Fermilab

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SRF R&D @FNAL

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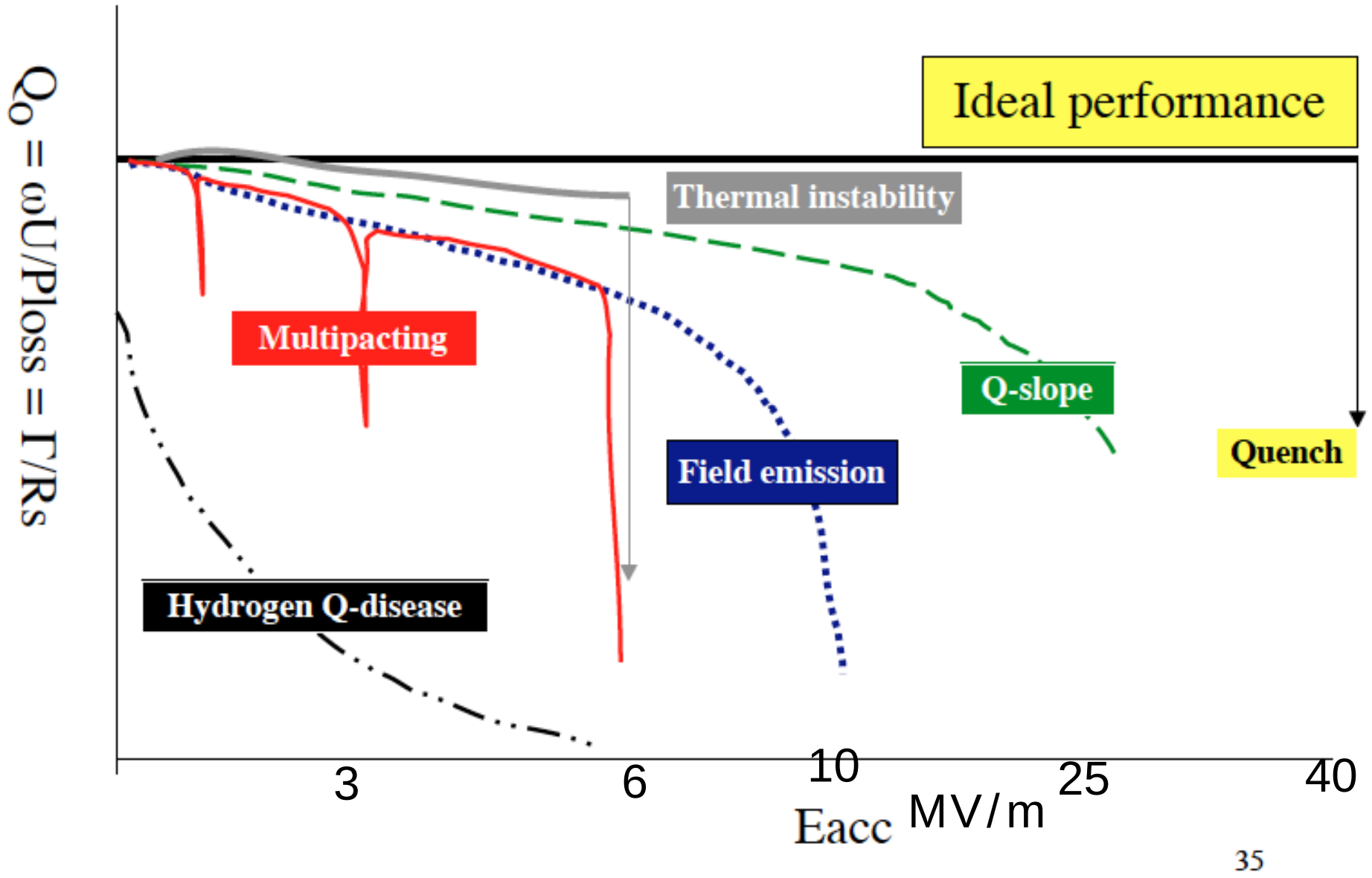
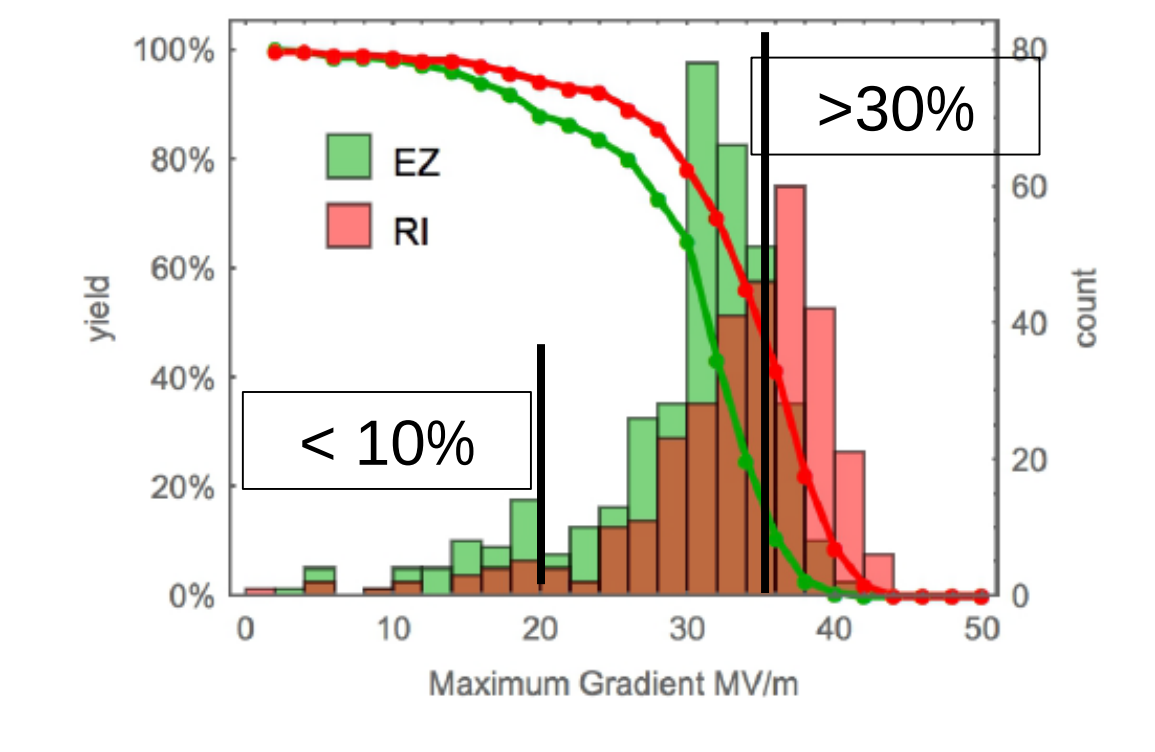

Ideal performance
Thermal instability
Multipacting
Q-slope
Field emission
Quench
Hydrogen Q-disease
$Q_0 = \omega U/P_{loss} = \Gamma/R_s$
3
6
10
25
40
Eacc MV/m
35

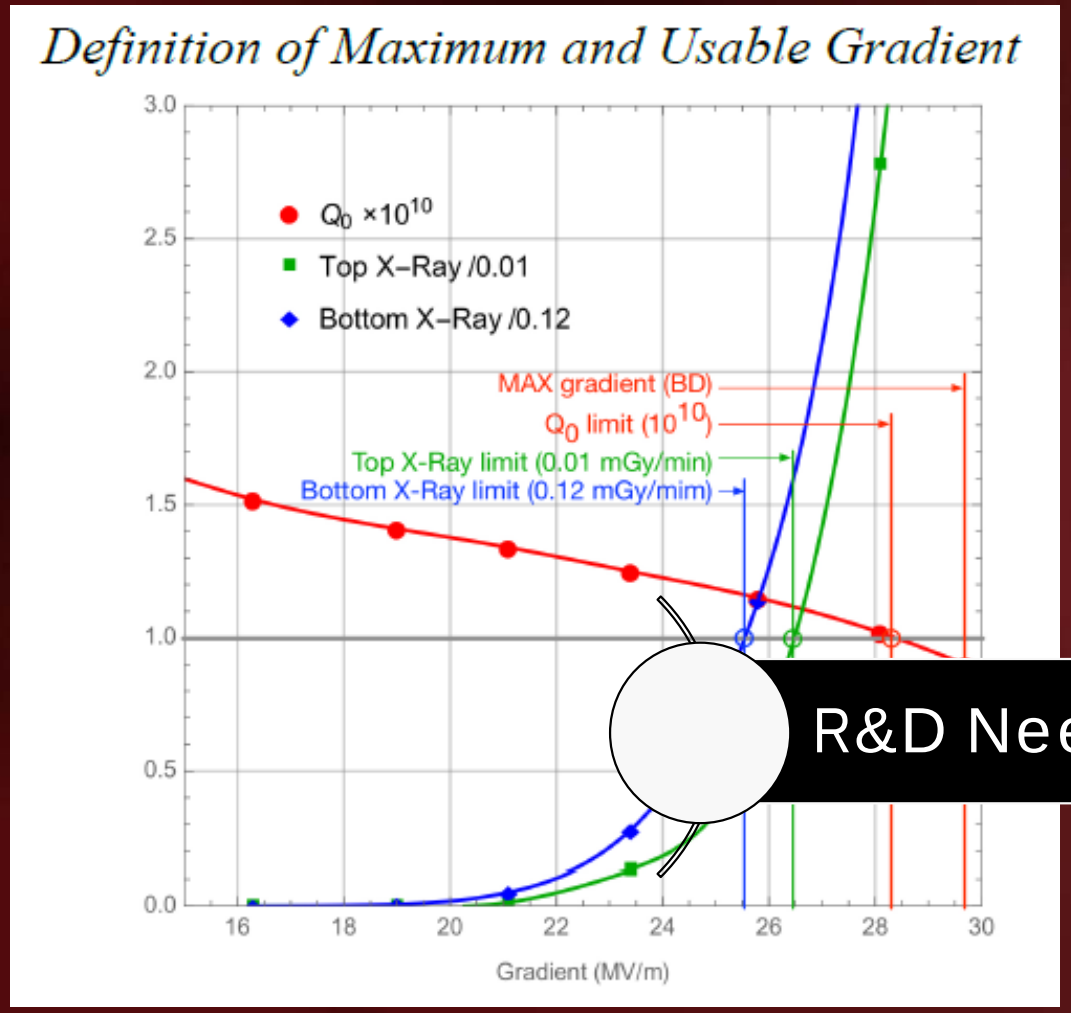
Gradient Yield after First Treatment (as of Sept 2015)



- 738 cavities
  - from two vendors, RI and EZ
- EZ vendor used Bulk EP and Final BCP
- RI vendor use Bulk EP & Final EP (as for ILC)
- Final EP gives 3 – 4 MV/m higher performance
- Lesson for highest gradients
  - Don't use BCP

	Max Gradient			Usable Gradient		
	RI	EZ	C	RI	EZ	C
<G>MV/m	33	29.6	31.4	29.4	26.3	27.7
28MV/m	86%	73%	79%	66%	44%	54%
Yield at						

Definition of Max and Usable Gradients



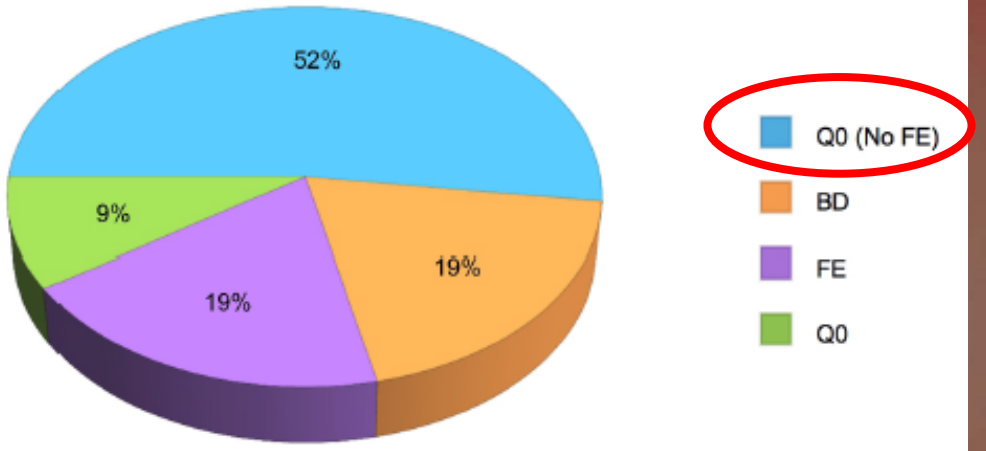


Figure 8: Breakdown of usable gradient limiting criteria for as received tests.

