Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

High Q_0 High Gradient Update from Fermilab

Sam Posen

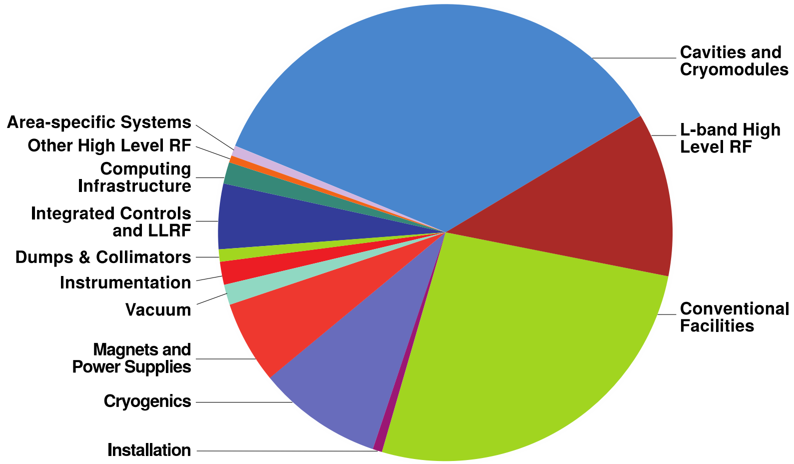
ALCW 2018 – Fukuoka, Japan

May 31, 2018

Fermilab High Gradient High Q_0 R&D

- SRF cavity R&D with focus on regime relevant for ILC
- Focuses on cost reduction based on cavity performance improvement (and cavity processing optimization)
  - ILC TDR: “[the cost] is dominated by the SRF components and related systems, together with the conventional facilities. These two elements account for 73% of the total. The main linac itself corresponds to 67% of the total project.”
  - Investing in carefully selected main linac R&D should be most efficient in bringing the ILC cost down.

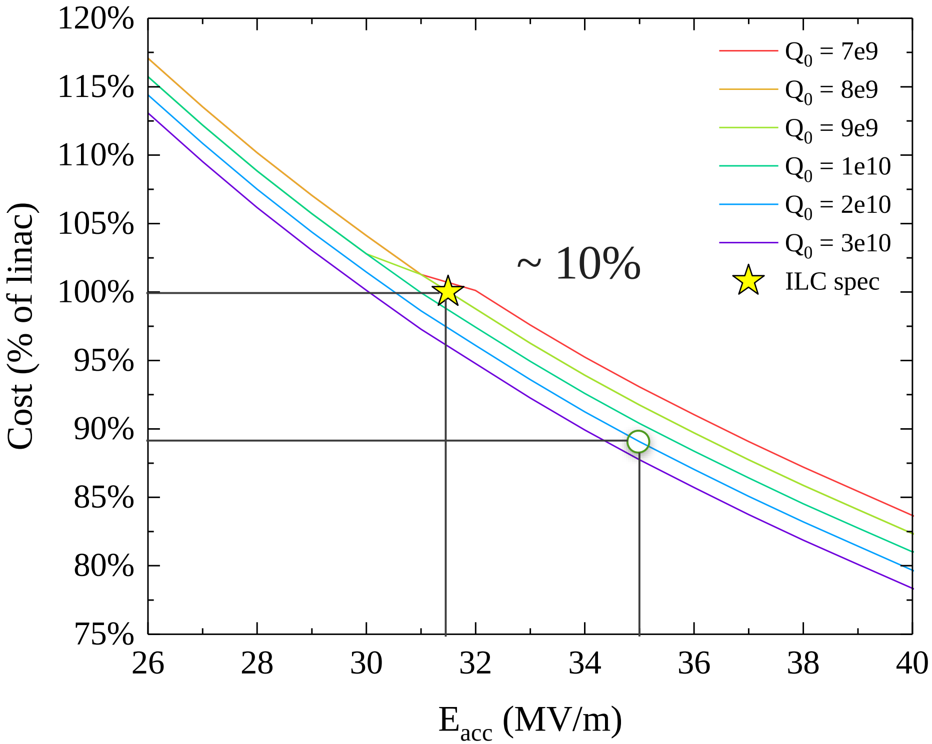
Main Linac Cost Breakdown from ILC TDR

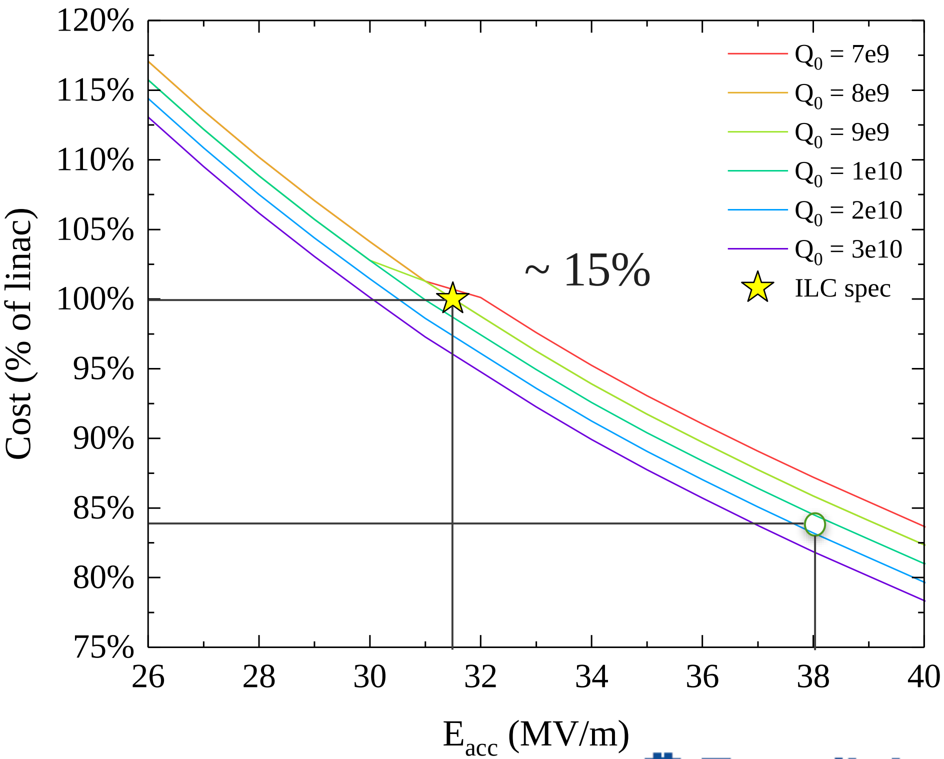


M. Checchin

High Q High Gradient & Effect in ILC Cost Model

- A cost model has been developed based on the ILC TDR to estimate the impact of new progress in SRF technology
- Cavity Q_0 and E_{acc} are among the main cost drivers
- Improving simultaneously Q and gradient can give substantial cost cut >10% of the total linac cost





ILC cost reduction –R&D pathways

- Three crucial R&D pathways to achieve higher gradient with higher Q:
  1. Achieving lowest possible trapped magnetic field in the cavity walls : potential ~1.5e10 at 31.5 MV/m
  2. Nitrogen Doping/Infusion: potential >2e10 at >35 MV/m
  3. Reduce Field Emission (to maintain performance and increase yield)
  4. [Long Term]: Increase gradients beyond 50 MV/m via high frequency, by-layer structures, or Nb_3Sn

European XFEL

RI XFEL: Maximum Gradient Yield (2D)

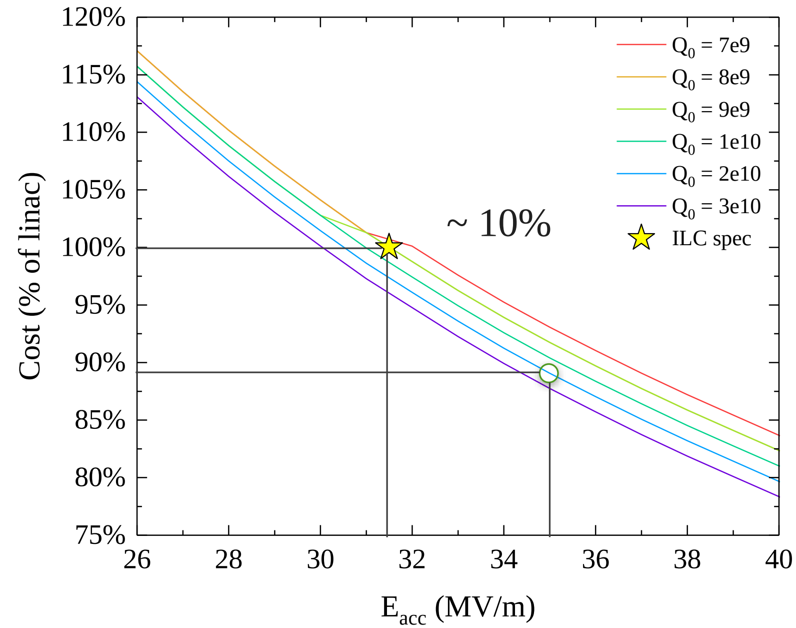
11

RI XFEL cavities accepted for module assembly
(includes those cavities which have been retreated)

N. Walker, ECFA LC (2016)

$\geq G_{max}$ MV/m

$\geq Q_0$	20	25	30	35	40	45
0.	100%	98%	84%	51%	10%	0%
$5.\times10^9$	98%	97%	84%	51%	10%	0%
$1.\times10^{10}$ (XFEL)	31%	30%	25%	15%	6%	0%
1.5×10^{10}	1%	1%	1%	1%	0%	0%
$2.\times10^{10}$	0%	0%	0%	0%	0%	0%



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Minimizing Trapped Magnetic Flux

Trapped Magnetic Flux Minimization

- The SRF field has made very large progress since ILC TDR in understanding the impact of trapped magnetic field in SRF cavities and demonstrating how to minimize trapped flux
- Trapped magnetic field can cause large cryogenic losses, especially at high accelerating fields, which could also lead to degraded maximum fields in cryomodules
- Recent key findings:
  - Cooling cavities slowly traps all magnetic field, so linac has to be cooled fast–A. Romanenko et al, Journal of Applied Physics **115**, 184903 (2014)
  - Material properties vary vendor by vendor and that causes more or less flux trapping, even in fast cooling – but increasing bake T to 900-950C mitigates this effect (implemented in LCLS-II cavities) - S. Posen et al, Journal of Applied Physics **119**, 213903 (2016)
  - Magnetic fields in cryomodule can be strongly reduced via active cancellation coils + passive shielding – demonstrated 3 mGauss avg in LCLS-II cryomodules @FNAL – G. Wu et al, Overview on Magnetic Field Management and shielding in High Q modules, Proceedings of SRF15

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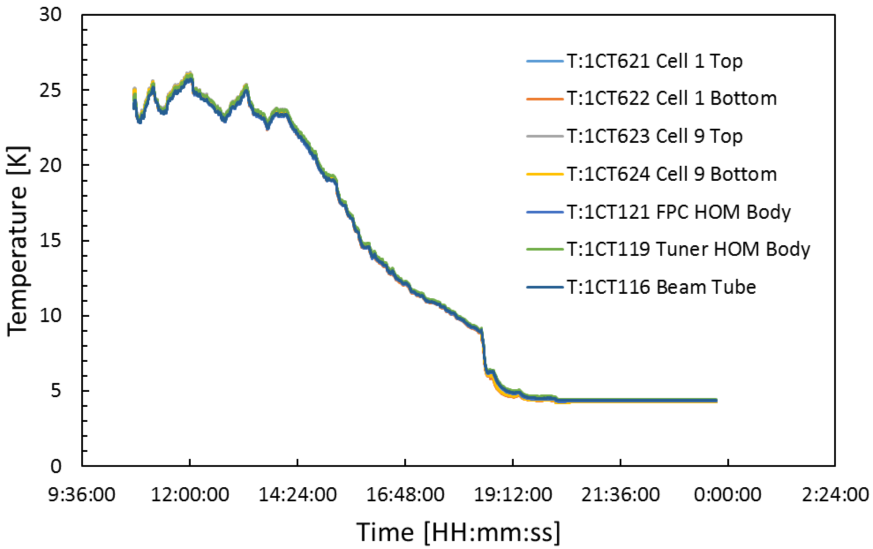
Slide courtesy A. Grassellino

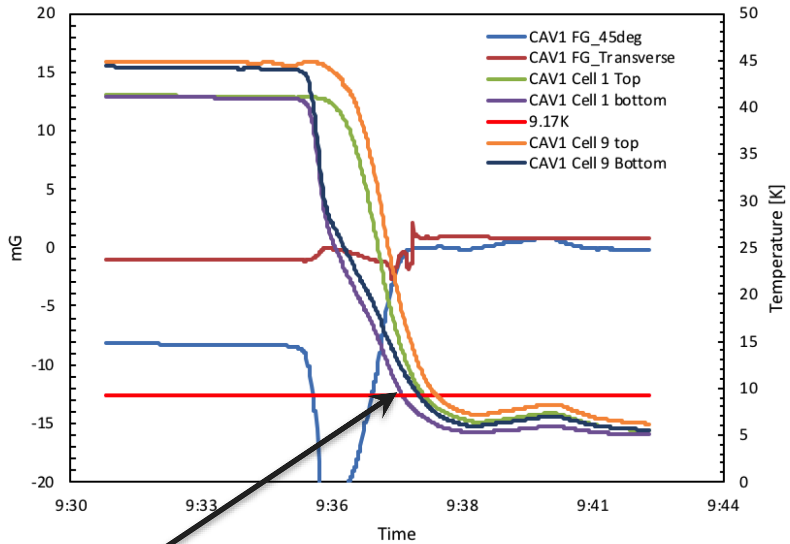
Fermilab LCLS-II Prototype Cryomodule

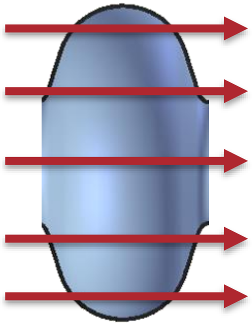
Effect of ΔT at Cooldown

"Slow" cooldown
Mass flow ~a few g/s

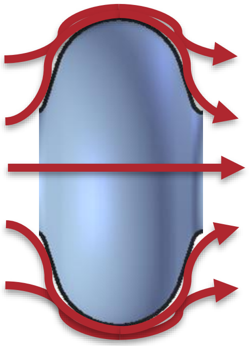
"Fast" cooldown
Mass flow ~60-80 g/s







High mass flow during cooldown generates top-bottom ΔT at transition to expel flux

