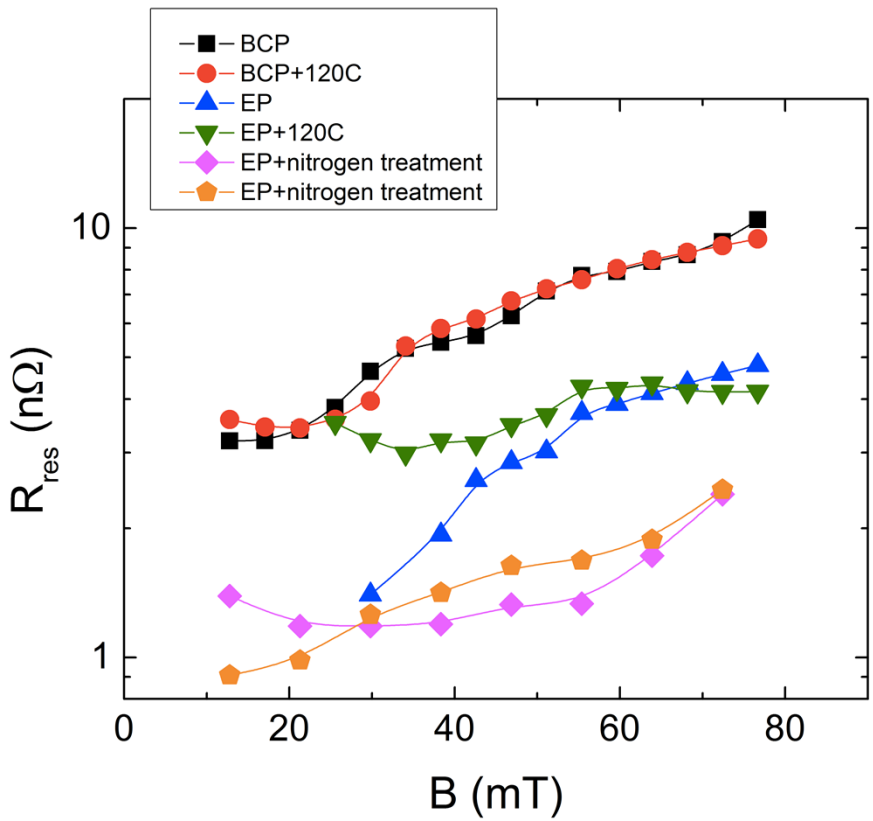


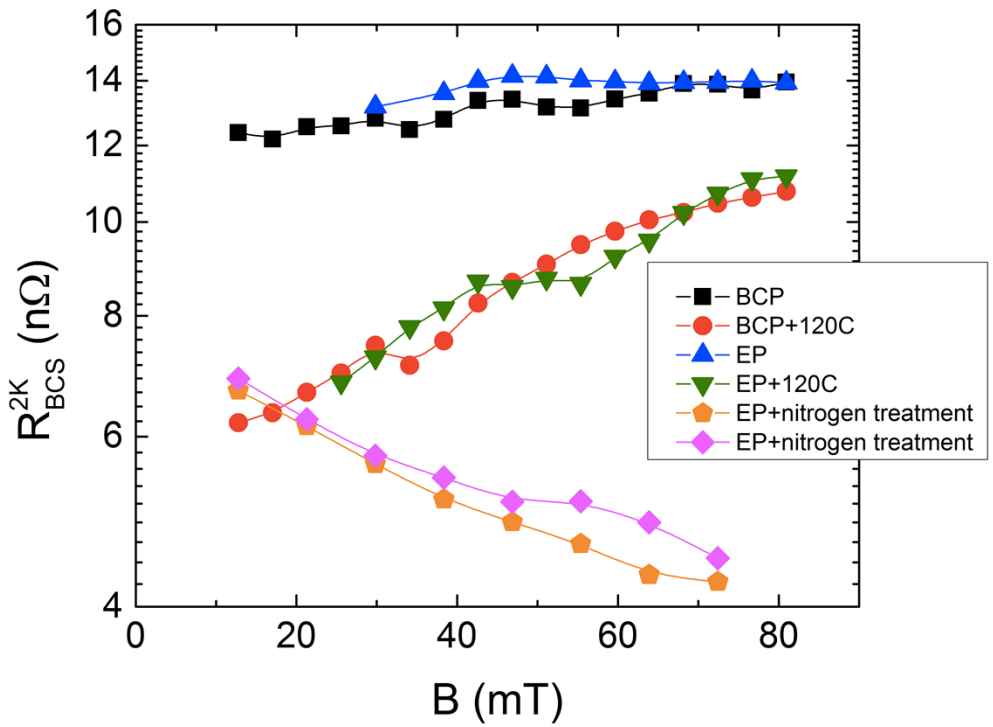
Understanding the underlying mechanisms

“Reversed” field dependence of R_{BCS}

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

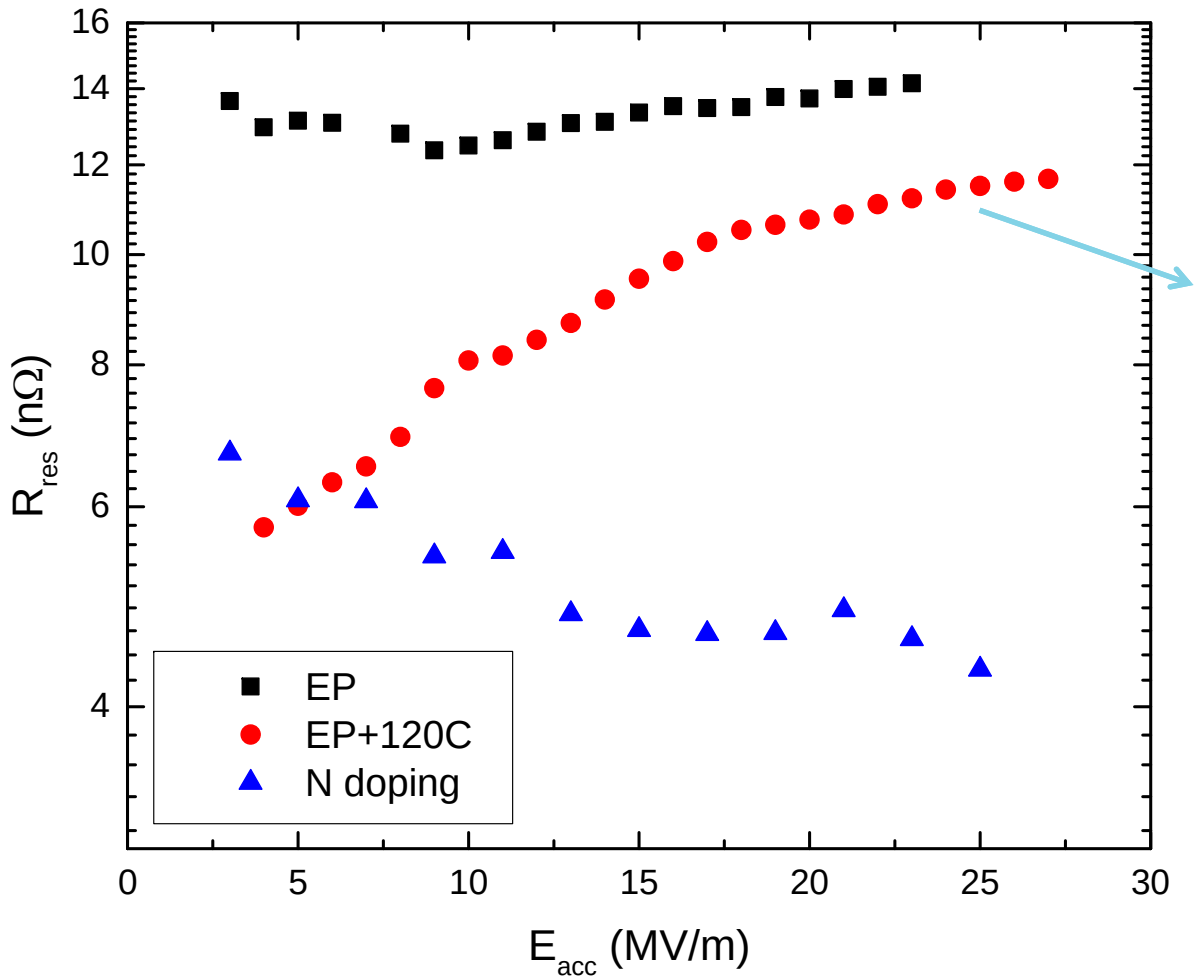
$$P_{diss} \propto \frac{1}{Q} \propto R_s$$





A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication), highlights of 2013
A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

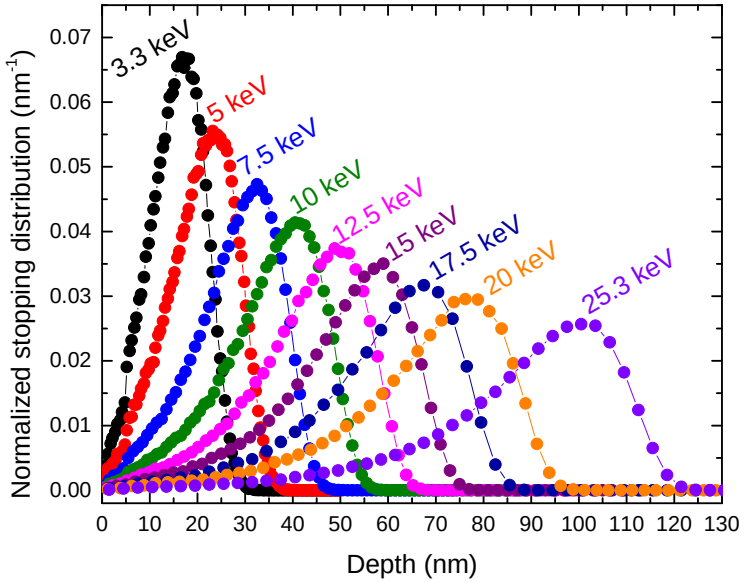
New boundary for $R_{BCS}(B)$ at higher fields – 3 times lower BCS resistance

