Future of Superconducting RF Technology

Sam Posen

Americas Workshop on Linear Colliders

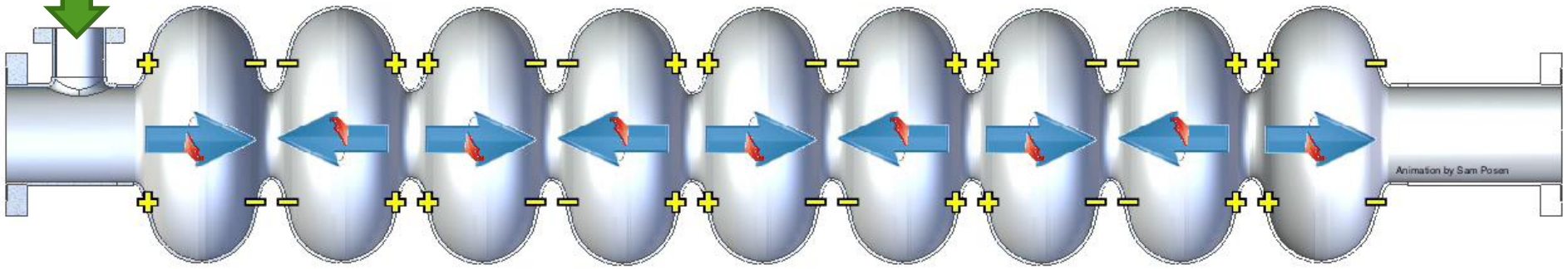
29 June 2017

Enabling Accelerator Technology: SRF Cavities

- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Tens of MV/m accelerating gradients with high efficiency, large aperture, and up to 100% duty factor
- Accelerator technology for production of **high current, high energy, high brightness beams**

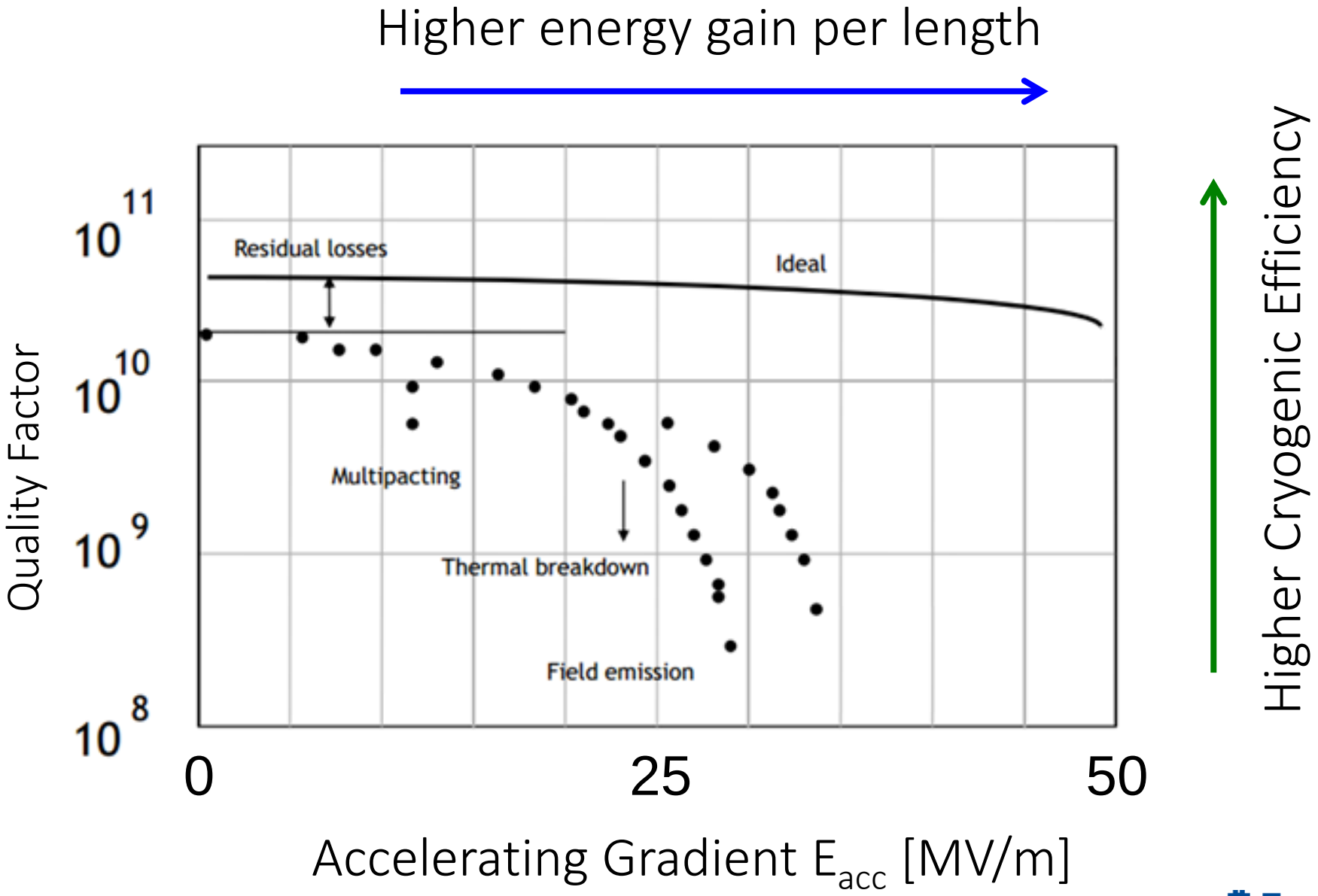
Input RF power at 1.3 GHz

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

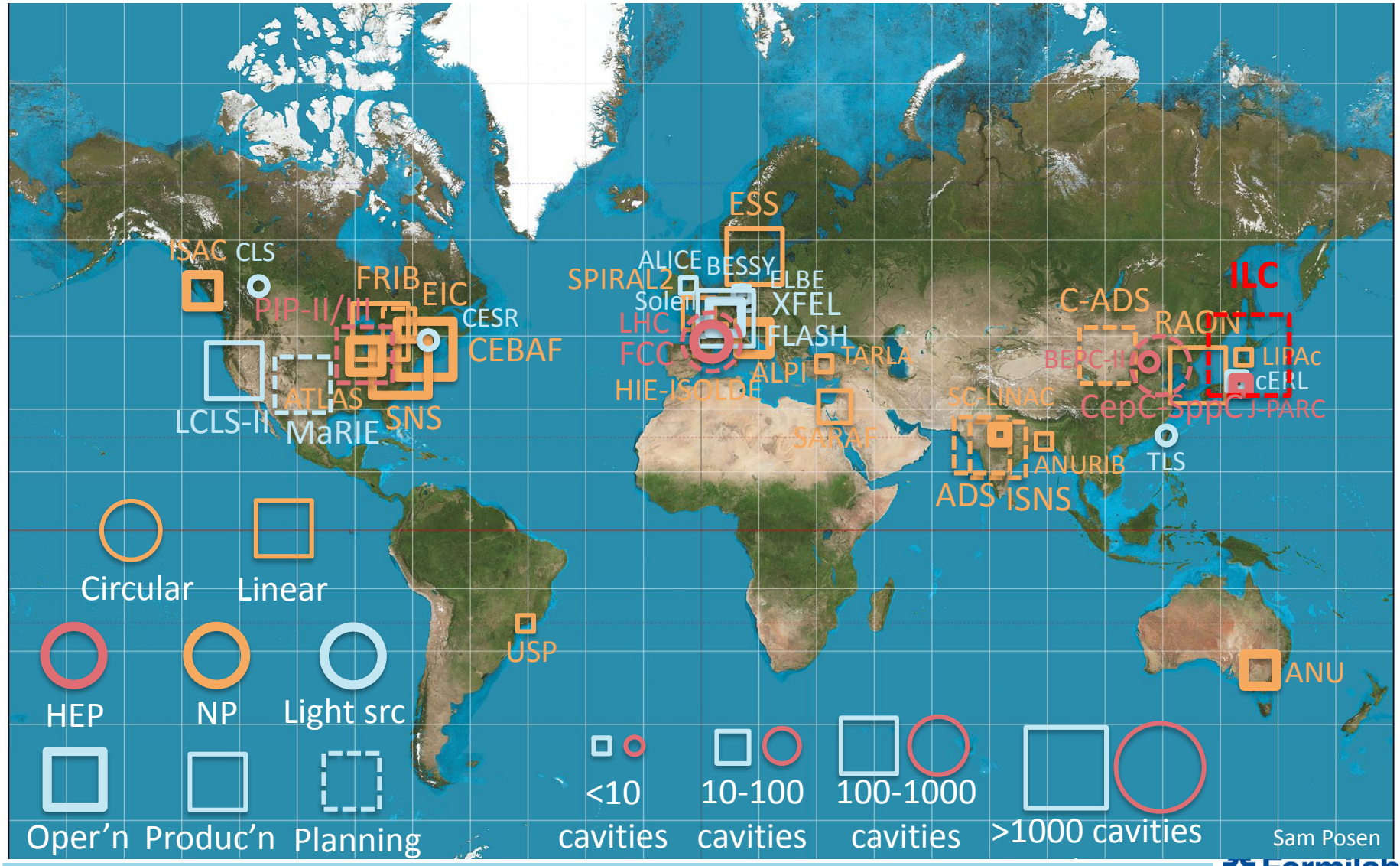


Images from linearcollider.org, WIkipedia

SRF Cavity Figures of Merit

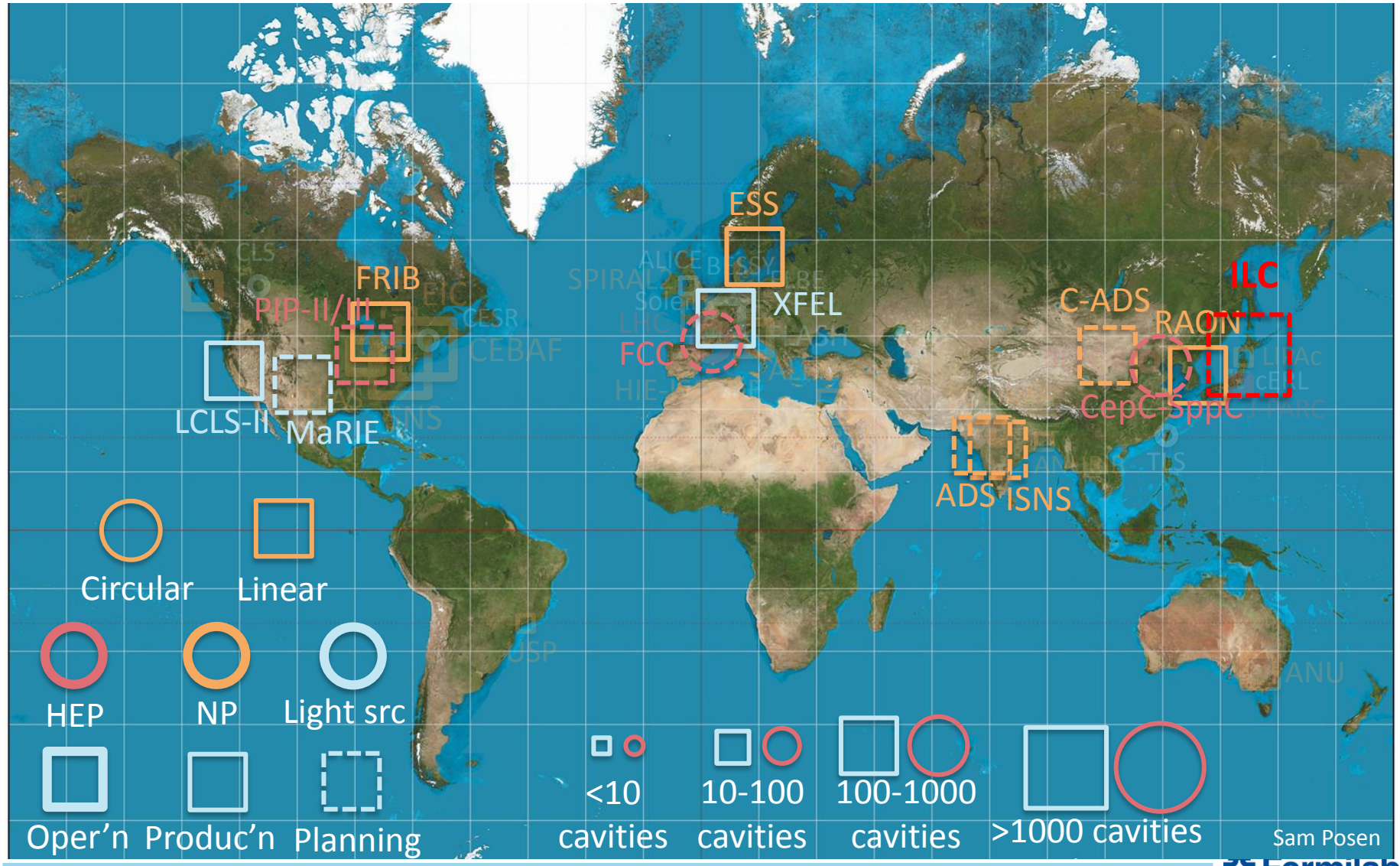


SRF Accelerators Around the World



Map from Wikipedia. Non-exhaustive facility list.

SRF Accelerators Around the World – Upcoming



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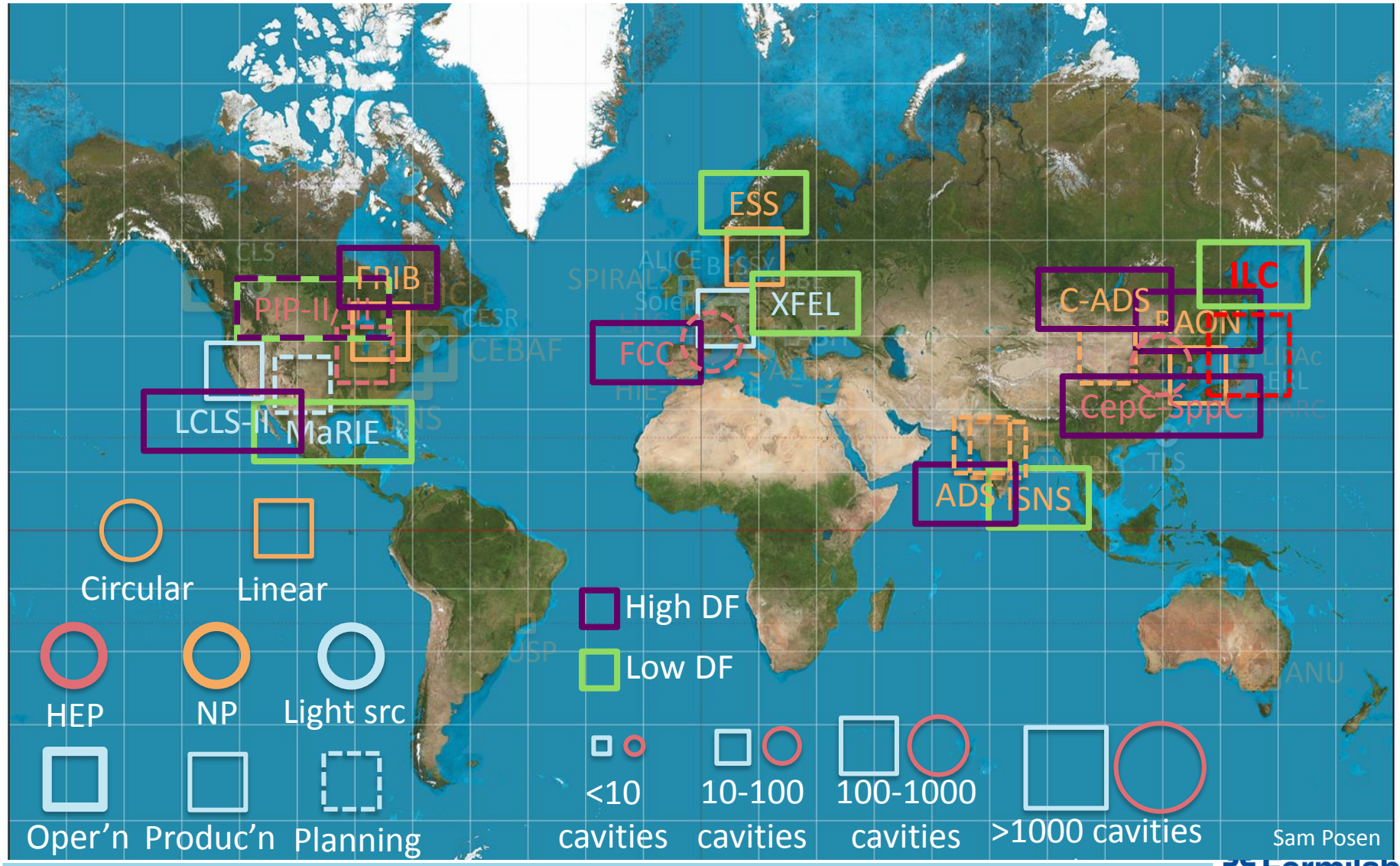
SRF Accelerators Around the World – Upcoming

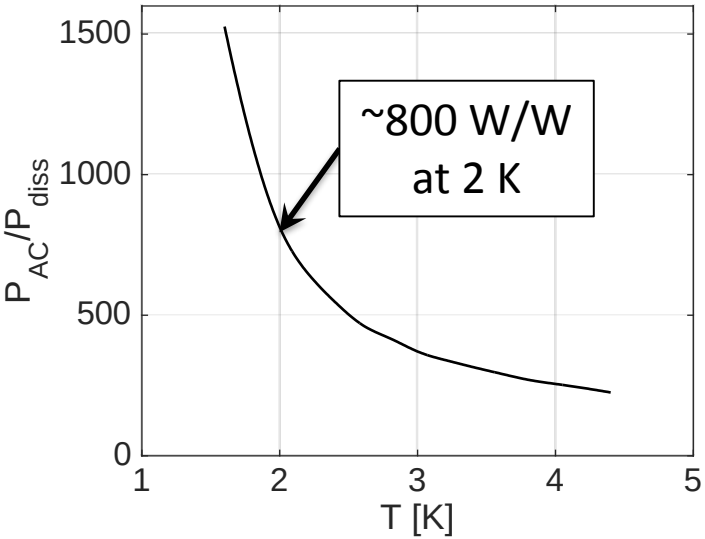


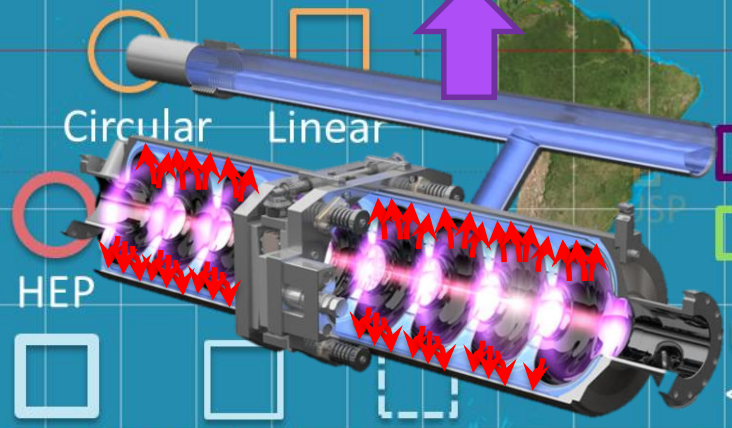
Fermilab

Map from Wikipedia. Non-exhaustive facility list.

Q_0 -> Cryogenic Infrastructure, Operating Cost

— Crucial for high duty factor machines





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

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

Sam Posen

Fermilab

Map from Wikipedia. Non-exhaustive facility list.

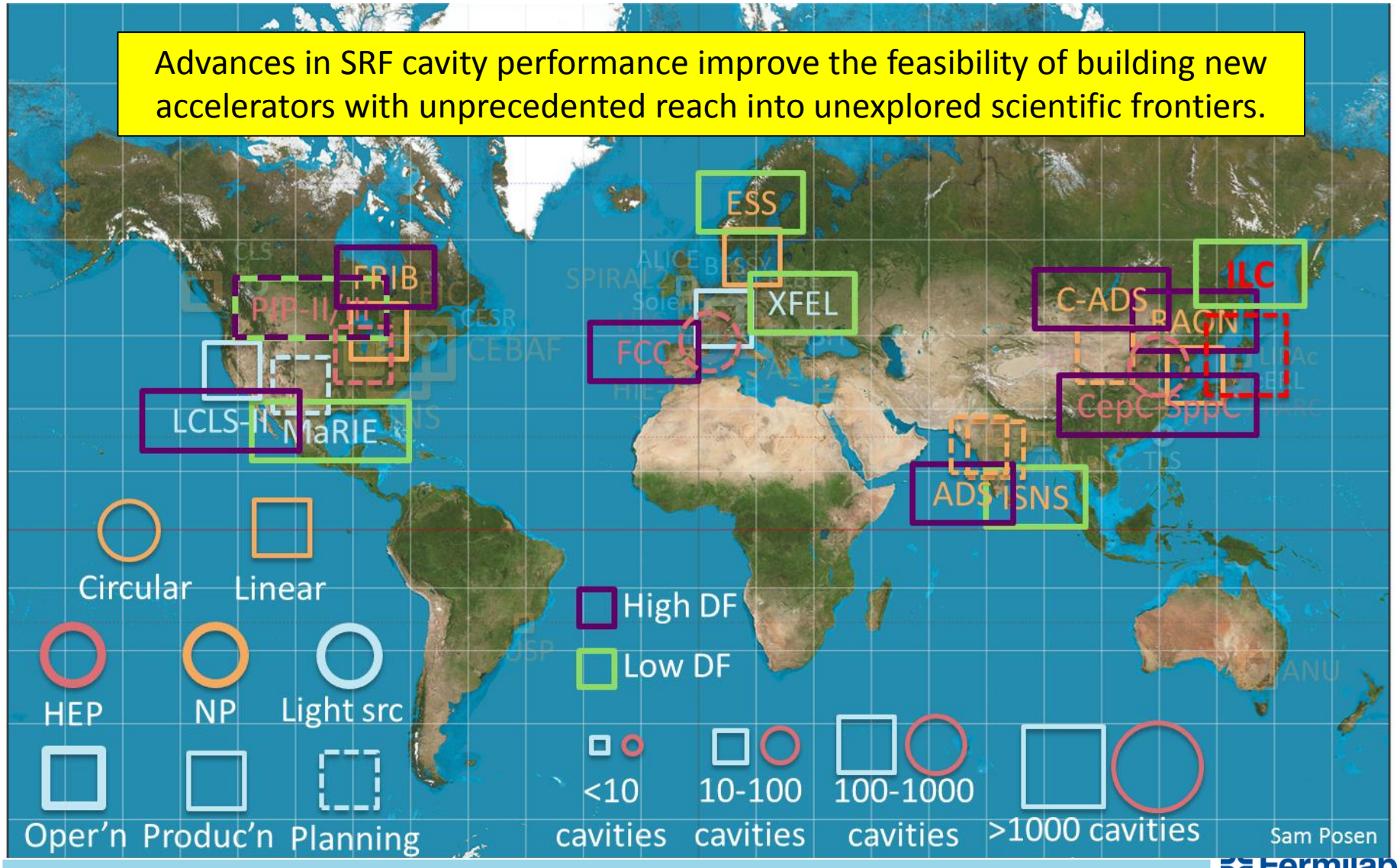
E_{acc} -> Length for Linear Accelerator

— In low duty factor machines, high gradient with high Q_0 can shrink length

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

Map from Wikipedia. Non-exhaustive facility list.

