Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

State-of-the-Art Superconducting RF Technology for Accelerators

Sam Posen

Fermilab Colloquium

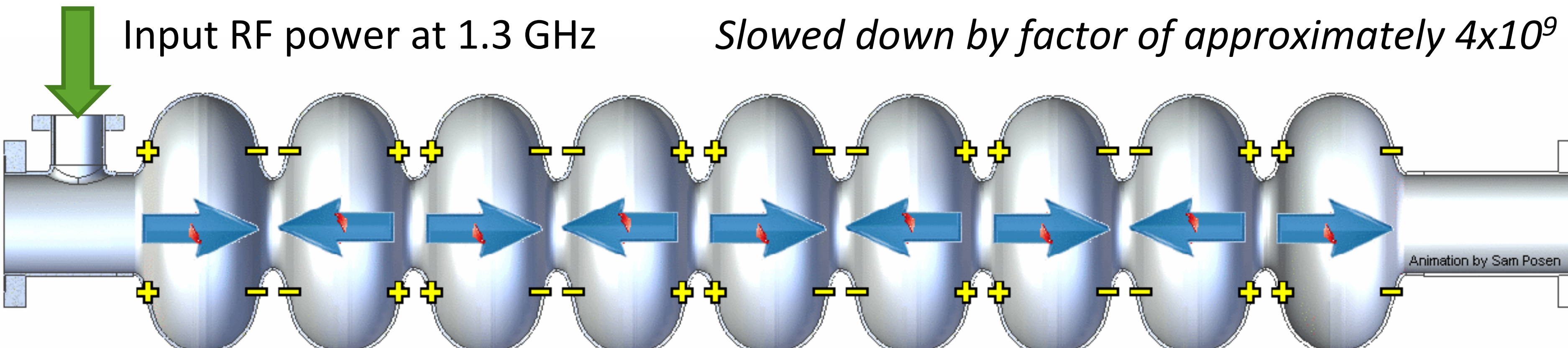
15 February 2017

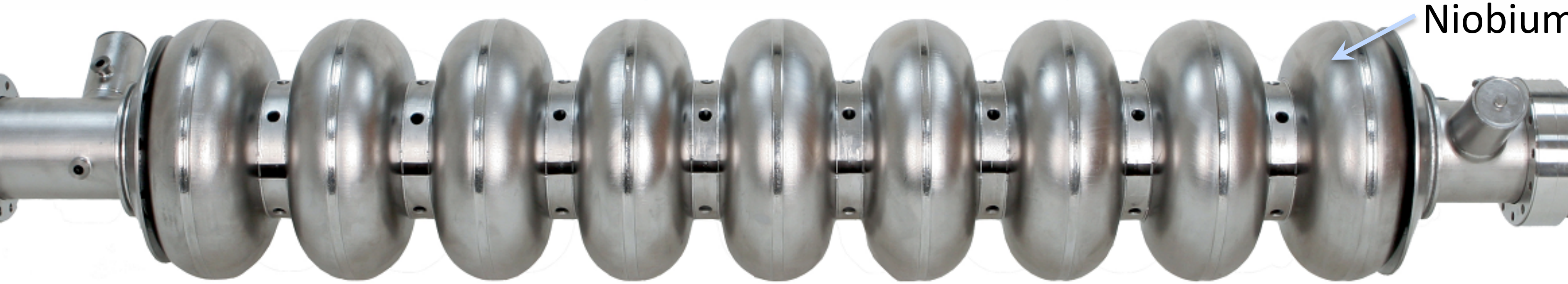
Particle Acceleration via SRF Cavities

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Over billions of cycles, large electric field generated
- Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

Slowed down by factor of approximately $4x10^9$





~1 m

Images from linearcollider.org, WIkipedia

Particle Acceleration via SRF Cavities

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- Over billions of cycles, large electric field generated
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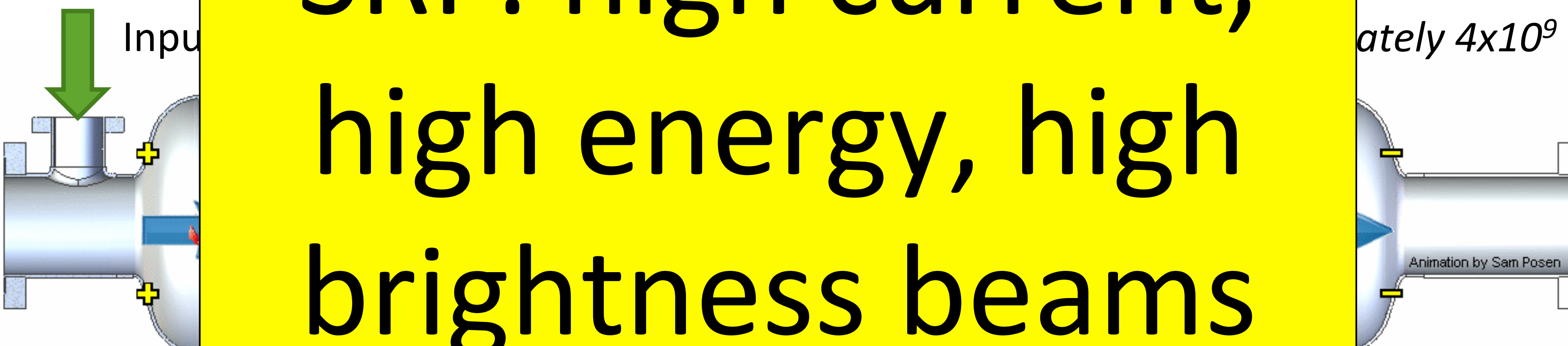
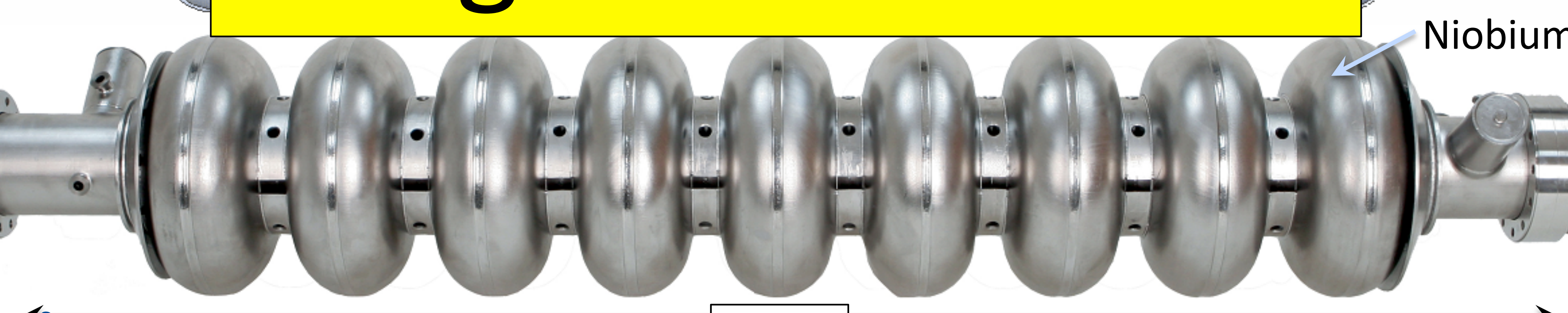


SRF: high current, high energy, high brightness beams



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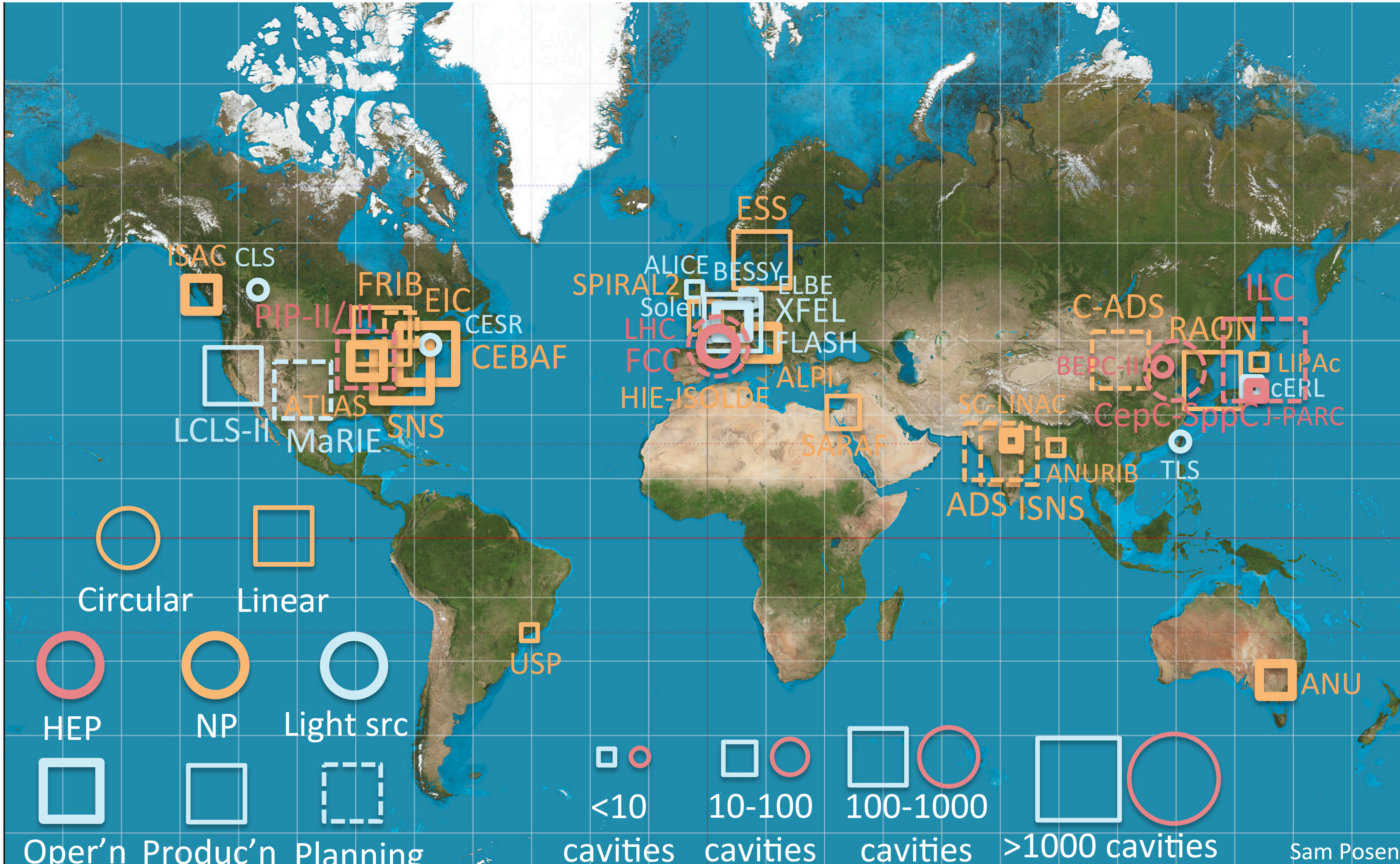
SRF Accelerators Around the World



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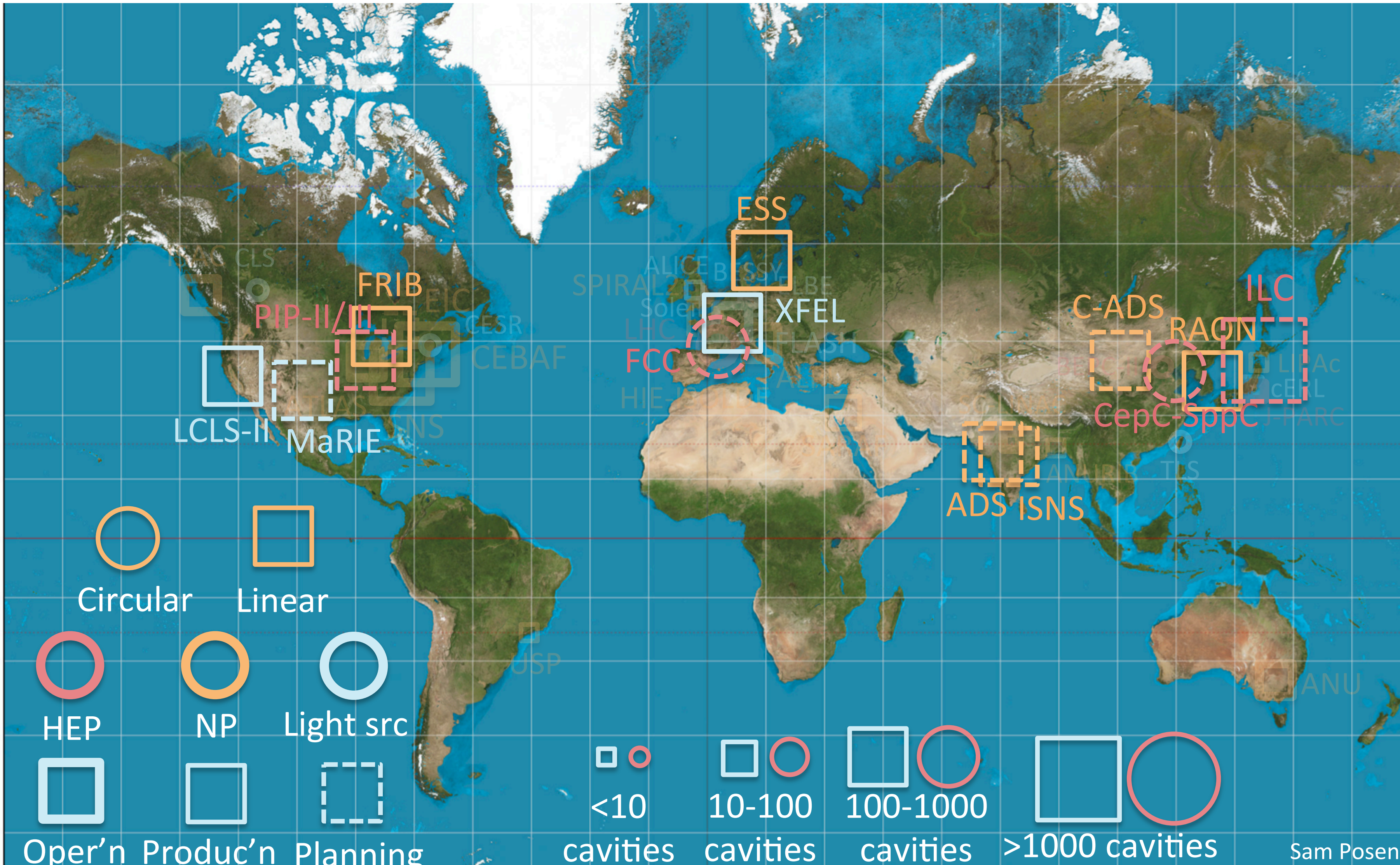
Map from Wikipedia. Non-exhaustive facility list.

SRF Accelerators Around the World



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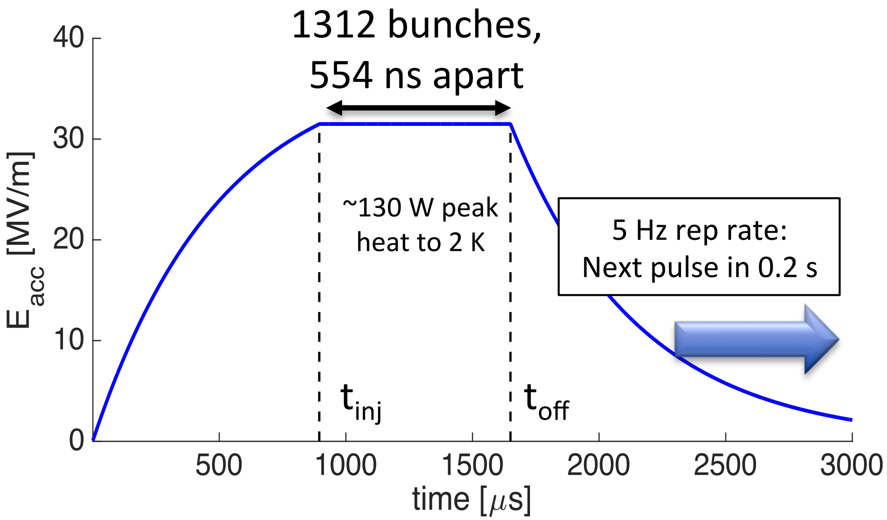
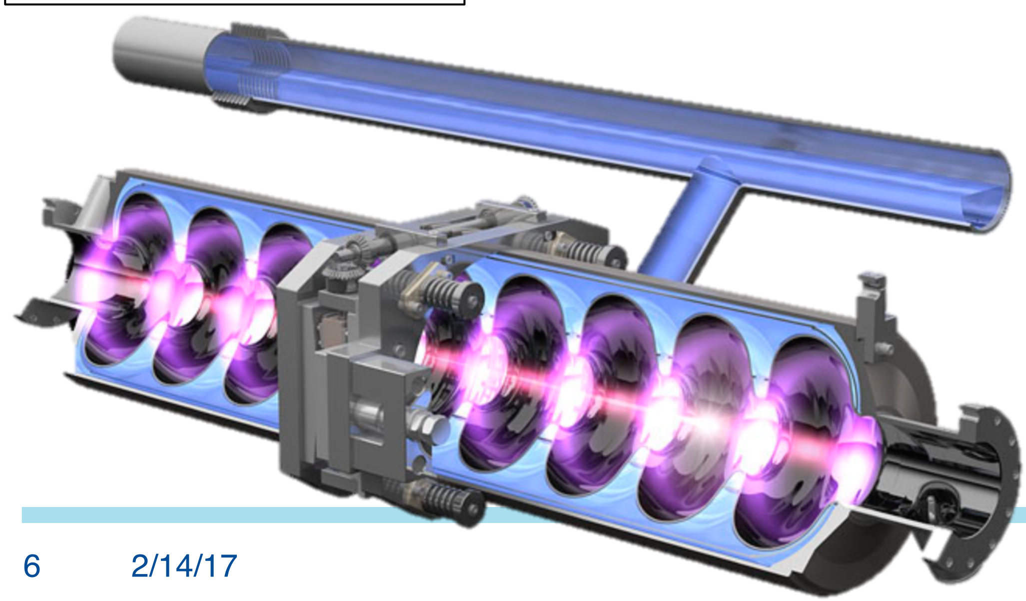
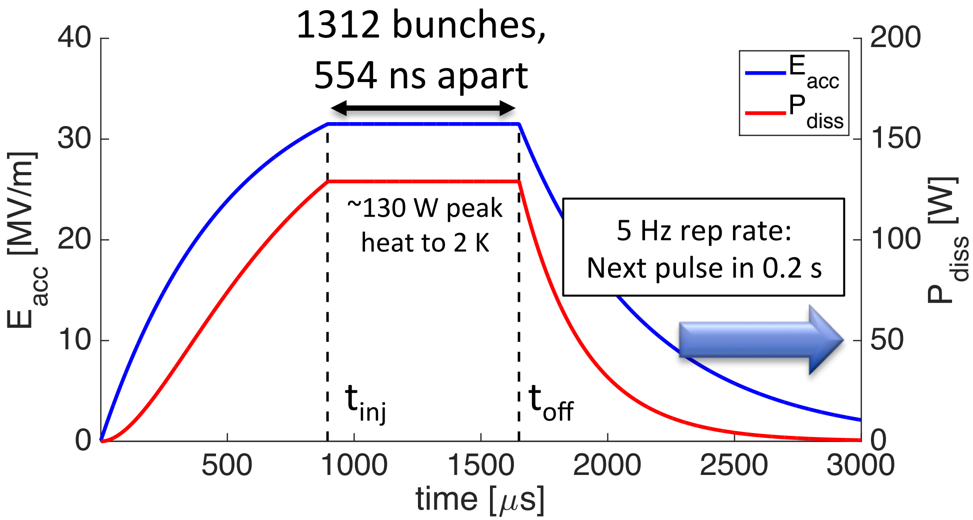
Duty Factor



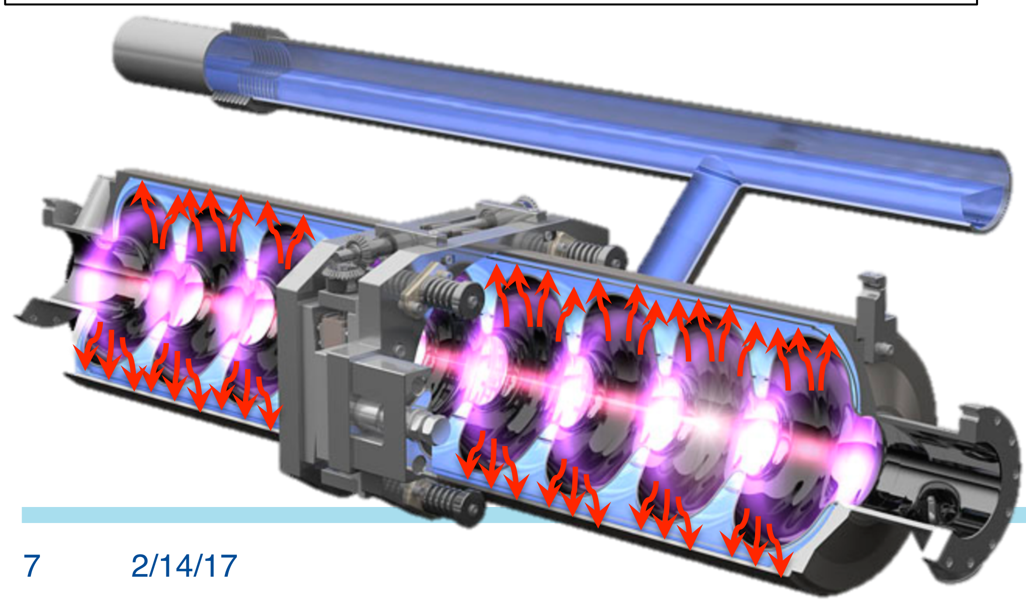
ILC (pulsed, <1% DF)
LCLS-II (CW, 100%DF)



Duty Factor and Cryogenic Costs



ILC (pulsed, <1% DF) ~0.5 W average per cavity
LCLS-II (CW, 100%DF) ~10 W average per cavity



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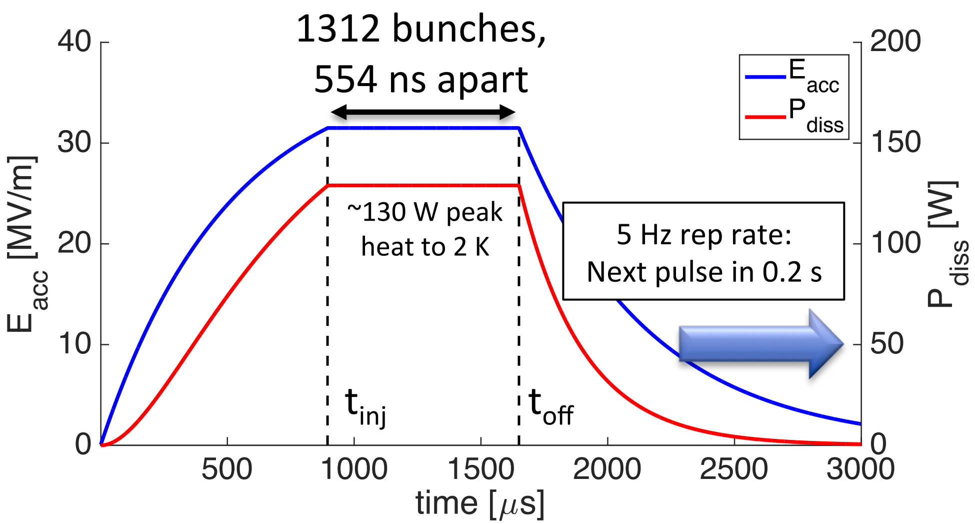
Cavity image: Rey Hori. Cryoplant image: CERN.

Duty Factor and Cryogenic Costs



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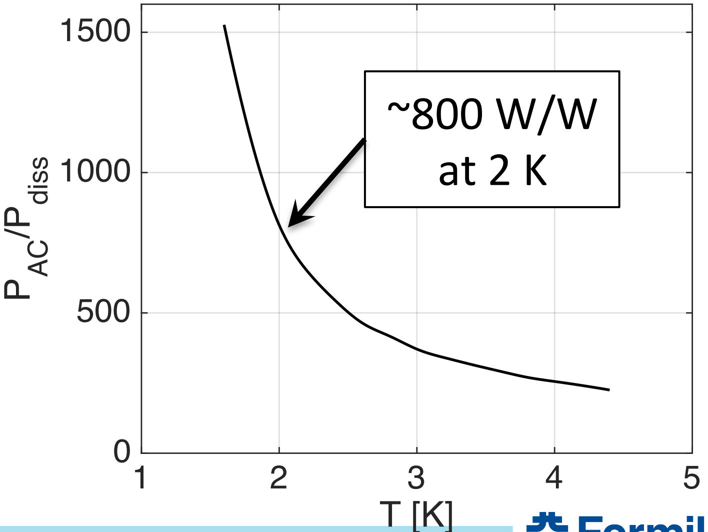
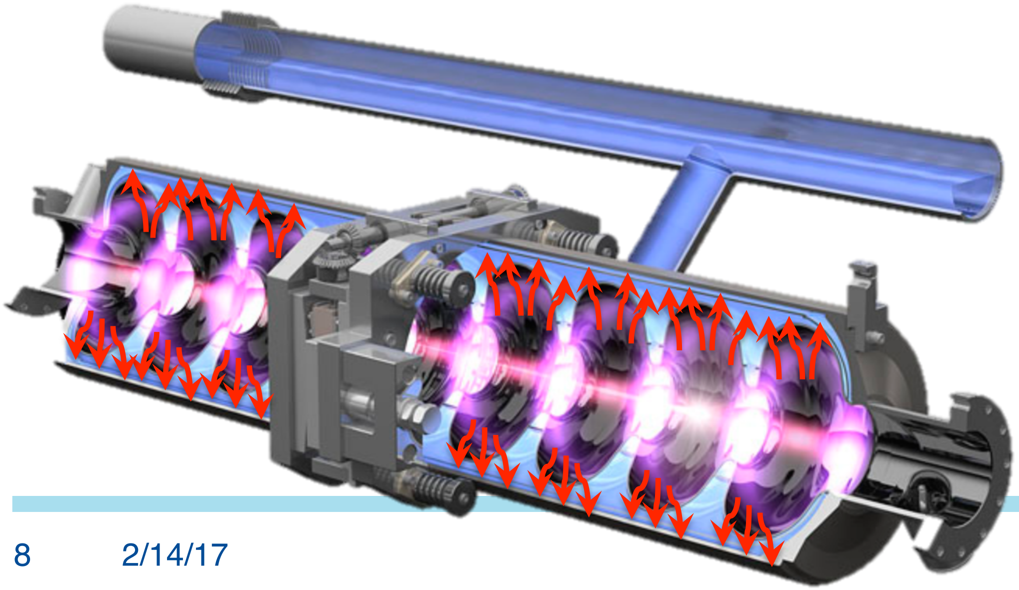
LCLS-II (CW, 100%DF) ~10 W average per cavity

$P_{diss} \sim E_{acc}/Q_0$ (for fixed E_{max})





Cavity image: Rey Hori. Cryoplant image: CERN.

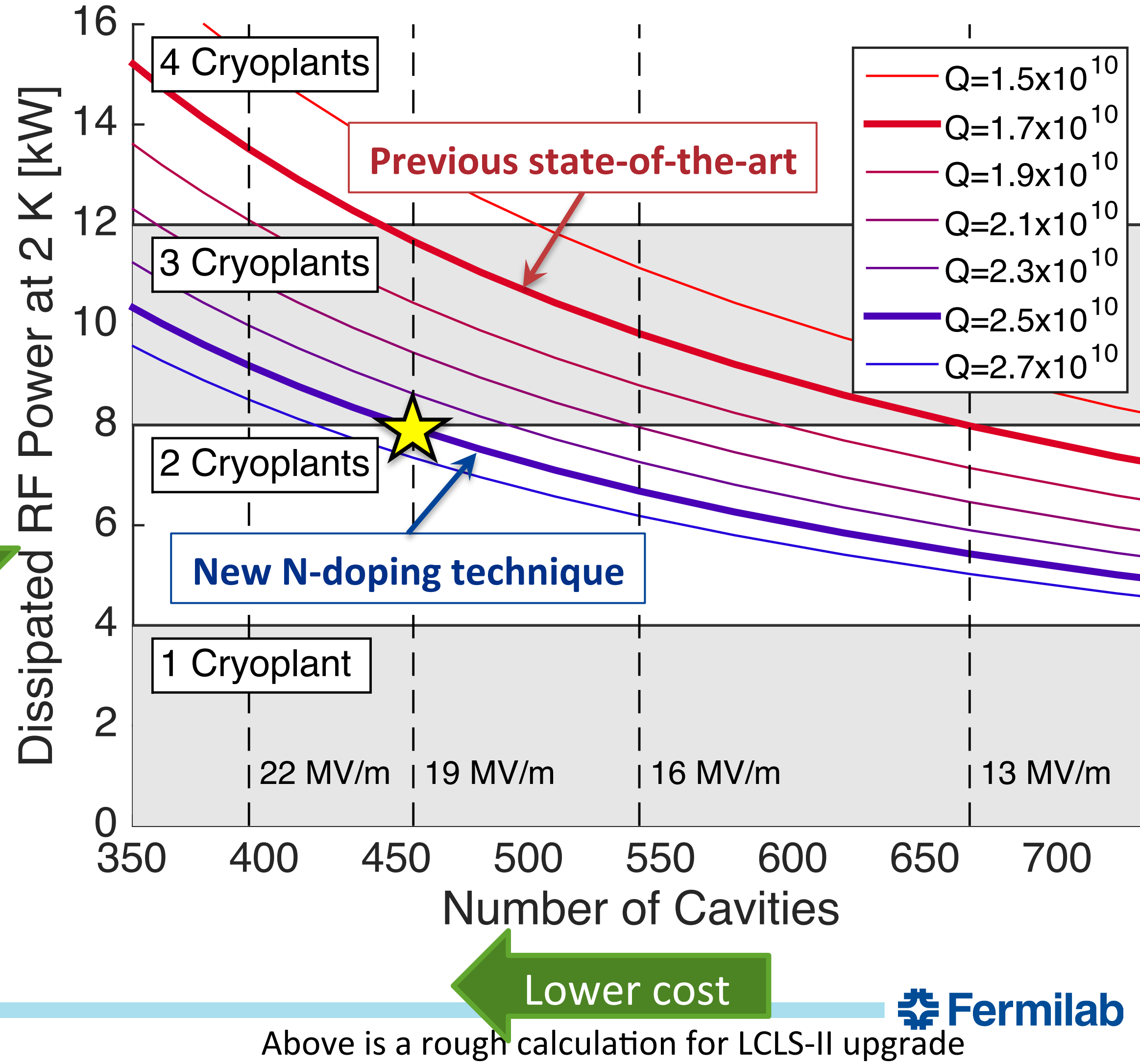
Q_0 -> Cryogenic Infrastructure, Operating Cost

$$P_{diss} \sim E_{acc}/Q_0$$

(for fixed E_{max})

Lower cost

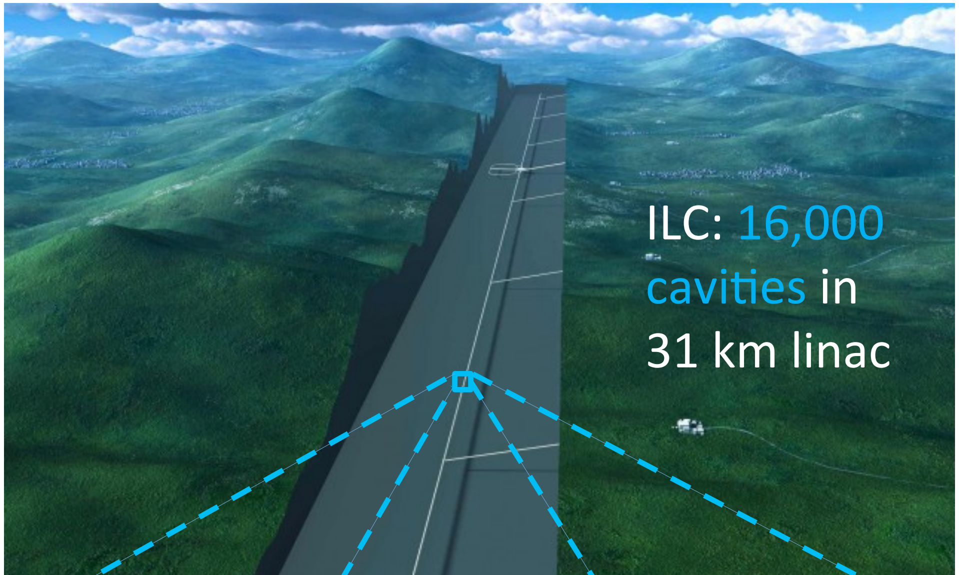
8 GeV CW SRF Linac



Above is a rough calculation for LCLS-II upgrade
(from me, not to be considered official numbers from project)

Gradient -> Length for Linear Accelerator

Q_0 also important!