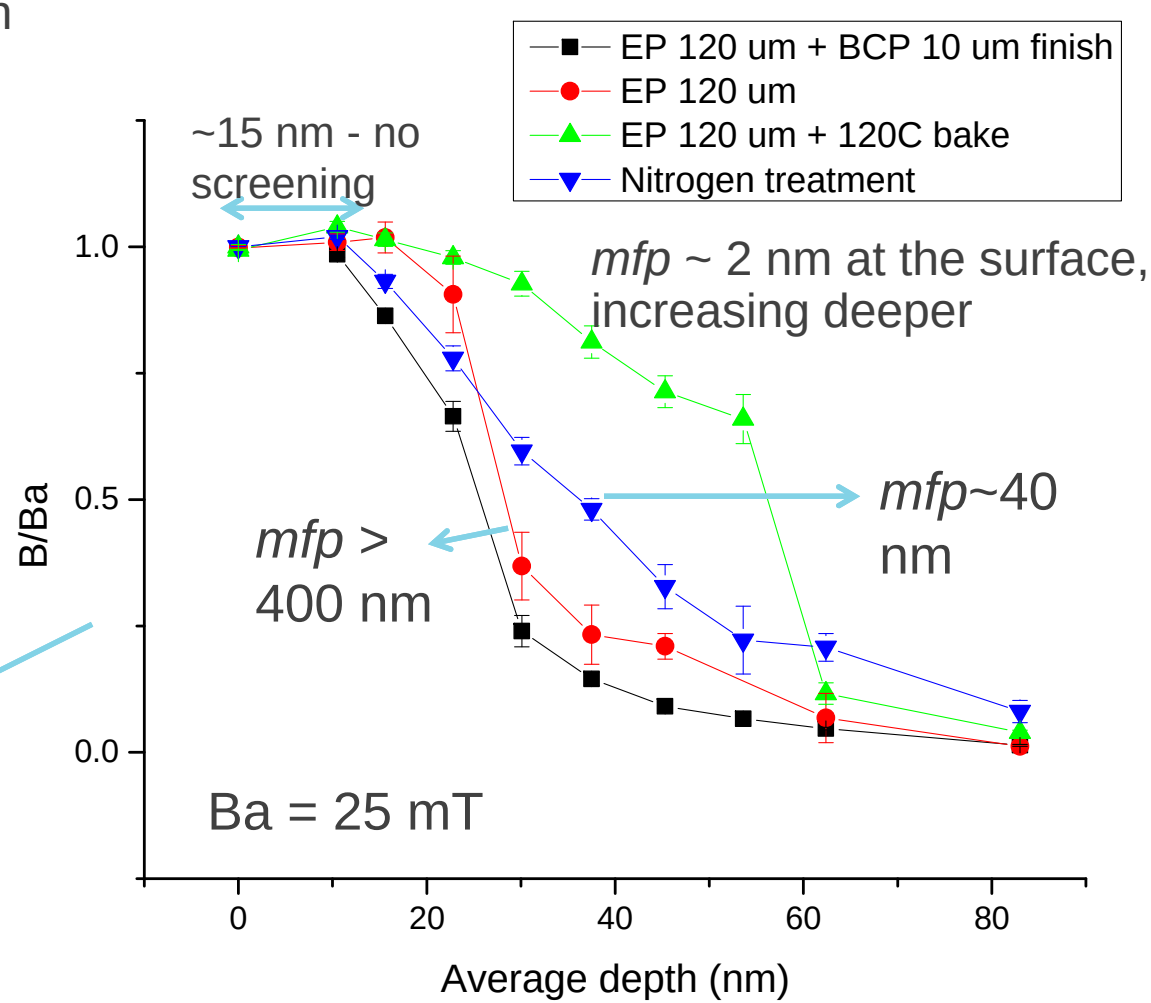


Previously thought to be the "BCS" limit

Muon spin rotation – nitrogen doping

Use variable energy muons, which stop in the first ~100nm



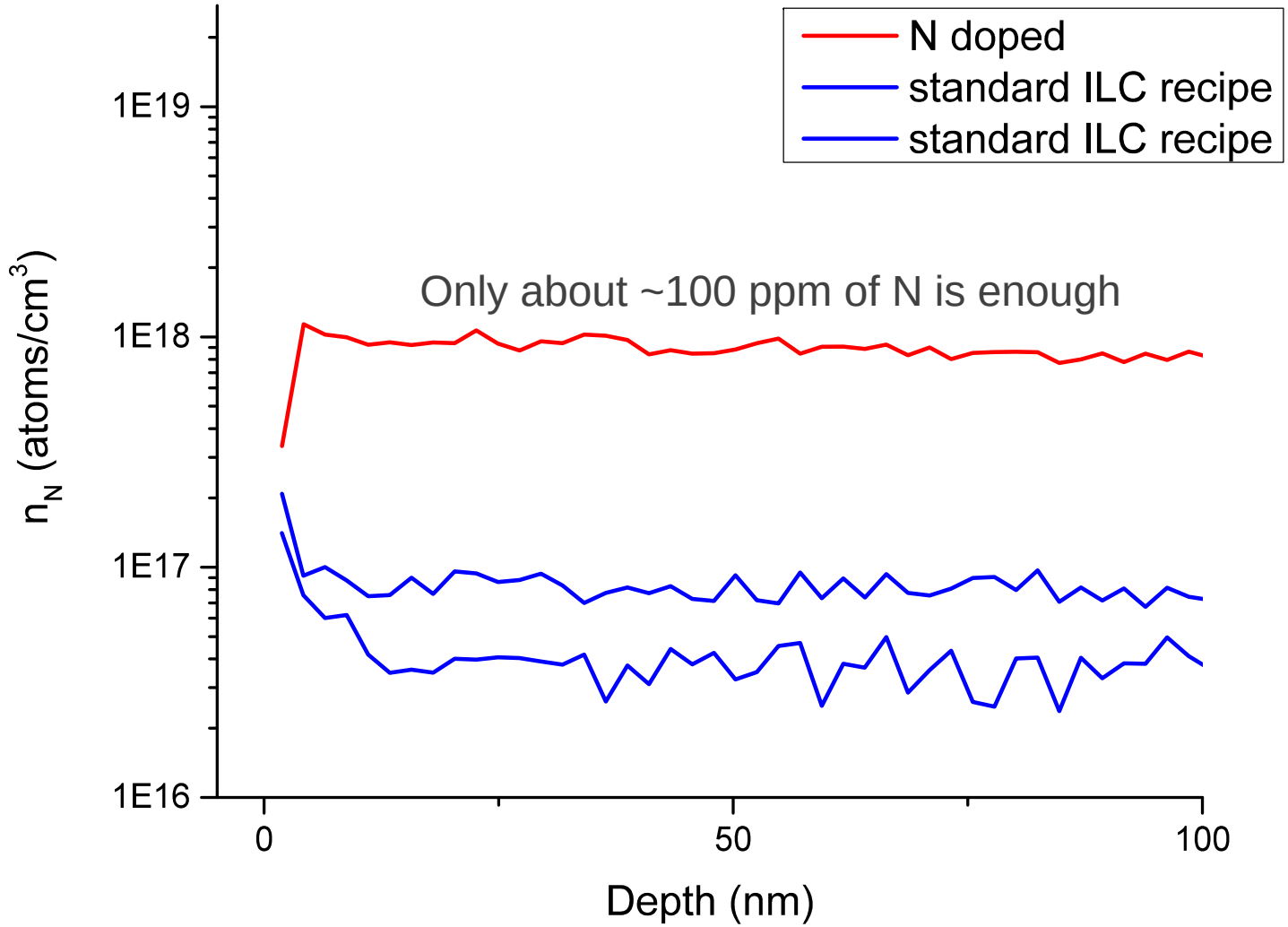


BCP and EP unbaked -> strong screening, excellent fit provided by the clean limit Pippard/BCS model

EP+120C bake-> strongly suppressed m.f.p., gradient of the m.f.p. from the surface, dirty limit

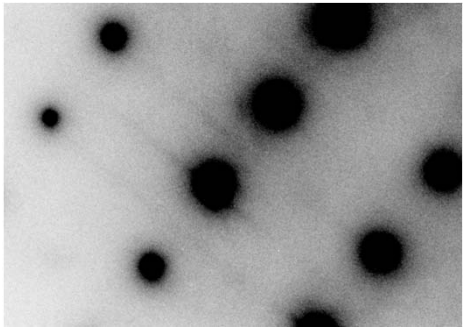
N-doped -> intermediate m.f.p., no gradient

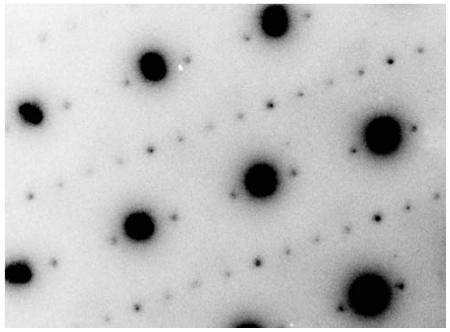
Nitrogen doping – SIMS data



No nanohydrides found in nitrogen doped cutouts

T-dependent TEM structural characterization (NED) at room T and at 94K.





Room T and 94K: **NO** additional Nb hydride phases right underneath an oxide (within ~50 nm)!

94K: stoichiometric Nb hydrides as observed in non-doped cutouts

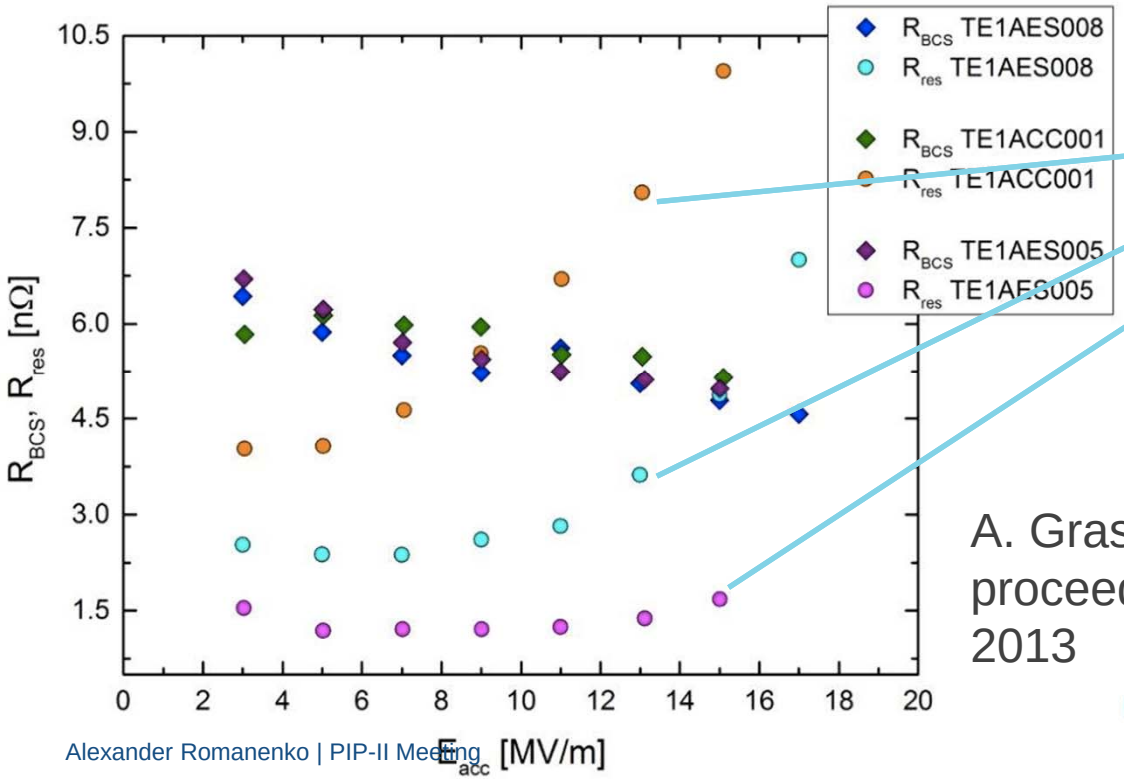
Nitrogen doping may fully trap hydrogen => only intrinsic Nb behavior is then manifested?