Motivation State-of-the-Art SRF Technology

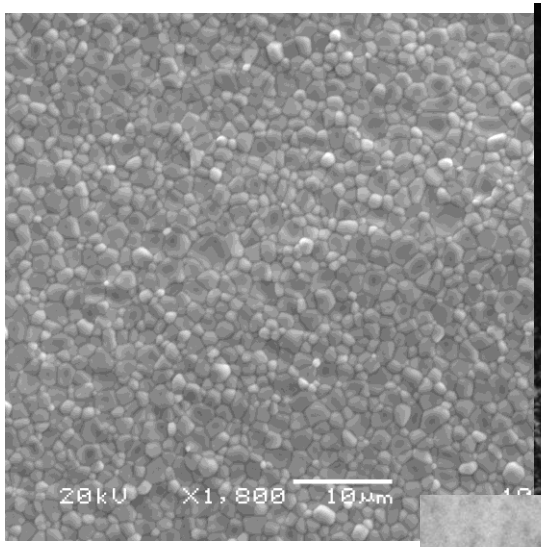


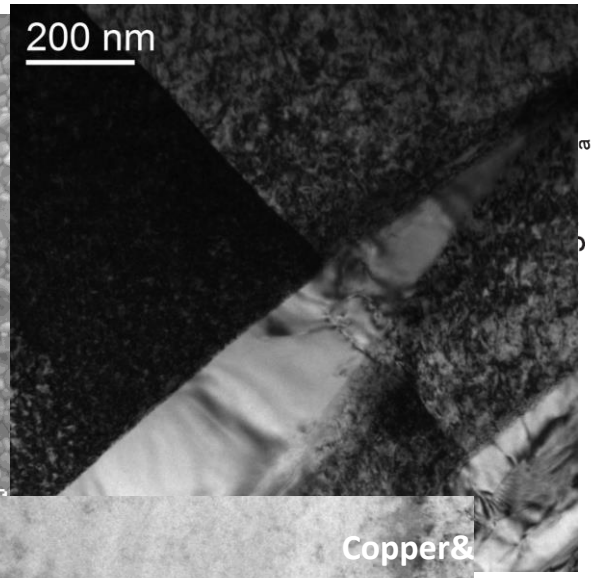
Map from Wikipedia. Non-exhaustive facility list.

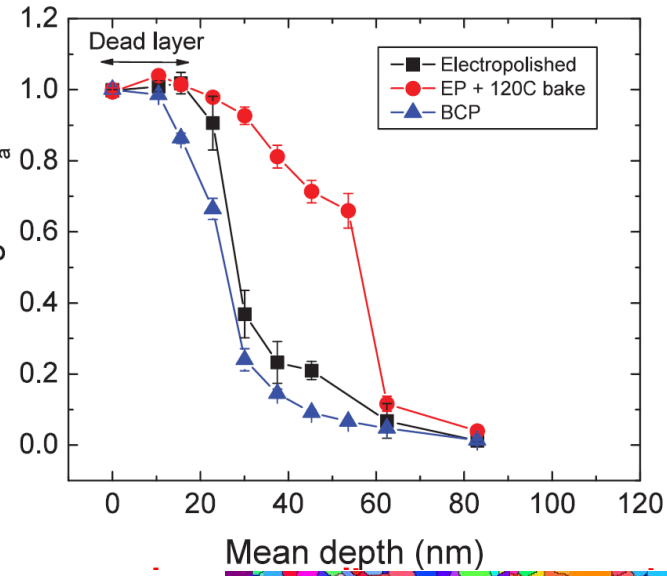
How to Push SRF Cavity Performance?
1) Improve understanding via surface science

- Material science tools are <u>essential</u> to understand the nanometer-scale structural changes that lead to dramatic changes in performance

A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)







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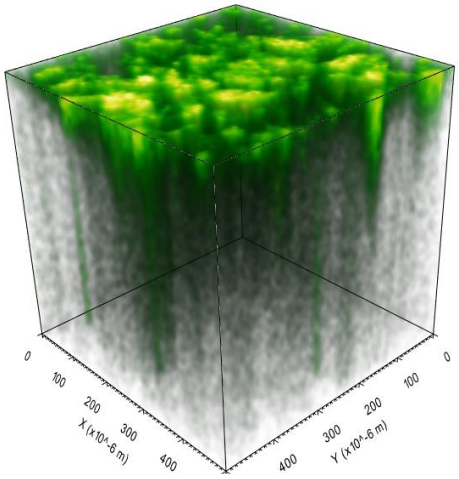
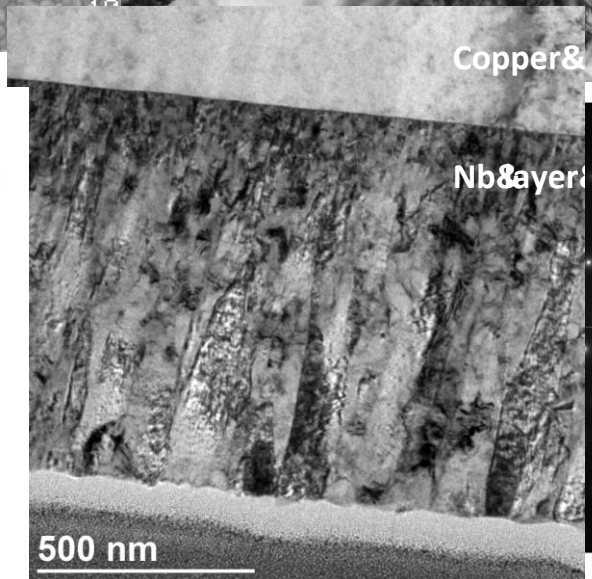
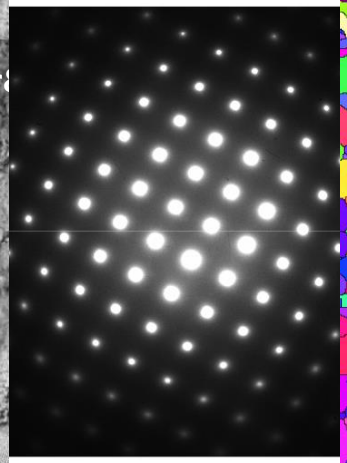
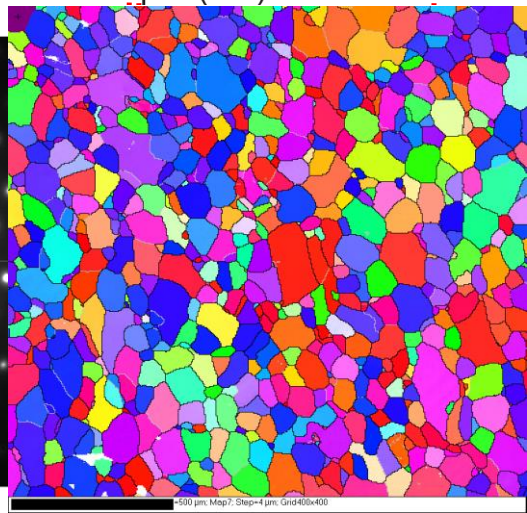


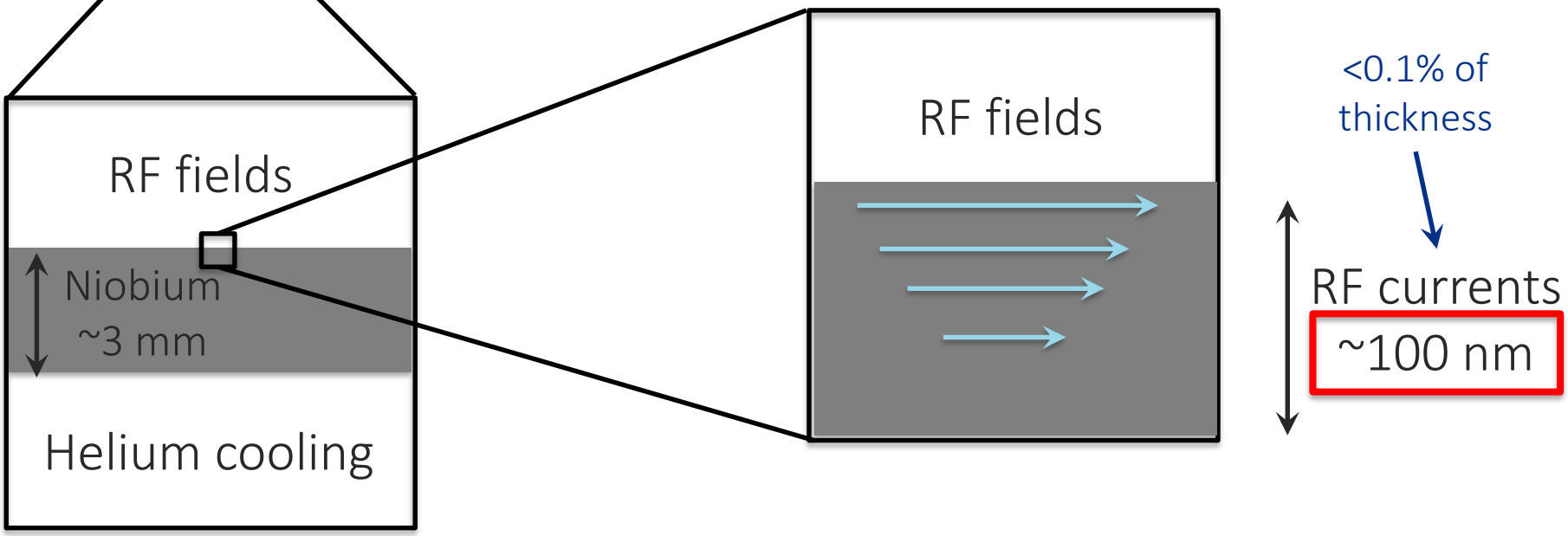




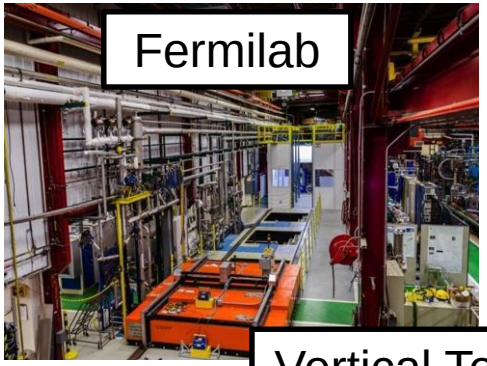


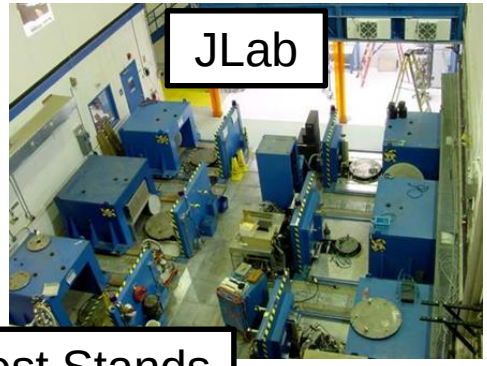
Performance are determined by nanometer scale structure of inner surface

Image from linearcollider.org



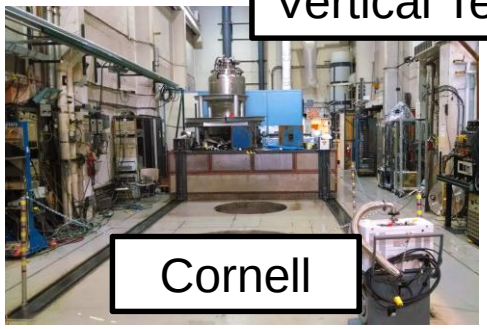
How to Push SRF Cavity Performance?
2) R&D Cavity Processing and SRF Experiment



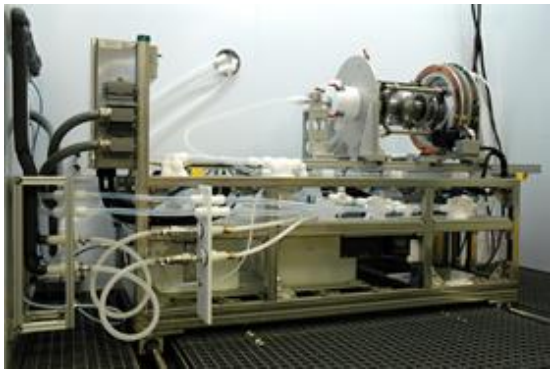


Vertical Test Stands

Horizontal Test Stands



Cavity Processing Facilities

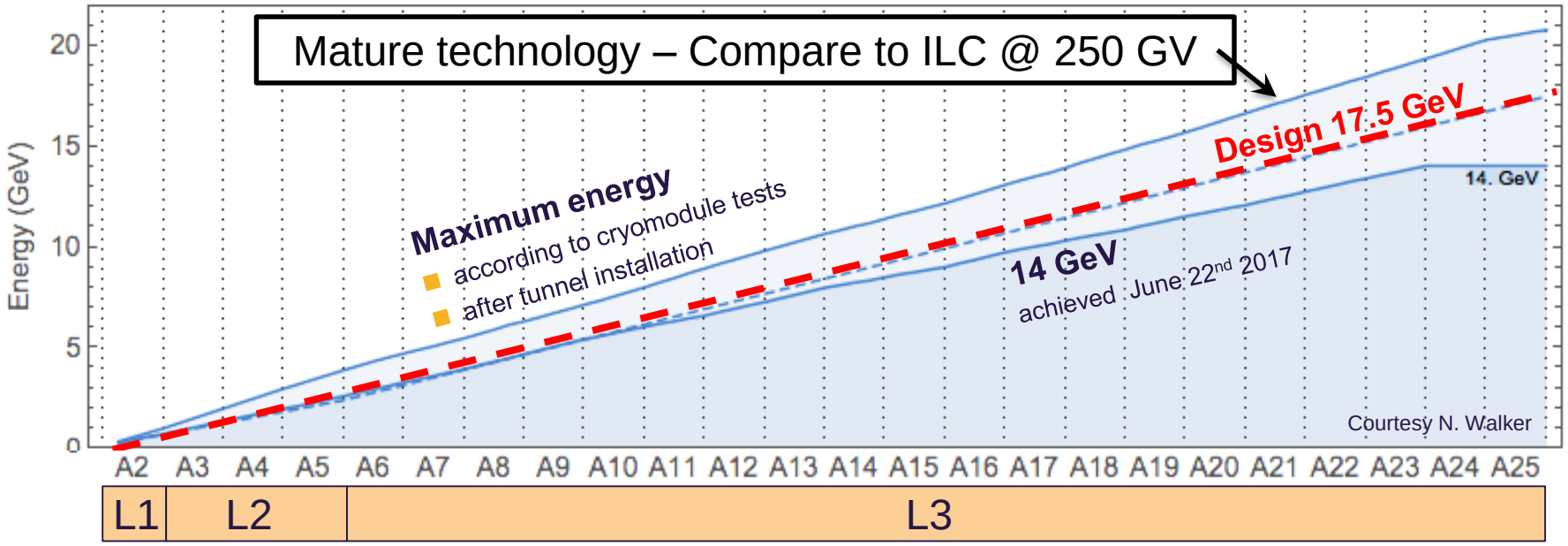


Superconducting RF Technology

Recent Advances

European XFEL

PRELIMINARY RESULTS: Energy reach



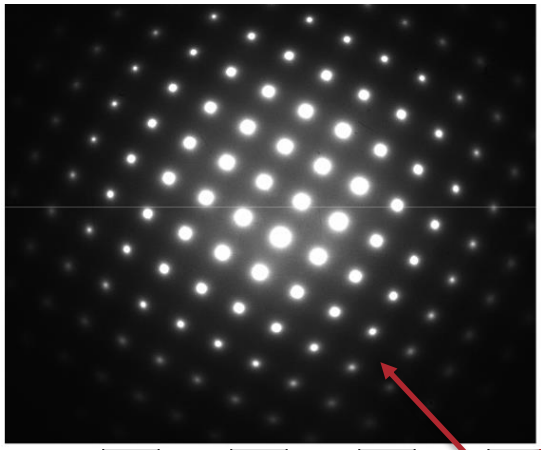
- Design accelerating gradient: 23.5 MV/m
- Average accelerating gradient: 26.0 MV/m
  (after module test and waveguide tailoring)
- After initial commissioning design gradient almost reached
- On-going measurement campaign to assess limits and reasons

DESY HELMHOLTZ ASSOCIATION

2013 R&D Advance: Nitrogen doping treatment for high Q_0

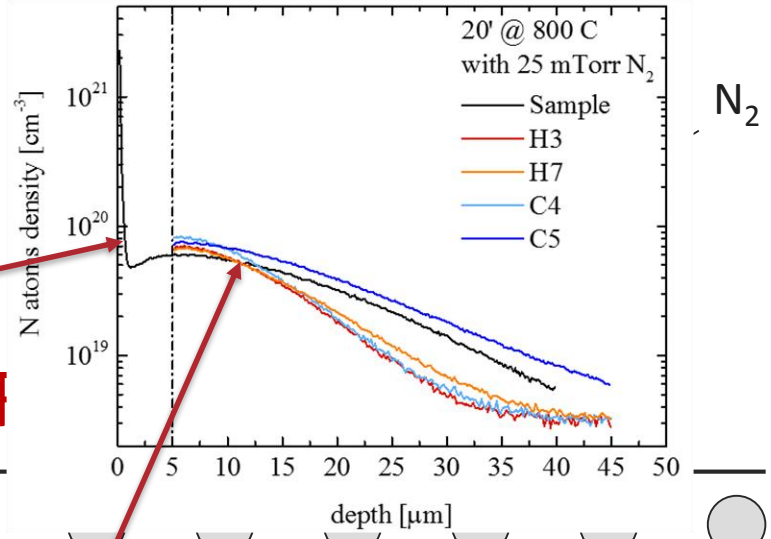
800C UHV, 3 hours → 800C N_2 p = 25 mTorr 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