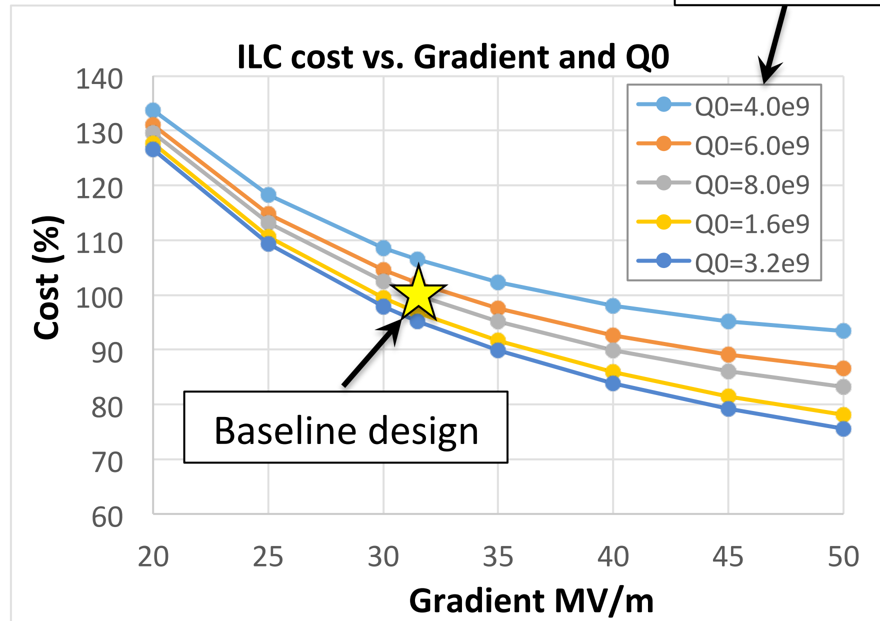


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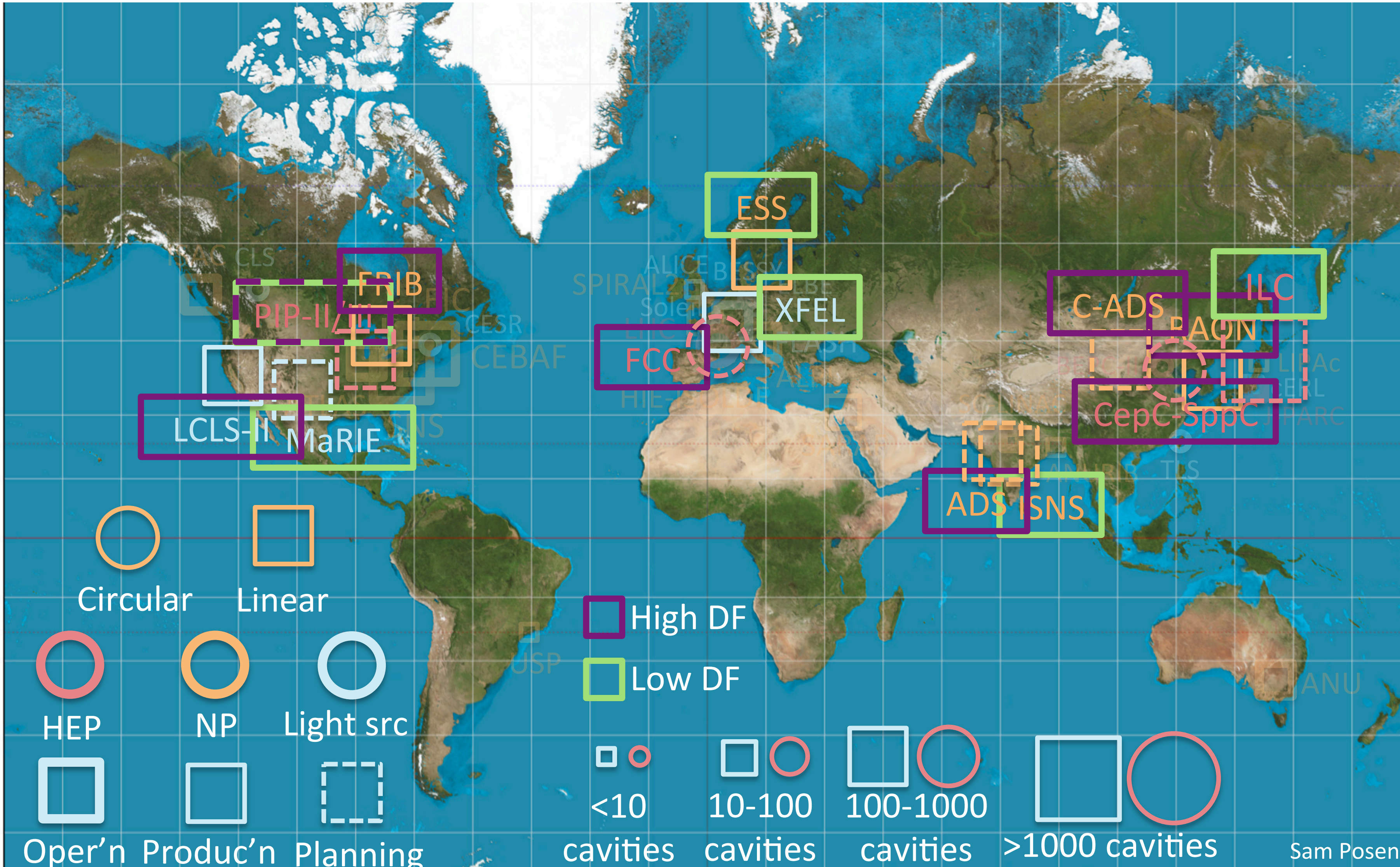
Image from linearcollider.org. Tunnelflug video by European XFEL. Cost analysis by N. Solyak

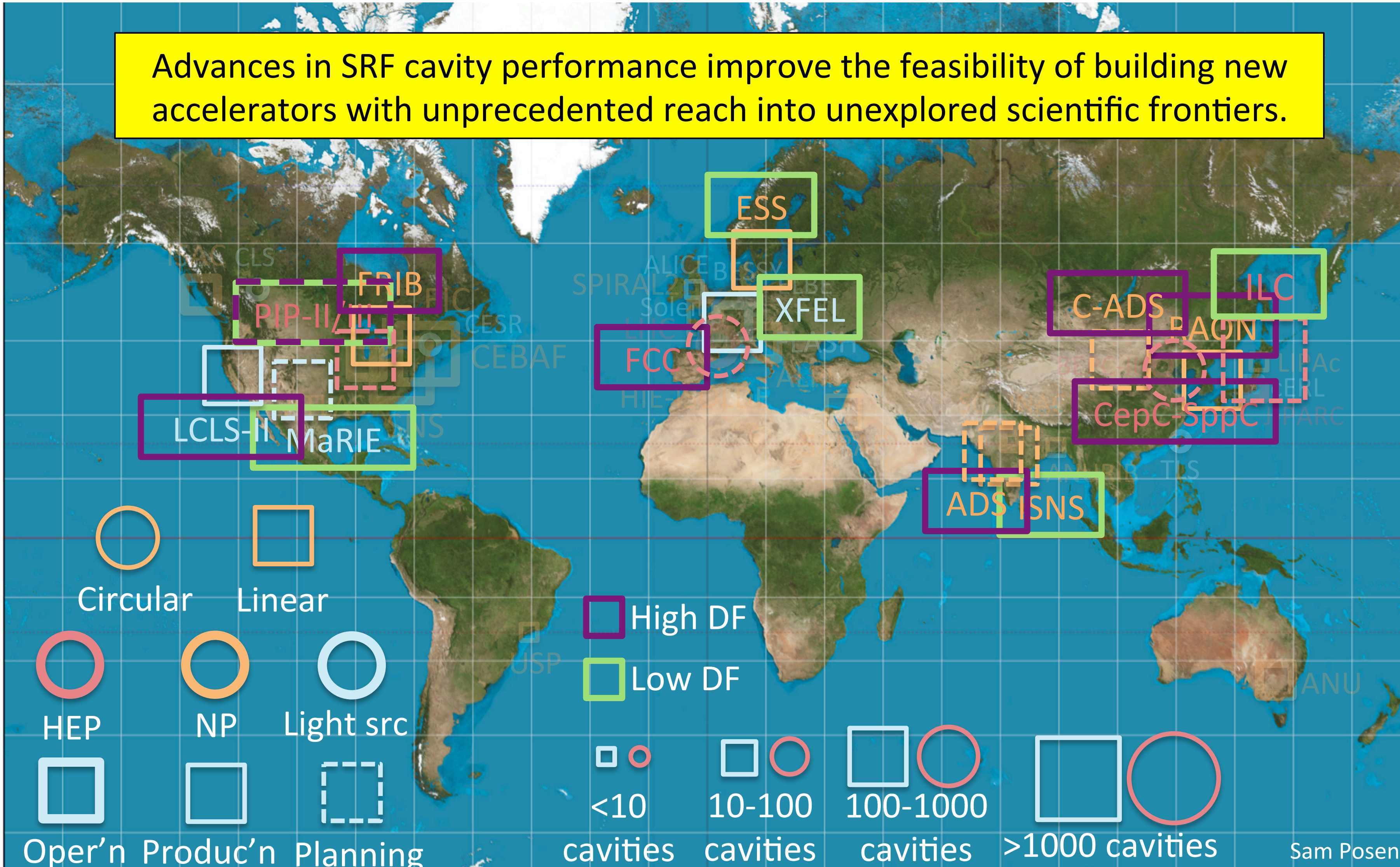
Motivation State-of-the-Art SRF Technology



Map from Wikipedia. Non-exhaustive facility list.

Motivation State-of-the-Art SRF Technology

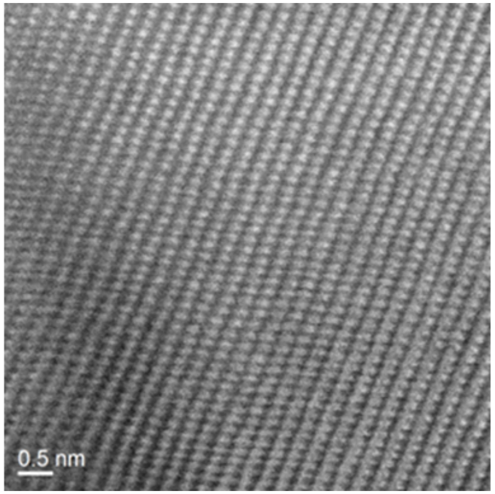
Advances in SRF cavity performance improve the feasibility of building new accelerators with unprecedented reach into unexplored scientific frontiers.



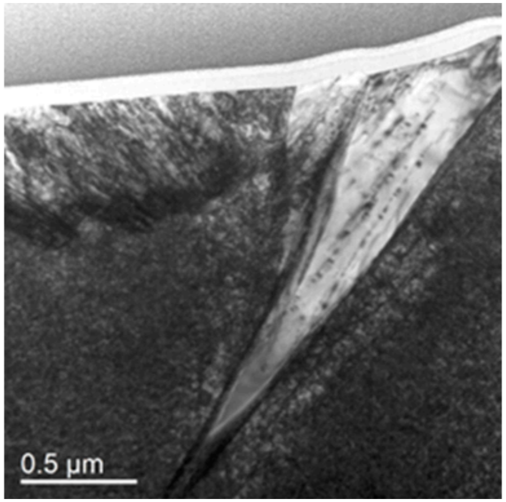
Map from Wikipedia. Non-exhaustive facility list.

Outline

- High Q_0 (medium E_{acc})
  - Nitrogen doping
  - Flux expulsion
- High E_{acc} and high Q_0
  - Nitrogen infusion
  - Nb_3Sn
  - Plasma cleaning



Aberration-corrected STEM image of the near-surface of Nb cavity - Y. Trenikhina

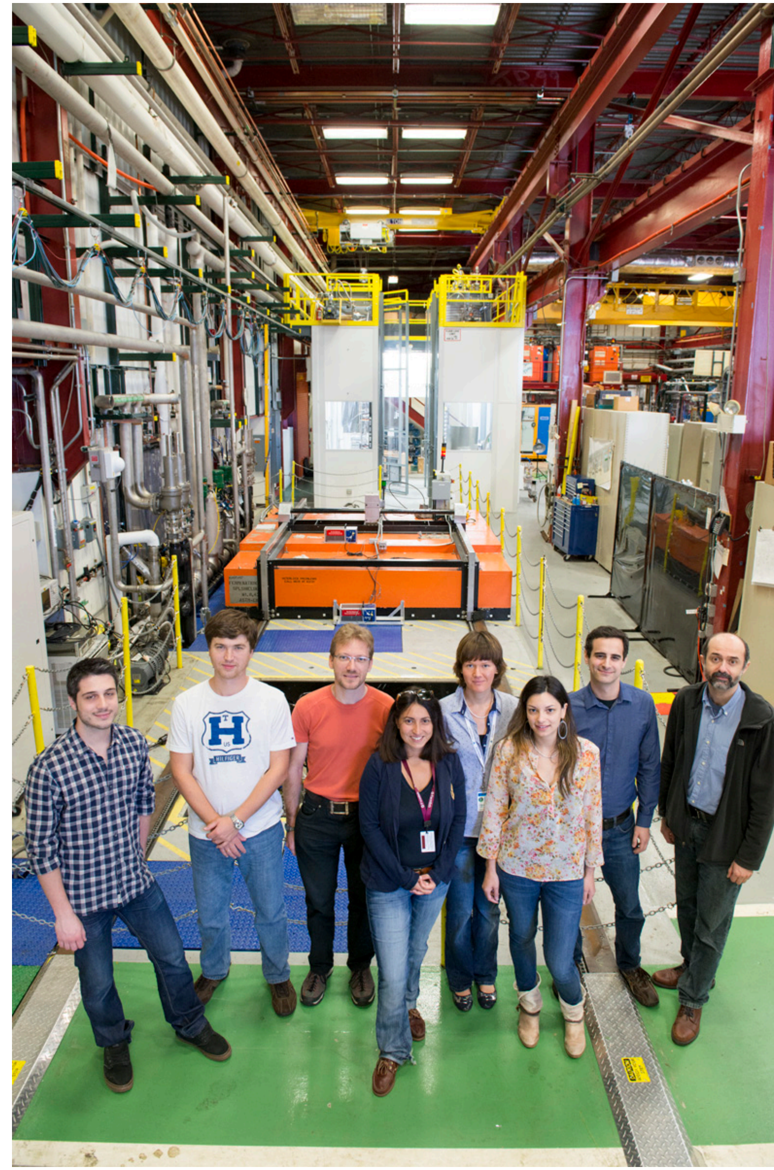


Niobium near-surface after the first step of nitrogen doping - Y. Trenikhina

ILC cryomodule with record average gradient for FAST facility

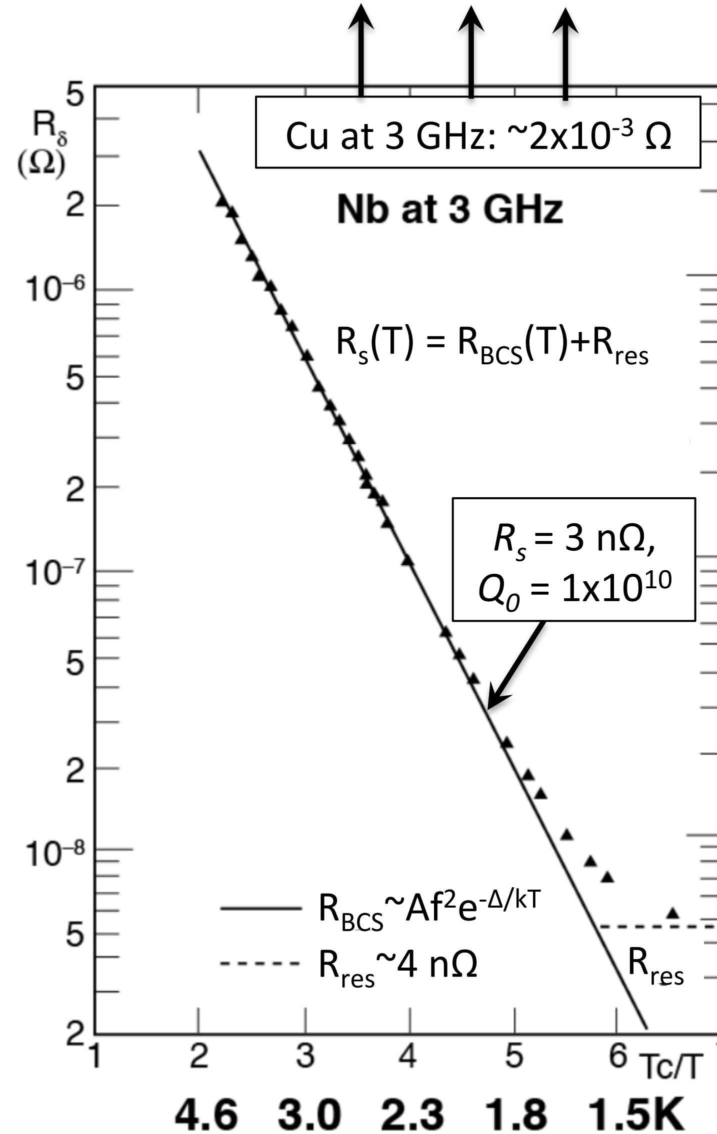
Team Effort

- Results shown here are due to many hardworking people
- Thanks to SRF department and Fermilab LCLS-II team for contributions



Note on Q_0 and BCS/Residual Surface Resistance

- Q_0 and R_s are related by a geometrical constant G: $Q_0 = G/R_s$
- They measure efficiency
- Heat dissipated in the walls of the cavity: $P_{diss} \sim R_s \sim Q_0^{-1}$
- R_s decreases exponentially with decreasing T/T_c but it saturates at low T: residual resistance R_{res}
- Generally we decompose R_s into temperature dependent R_{BCS}(T) and temperature independent R_{res}
- Cavities often operate at ~2 K where both are significant



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Treatment for Enhancement of RF Penetration Layer

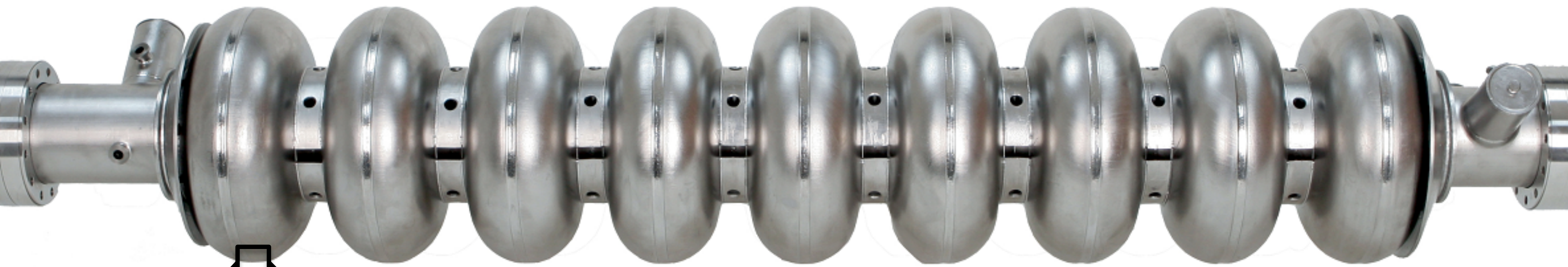
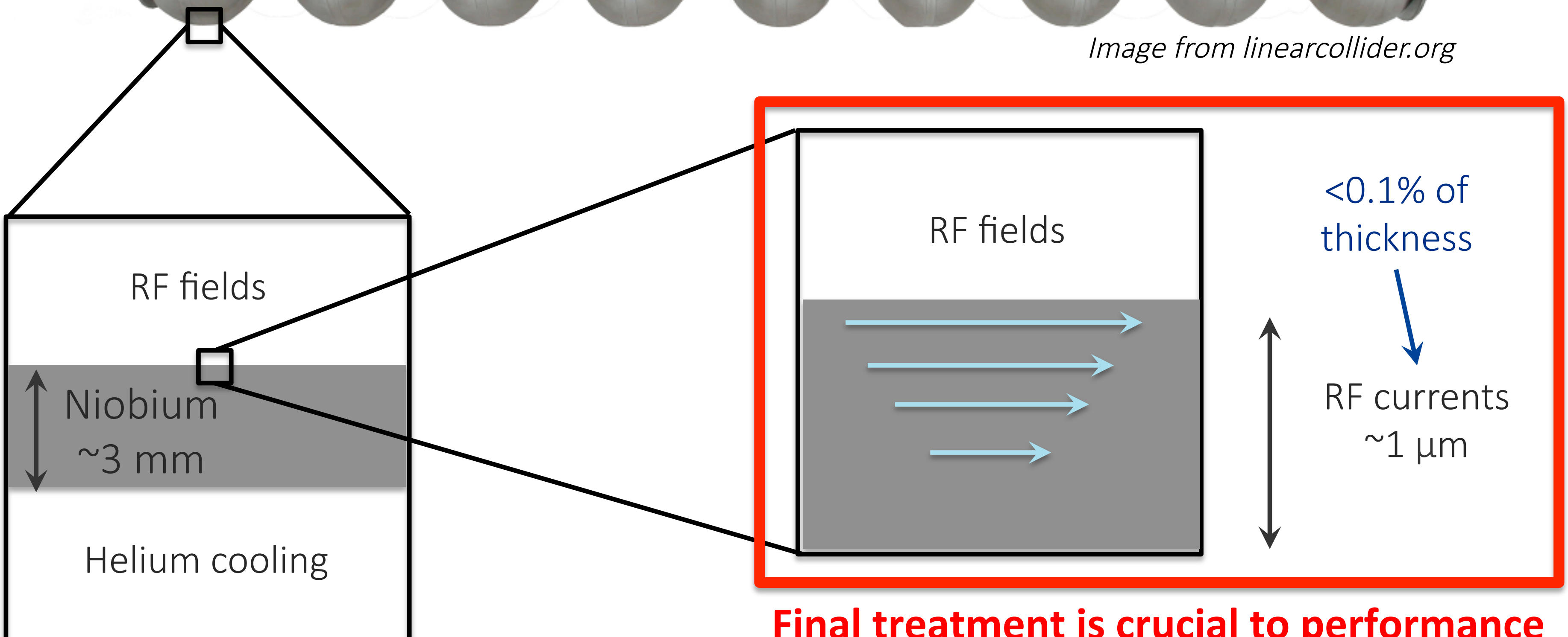
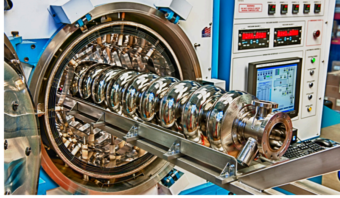


Image from linearcollider.org



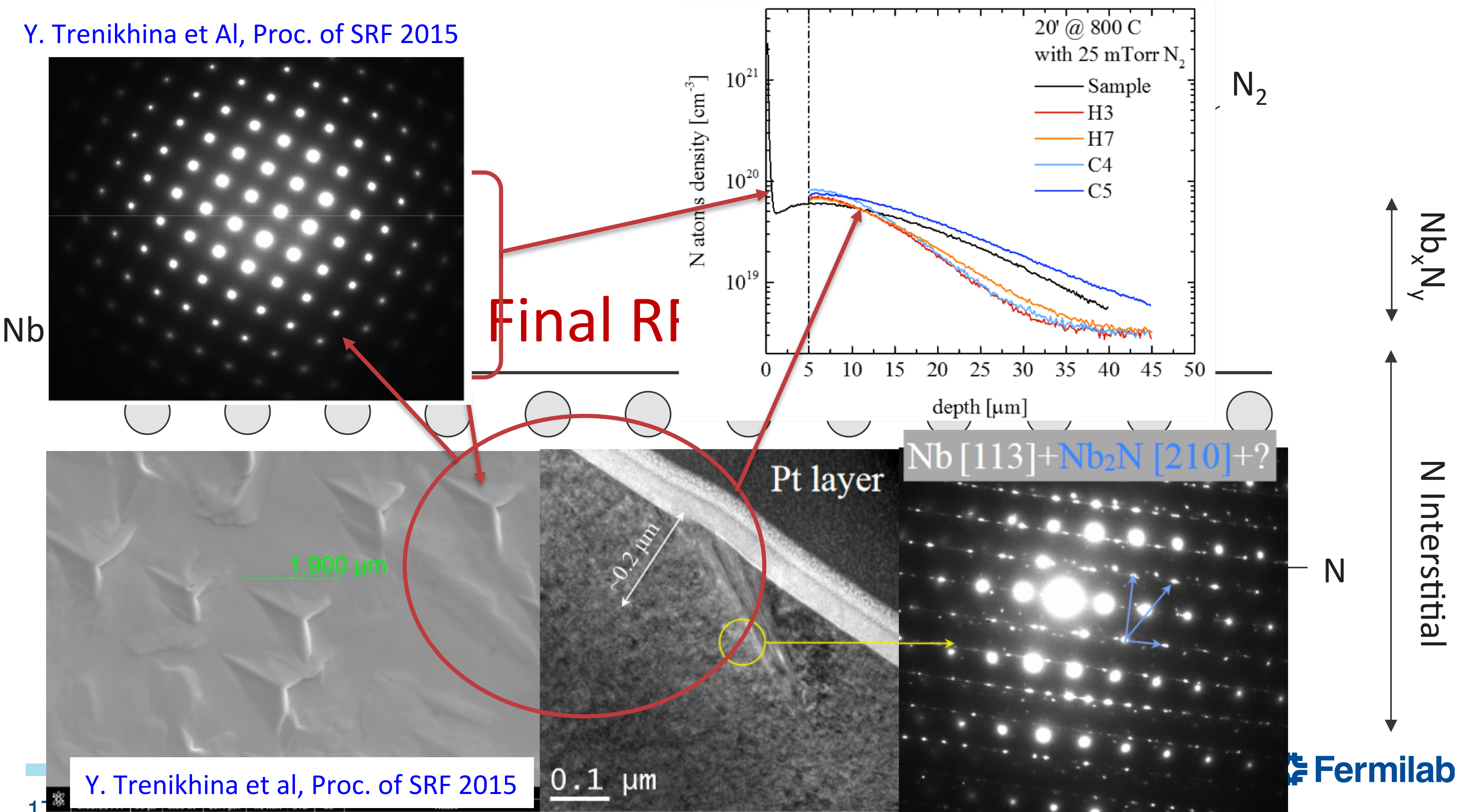
Final treatment is crucial to performance

N-doping treatment



800C UHV, 3 hours → 800C N_2 p = 25 mTorr 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

Y. Trenikhina et Al, Proc. of SRF 2015



Y. Trenikhina et al, Proc. of SRF 2015

Slides adapted from M. Martinello

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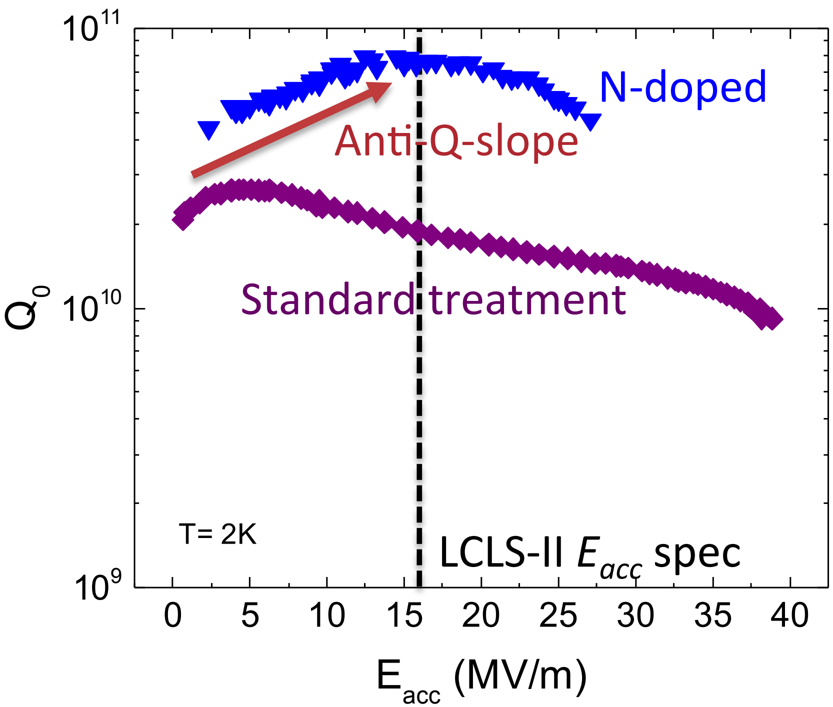
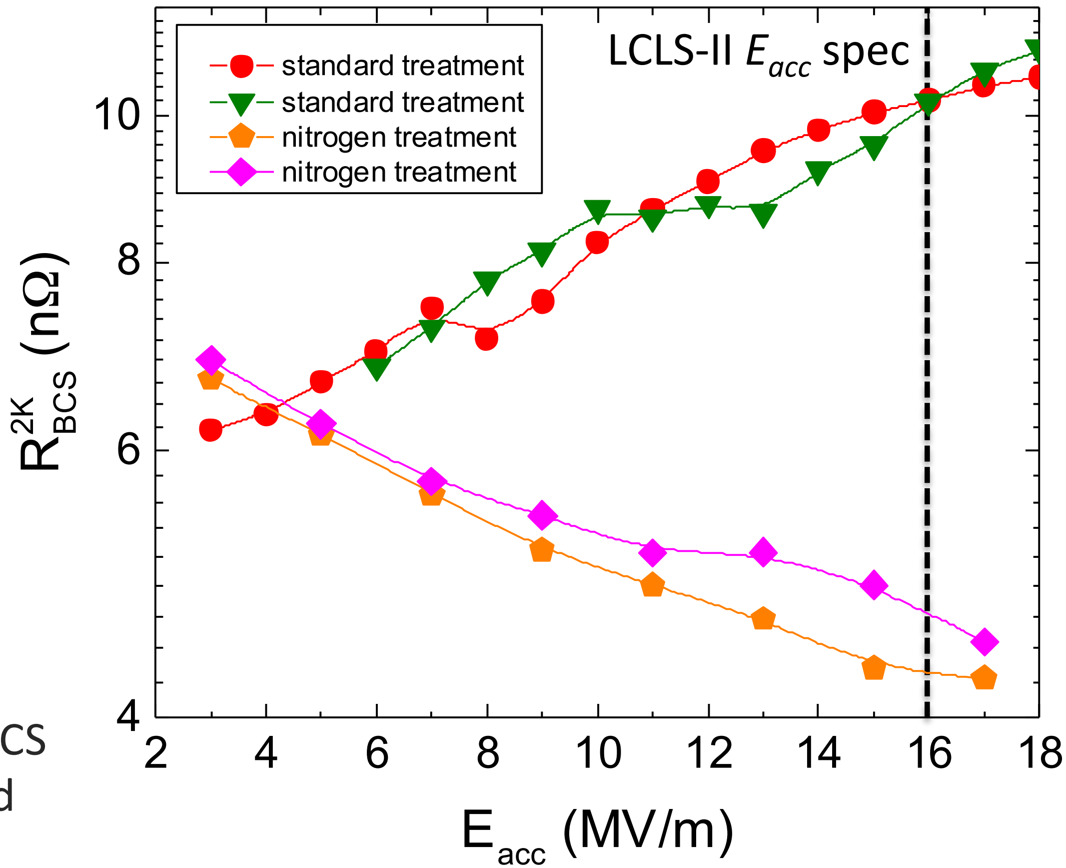
Effect on Surface Resistance (and therefore $Q_0 = G/R_s$)





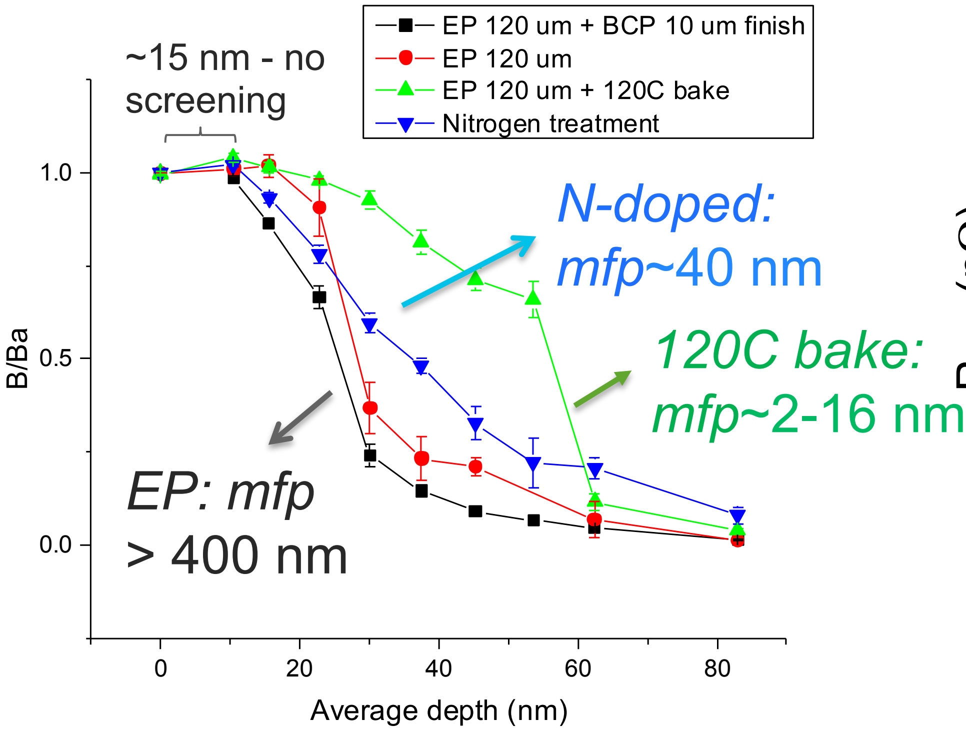
Anti-Q-slope emerges from the BCS surface resistance decreasing with field
→ **Unexpected, unprecedented**