Y. Trenikhina et al, Proceedings of SRF'2013

Progress in single and nine cell work for LCLS-II

Recipe - state of the art

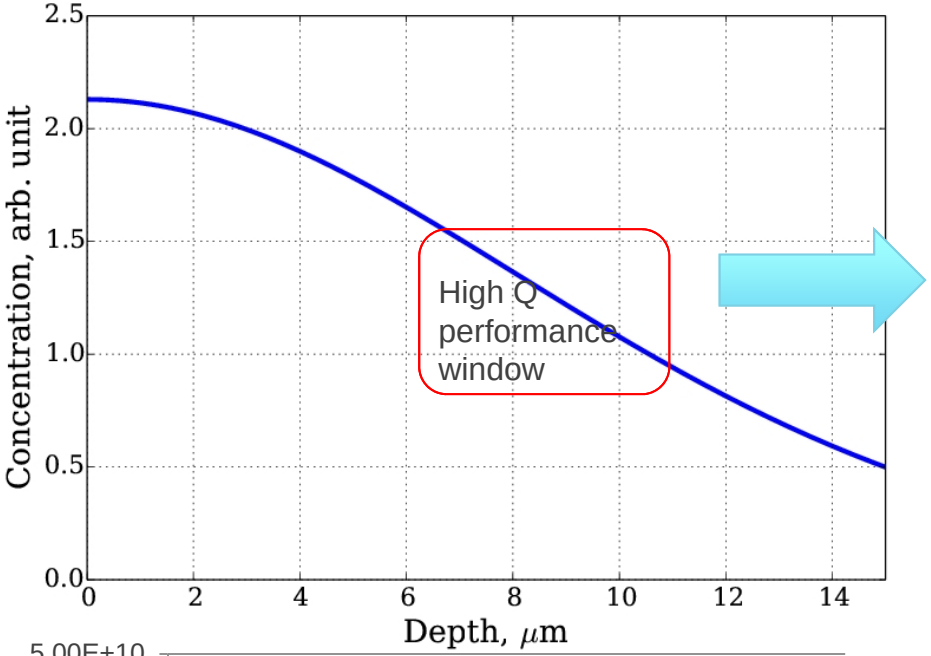
- First developments at FNAL had one step diffusion recipe sensitive to +- 2 microns removal
- This is less suitable for a processing technique to be transferred to industry
- Goal: develop ROBUST (Acceptable EP removal range is wider) nitrogen processing for Q= 2.7e10 @ 16 MV/m, 2K
- High Q for LCLS-II collaboration with Cornell and Jlab, Marc Ross @SLAC

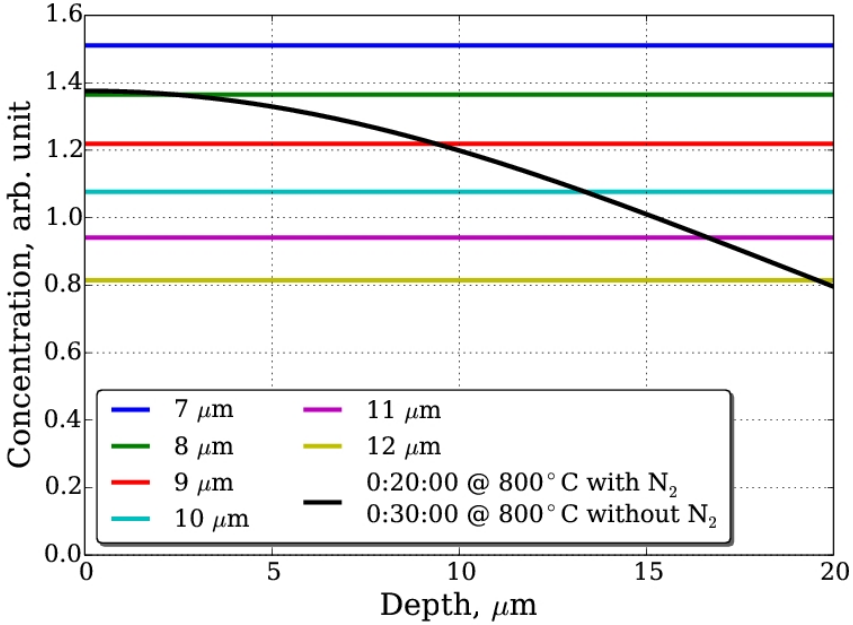


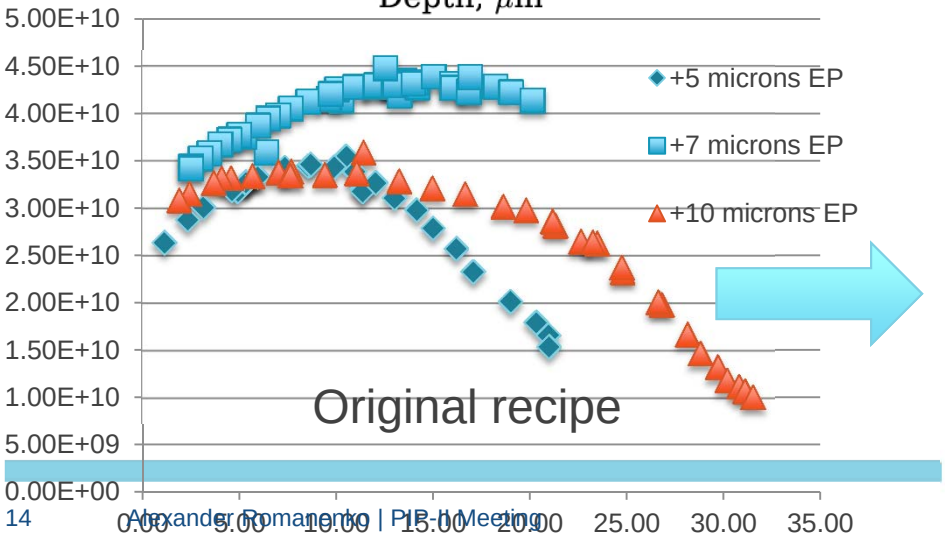
Rres was very sensitive to material removal in the original recipe

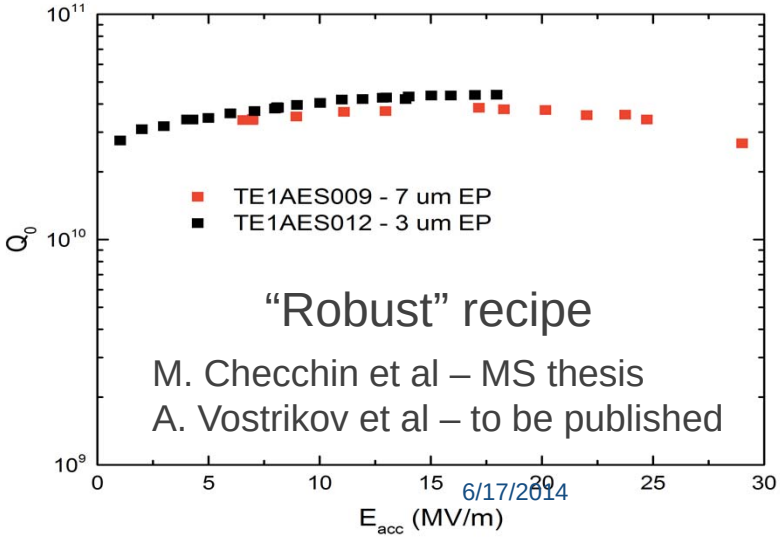
A. Grassellino et al, proceedings of SRF 2013