Y. Trenikhina et Al, Proc. of SRF 2015



Nb

Final RF

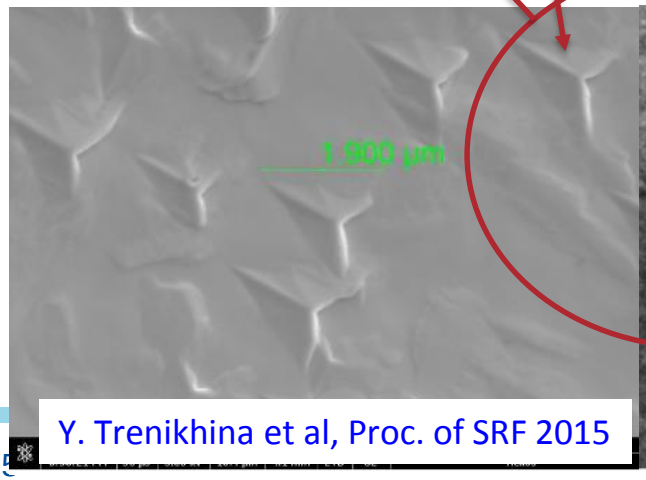


N_2

Nb_xN_y

N Interstitial

N



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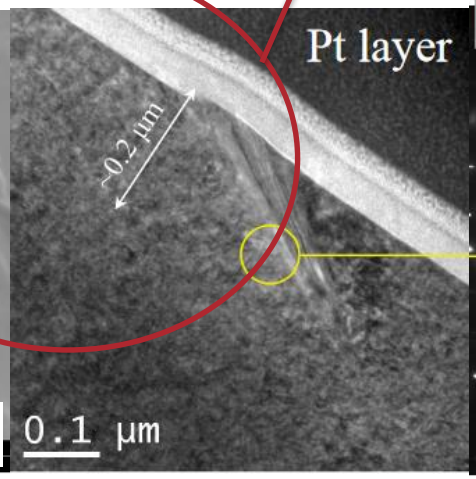
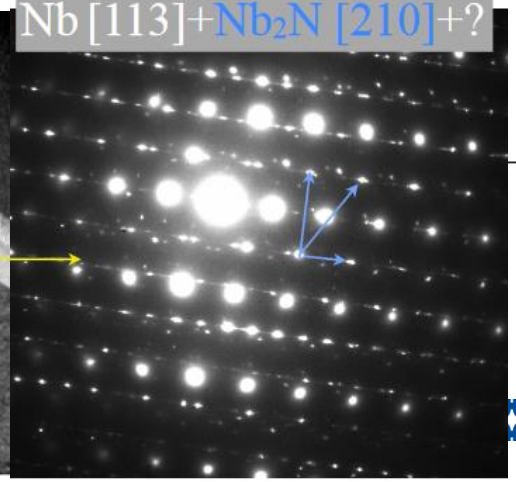
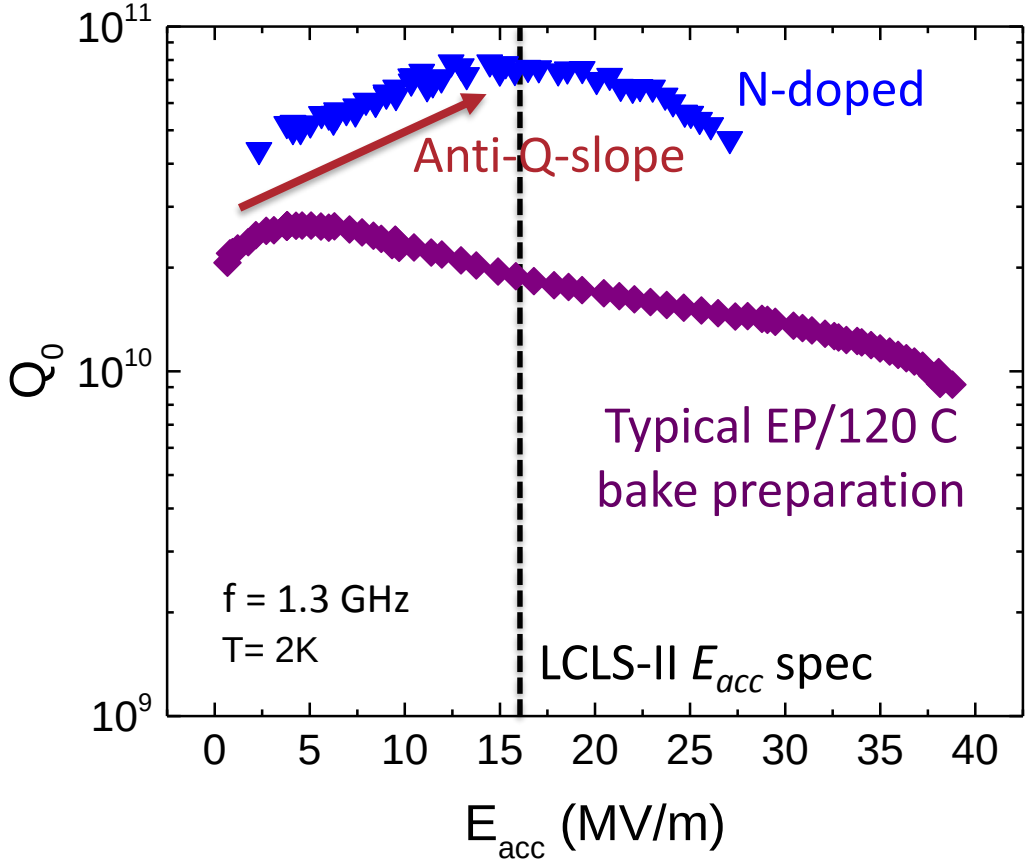




Fermilab

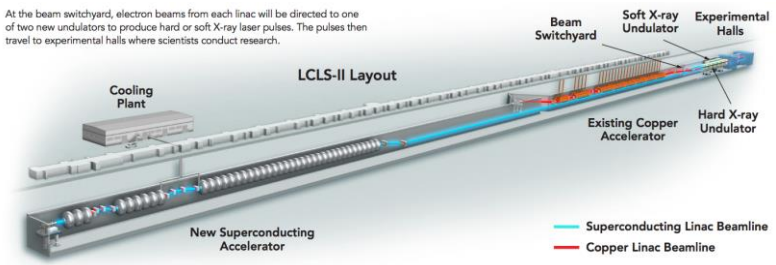
Improved Q_0 from N-doping



- >2x Q_0 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)

LCLS-II – High Repetition Rate X-Ray FEL at SLAC

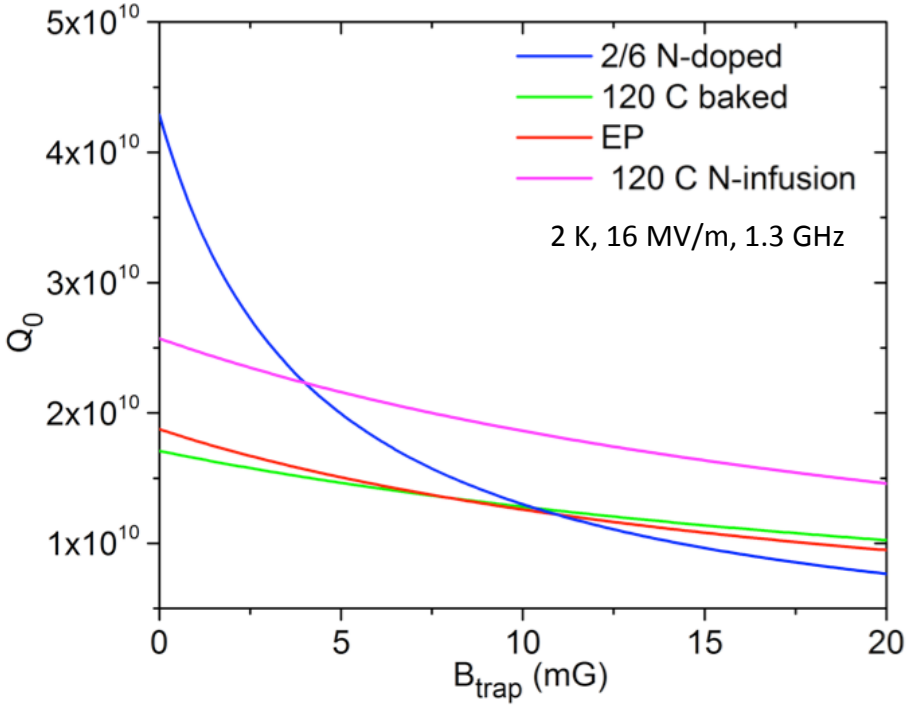


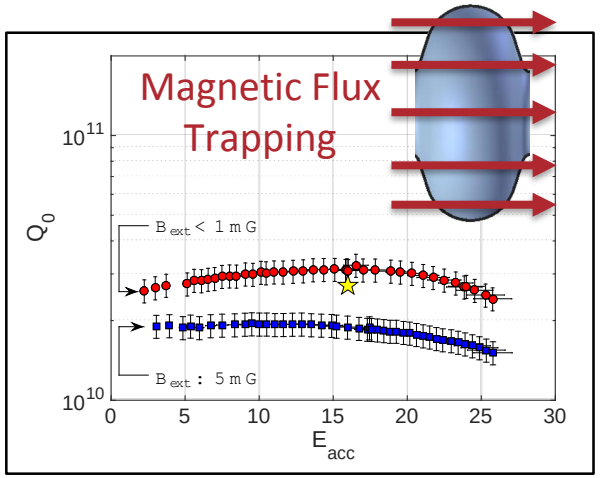
See also talk on Wednesday from Andrew Burrill, SLAC

Magnetic Flux – Sensitivity and Expulsion

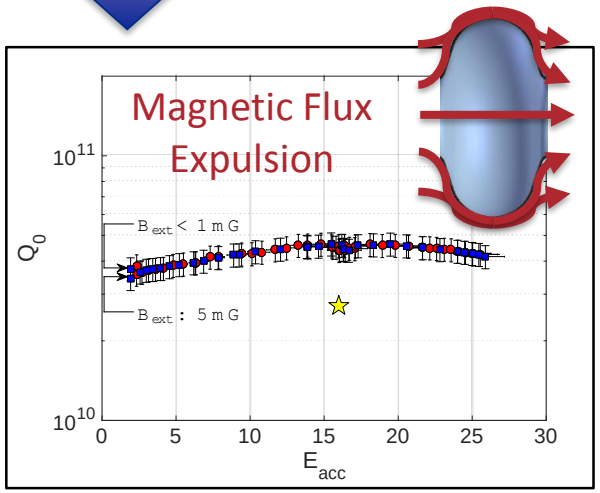
- Infusion: low sensitivity to trapped flux
- New understanding of expulsion

↳ Preservation of Q in CM environment





900°C furnace treatment



M. Martinello et al. "Effect of interstitial impurities on the field dependent microwave surface resistance of niobium," **Appl. Phys. Lett. 109**, 062601 (2016)

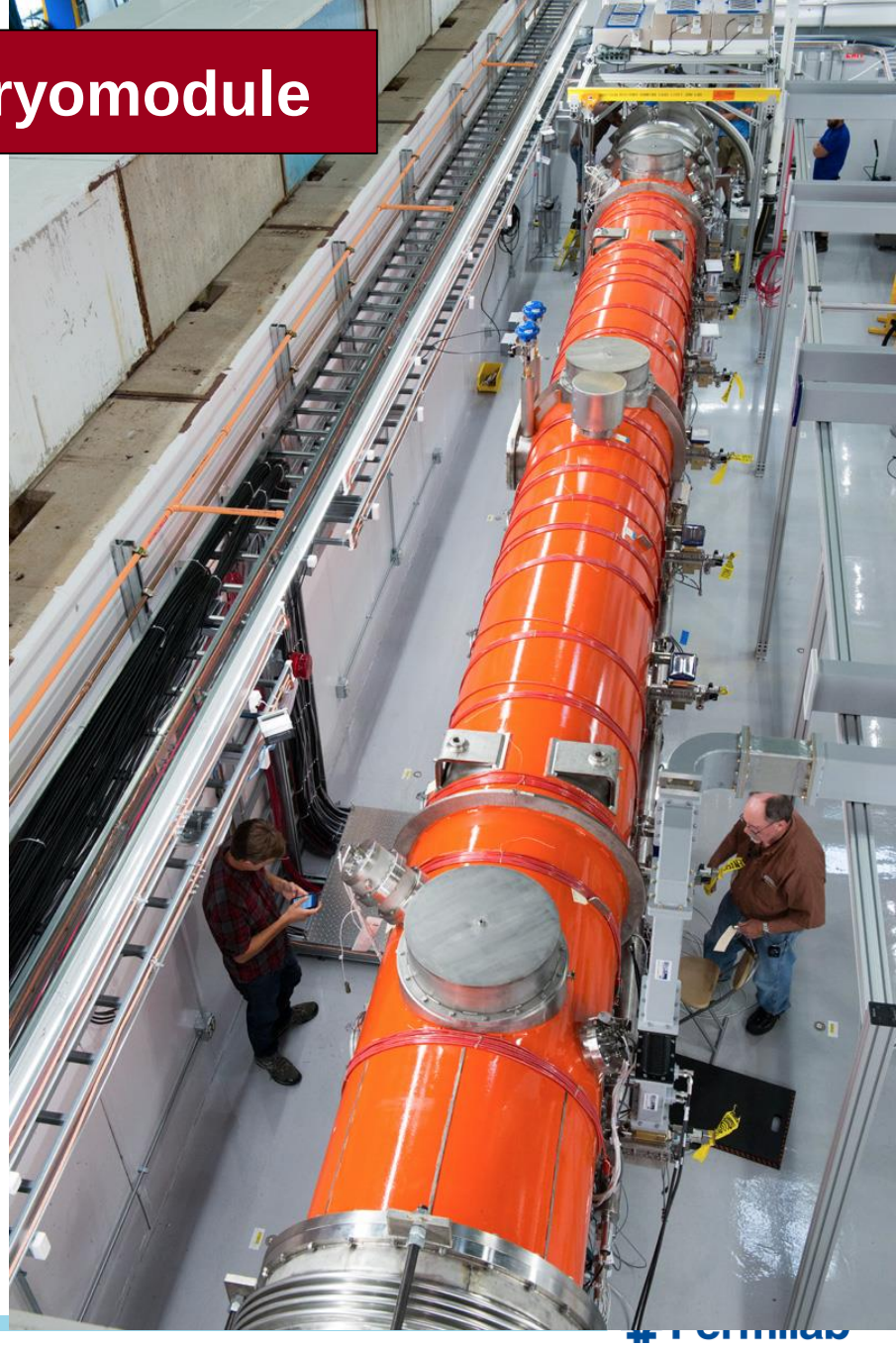
S. Posen et al. "Efficient expulsion of magnetic flux in SRF cavities for high Q0 applications," **Journal of Applied Physics 119**, 213903 (2016)

Fermilab Prototype LCLS-II Cryomodule

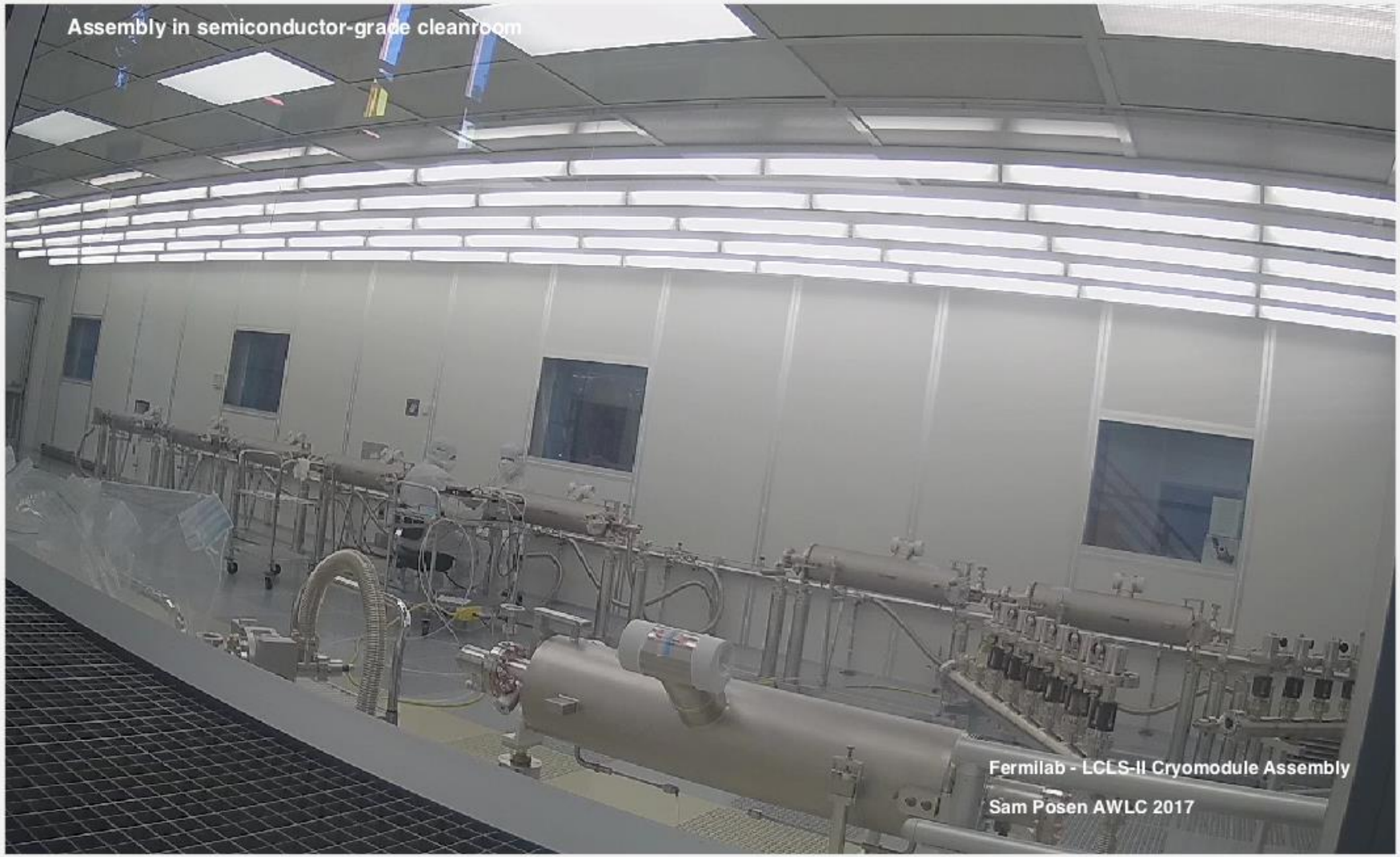
Cavity	Usable Gradient* [MV/m]	Q0 @16MV/m* 2K Fast Cool Down
TB9AES021	18.2	2.6E+10
TB9AES019	18.8	3.1E+10
TB9AES026	19.8	3.6E+10
TB9AES024	20.5	3.1E+10
TB9AES028	14.2	2.6E+10
TB9AES016	16.9	3.3E+10
TB9AES022	19.4	3.3E+10
TB9AES027	17.5	2.3E+10
Average	**18.2**	**3.0E+10**
Total Voltage	**148.1 MV**	

Spec: 133 MV

Spec: 2.7×10^{10}



LCLS-II Cryomodule Production Underway



Superconducting RF Technology

On the Horizon

Exploring Phase Space of Nitrogen Treatment

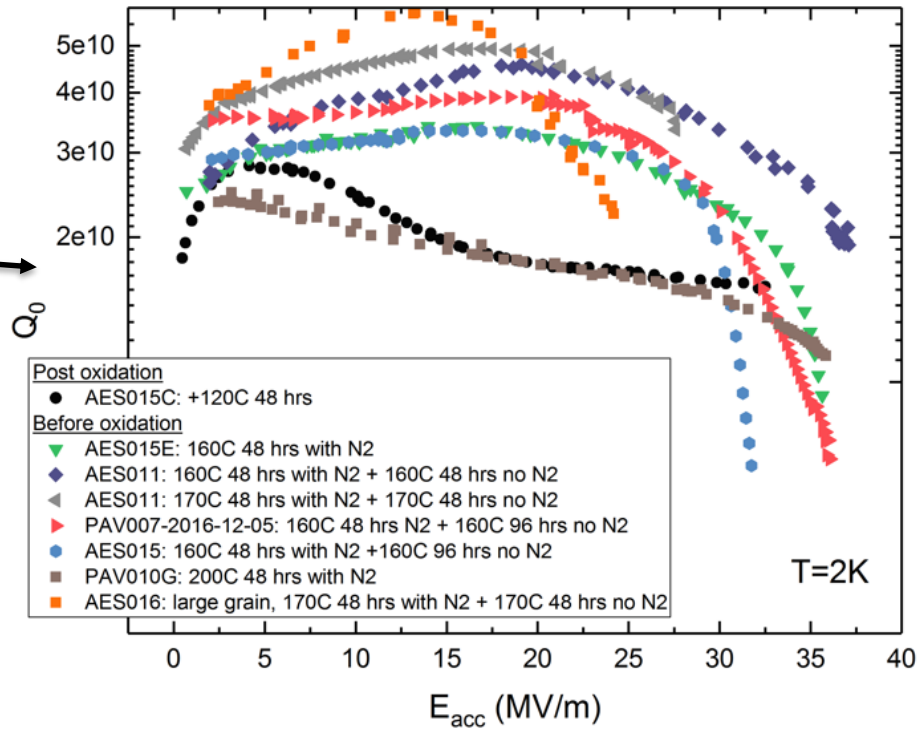
"2/6" Nitrogen "Doping"

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

120 C Nitrogen "Infusion"

800C UHV, 3 hours → 120C N_2 p = 25 mTorr 48 hours → UHV cooling

Can tailor treatment to application (optimize for Q_0 at a given E_{acc})

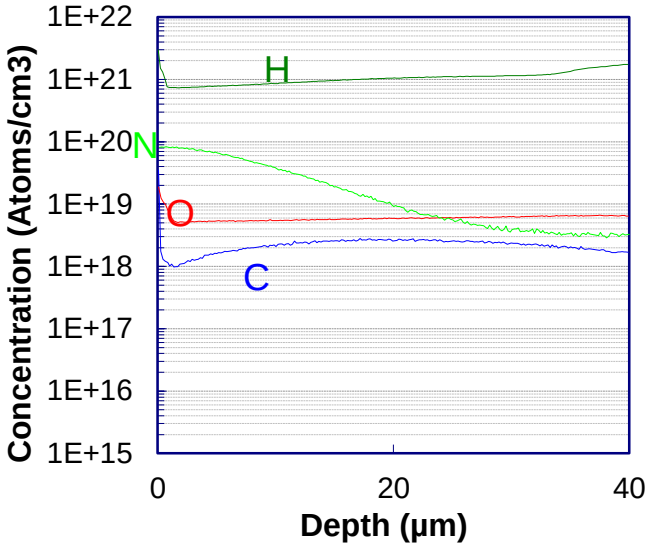


A. Grasselllino et al. arXiv:1701.06077

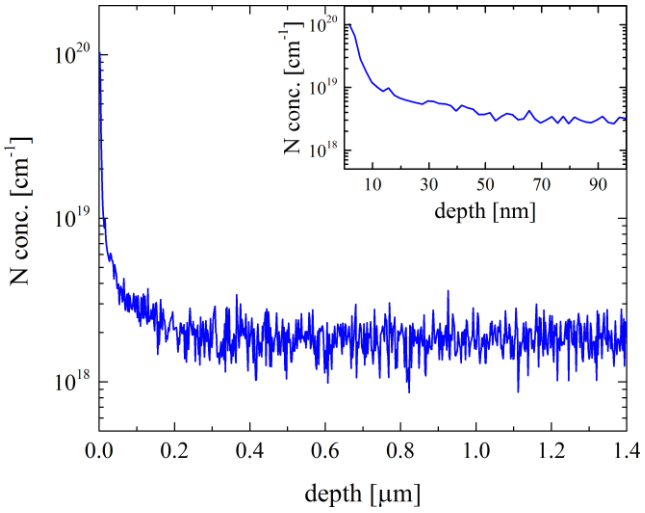
Fermilab

“Nitrogen Infusion” Treatment

- Furnace treatment of cavity developed at Fermilab in 2016
- Designed to diffuse nitrogen interstitial impurities tens of nm deep into surface