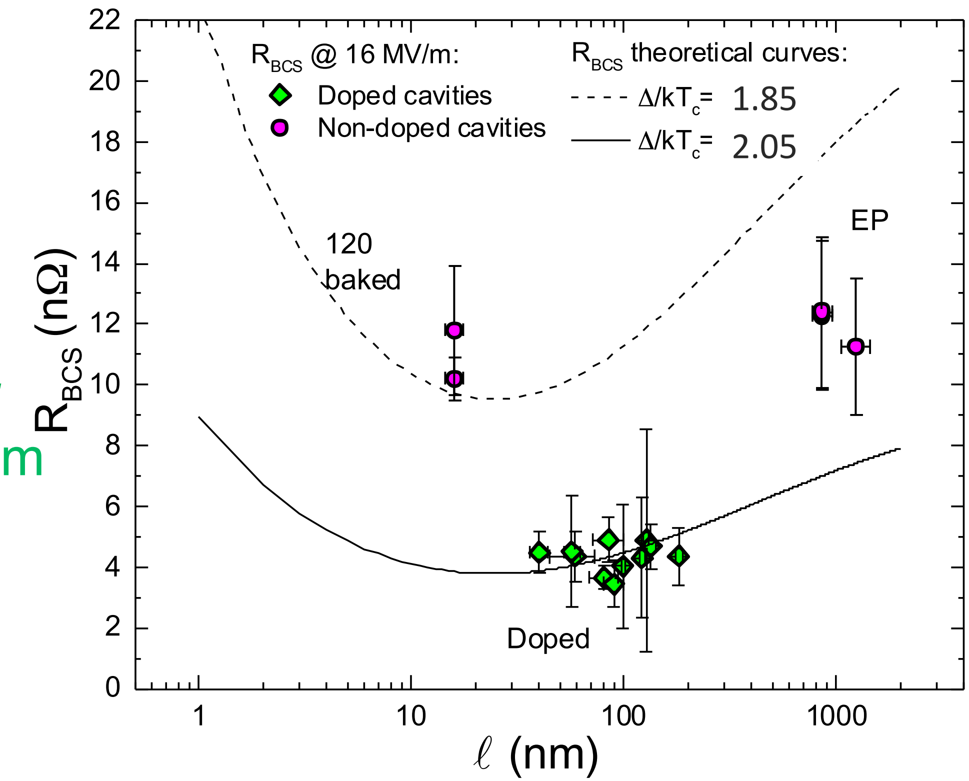
- >2x R_{BCS} improvement at 2 K, 16 MV/m
- Reduced maximum field OK for high duty factor applications

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

Origin of Improved Surface Resistance due to N-Doping

LE-μSR measurements (Ba=25mT)





A. Romanenko et al, Appl. Phys. Lett. **104**, 072601 (2014)
A. Grassellino et al, Proc. of SRF2015

M. Martinello et al, Appl. Phys. Lett. **109**, 062601 (2016)

- ✓ N-doping modify the mean free path
  - →Mean free path close to theoretical minimum of R_{BCS}
- ✓ N-doping seems to increase the reduced energy gap Δ/k_BT_c

Slide adapted from M. Martinello

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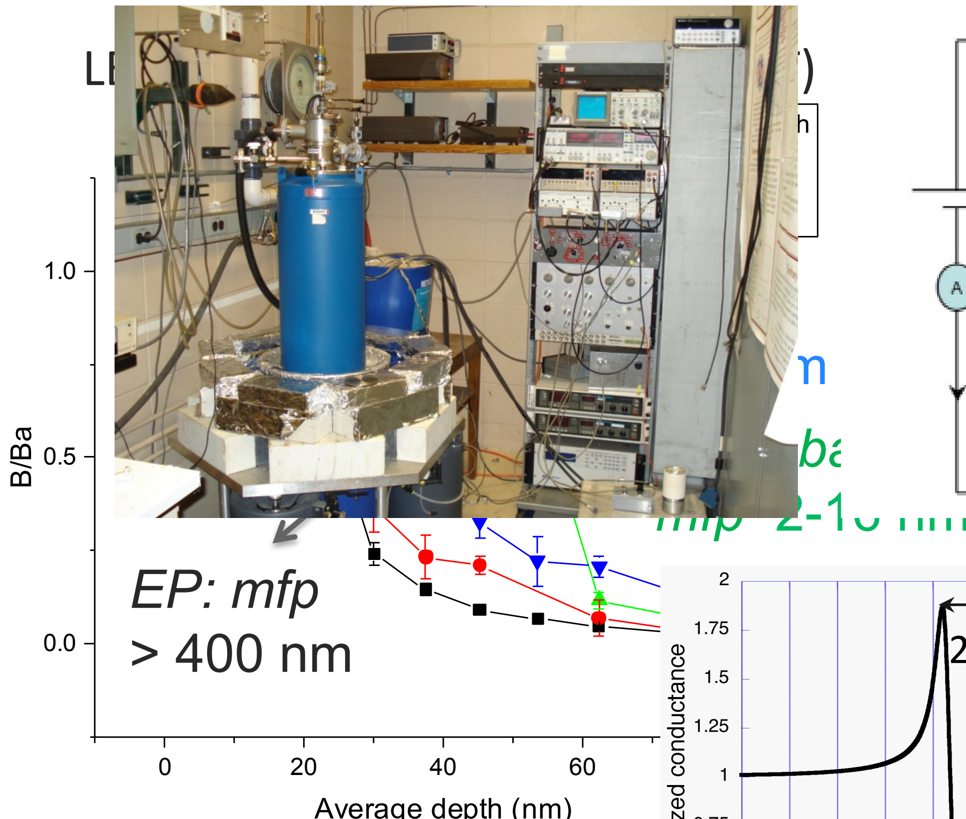

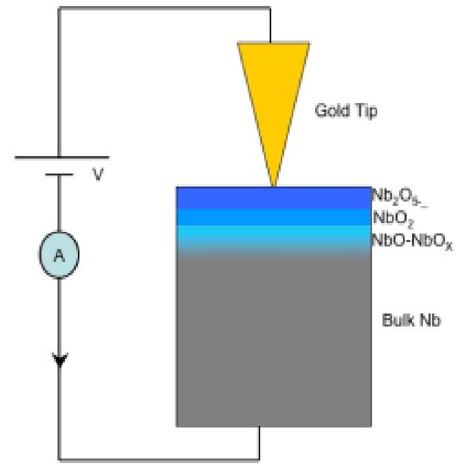

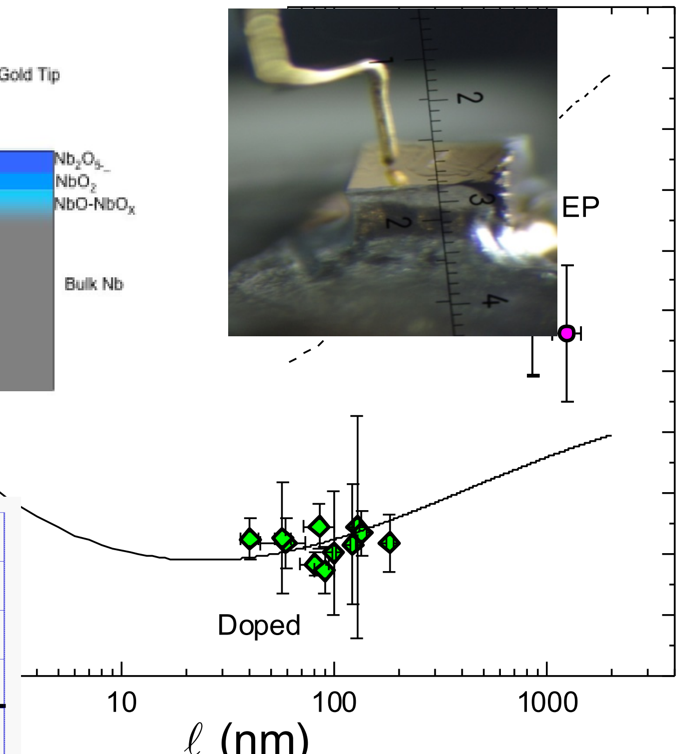

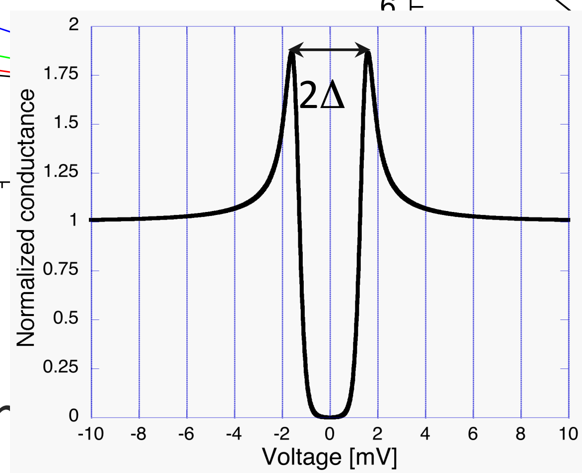

A. Romanenko et al, Appl. Phys. Lett. **104**, ... lo et al, Appl. Phys. Lett. **109**, 062601 (2016)

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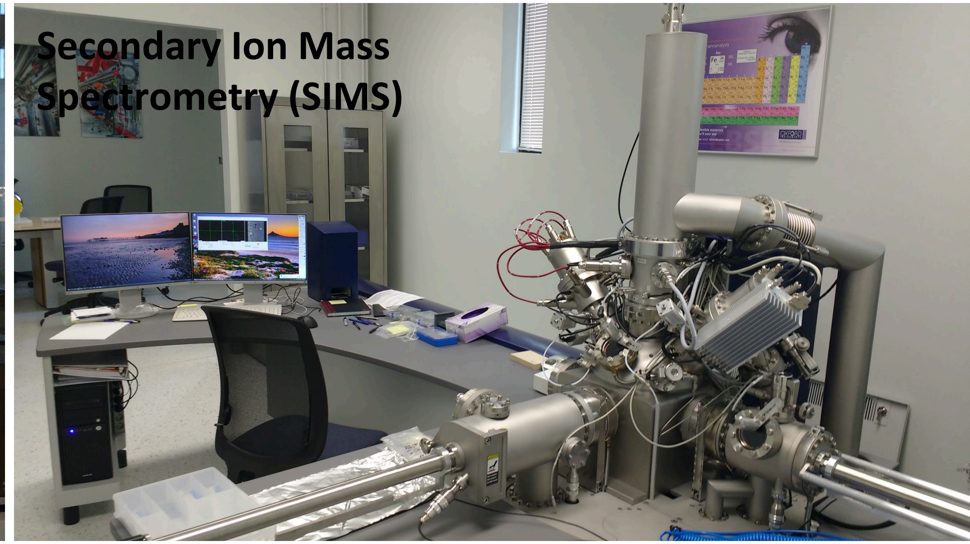
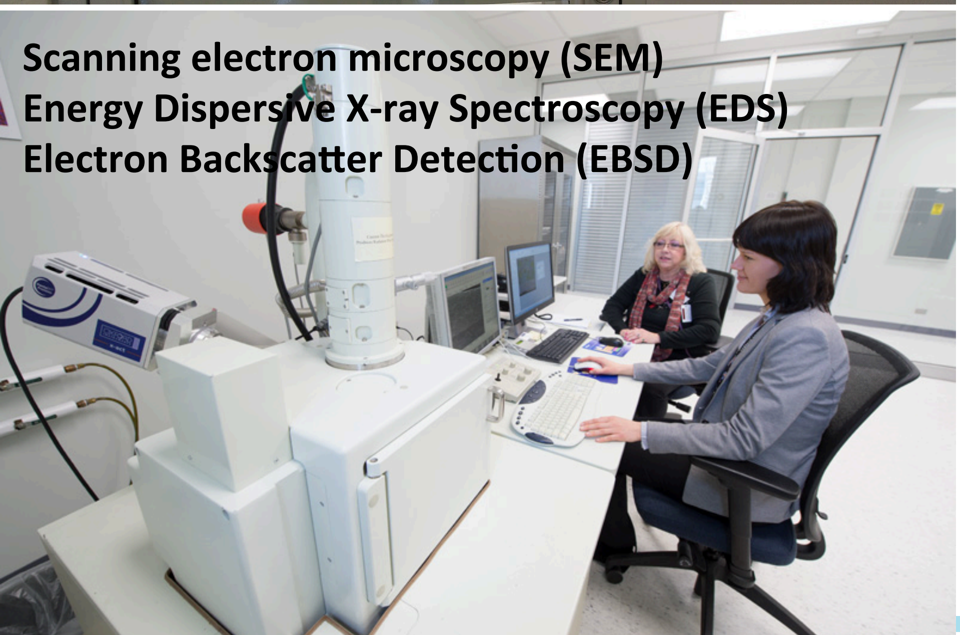
Slide adapted from M. Martinello

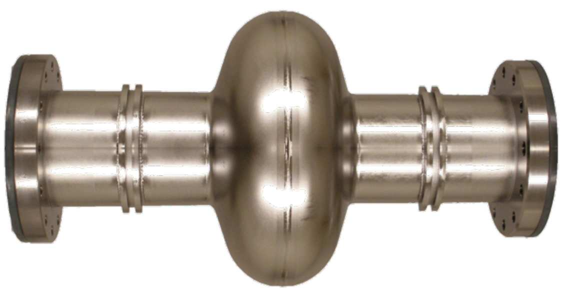
Materials Science Lab

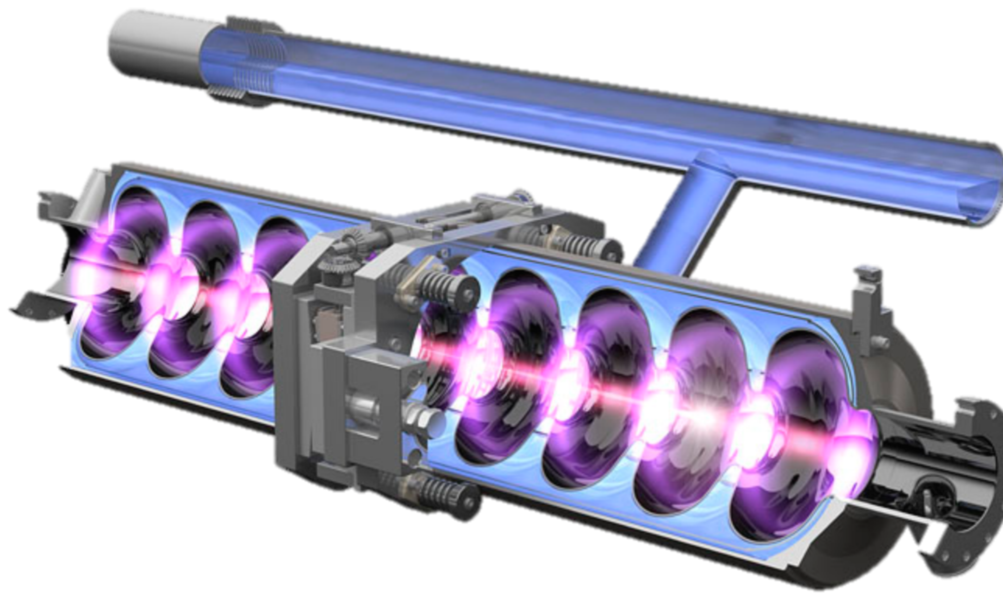




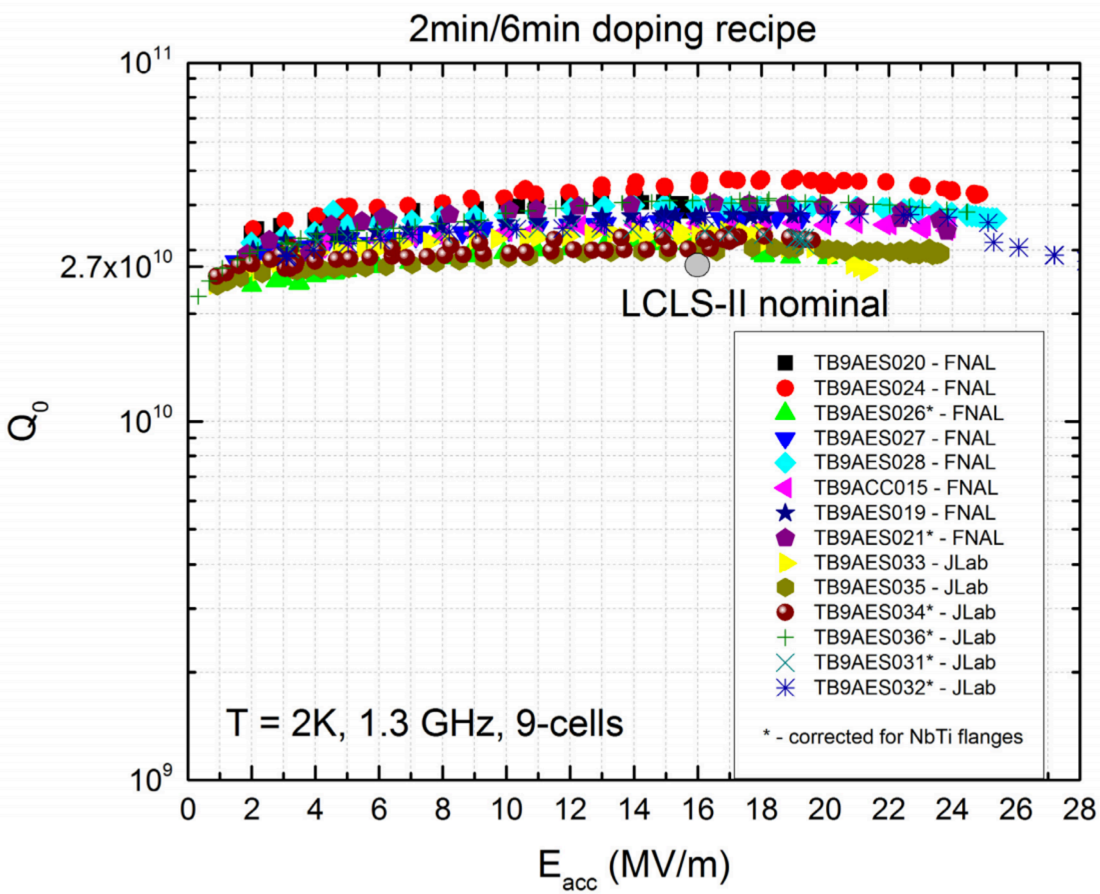
Scale-Up

- Initial studies on single cell R&D-style cavities
- Several milestones required to demonstrate technology maturity for accelerator applications





From single cell R&D to cryomodule ready technology: the two LCLS-II prototype cryomodules (FNAL and Jlab)



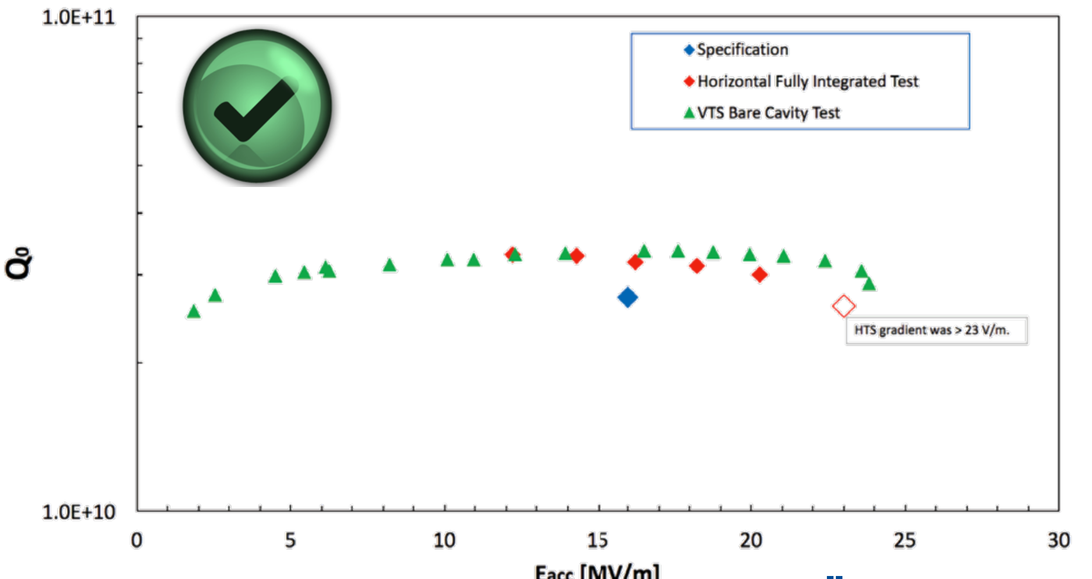
$\langle Q \rangle$=3.6e10
$\langle E_{max} \rangle$=22.2 MV/m
E_{max}median=22.8MV/m

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)

Slide from A. Grassellino

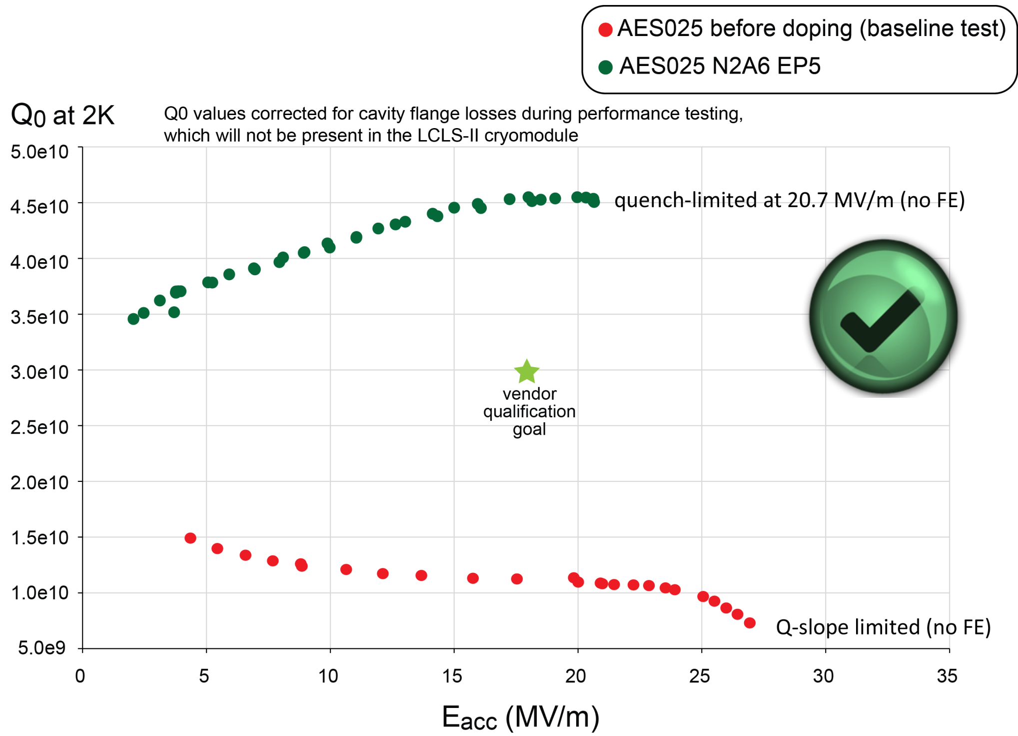
Integrated Testing

- Record $Q_0 > 3x10^{10}$ at 16MV/m, 2 K for a LCLS-II dressed cavity in fully integrated horizontal test (with high power coupler, HOMs, tuner etc.)
- Important milestone to show new readiness for implementation in application



Technology Transfer

- SRF cavity vendors: from niobium material to N-doped cavities ready for qualification testing

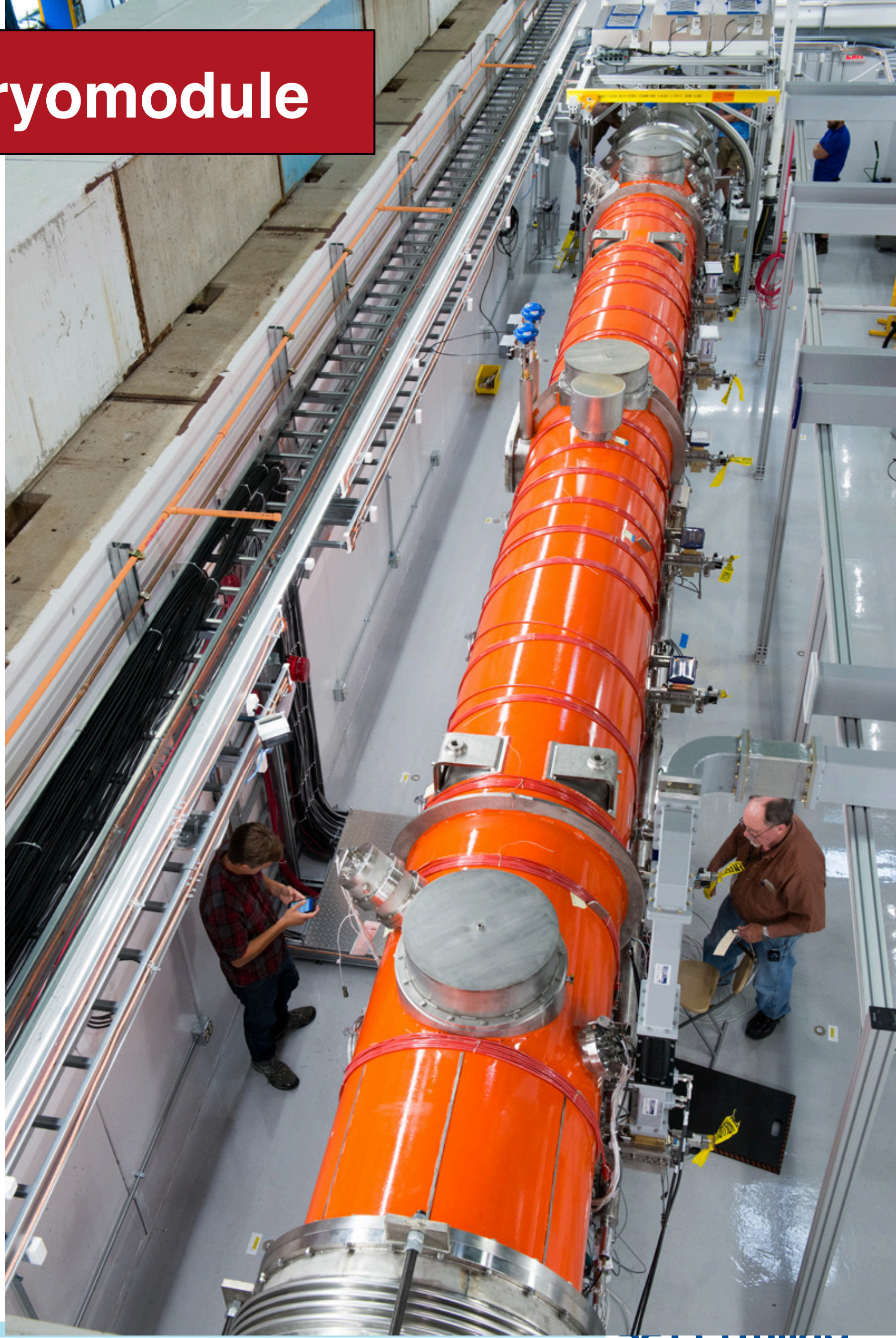


Fermilab Prototype LCLS-II Cryomodule

Cavity	Usable Gradient* [MV/m]	Q0 @16MV/m* 2K Fast Cool Down
TB9AES021	18.2	2.6E+10
TB9AES019	18.8	3.1E+10
TB9AES026	19.8	3.6E+10
TB9AES024	20.5	3.1E+10
TB9AES028	14.2	2.6E+10
TB9AES016	16.9	3.3E+10
TB9AES022	19.4	3.3E+10
TB9AES027	17.5	2.3E+10
Average	**18.2**	**3.0E+10**
Total Voltage	**148.1 MV**	

Spec:
133 MV

Spec:
2.7×10^{10}



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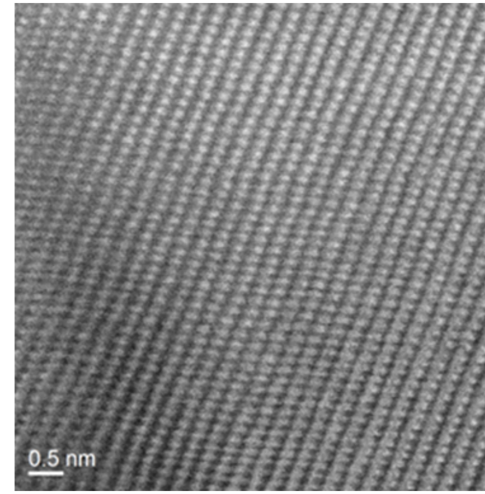
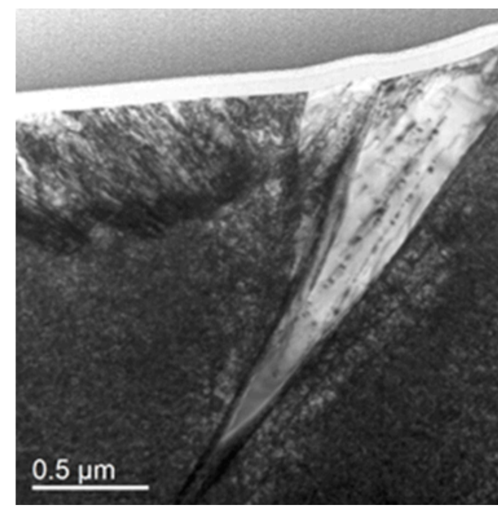


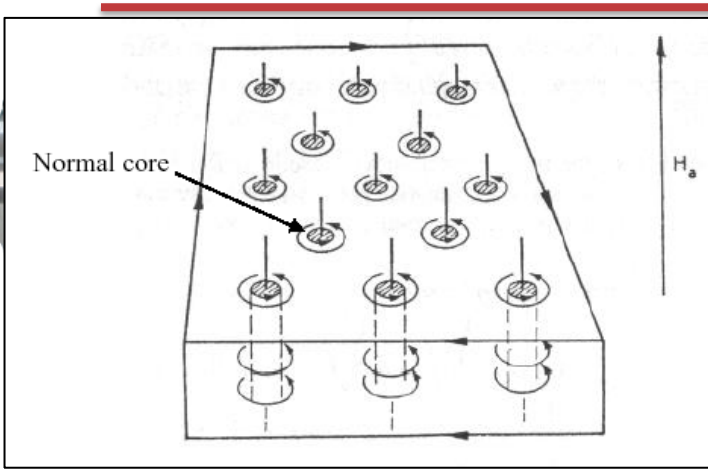
Aberration-corrected STEM image of the near-surface of Nb cavity - Y. Trenikhina

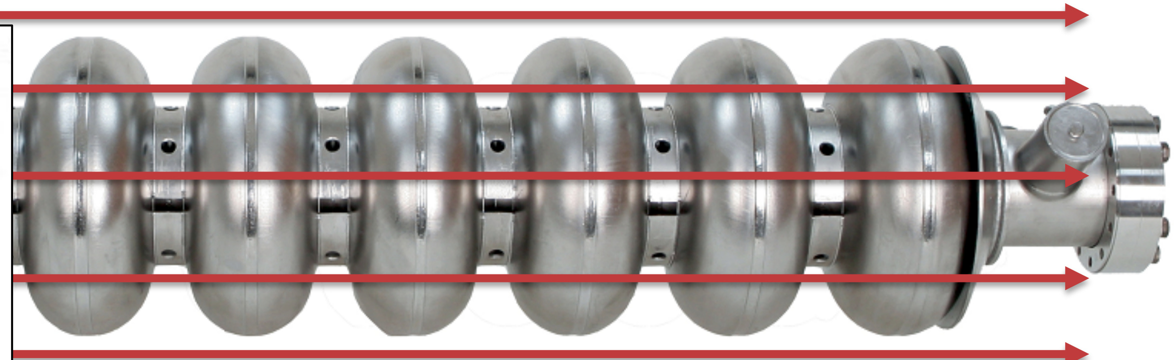


Niobium near-surface after the first step of nitrogen doping - Y. Trenikhina

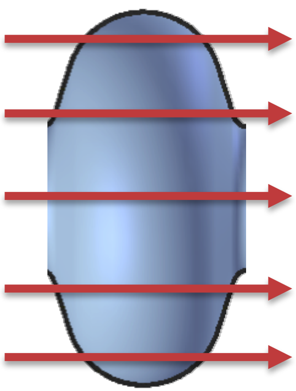
ILC cryomodule with record average gradient for FAST facility