Two steps diffusion developed at FNAL

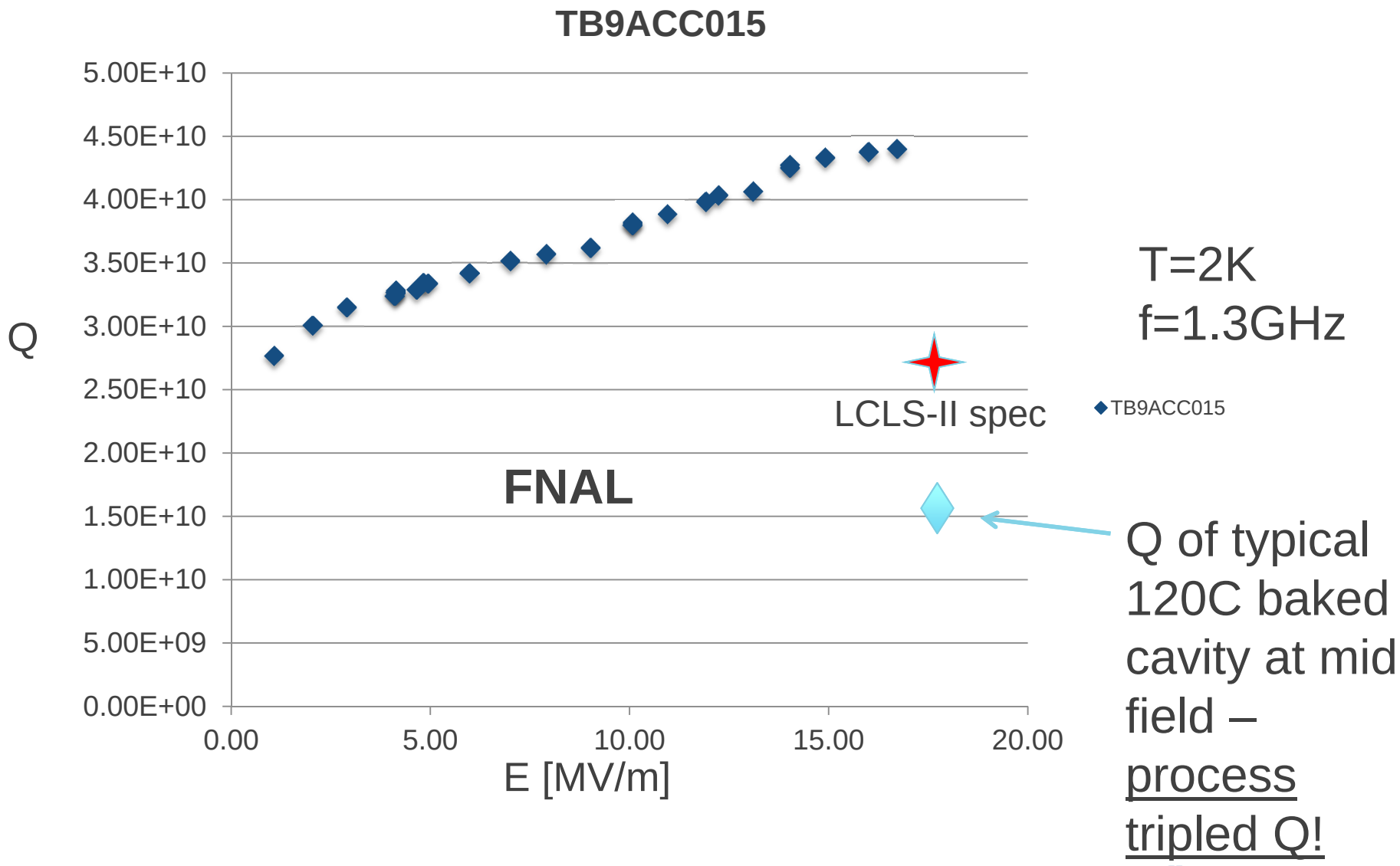




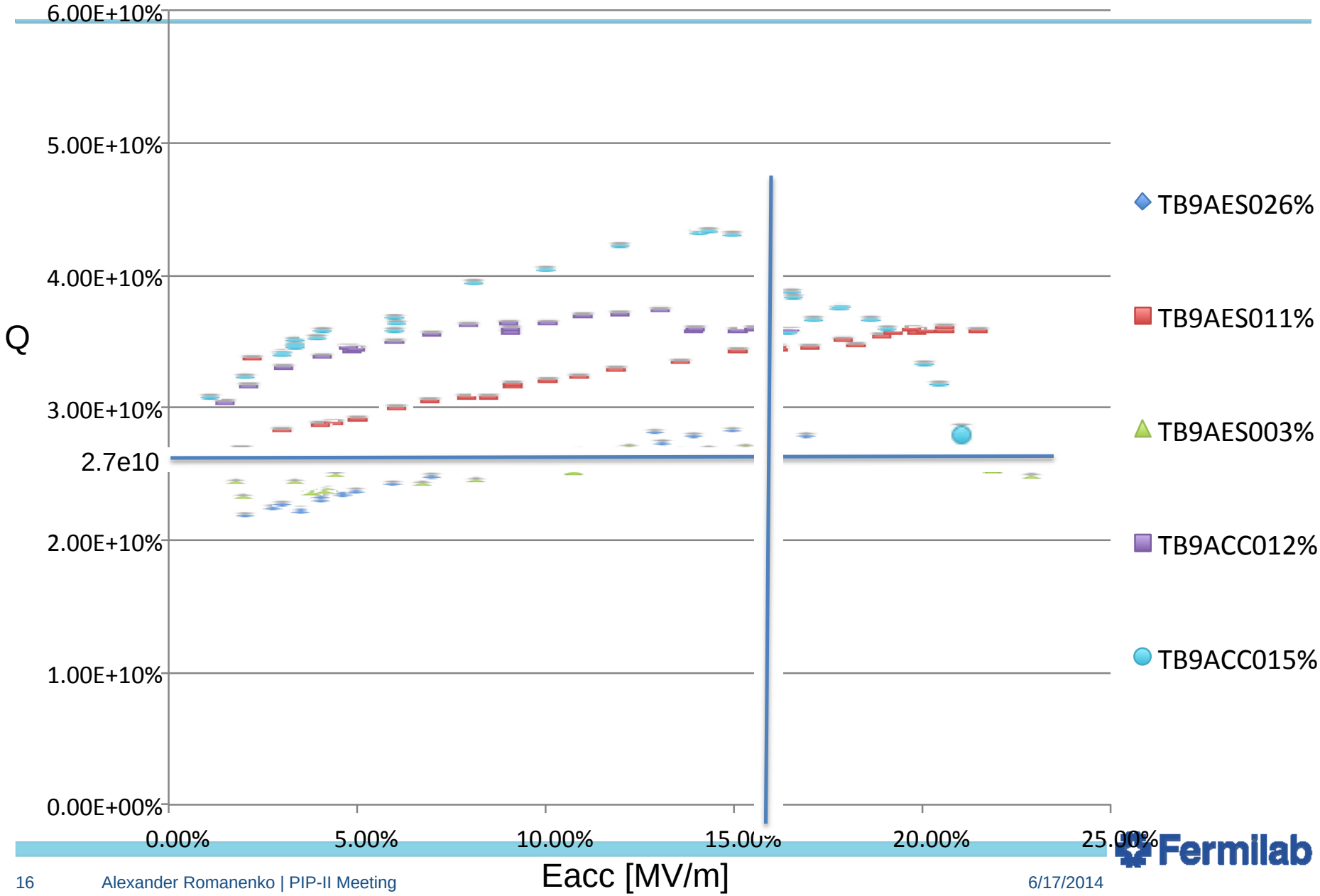




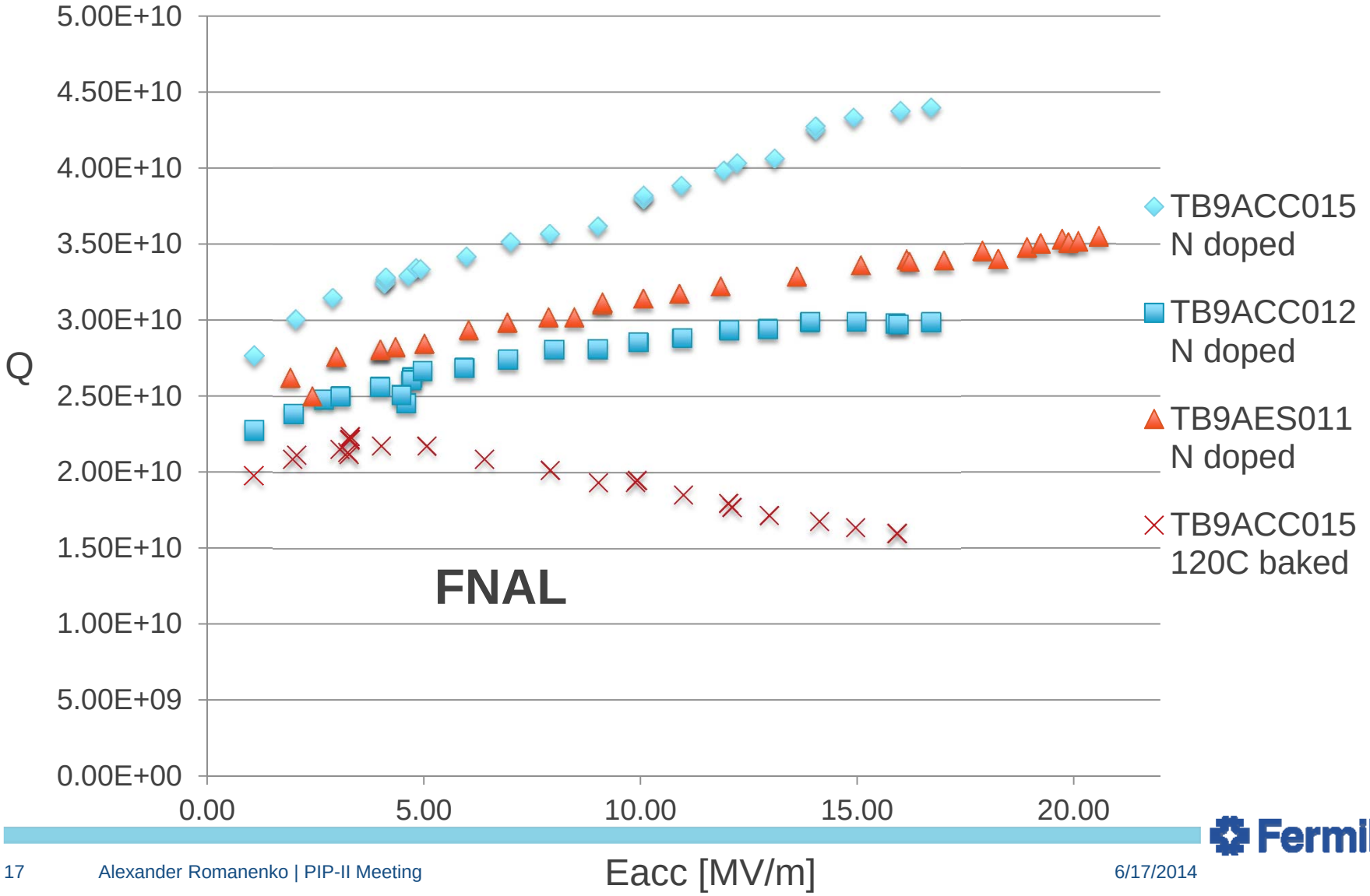
Nine cell TB9ACC015 – world record Q at mid E_{acc}



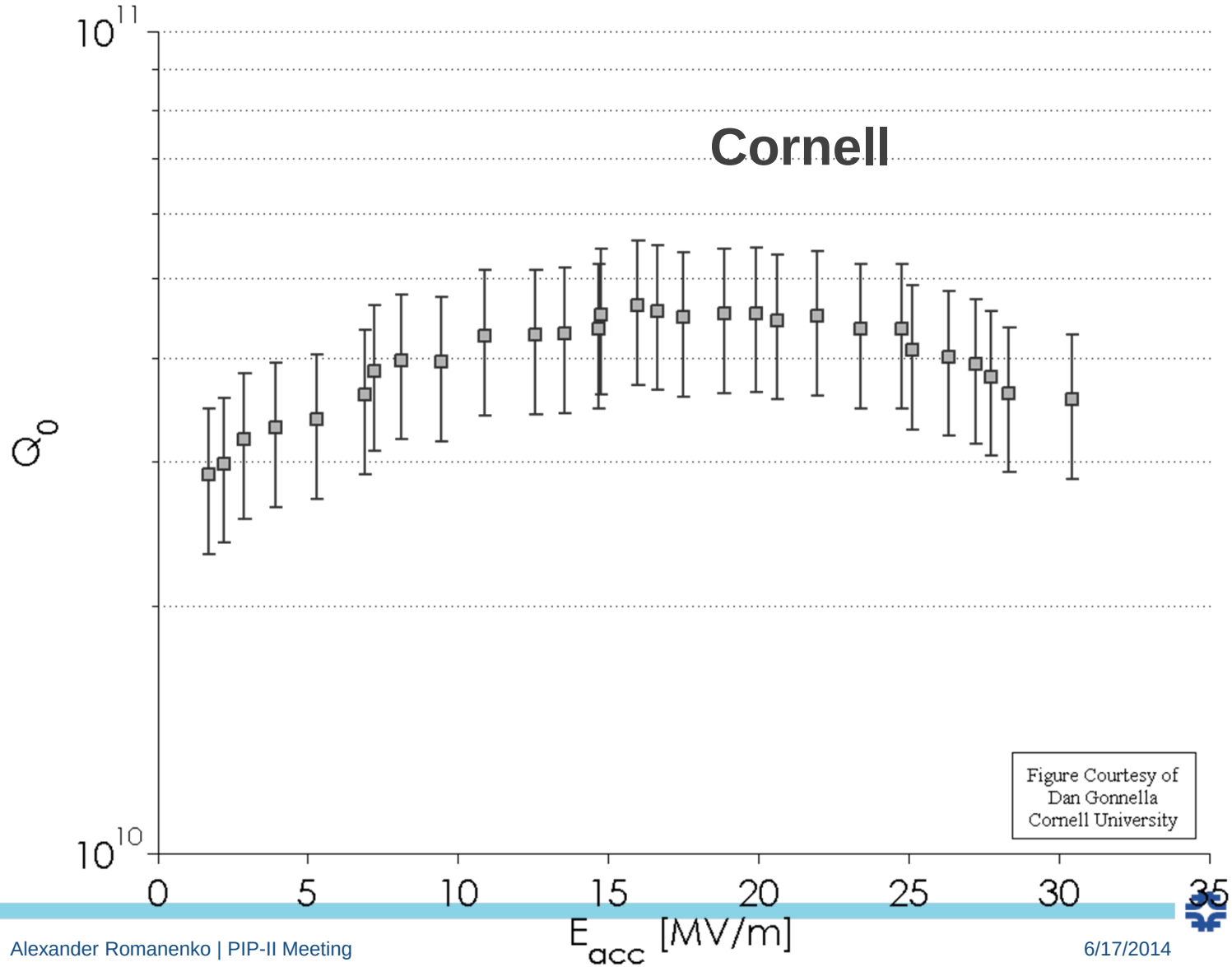
FNAL doped nine cells meet LCLS-II specs Q(2K, 16 MV/m) ~2.7e10