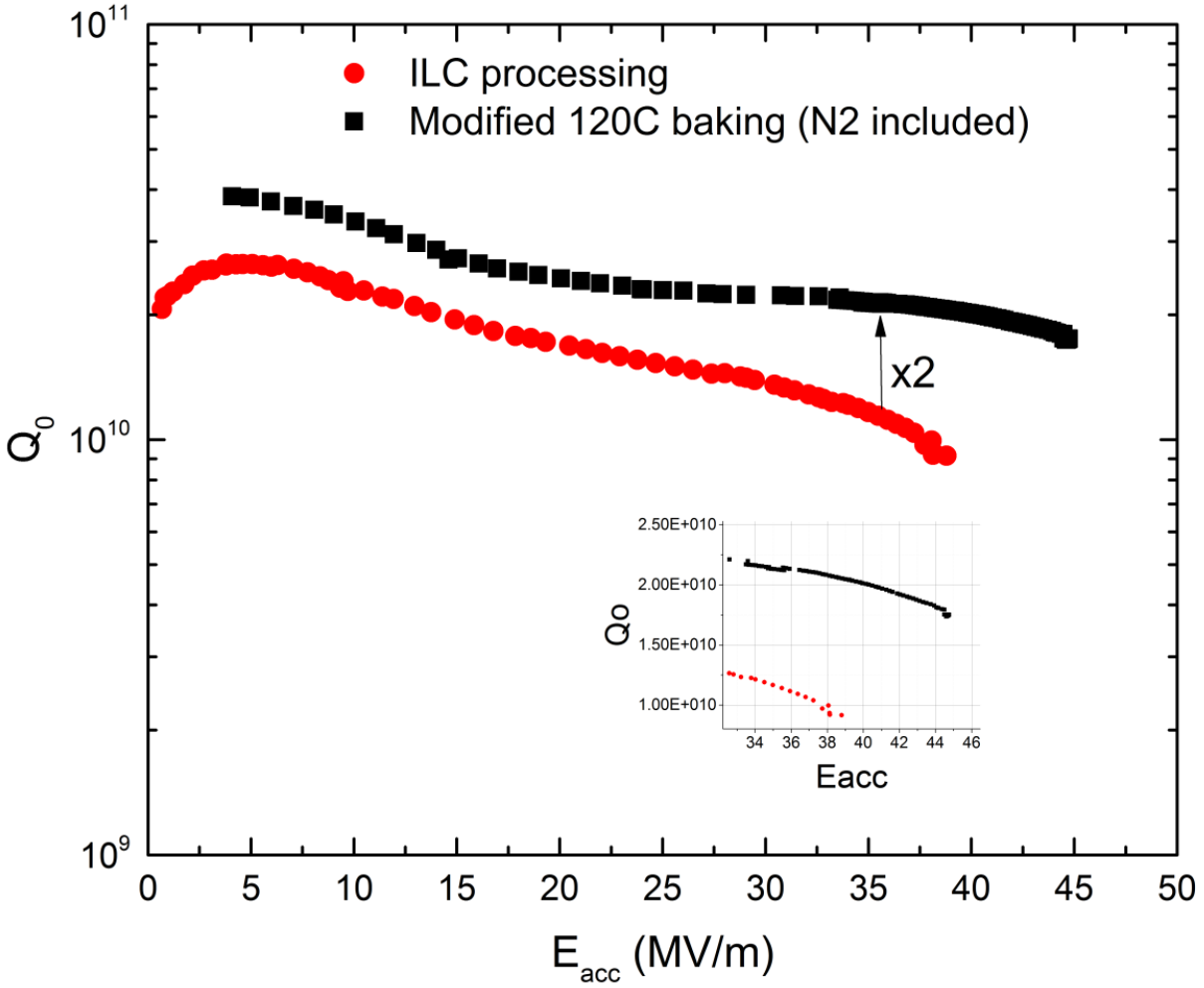
“N-doping” treatment – μm-scale



“N-infusion” treatment – 10s of nm

Fermilab

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

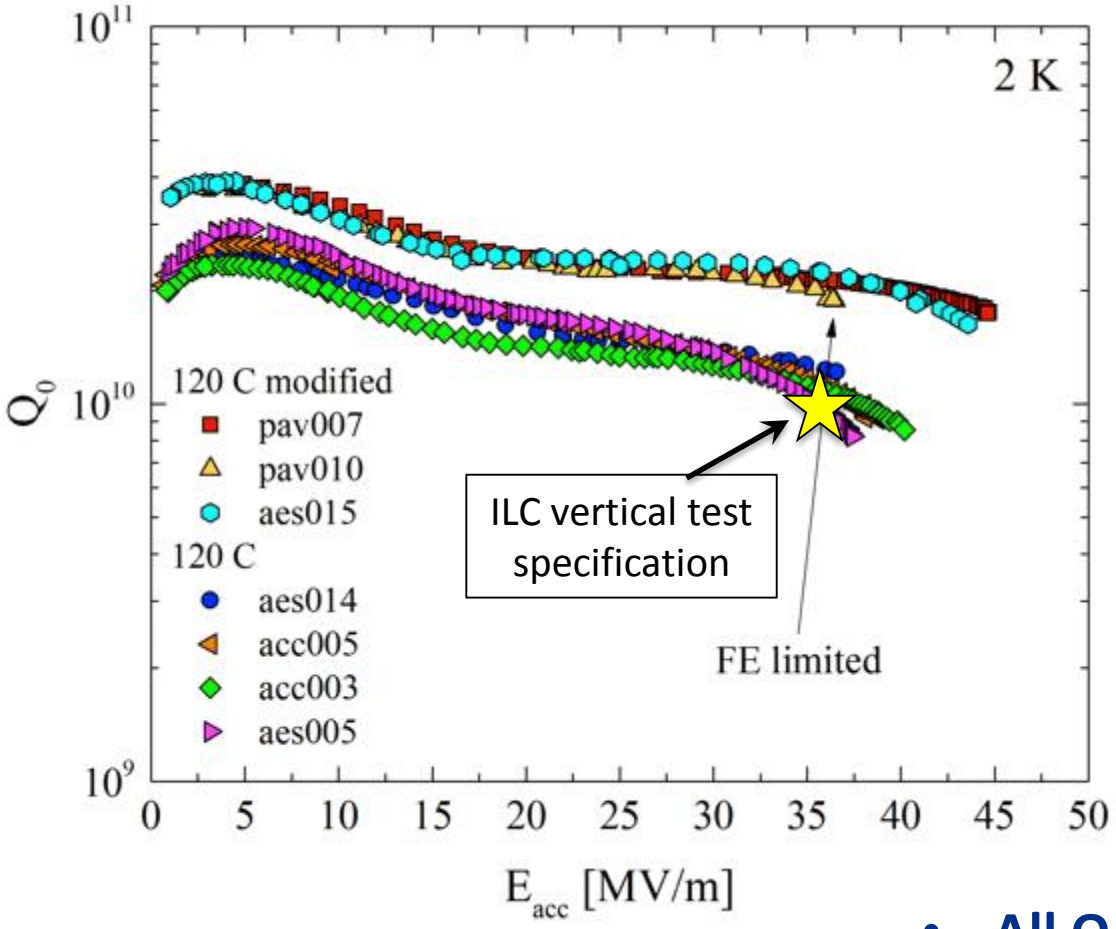


- Same cavity, sequentially processed, no EP in between
- Achieved: 45.6 MV/m → 194 mT With Q ~ 2e10!
- Q at ~ 35 MV/m ~ 2.3e10
- **All Q vs E curves shown are for 1.3 GHz single cells, T=2K**

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

A. Grassellino et al. "Unprecedented Quality Factors at Accelerating Gradients up to 45 MV/m in Niobium Superconducting Resonators via Low Temperature Nitrogen Infusion," arXiv:1701.06077

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

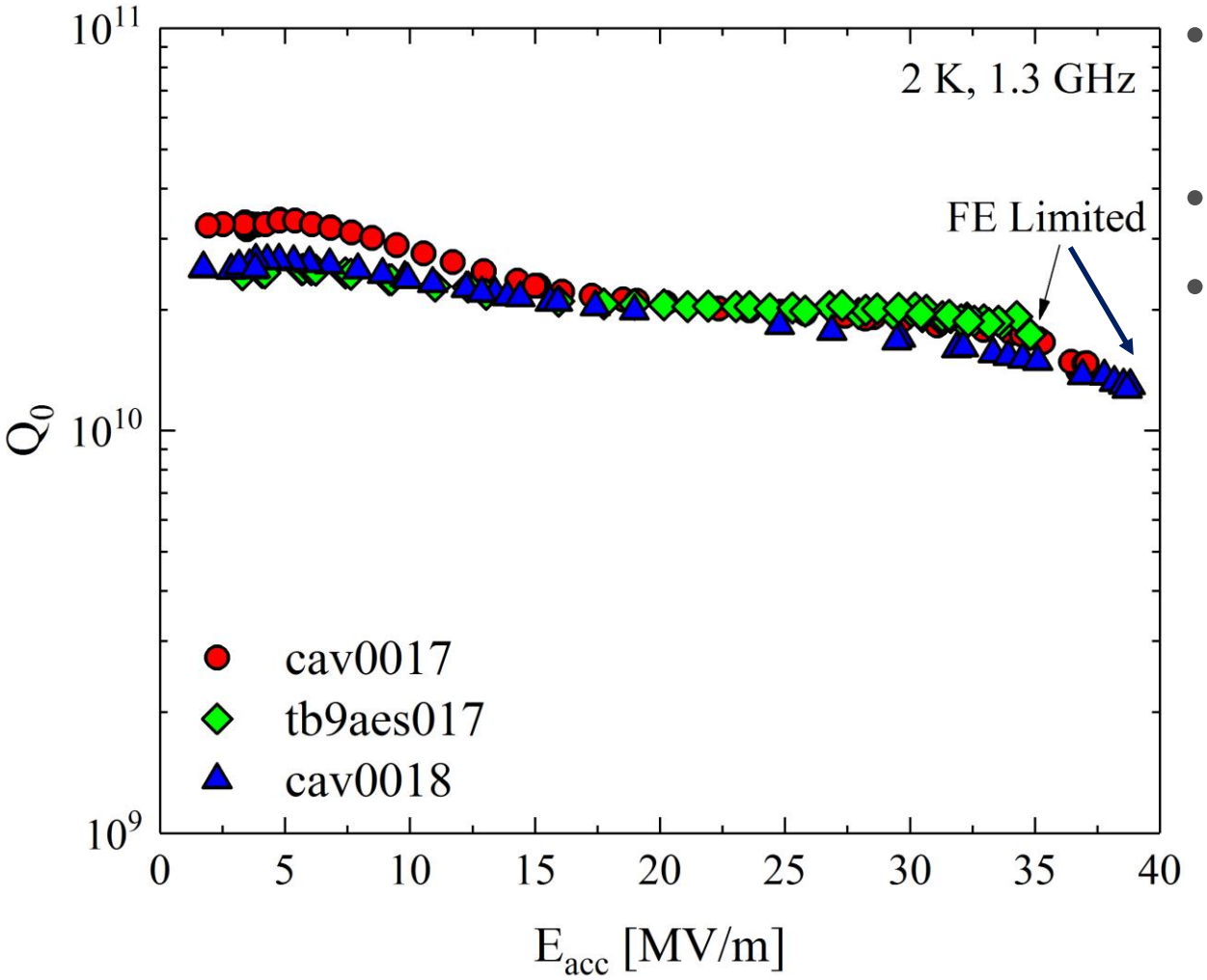


- So far three out of 4 cavities processed with this regime have reached 45 MV/m with high Q
- First attempts of N-infusion on 9-cell cavities are underway

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

A. Grassellino et al. "Unprecedented Quality Factors at Accelerating Gradients up to 45 MV/m in Niobium Superconducting Resonators via Low Temperature Nitrogen Infusion," arXiv:1701.06077

9-cell cavity results, 120C infusion



- Same high Q as single cells
- Highly reproducible
- CAV0018 limited by FE -> might have gone even higher in gradient

1.3 GHz cavities, tested at 2K

Fermilab

How Does this Compare to Statistics from XFEL?

European XFEL: RI XFEL: Maximum Gradient Yield (2D)

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

N. Walker

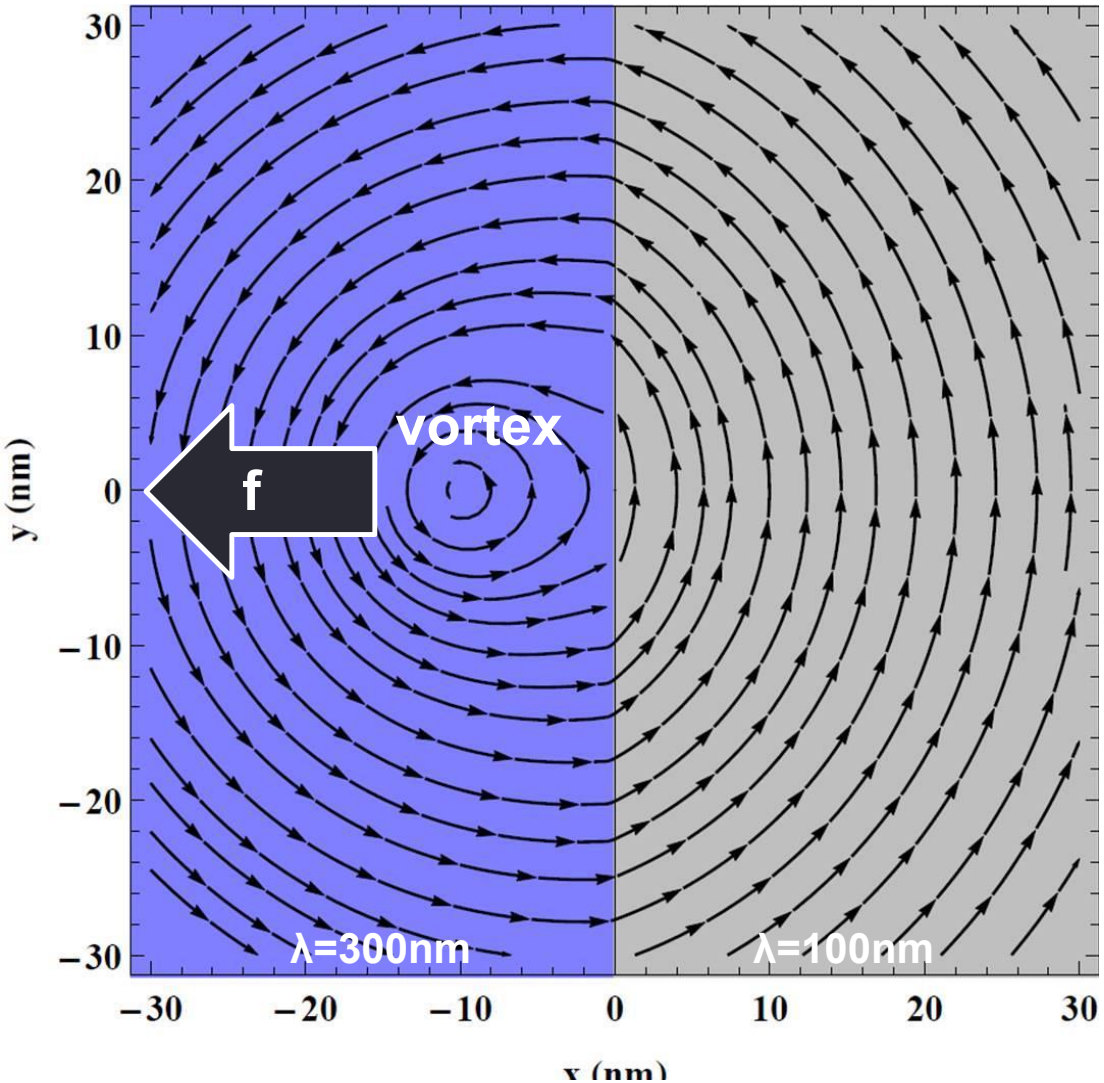
$\geq G_{max}$ MV/m

$\geq Q_0$	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%

→Compared to this table values for XFEL, result would lay in top 1%

Trick to delay flux penetration - layering

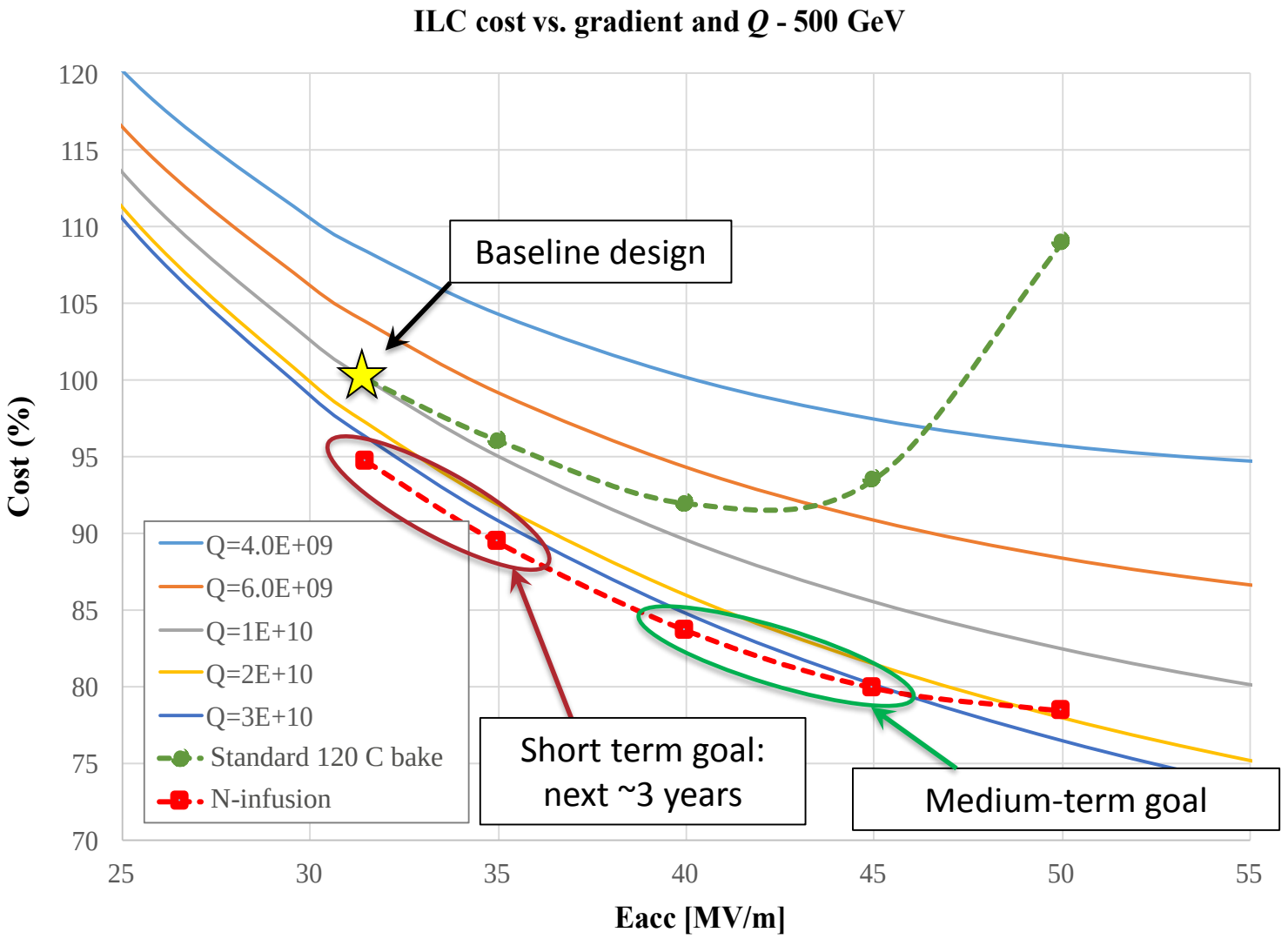
The vortex is pushed by the S-S boundary to the direction of the material with a larger λ.