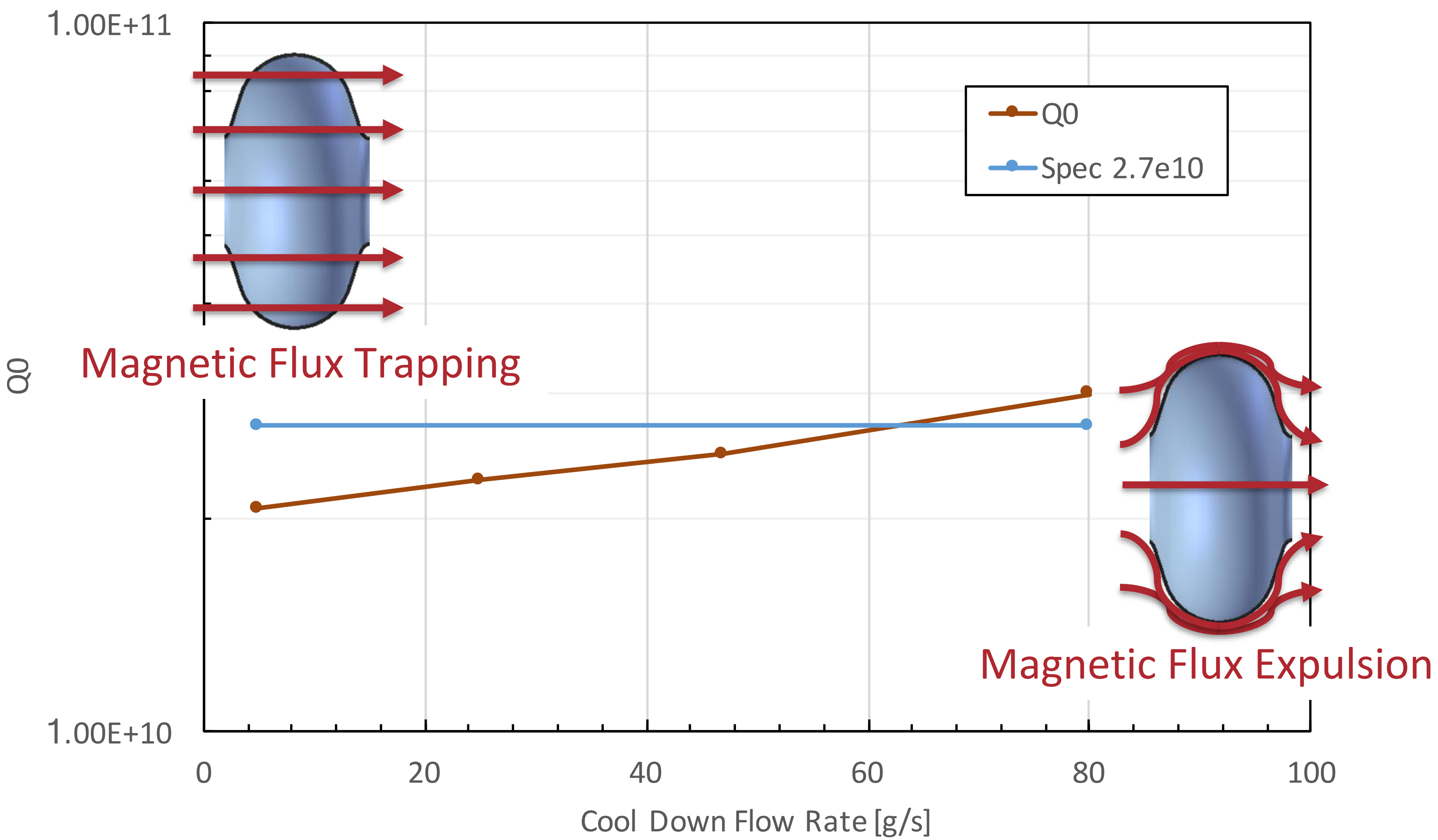


Magnetic Flux Trapping

Magnetic Flux Expulsion

pCM Q_0 vs Mass Flow During Cooldown

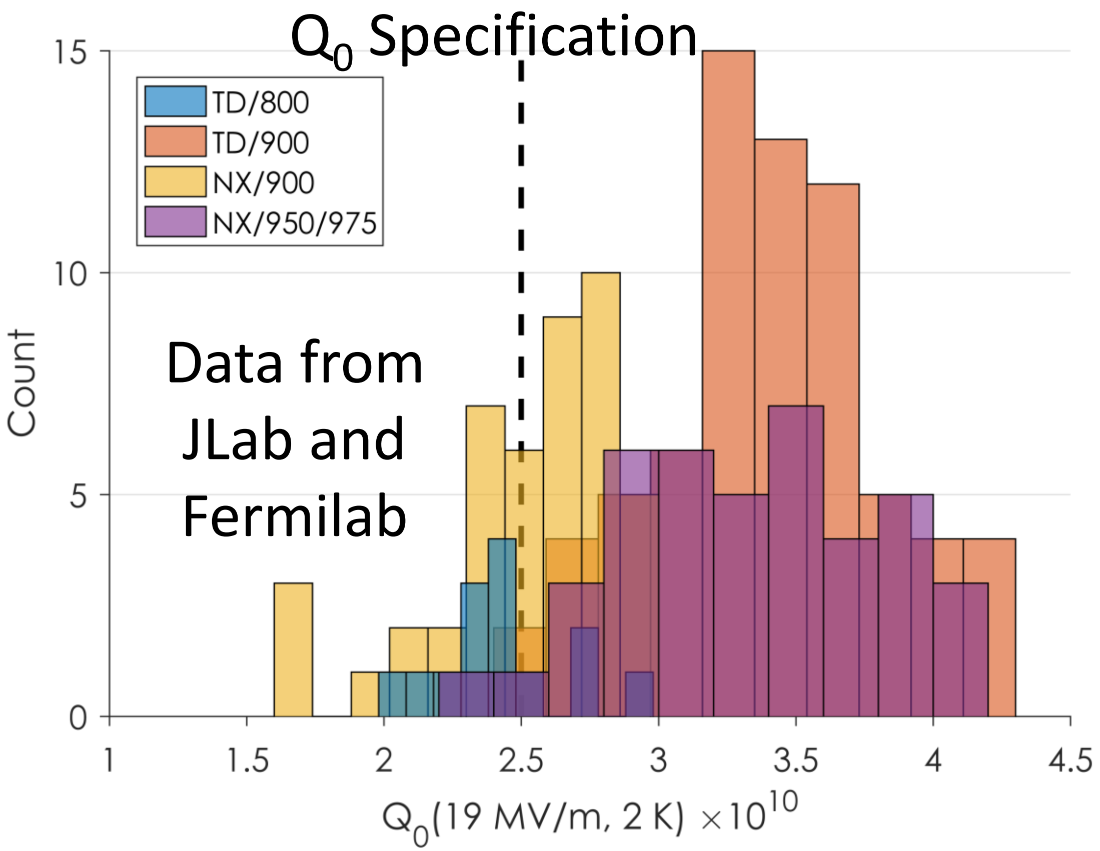
Effect of ΔT at Cooldown

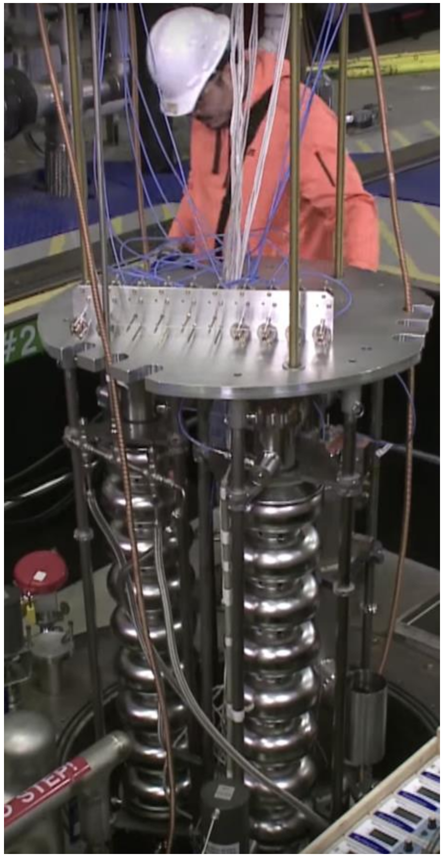


Material and Heat Treatment Temperature

Mat'l & Heat Treatment

Vertical Test qualification data for LCLS-II





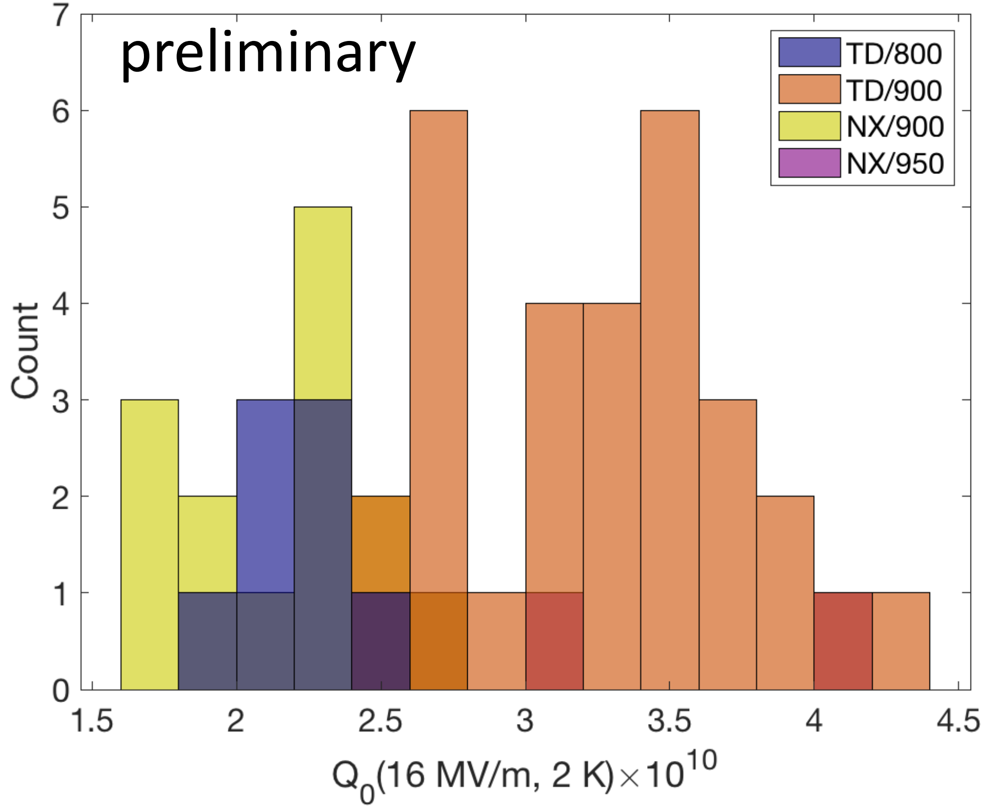
- TD and NX respectively show significant improvement after heat treatment >~900 C and >~950 C to improve expulsion

Plot from D. Gonnella et al., TTC Milan

Material and Heat Treatment Temperature

Mat'l & Heat Treatment

Cryomodule testing for LCLS-II at Fermilab



- Cryomodule test with "fast" cool – Higher Q_0 in cavities with material treated to maximize expulsion

Trapped Flux for *Non*-doped Cavities – E-XFEL

Mat'l & Heat Treatment

European XFEL

RI XFEL: Maximum Gradient Yield (2D)

RI XFEL cavities accepted for module assembly
(includes those cavities which have been retreated)

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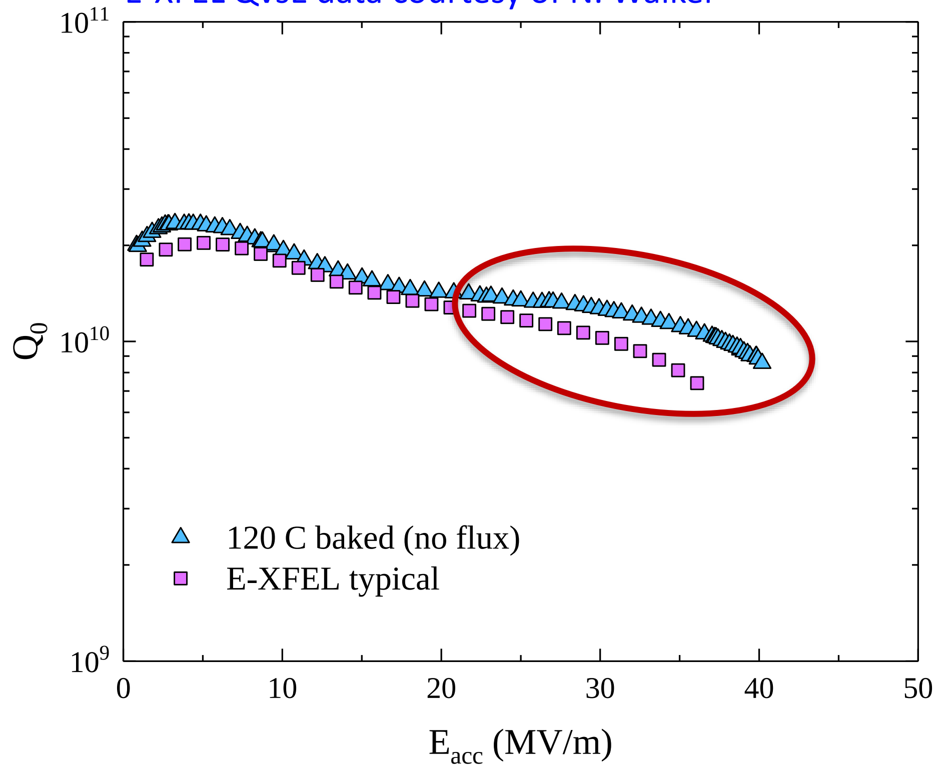
XFEL cavity results • ECFA LC 2016 • Santander - Spain • 31-05-2016
Nicholas Walker • DESY • nicholas.walker@desy.de

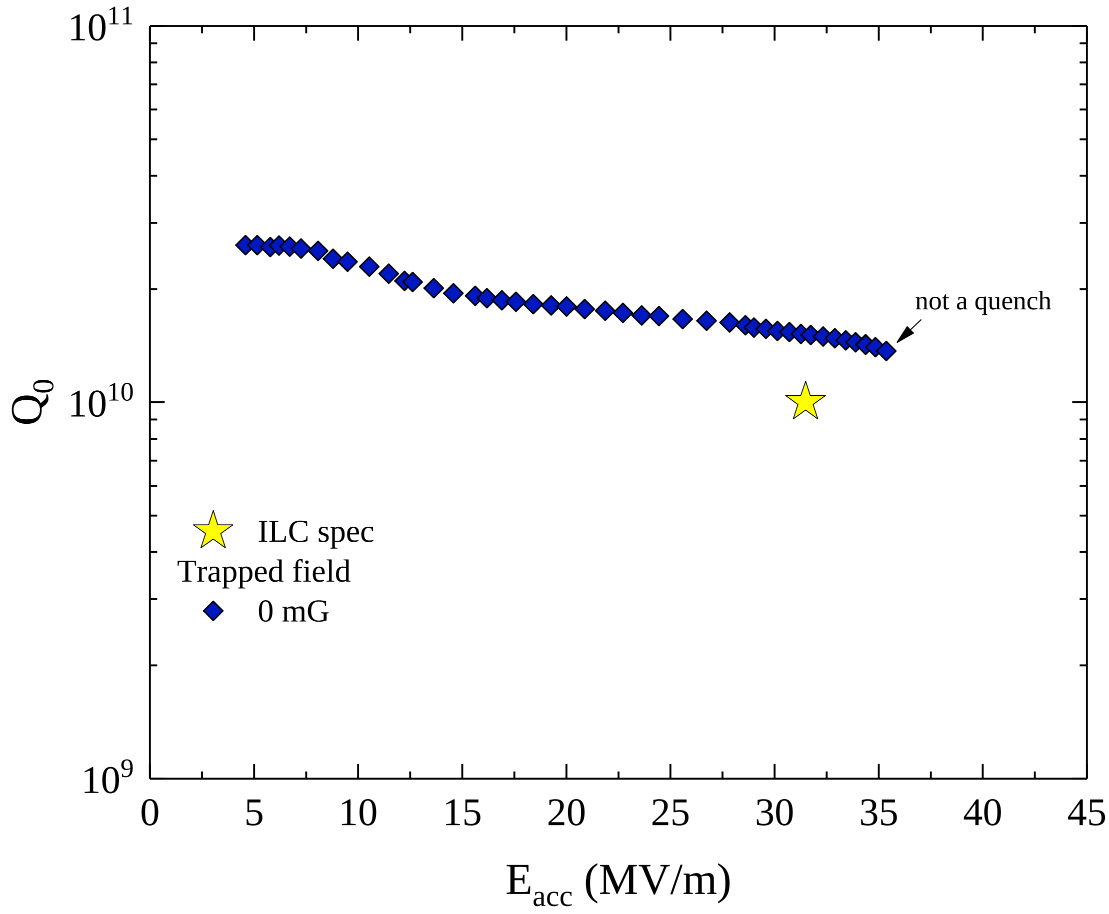
E-XFEL QvsE data courtesy of N. Walker



Only about 25% of the E-XFEL production cavities reach $1 \cdot 10^{10}$ above $30\ MV/m$.