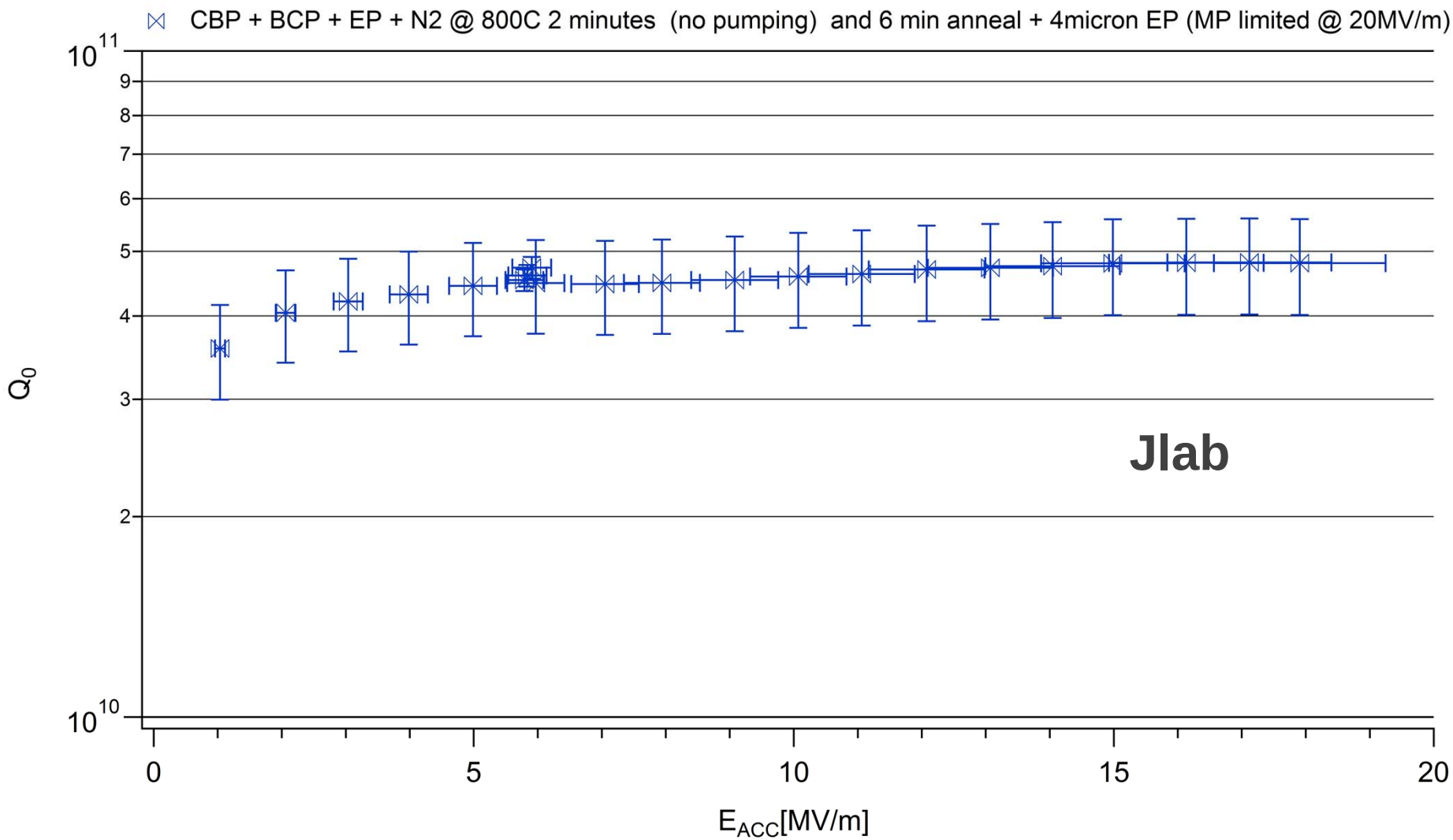
Nine cells N doped vs typical 120C bake – Q comparison at 2K, mid field: 2-3 times higher Q



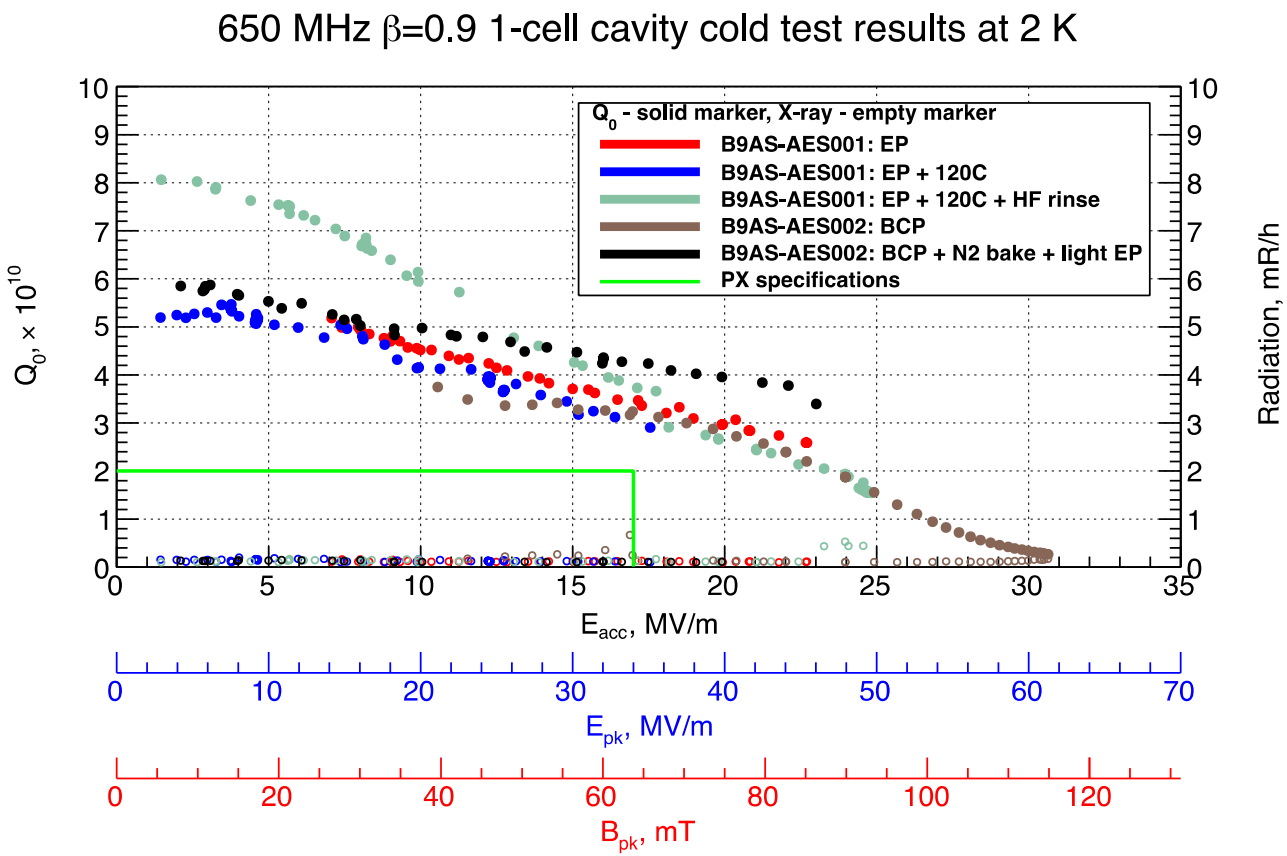
Transfer of FNAL technology - Cornell



RDT-5 JLAB/LCLSII baseline N2 doping cavity - 2K data



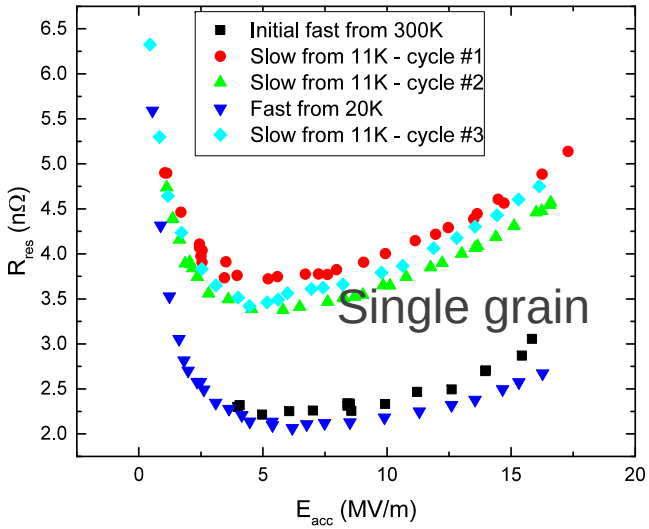
Surface processing studies for 650 MHz

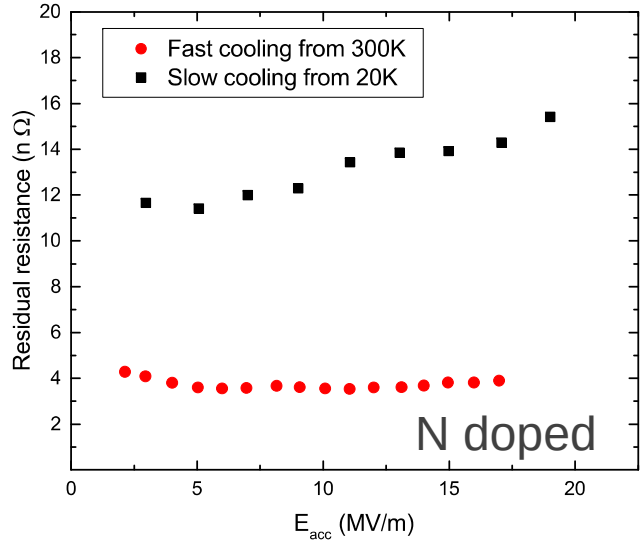


- Explored several different surface processing techniques on 650 MHz single cells
- All cases largely exceed the PIP-II specs of Q ~ 2e10 at 17 MV/m

High Q (low trapped flux-induced residual resistance) preservation via efficient flux expulsion cooling

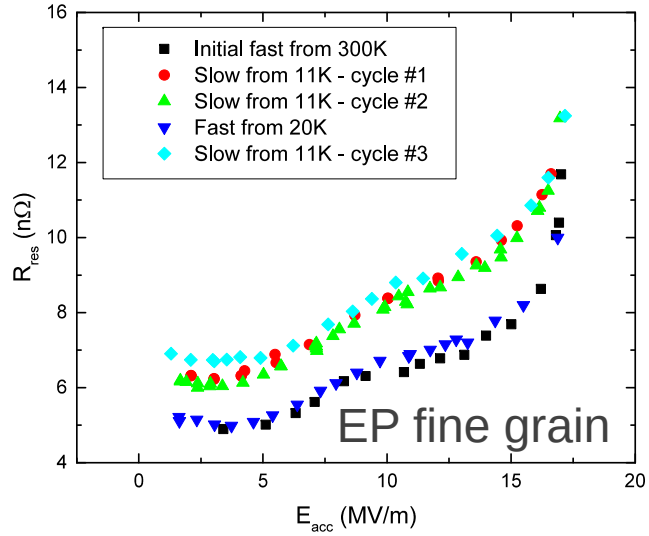
Effect of cooling dynamics around T_c on Q –bare cavities





Slow cooling: <0.3K/min

Fast cooling: 1.8-2.4K/min

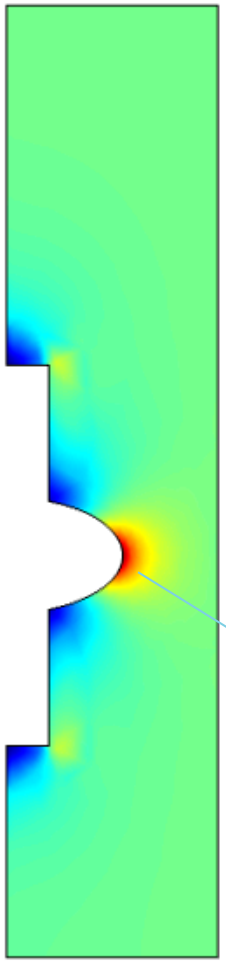


By only varying the speed of cavity cooling through T_c=9.25K the residual surface resistance can be systematically and reversibly varied!