Cooldown through Critical Temperature





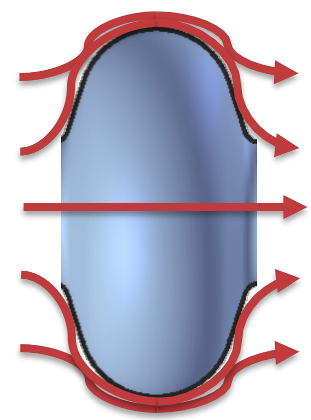
~ 5 mOe ~ 1% of Earth's field



Magnetic Flux Trapping

Trapped flux increases R_{res}

Closer to intrinsic R_{res}

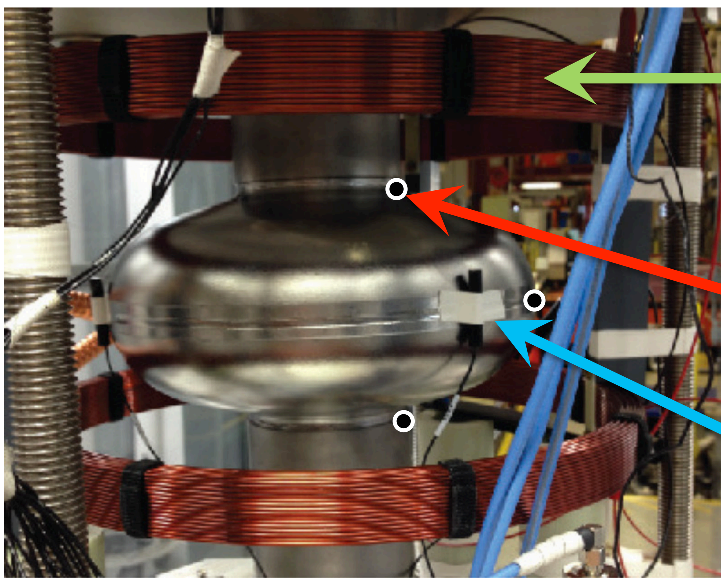


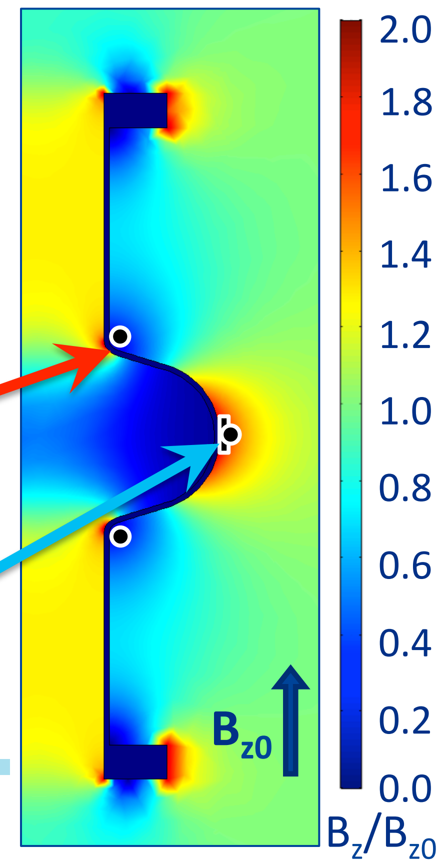
Magnetic Flux Expulsion

Flux image from Rose-Innes and Roderick, Introduction to Superconductivity

Measuring Flux Expulsion

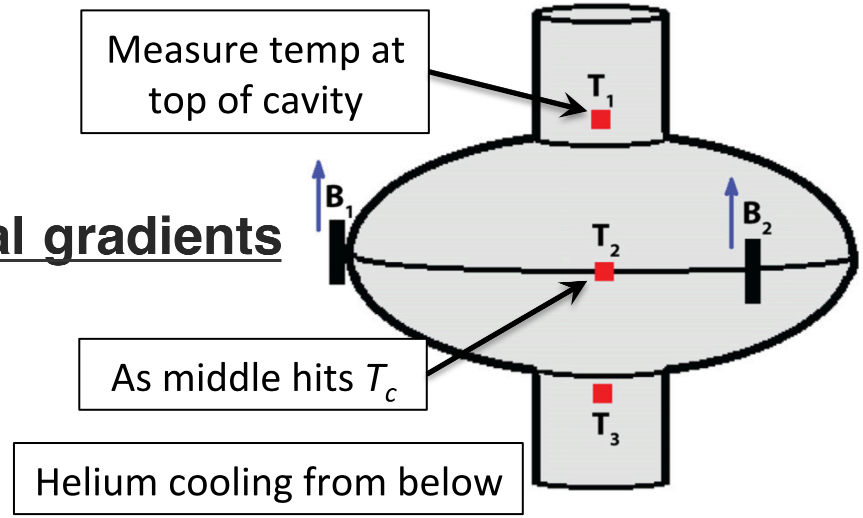
- An axial magnetic field is applied during cooldown. Fluxgate magnetometers at the equator measured the magnetic field before B_{NC} and after B_{SC} superconducting transition.
  - Complete trapping: $B_{SC}/B_{NC} = 1$
  - Complete expulsion: $B_{SC}/B_{NC} \sim 1.7$

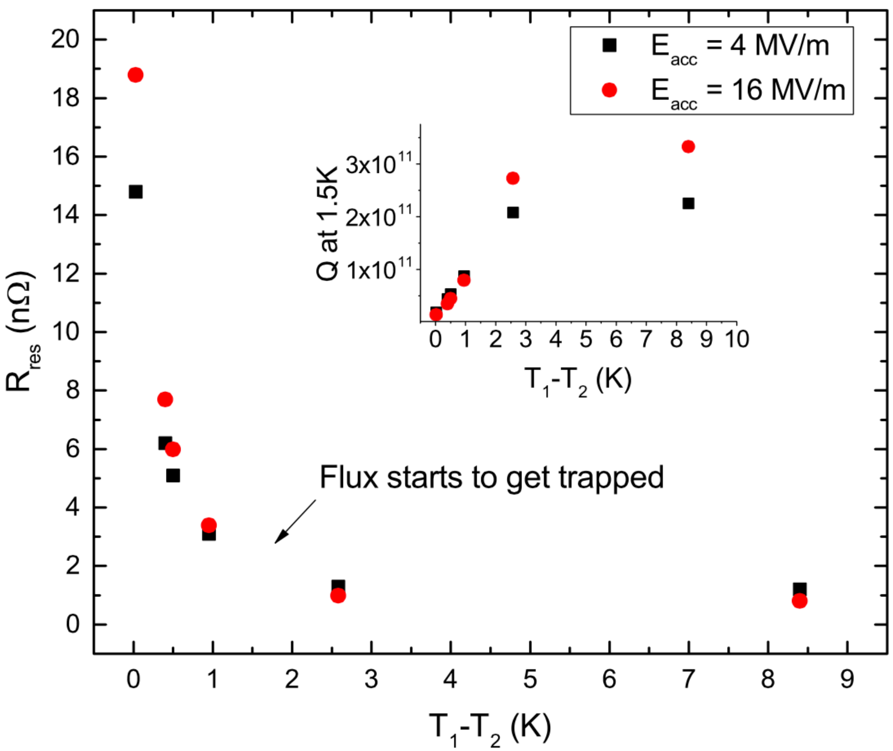


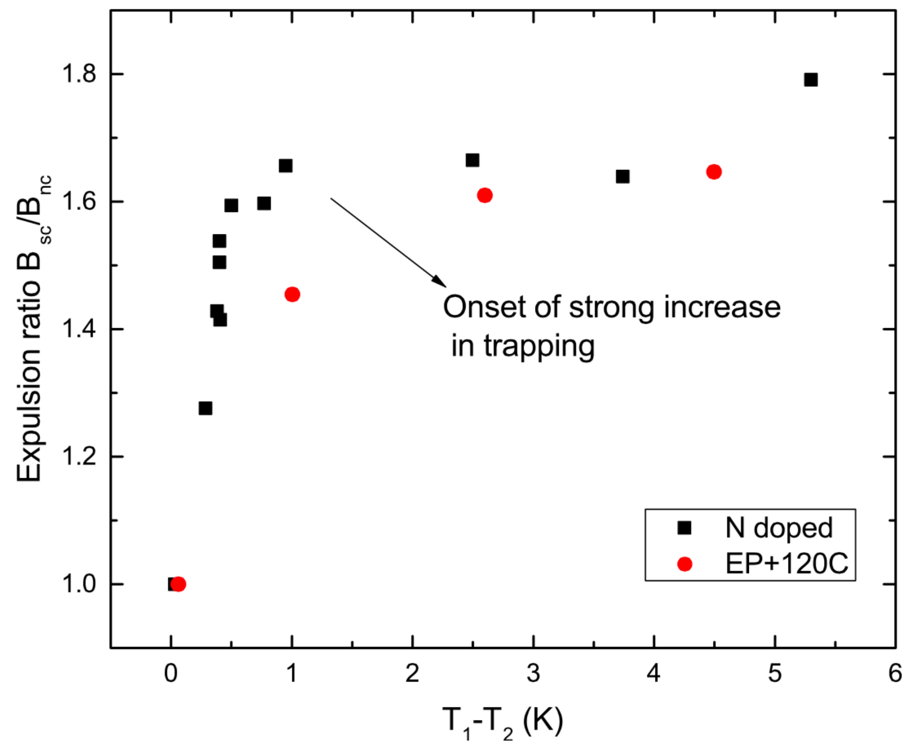


Thermal Gradients

- **Fast cool-down** lead to **large thermal gradients** which promote efficient flux expulsion
- Slow cool-down → poor flux expulsion
- Suggests depinning by thermal forces







A. Romanenko et al., Appl. Phys. Lett. 105, 234103 (2014)

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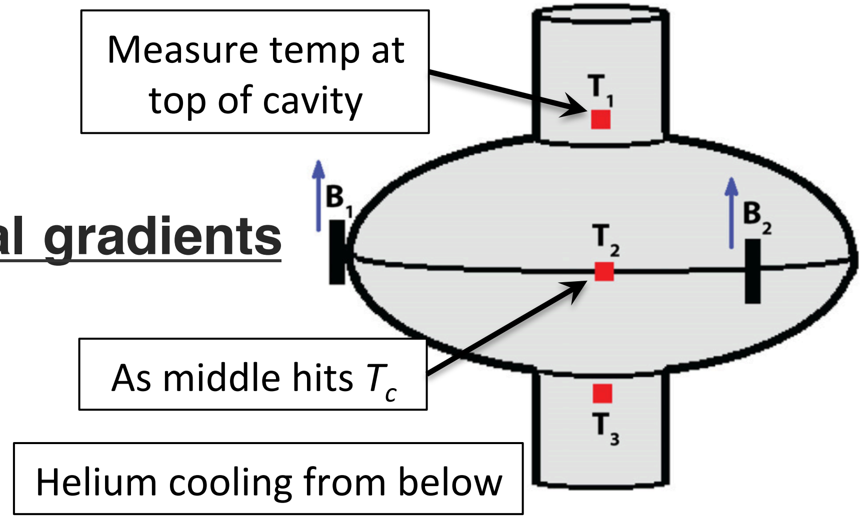
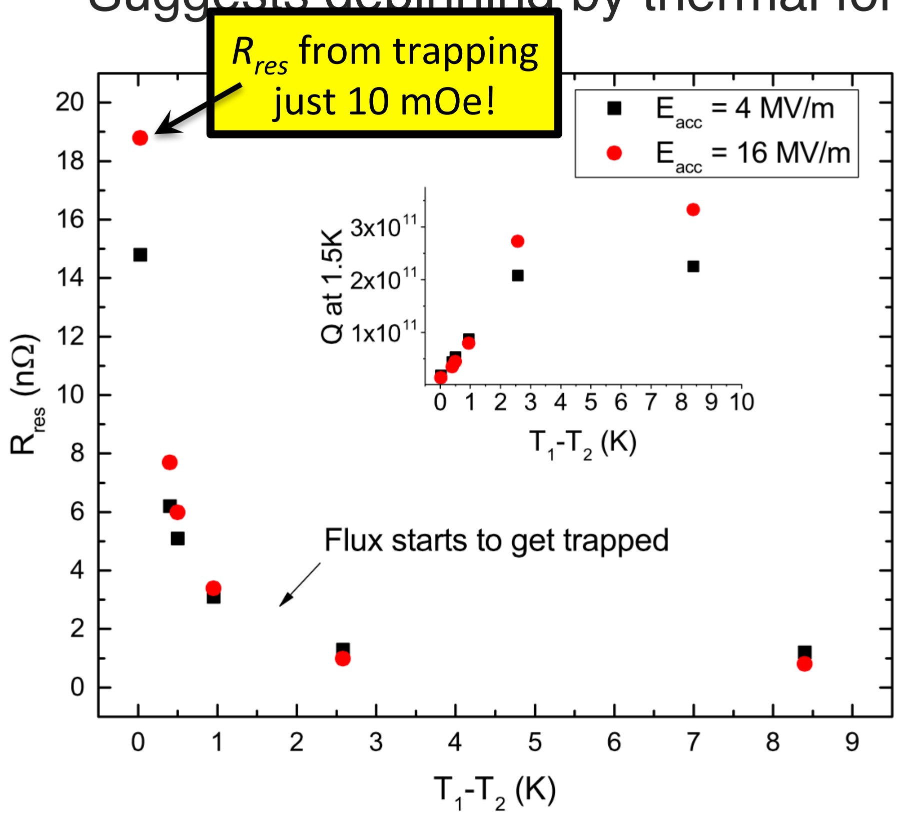
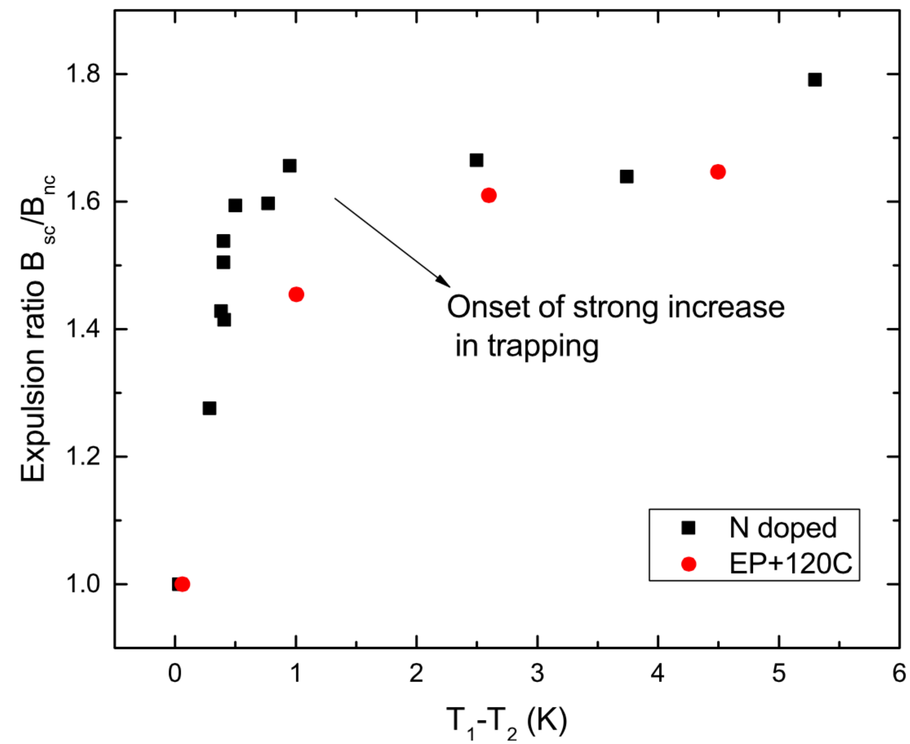
- Suggests depinning by thermal forces



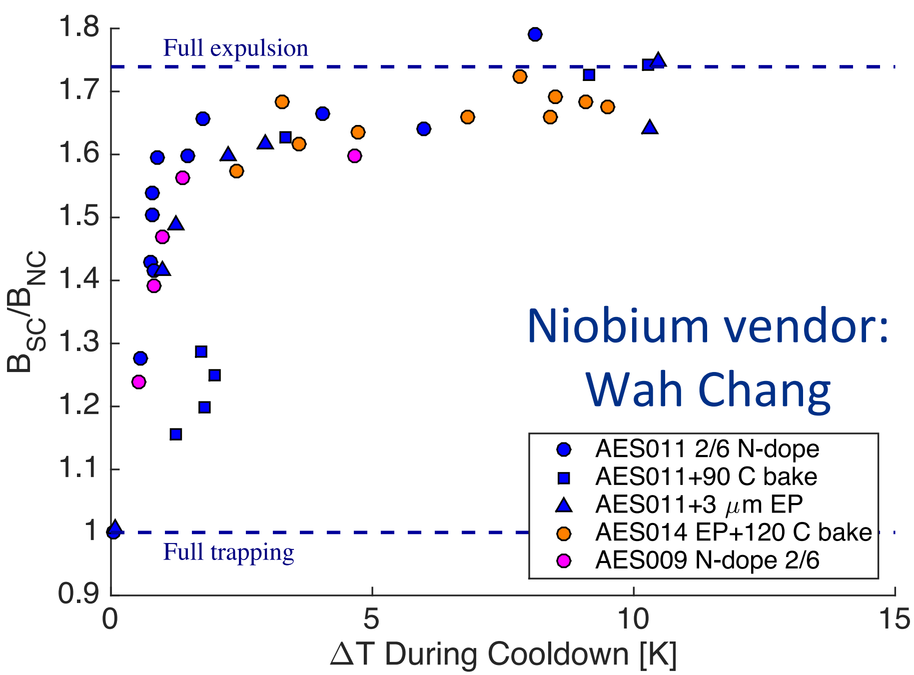


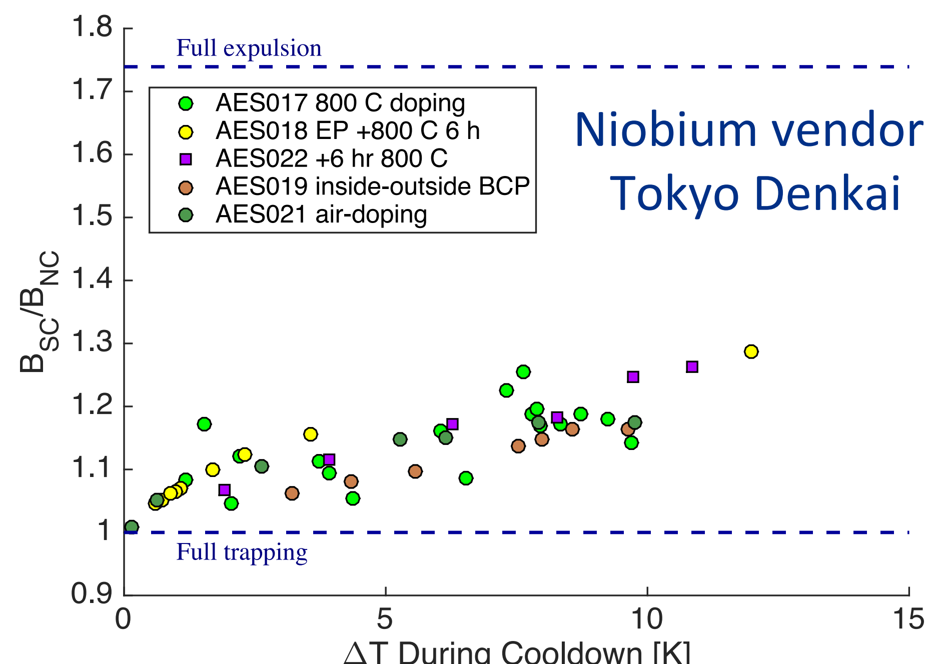


A. Romanenko et al., Appl. Phys. Lett. 105, 234103 (2014)

Variability in Material and Modifying Expulsion Behavior

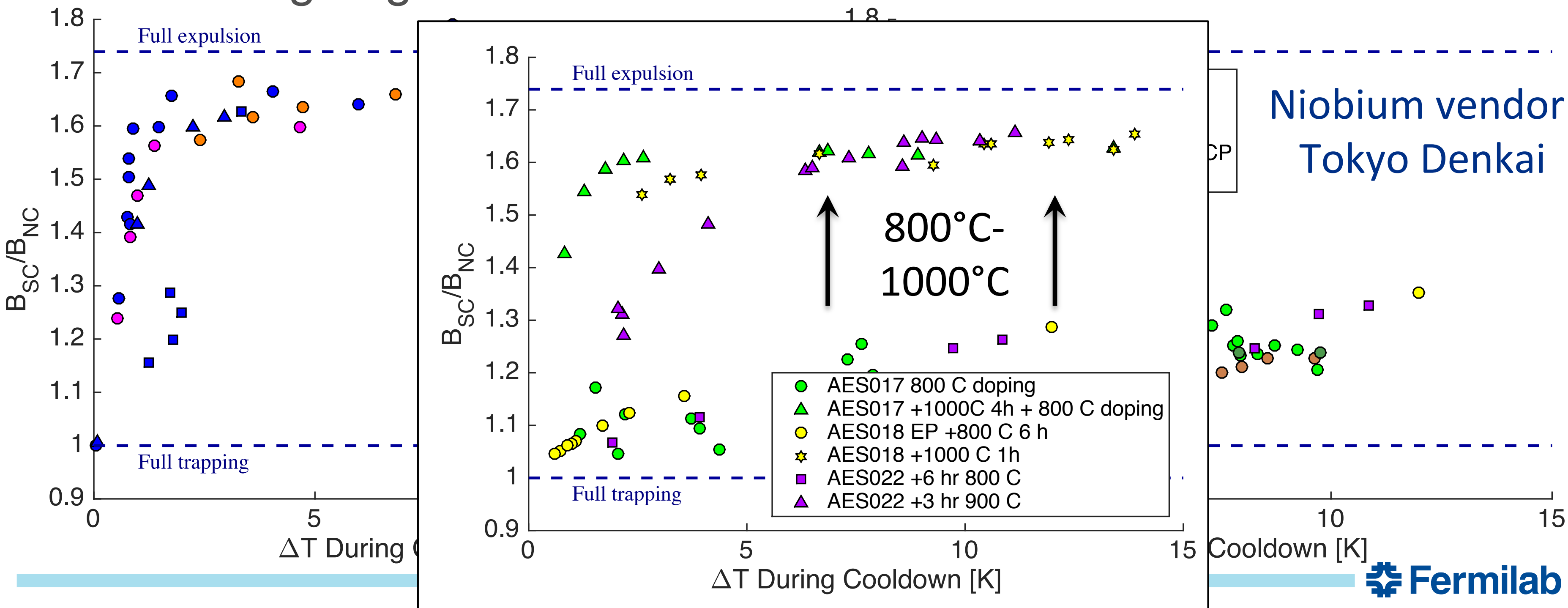
- Seems to be a great deal of variability in as-received material
- Variability from batches even within a single vendor



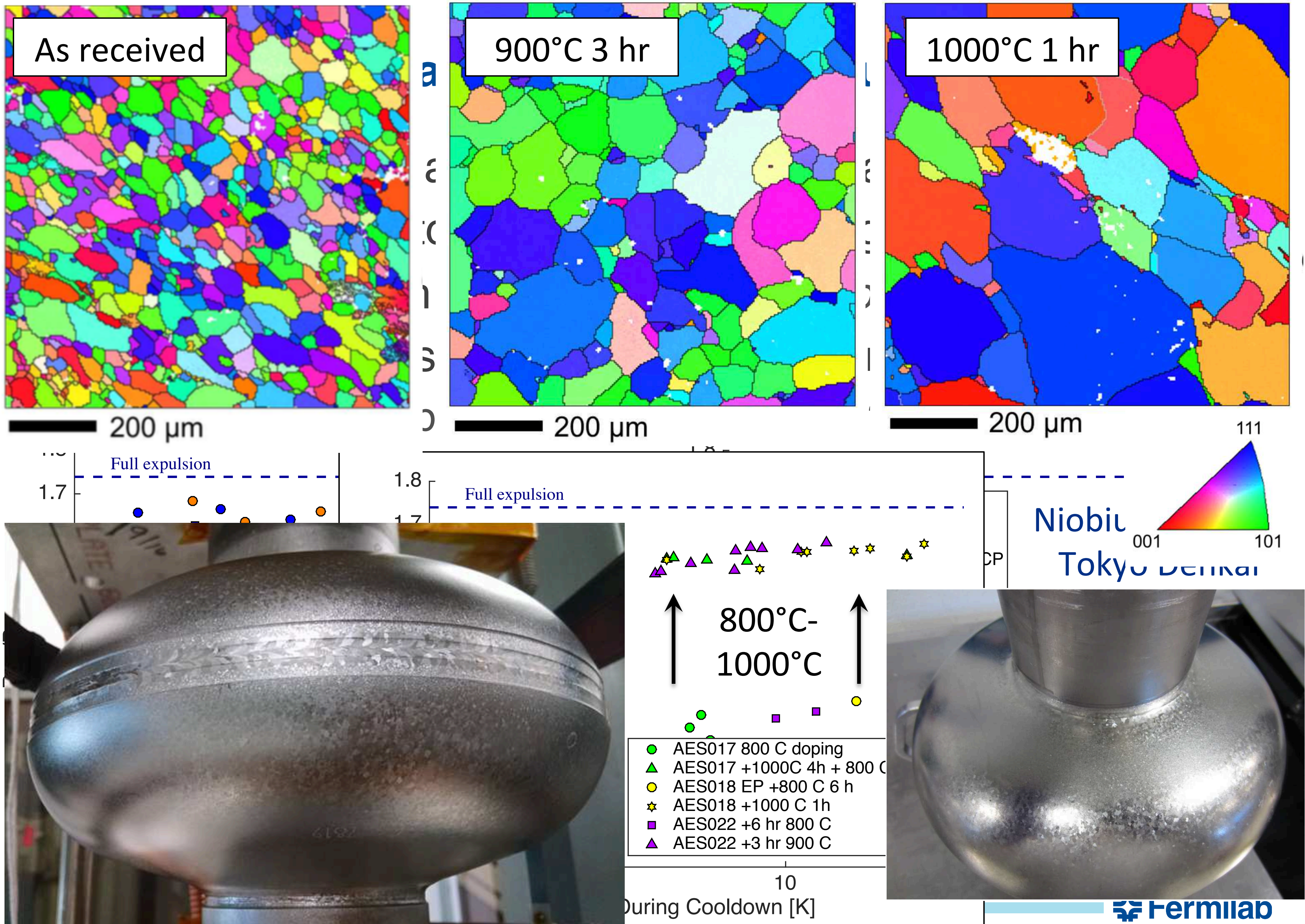


Variability in Material and Modifying Expulsion Behavior

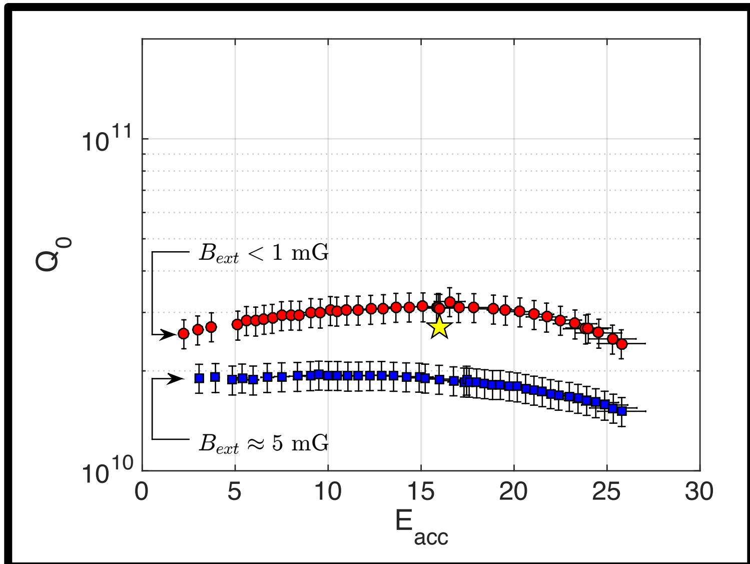
- Seems to be a great deal of variability in as-received material
- Variability from batches even within a single vendor
- High temp vacuum furnace treatment *improves* expulsion
- Surface treatments do not affect expulsion → bulk property
  - Pinning at grain boundaries? Dislocations?

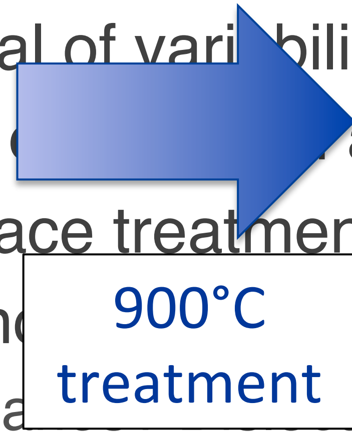


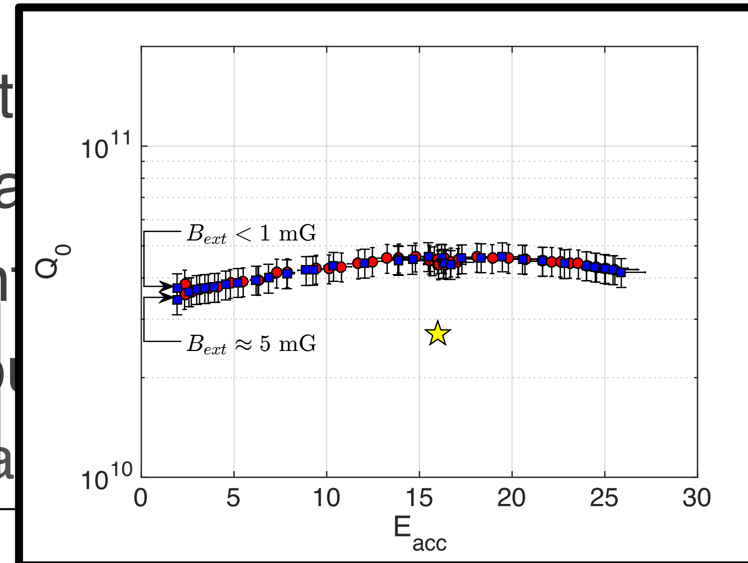
Fermilab


As received
900°C 3 hr
1000°C 1 hr
200 µm
200 µm
200 µm
111
001
101
Full expulsion
1.7
1.8
Full expulsion
800°C-
1000°C
AES017 800 C doping
AES017 +1000C 4h + 800 C
AES018 EP +800 C 6 h
AES018 +1000 C 1h
AES022 +6 hr 800 C
AES022 +3 hr 900 C
10
During Cooldown [K]
Niobiu
Tokyo Denkai
Fermilab

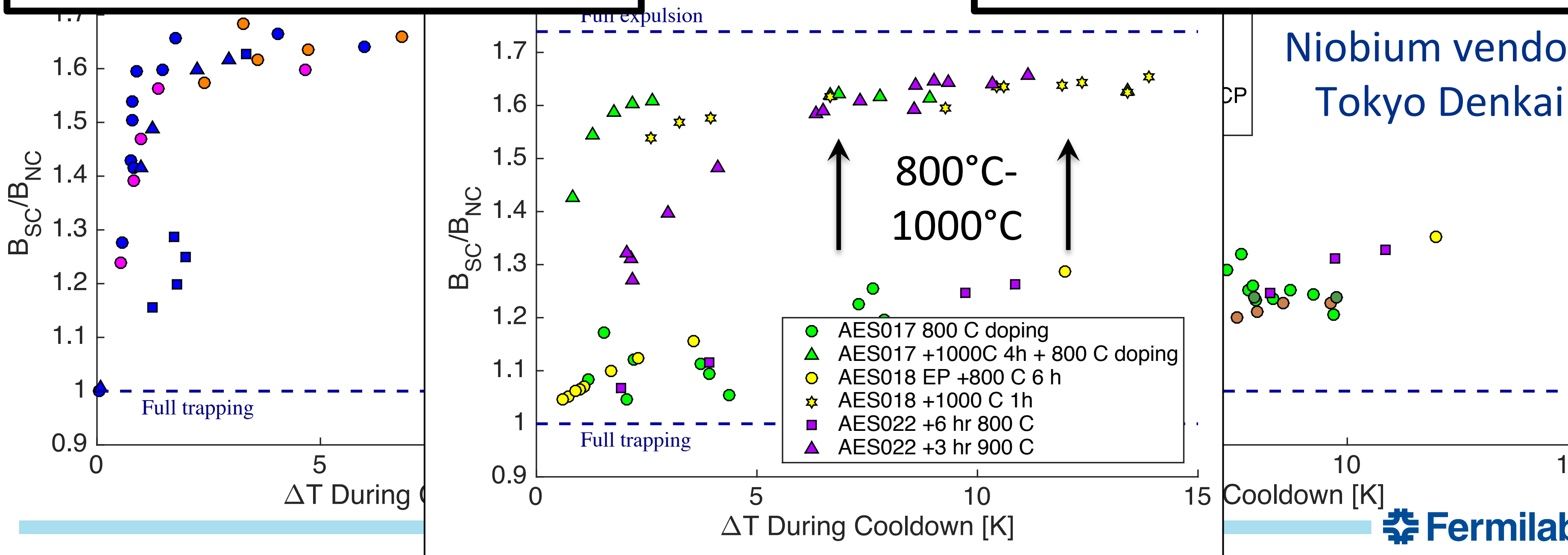
Variability in Material and Modifying Expulsion Behavior