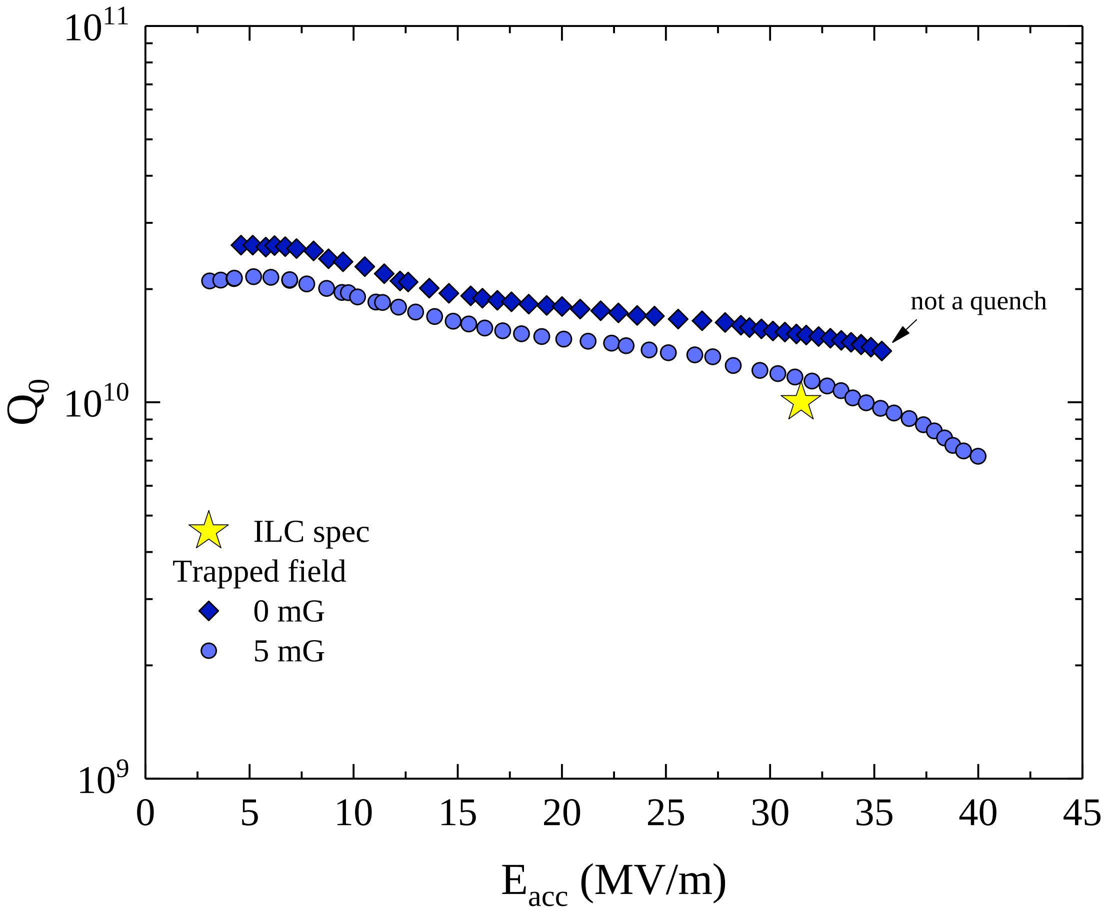
Trapped flux- induced surface resistance may be one important cause of the spread in Q values with XFEL production

Typical 120 C baked cavity performance (no trapped field)



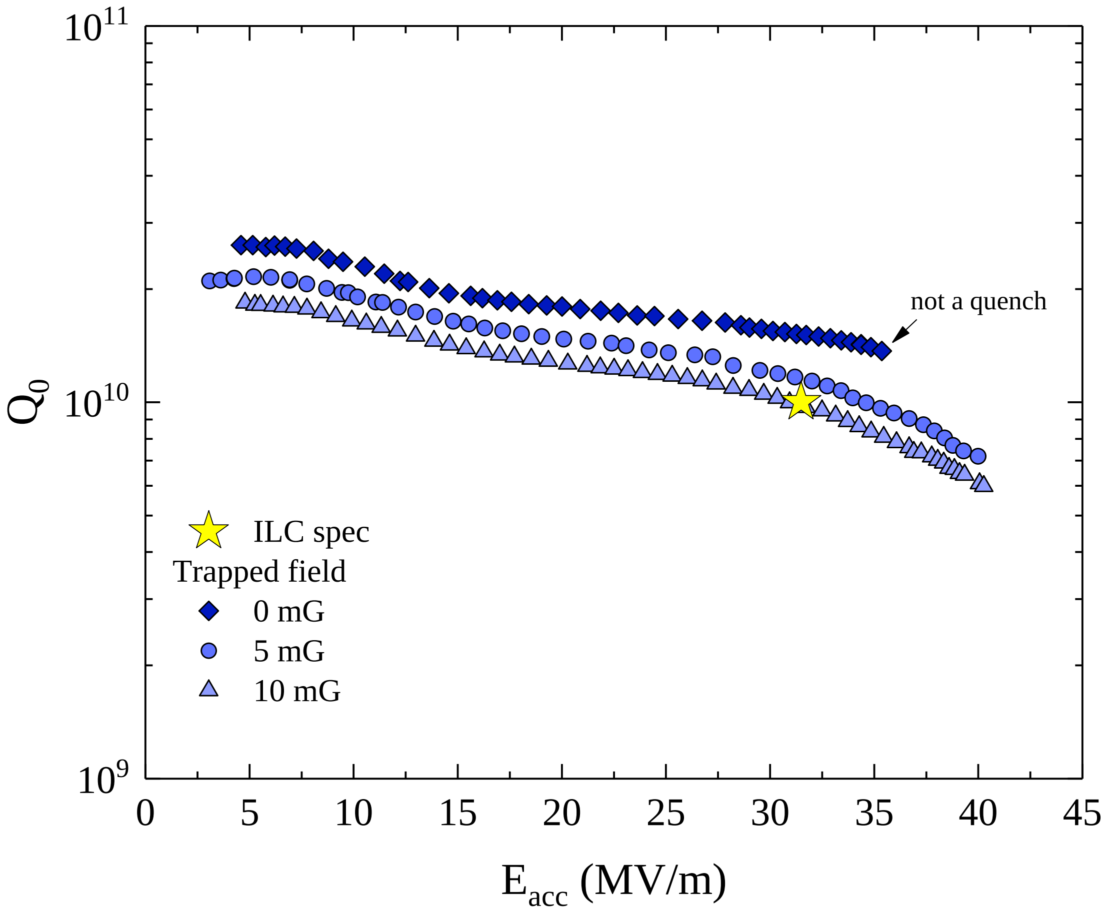
M. Checchin et al, FNAL, to be published

5 mG trapped



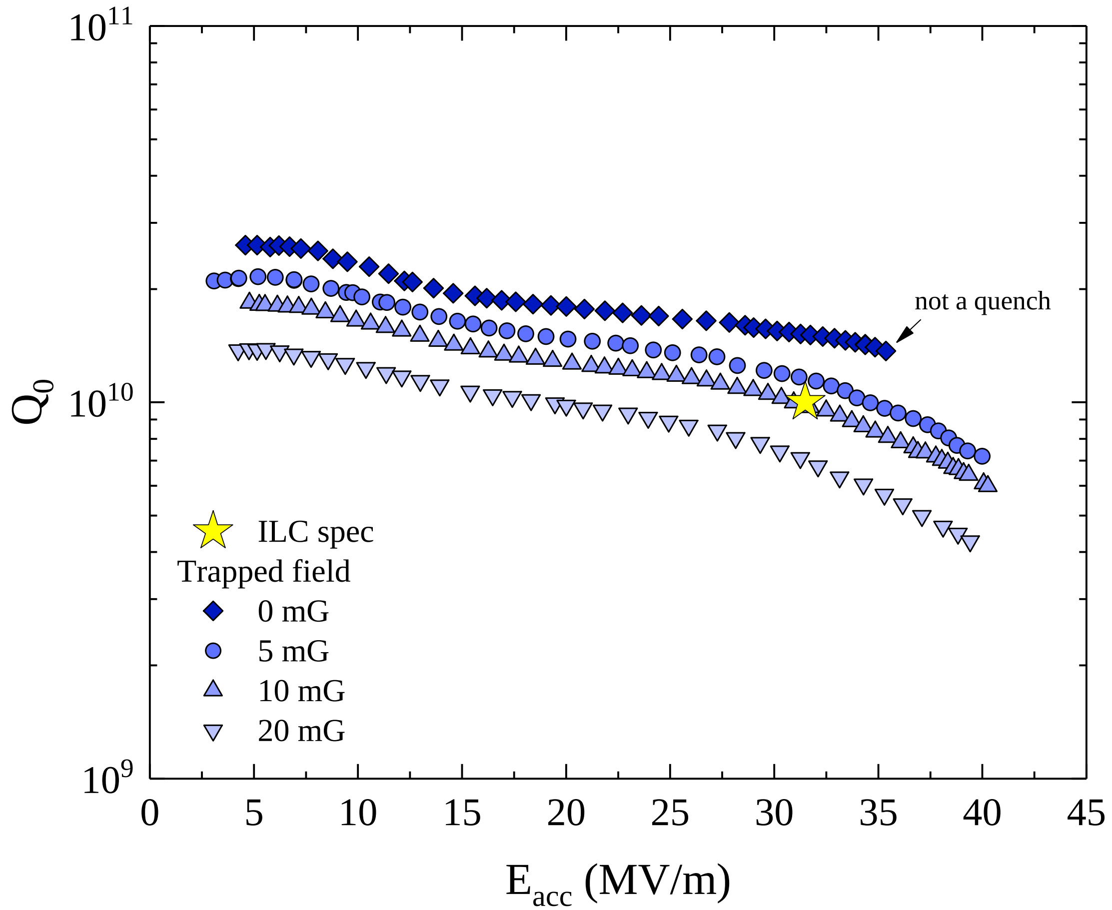
M. Checchin et al, FNAL, to be published

10 mG trapped



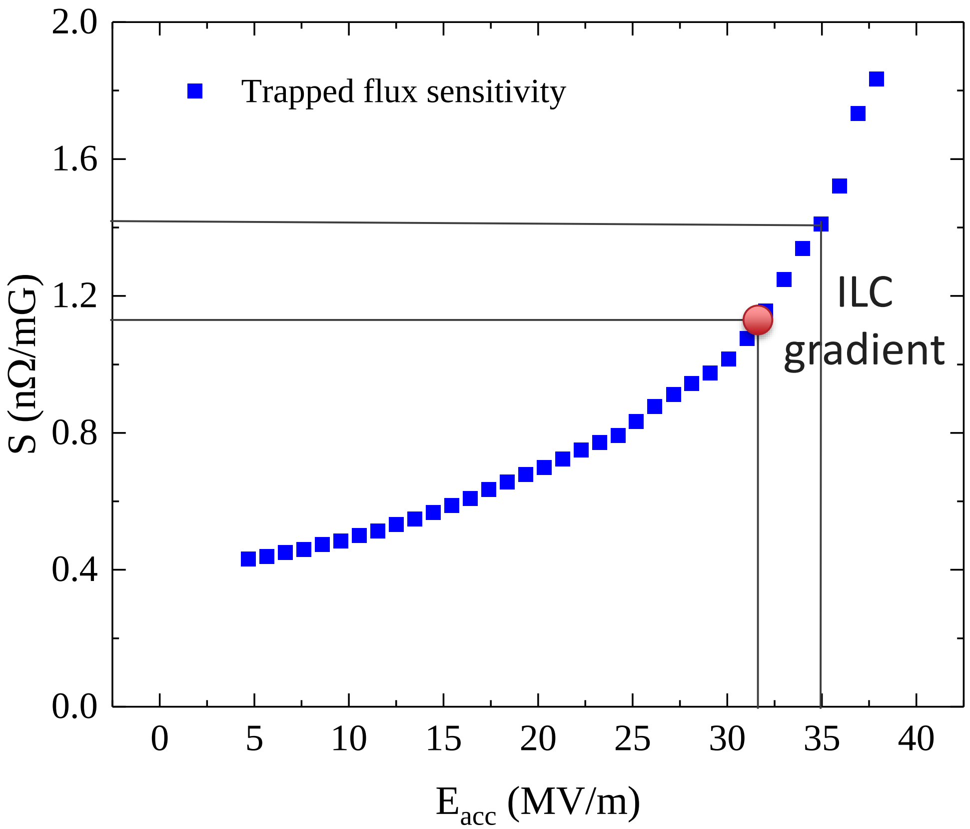
M. Checchin et al, FNAL, to be published

20 mG trapped



M. Checchin et al, FNAL, to be published

Additional recent studies at FNAL (regular 120C bake cavity) reveal high trapped flux sensitivity <u>at high accelerating fields</u>



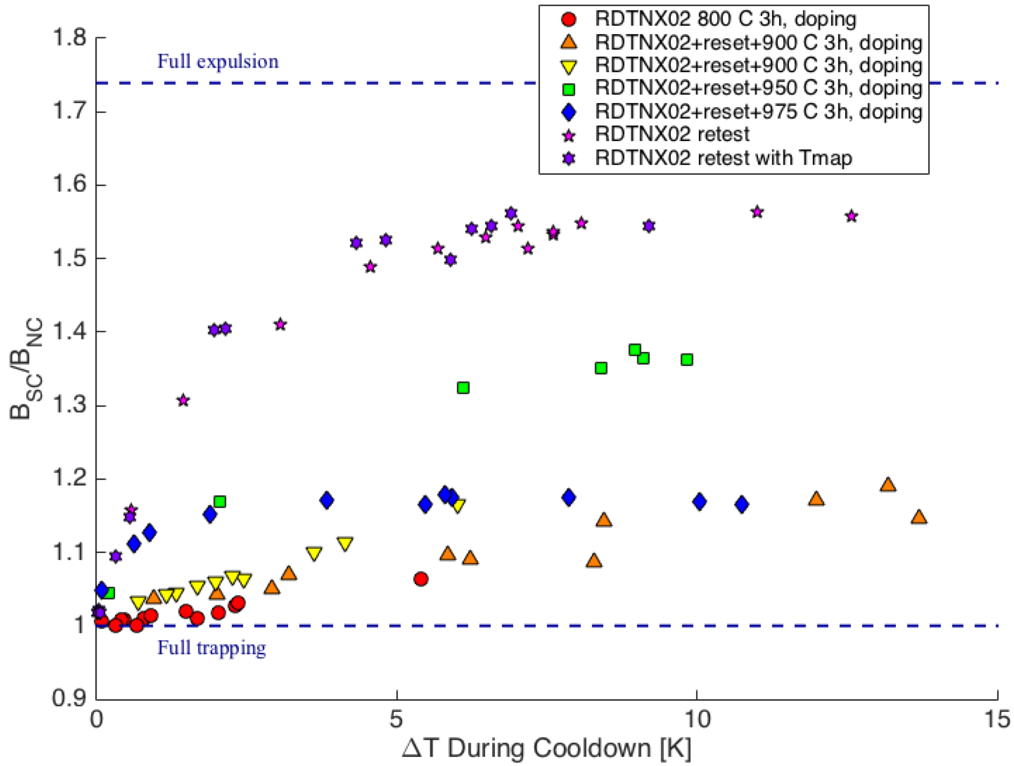
-Trapped flux at high gradients can lower Q significantly
-Sensitivity is strongly field dependent:
- 5 MV/m → ~ 0.4 nΩ/mG
- **31.5 MV/m → ~ 1.15 nΩ/mG**
- **35 MV/m → ~ 1.4 nΩ/mG**

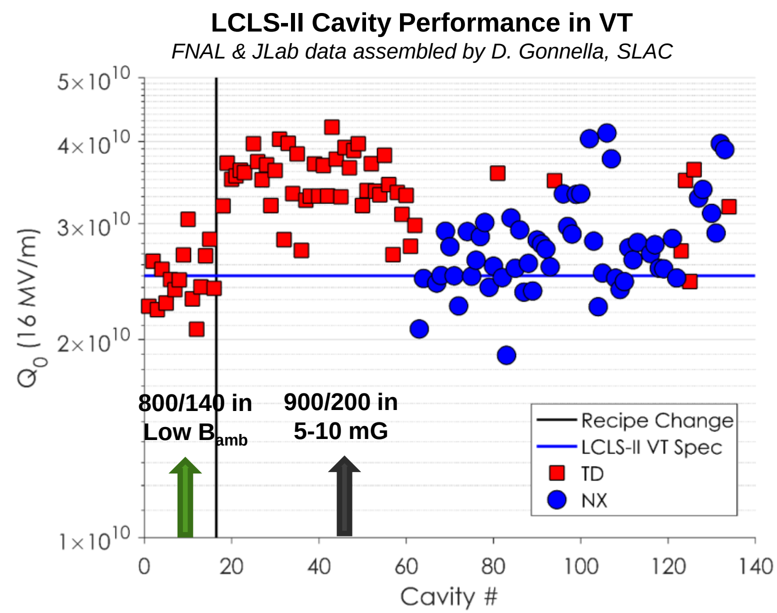
-ILC TDR B field spec is currently 10 mGauss

- Many lessons already learnt from R&D and implemented in LCLS-II:
  - Good flux-expelling material
  - Fast cool-down
  - Double shielding and active compensation
- May be useful for cost reduction for ILC

Towards Developing Improved Material Specs

- Several 1-cell cavities were made with LCLS-II material
- We put a T-map on the 1-cell cavity that showed the worst expulsion (RDT-NX-02) and measured after different cooldowns – **made with "stubborn" material**