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

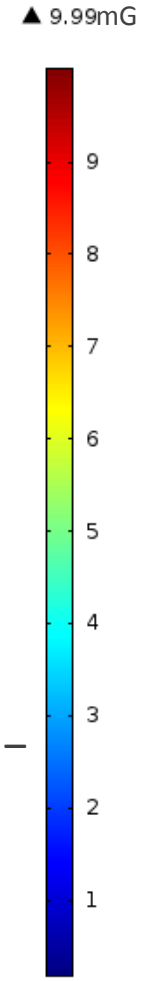
Direct magnetic probe measurements for understanding

Fluxgate magnetometers



H=5mG

Field enhancement due to Meissner effect – ambient flux expulsion



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

What did magnetic probes reveal?

- Systematic strong difference in magnetic flux expulsion efficiency between slow and fast cooling
- Similar magnetic field at transition between fast/slow
  - No additional field generated during fast cooling

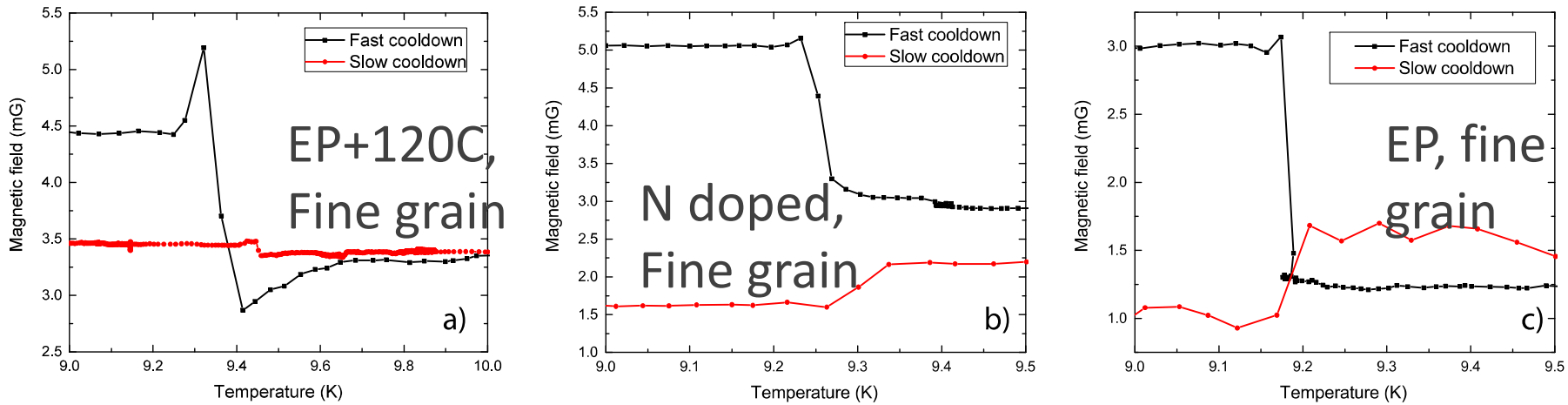
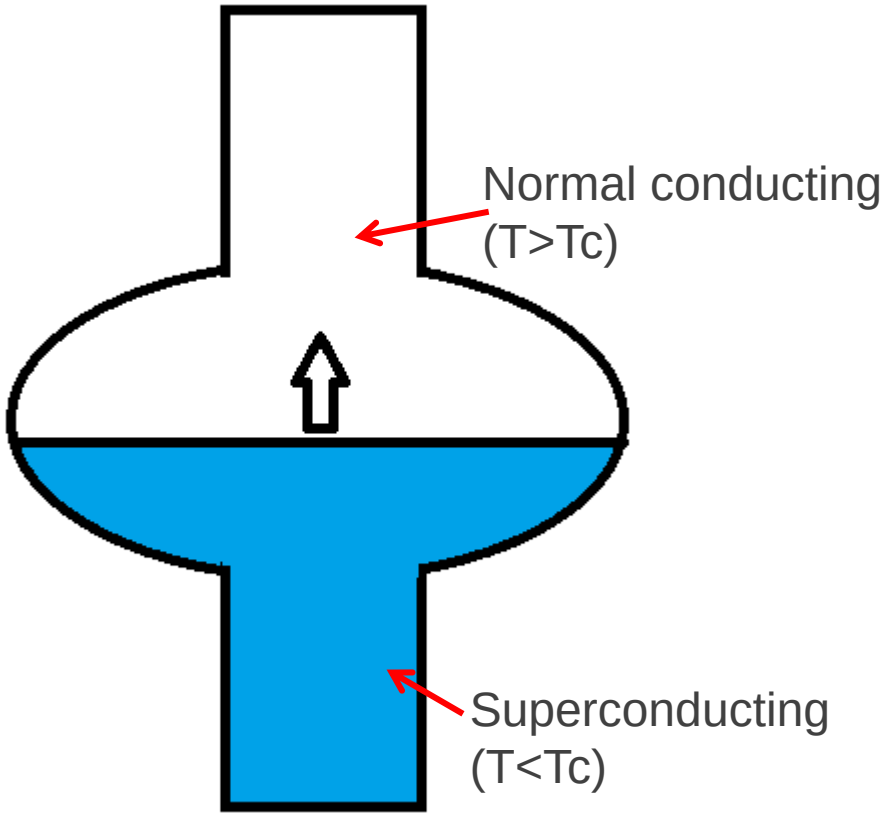


FIG. 6. Characteristic magnetic field expulsion data for: a) 9-cell EP+120°C baking; b) nitrogen doped 1-cell; c) EP 1-cell. A strong systematic difference in the field expulsion at different cooling rates is observed for all surface treatments.

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

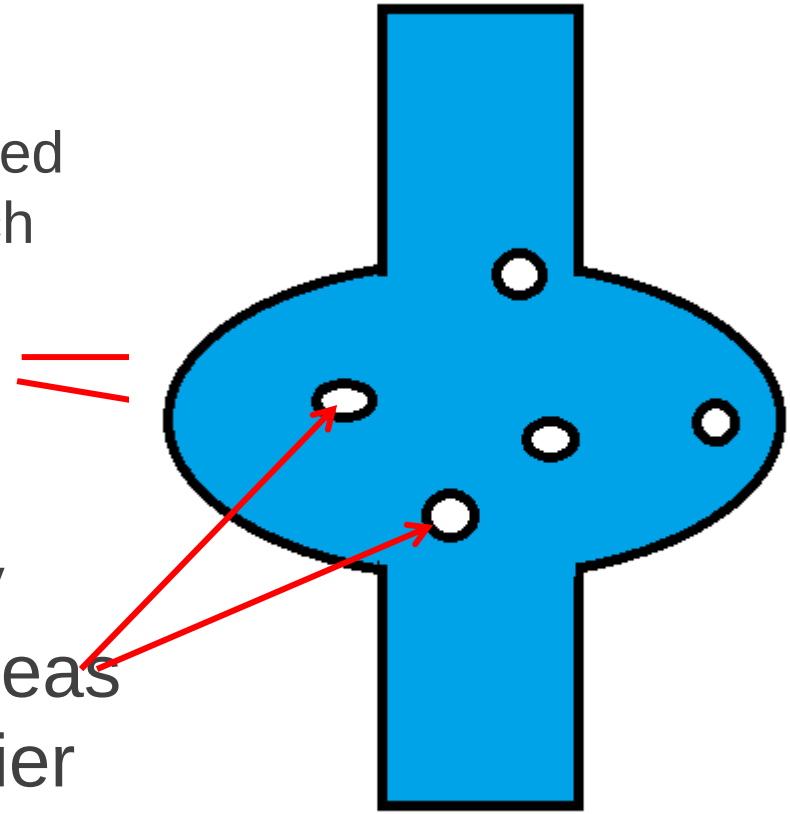
Details of superconductivity nucleation matter

Fast cooldown in vertical configuration – well-defined superconducting/normal boundary is moving from bottom to the top => <u>no energy barrier</u> for flux to be expelled



Slow uniform cooldown

Slow uniform cooldown – superconductivity is nucleated at multiple spots which reach T<Tc



Flux surrounded by superconducting areas has an energy barrier for escape=> more trapping is possible

Implications and dressed cavities

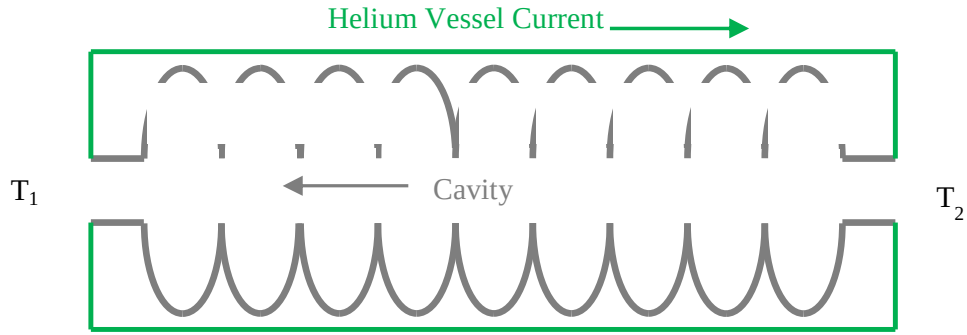


Figure 1. System Geometry

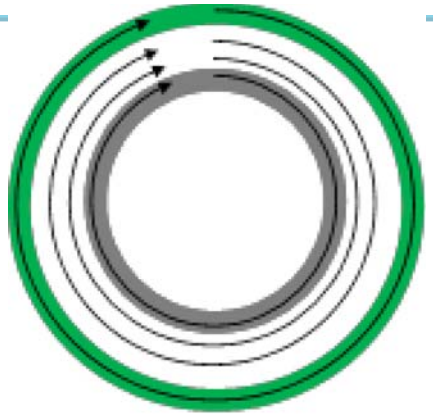
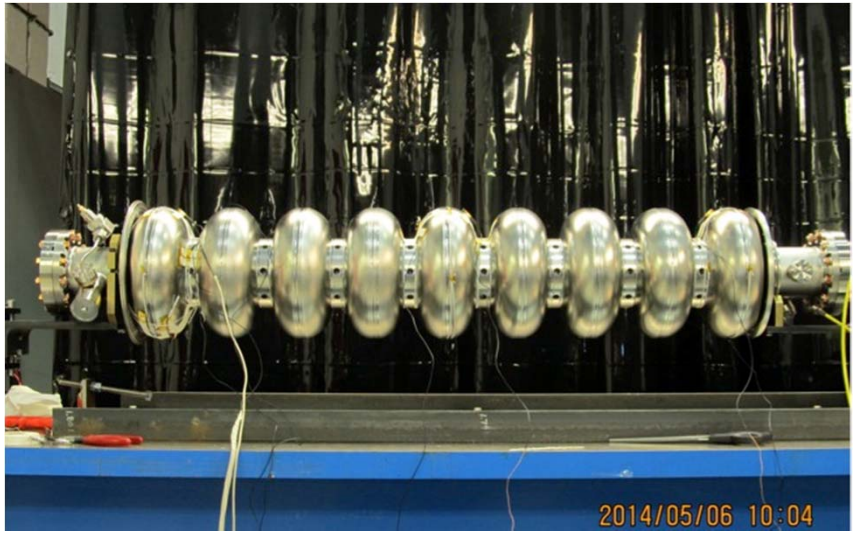