T.Kubo, in proceedings of LINAC14, Geneva, Switzerland (2014), p. 1026, THPP074

G. S. Mkrtchyan, F. R. Shakirzyanova, E. A. Shapoval, and V. V. Shmidt, Zh. Eksp. Theor. Fiz. **63**, 667 (1972).

Impact in Cost Model for ILC



ILC Cost Reduction Collaboration

Taking Advantage of New SRF Developments

Money awarded recently

- Harness recent SRF R&D advances
- Harness strengths of different laboratories
- N-infusion, reduced field emission, minimized flux losses
- Demonstrate that significant reduction in the cost of the ILC is possible to help make the project **realizable**
- Progress will benefit programs also outside of ILC

Fermilab

Jefferson Lab

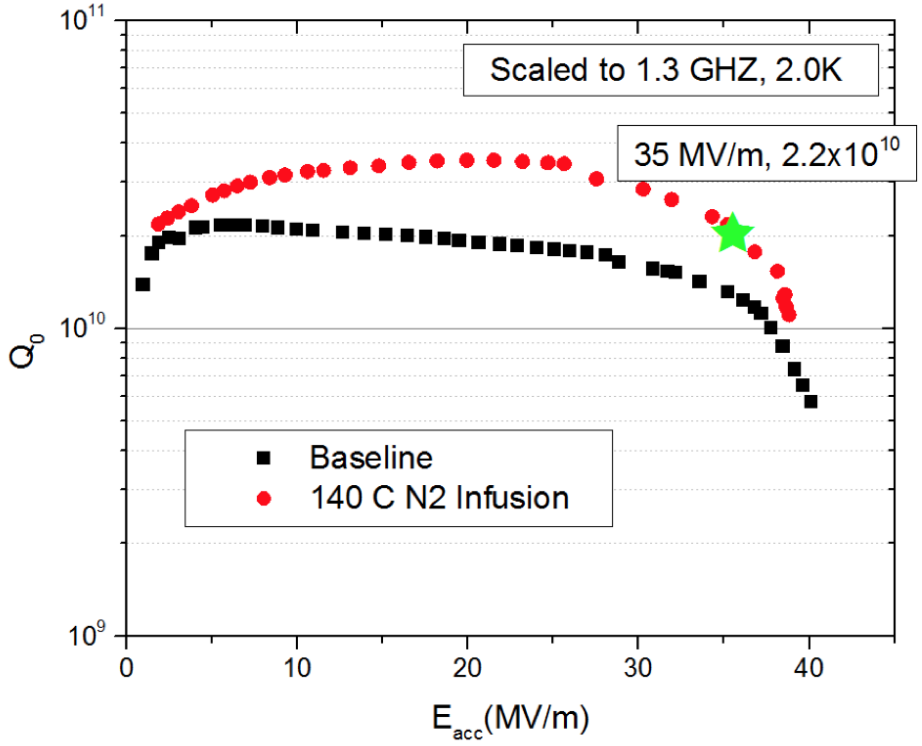
CORNELL UNIVERSITY FOUNDED A.D. 1865

KEK-JAPAN

U.S. DEPARTMENT OF ENERGY

Spreading N-Infusion Capability

RECENT WORK AT JLAB



Work in Large grain cavities as well as process control are in progress.

Jefferson Lab

P. Dhakal (JLab)

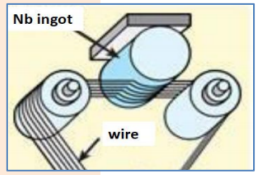
See also talks on Tuesday from F. Furuta (Cornell), M. Wenskat (DESY), and E. Kako (KEK)

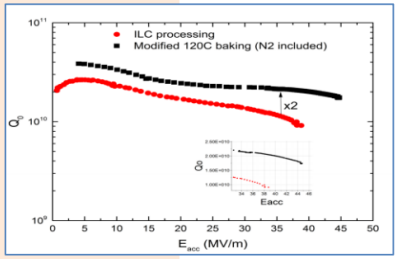
Combine N-Infusion with Other Reduction Methods

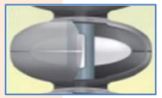
A plan for ILC Cost-Reduction R&D in Japan and US focusing on SRF Technology, in 2~3 years

Based on recent advances in technologies;

- Nb material preparation
  - w/ optimum RRR and clean surface
  - Reduction fraction to Total ILC Cost : (~200 Oku) 2~3 %
- SRF cavity fabrication for high-Q and high-G
  - w/ a new baking recipe with N-infusion
  - Reduction fraction (~750 Oku): 8~9 % → 4~5 %
    - Revised because of CFS (unchanged), HLRF increase, and Cryo-plant of 3
- Power input coupler fabrication
  - w/ new (low SEE) ceramic without coating
  - Reduction fraction (~120 Oku): 1~2 %
- Cavity chemical process
  - w/ vertical EP and new chemical (non HF) solution
  - Reduction fraction (~120 Oku): 1~2 %
- Others







– SRF R&D effect : ~ ≥ 10 % at 500 GeV

→ ~≥ 5 % at 250 GeV (staging)

A. Yamamoto, 17/05/22 8

A. Yan

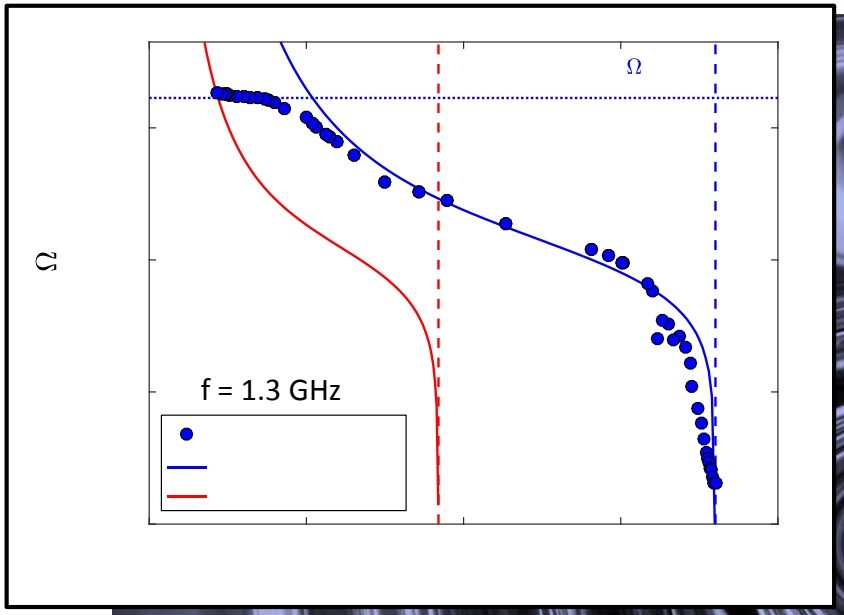
See talk on Wednesday from Akira Yamamoto (KEK)

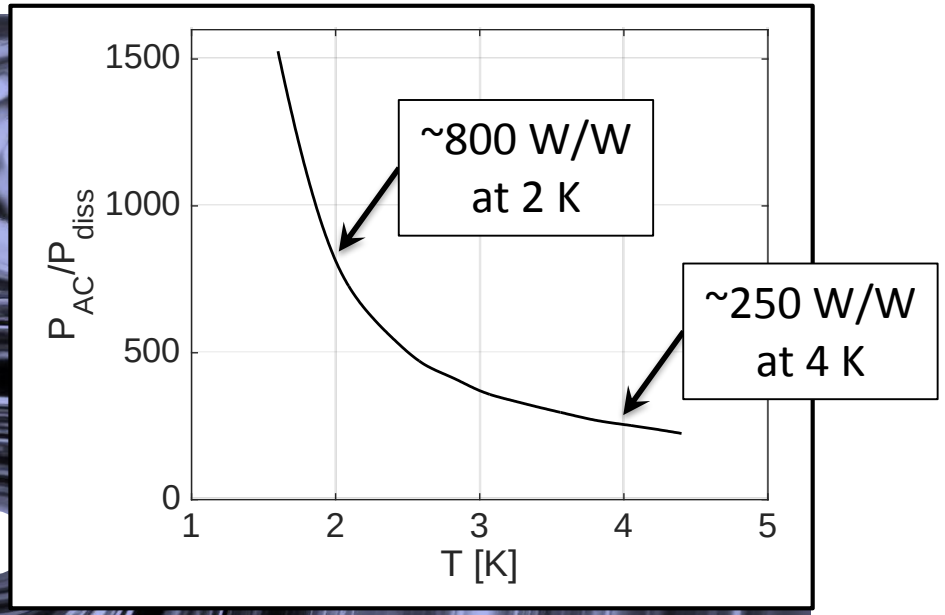
Superconducting RF Technology

Next Generation R&D

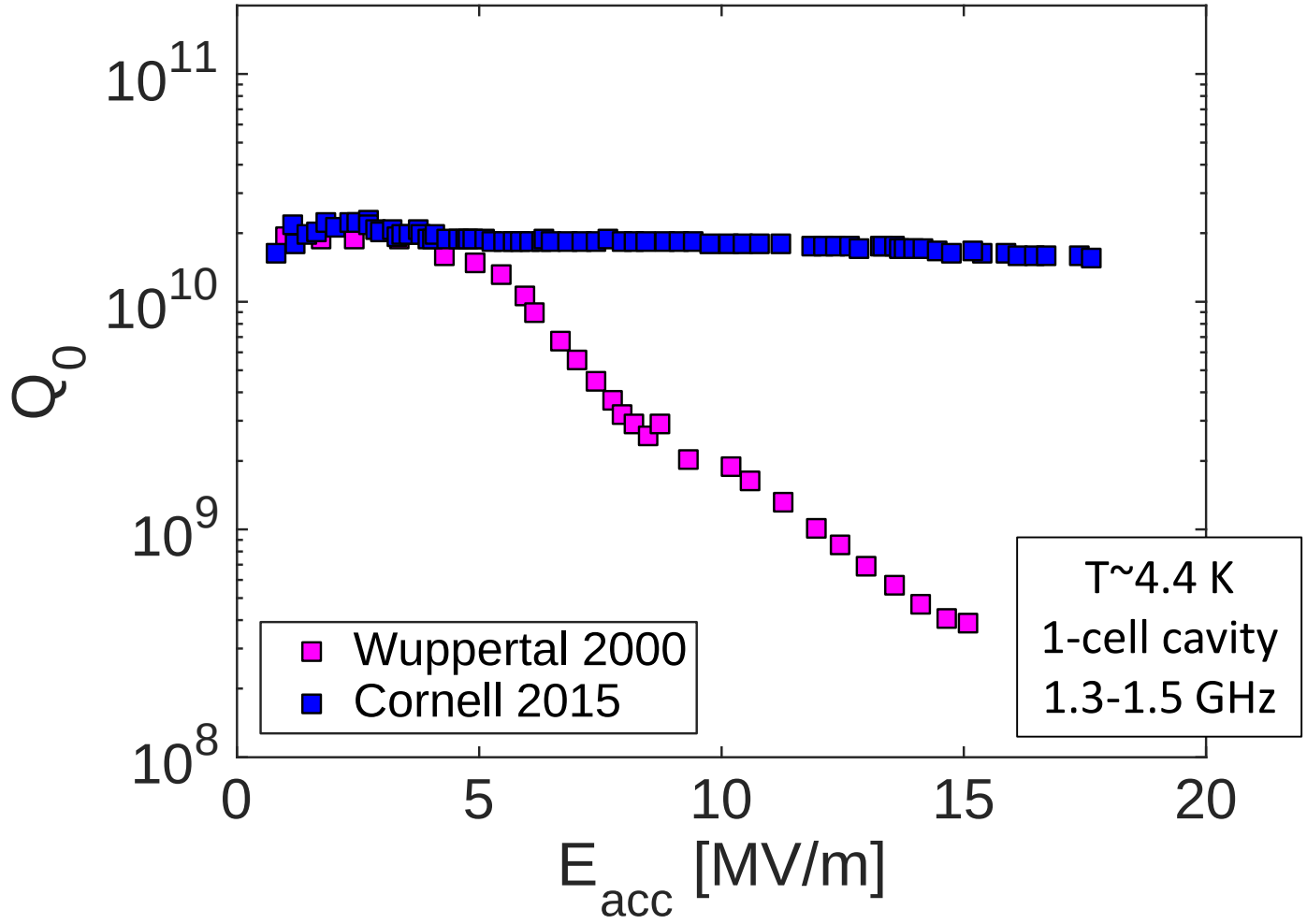
Beam view, inside the cavity

Beam view, inside the cavity



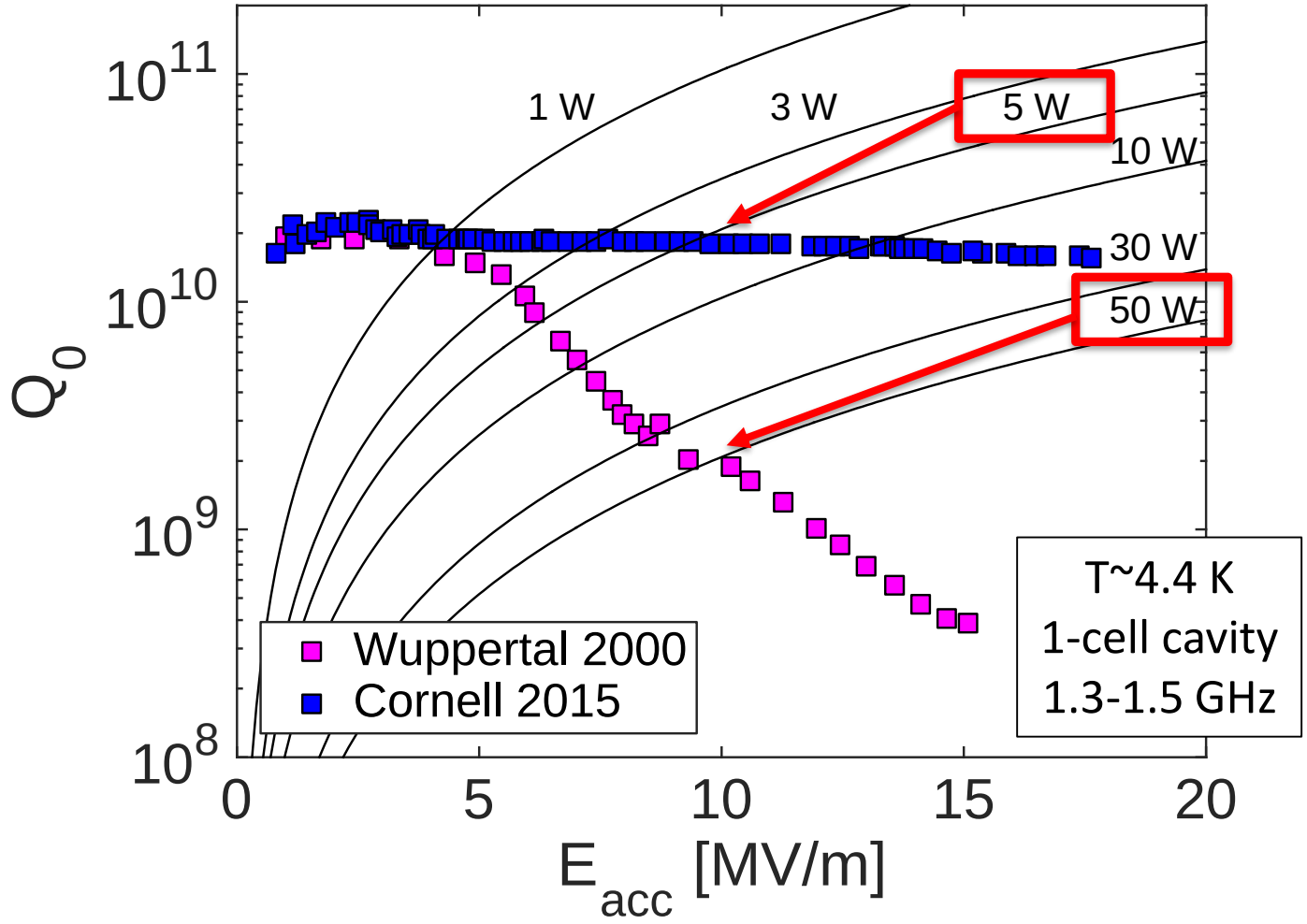


Recent Developments in Nb_3Sn SRF Cavities



S. Posen, M. Liepe and D. Hall, *Appl. Phys. Lett.*, **106**, 082601 (2015).
S. Posen and D.L. Hall, *Supercond. Sci. Technol.*, **30** 033004 (2017).

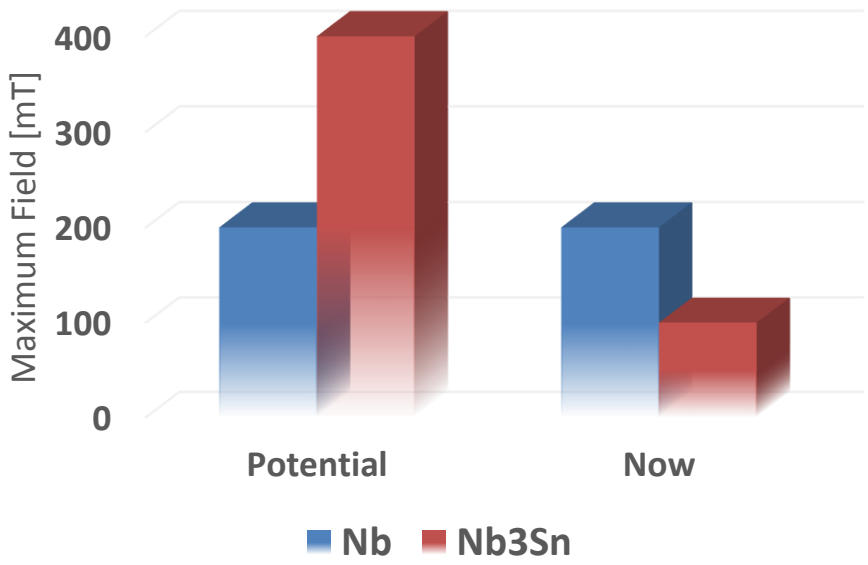
Recent Developments in Nb_3Sn SRF Cavities

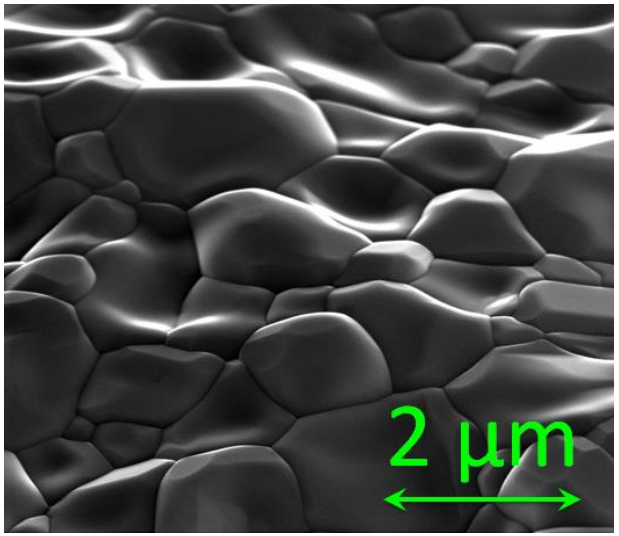


S. Posen, M. Liepe and D. Hall, *Appl. Phys. Lett.*, **106**, 082601 (2015).
S. Posen and D.L. Hall, *Supercond. Sci. Technol.*, **30** 033004 (2017).

High H_{sh} with Nb_3Sn

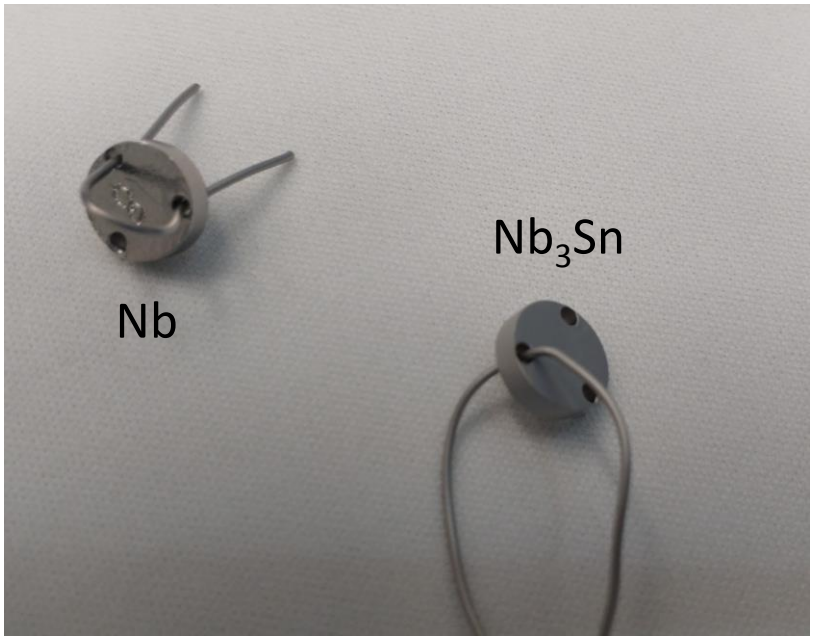
- Nb_3Sn is predicted to have **2x** the fundamental metastable limit of niobium