Niobium vendor:
Tokyo Denkai

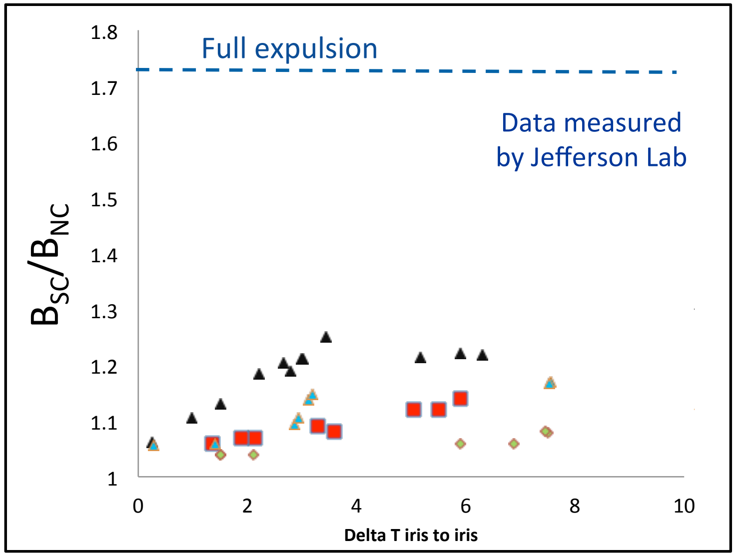


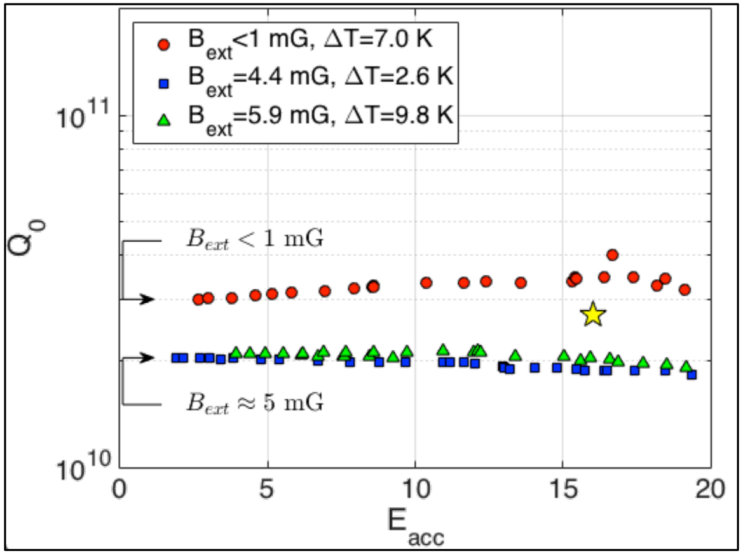
Fermilab

LCLS-II - Preproduction

Cooling in 5 mG applied field
(spec for background field in module)

As-received niobium material for LCLS-II production: very poor expulsion





LCLS-II - Preproduction

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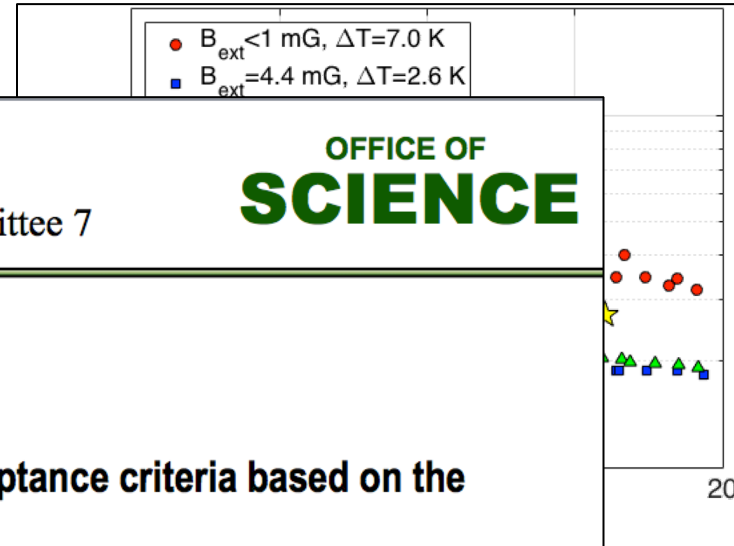
(spec for background field in module)



As-rec
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U.S. DEPARTMENT OF ENERGY

2.7 Cryomodules
D. Stout, MSU / Subcommittee 7

OFFICE OF SCIENCE

Recommendations

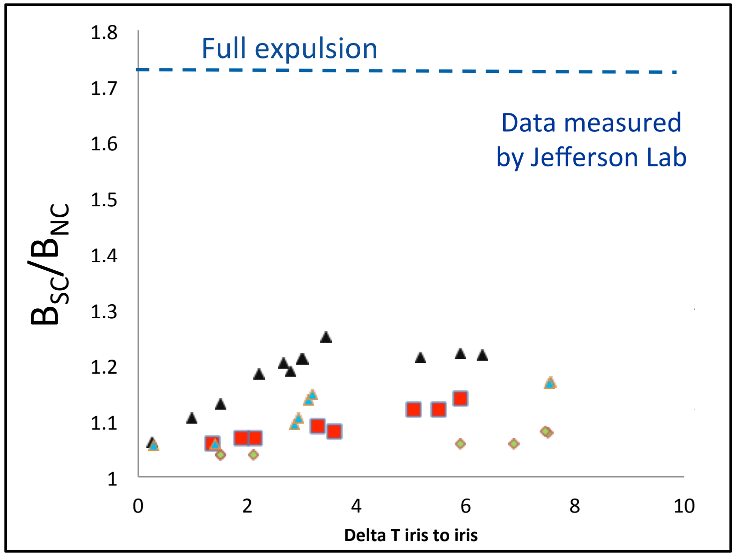
1. **The Project is ready to proceed to CD-2/3**
2. **Finalize cavity and cryomodule minimum acceptance criteria based on the current project baseline – by 3/2016**
3. **Conduct a supply chain risk assessment of critical cryomodule assembly components to identify items needing second sources or other mitigations – by 3/2016**
4. **Develop a cure to improve the flux expulsion of the procured niobium material and implement before cavity production.**
5. **Conduct an independent peer review of the detailed assembly methods for connecting cryomodules – prior to first connection in 2017**

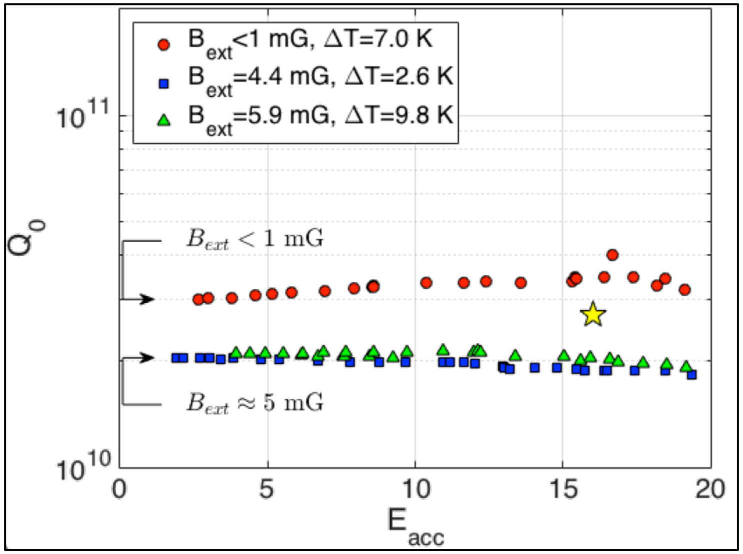
LCLS-II CD2/3 Review Closeout, Dec 2015

LCLS-II - Preproduction

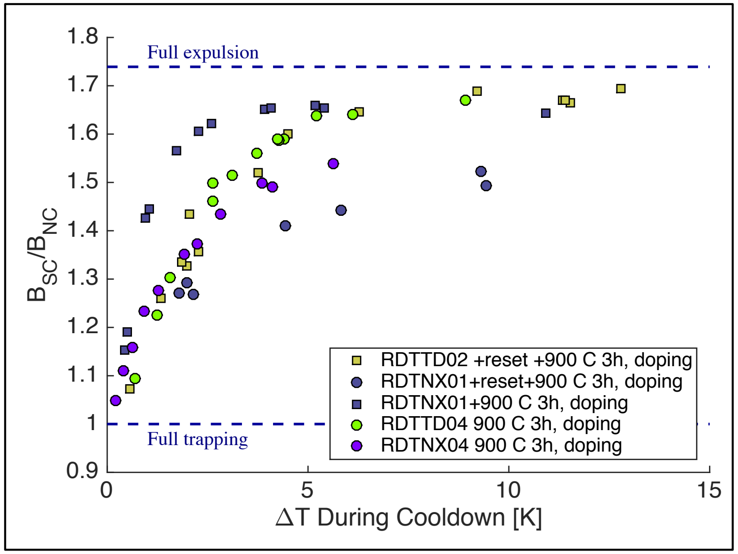
Cooling in 5 mG applied field (spec for background field in module)

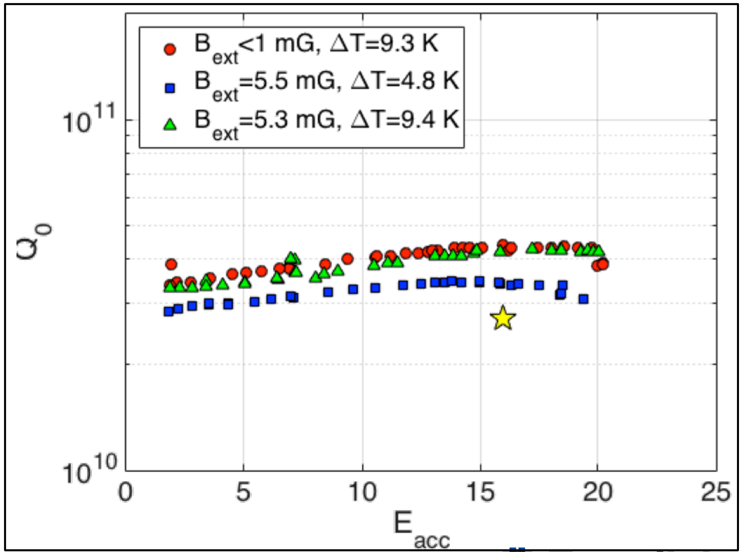
As-received niobium material for LCLS-II production: very poor expulsion





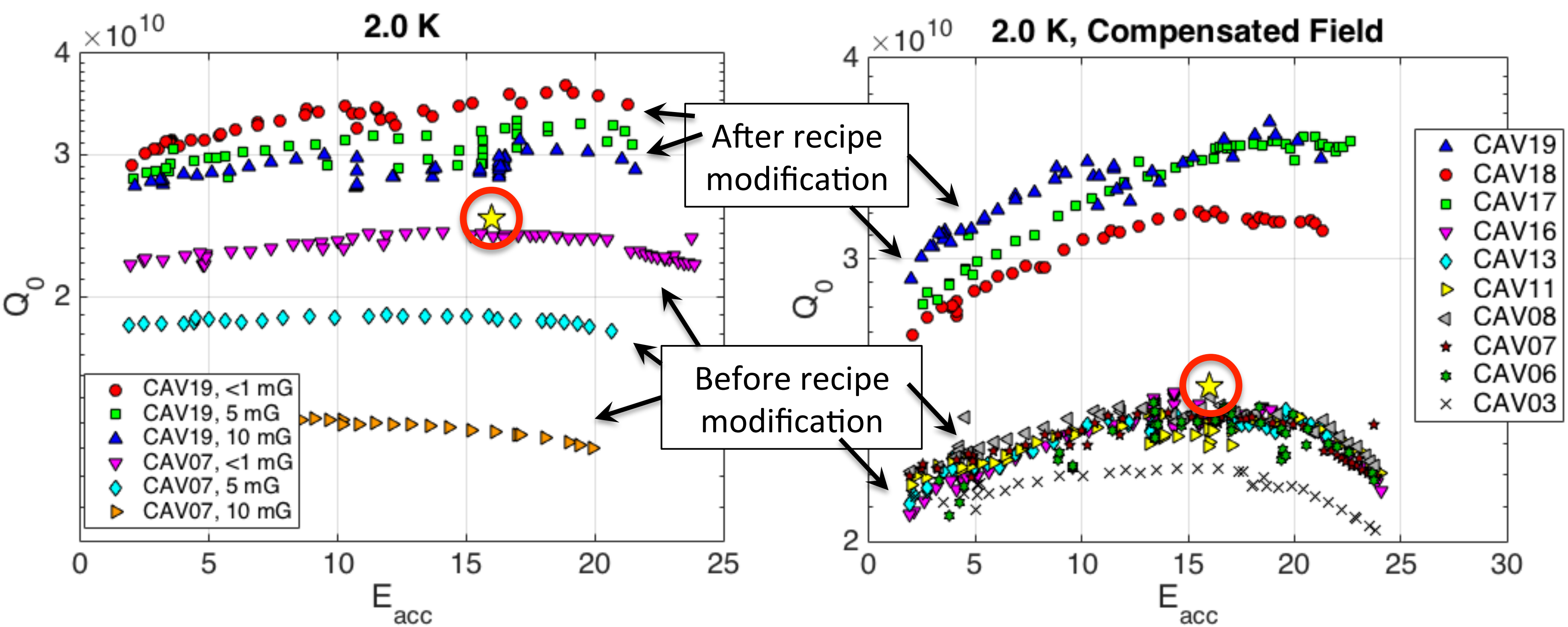
After 900°C treatment: much improved





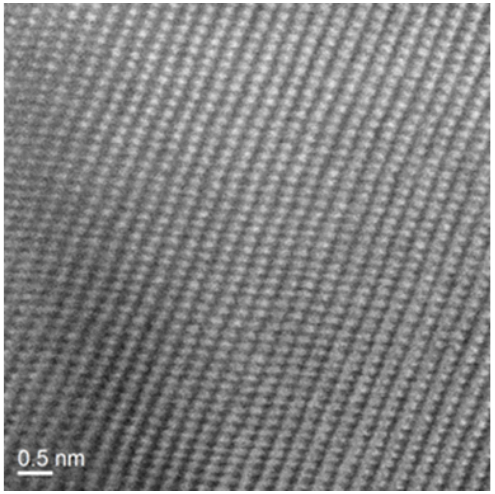
LCLS-II - Production

- After seeing results of first batch of 16 cavities, planned for modifications for next batch
- Modified recipe – 900 C now standard
- Still some stubborn material, but now qualifying great cavities!

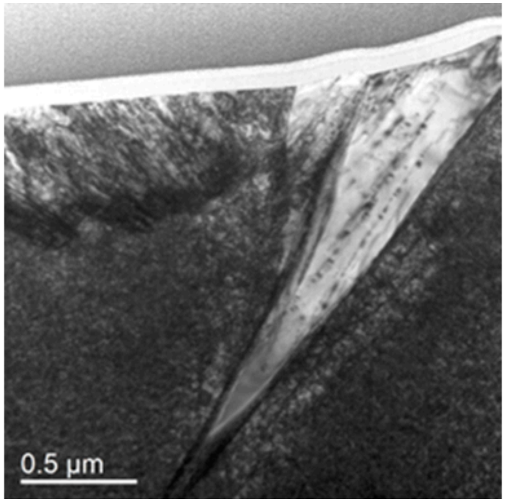


Outline

- High Q_0 (medium E_{acc})
  - Nitrogen doping
  - Flux expulsion
- High E_{acc} and high Q_0
  - Nitrogen infusion
  - Nb_3Sn
  - Plasma cleaning



Aberration-corrected STEM image of the near-surface of Nb cavity - Y. Trenikhina

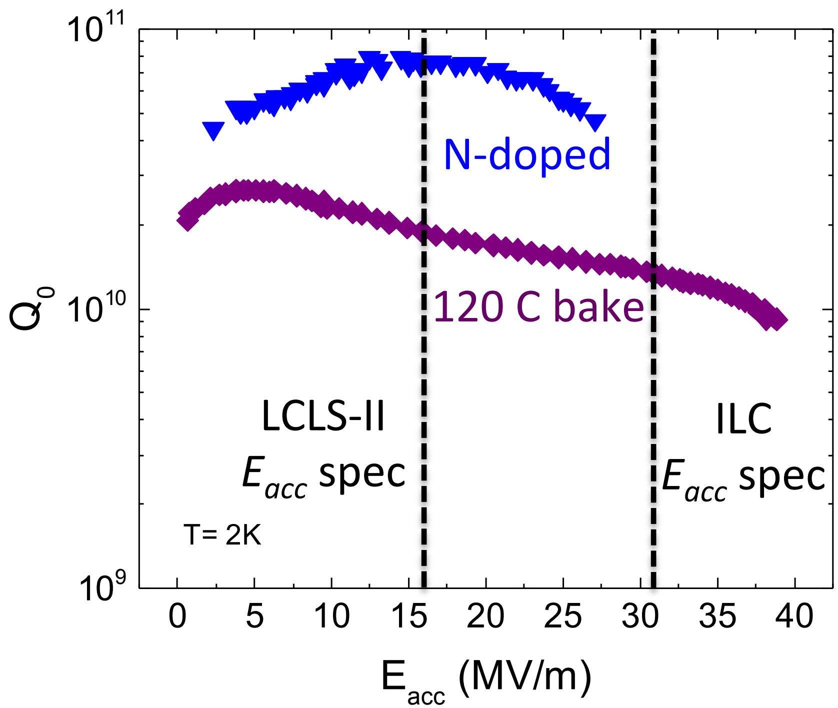


Niobium near-surface after the first step of nitrogen doping - Y. Trenikhina

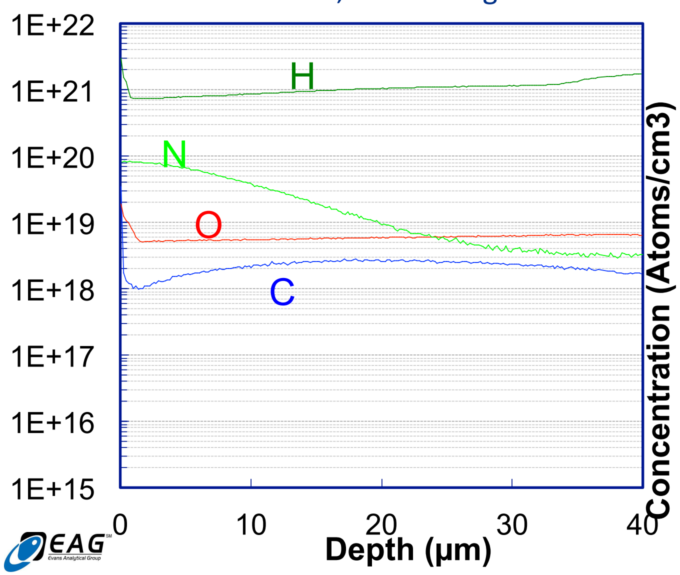
ILC cryomodule with world record gradient for FAST facility

Motivation behind experiments

- **N Doping** at T> 800C proven to manipulate mean free path, but constantly throughout several microns, **giving high Q**
- **120C bake** known to manipulate mean free path at very near surface on clean bulk, and **produce the highest gradients**



A. Grasselino et al, Proceedings of SRF 2015



N doping, nitrogen throughout several microns

Slide from A. Grassellino

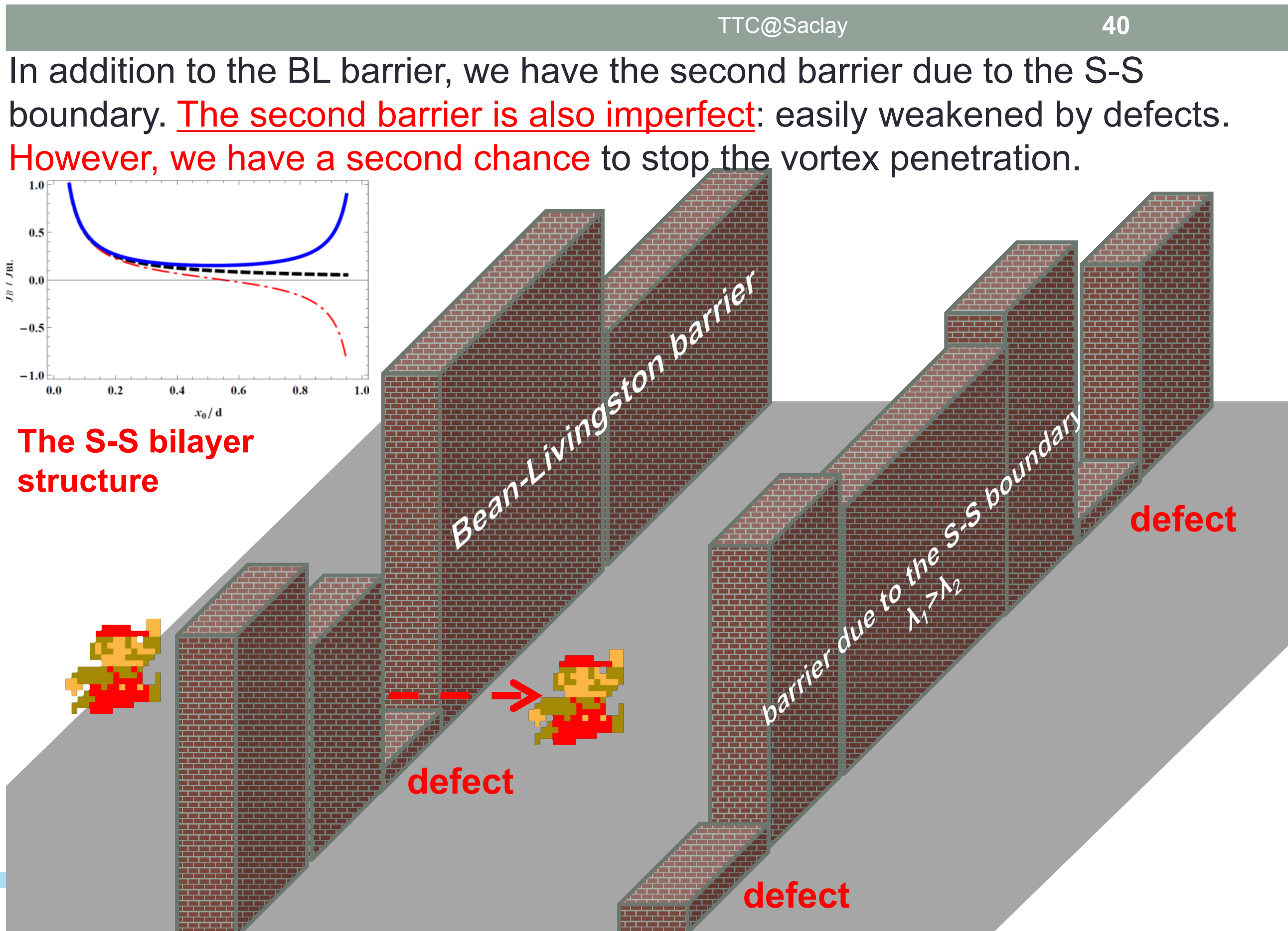
Motivation behind experiments

- Therefore, we decided to study how to better "**engineer**" a dirty layer on top a clean bulk, using low T nitrogen treatments → aim to **create few to several nanometers of nitrogen enriched layer** on top of clean EP bulk, to attempt to bring together the benefit of the Q and gradient
- Nitrogen enriched nanometric layer to be created in the furnace post 800C treatment – when no oxide is present at the moment of injection of nitrogen at low T
- Studies aim also at fundamental understanding of HFQS and 120C cure of high field Q slope

Slide from A. Grassellino

Kubo and Checchin models on bi-layer potentially increasing achievable accelerating gradients

- This idea is further strenghtened by Checchin (FNAL) and Kubo (KEK) models on bi-layer structure (eg dirty N doped layer on clean Nb) –claim that can enhance the achievable accelerating gradient
- Ideal Depth of this layer ? Can this trick help push beyond the 200 mT or achieve 200 mT with higher yield? <u>We are investigating this empirically via low T N infusion (different T and durations)</u>

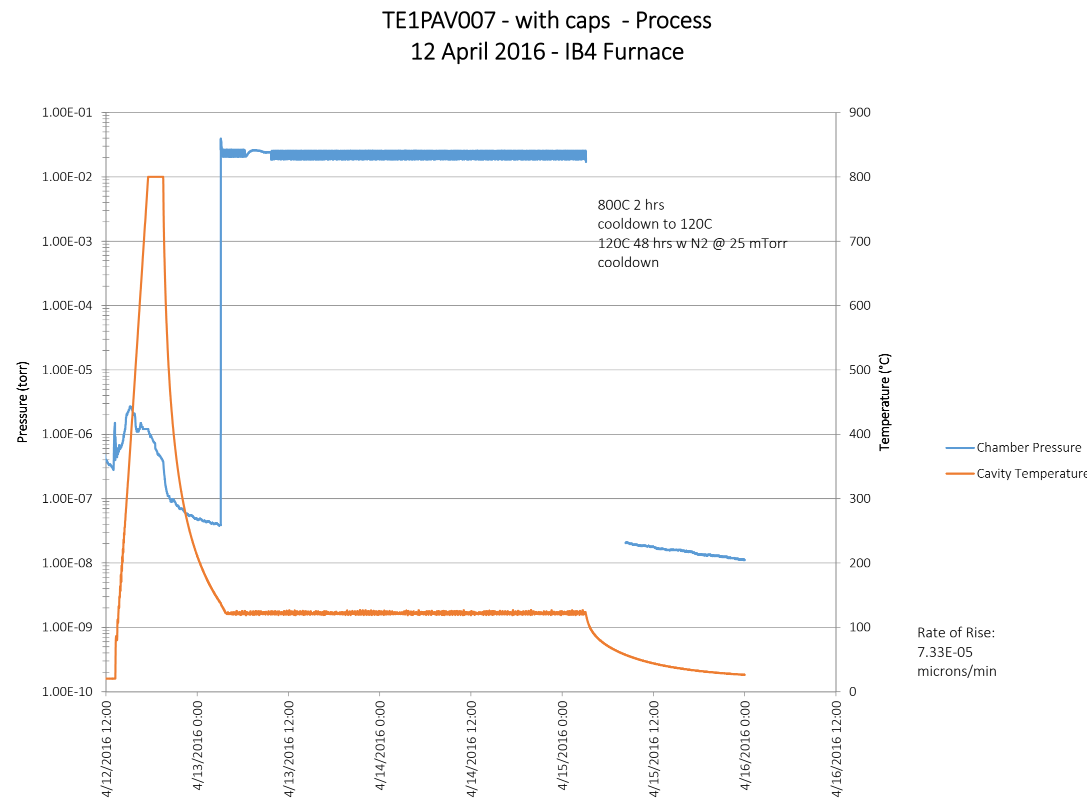


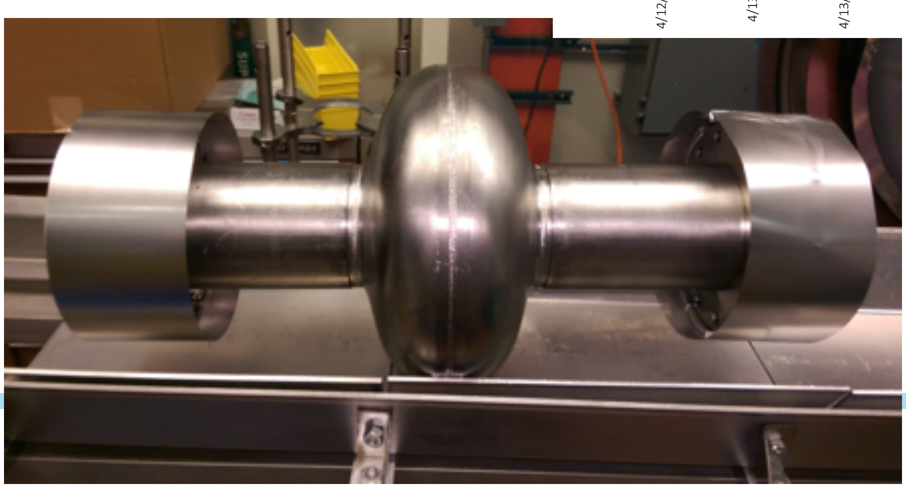
T. Kubo, TTC Meeting 2016

Slide from A. Grassellino

Example of new surface processing sequence

- Bulk electro-polishing
- High T furnace with caps to avoid furnace contamination:
  - 800C 3 hours HV
  - 120C 48 hours with N2 (25 mTorr)
- NO chemistry post furnace
- HPR, VT assembly





Protective caps and foils are BCP'd prior to every furnace cycle and assembled in clean room, prior to transporting cavity to furnace area

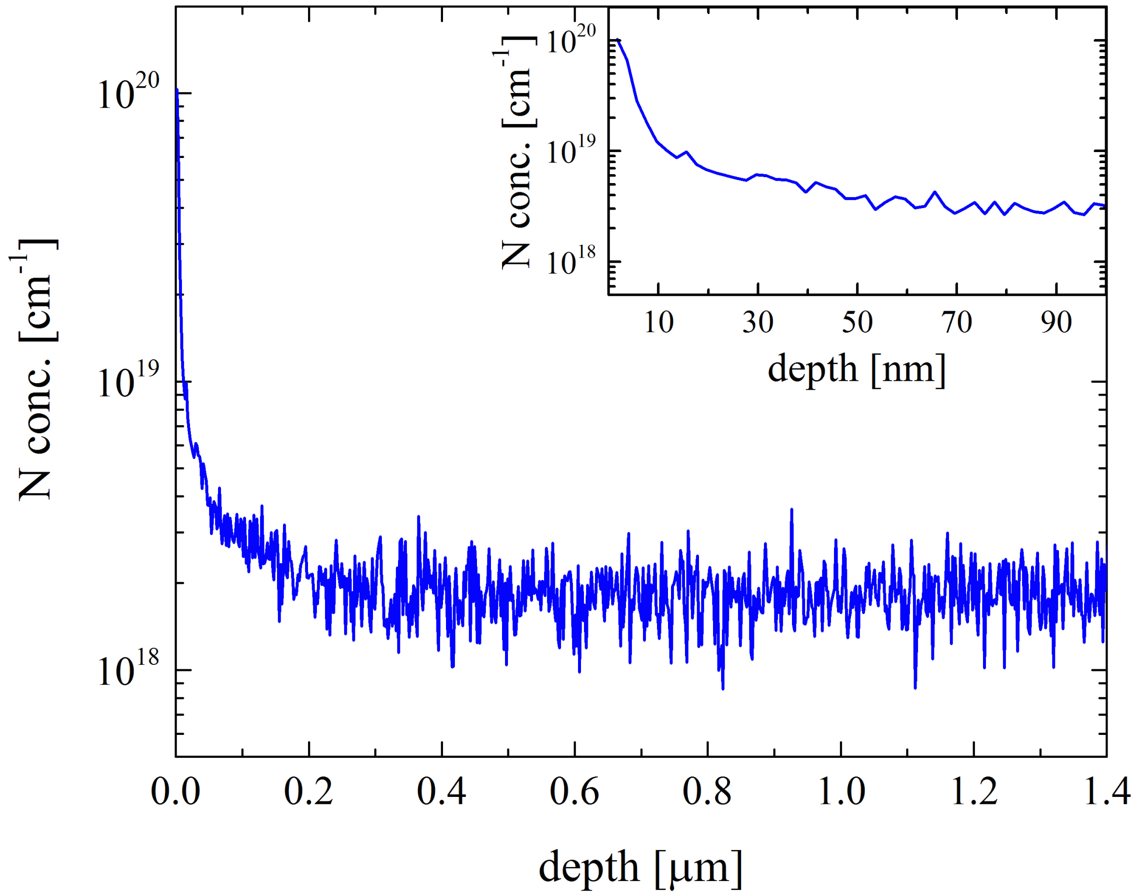
A. Grassellino et al, **arXiv:1305.2182**

Fermilab

Slide from A. Grassellino

To what depth does nitrogen diffuse?