R&D Needed on Medium Field Q-Slope

- Max gradient is 30 MV/m
- Usable gradient is 25.5 MV/m limited by bottom x-rays

Compare XFEL to ILC need

- We can anticipate (optimistically)
- Ave Max Gradient will rise to from 33 to 36 MV/m on 2nd treatment
  - More than 25% re-treatments may be required for ILC
- But yield of usable gradient needs to be improved
  - We need 90% yield for gradient > 28 MV/m with average of 35 MV/m
- Substantial gain possible if Medium Field Q-slope is overcome
  - > 50% cavities fall below Q 10^{10}
- **Fix medium Field Q-slope**
  - **Proper doping? to be invented?**
- **Next addressable limit is field emission**
  - **limits about 20% of cavities**

Future R&D Areas for ILC and TeV Upgrade

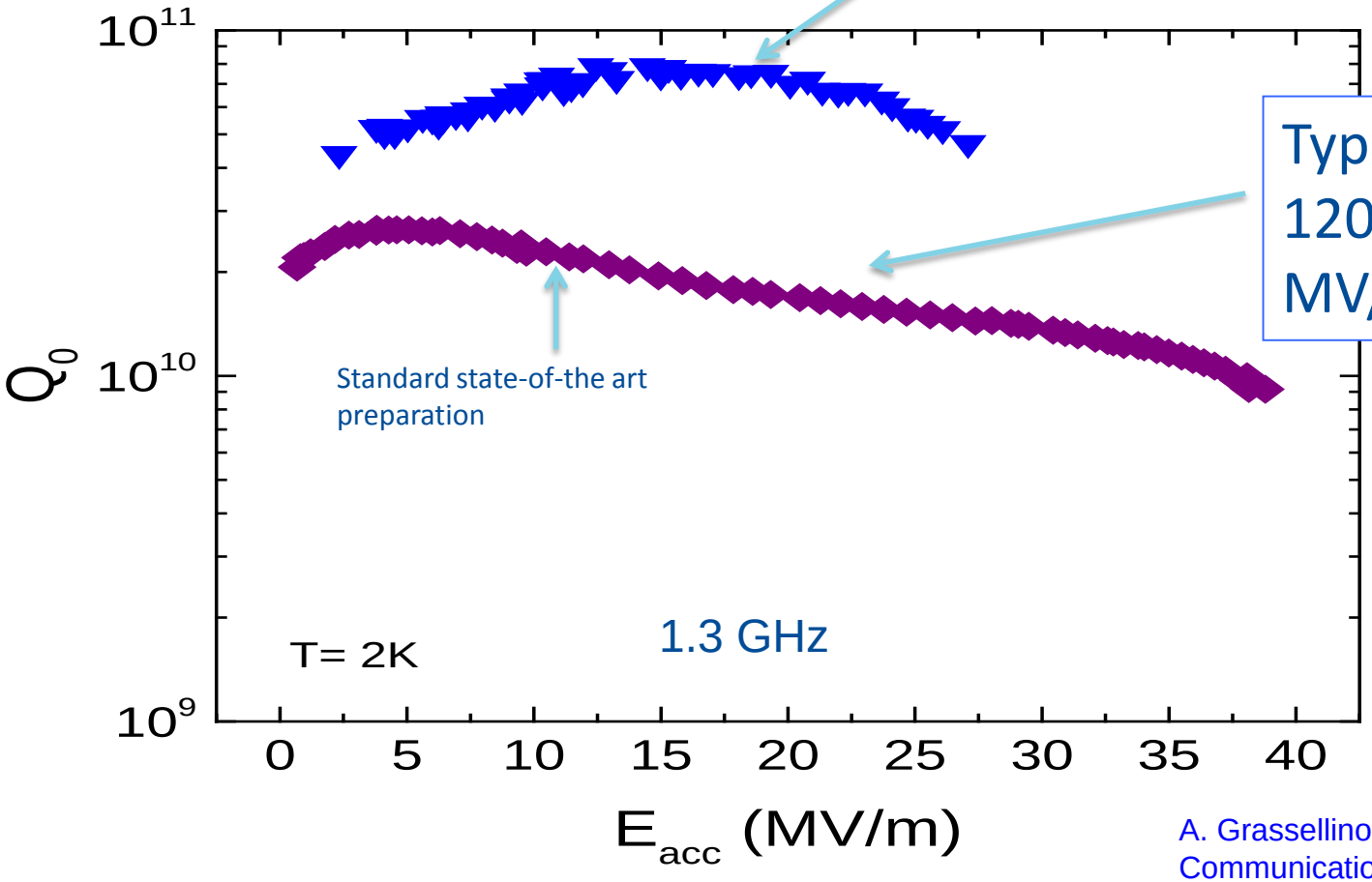
- **Raise gradients**
  - Nb cavities of improved shape
  - New materials, in particular Nb_3Sn
- **Raise Q**
  - Improve understanding of Q-drops
  - Explore Nitrogen (or other) doping
  - Reduce magnetic field in cryomodules!
  - Improve flux expulsion via cooling in cryomodule
  - Reduce field emission
- **Lower costs**
  - Reduce Nb material cost
    - Explore Nb-Cu composite
    - Large grain Nb
  - Reduce cavity fabrication cost
    - Hydroforming and Spinning

FNAL high grad/high Q R&D plan

- Revolutionary:
  - Nb3Sn (will hear from S. Posen)
  - Different doping (can change field of first penetration and has potential therefore of increasing dramatically gradients)
- Incremental:
  - N doping recipe refinement
  - Magnetic field management (efficient cooling and magnetic shielding)
  - Change shape (see G.Wu)
  - Field emission in vertical test and cryomodule
    - In vertical test, try innovative HPR techniques
    - In cryomodule, explore FE processing – we have the perfect tool on the floor here at FNAL
- Material cost:
  - Nb on Cu films or explosion bonded

Nitrogen Doping: a breakthrough in Q

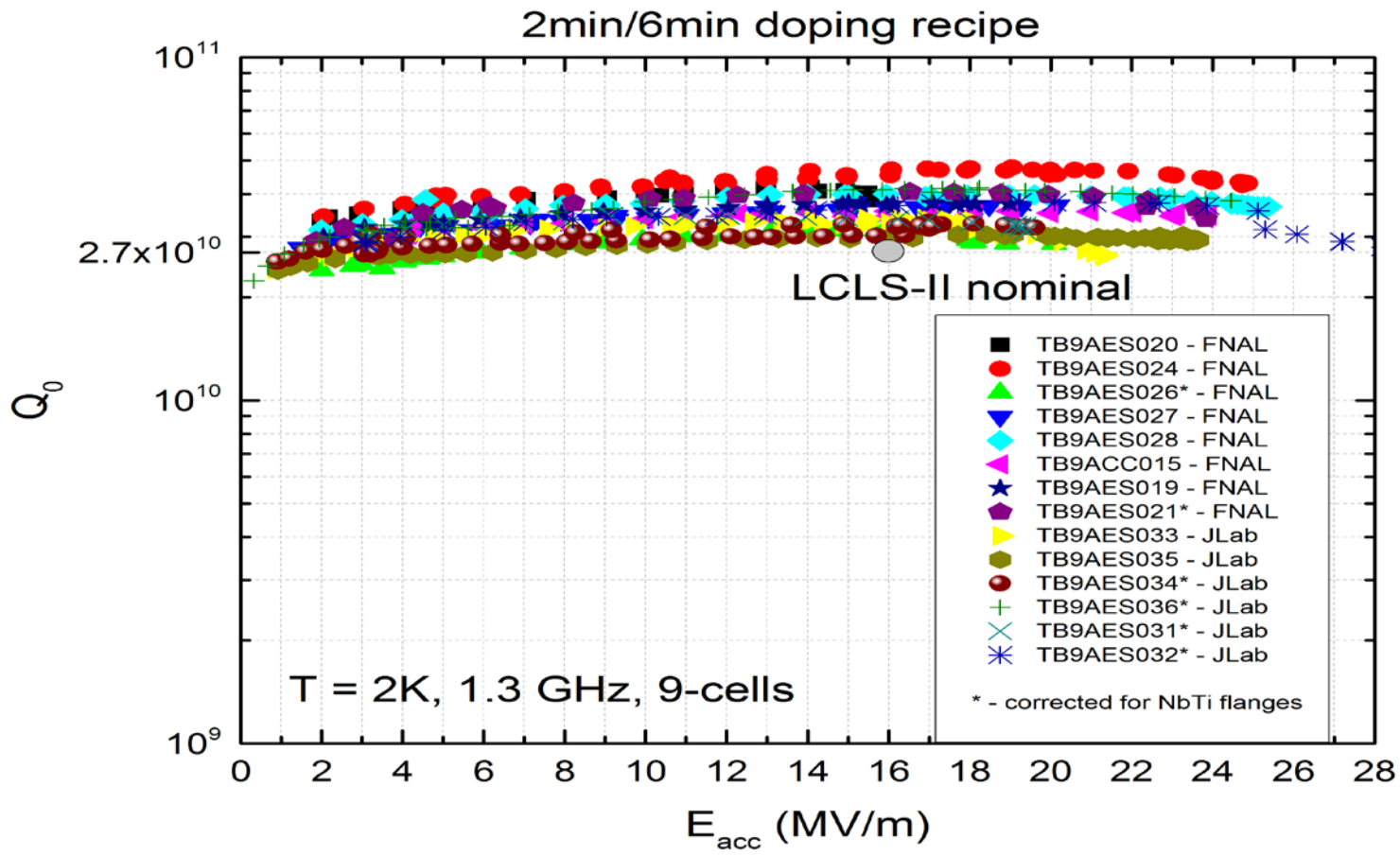
Record after nitrogen doping – up to 4 times higher Q! Average values obtained on nine cell Q(2K, 16MV/m)~ 3.5e10



Typical Q obtained in VTS with 120C bake ~ 1.7e10 at 2K, 16 MV/m

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

From single cell R&D to cryomodule ready technology: FNAL, Jlab, Cornell, SLAC together towards record Q >2.7e10 @16MV/m, 2K



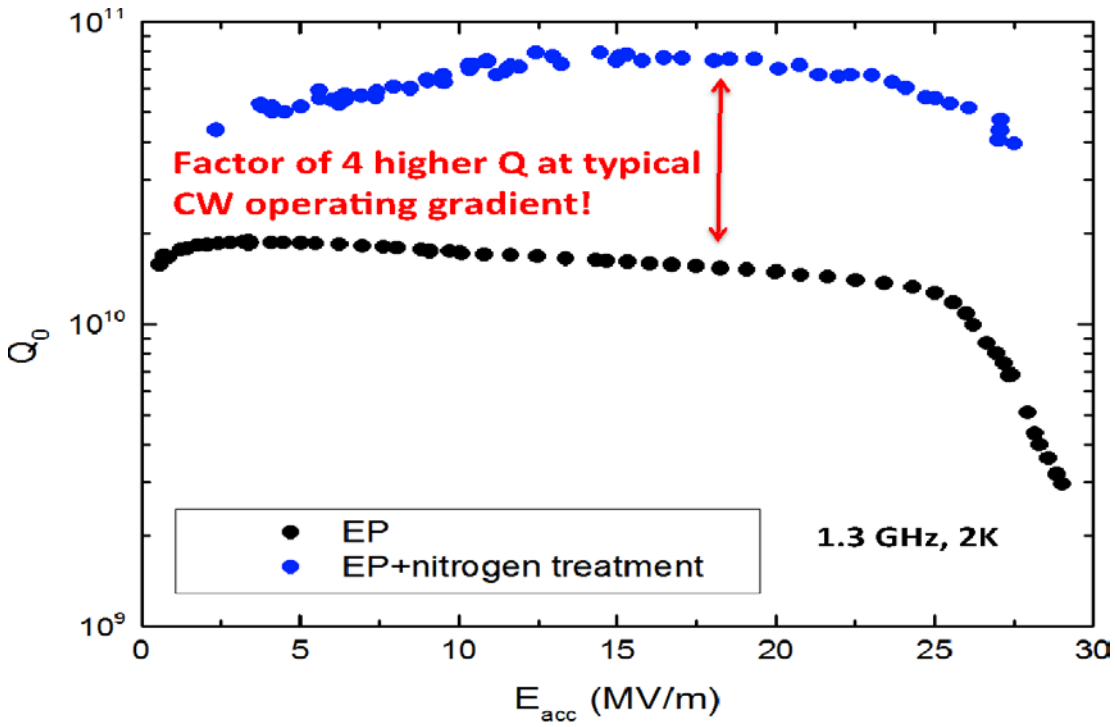
<Q>=3.5e10
$<E_{max}>$=22.2 MV/m
E_{max}median=22.8MV/m