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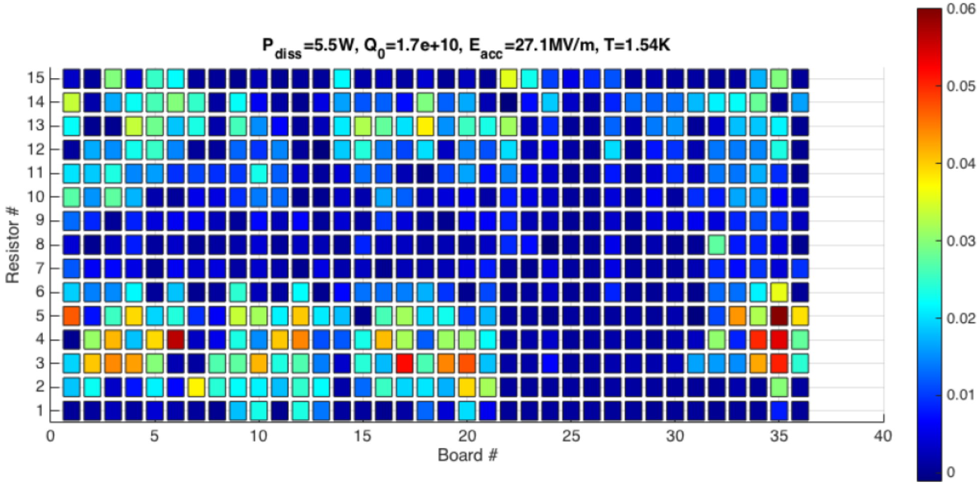
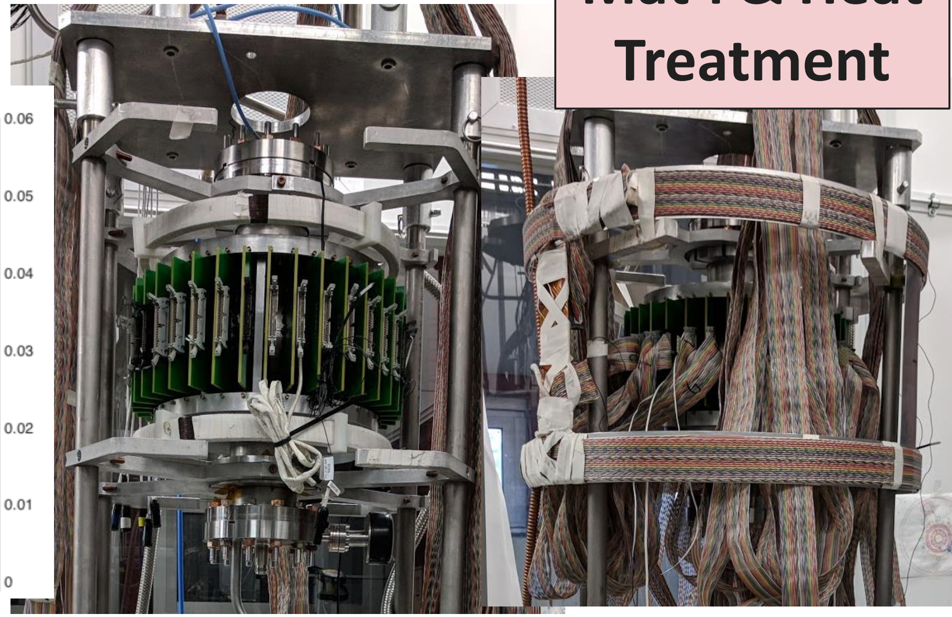
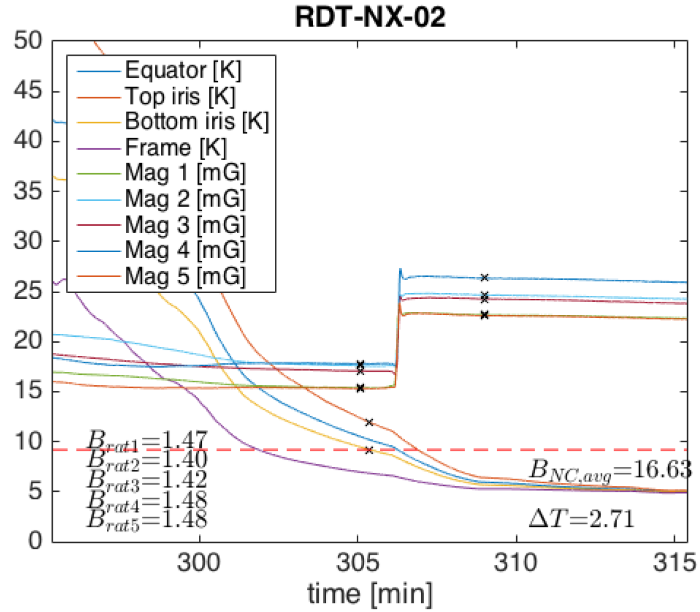
Experimental Setup

Mat'l & Heat Treatment



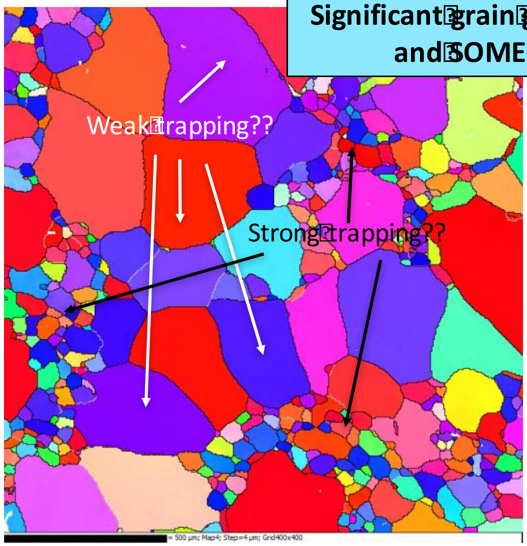


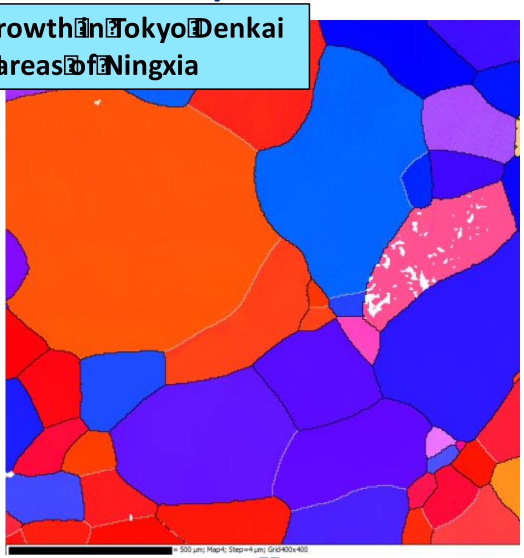


Curved Ningxia 11301

Curved Tokyo Denkai 10974

Significant grain growth in Tokyo Denkai and SOME areas of Ningxia





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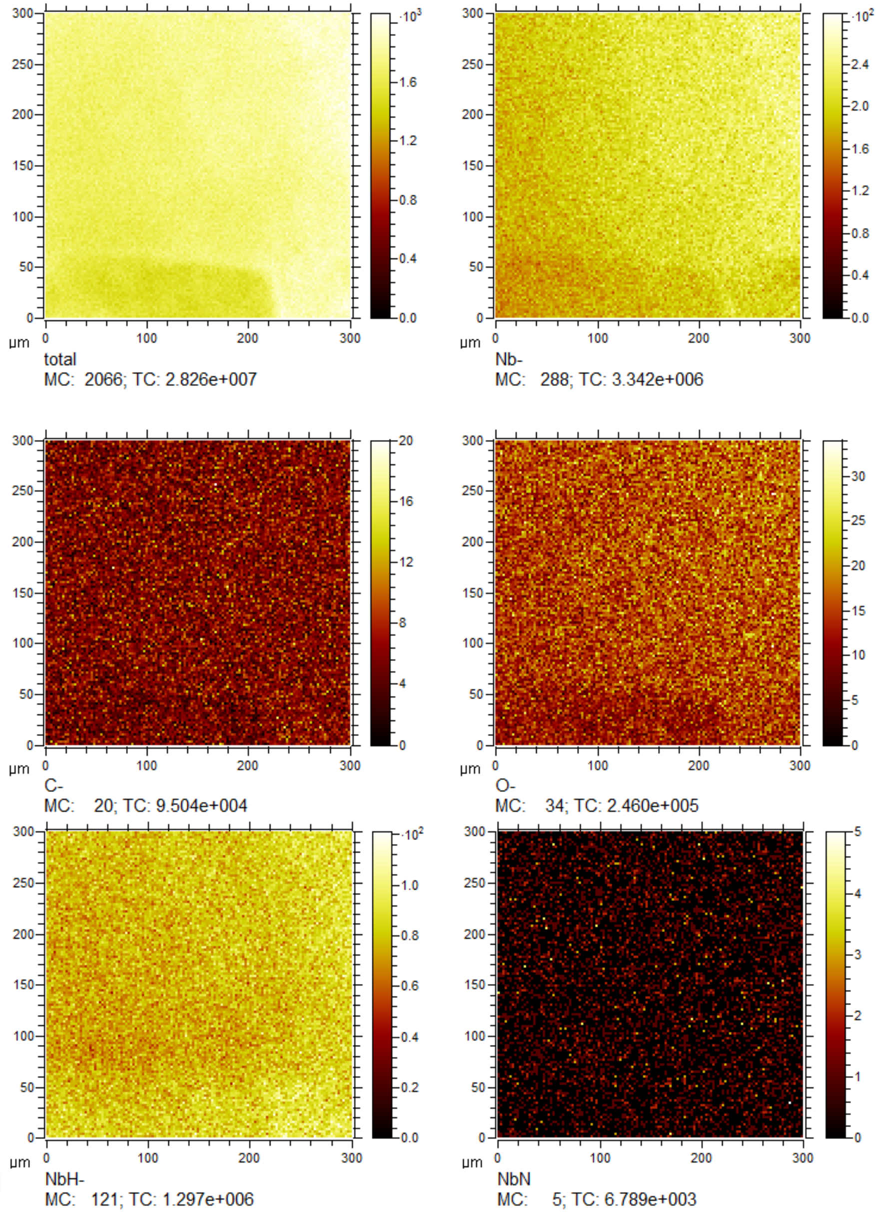
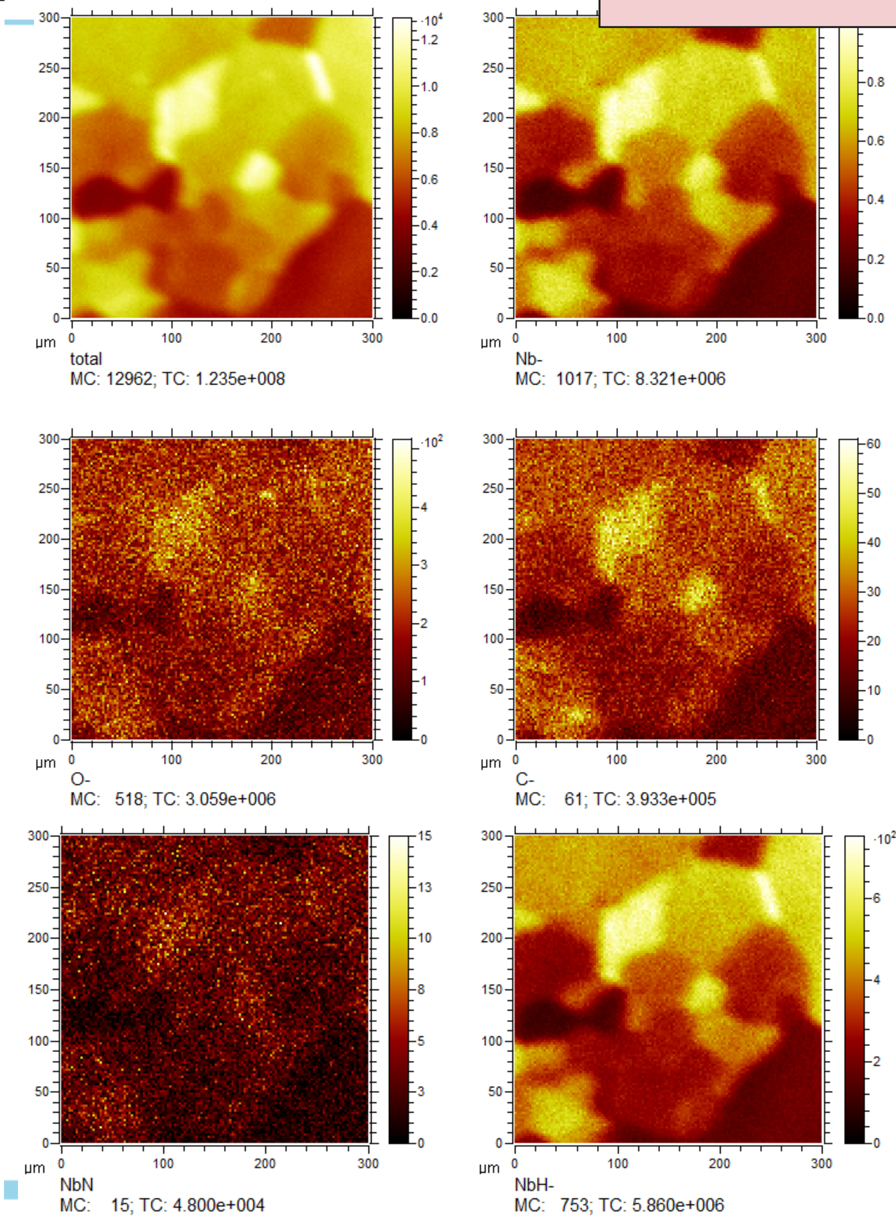
SIMS Investigation of Impurities

TD 10974

Ningxia 11301

Mat'l & Heat Treatment

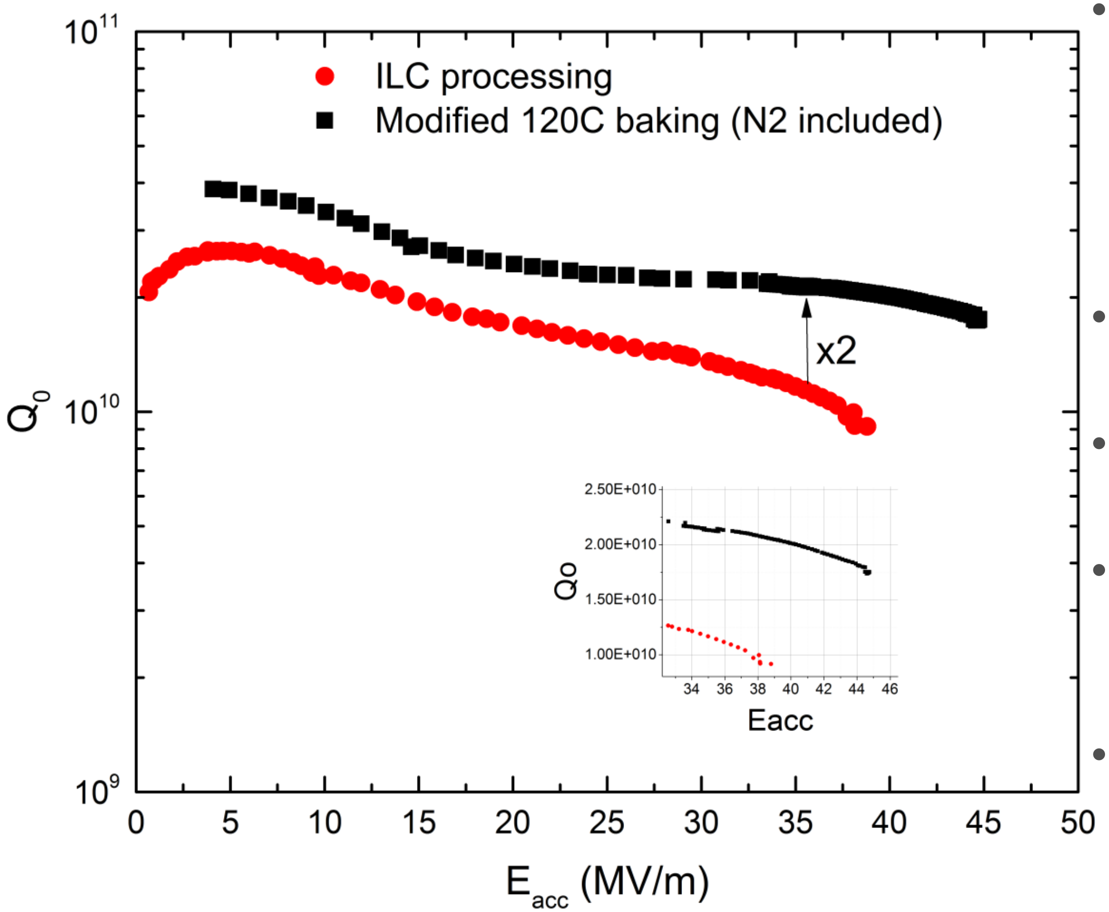




High Q at High Gradients via Nitrogen Infusion

Cavity performance progress at FNAL: "standard" vs "N infused" cavity surface treatment