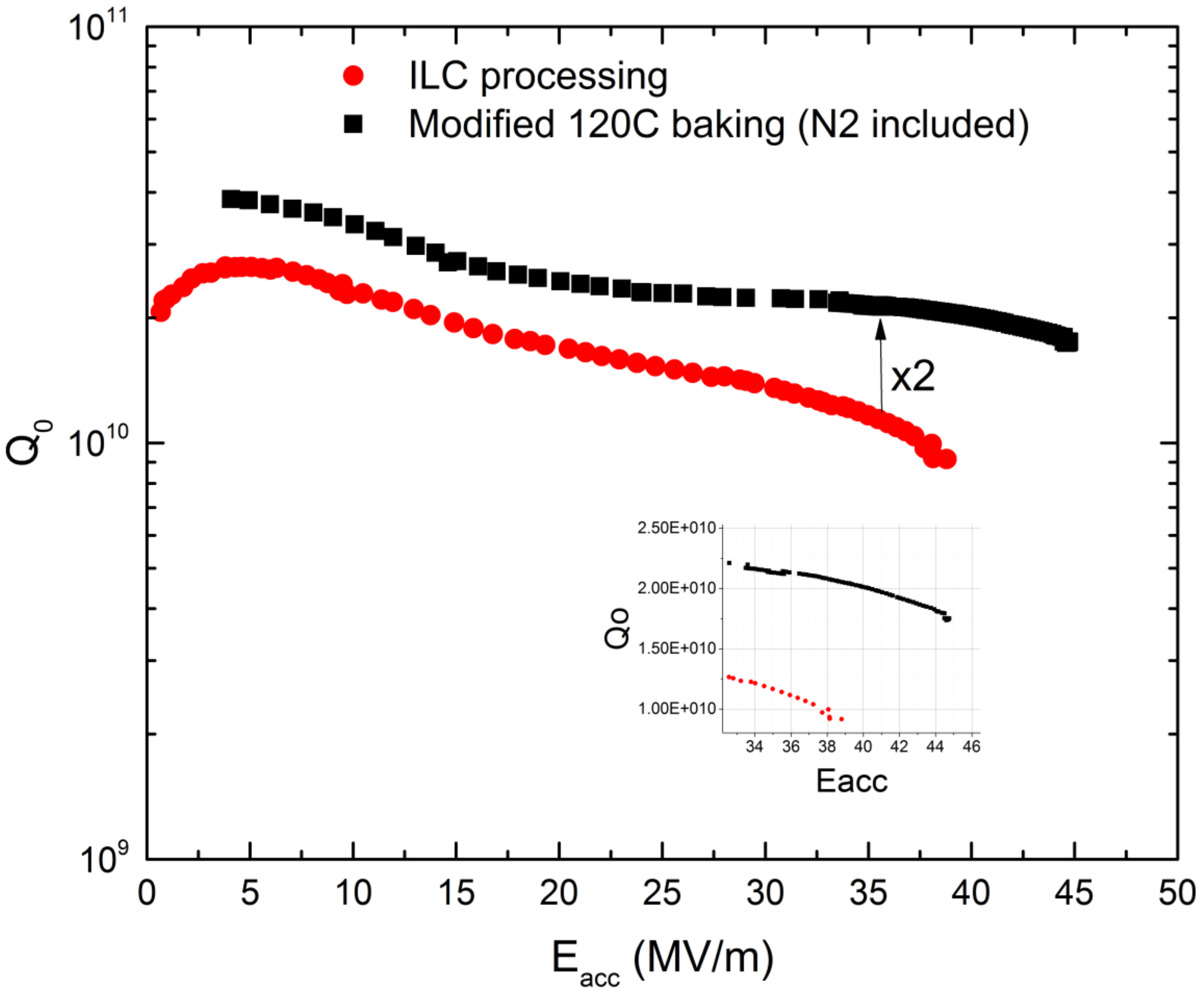
- First SIMS measurements on samples baked with cavities in furnace with N at low T show ~ few-tens nm potential nitrogen enriched layer, depending on T used



Fermilab

Slide from A. Grassellino

Results comparison :
"standard" 120C bake vs "N infused" 120C bake

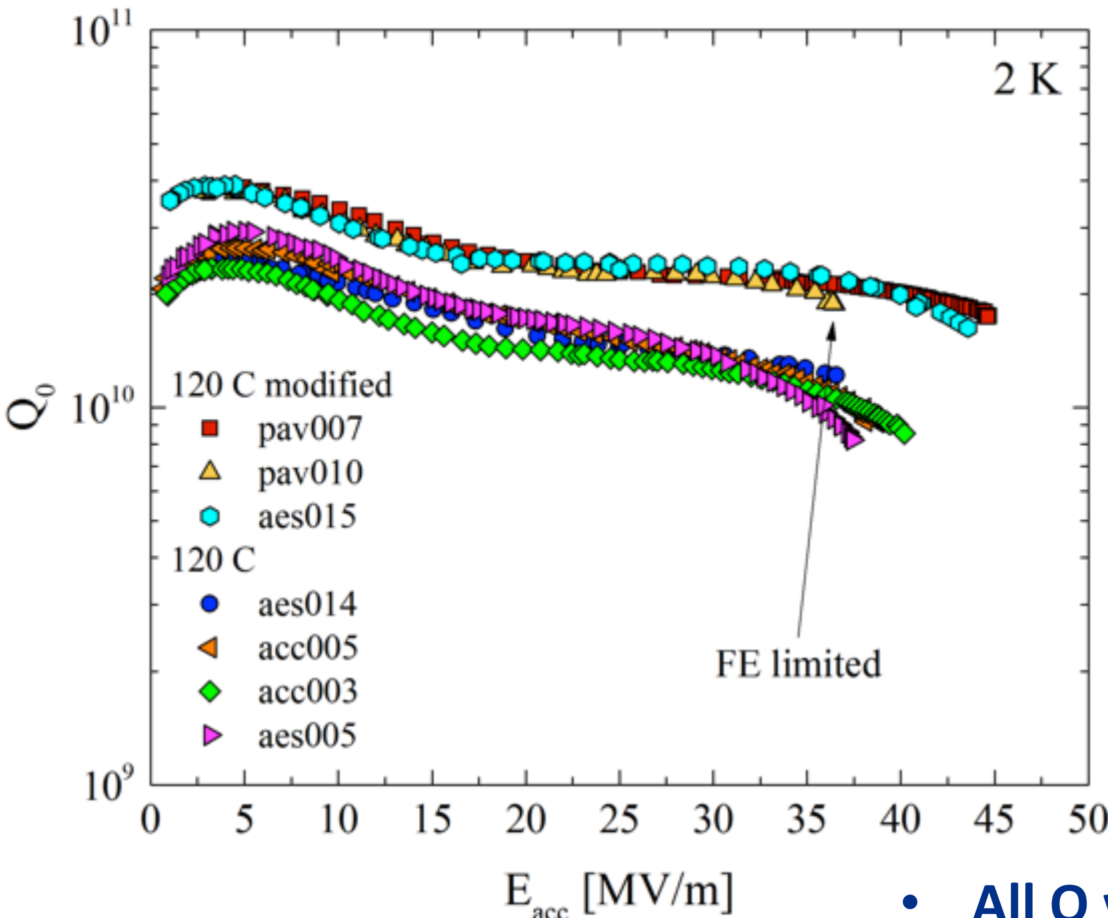


Increase in Q factor of two, increase in gradient ~15%

- Same cavity, sequentially processed, no EP in between
- Achieved: 45.6 MV/m → 194 mT With Q ~ 2e10!
- Q at ~ 35 MV/m ~ 2.3e10
- **All Q vs E curves shown are for 1.3 GHz single cells, T=2K**

Slide from A. Grassellino

Reproducibility: repeatedly highest Q ever measured >2e10 at very high gradients > 40 MV/m!



- So far three out of 4 cavities processed with this regime have reached 45 MV/m with high Q

- Performed slow cooldown in 10mG and extracted very low sensitivity to B on order of 0.3 nOhm/mG -> very robust for Q preservation

- **All Q vs E curves shown are for 1.3 GHz single cells, T=2K**

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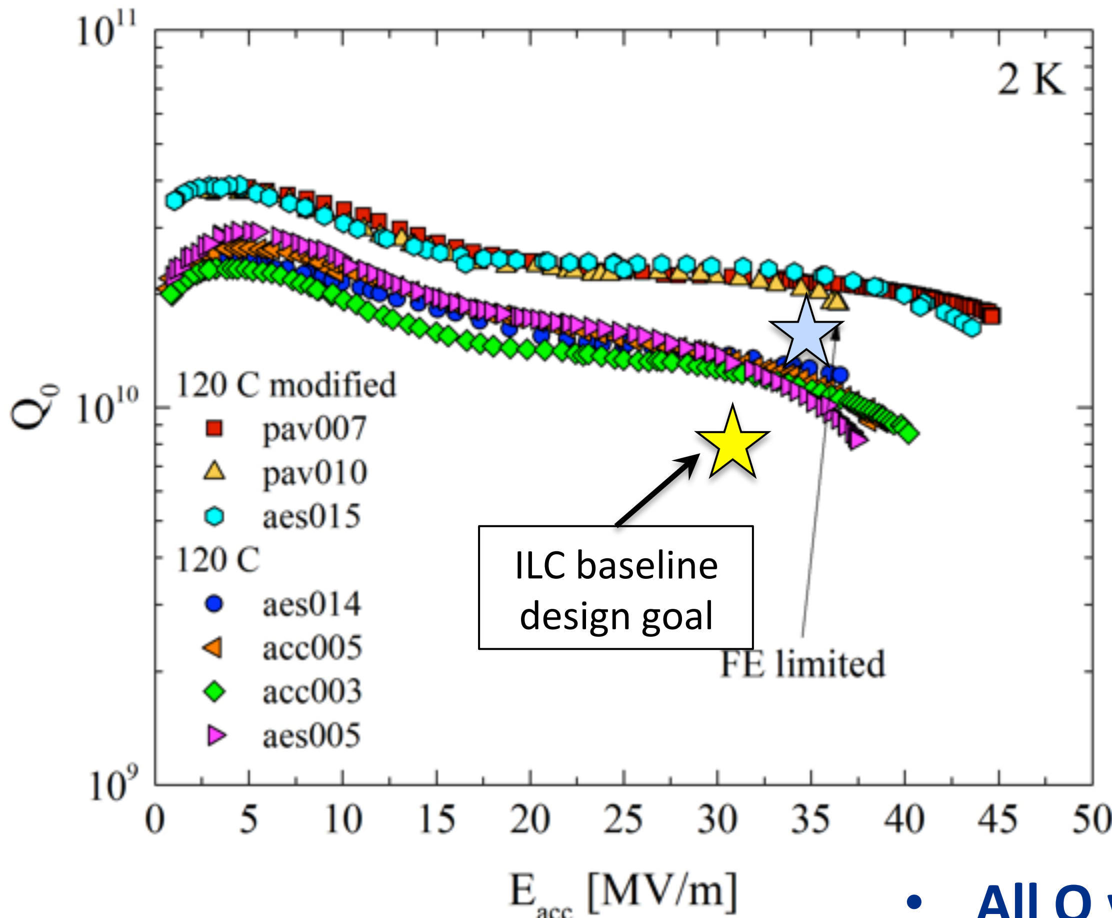

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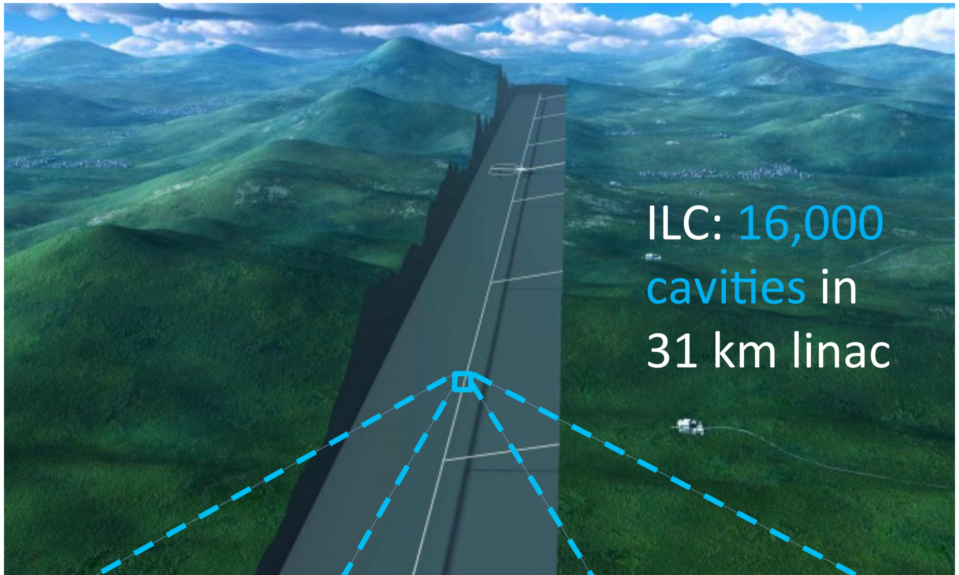
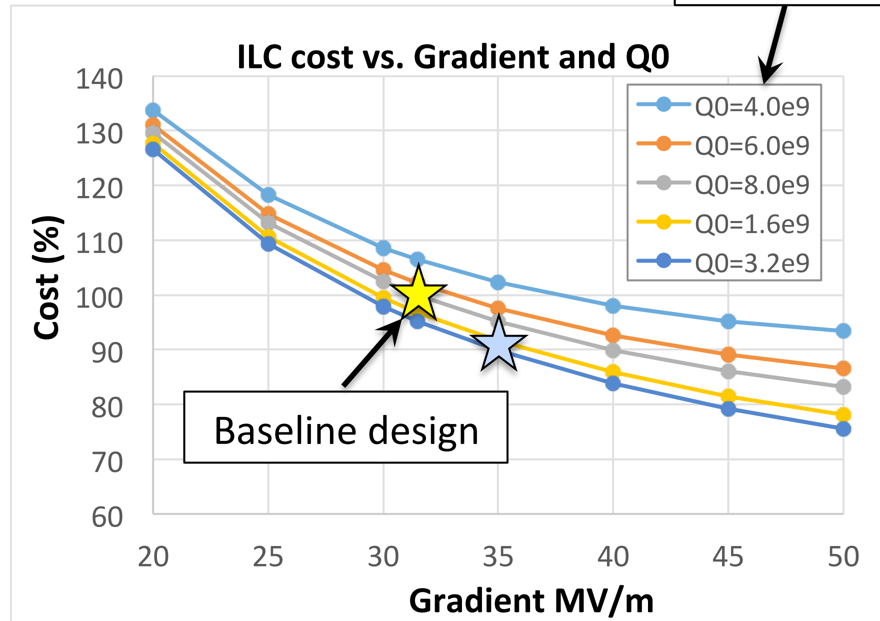
Slide from A. Grassellino

Gradient -> Length for Linear Accelerator

Q_0 also important!





8 cavities

~10 m

Fermilab

Outline

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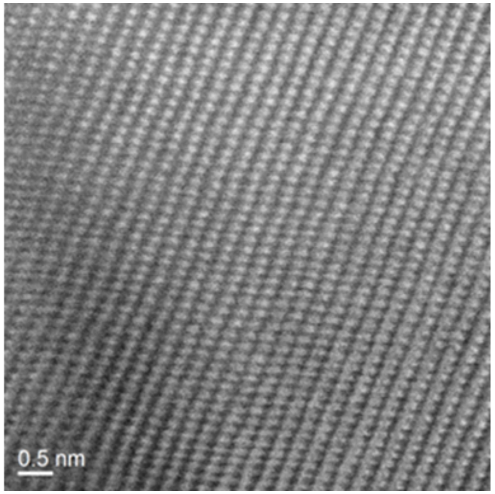
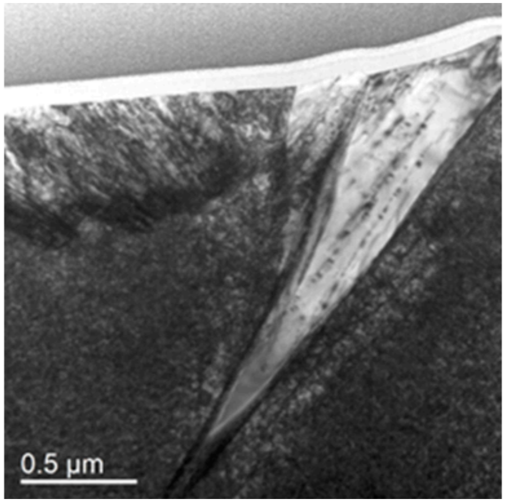


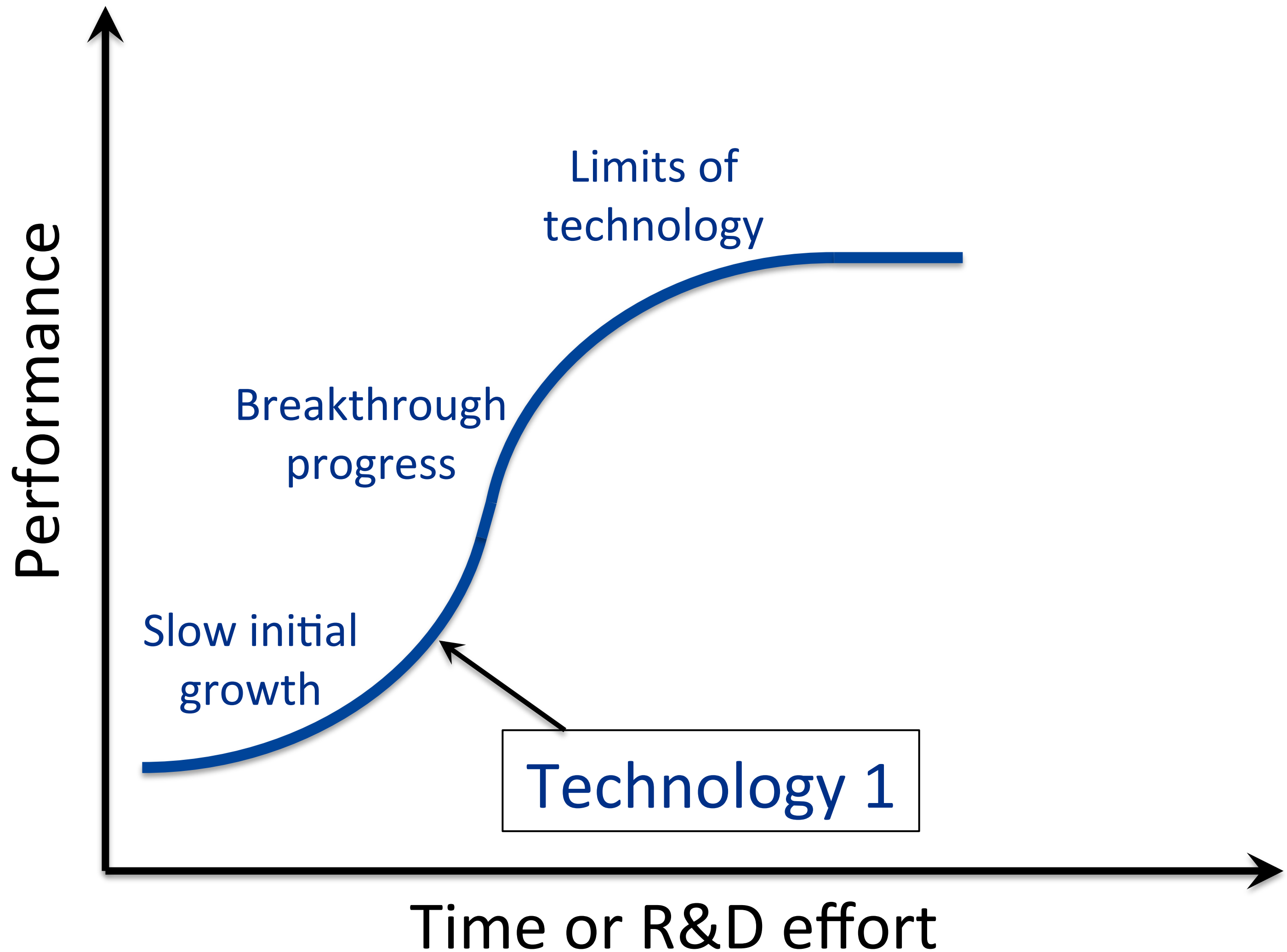
Aberration-corrected STEM image of the near-surface of Nb cavity - Y. Trenikhina



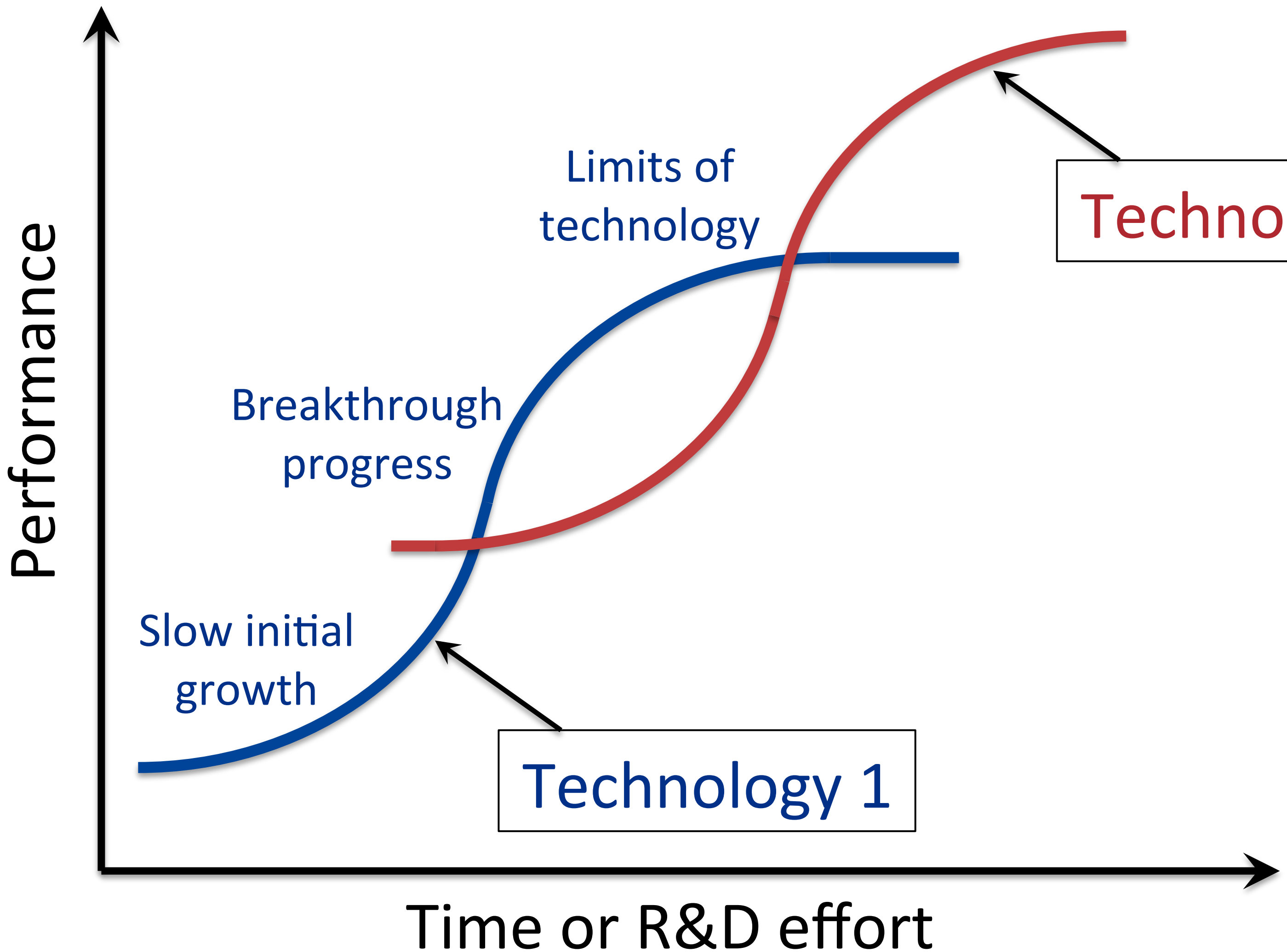
Niobium near-surface after the first step of nitrogen doping - Y. Trenikhina

ILC cryomodule with record average gradient for FAST facility

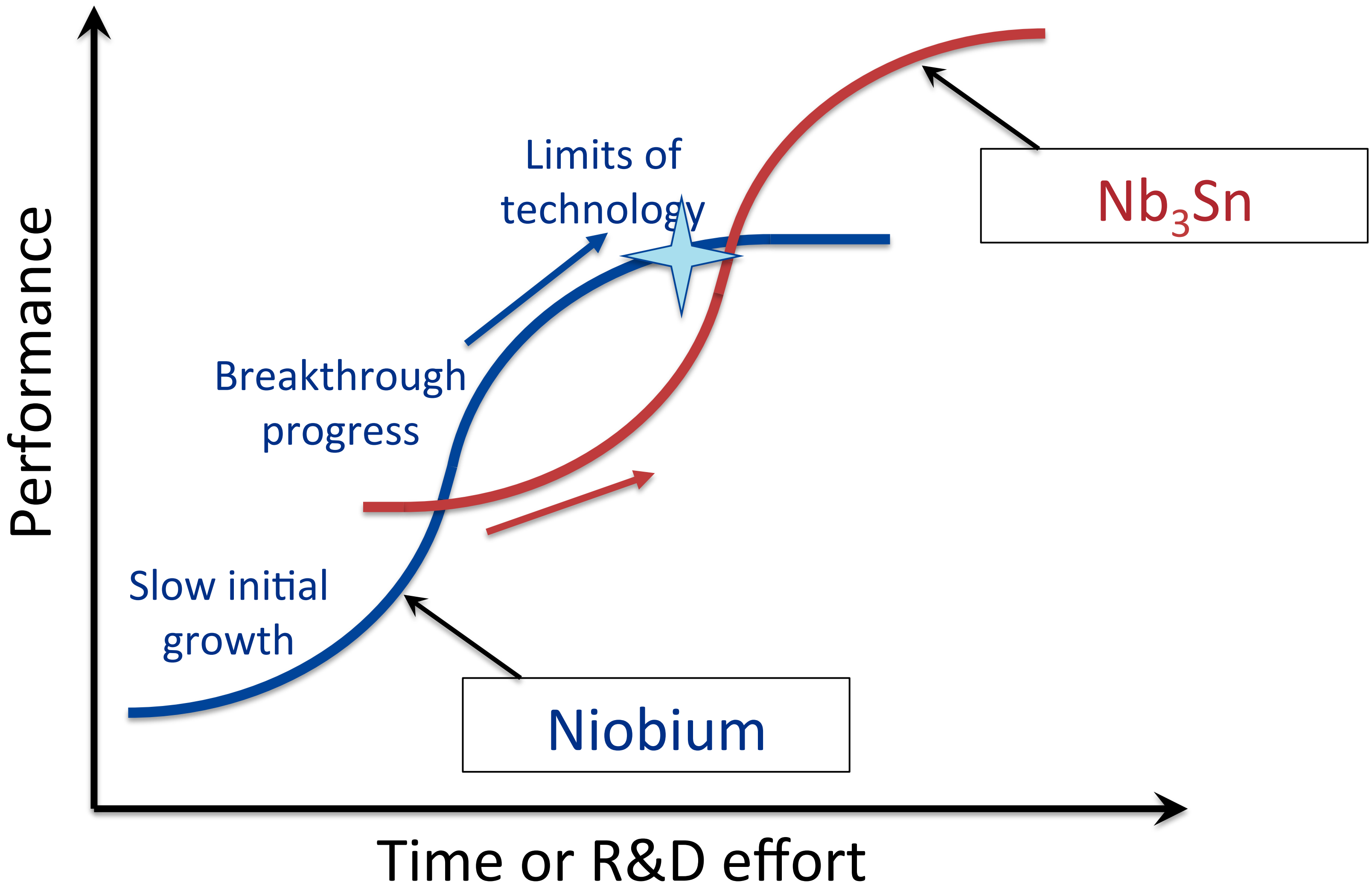
‘S-shaped technology curve’



‘S-shaped technology curve’



‘S-shaped technology curve’

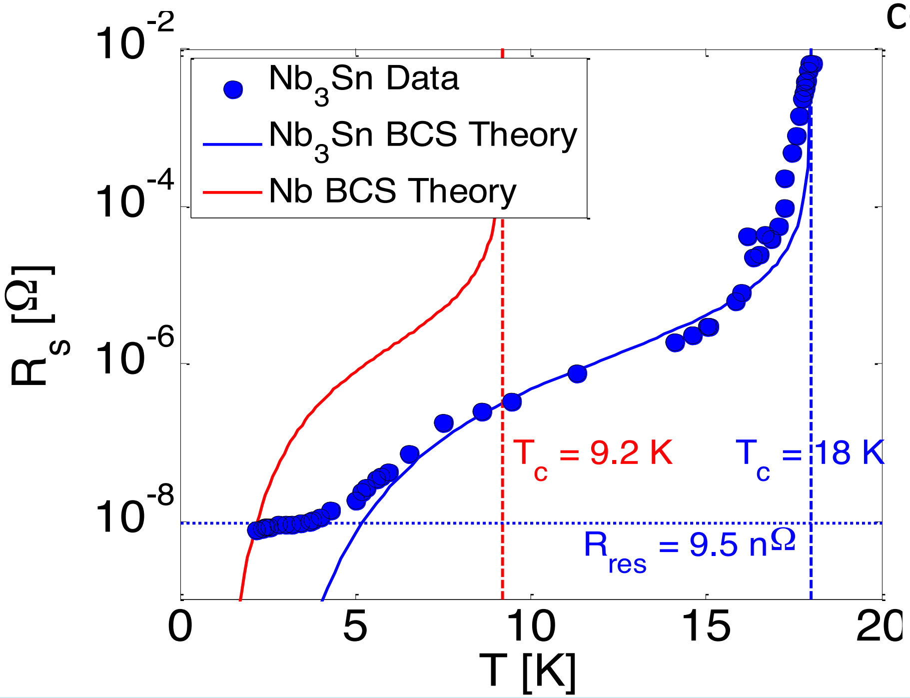


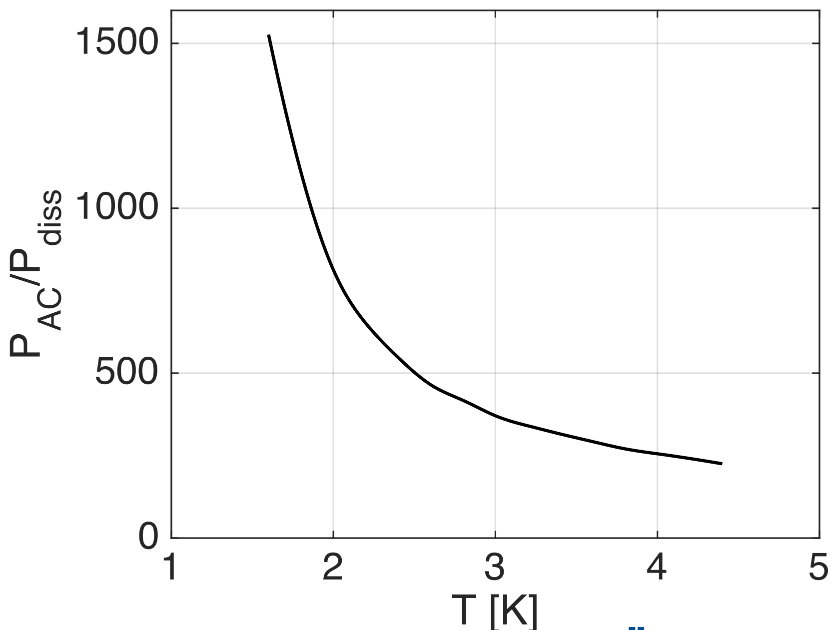
Fermilab

Nb_3Sn $Q_0(T)$

- Large $T_c \sim 18$ K
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76T_c/T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

Big effect! Cryoplants for large installations cost ~$100 million and require MW of power

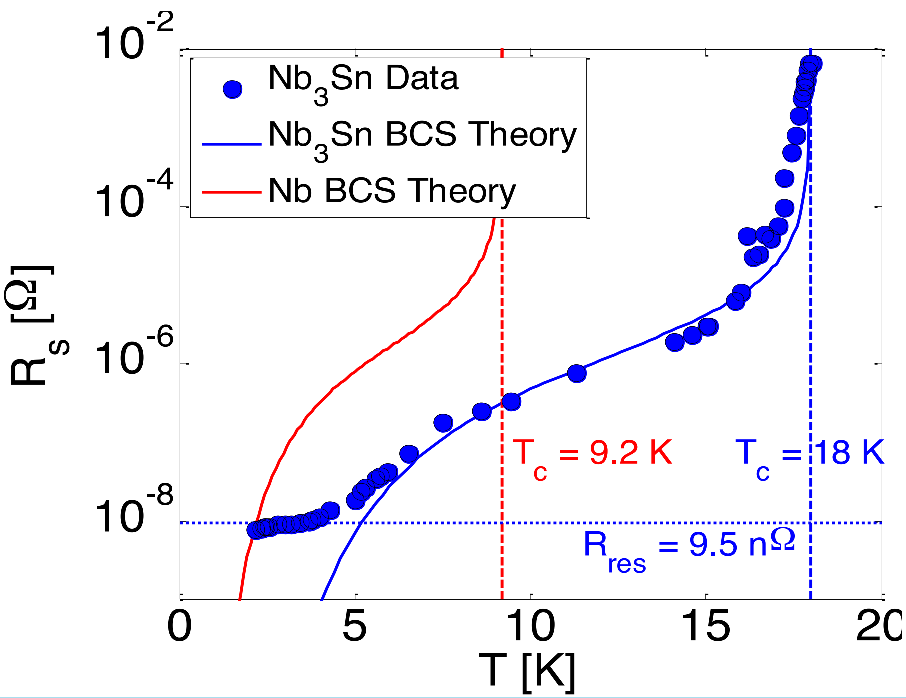


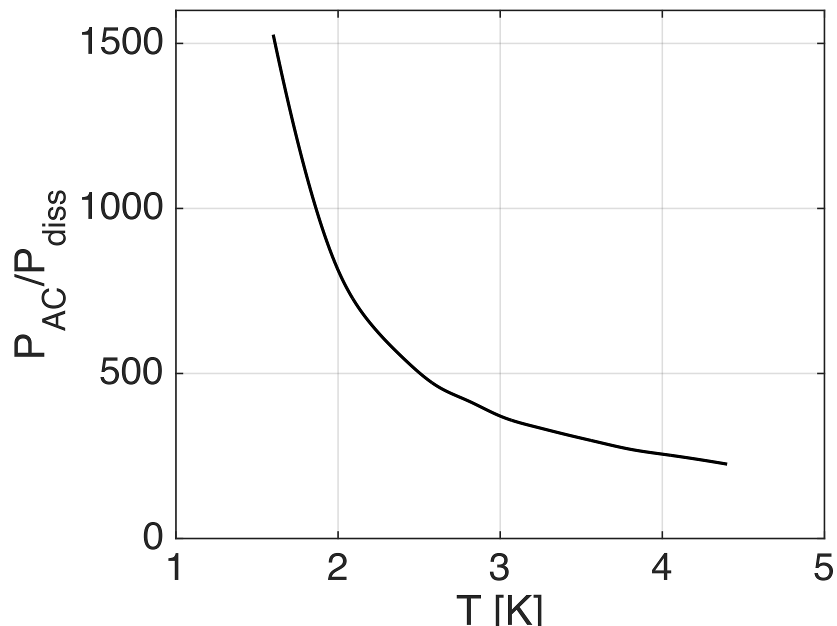


Higher $Q_0(T)$ with Nb_3Sn

- Large T_c ~ 18 K
  - Very small $R_{BCS}(T)$ – $R_{BCS}(T) \sim e^{-1.76 T_c / T}$
  - High Q_0 even at relatively high T
- Higher temperature operation
  - Simpler cryogenic plant
  - Higher efficiency