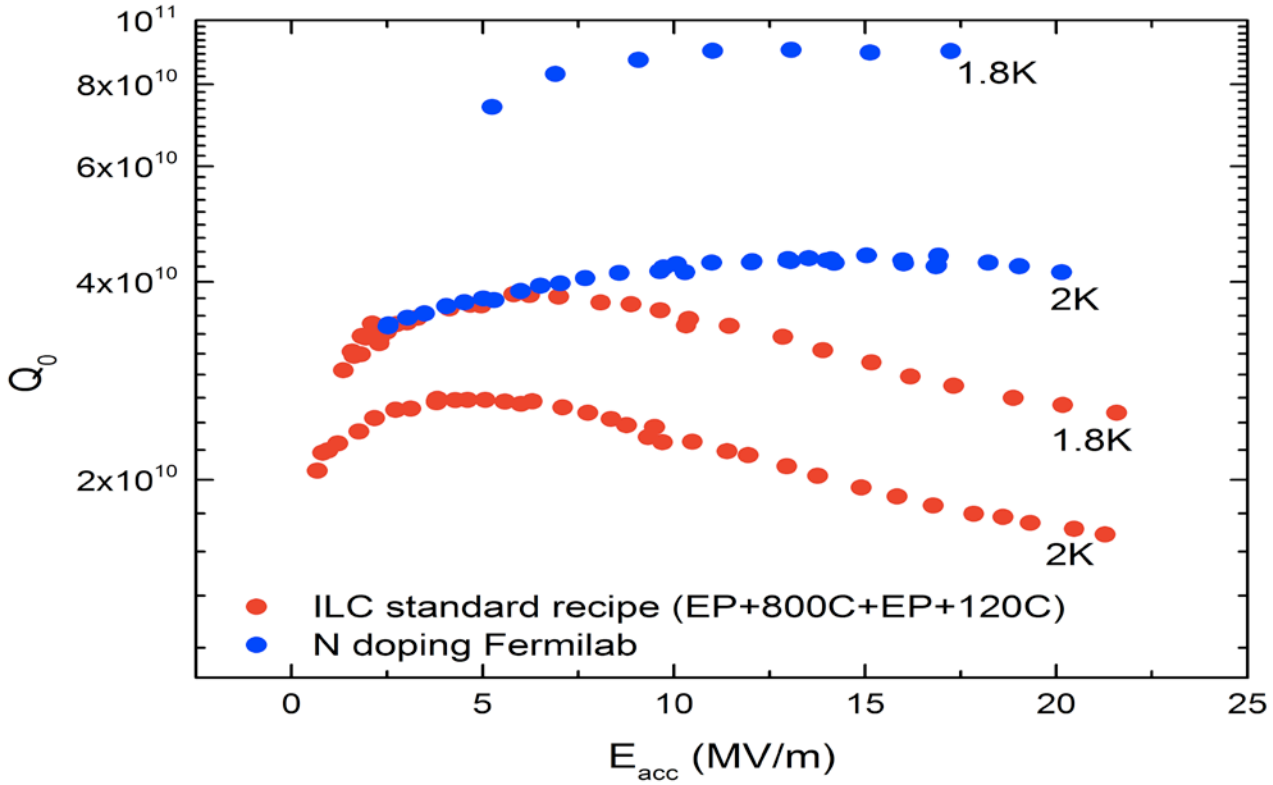
A.Grassellino et al, IPAC15

See at this conference:
MOPB033
MOPB029
MOBA07
MOBA08

It is the highest average Q ever demonstrated in vertical test for 1.3 GHz nine cells at 2K, 16 MV/m in the history of SRF (larger than a factor of two the state of the art)

Comparing to standard treatments

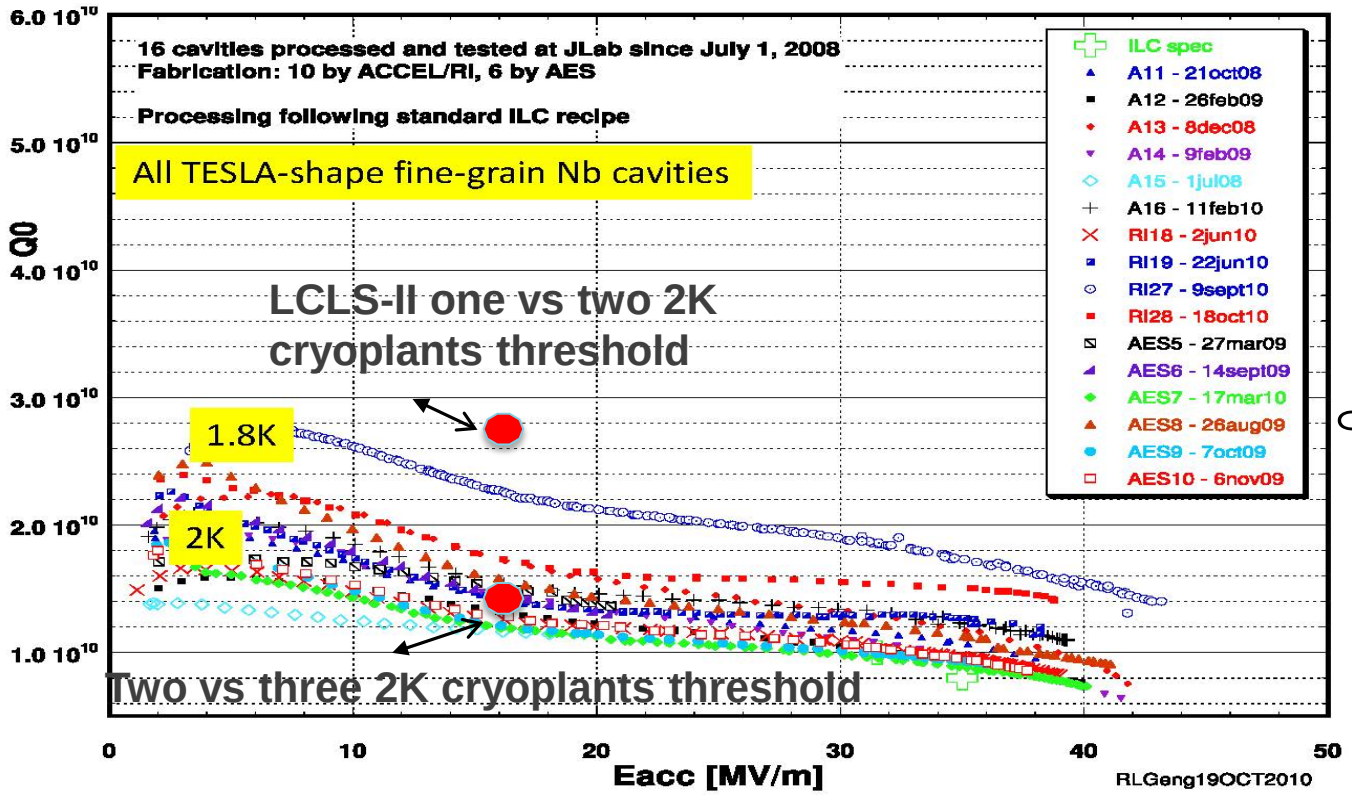




The importance of a high Q technology – the case of the CW machine LCLS-2

Example of 120C baked (standard ILC/XFEL technology)

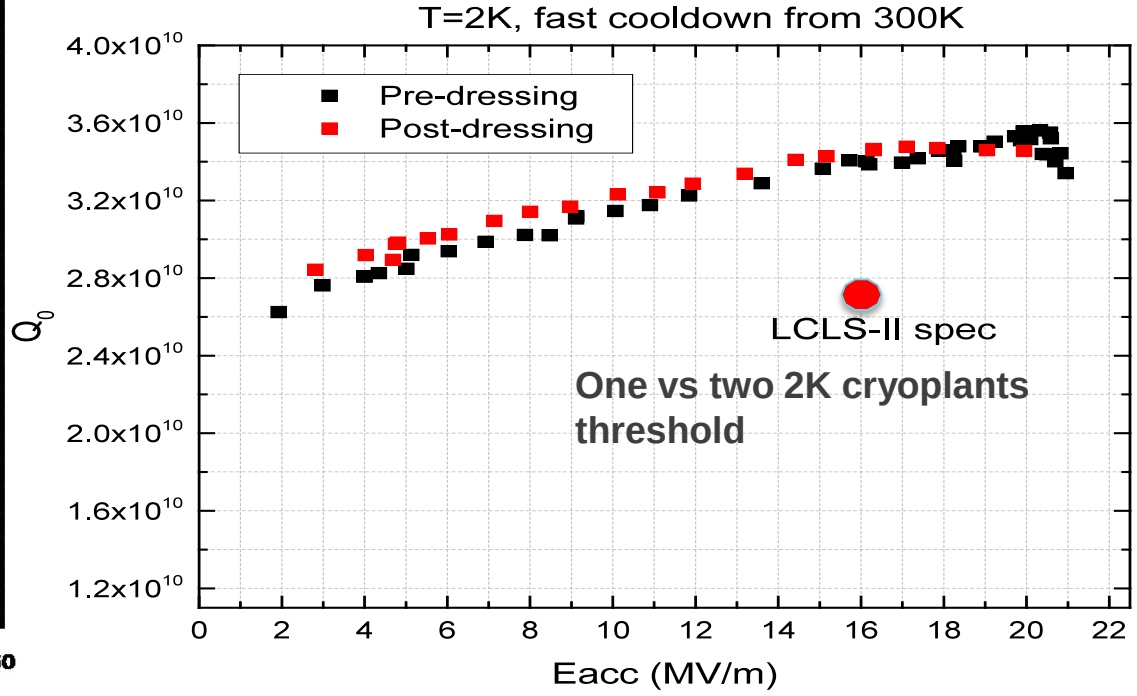
Would likely require > 2 full cryoplants



Example of N doped

Dressed cavity for LCLS-2

Below the one cryoplant threshold

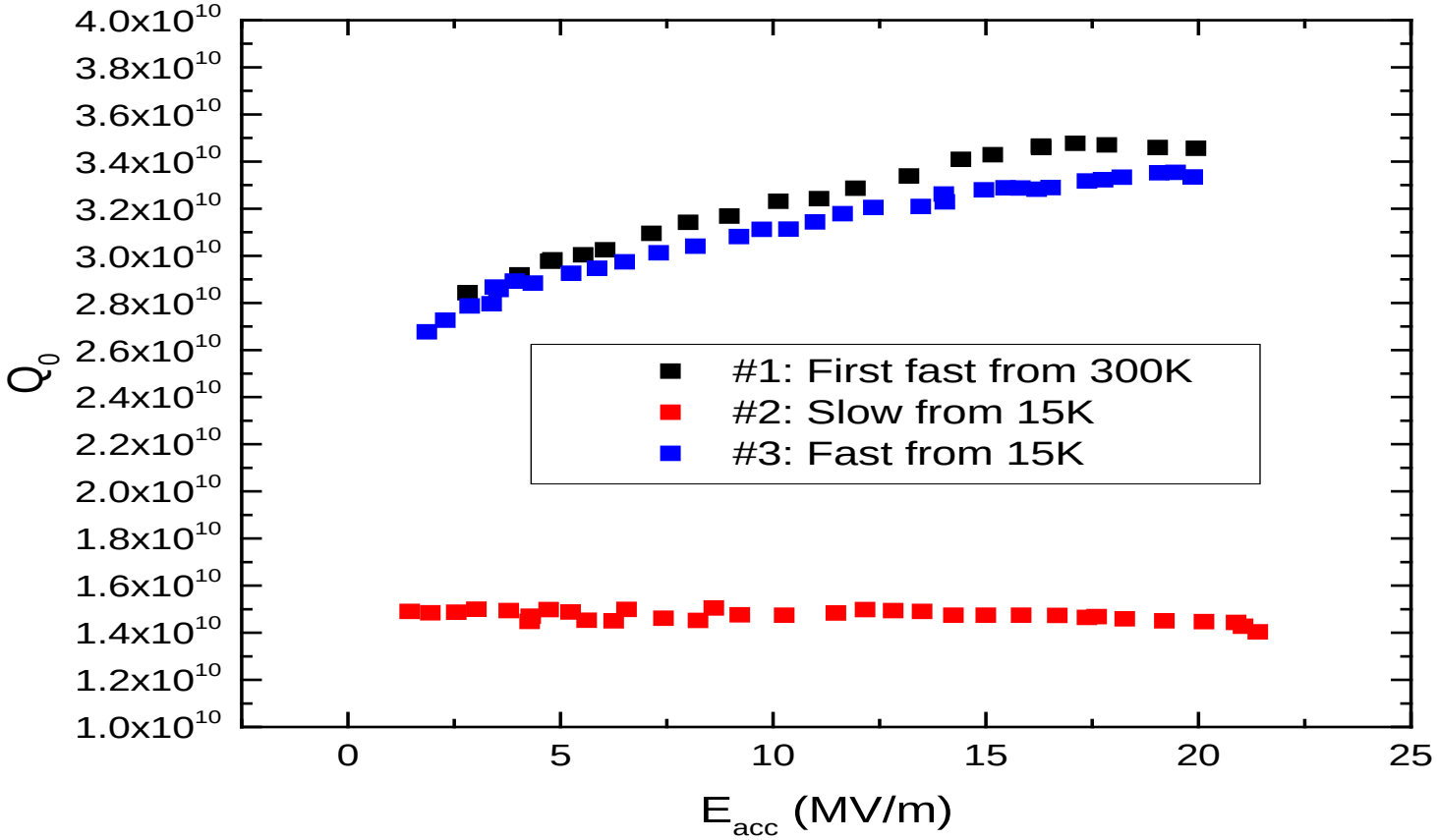


- N doping technology allows significantly lower refrigeration costs (capital, operating)
- Larger margin and possibility for an energy upgrade for same refrigeration cost

Currently highest achievable gradients with N doping

- Single cells can reach > 30 MV/m (Jlab 39 MV/m, Cornell and FNAL 35 MV/m)
- Nine cell ~ 29 MV/m
- Need more work to refine the doping procedure to reach higher gradients, but getting close already
- Work ongoing, potential to raise ILC yield by increasing Q