Figure 2. Magnetic Field Lines

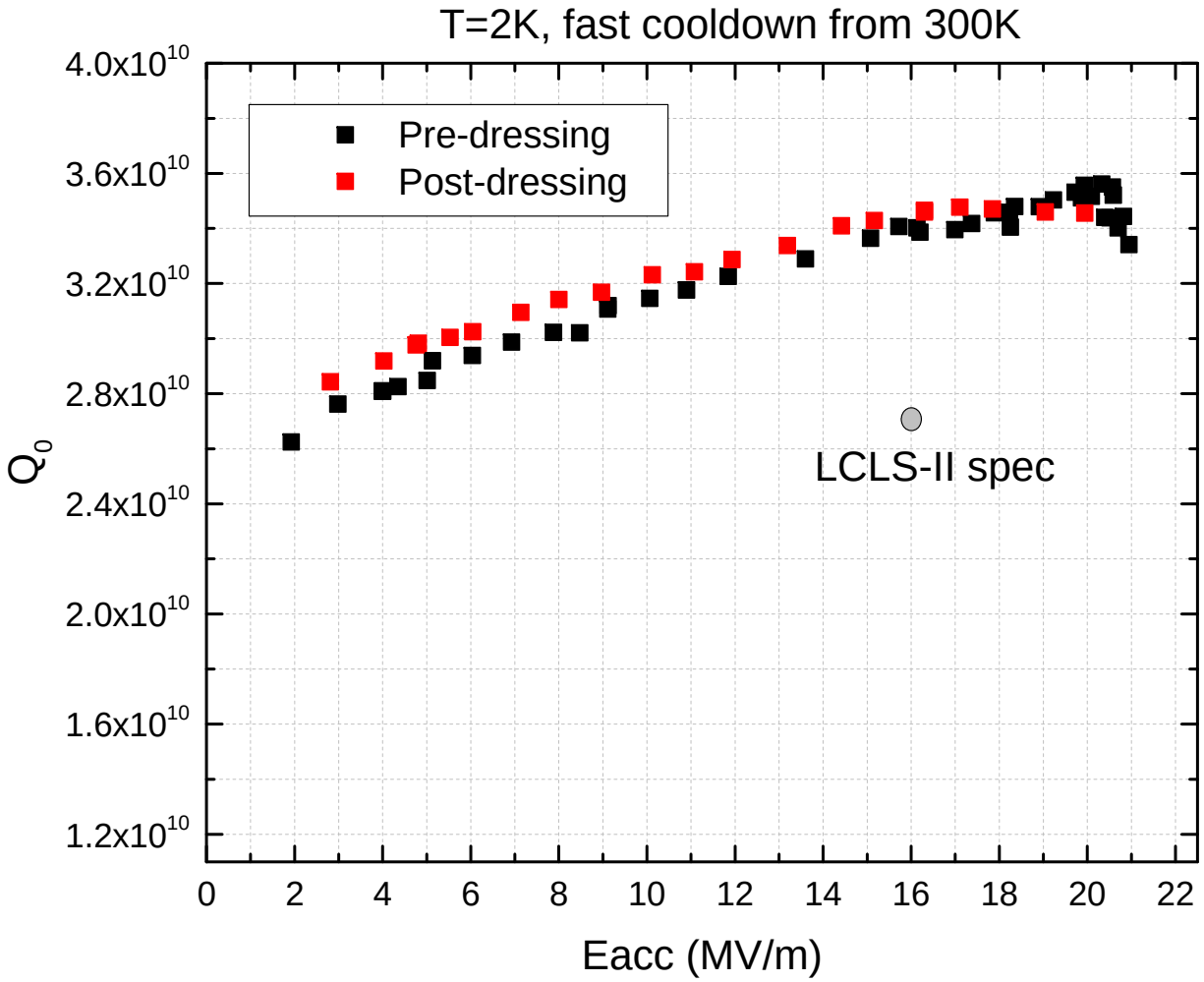
- Cooling details matter for high Q performance even for bare cavities
- In dressed cavities additional constraints may arise from thermocurrents generated by bimetal junction Nb-Ti vessel, as suggested by pioneering studies by Kugeler, Vogt et al at HZB
- FNAL investigated two dressed cavities and large fields at the OUTSIDE wall of the cavities have been observed to be generated during fast cooling with large thermogradients
- However, due to the symmetry of the problem, fields are expected to become quite low at the inner surface – low to no impact on flux trapping (unless asymmetries present) – see A. Crawford, **arXiv:1403.7996**

LCLS-II FNAL first dressed nitrogen doped nine cell

- Studies undergoing for LCLS-II on first nitrogen doped dressed nine cell
- Cavity was dressed with 4 flux gate probes and 4 T sensors installed on cells
- Recommendations on ideal cooling procedure for LCLS-II will follow from the HTS test