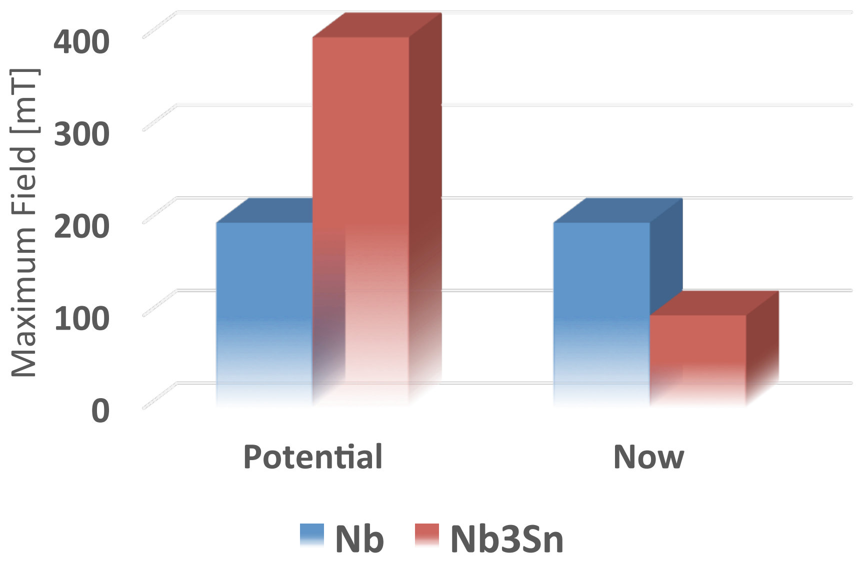
Possibility of cryocooler operation! Industrial accelerators for treatment of wastewater & flue gas, border security…

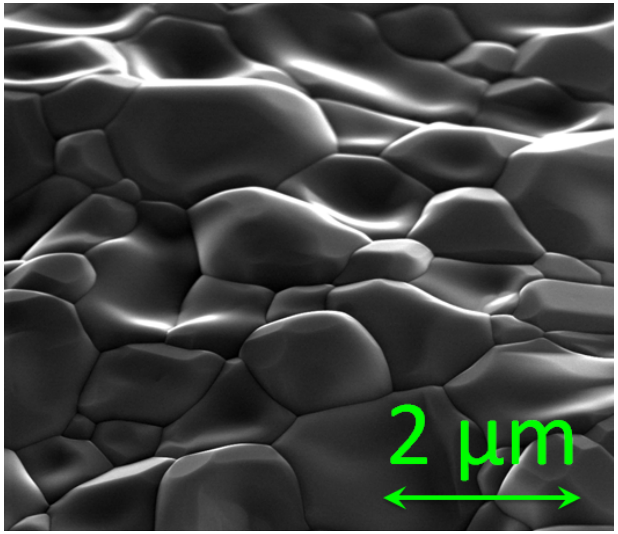




High H_{sh} with Nb_3Sn

- Nb_3Sn is predicted to have **2x** the fundamental metastable limit of niobium

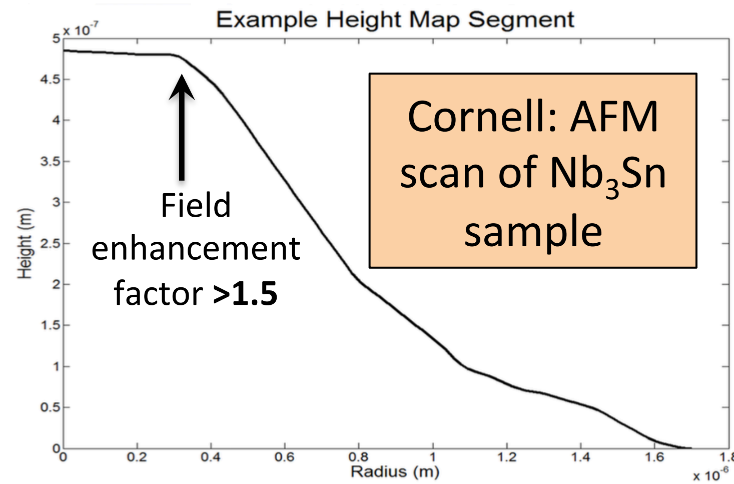


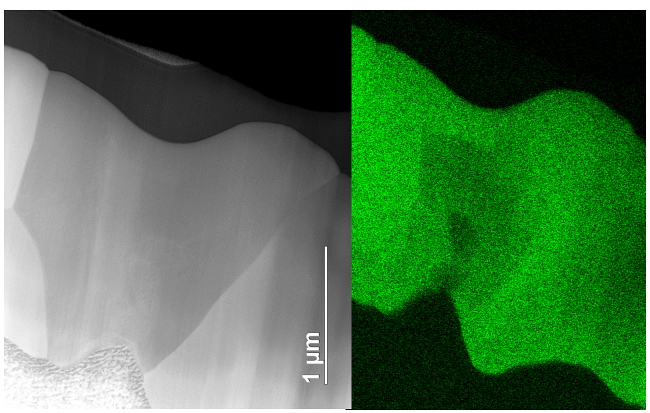


- Twice the energy gain per cavity?
- Not there yet—additional R&D required

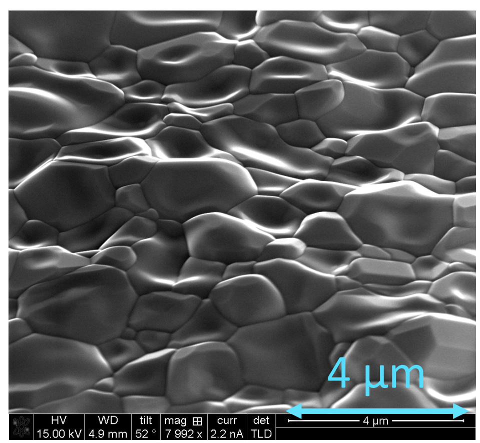
Increasing E_{acc} in Nb_3Sn Cavities

- Substantial recent improvement in maximum E_{acc} with high Q_0
- Several promising paths forward for continued progress including:
  - Smooth sharp-edged surfaced
  - Reduce low tin content regions
- 20-40% increase: 22-25 MV/m

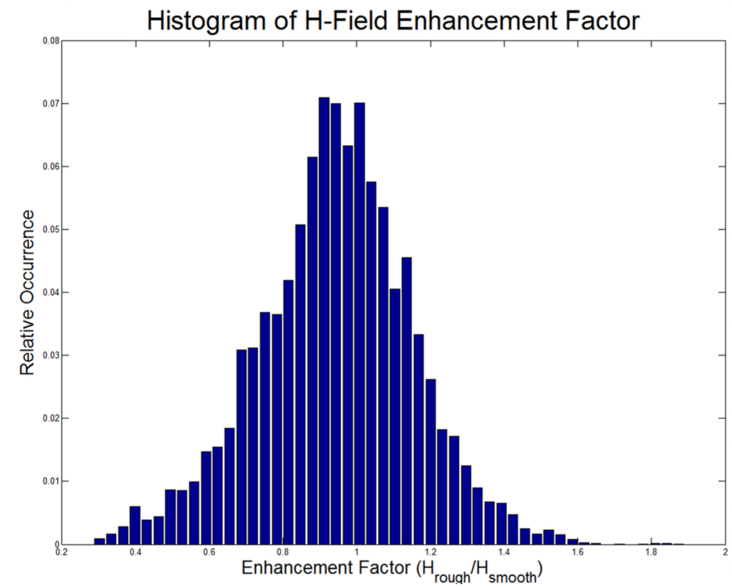




Y. Trenikhina, S. Posen, D. Hall, and M. Liepe, Proc. SRF Conference 2015, TUPB056, 2015



S. Posen, Ph.D. Thesis, Cornell University (2015).

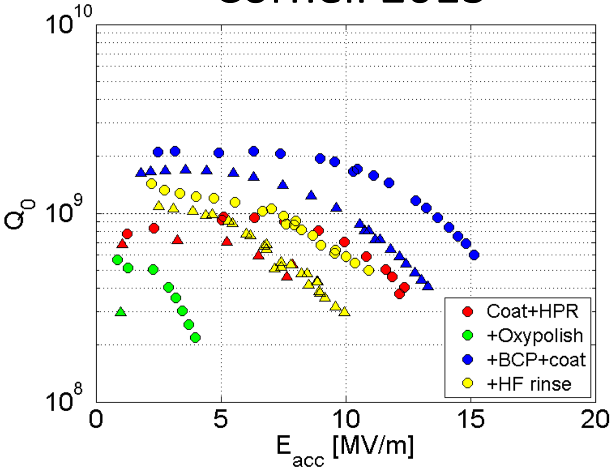


R. Porter, D. L. Hall, M. Liepe, J. T. Maniscalco, Proc. Linac Conference 2016, MOPRC027 (2016).

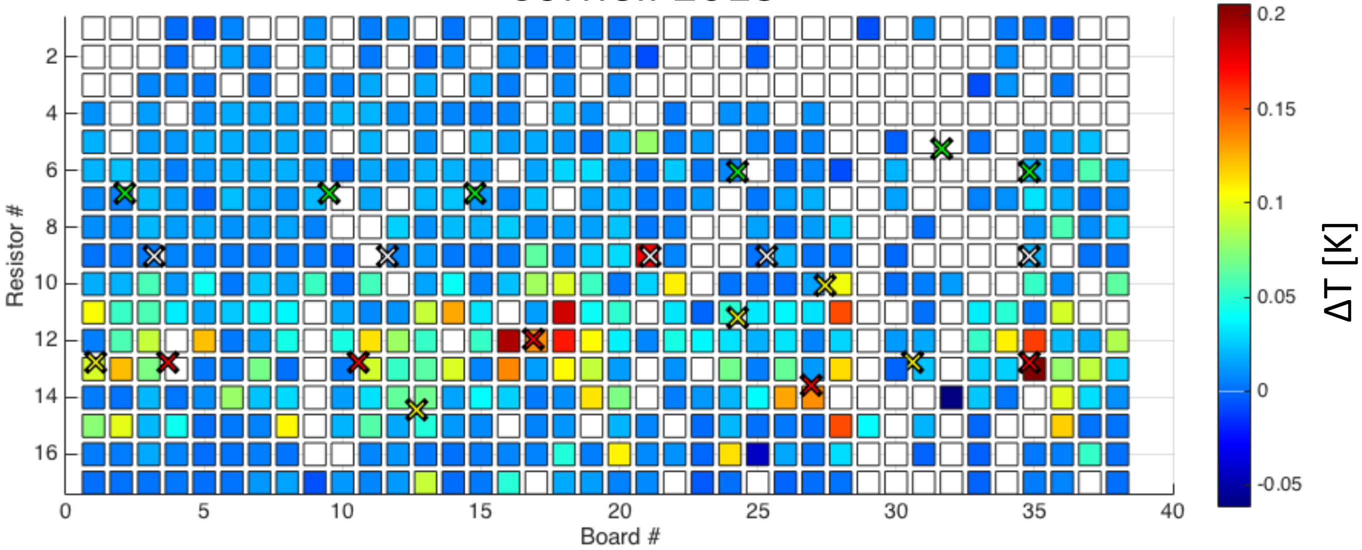
Coupons from Poorly Performing Cavity

- Poorly performing cavity coated in 2013
- In collaboration with Cornell, both labs retested it and cut out coupons from regions that showed high R_s and low R_s (hot spots and cold spots)

Cornell 2013

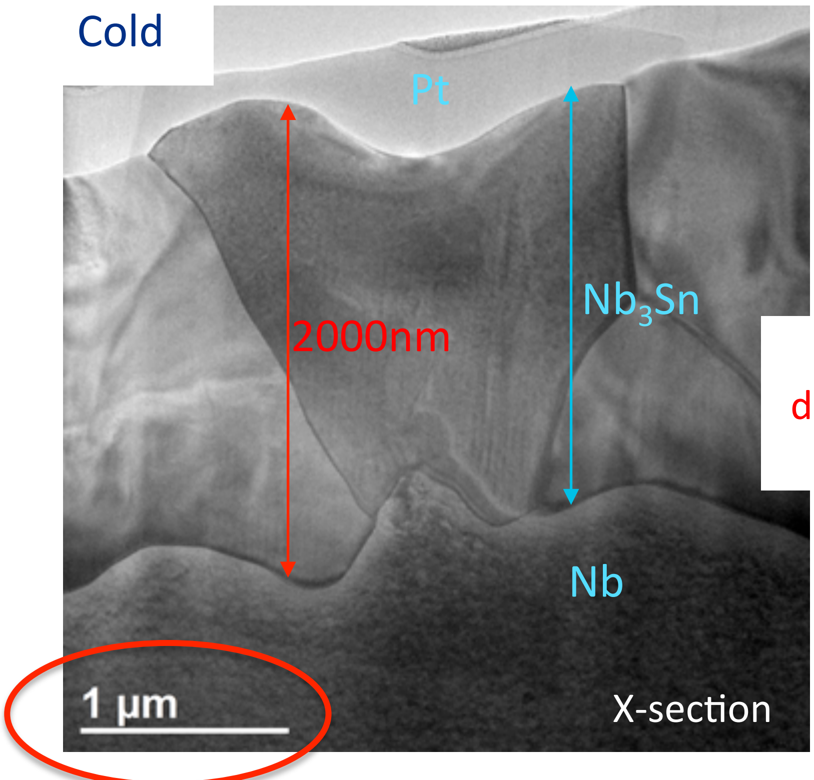


Cornell 2013

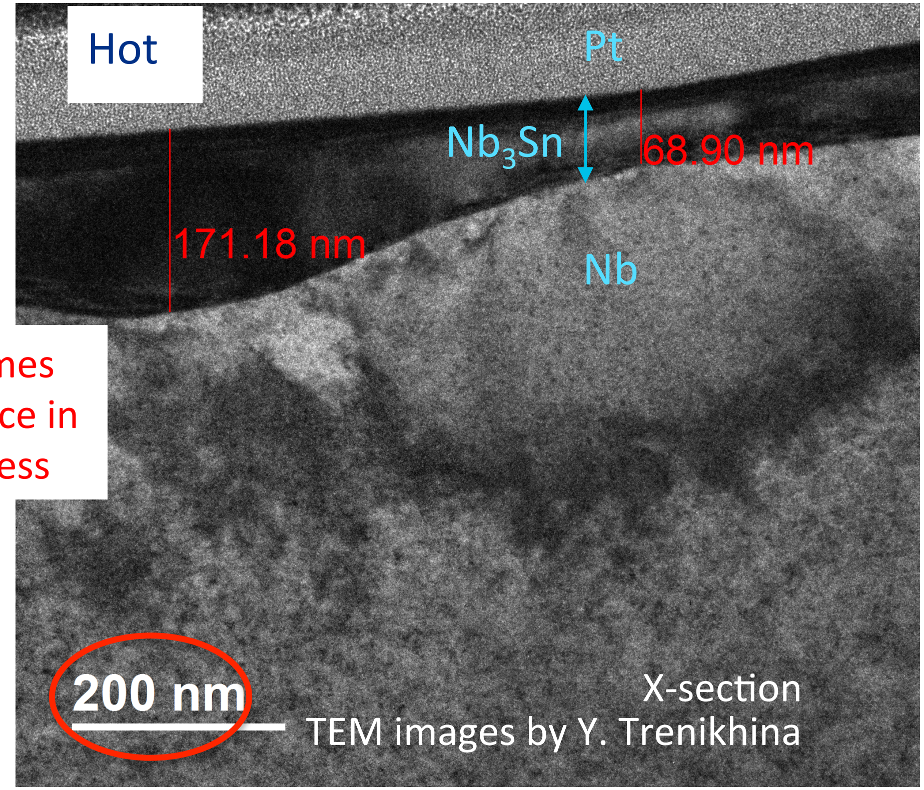


Fermilab

Thin Coatings in High Dissipation Hot Spots



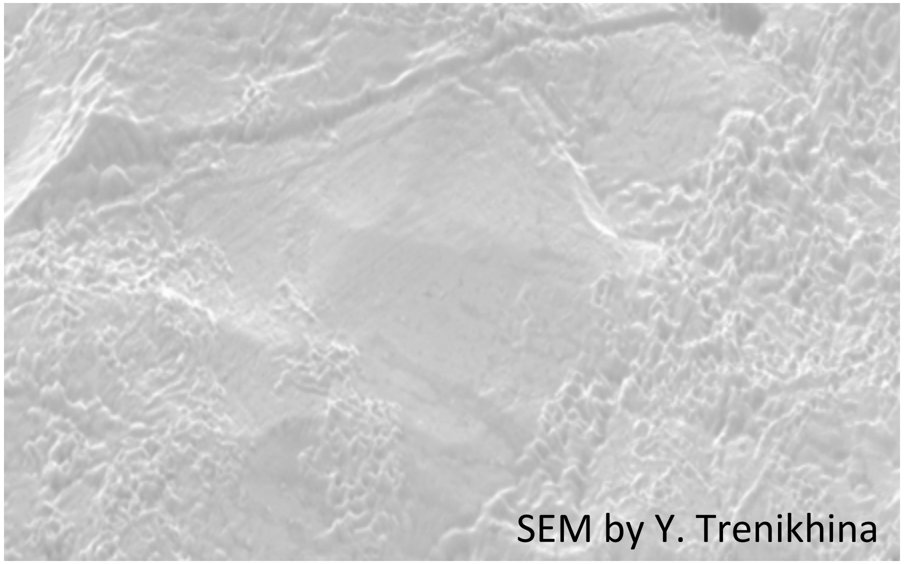
>10 times difference in thickness

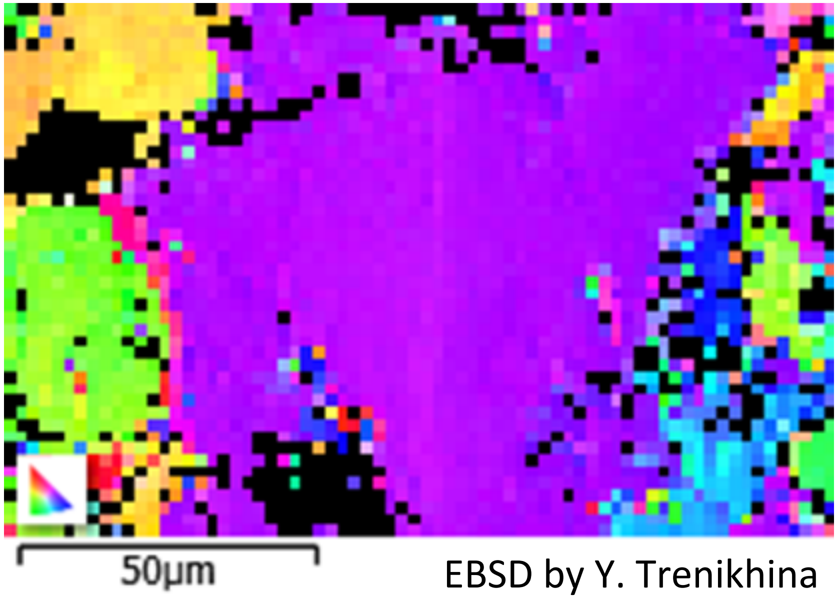


- Regions with highest dissipation show very thin coatings, not thick enough to fully screen RF currents from Nb and intermediate Nb-Sn phases below Nb_3Sn layer

Thin Regions are Unusually Large Grains

- EBSD analysis of grain orientation reveals that the thin regions in the hot spots are in fact large grains, with diameter ~100 microns vs ~1 micron for standard Nb_3Sn grains

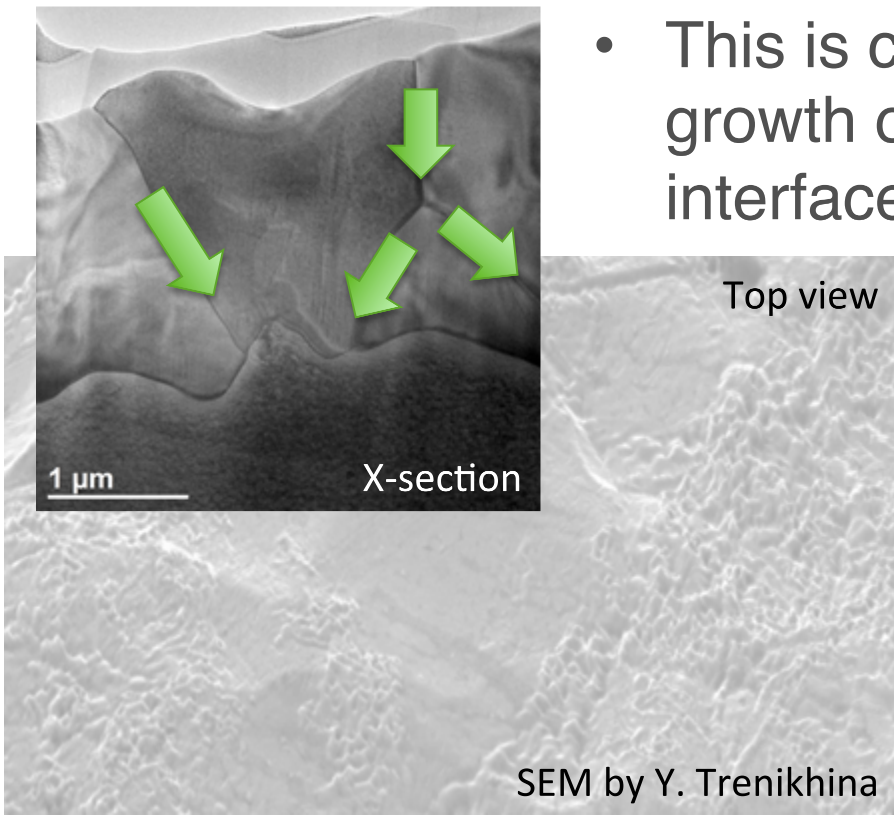

SEM by Y. Trenikhina

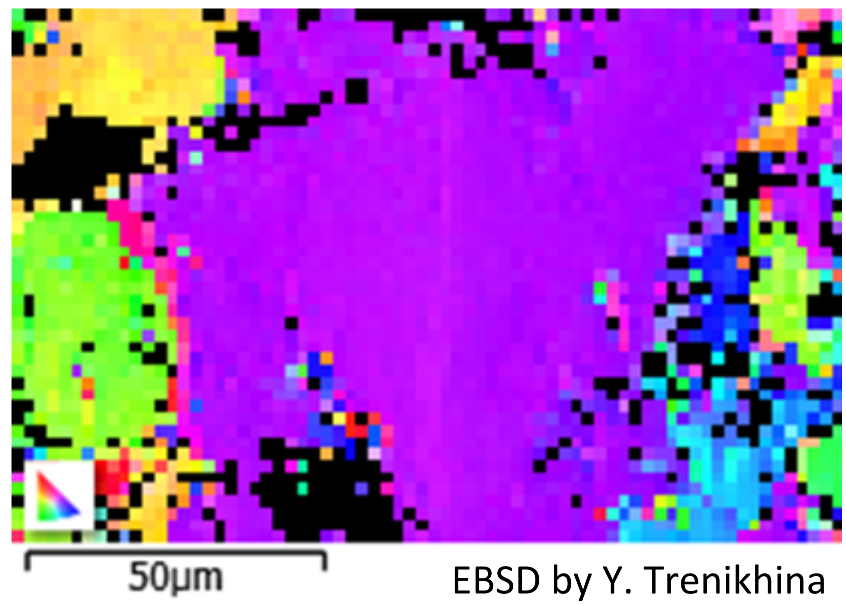


EBSD by Y. Trenikhina

Thin Regions are Unusually Large Grains

- EBSD analysis of grain orientation reveals that the thin regions in the hot spots are in fact large grains, with diameter ~100 microns vs ~1 micron for standard Nb_3Sn grains
  - This is consistent with mechanism for growth of grains: diffusion of tin to interface via grain boundaries





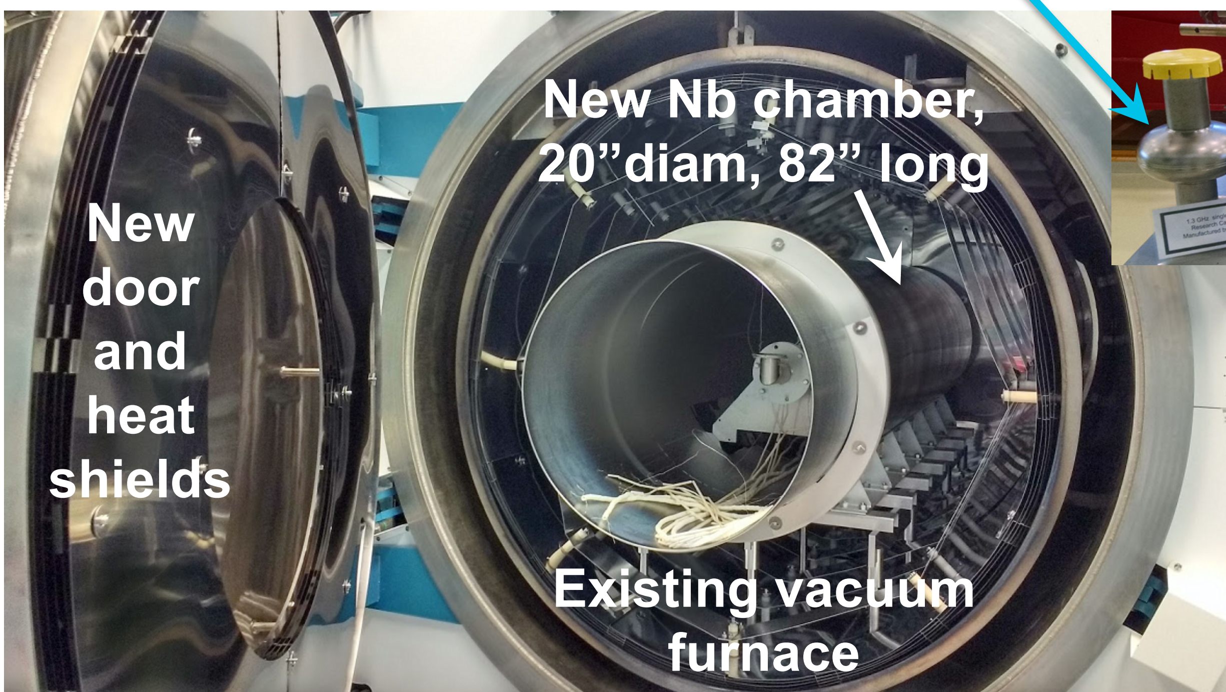
EBSD by Y. Trenikhina

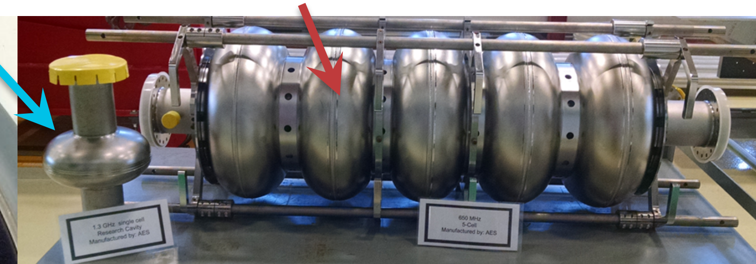
Nb_3Sn SRF Experimental Program at Fermilab

- Goals: 1) further improvement to Q_0 and E_{acc} 2) scale up to production-style cavities
- Large Nb_3Sn SRF coating apparatus recently commissioned
- First samples coated Jan 30, 2017

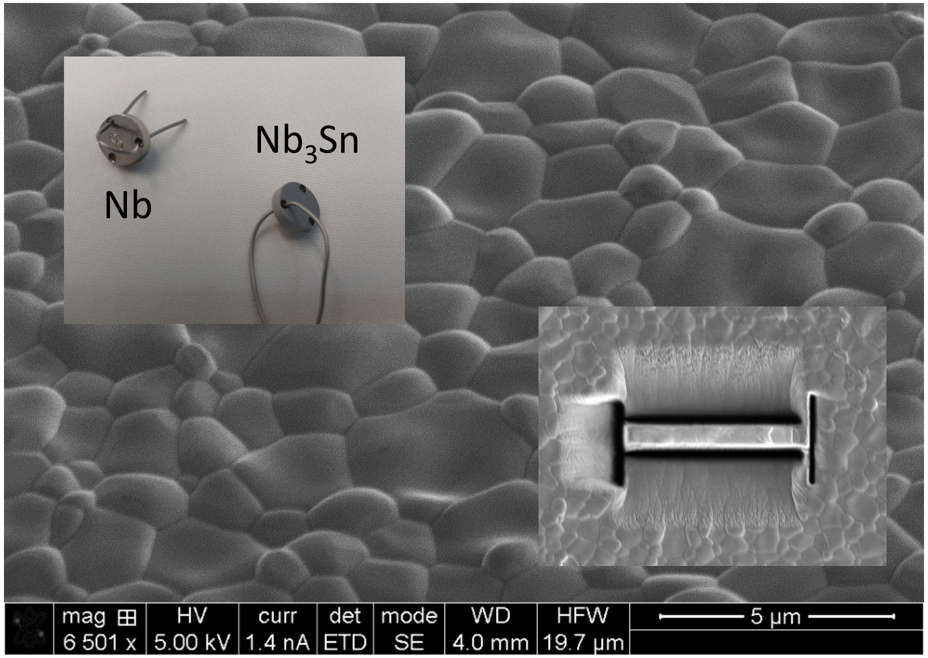
1.3 GHz 1-cell (current state of Nb_3Sn R&D)

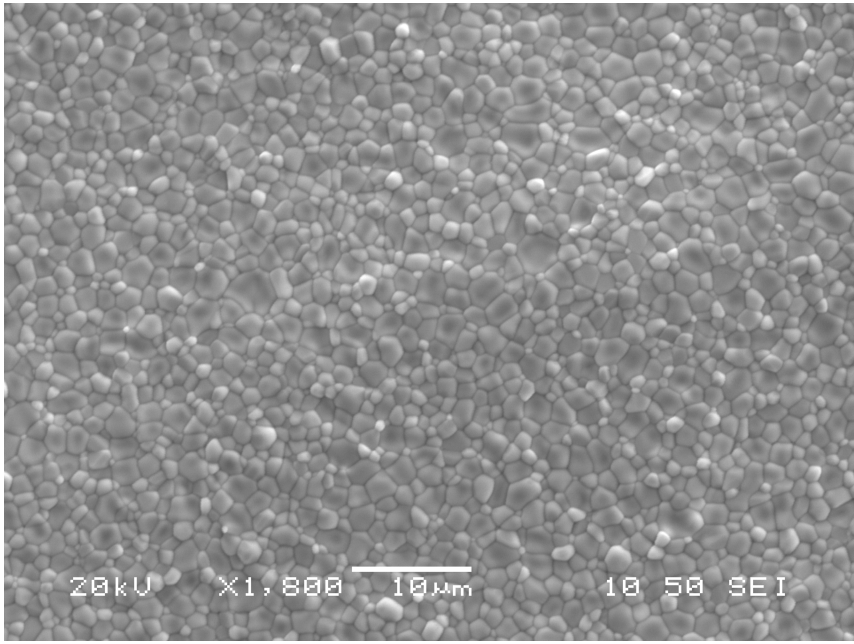
650 MHz 5-cell (future)