A. Grassellino



Increase in Q by > a factor of two
Increase in gradient ~15%

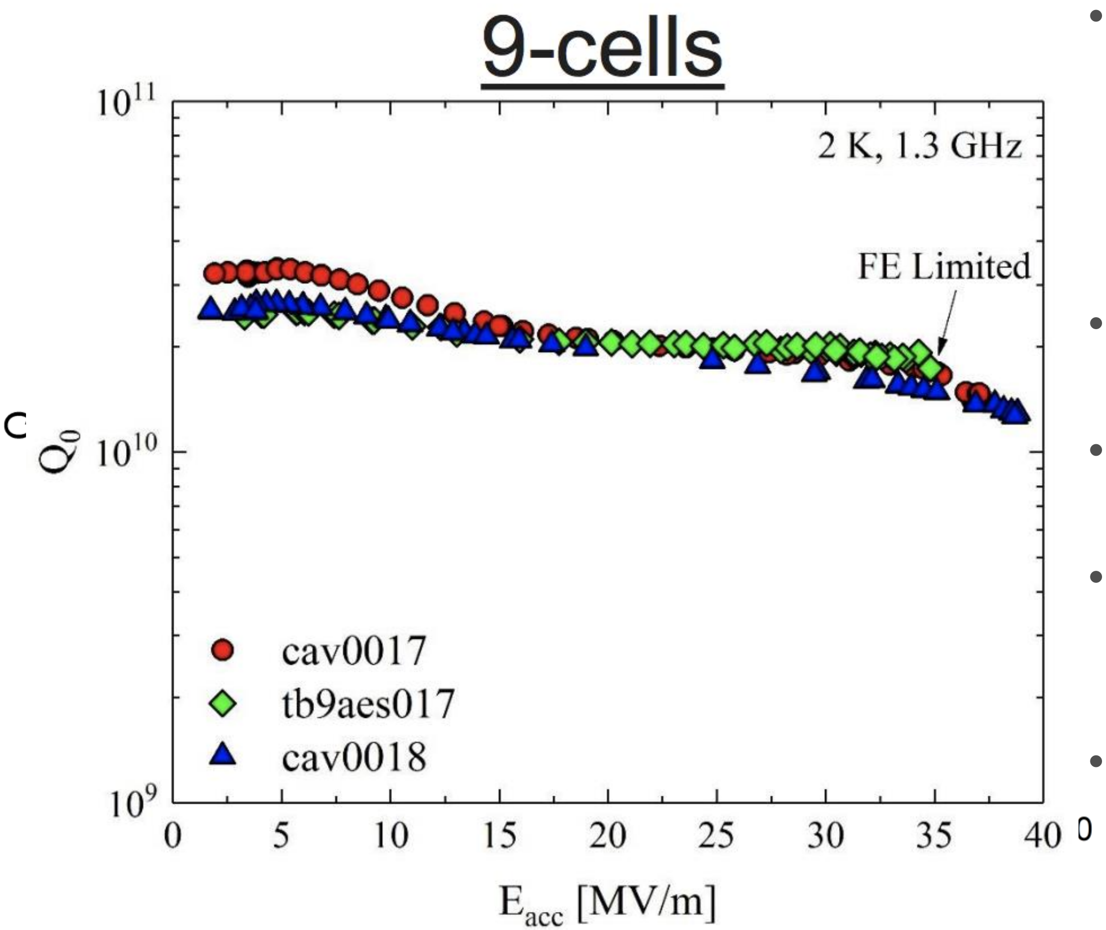
- FNAL recently demonstrated a new treatment, which utilizes "nitrogen infusion", achieving
  45.6 MV/m → 194 mT
  with Q ~ $2x10^{10}$
- Systematic effect observed on several single cell cavities
- FNAL has now successfully applied it on three nine cell cavities
- Jlab, KEK have reproduced similar results on single cell cavities with Q >2e10 at 35 MV/m
- R&D work towards:
  - Best recipe for higher Q at high gradient
  - Robustness of process

A Grassellino *et al* 2017 *Supercond. Sci. Technol.* **30** 094004

Fermilab

Cavity performance progress at FNAL: "standard" vs "N infused" cavity surface treatment

A. Grassellino



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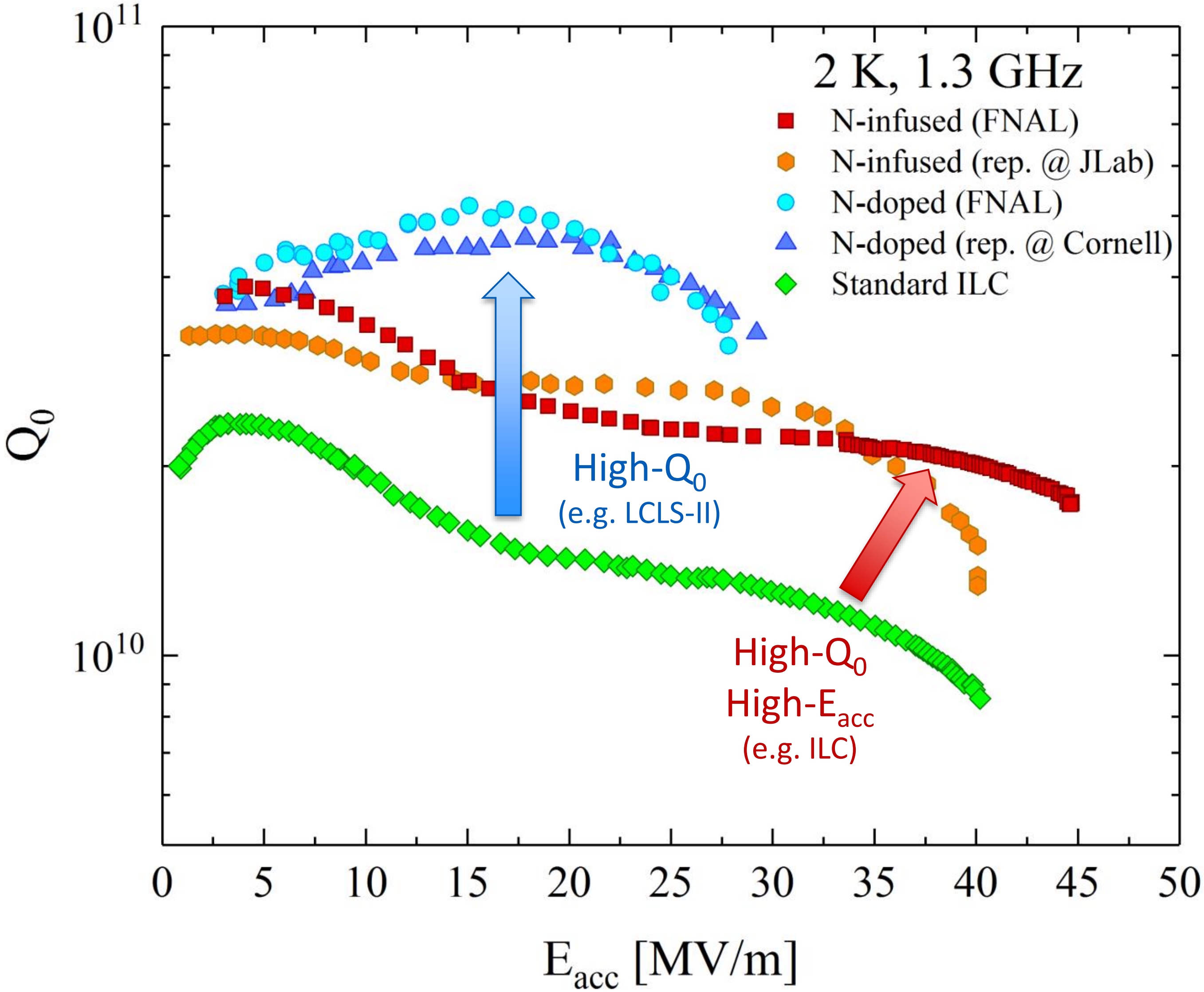
A Grassellino *et al* 2017 *Supercond. Sci. Technol.* **30** 094004

A. Grassellino

Potential for very high Q at very high gradients



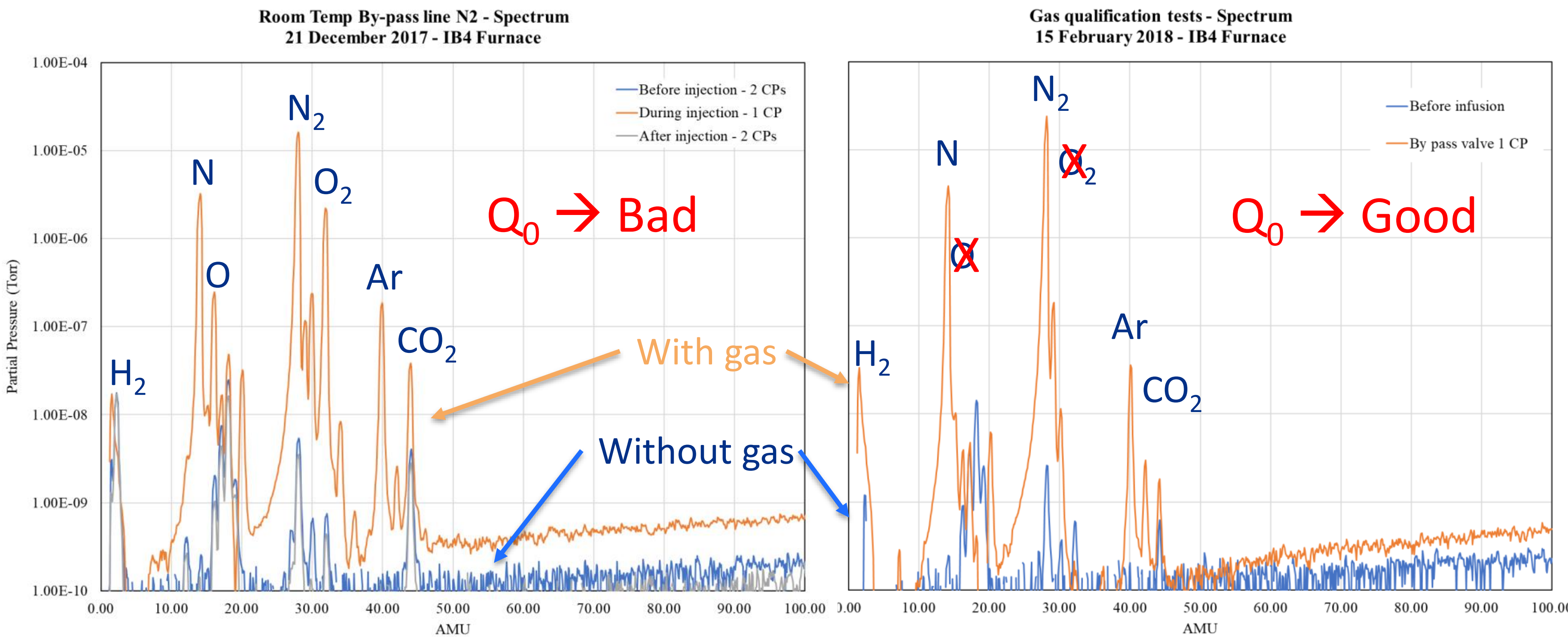
ILC Cost Reduction R&D global effort will explore doping parameter space to extend high Q at the highest gradients

Currently working on this R&D direction: FNAL, KEK, Jlab, Cornell, DESY

Experimental Progress with N infusion: degradation issue resolved

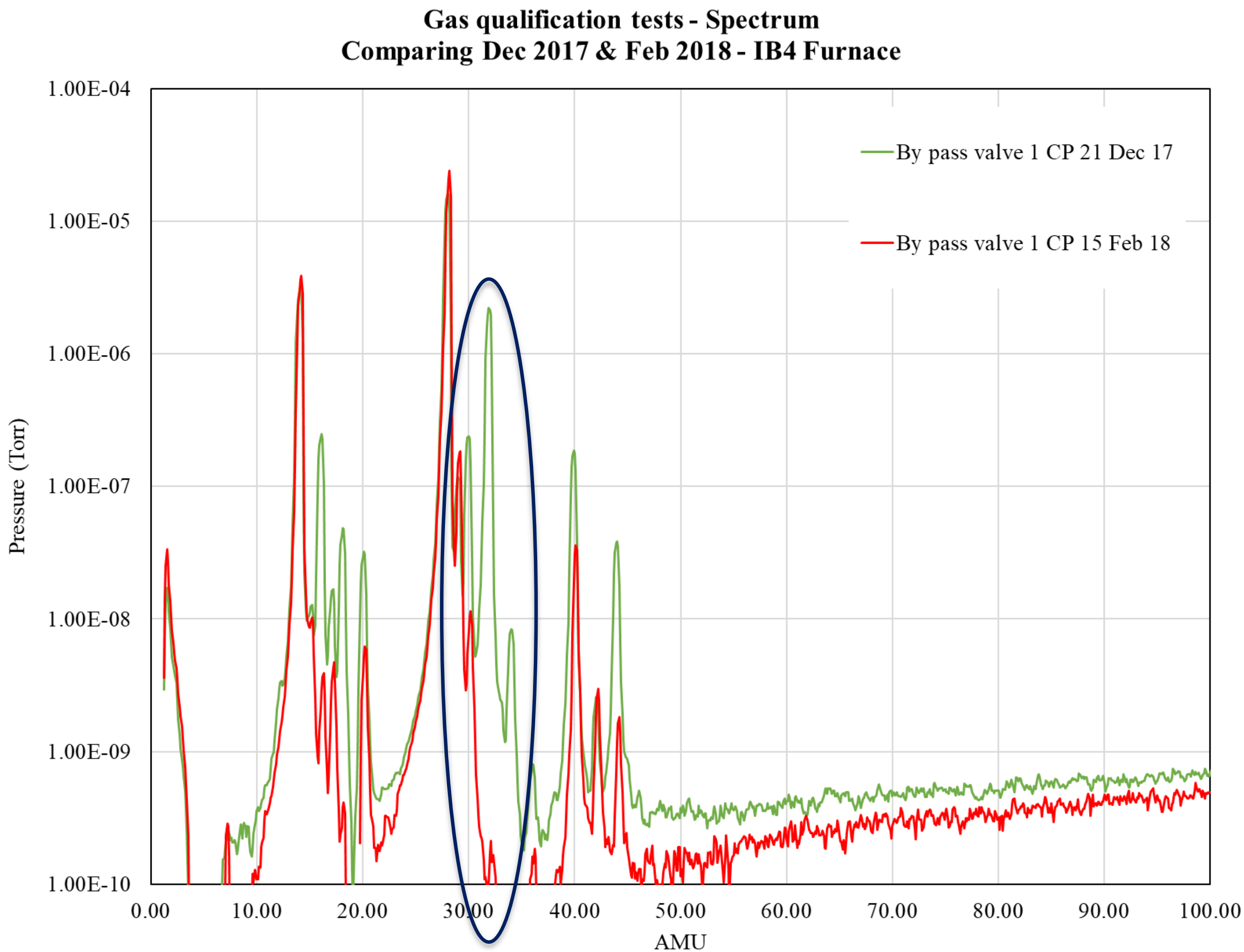
A. Grassellino

- Oct Q degradation observed
- Nov Extensive traditional leak checks performed
- Dec Innovative gas qualification method resulted in observing signs of air in infusion gas line
- Jan/Feb Further tests on the line revealed valve problematic
  - Replaced valve & Initial cavity Q improved & per expectations
- Degradation attributed to excessive O_2