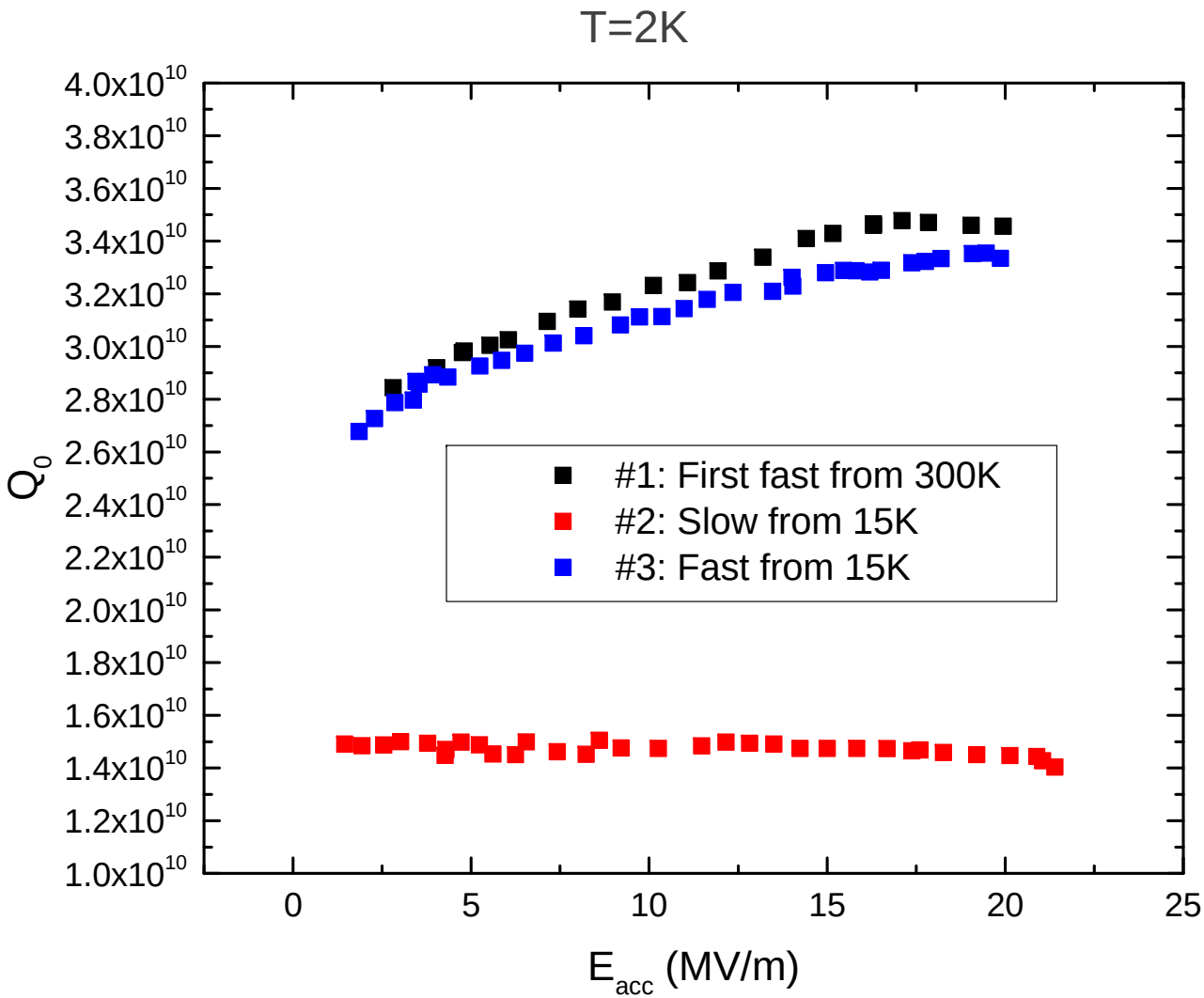


TB9AES011 dressed – vertical test results

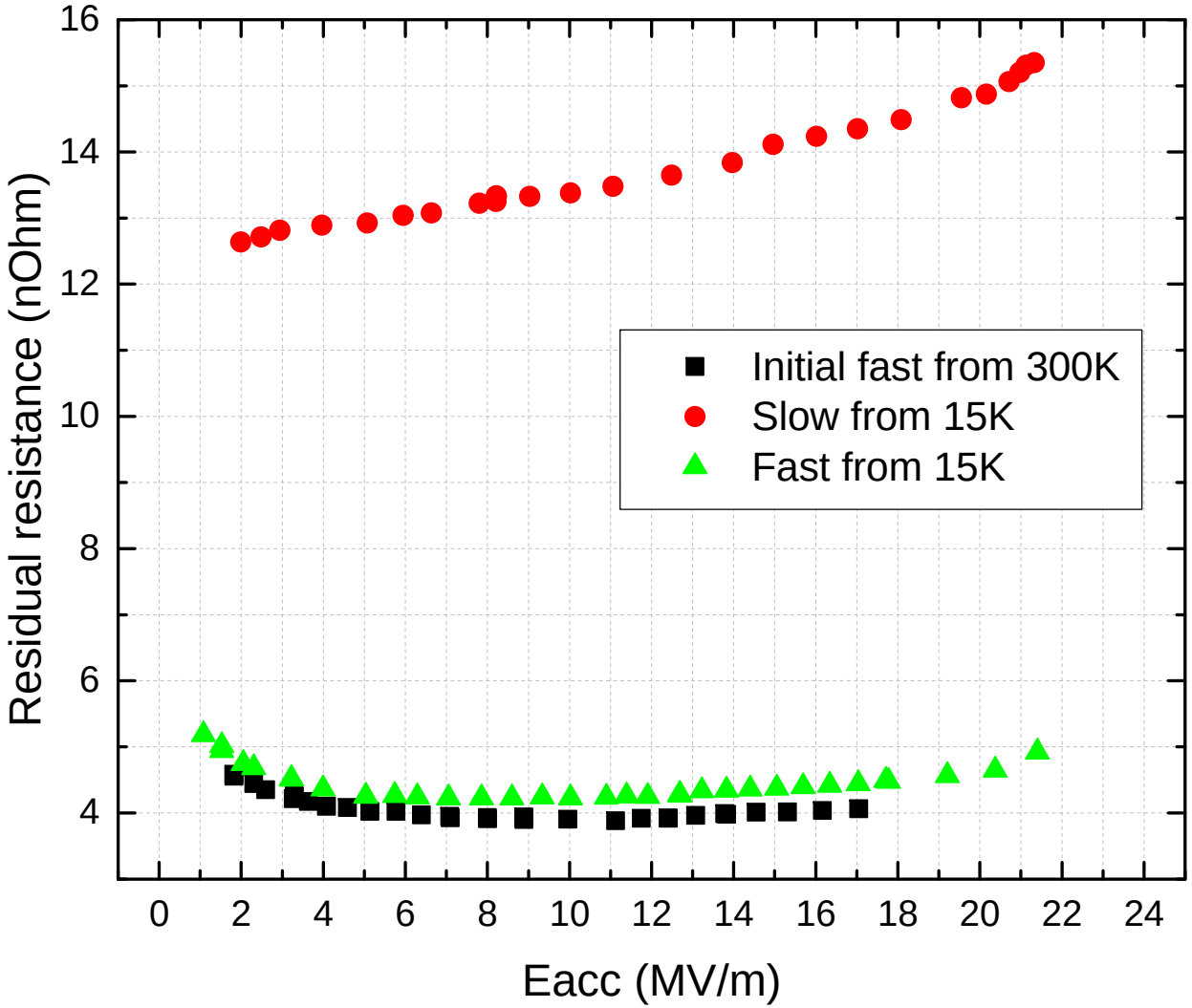


Coupler Qext ~3e10

Dressed TB9AES011 vertical testing

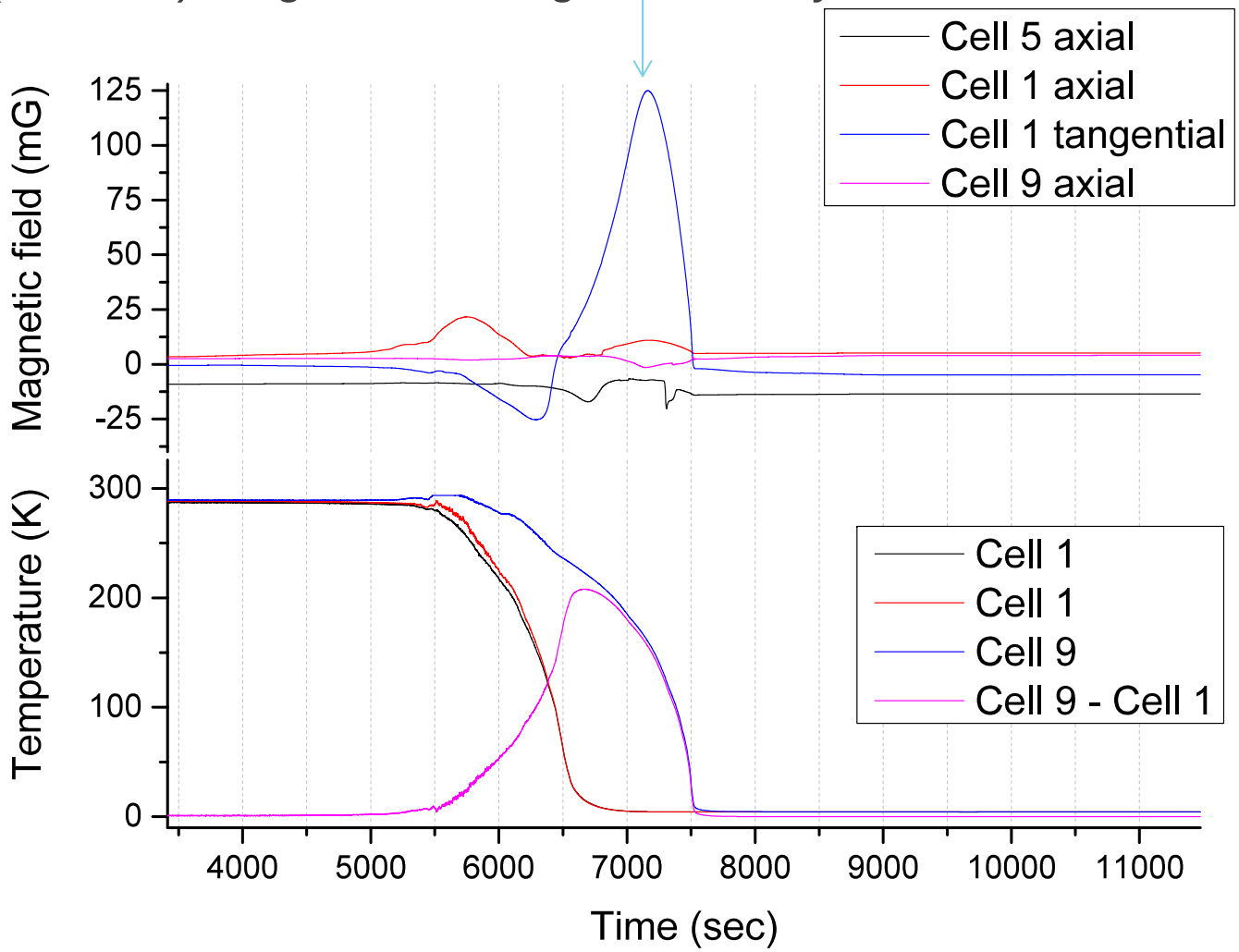


Residual resistance

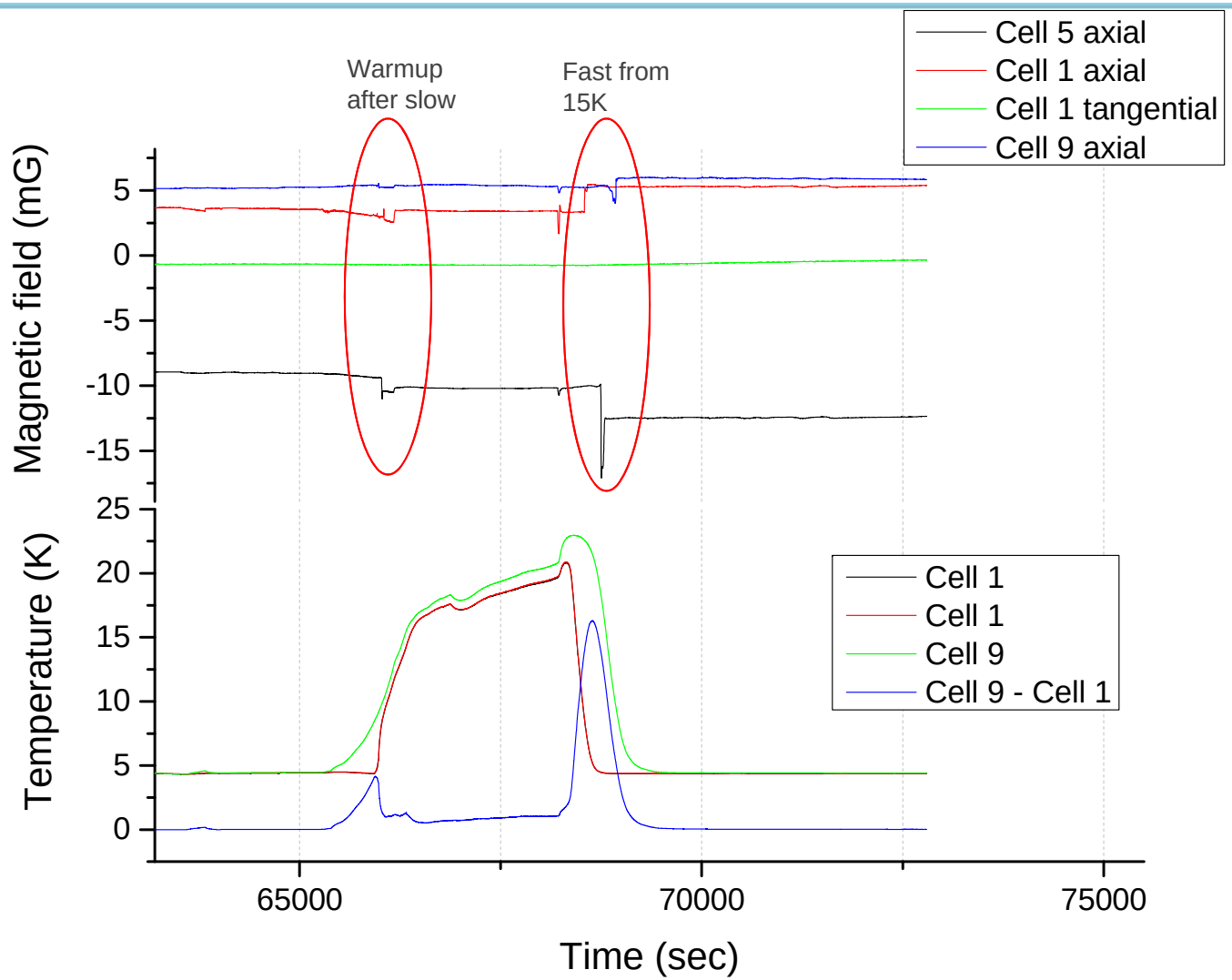


No observable effect of thermal currents on Q

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



Flux expulsion behind the effect - same as in bare



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

Summary

- Important breakthroughs in understanding and improving surface resistance have been recently achieved at FNAL
  - Reaching above (previously) expected boundaries for niobium. How far can we push?
- Lots of work to be done and details to get right to take it from proof of principle to a working technology in a machine like LCLS-II or PIP-II
  - First cryomodule-ready dressed cavity is to be horizontally tested in 2 weeks
- High Q collaboration established to get the details right in a short timeframe for LCLS-II – big challenge, but potential game changing technology
- Need to expand to different frequencies, understand physics better
  - 2014-2019 DOE Early Career Award of A. Grassellino
  - R&D for LCLS-II and PIP-II

Acknowledgements

- FNAL and ANL SRF processing team –B. Golden, R. Espinoza, T. Reid, B. Stone, R. Murphy, C. Baker
- FNAL T&I dept and cryo group – Y. Pischalnikov, B. Squires, A. Diaz, D. Marks et al
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