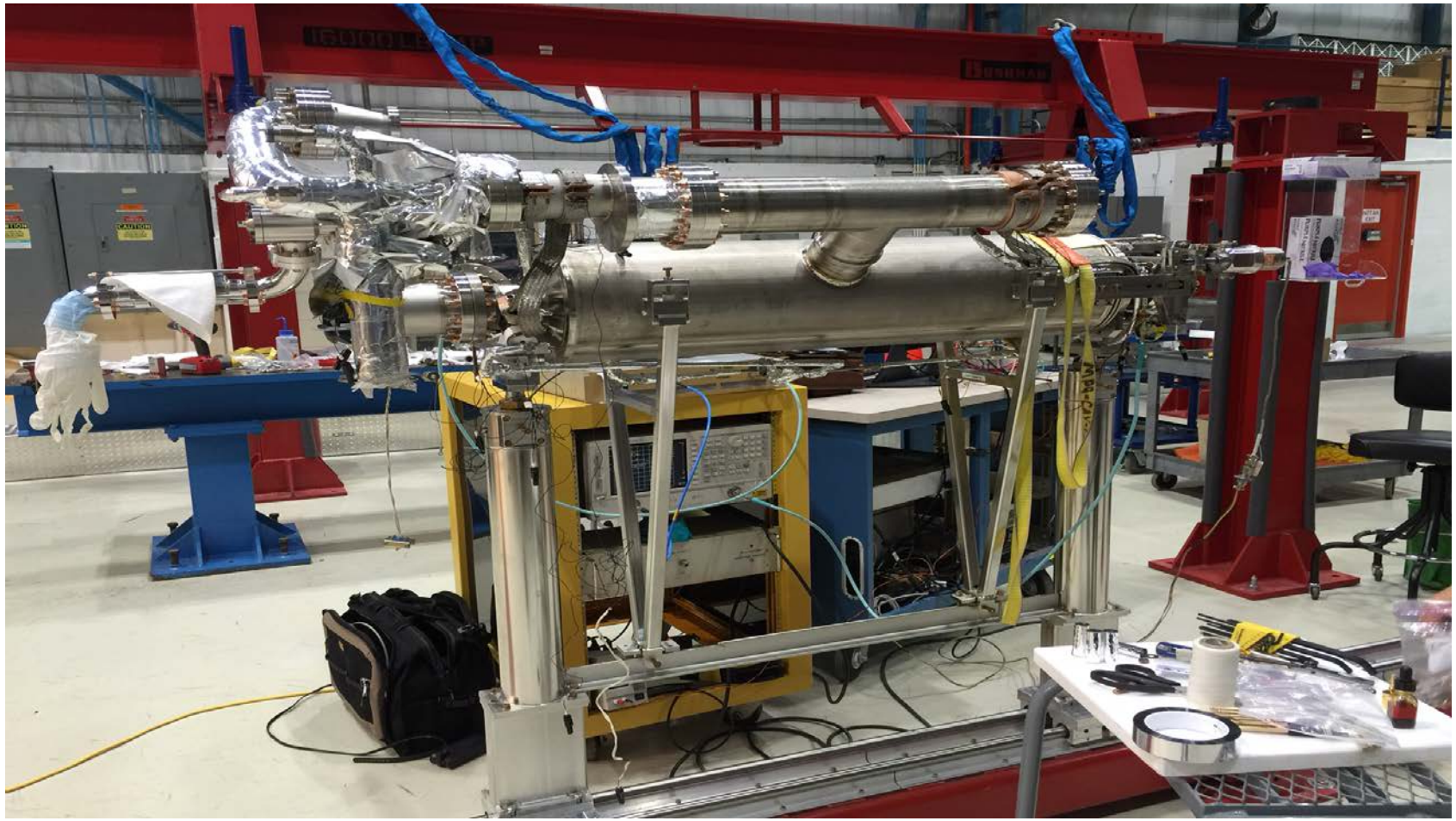
Need to cool down fast through Tc to expel magnetic flux efficiently



- Dressed 1.3 GHz N doped nine cell cavity vertical test at T=2K
- Effect less severe at 650 but still important

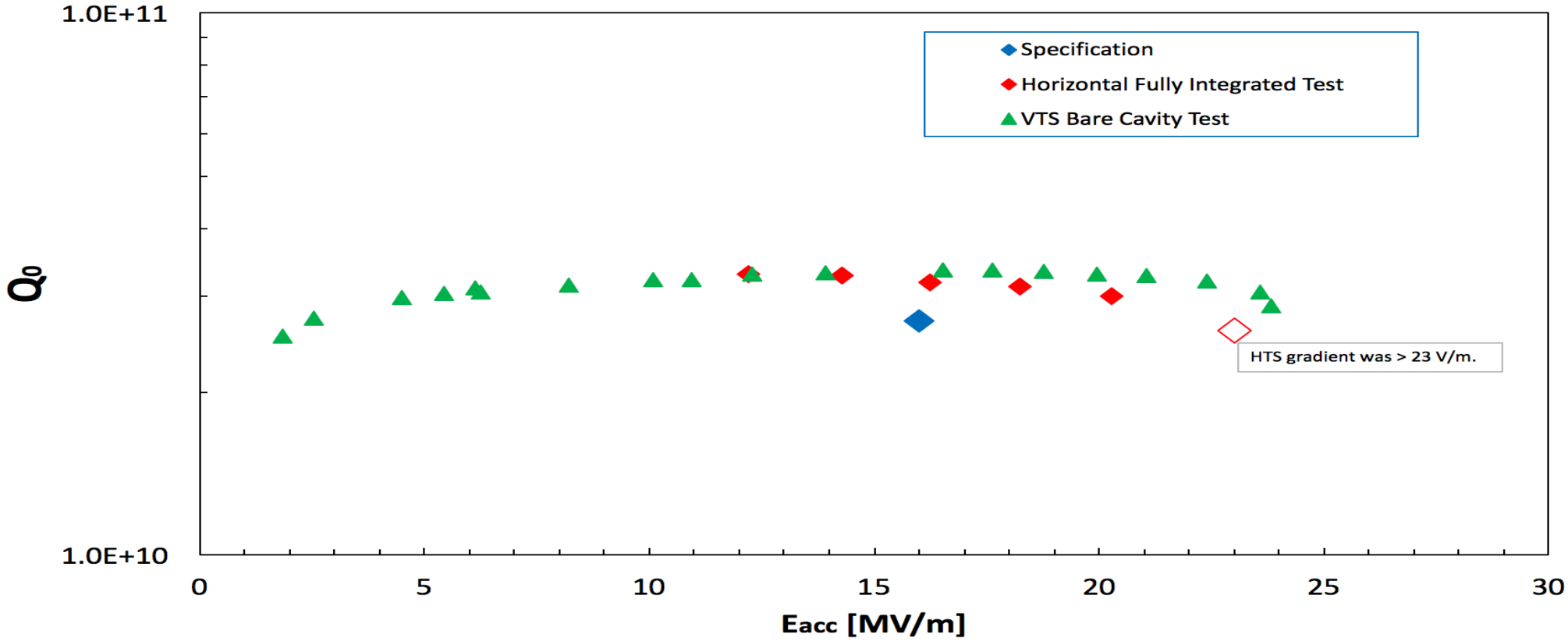
A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. ***115****, 184903 (2014)*
A. Romanenko, A. Grassellino, A.Crawford, D. A. Sergatskov, Appl. Phys. Lett. 105, 234103 (2014)
D. Gonnella et al, J. Appl. Phys. ***117****, 023908 (2015)*
M. Martinello, M. Checchin, A. Grassellino,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

Fully Integrated Test at FNAL – TB9AES021



High power coupler, HOMs, tuner, double layer magnetic shielding…

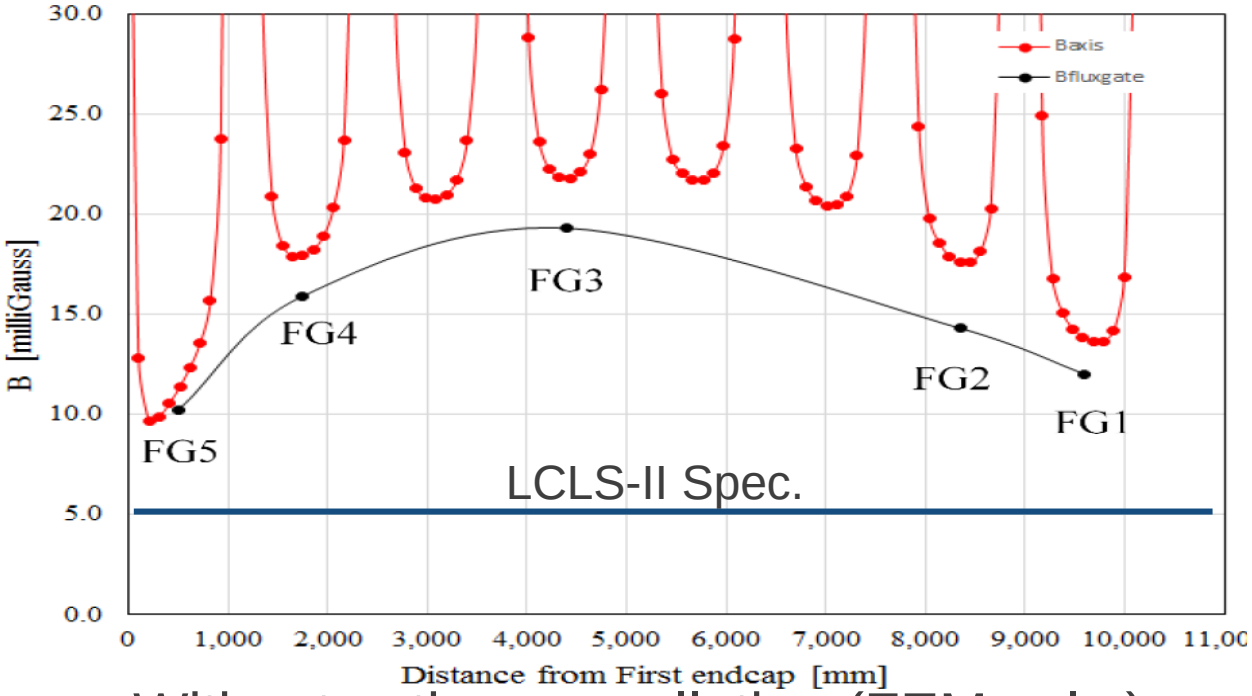
Fully Integrated Test at FNAL – TB9AES021



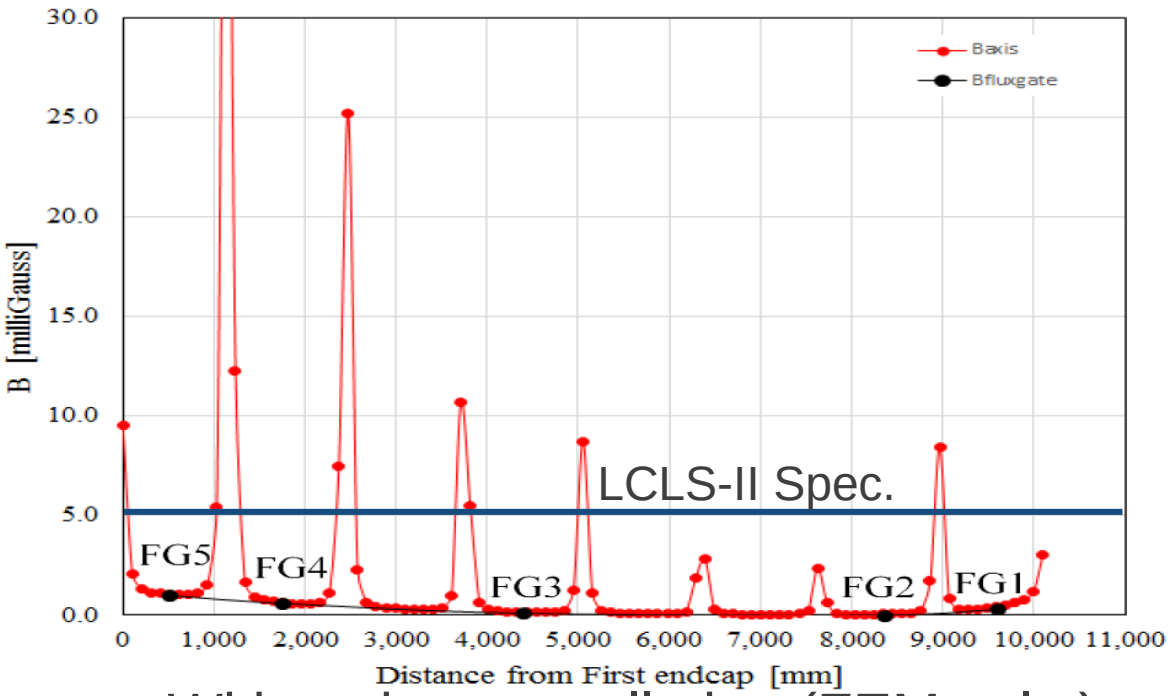
No degradation from bare to horizontal dressed test with right cooldown procedure, HOMs and high power coupler thermal strapping, and magnetic shielding

Why do we need degaussing & cancellation coils?