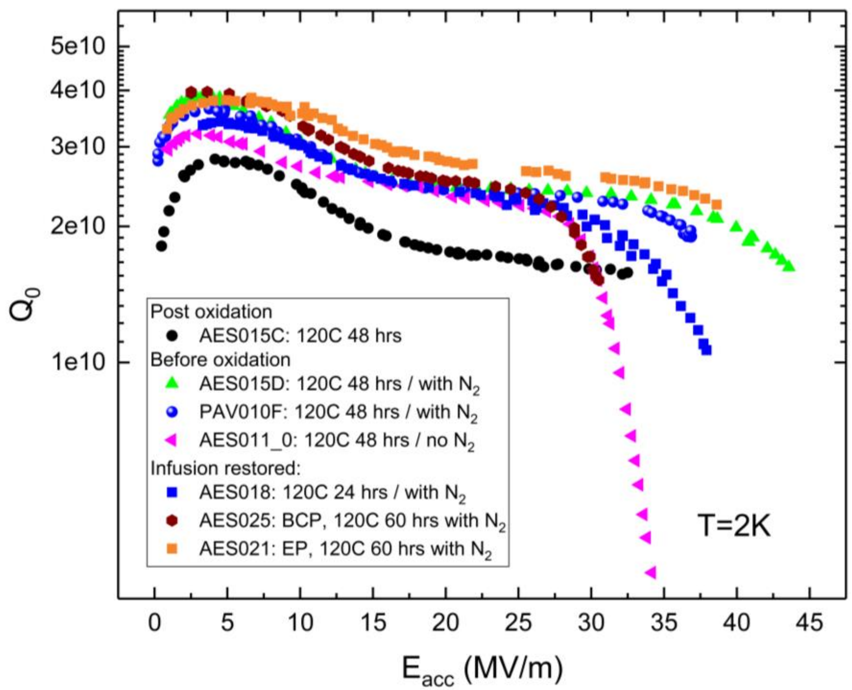


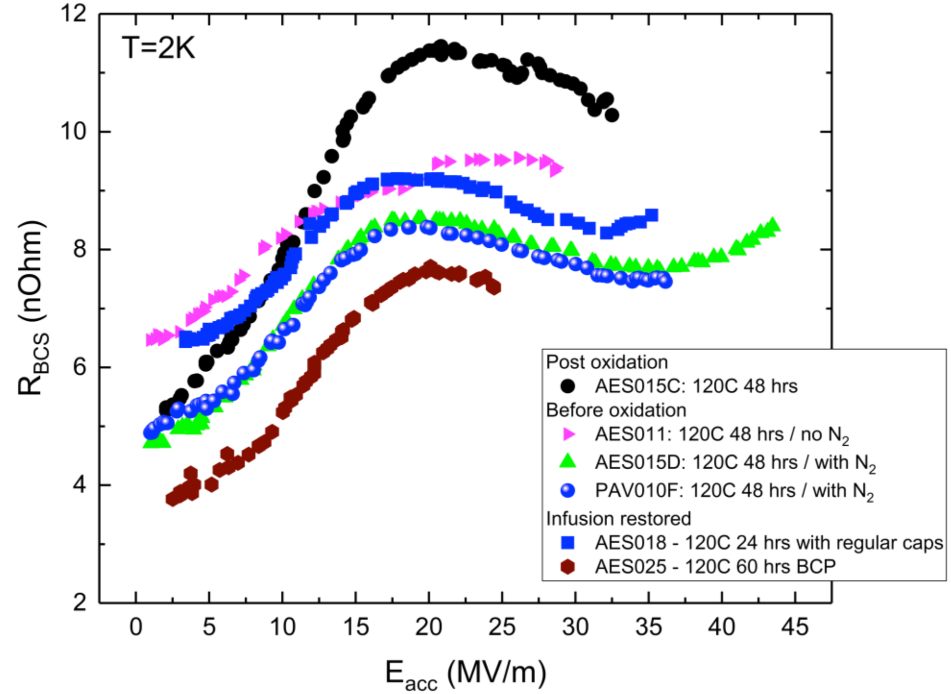
A. Grasselllino

RGA scans – before & after



Experimental progress with N infusion at FNAL

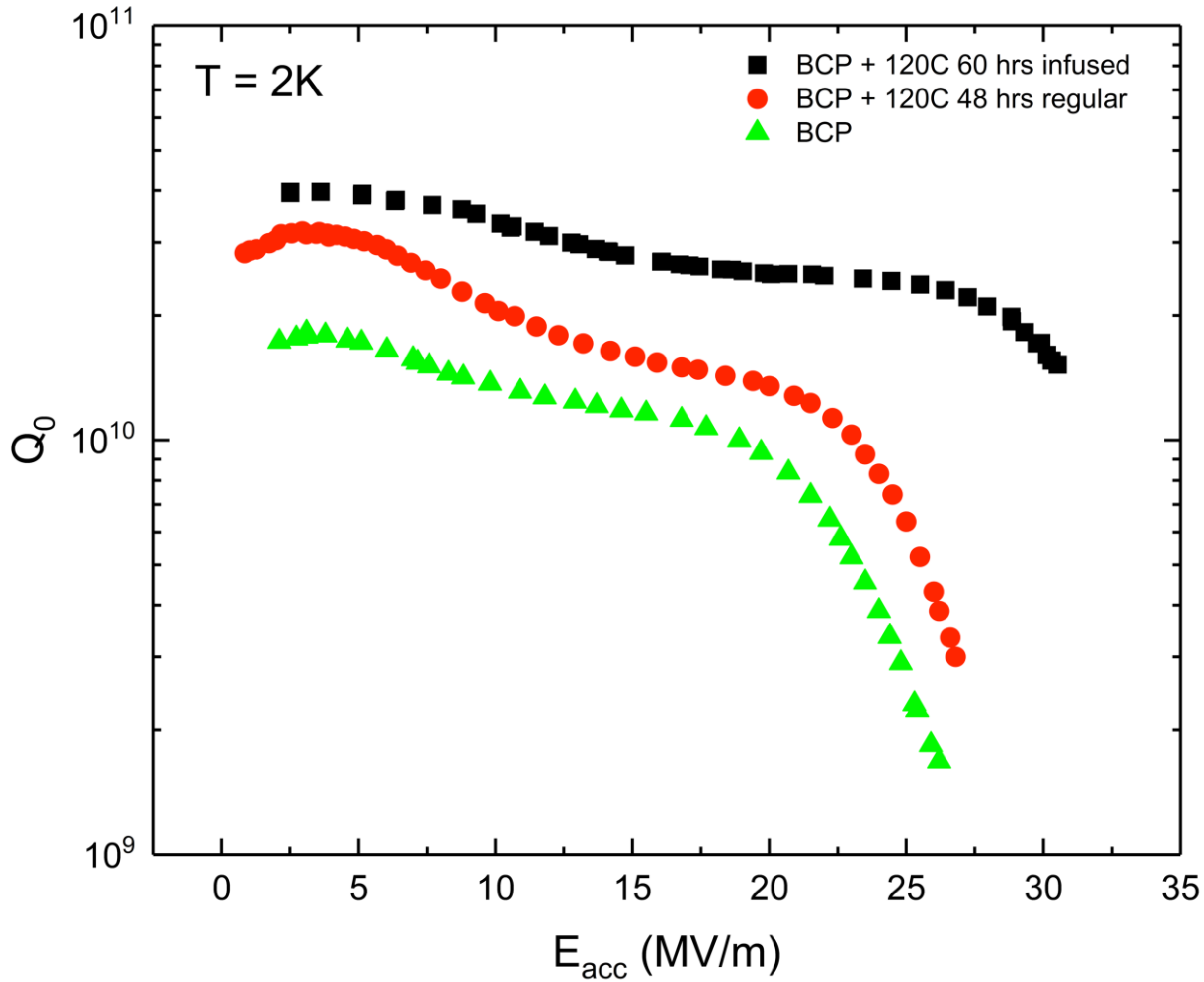




Exploring T, duration and pressure parameter space

A. Grassellino et al, to be published

N infusion on BCP surface – record Q/grad values for BCP



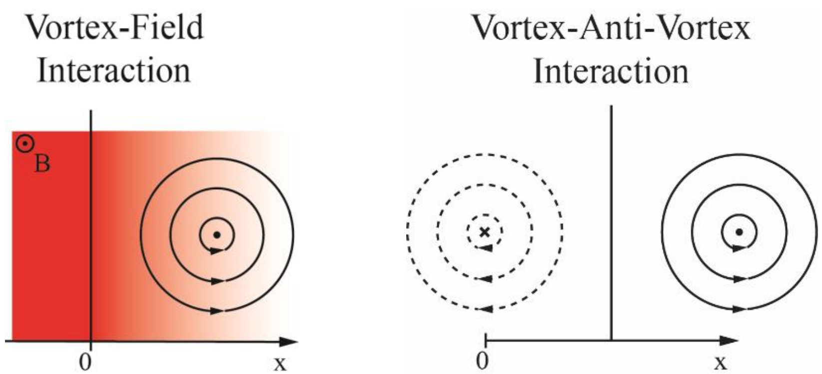
A. Grassellino et al, tbp

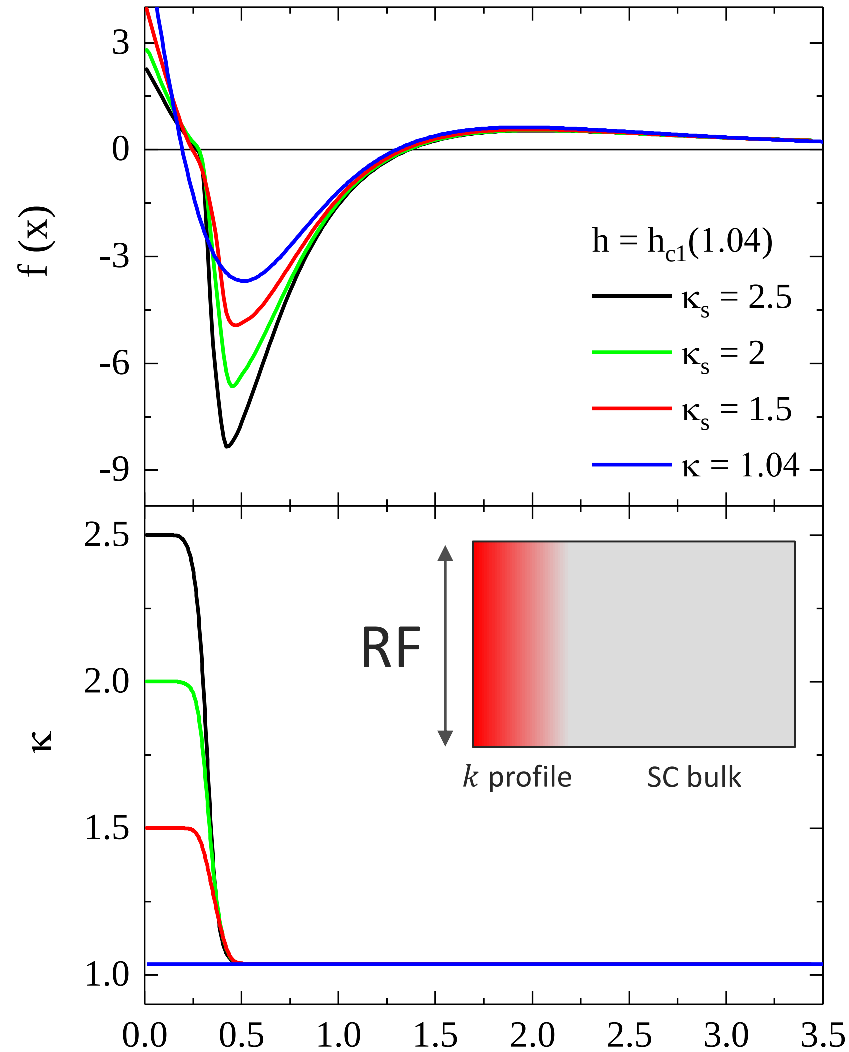
A. Grassellino

Theoretical Understanding -Impurity profile: high gradients

Numerical calculation of Bean-Livingston barrier from GL equations predicts:

- ***High κ layers*** at the surface ***delay vortex penetration***
- Higher force pushing vortices out of the superconductor





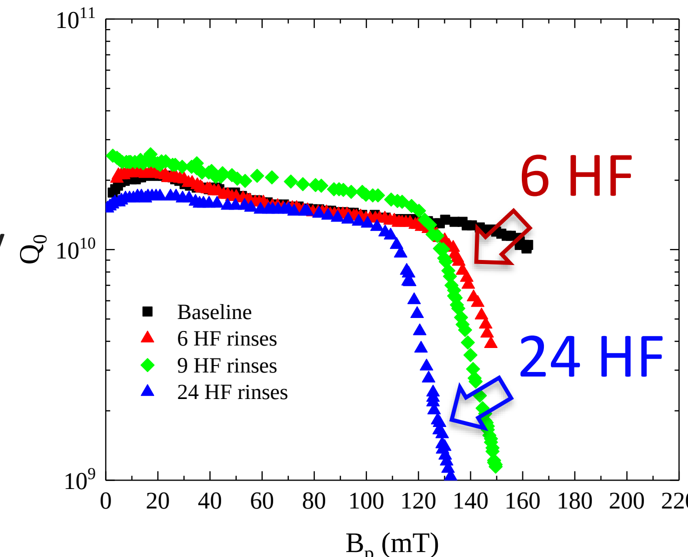
M. Checchin, FNAL, Ph.D. Thesis (2016)
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017)
W. Ngampruetikorn, NU, TTC FNAL (2017) , in submission

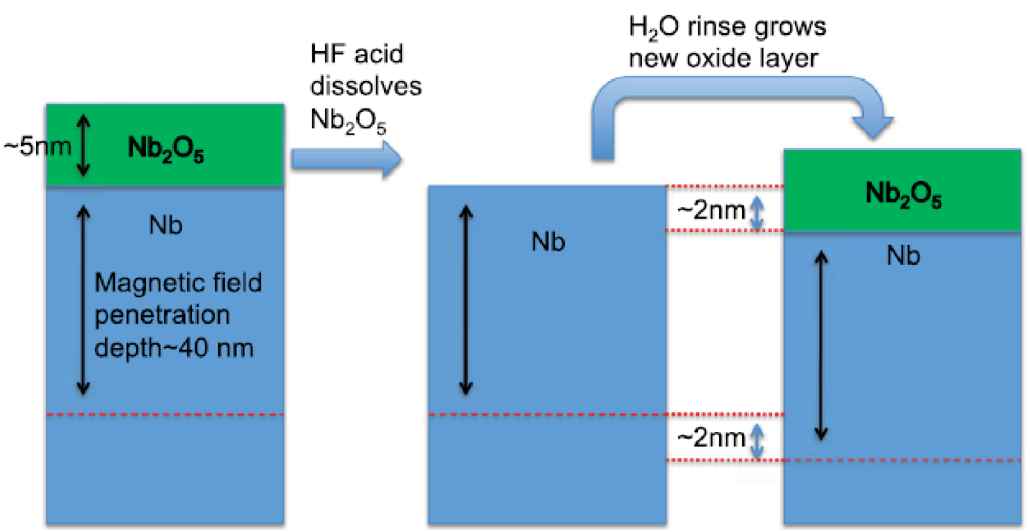
Work in partnership with Northwestern University (CAPST)

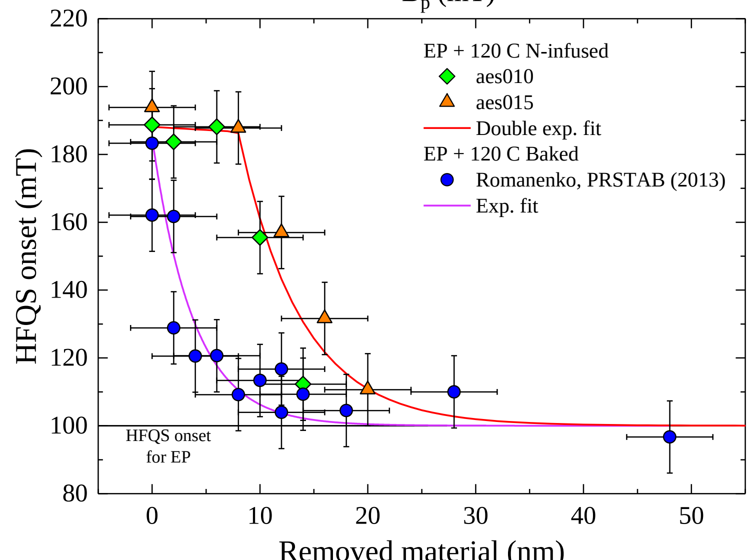
M. Checchin

N infusion progress – understanding: HF rinse experiment

- HF rinsing experiments to *depth-profile the RF performance of standard 120 C cavities*:
  - HFQS reappears already after $\sim 2\ nm$ removal
  - Total of $\sim 48\ nm$ removal needed to completely revert to HFQS behavior (onset at $100\ mT$)
- The same technique was adopted to study 120 C N-infused cavities