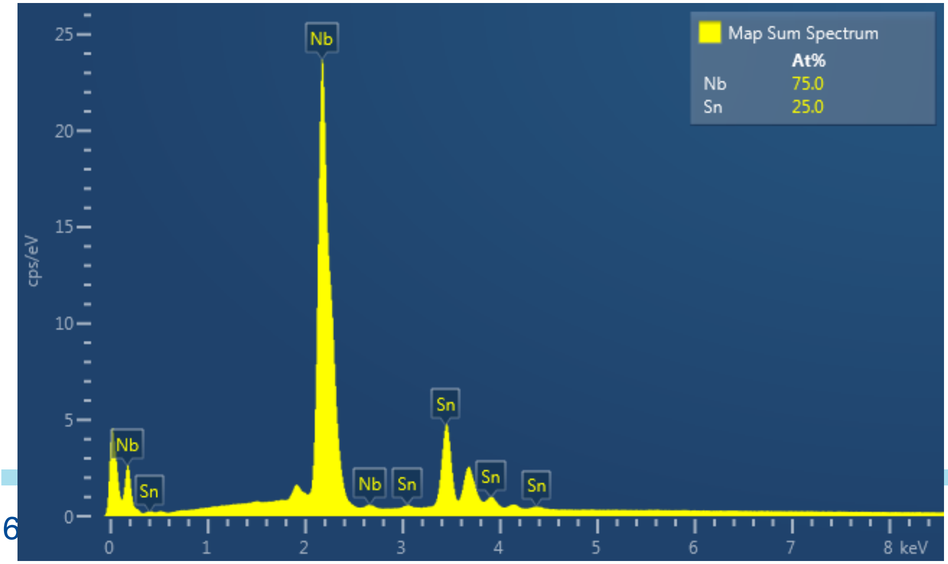


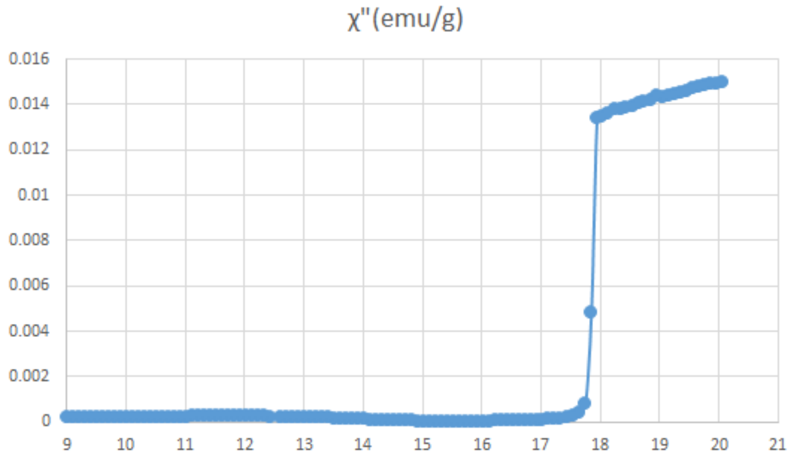


First Nb_3Sn Samples via Vapor Diffusion at FNAL



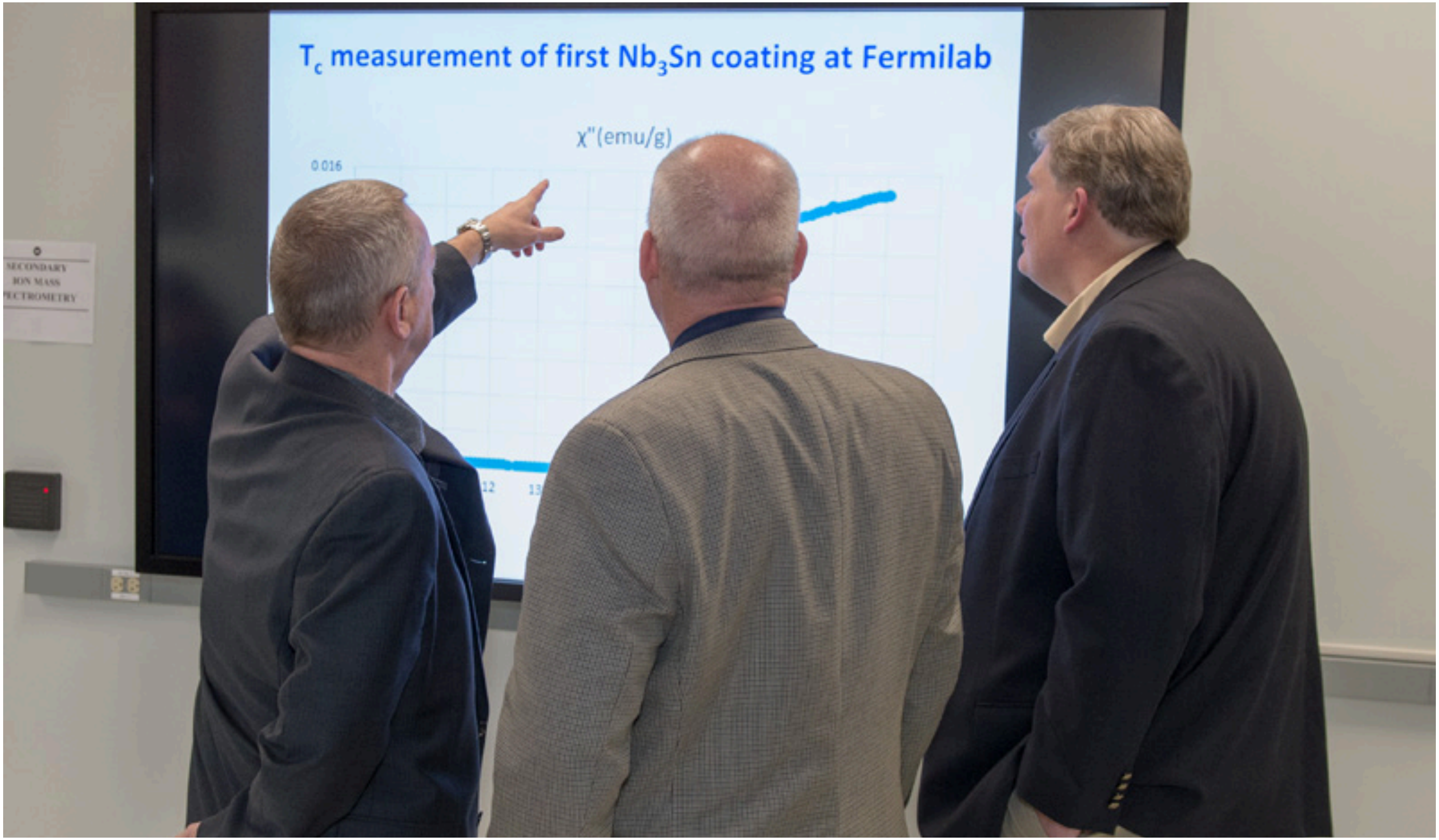




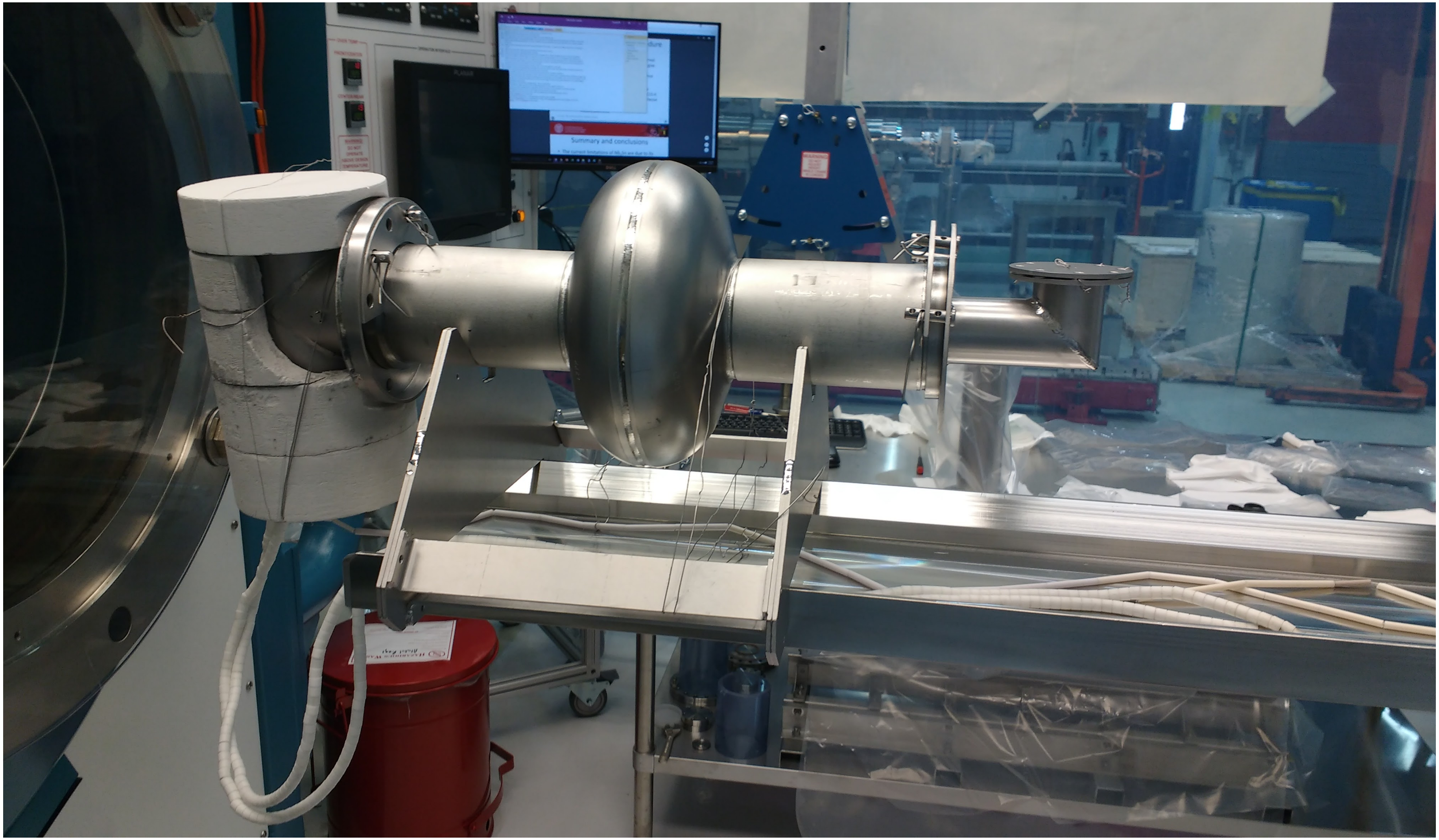


Measurements by Yulia Trenikhina (FNAL), Jae-Yel Lee (Northwestern), and Zuhawn Sung (FNAL)

Excitement Brewing for Nb_3Sn SRF Coatings

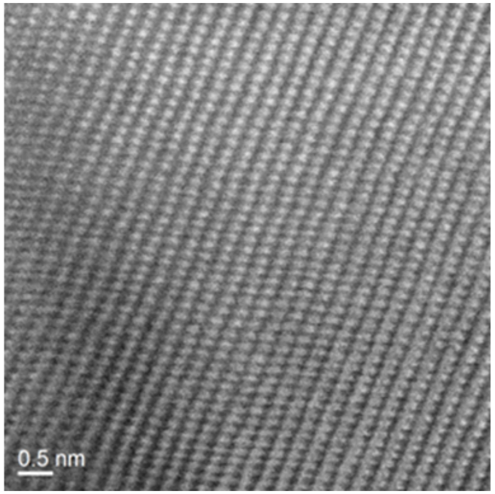


First Fermilab Nb_3Sn Cavity Coated – RF Test Soon

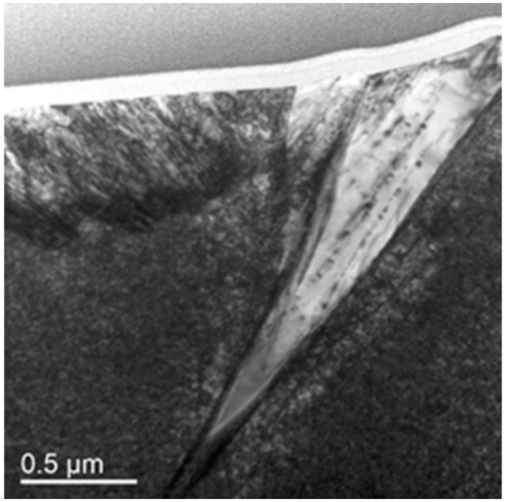


Outline

- High Q_0 (medium E_{acc})
  - Nitrogen doping
  - Flux expulsion
- High E_{acc} and high Q_0
  - Nitrogen infusion
  - Nb_3Sn
  - Plasma cleaning



Aberration-corrected STEM image of the near-surface of Nb cavity - Y. Trenikhina



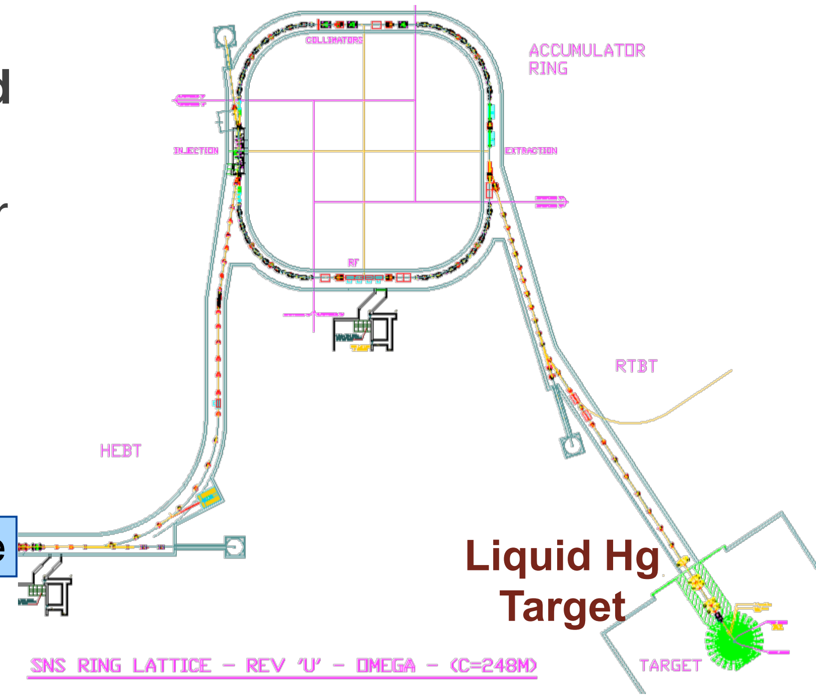
Niobium near-surface after the first step of nitrogen doping - Y. Trenikhina

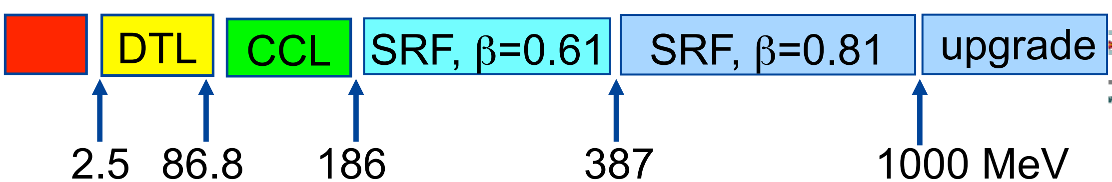
ILC cryomodule with record average gradient for FAST facility

In-situ plasma processing at SNS

- **Most cavities at SNS are limited by field emission (FE) leading to thermal instability in end-groups**
  - Avg. Eacc are ~12 and 13 MV/m for the two cavity geometries
- **In-situ plasma processing to reduce FE and increase accelerating gradients**
  - Higher linac output energy adds margin for reliable operation at 1.4 MW
  - Aim is to increase high-beta SRF cavities gradient by15%

Accumulator Ring:
Compress 1 msec long pulse to 700 ns





Front-End:
1 msec long chopped H- beam at 60 Hz

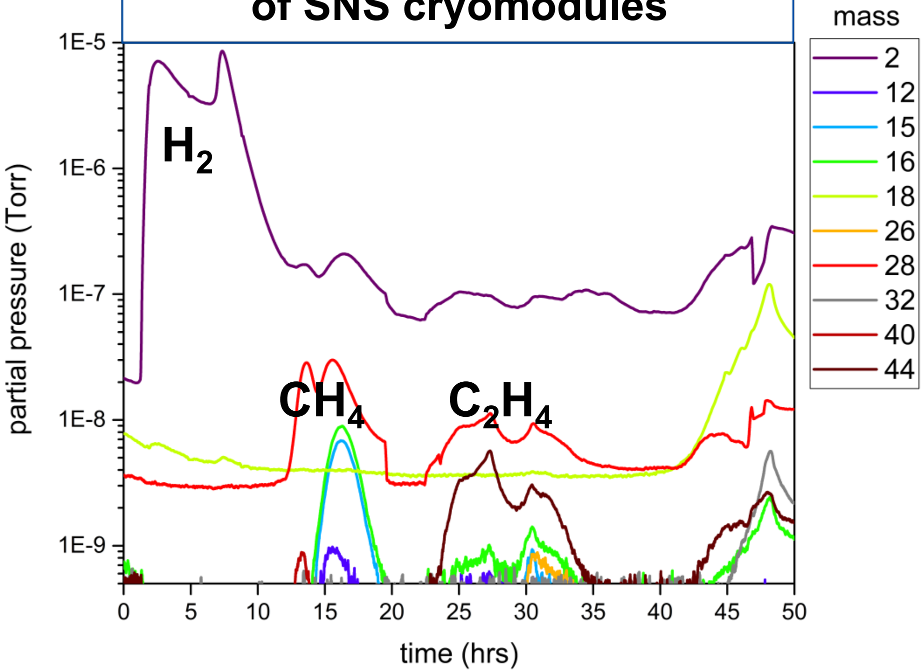
Linac:
Accelerates beam to 1 GeV
SRF linac: 23 cryomodules

Slides courtesy M. Doleans, ORNL

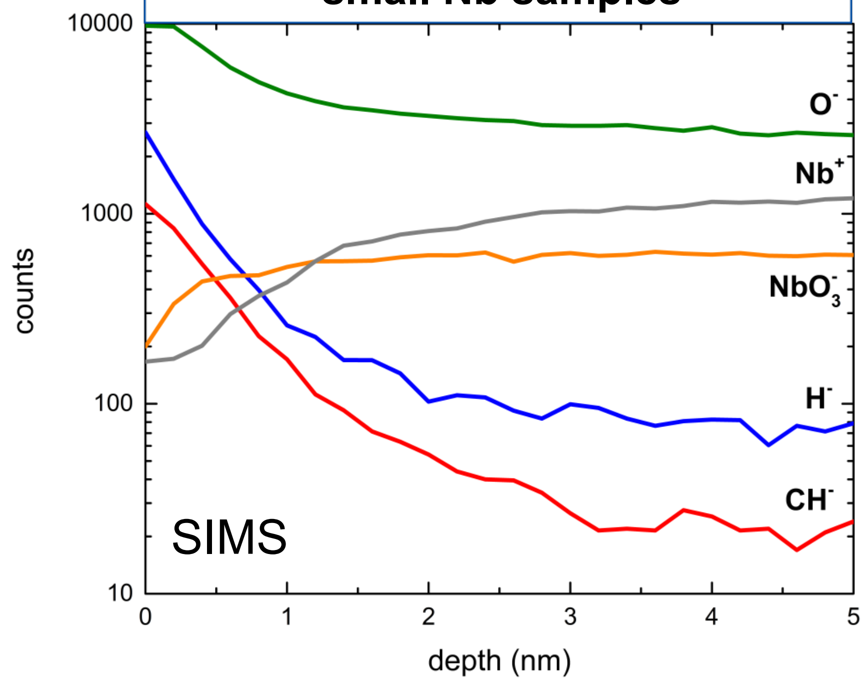
Hydrocarbon contaminants on Nb surfaces

- **Hydrocarbon contamination observed on various Nb surfaces**
- **Hydrocarbons lowers the work function of Nb surface**
  - Lower work function aggravates field emission
  - In-situ plasma processing at SNS removes hydrocarbons from cavity RF surface

Volatile hydrocarbons observed during thermal cycle of SNS cryomodules



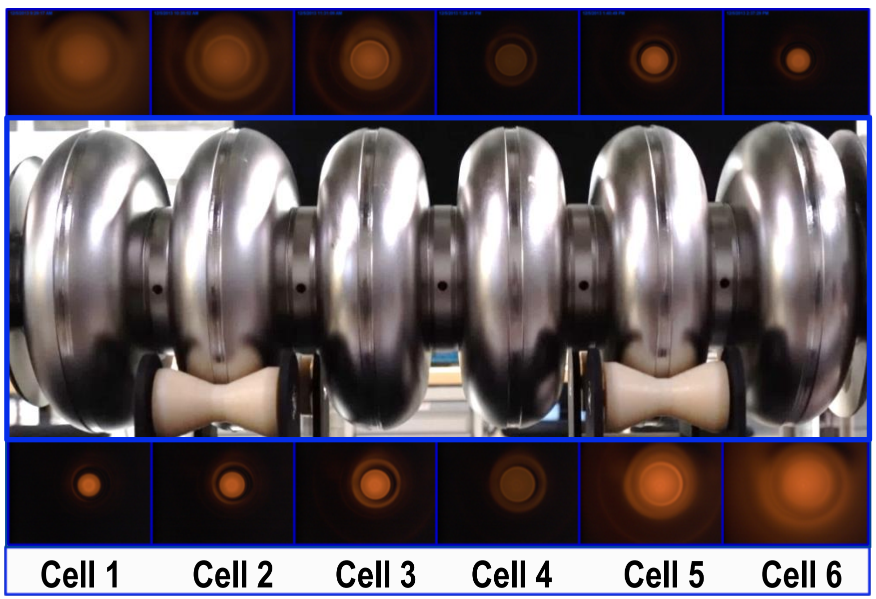
Hydrocarbons fragments observed at top surface of small Nb samples

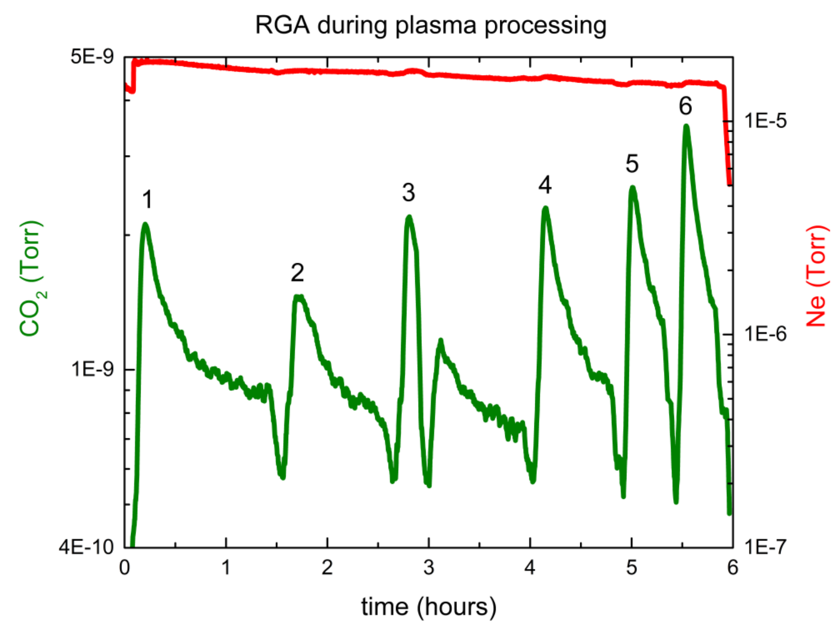


Slides courtesy M. Doleans, ORNL

Neon-oxygen cleaning applied to SNS HB cavities

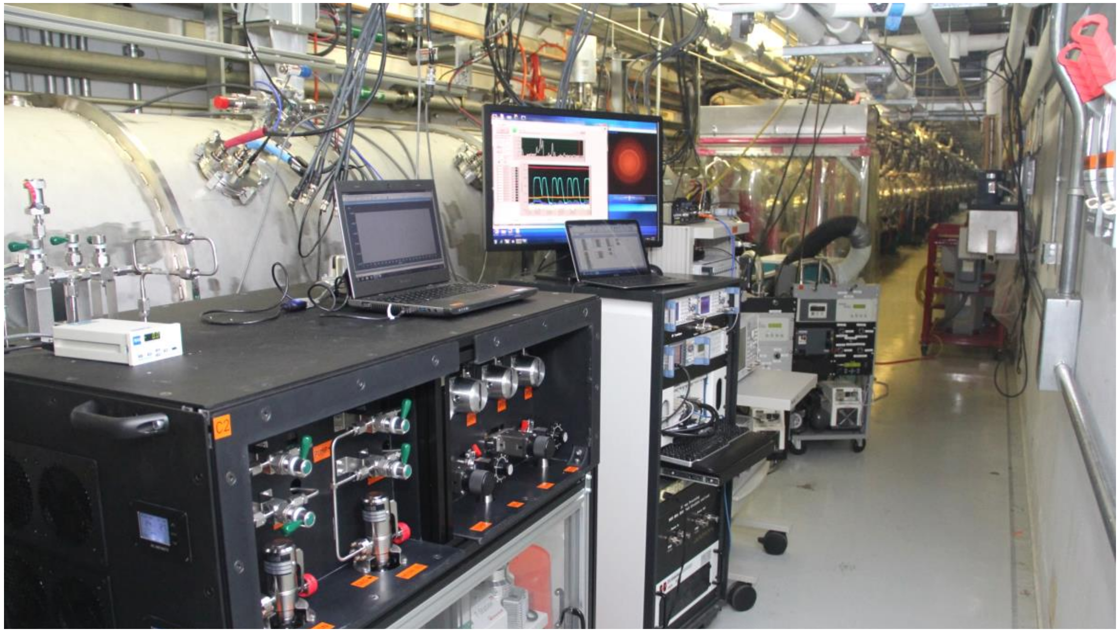
- **Reactive oxygen plasma at room-temperature**
  - 150 mTorr neon gas with ~1% oxygen
- **Hydrocarbons removed from top surface through oxidation and formation of volatile by-products such as CO_2**
- **Residual gas analysis used to monitor plasma cleaning**
  - Observed removal of ~monolayers equivalent of hydrocarbons
  - Six cells of SNS cavities cleaned sequentially

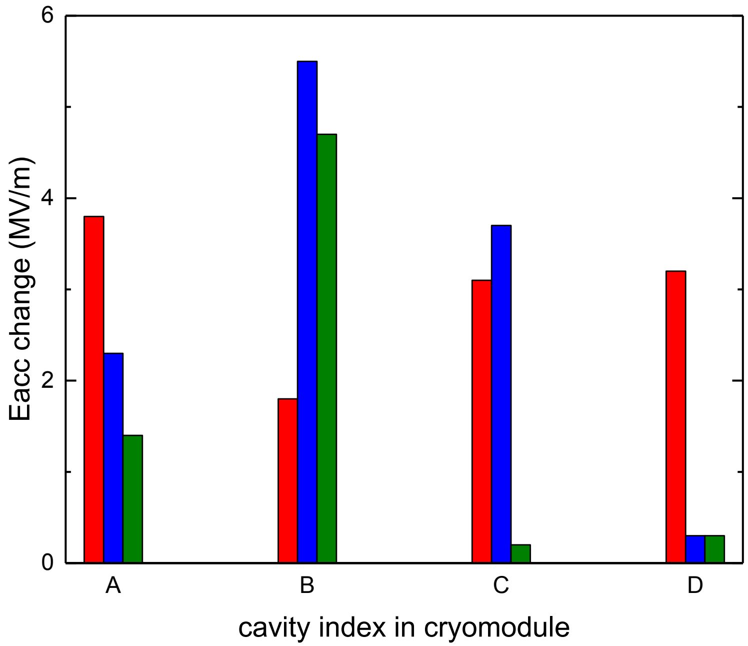




Slides courtesy M. Doleans, ORNL

Plasma processing in SNS tunnel started





- **Improvement of Eacc after plasma processing of 3 cryomodules**
  - Ranges from 0.2 MV/m to 5.5 MV/m
  - 2.5 MV/m increase on average so far (21%)
- **SNS linac**
  - Currently operating at 972 MeV
  - Highest energy on production target at 60 Hz to date
  - Plan to reach 1 GeV in FY17

Slides courtesy M. Doleans, ORNL

Mid-Term Goals: Plasma processing for LCLS-II

2017

Present

- Applicability of SNS plasma processing to LCLS-II
- Design of RF and vacuum system

Goals

- Plasma processing of 1.3 GHz single-cell cavity
- RF test in VTS

2018

Goals

- Plasma ignition in 9-cells cavity
- Plasma processing and RF test of 9-cell cavities in VTS
- Improve maximum E_{acc} of field emitting cavities

2019

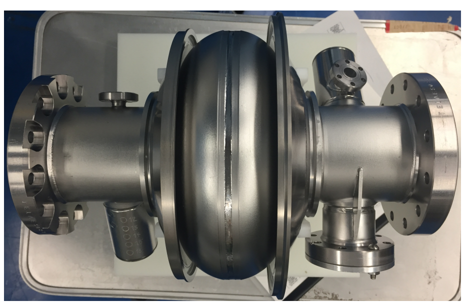
Goals

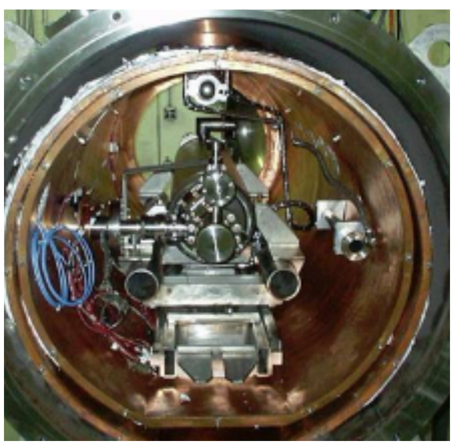
- Plasma processing in-situ in a cryomodule-like environment (HTS)
- Monitor of plasma ignition based on resonance shift

2020

Goals

- Plasma processing in-situ in LCLS-II cryomodules
- Improve maximum E_{acc} of ~ 15-20 %





Slide from M. Martinello

State-of-the-Art SRF Technology

- Exploring the limits of Q_0 and E_{acc} for accelerators
  - Impurity doping, Nb_3Sn, flux expulsion, plasma cleaning
- Science of RF Superconductivity
  - Manipulation of mean free path and energy gap with impurities
  - *Decrease* of surface resistance with increasing field
  - Flux trapping at grain boundaries and dislocations
  - Ultra-fast pulses to outpace vortex dissipation
  - Q_0 at *tiny* gradients (quantum computing)
- Auxiliaries: tuners, couplers, resonance control…
- Accelerators
  - LCLS-II
  - SRF for intensity frontier experiments at Fermilab
  - Future collider (circular or linear)

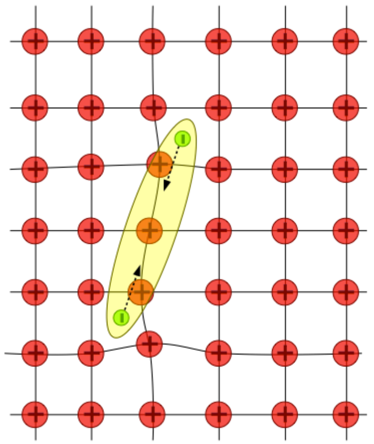
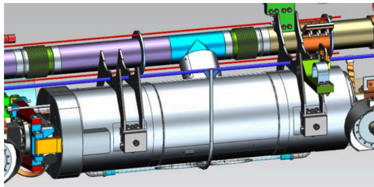
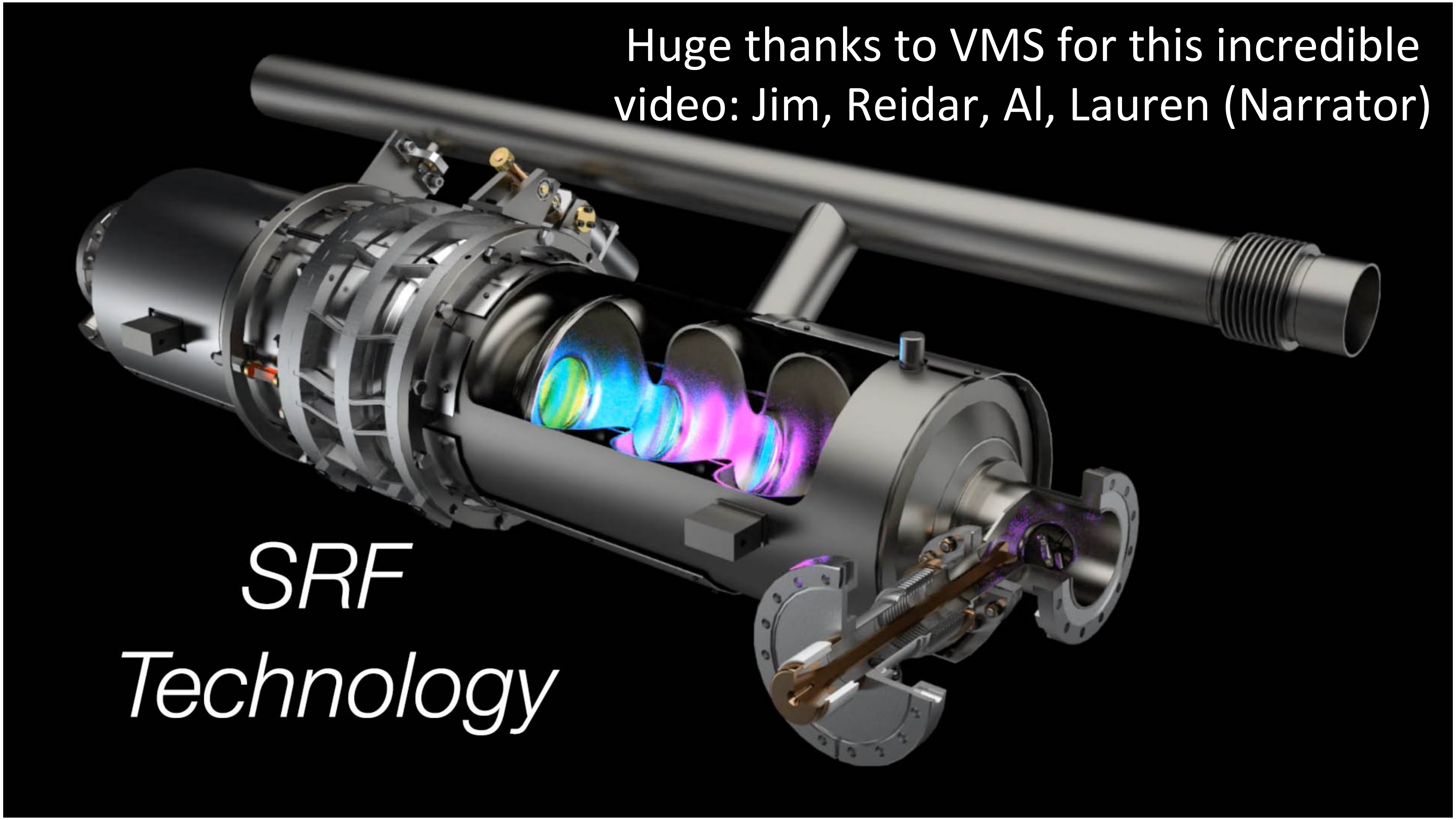


Image - arXiv:1208.5025



Video


Huge thanks to VMS for this incredible video: Jim, Reidar, Al, Lauren (Narrator)
SRF Technology

SRF Technology Video