- Need to shield longitudinal component of *B*
  - Active cancellation proven to be effective method [2,5,6]



Without active cancellation (FEM calc.)
we expect B_{avg} ~ 15-20 mG

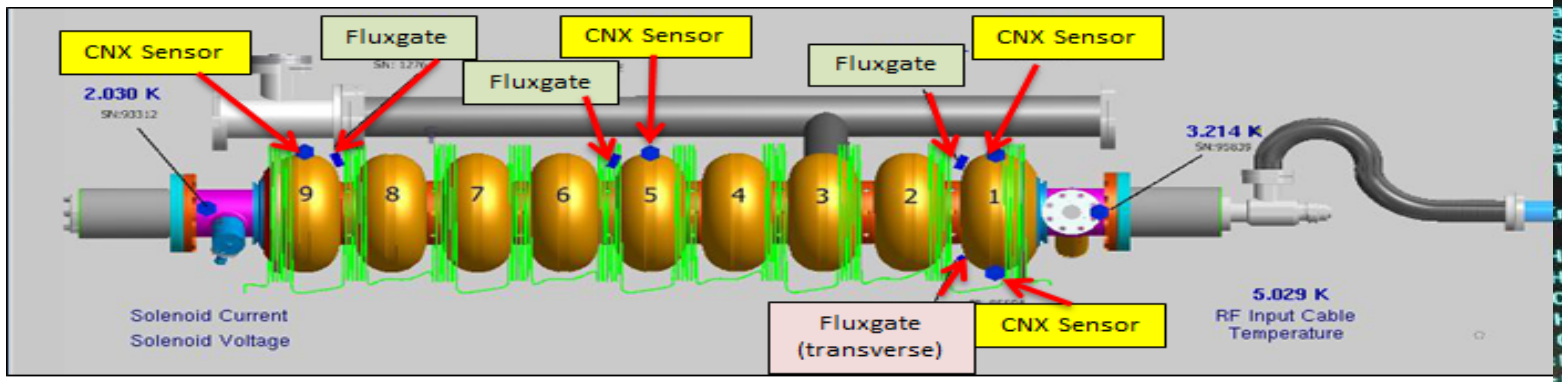


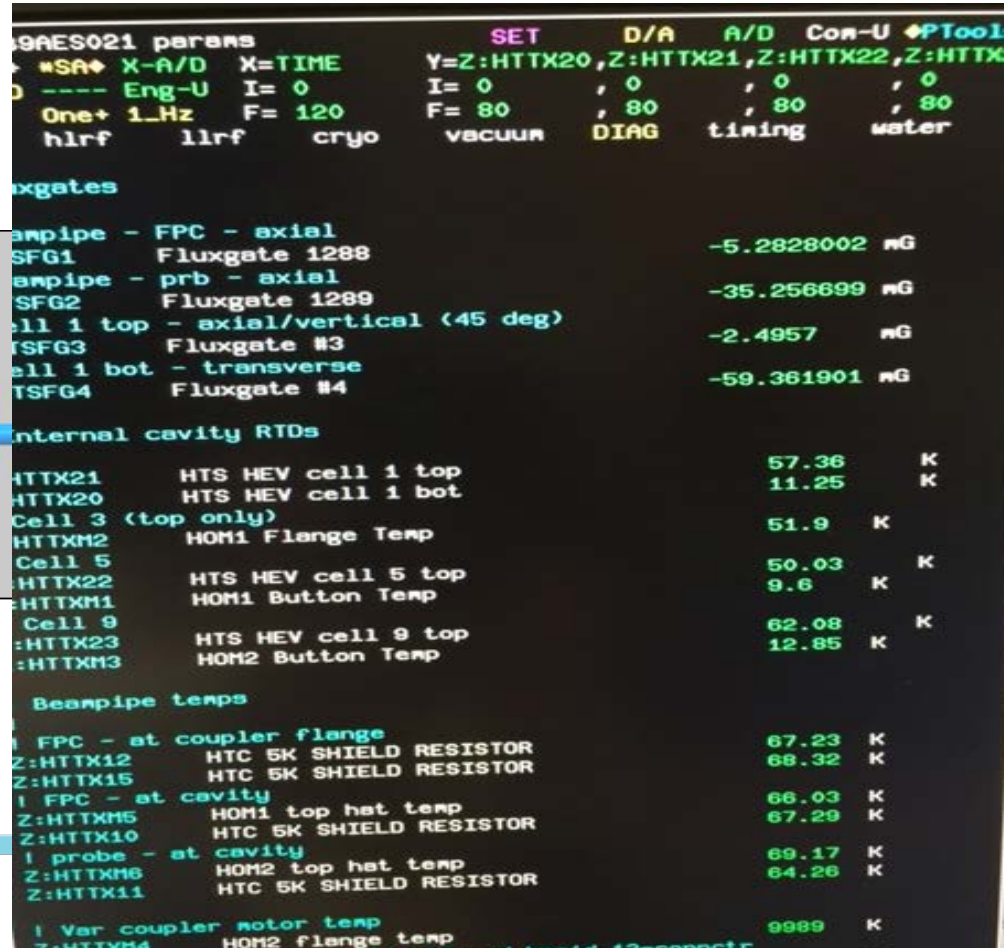
With active cancellation (FEM calc.)
we expect B_{avg} < 3 mG

[2] A. Crawford, arxiv.org/ftp/arxiv/papers/1507/1507.06582.pdf.
[5] The Conceptual Design Report for the TeSLA Test Facility Linac, Version 1, 1995.
[6] T. Bitter et al., Nucl. Instrum. Methods A, 309, 1991.

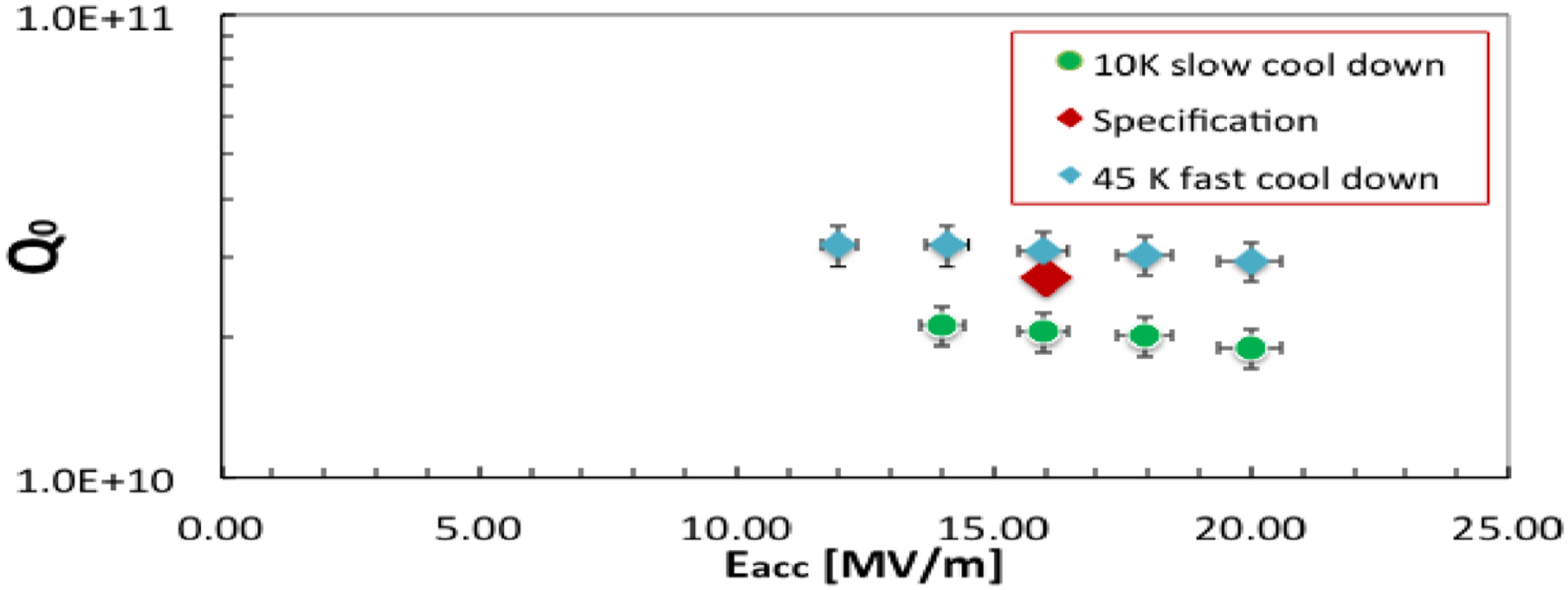
Ideal cooldown/shielding evaluation on dressed doped 9-cell cavities: instrumentation

- Four LCLS-2 cavities dressed at FNAL with 4 flux gate probes and 4/6 T sensors installed on cells
- Goal: study how to achieve best cooldown conditions in horizontal dressed configuration and in cryomodule