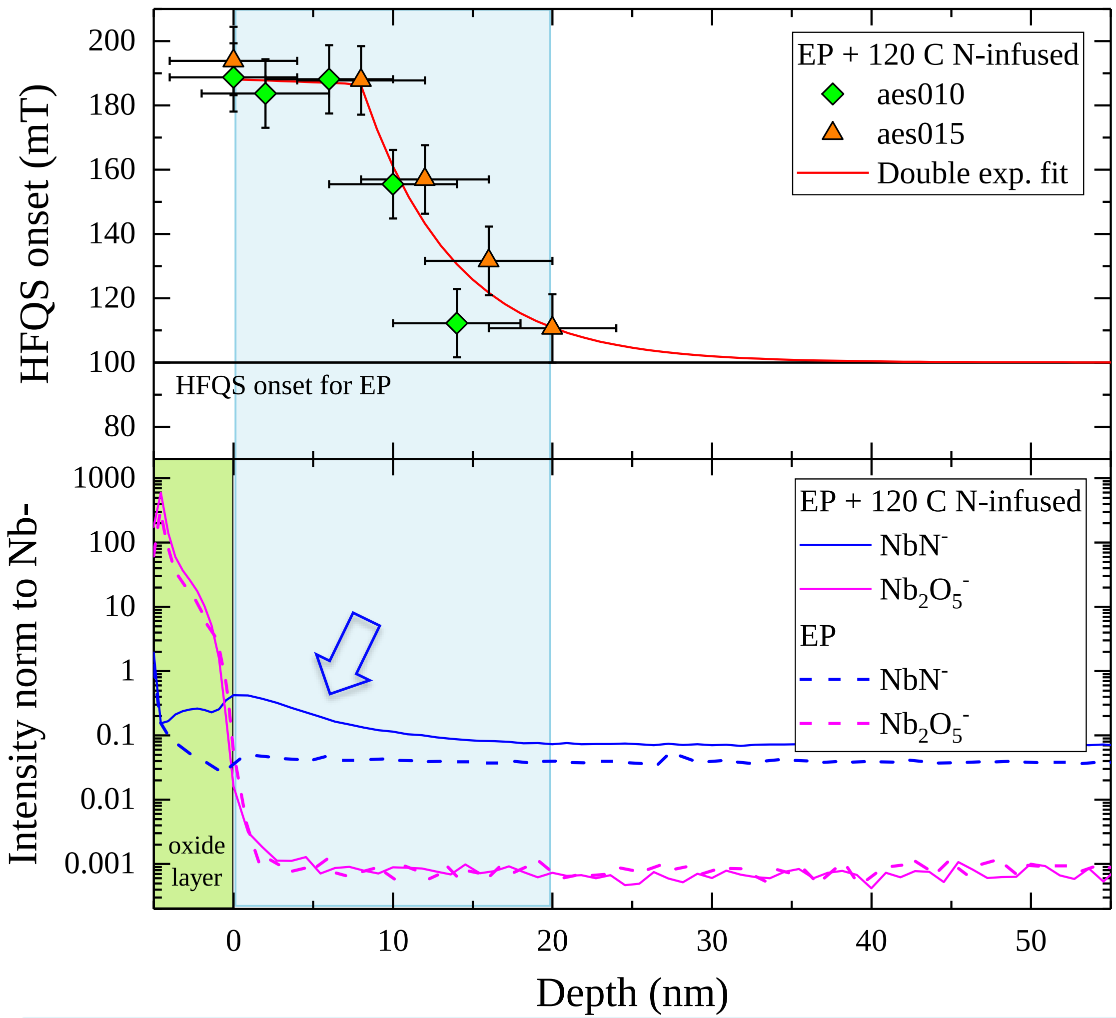


A. Romanenko et al., Phys. Rev. ST – Accel. Beams 16, 012001 (2013)
M Checchin et al, in preparation

M. Checchin

RF and TOF-SIMS data comparison

N-infusion performance dictated by the nitrogen profile



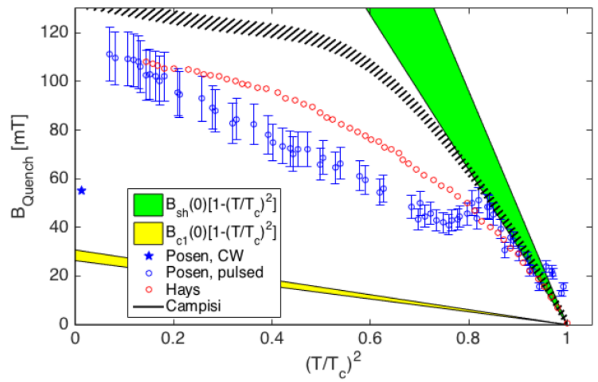
- Onset of HFQS in 120 C N-infused cavities in ***agreement with the diffusion profile of nitrogen***

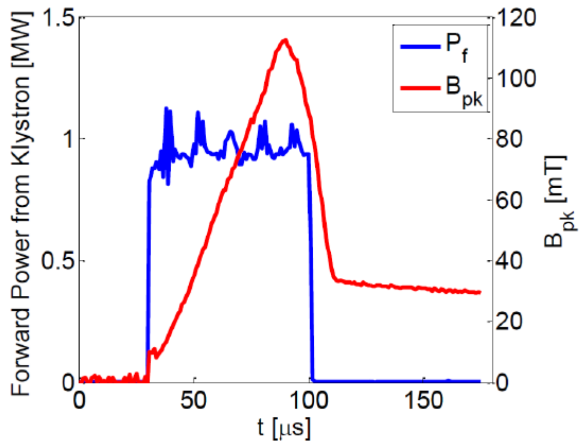
- Oxygen and carbon are changing in a scale length not relevant for HFQS

High Power Pulsed RF

New VTS Capability at FNAL: High Power Pulsed RF

- RF station under development at FNAL
- **~3 MW**, up to 100s of μs pulses at ~1 Hz rep rate to vertical test stand
- Quickly raise fields in cavity (tens of μs)
  - Push through and reduce **field emission**
  - Outpace many **thermal effects**, reach closer to fundamental limit of material
- Benefits to many programs:
  - Field emission – study HPP for use in CM
  - Nb_3Sn, Nb/Cu, new materials – bypass small defects to study fundamental limits
  - N-infusion – investigate possible increase of superheating field





S. Posen, N. Valles, and M. Liepe, ***Phys. Rev. Lett.*** 115, 047001 (2015)

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Klystron Timeline

Preparation — Oct – Nov

Install trench in vertical test stand	Ship RF Station from DESY	Utilities: electrical, water

Installation — Dec – Jan

Bring RF station components to site	Evaluate damaged/missing items	Design waveguide run

RF Station Start Up and Top Plate Fabrication — Feb – Aug

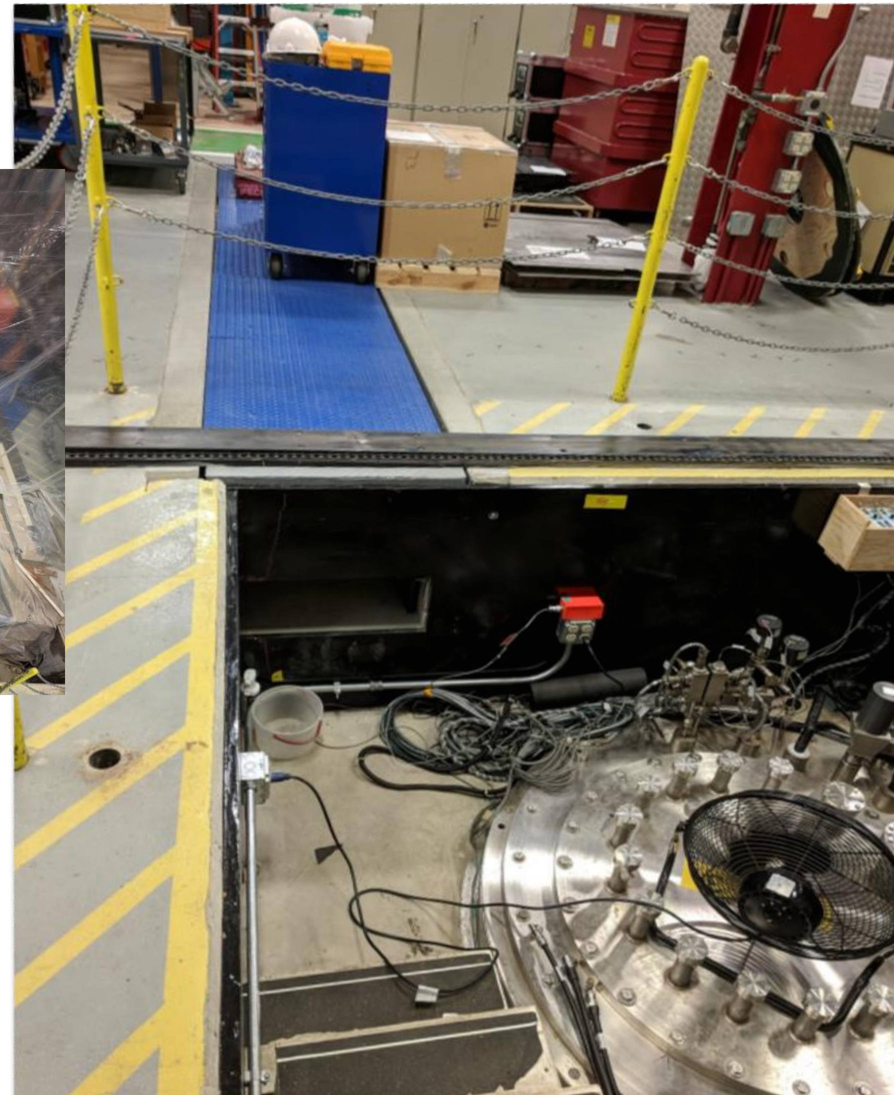
Set up RF station and commission with dummy load	Fabricate new top plate with waveguide/doorknob	Interlocks design and setup

Prepare for Operational Readiness — Aug – Sep

ORC documentation and review	Training of VTS personnel	Preliminary tests into VTS dewar

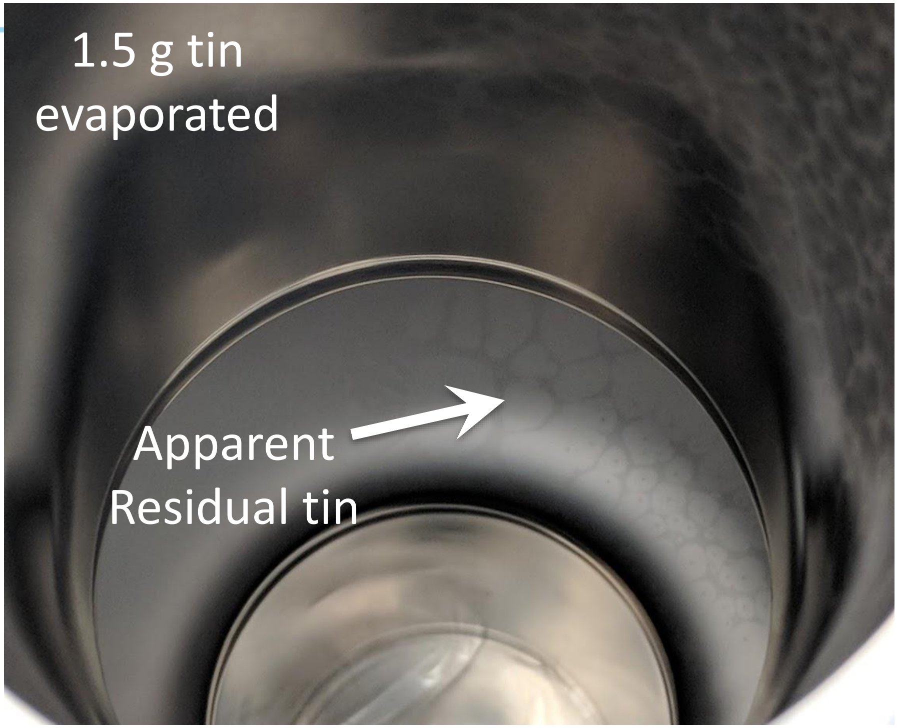
RF Station Transferred from DESY to FNAL-VTS

Many thanks to Wolf Dietrich Muller, Thomas Froelich, Stephane Choroba!



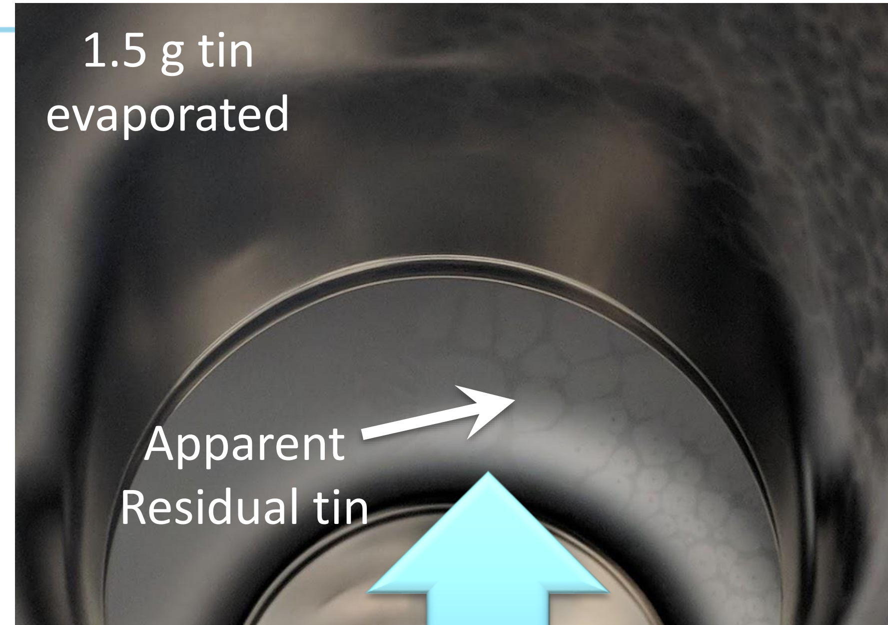
Long Term R&D: Nb_3Sn and Films

Recipe Development

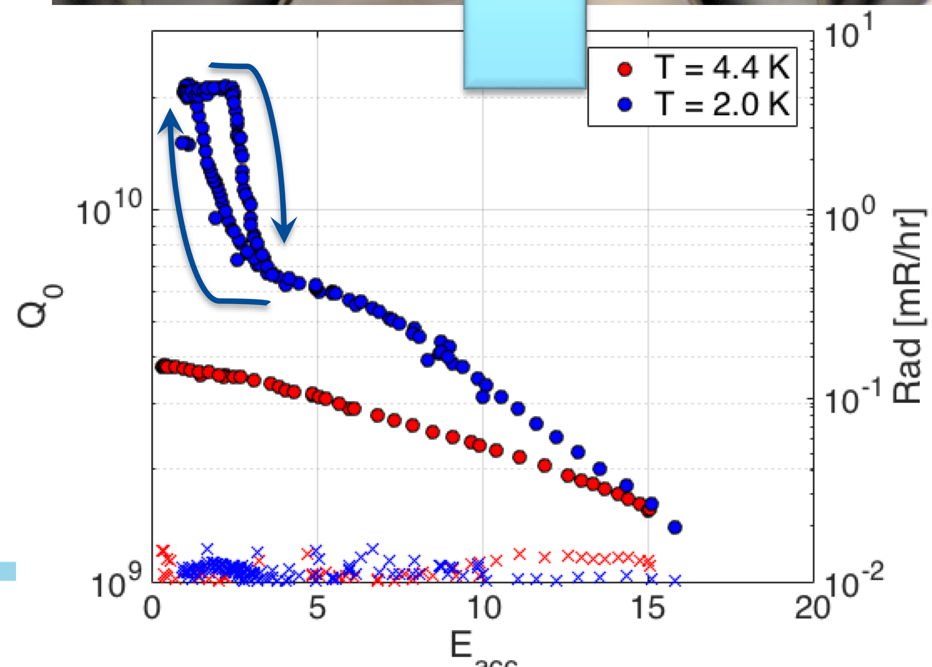


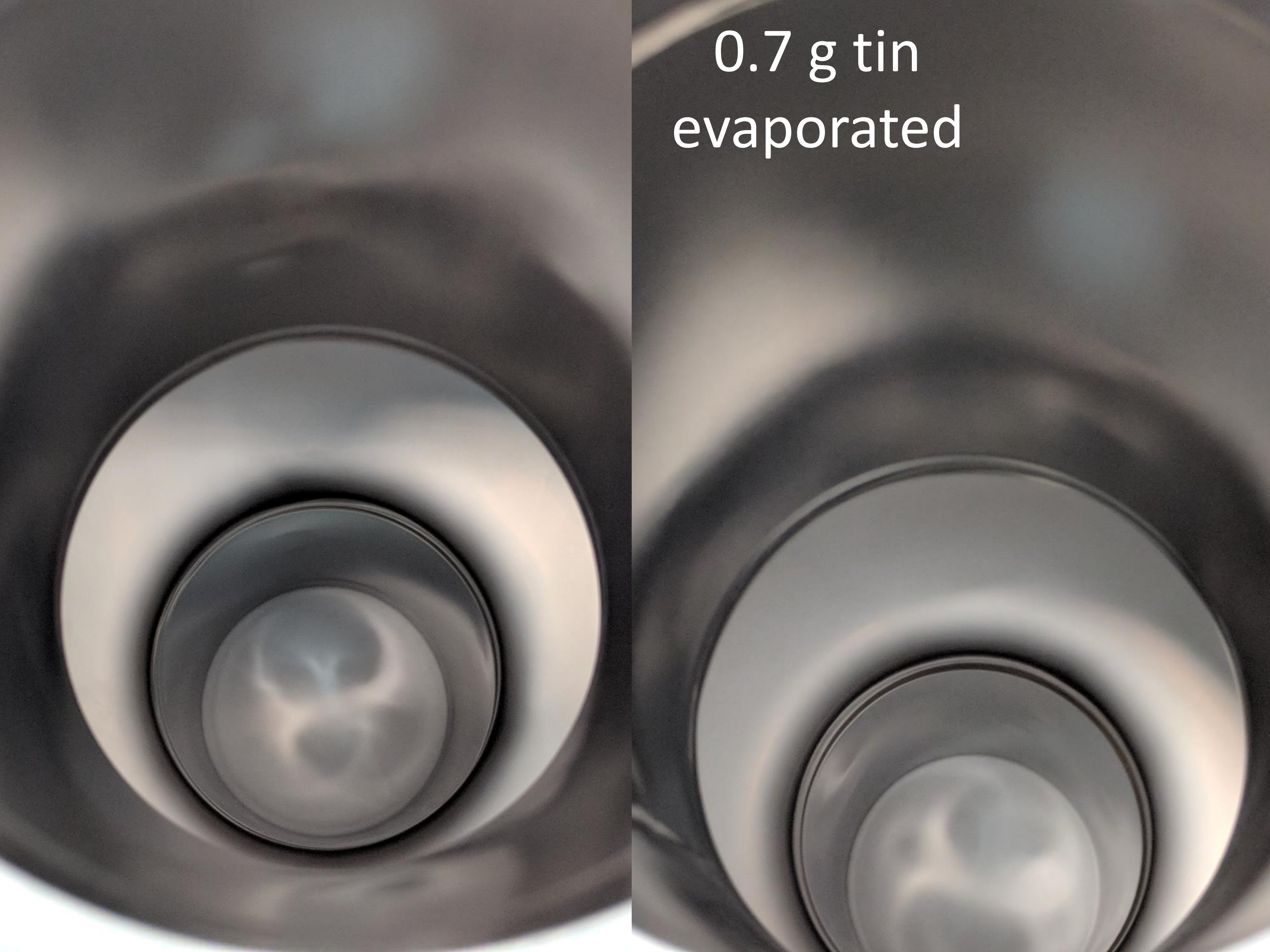
- Appearance appears to correlate with performance
- Several parameters found to be important:
  - Crucible diameter
  - Heater power
  - Coating time
  - Annealing time