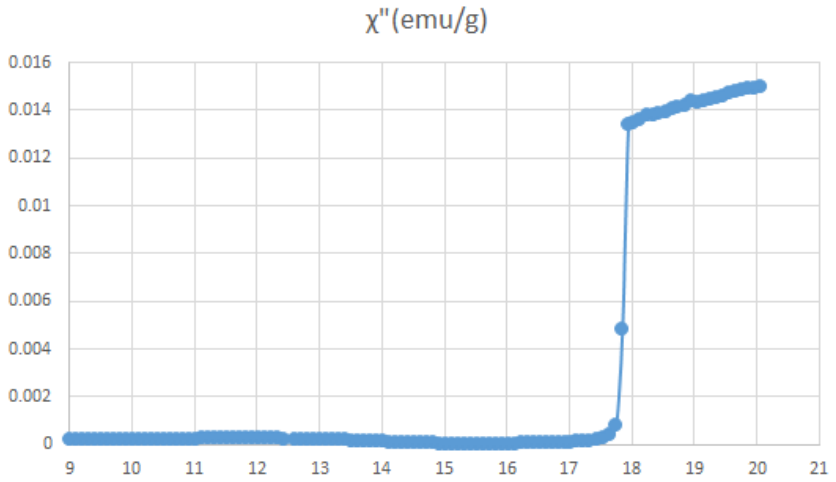


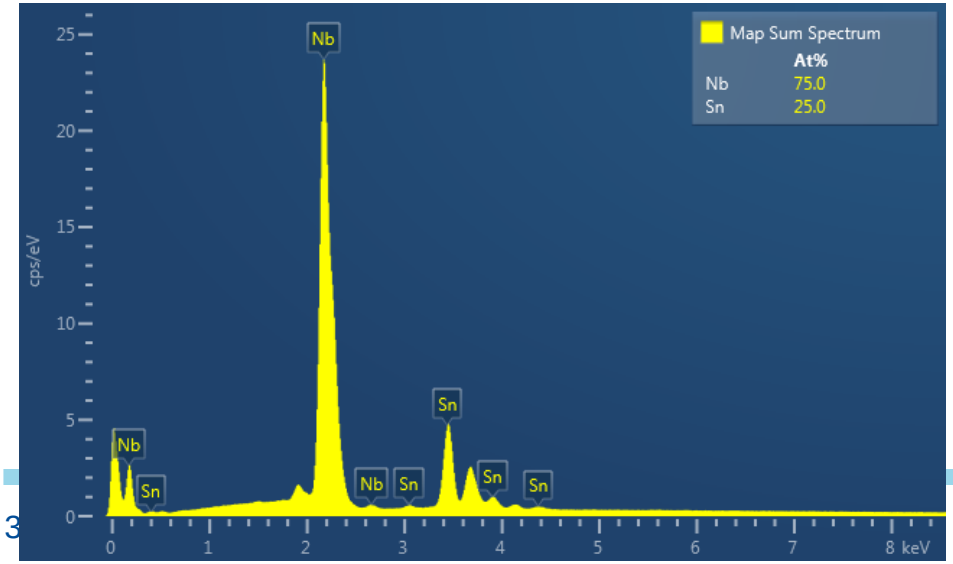


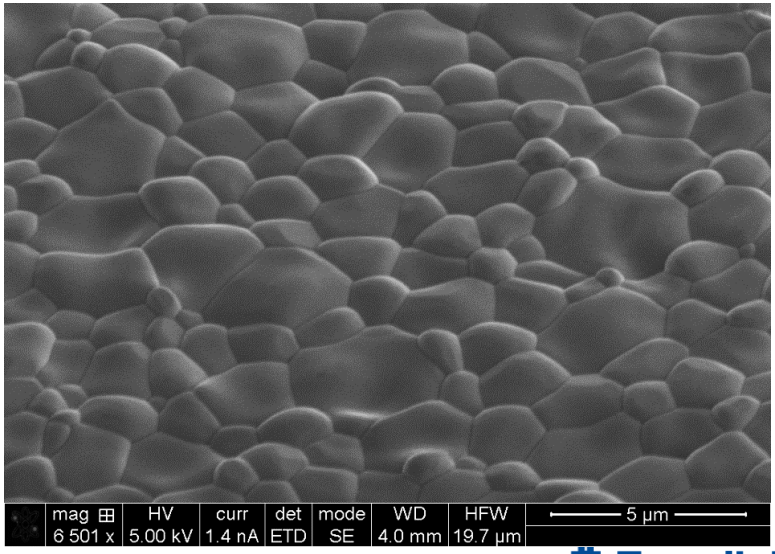
- Twice the energy gain per cavity?
- Not there yet—additional R&D required

Nb_3Sn Samples via Vapor Diffusion at Fermilab



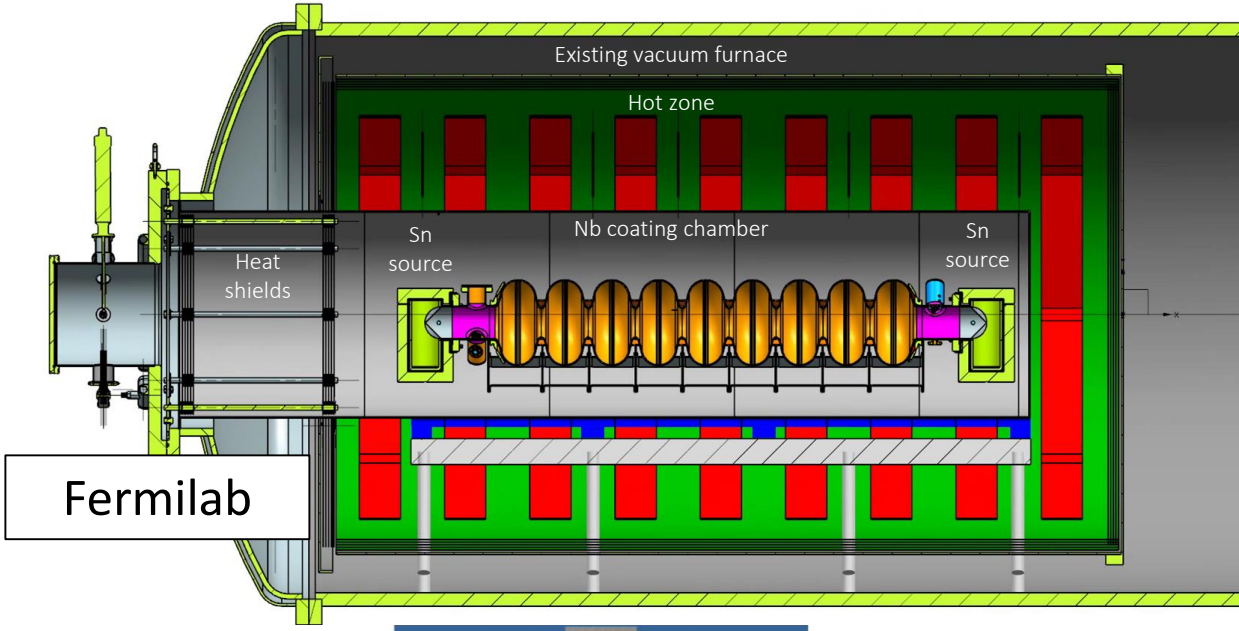




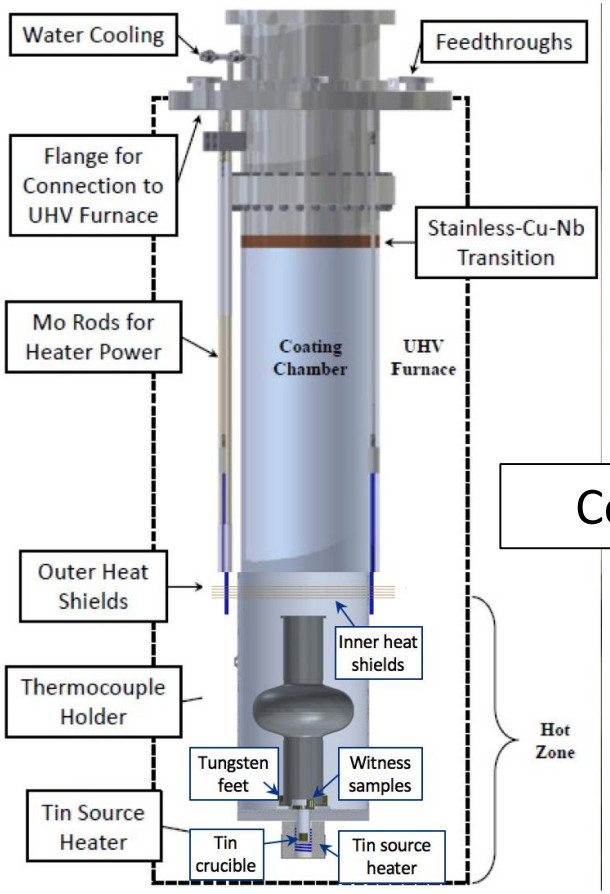


Sample measurements by Yulia Trenikhina (FNAL), Jae-Yel Lee (Northwestern), and Zuhawn Sung (FNAL)

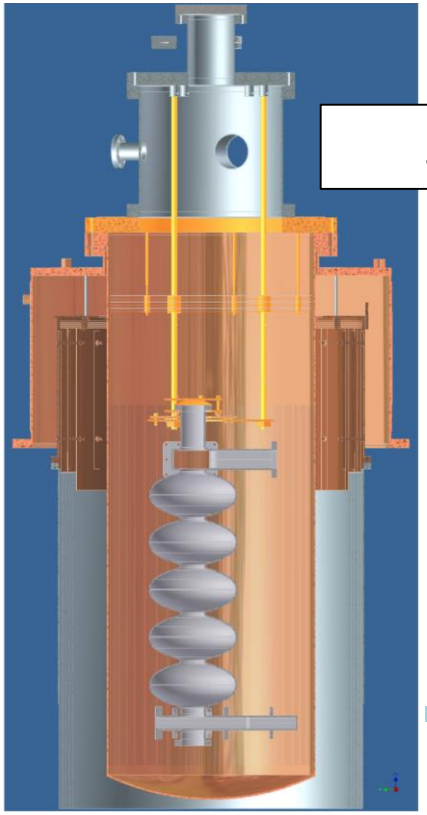
Nb_3Sn Coating Chambers



Fermilab



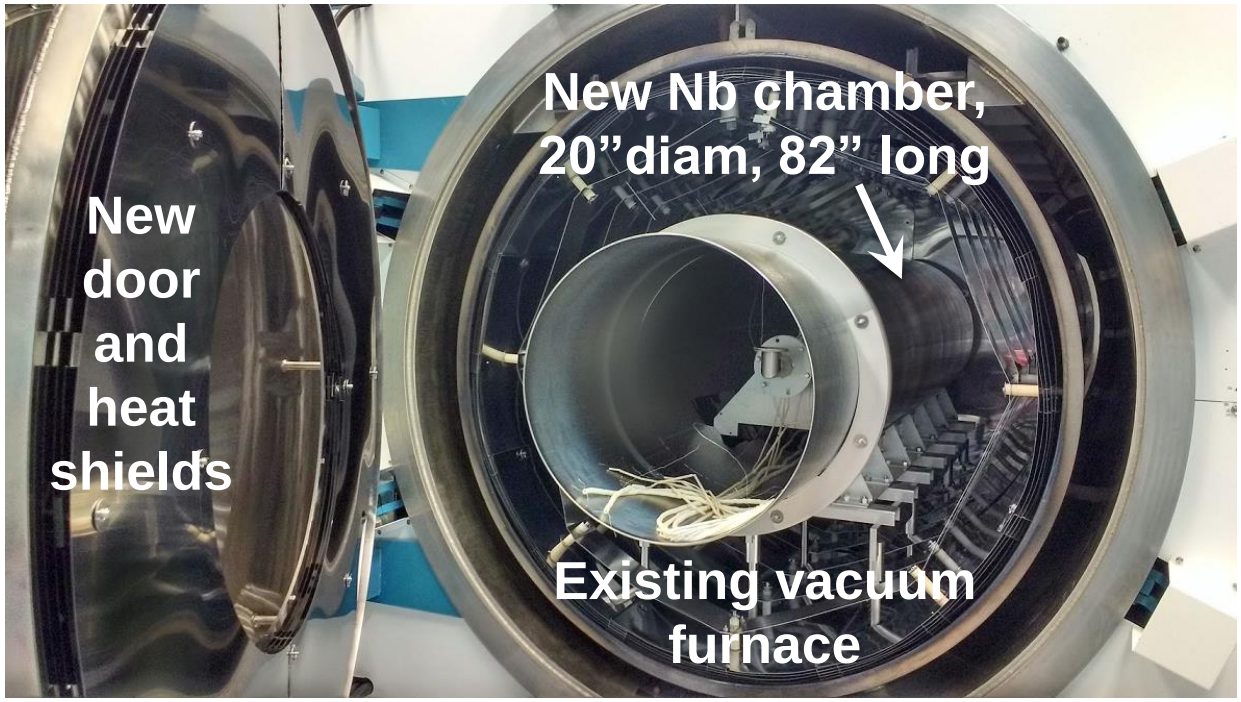
Cornell



JLab

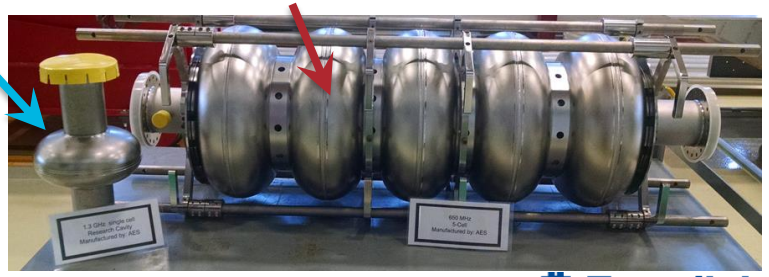
Fermilab

Nb_3Sn Coating System at Fermilab



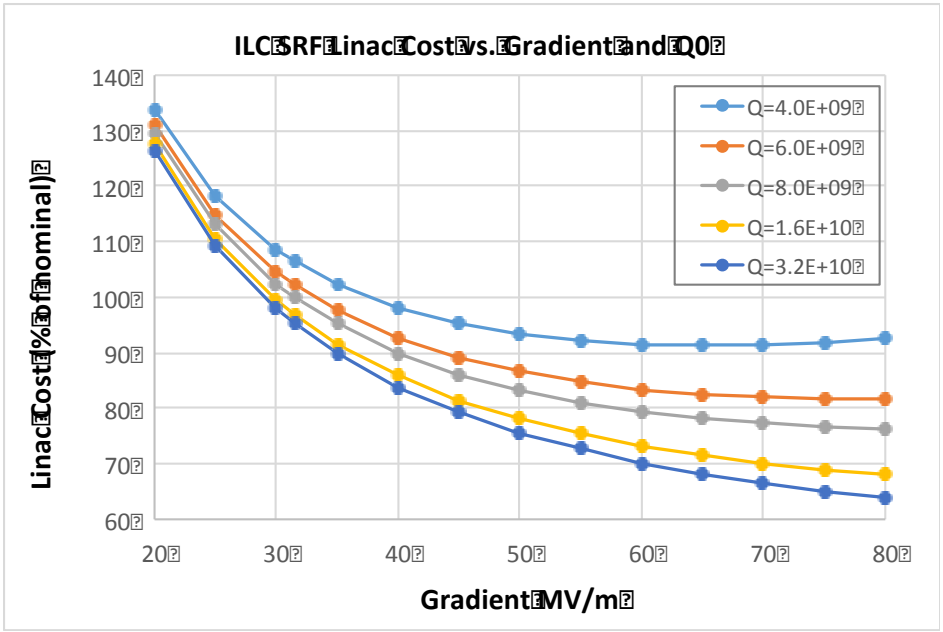
1.3 GHz 1-cell (current state of Nb_3Sn R&D)

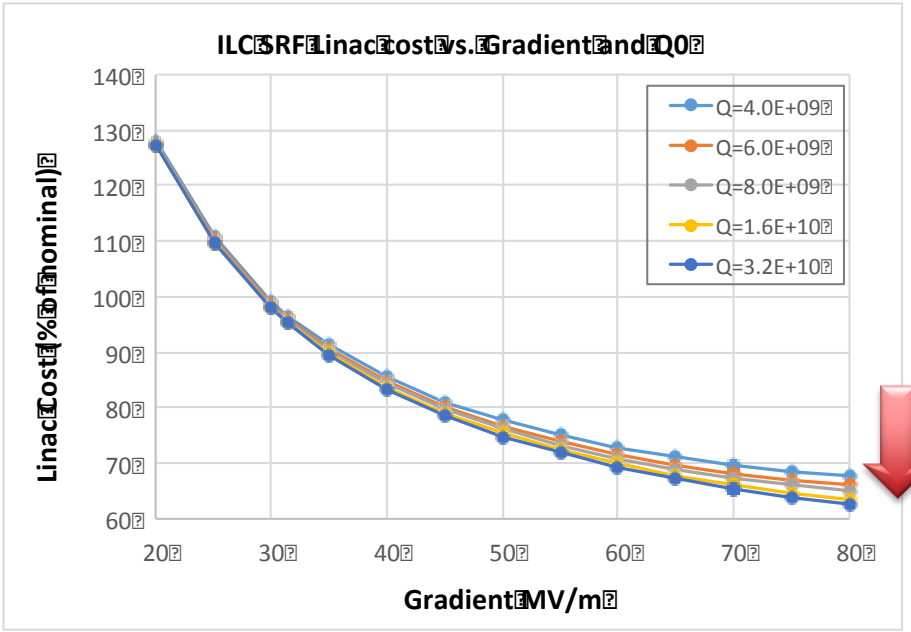
650 MHz 5-cell (future)



4.5 K ILC Upgrade?

4.5 K system helps reduce cryogenic costs (analysis by Tom Peterson). Analysis is specific to ILC, but representative of significant cost savings for machines large and small that would benefit from high gradients.





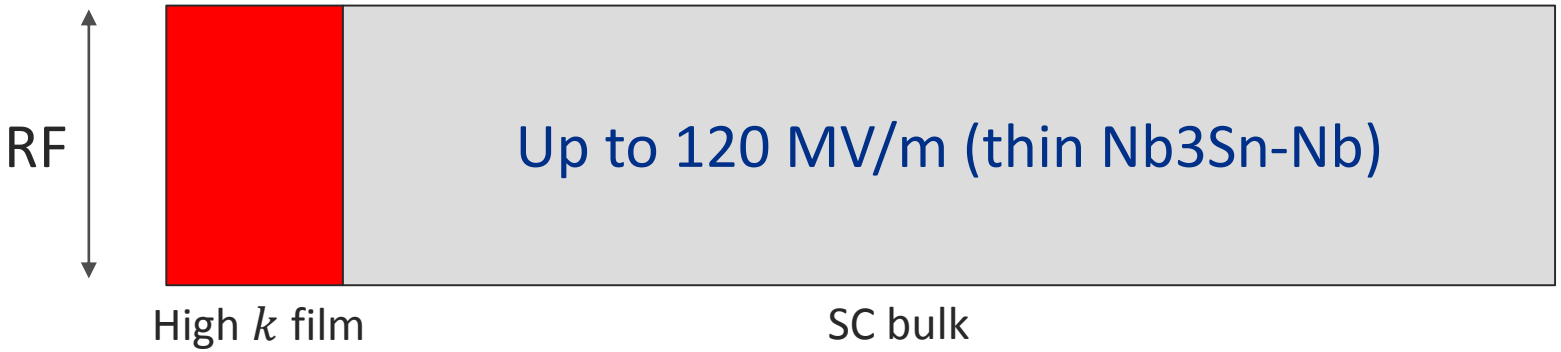
2.0 K

4.5 K

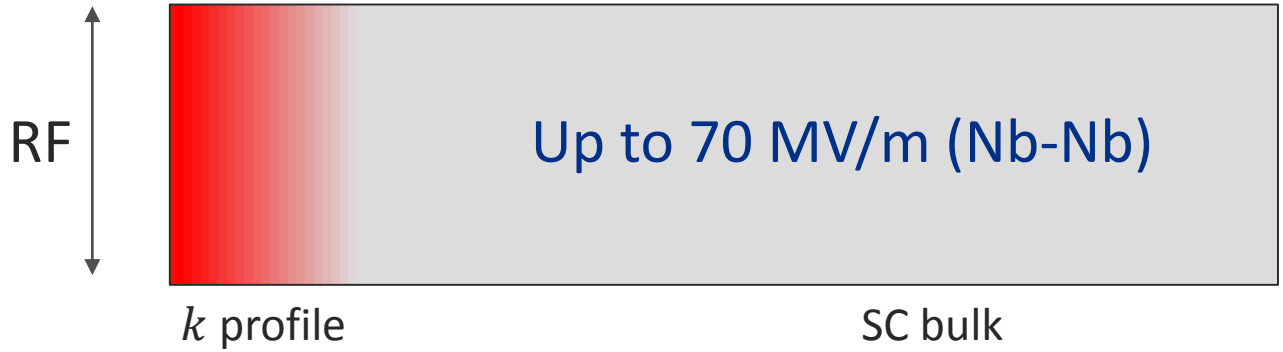
(In ILC staged approach, Nb_3Sn not ready for 250 GeV first step, but could be developed for high energy upgrade.)