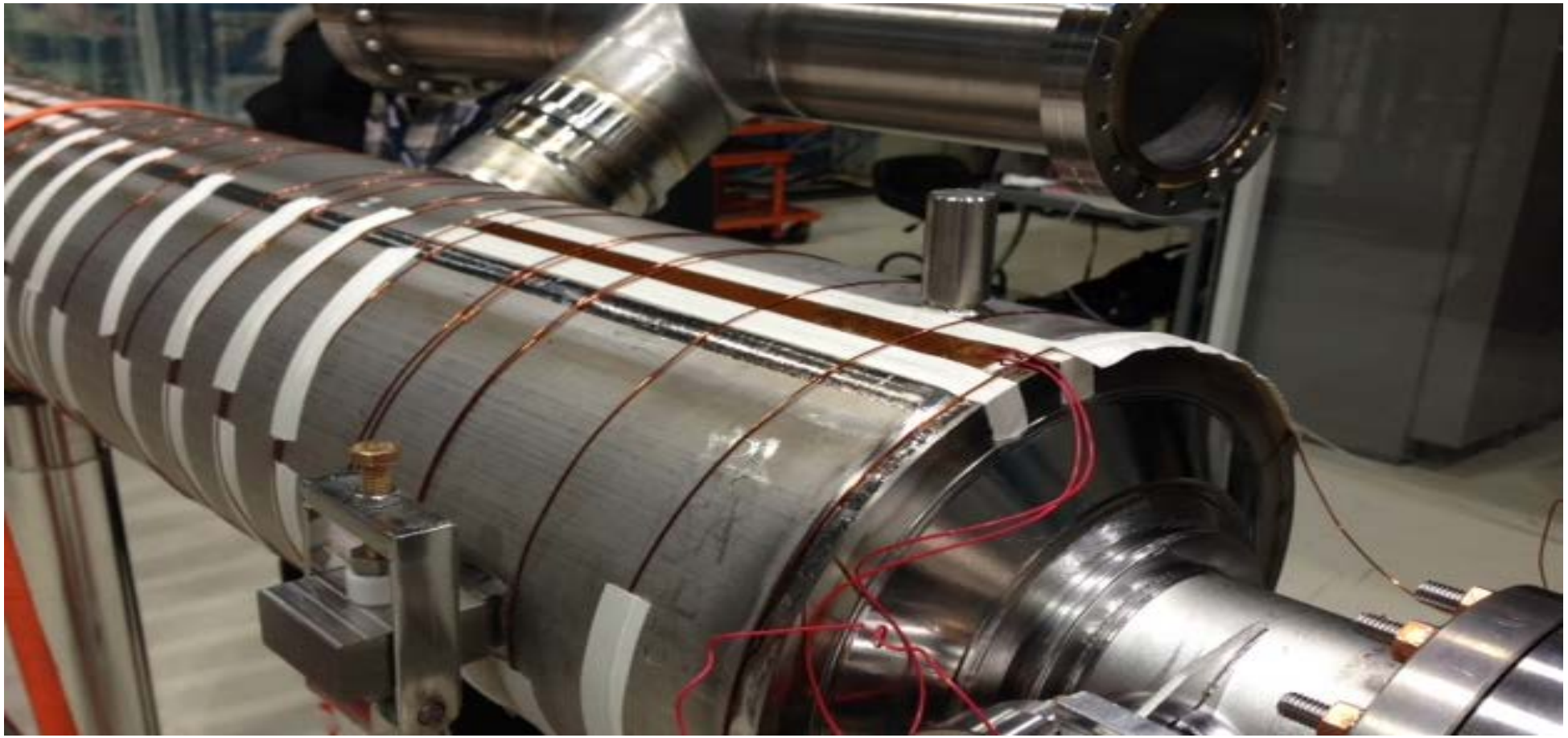


Fast versus slow cooldown in HTS confirms the findings



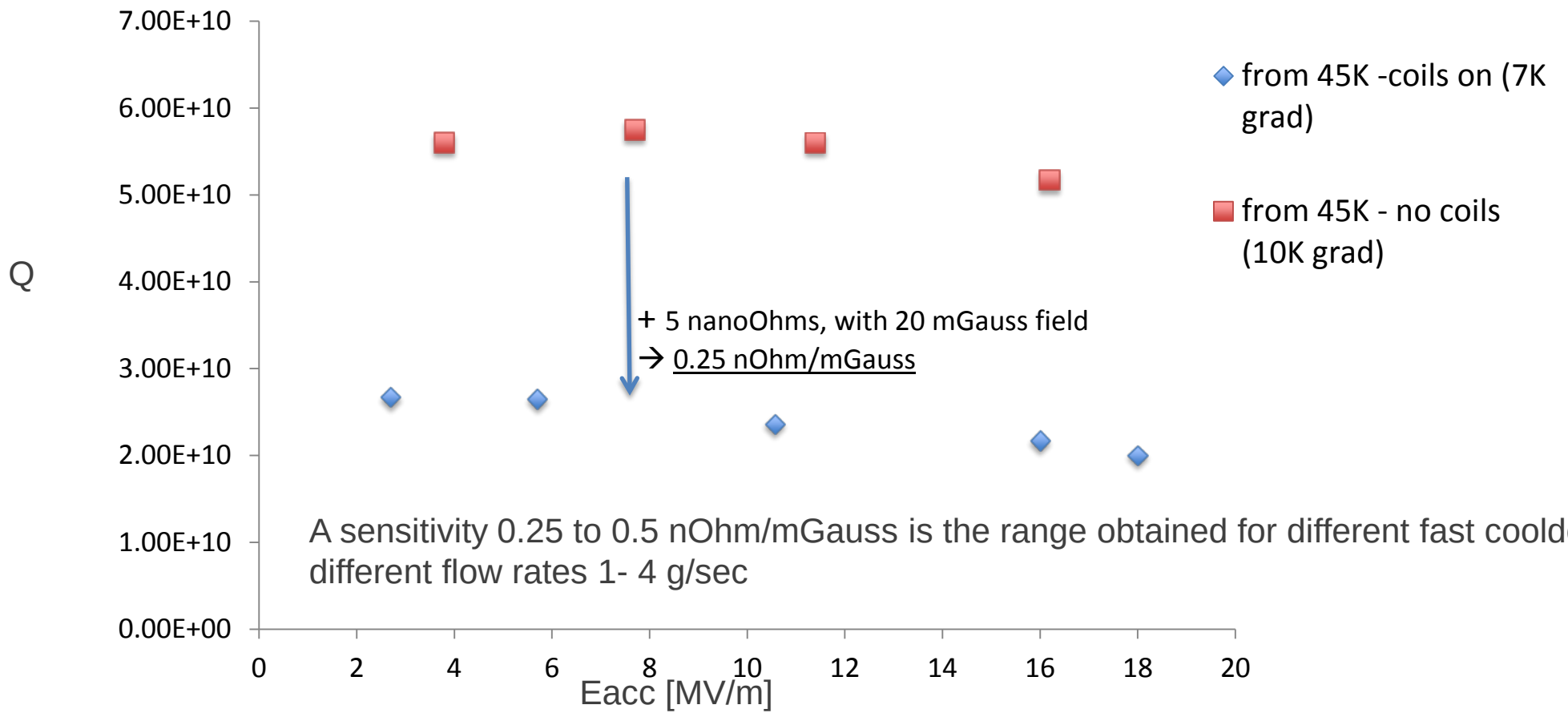
Cavity not meeting specifications with slow cooling in HTS with double shield cryoperm configuration (Q ~ 2.2e10 at 16 MV/m, 2K)

Solenoidal studies performed to study efficiency of flux expulsion



- Apply 20 mGauss and measure increase in residual resistance for different cooldowns with different cooling parameters

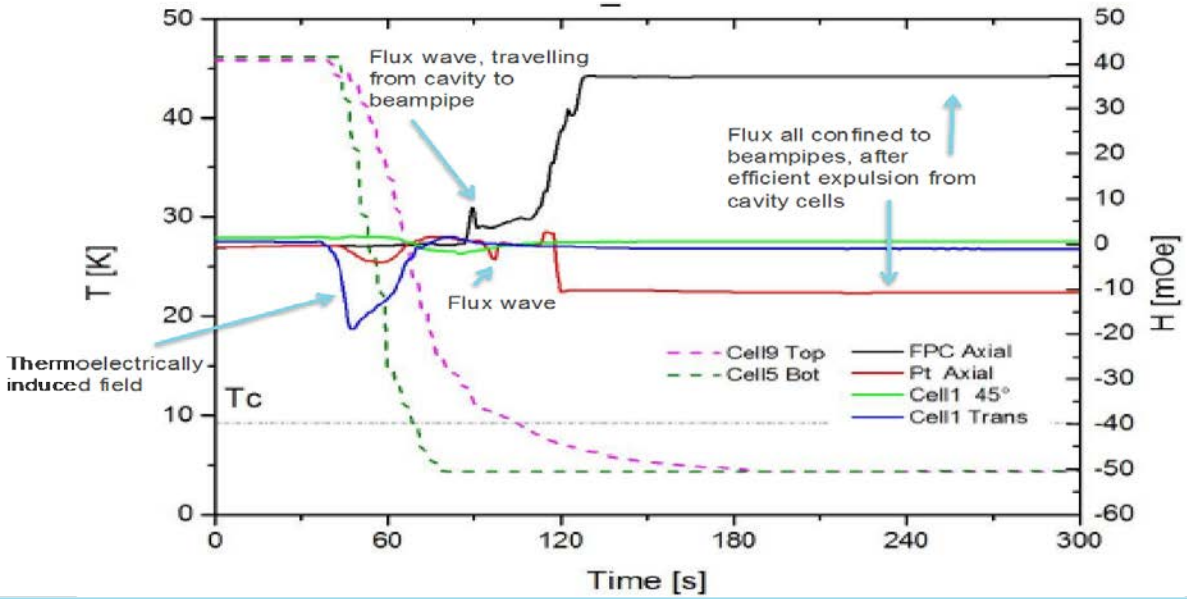
Efficiency of magnetic flux expulsion in HT: 60-80% detrapping

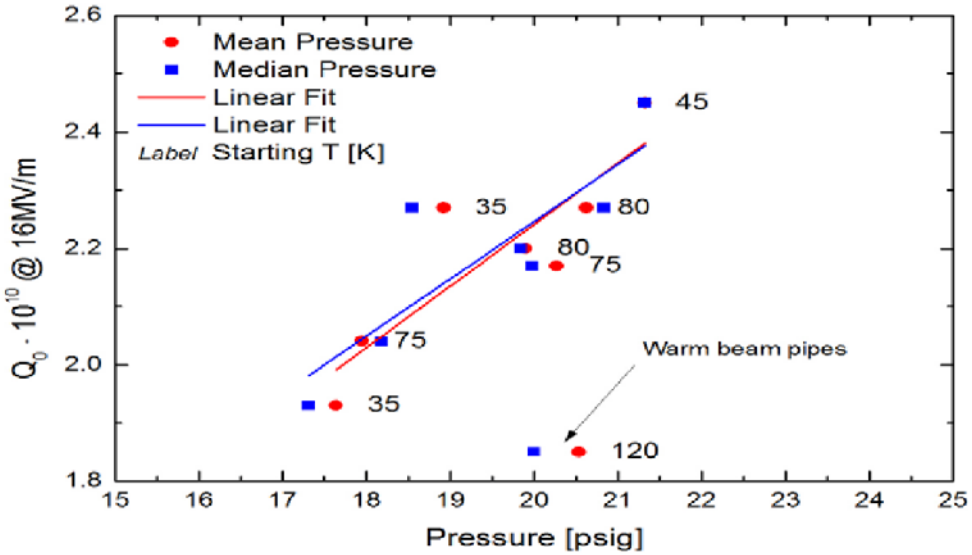


60% to 80% of flux is expelled depending on cooling parameters → **Achieving as low as possible magnetic field is crucial**

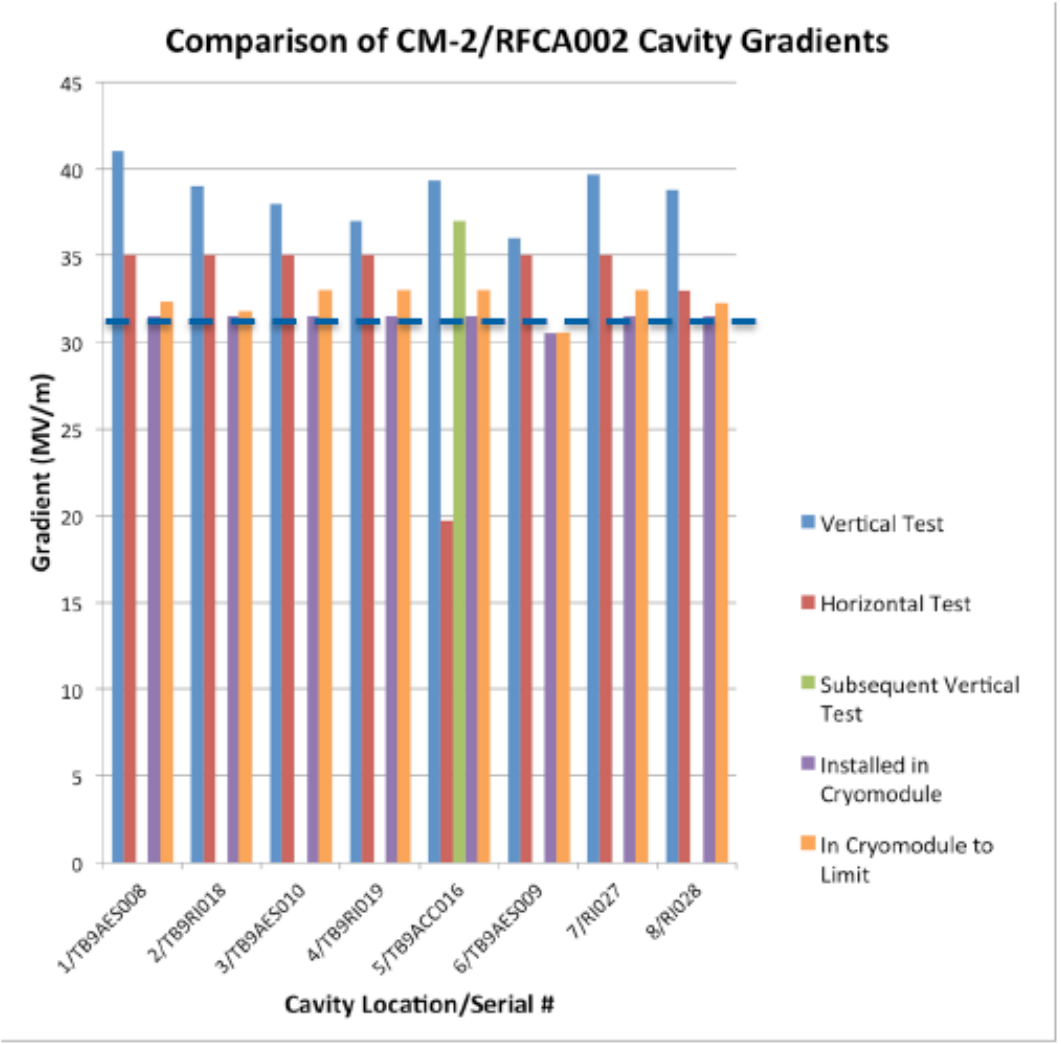
Ideal Cooldown Procedure Recommendation

- Cooldown to 45K
- Pause at 45K – then fast cooling from 45K with ~ 3 g/sec flow rate
- Low starting T for fast cooldown minimizes thermoelectrically induced fields but gives thermogradients large enough for expulsion
- Final verification of cooldown parameters will occur in test of pCM





8-cavity Cryomodule at Fermilab:

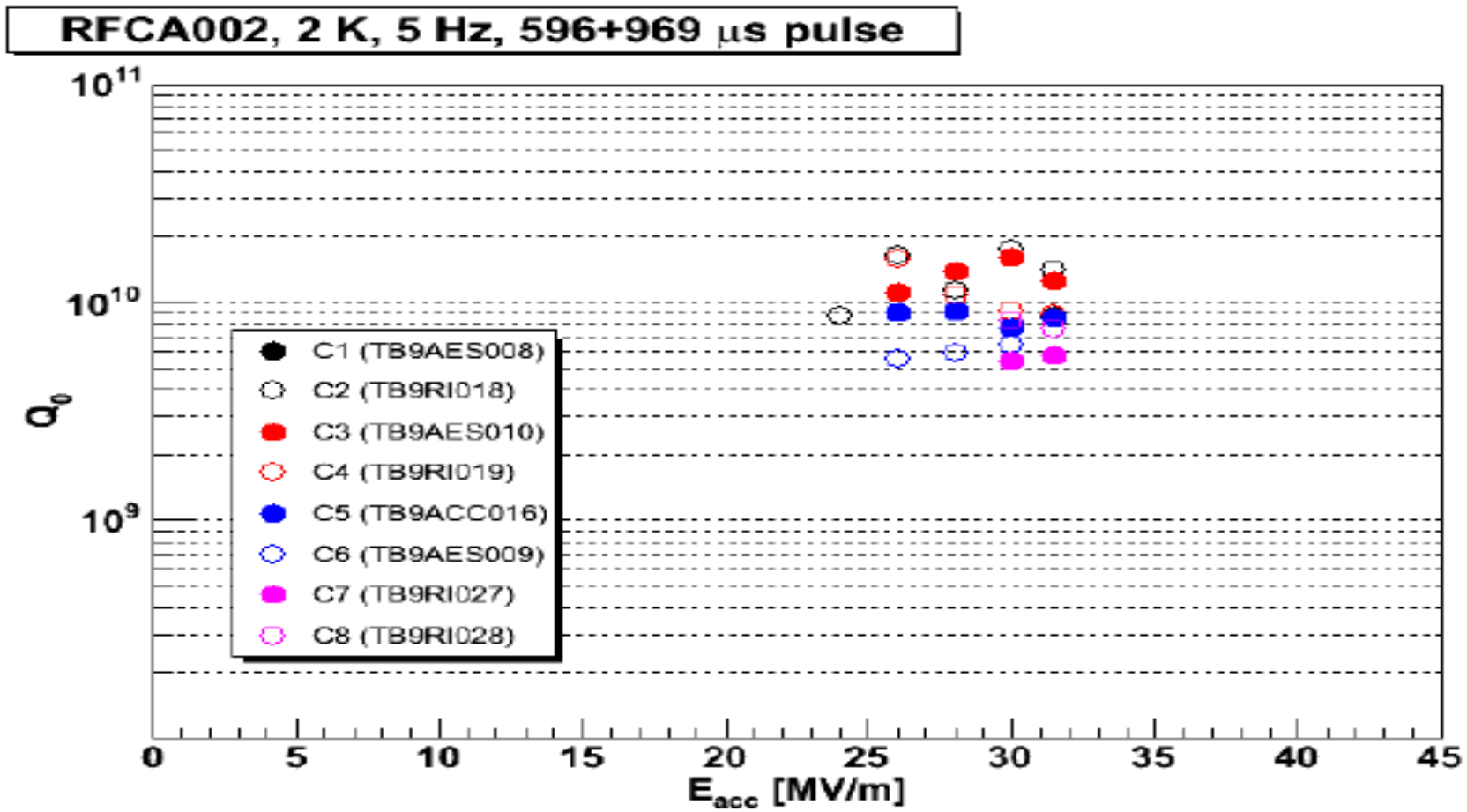


Cavity	Peak Gradient (MV/m)	Limitation
1/TB9AES008	32.3	Quench
2/TB9RI018	31.8	Quench
3/TB9AES010	≥ 33	tbd
4/TB9RI019	≥ 33	tbd
5/TB9ACC016	≥ 33	tbd
6/TB9AES009	29.8	Quench
7/RI027	≥ 33	tbd
8/RI028	32.2	Quench

Peak CM-2 Cavity Gradients with all 8 powered at once:

Sum = 258.1 MV, Average = 32.2 MV/m

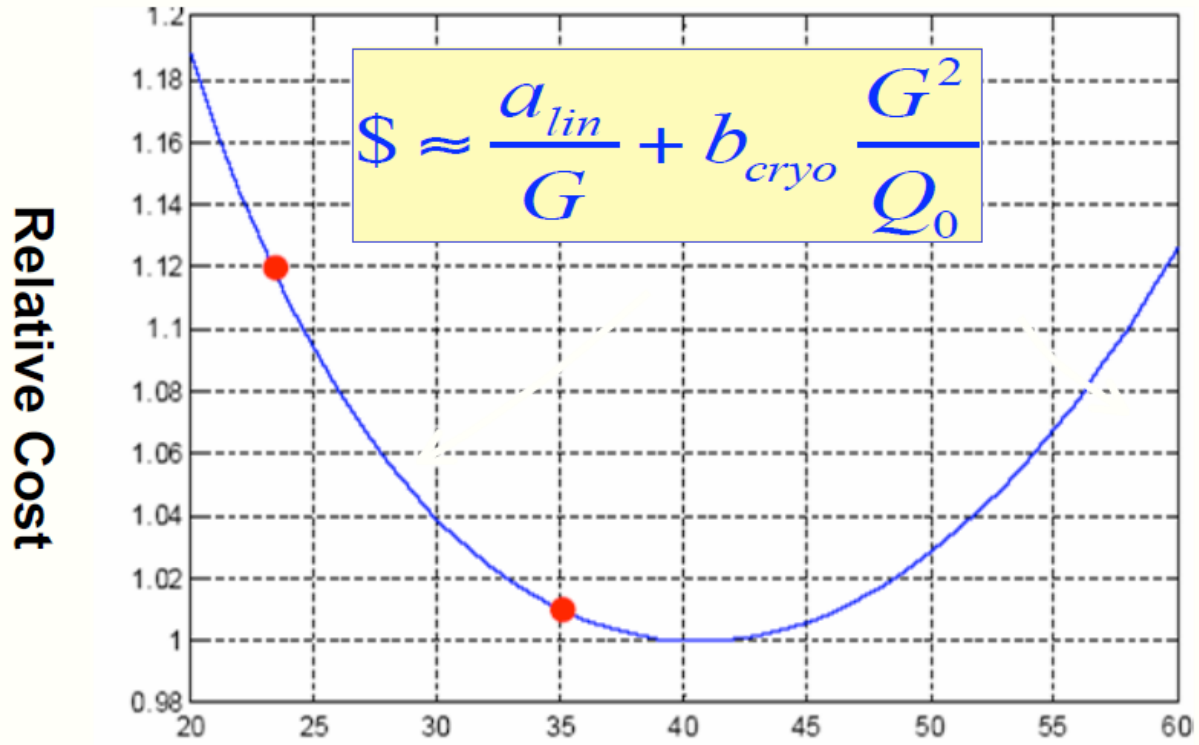
Q Values in CM at Fermilab



Q_0 vs. gradient

ILC-GDE

How do Costs Scale with Gradient?

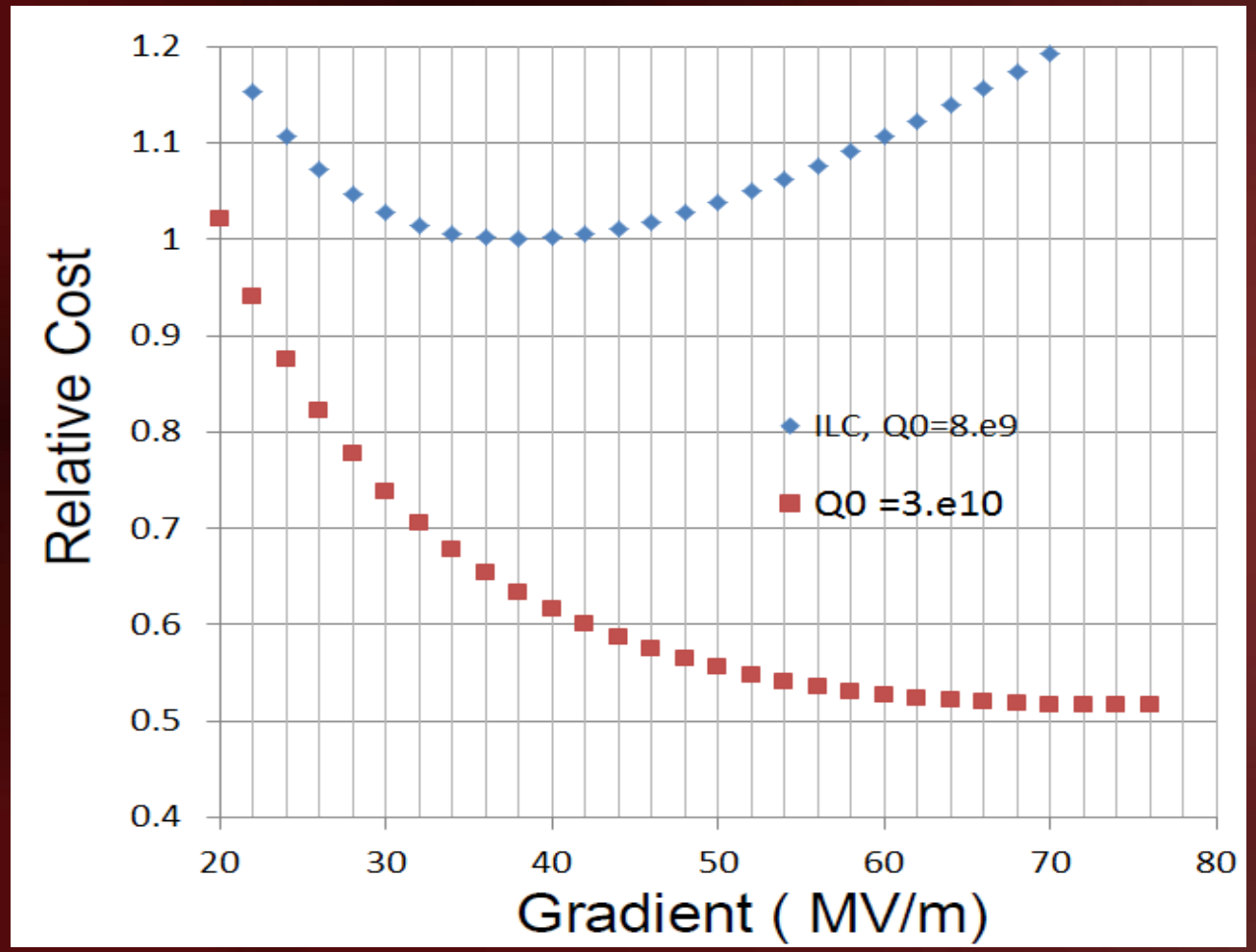


C. Adolphsen (SLAC)

35 MV/m is close to optimum

30 MV/m would give safety margin

Impact of Increasing Gradient and Q on ILC cost



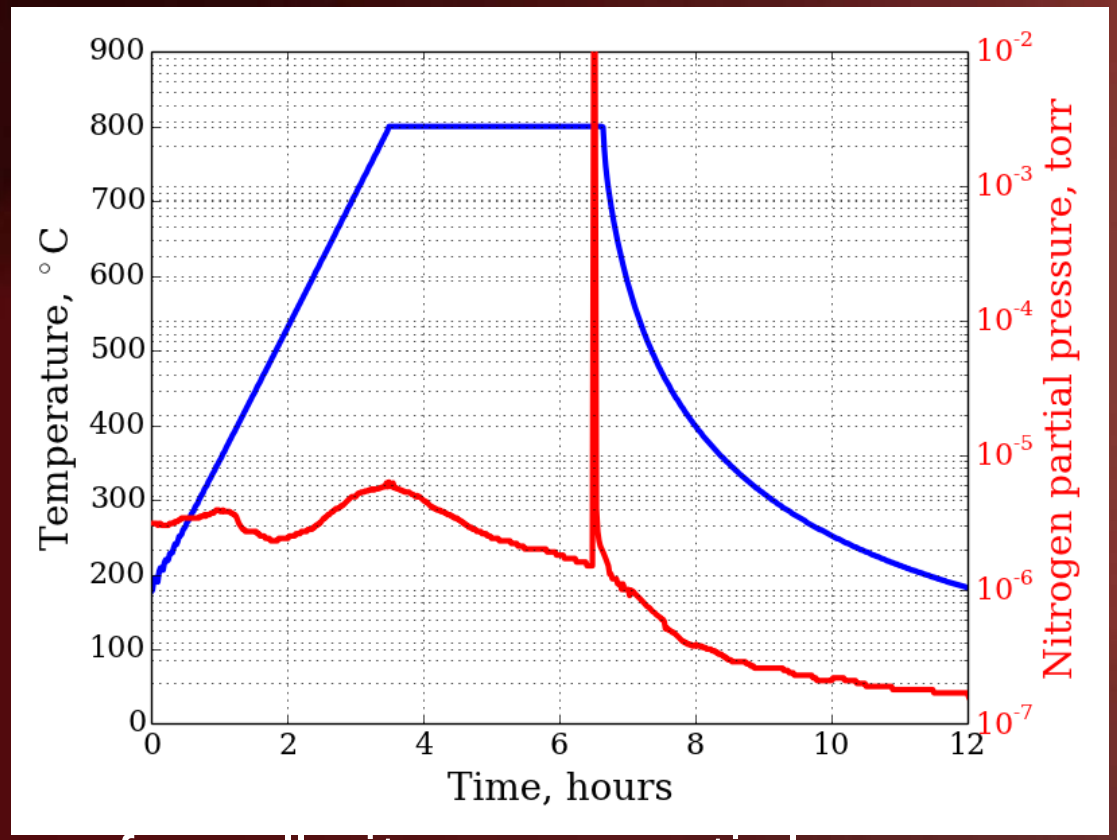
- **ILC requirements:**
- G > 35 MV/m/ Q0 > 0.8e10
- **Improving Q0 from 8e9 to 3e10 has big impact on machine cost.**
- **Optimal gradient moves to**
- **~ (70 - 80) MV/m**

Recent Breakthroughs in High Q (without FE)

- 1. Reverse the falling Q-slope!
- N doping exceeds familiar Q values!
  - But still demands deep physical understanding.
    - What is missing in simple BCS calculation for Q?
- 2. Reduce residual losses by completely expelling dc magnetic flux
  - leads to even higher Q values.
- R&D in fundamental understanding of both phenomena will reveal
  - What are the ultimate limits to the best Q?
  - Best parameters to optimize the preparation and cool-down protocol for highest Qs?