Recipe Development



- For residual tin:
  - $T_c \sim 3.7$ K
  - $H_c \sim 0.03$ T

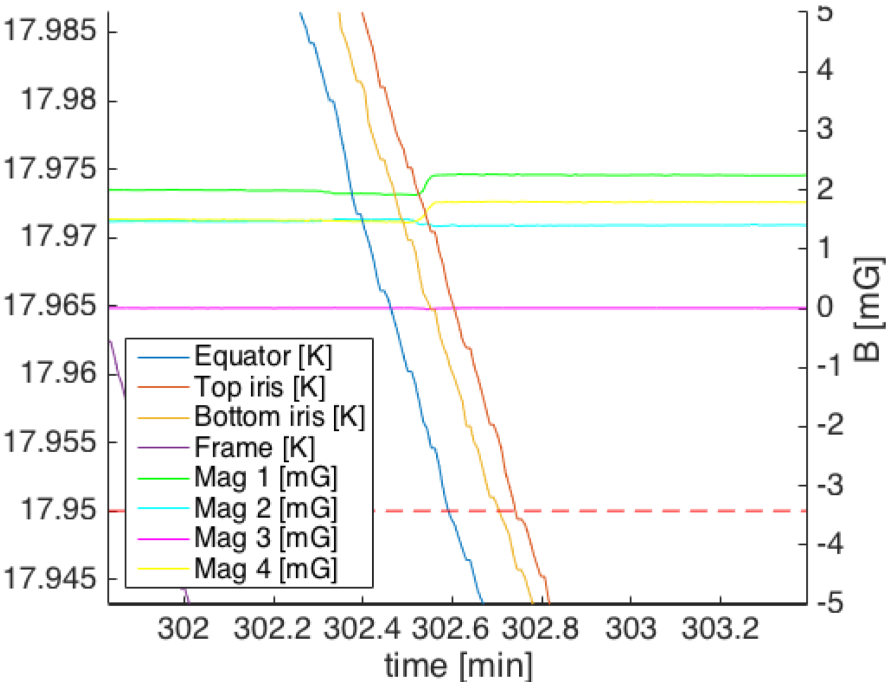


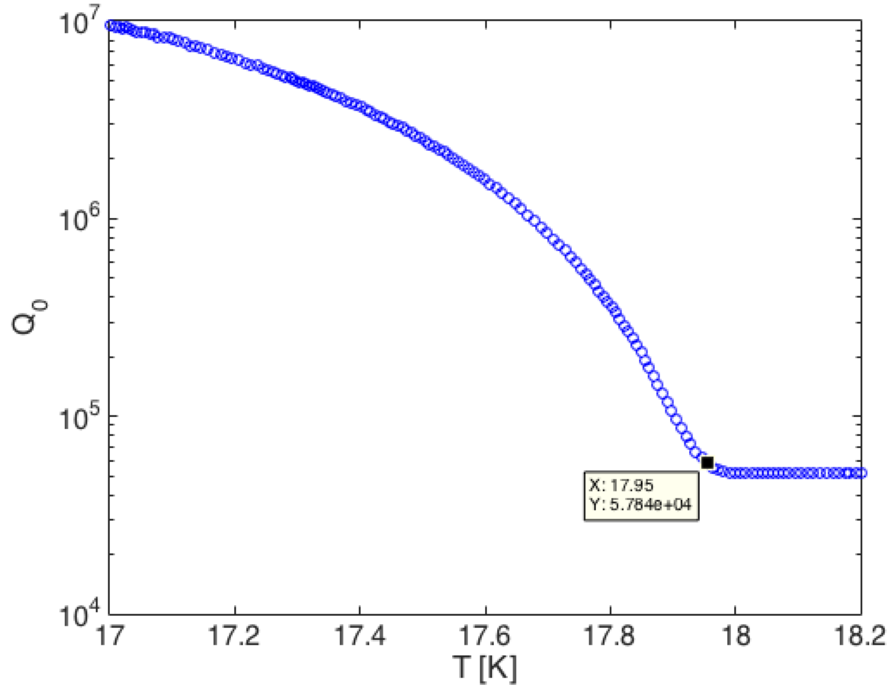

0.7 g tin
evaporated

Recipe Development

- To date, best appearance and performance at Fermilab achieved with:
  - Smallest diameter crucible tested
  - Heater at maximum power (crucible ~1200 C)
  - Large grain cavity anodized prior to coating (as advocated by Siemens in the 1970s and recently revived by Cornell)

Cooldown

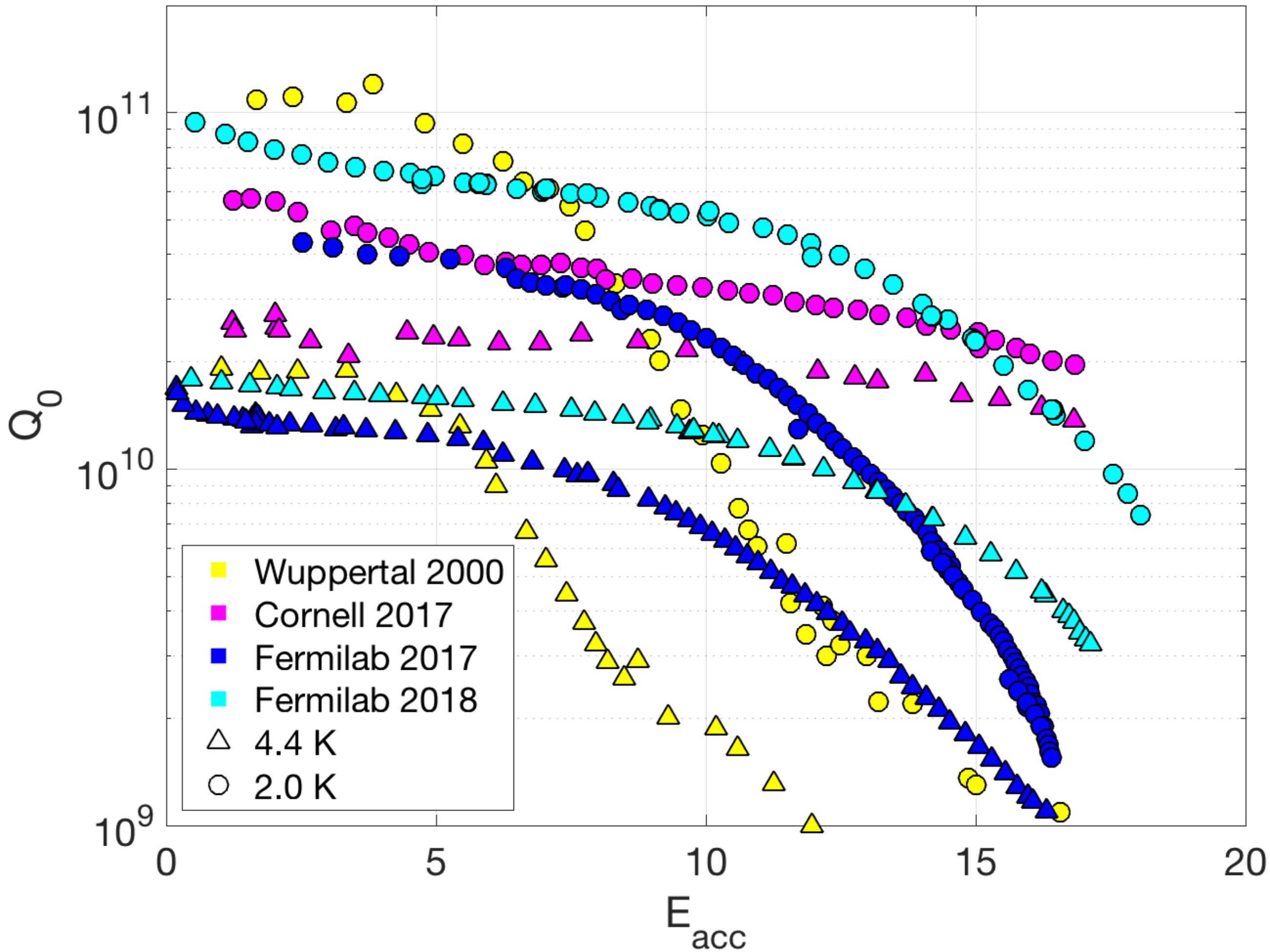




Fermilab

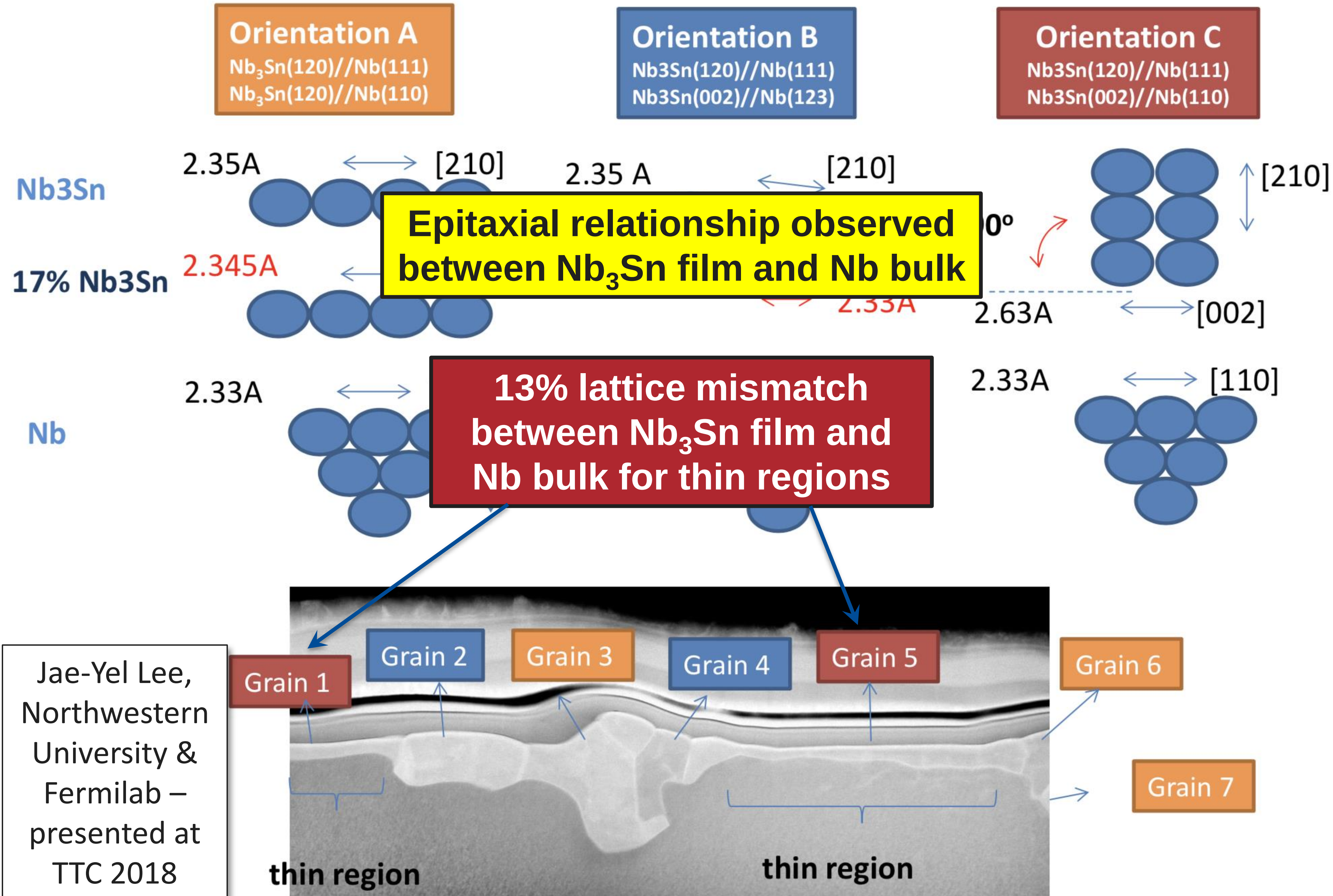
Q vs E

- Substantial improvement in our second year of coating
- Still some Q-slope, not yet flat Q_0 like Cornell
- Very high Q_0 at 2.0 K, similar to Wuppertal



Fermilab

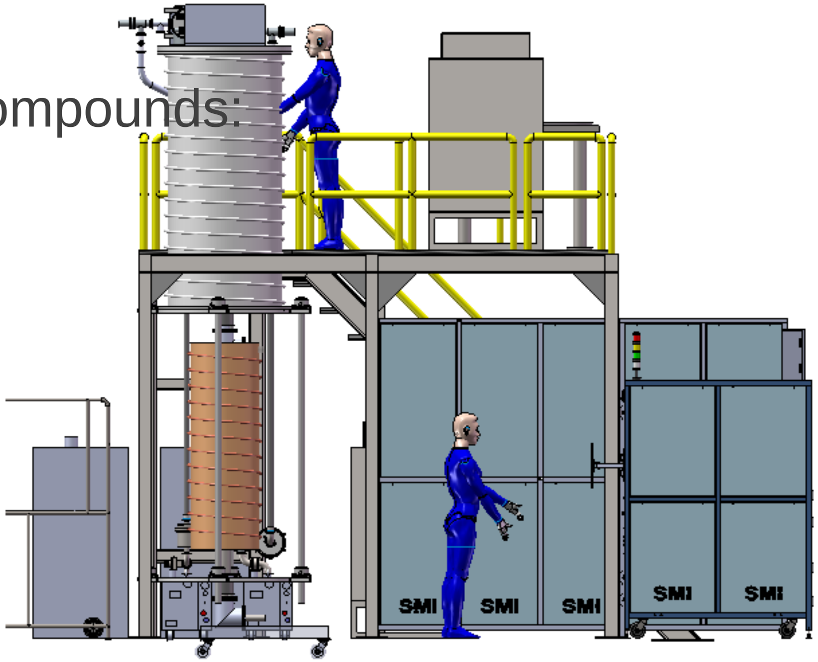
Orientation relationship vs Strains, Sn-deficient regions, GBs



Jae-Yel Lee, Northwestern University & Fermilab – presented at TTC 2018

New Furnace procured for clean/robust N infusion, and CVD/ALD capability for bi-layer structures

- CLEAN - Induction furnace with Doping capabilities:
  - N, Cl, C, Sn, Al, Ge, Ga, B, Si, …
- Deposition capabilities:
  - Large variety of superconducting compounds:
    - A15 (Nb_3Sn, Nb_3Ge, Nb_3Al, …)
    - Nitrides (MoN, NbN, $NbTiN$, …)
  - Superconducting elements:
    - Nb, Al, Pb, V, …
  - Insulators:
    - Oxides (Al_2O_3, Ce_2O_3, SiO_2, …)
    - Nitrides (AlN, SiN, …)



Jul 2017	Jan 2018	Jul 2018	Oct 2018
System purchased	Design optimization	Final design	Commissioning at FNAL

Summary

- Fermilab excited for potential to participate in ILC in Japan – strongly hoping for a positive decision from Japanese government
- ILC cost reduction activities proceeding at full speed at Fermilab – in collaboration with international partners – including JLab, Cornell, KEK, DESY
  1. Minimizing trapped magnetic flux
  2. Nitrogen infusion
  3. High power pulsed processing
  4. (long term): Nb_3Sn, layered structures