Superconductor-Superconductor (Dirty Layer) Structure

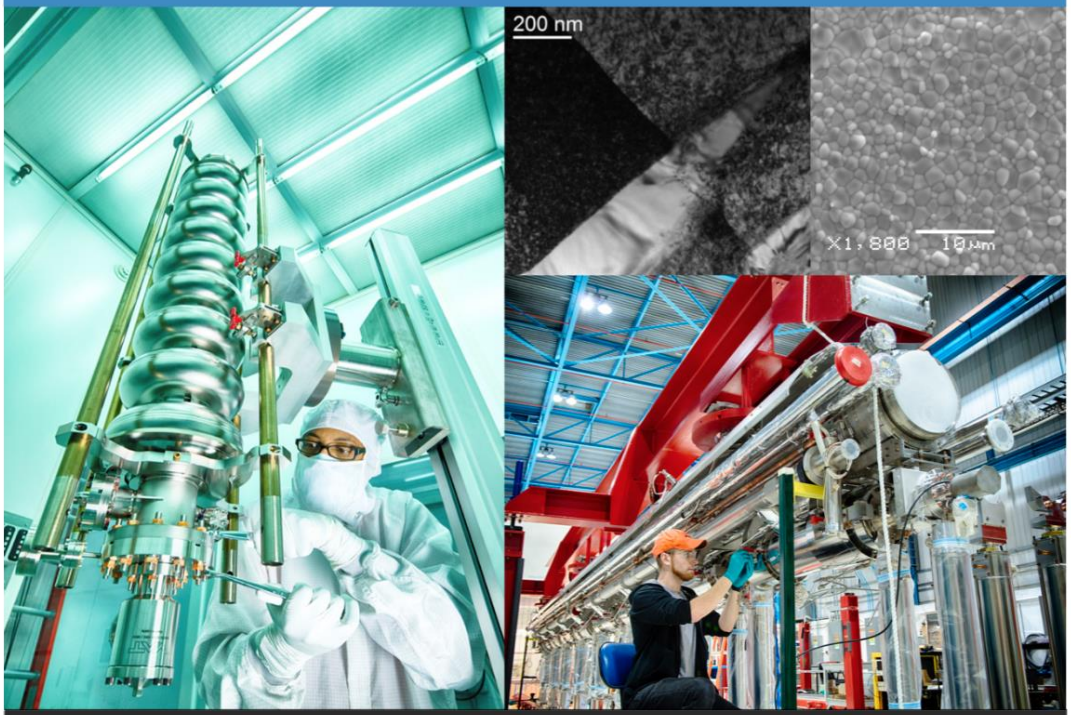
- High κ film: analytical from London eqs.
  T. Kubo, *Supercond. Sci. Technol.* **30,** 023001 (2017)



- Diffused κ profile: numerical from Ginzburg-Landau eqs.
  M. Checchin *et al.*, IPAC 2016 & LINAC 2016



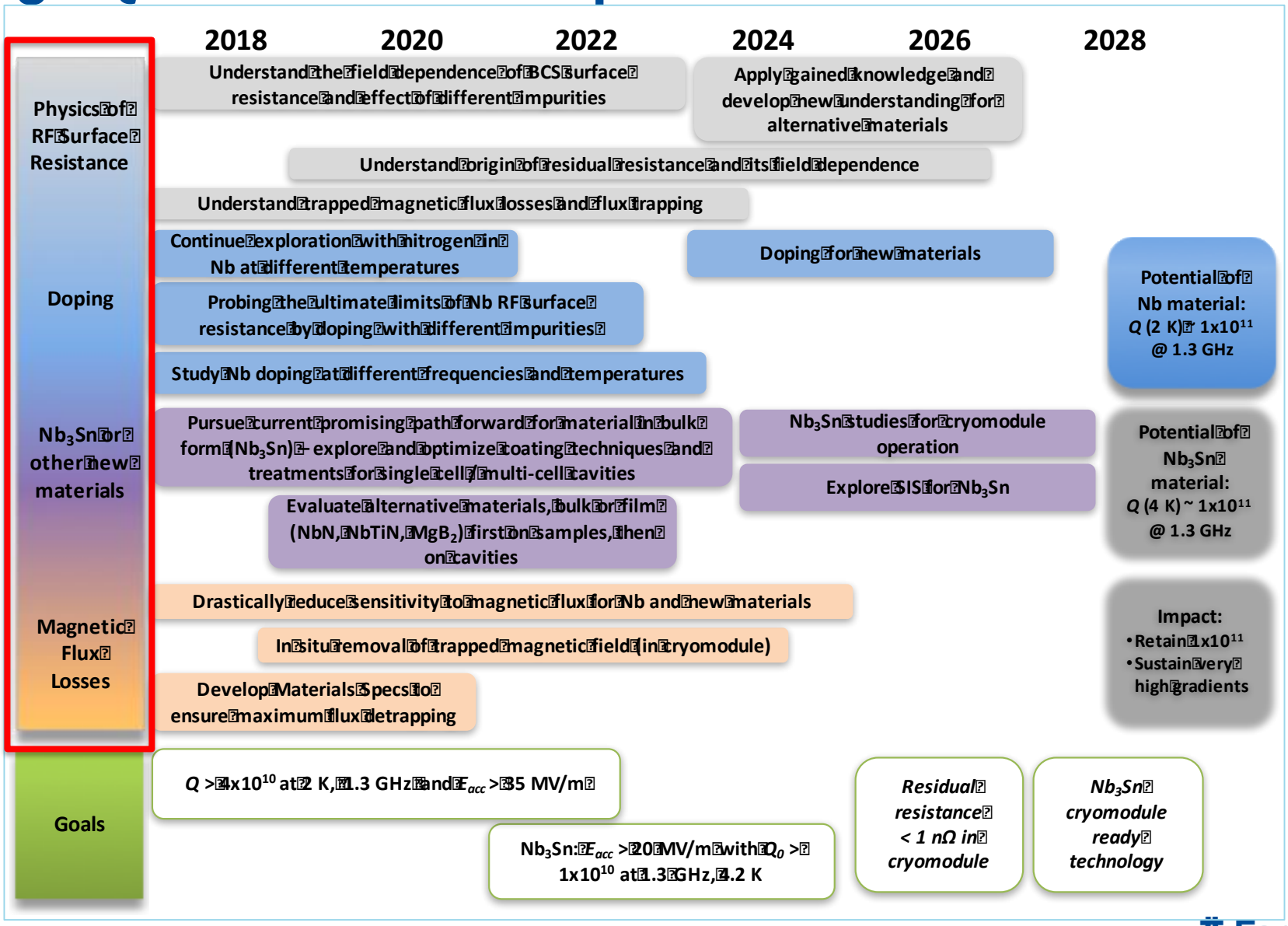
Can be produced by thermal diffusion!



DOE GARD-SRF Roadmap Workshop

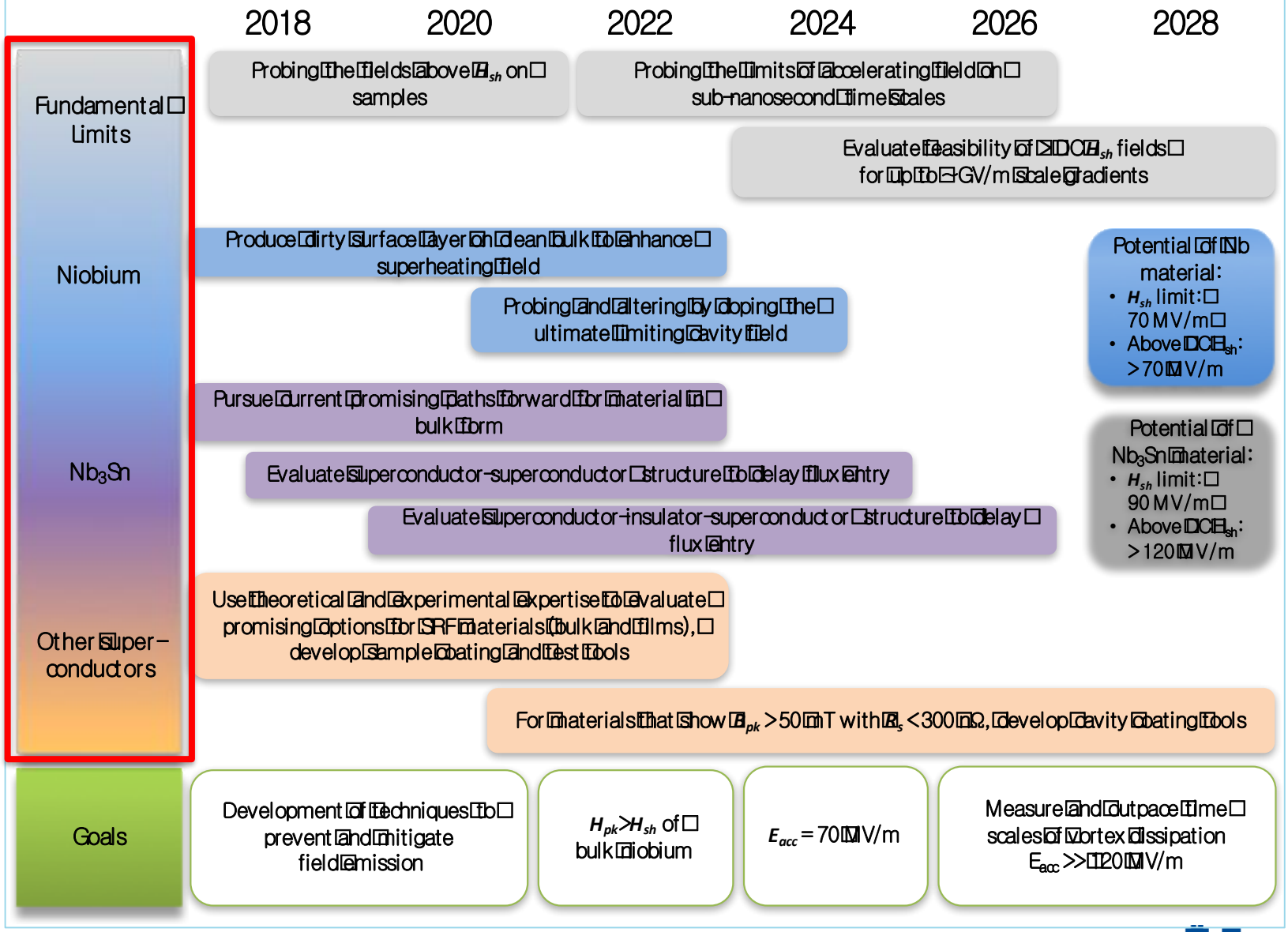
U.S. DEPARTMENT OF ENERGY | Office of Science

High *Q* frontier roadmap



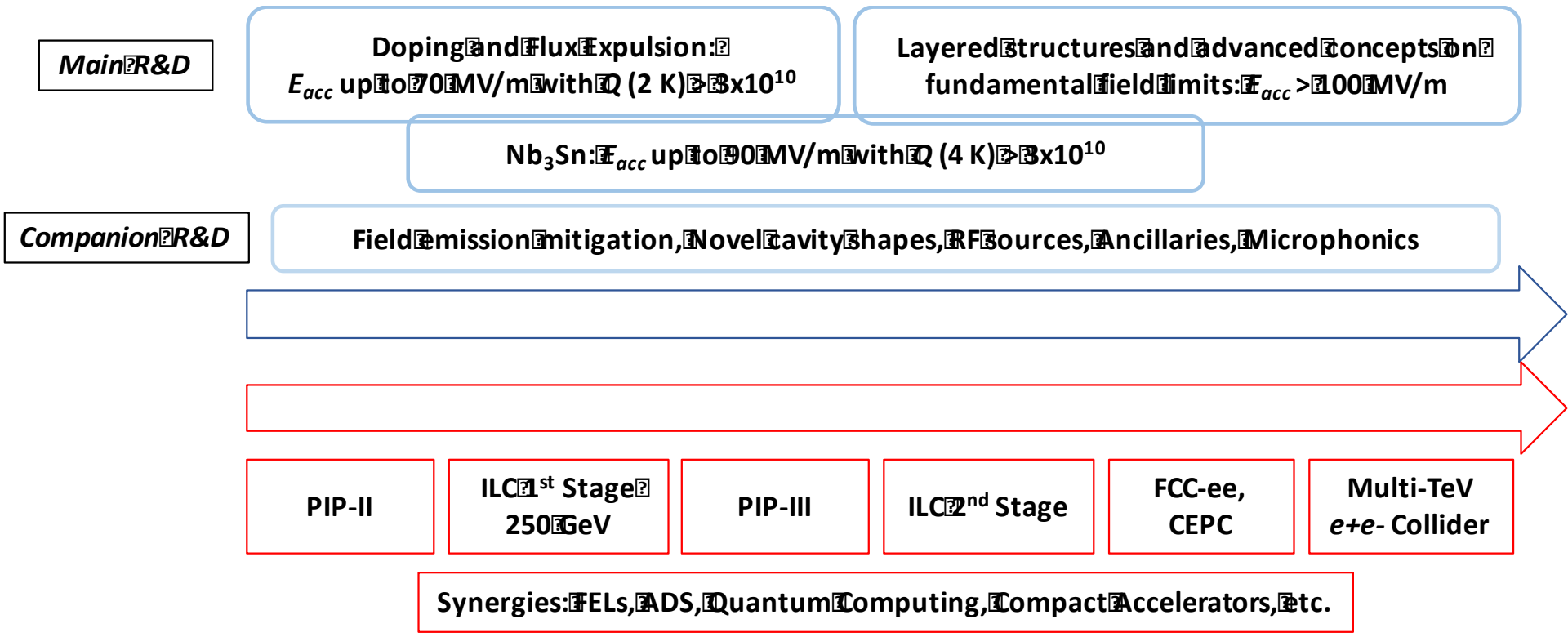
Fermilab

High Gradient frontier roadmap



Fermilab

Alignment of SRF R&D and future machines



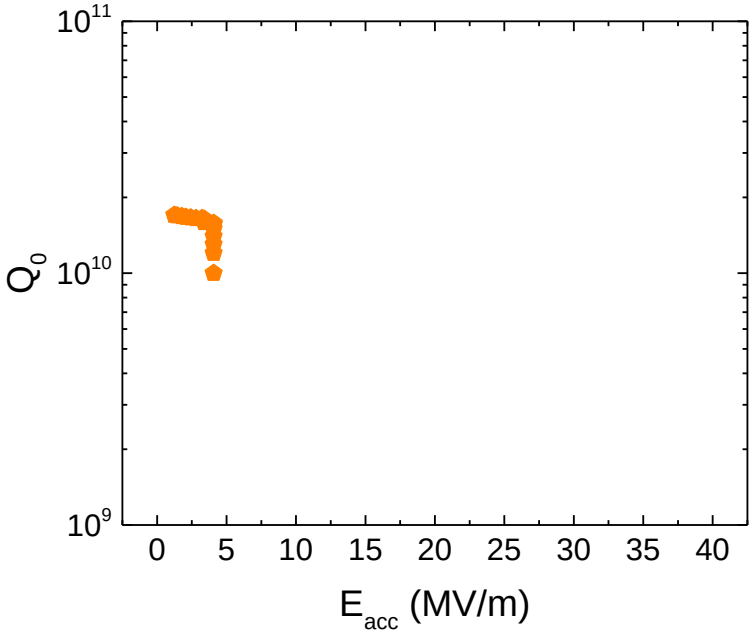
Fermilab

Superconducting RF Technology

Conclusion: Continuing Evolution

SRF Performance Evolution

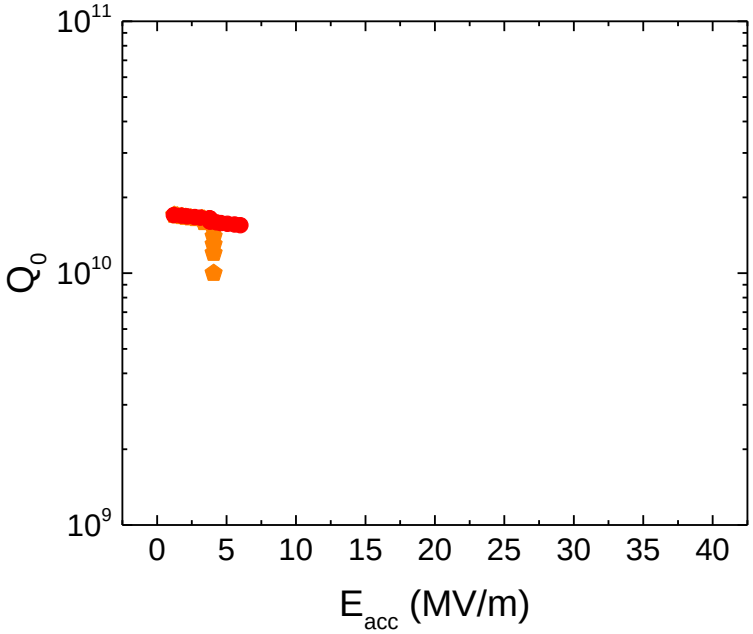
Courtesy A. Grassellino



3 – 4 MV/m
Multipacting

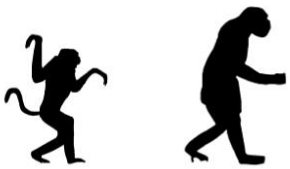
SRF Performance Evolution

Courtesy A. Grassellino



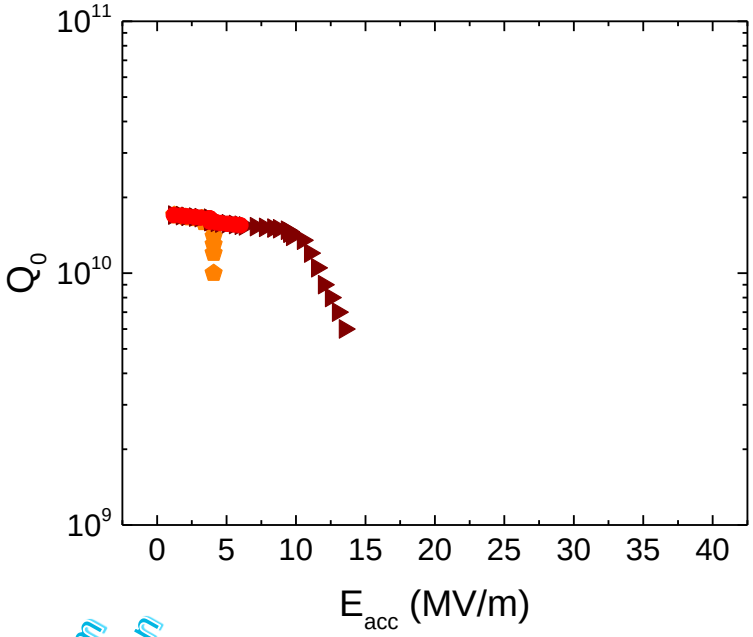
3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown



SRF Performance Evolution

Courtesy A. Grassellino



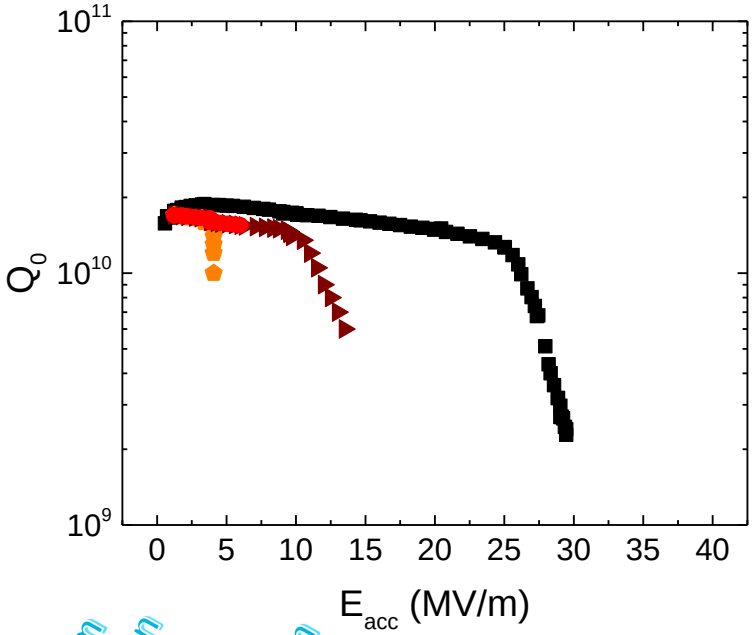
3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown

10 – 15 MV/m
Field Emission

SRF Performance Evolution

Courtesy A. Grassellino

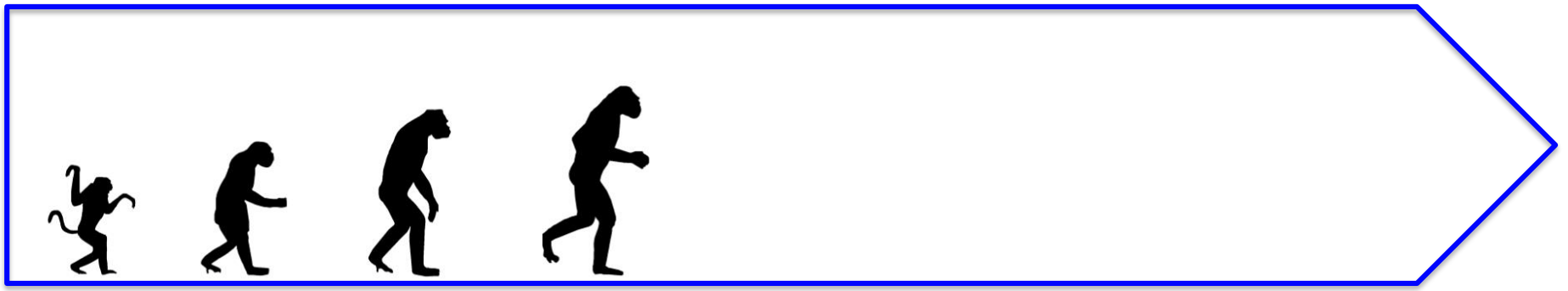


3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown

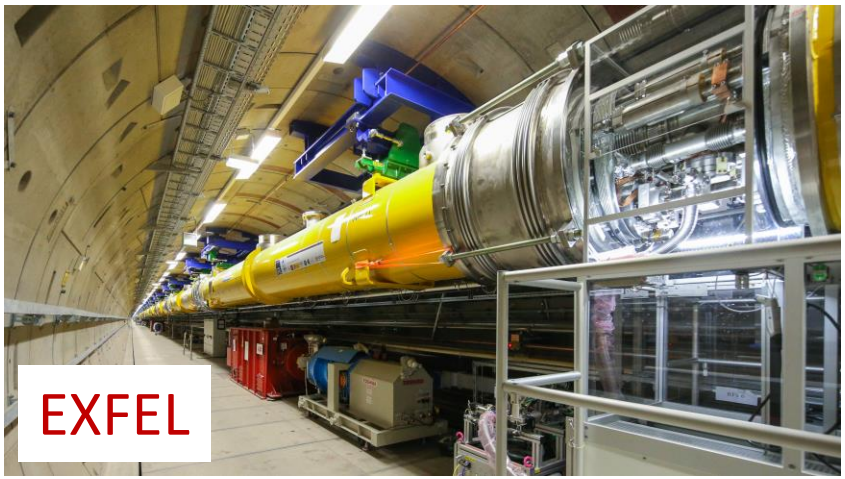
10 – 15 MV/m
Field Emission

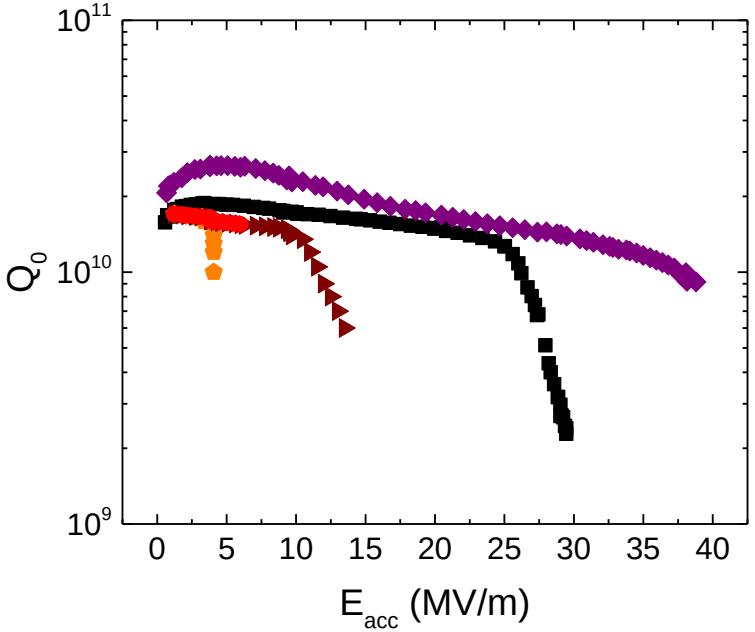
20 - 25 MV/m
Q-SLOPE



SRF Performance Evolution

Courtesy A. Grassellino





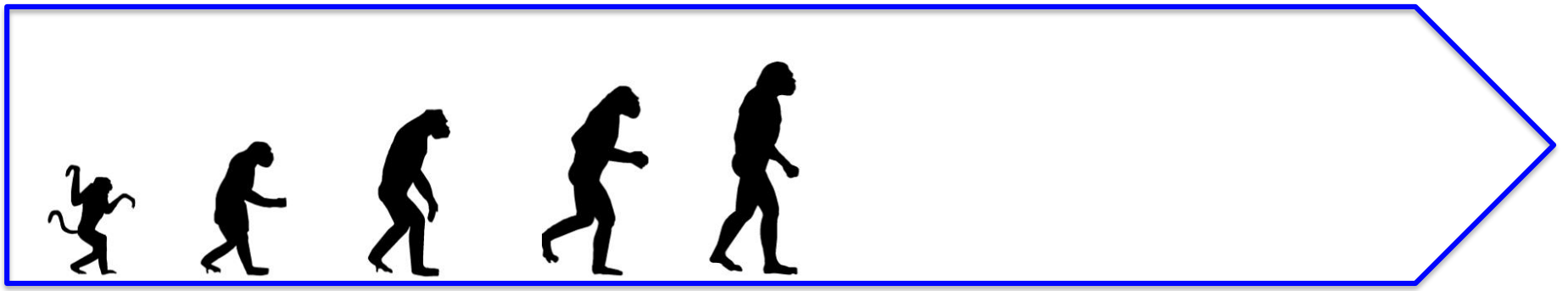
3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown

10 – 15 MV/m
Field Emission

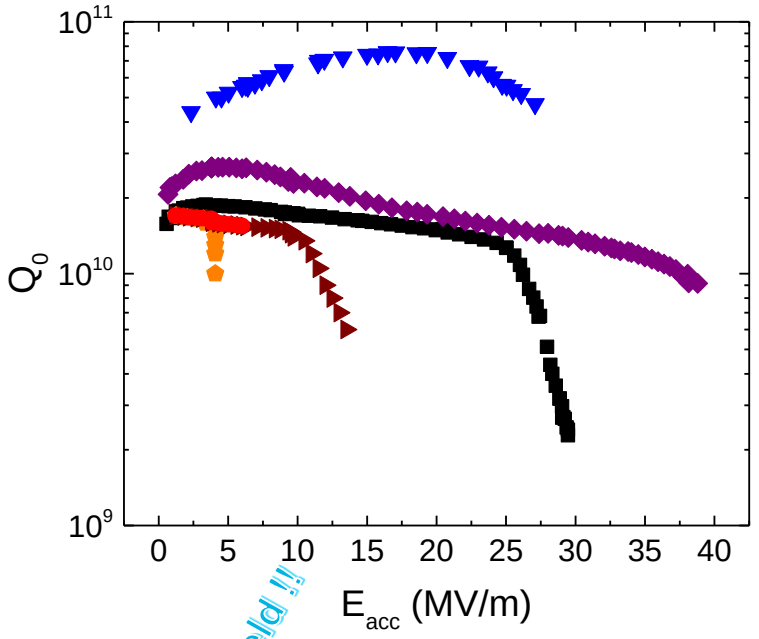
20 - 25 MV/m
Q-SLOPE

35 – 40 MV/m



SRF Performance Evolution

Courtesy A. Grassellino



3 – 4 MV/m Multipacting

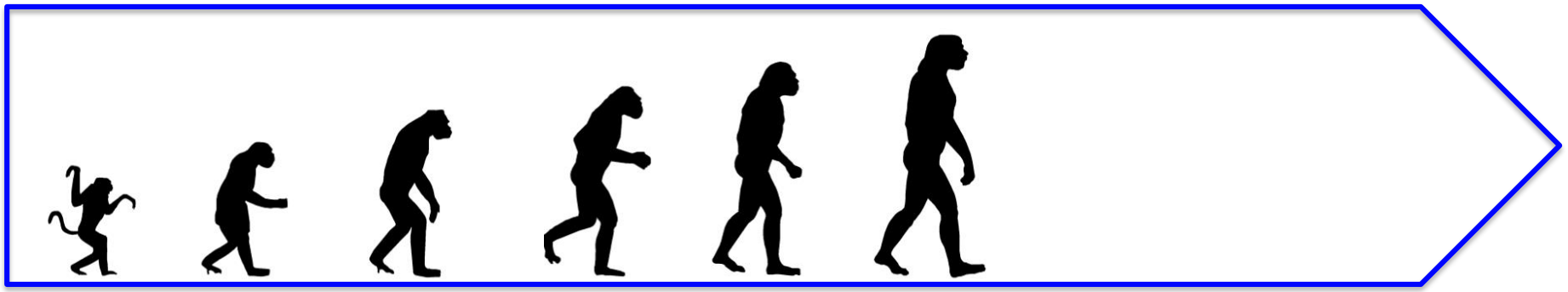
5 MV/m Thermal Breakdown

10 – 15 MV/m Field Emission

20 - 25 MV/m Q-SLOPE

35 – 40 MV/m

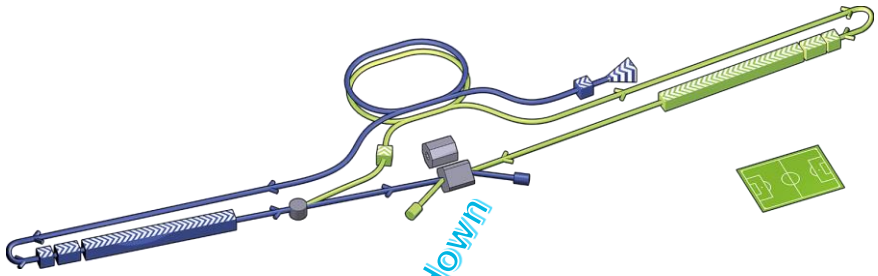
Q > 5e10 At medium field !!!

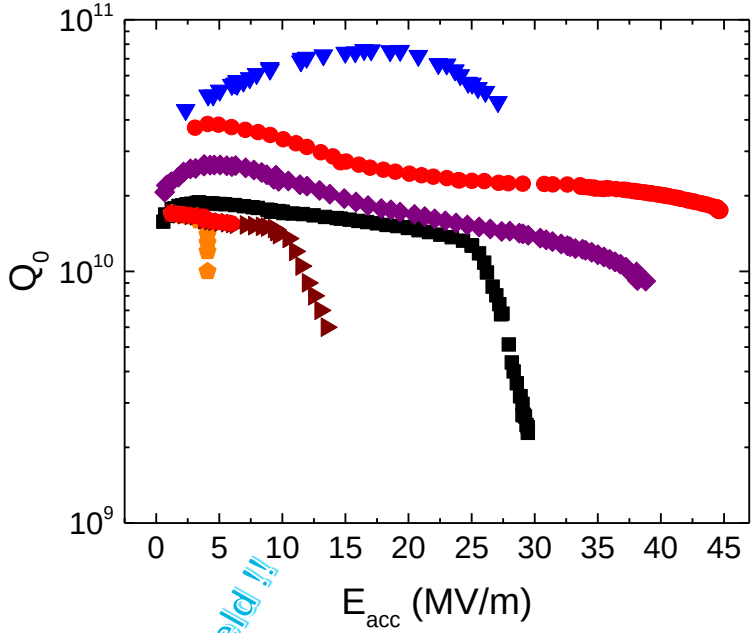


SRF Performance Evolution

Courtesy A. Grassellino

ILC cost reduction??





3 – 4 MV/m Multipacting

5 MV/m Thermal Breakdown

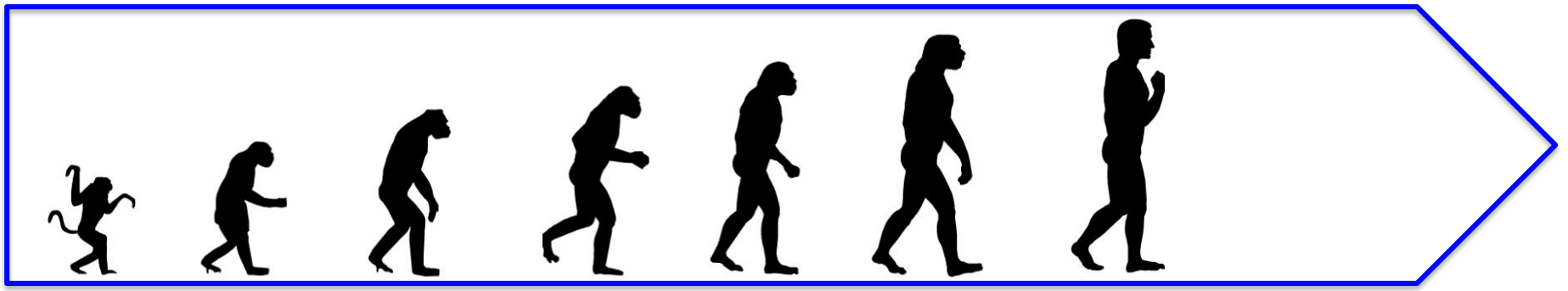
10 – 15 MV/m Field Emission

20 - 25 MV/m Q-SLOPE

35 – 40 MV/m

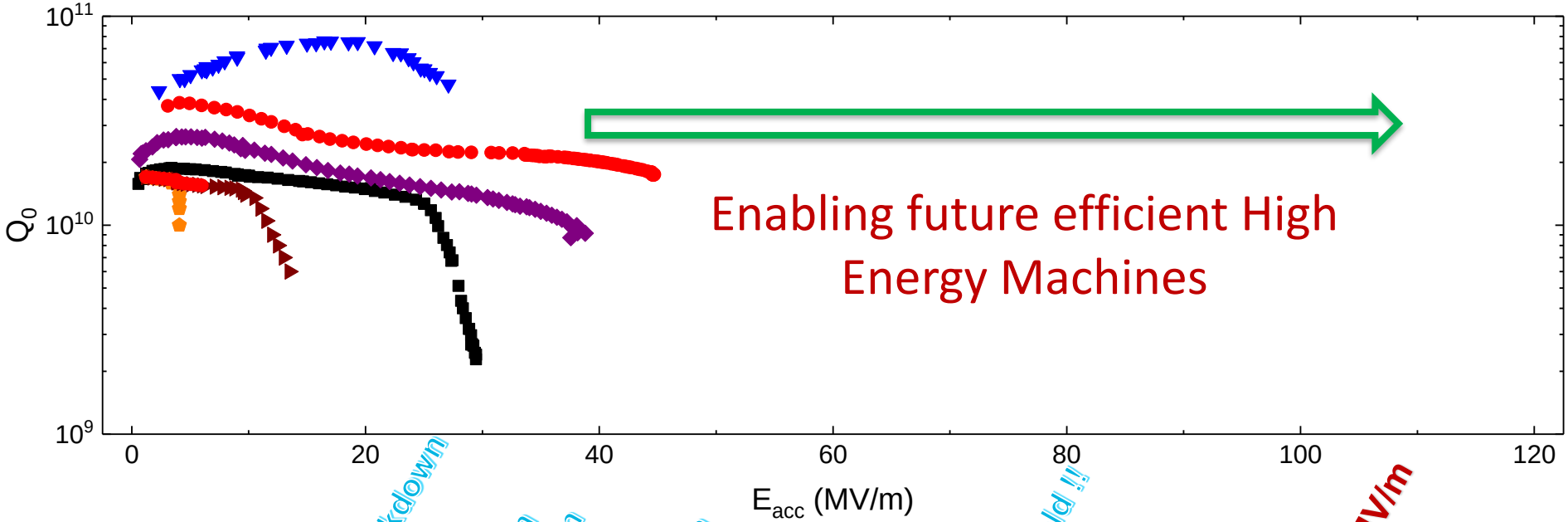
Q > 5e10 At medium field !!

Q > 2e10 At high field



SRF Performance Evolution

Courtesy A. Grassellino



3 – 4 MV/m Multipacting

5 MV/m Thermal Breakdown

10 – 15 MV/m Field Emission

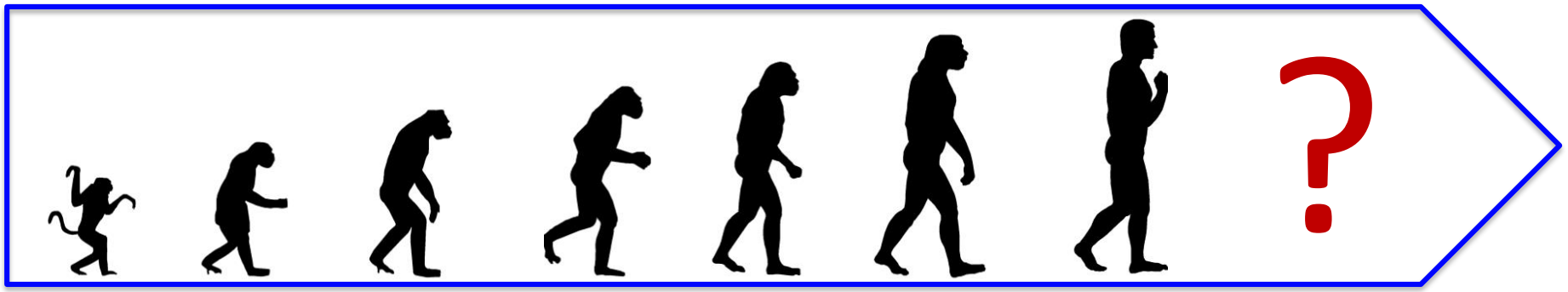
20 - 25 MV/m Q-SLOPE

35 – 40 MV/m

Q > 5e10 At medium field !!

Q > 2e10 At high field

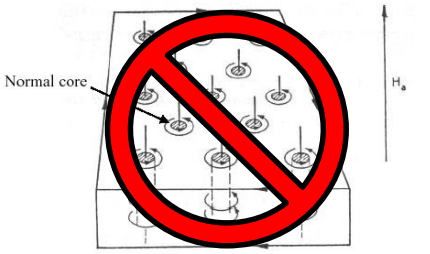
E_{acc} > 100 MV/m Q > 5e10

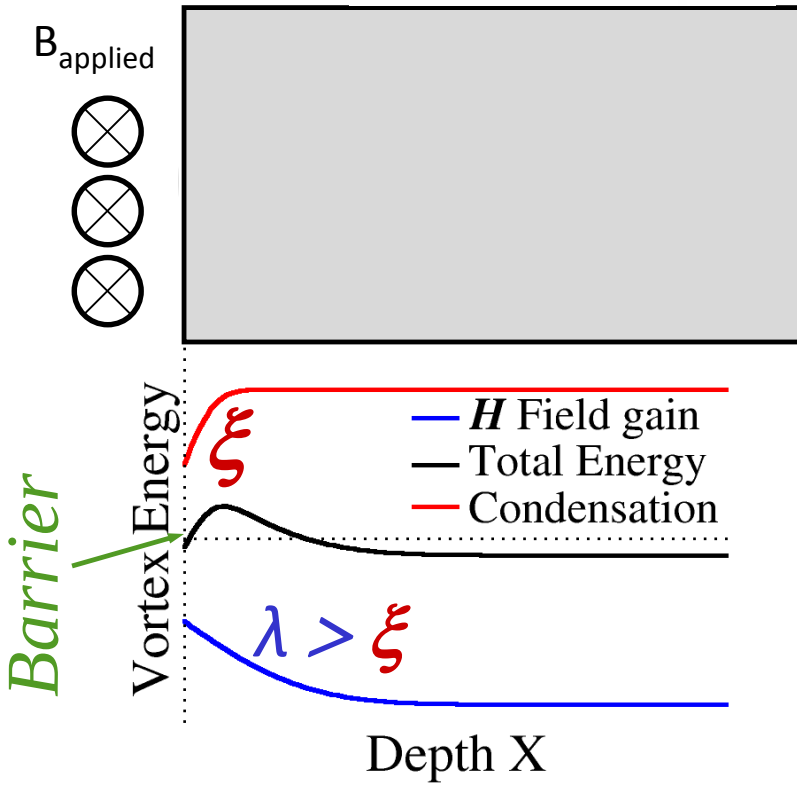


Thanks for your attention!

Increased Metastable Limit in Nb_3Sn

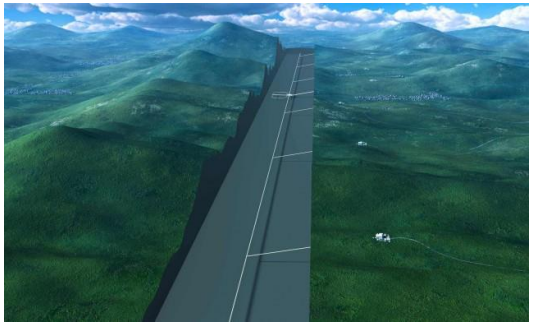
- Superconductors can remain flux-free even above H_{c1}
- Can reach DC "superheating field" H_{sh}
- H_{sh} of Nb: ~200 mT (~50 MV/m)
- Predicted H_{sh} of Nb_3Sn: ~400 mT
- Achieving H_{sh} would have huge impact on high energy colliders

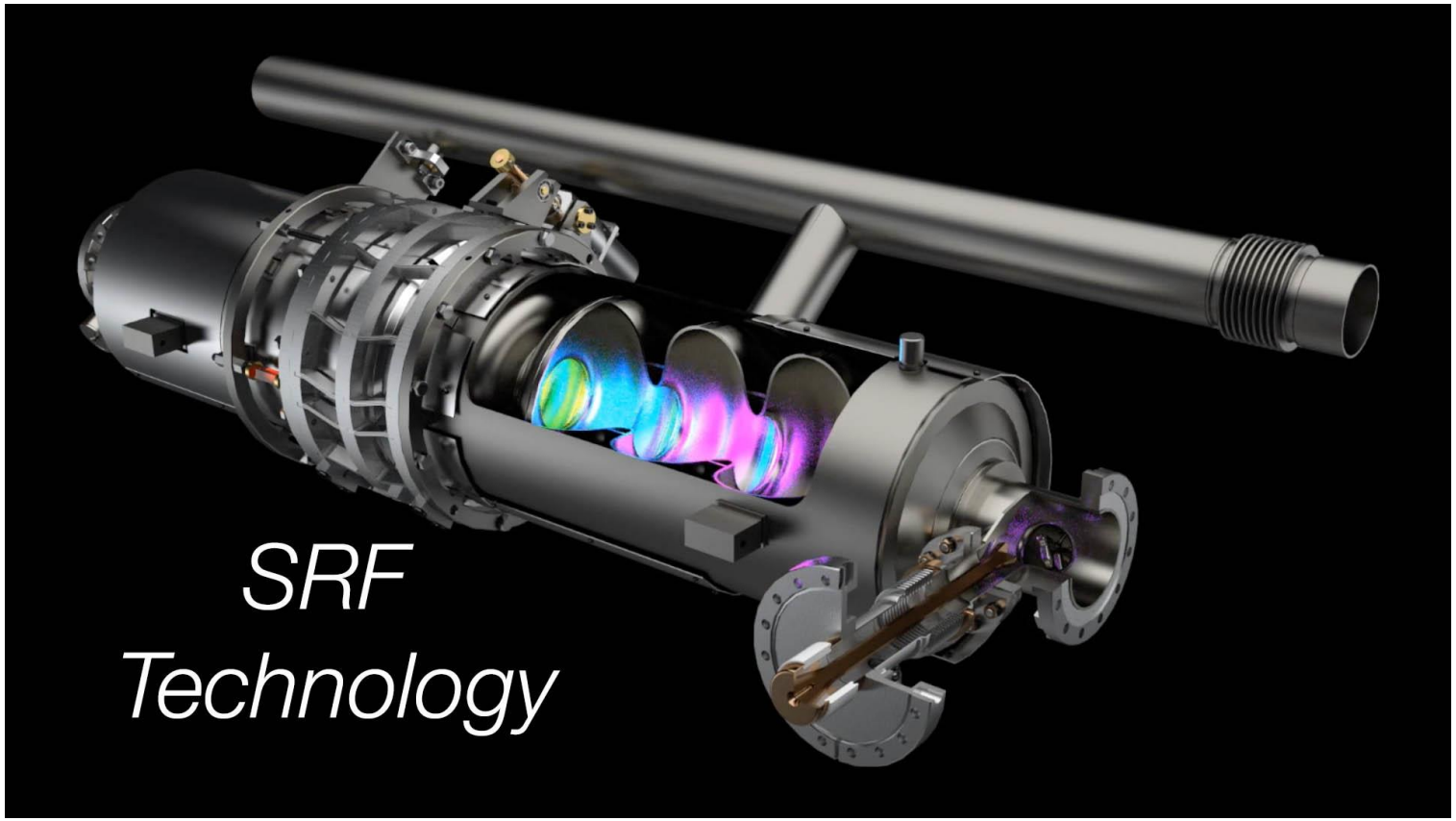




Energy cost from core (ξ) first;
Energy gain from field (λ) later

M. Transtrum, G. Catelani, and J.P. Sethna, *Phys. Rev. B*, **83**, 094505 (2011).



ILC: 16,000 cavities in 31 km linac

- New video on SRF cavities: https://www.youtube.com/watch?v=HqrSb36QYVk