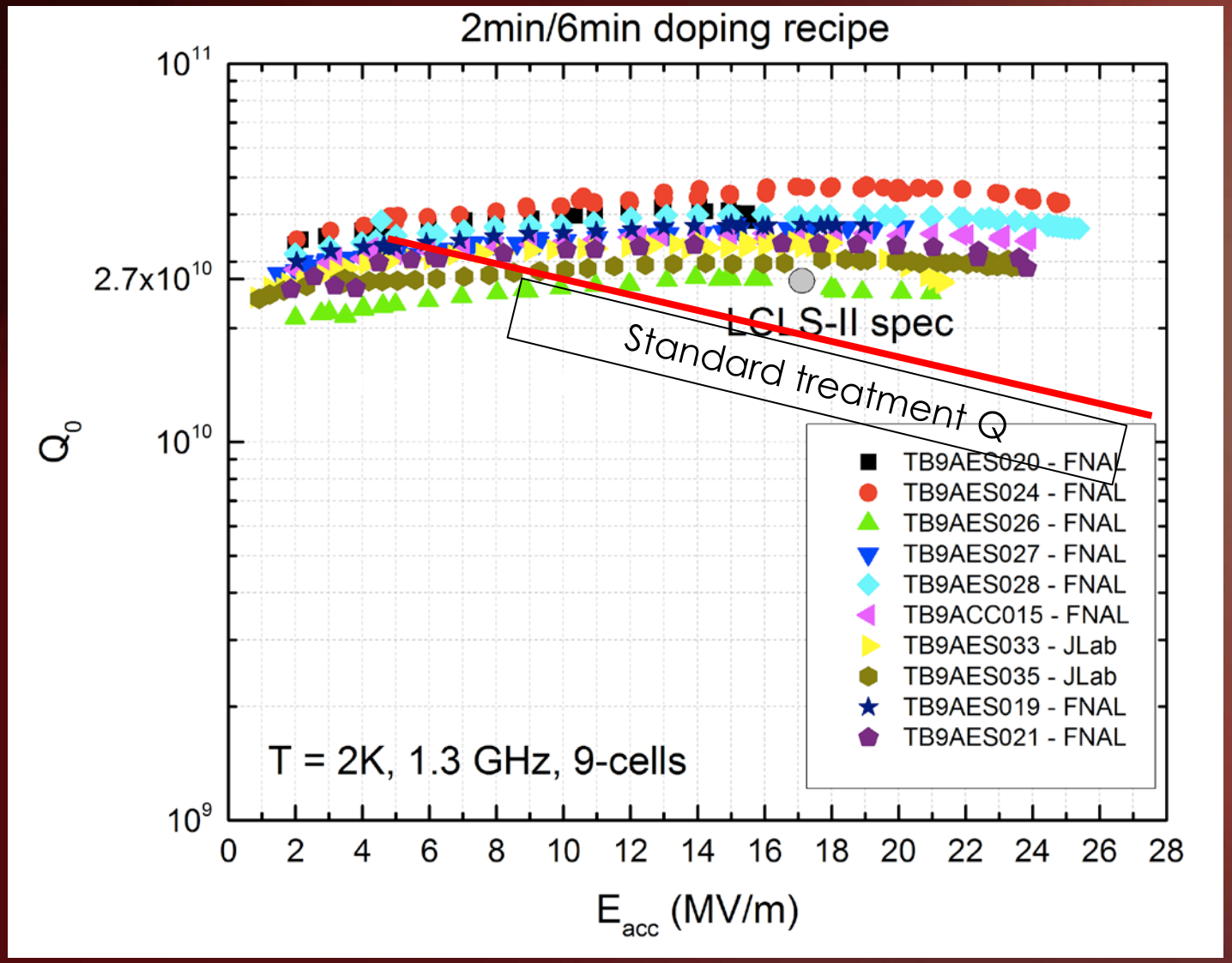
What is N doping?

infuse the cavity surface at 800 C
with a small concentration of nitrogen (about 50 ppm)

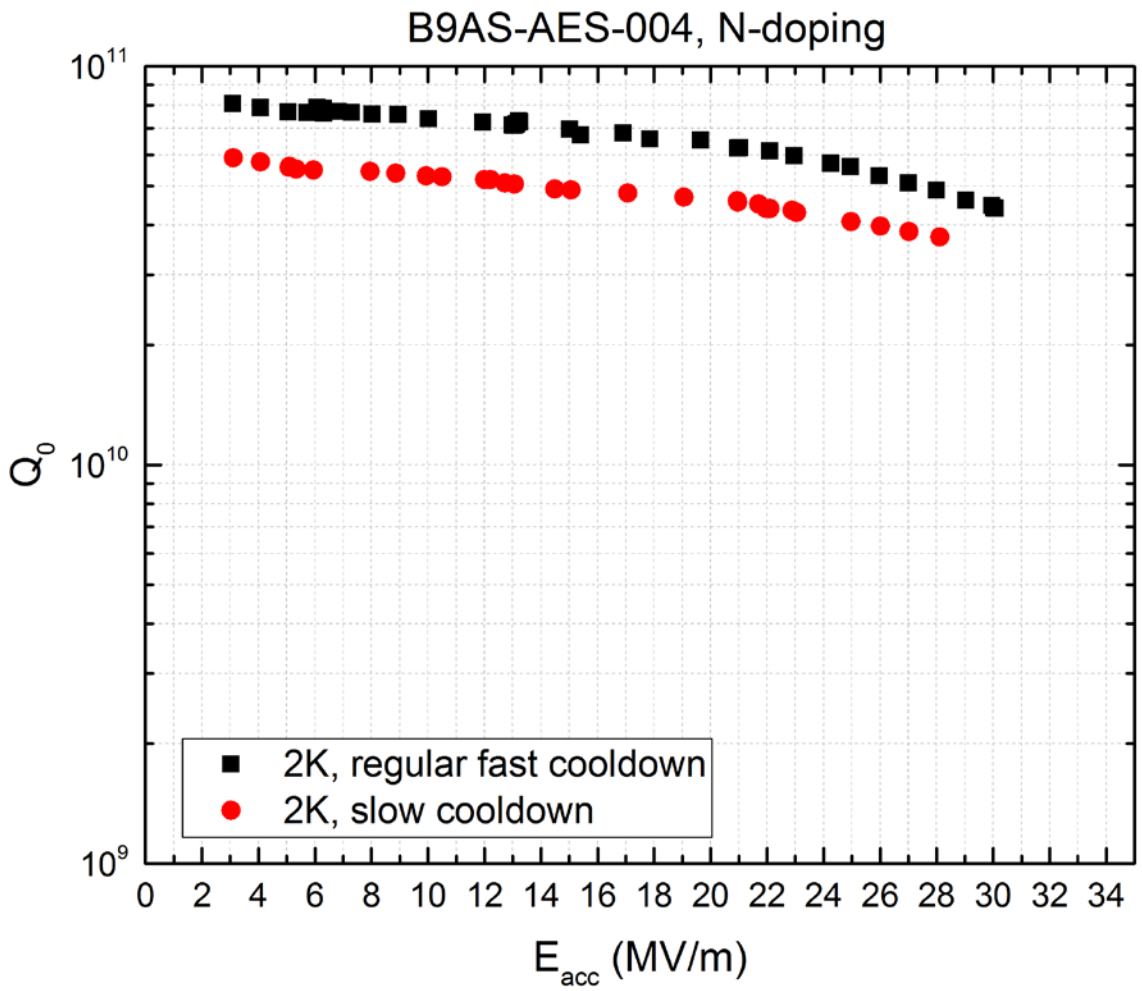


Injection of small nitrogen partial pressure at the end of 800C degassing-> drastic increase in Q

High Q values obtained by N-Doping doping repeatedly on 9-cell ILC Cavities for LCLS-II

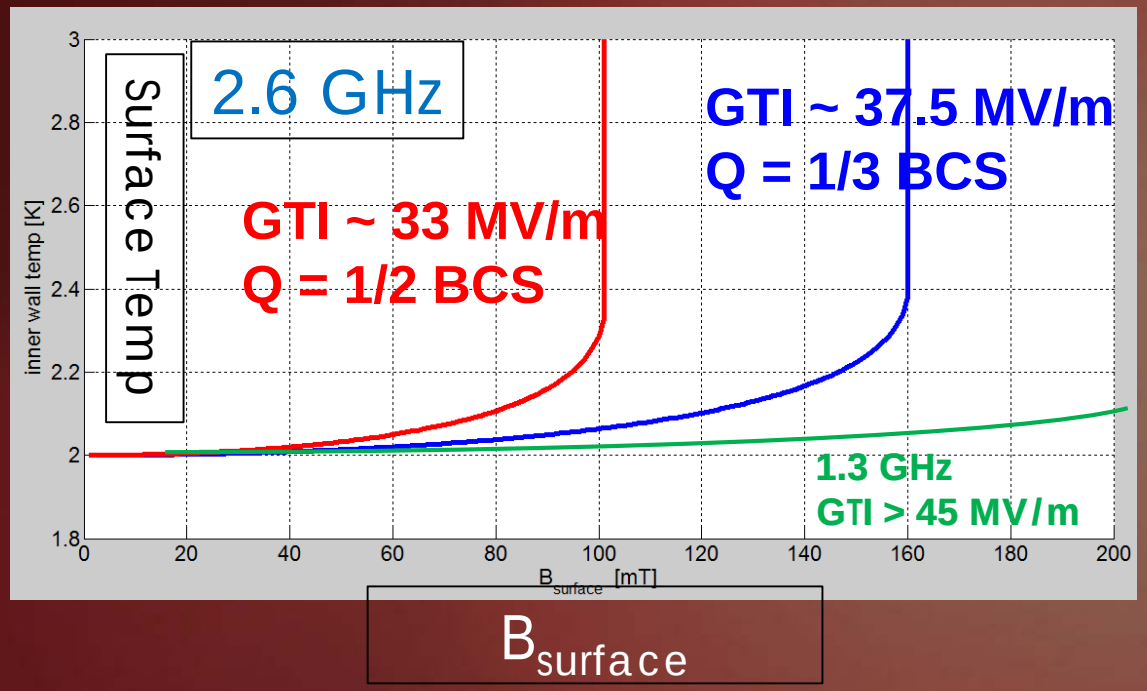


High Q to 30 MV/m (650 MHz)



High Q Opens Cost Reduction Possibilities: 1.3 => 2.6 GHz

- 1.3 GHz was originally chosen to avoid the global thermal instability ,(GTI) due to BCS resistance (increases as f^2)
- Pros for higher frequency
  - Material cost savings for cavity and CM parts
  - Optimistically 75%
- Smaller surface area
  - Less defects/field emission
- Cons
- Larger wakefields
- More HOM power



If N-doping can reduce BCS resistance by factor of 3

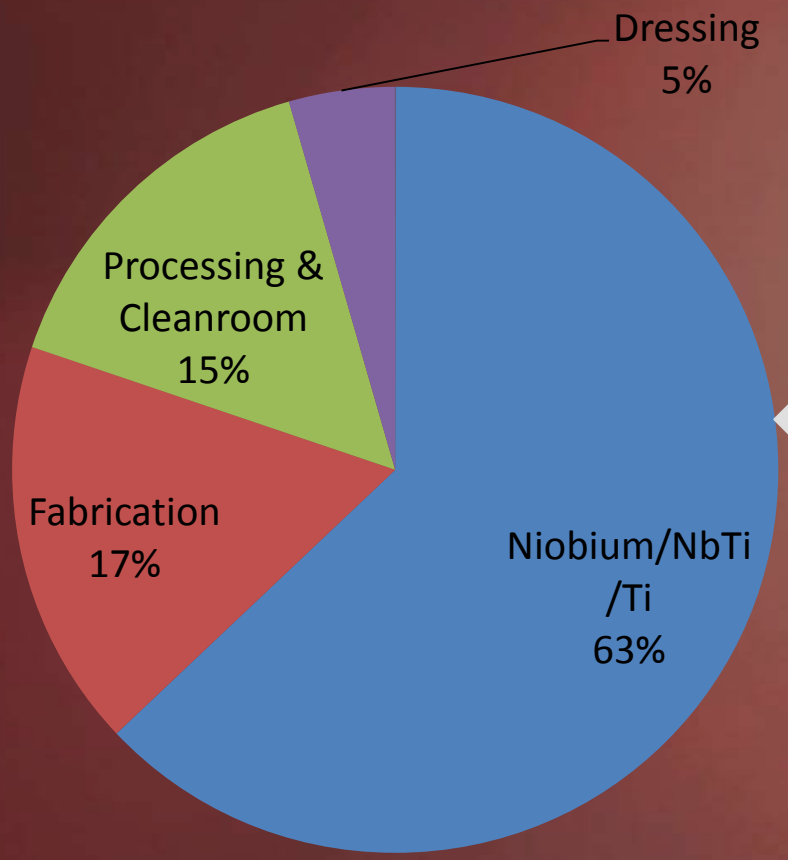
Global thermal instability due to BCS surface resistance can be managed

Cavity Material-Cost Reduction

- Cost of bulk niobium is a major factor
  - especially for low frequency (<650 MHz)
  - the required Nb per cell scales as $1/f^2$.

=> Cut Nb cost

>1000 Cavity Production Cost
1.3 GHz Cavities



Nb cost dominates for large scale production

Cavity Fabrication Cost Reduction via Seamless Techniques with Nb-Cu Composites

- Eliminate expensive e-beam welding and trim machining of parts
- High quality surface preparation possible
  - as with bulk Nb cavities that show high performance
- Rapid production rate
- Hydroformed and Spun 1-cell cavities already proven
  - Hydroformed 3-cells Nb proved to > 35 MV/m
  - Spun single cell Nb proved to 40 MV/m