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New Breakthroughs and Future Directions in SRF Technology Research

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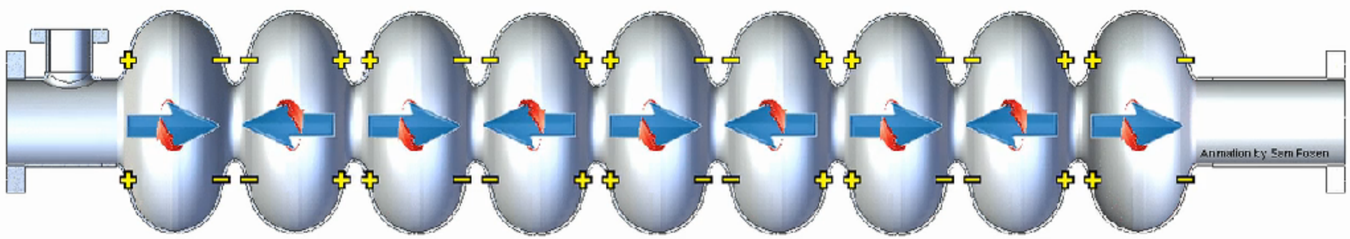
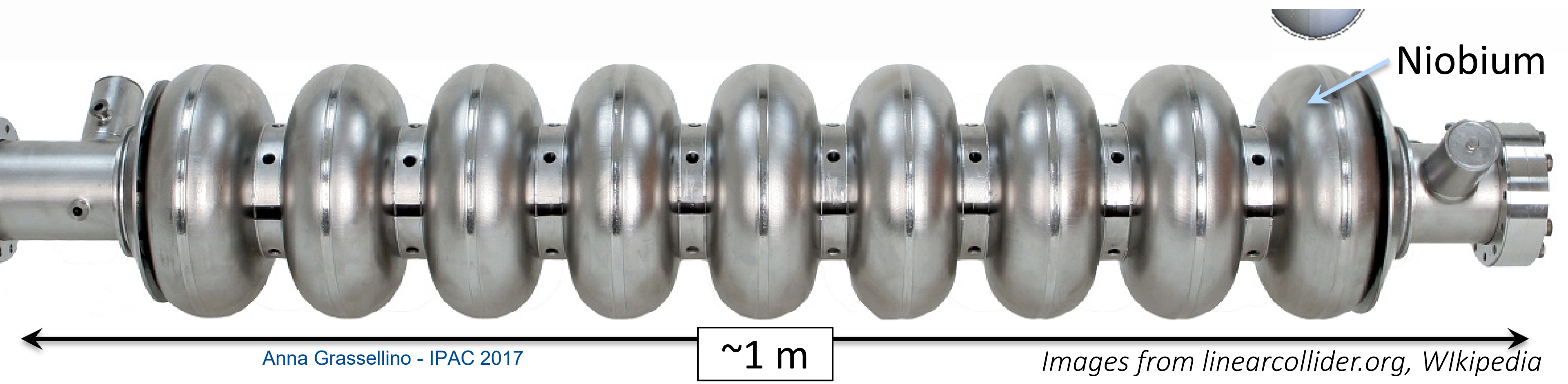
Particle Acceleration via SRF Cavities

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Over billions of cycles, large electric field generated
- Made of Niobium, Tc ~9.2K; frequency from 100MHz to several GHz

Input RF power at 1.3 GHz *Slowed down by factor of approximately $4x10^9$*





Images from linearcollider.org, WIkipedia

SRF cavities – extraordinarily high efficiency

- Wall dissipation (proportional to surface resistance R_s) is reduced by many orders of magnitude over a normal conducting copper cavity

- Among highest quality factors Q in nature
  - $Q>10^{11}$ achieved, $Q=2x10^{10}$ – routine

- **Affordable continuous wave and long pulse at high gradients**
  - **Field=acceleration can be ON all the time**

SRF cavities – extraordinarily high efficiency

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- Amo

  - (

- **Affo** **ts**

  - **F**

SRF: high current, high energy, high brightness beams

SRF cavities – extraordinarily high efficiency

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- Amo
  - C

- **Affo** **ts**
  - **F**

SRF: high current, high energy, high brightness beams

However….not quite zero dissipation in RF →
We battle ~ nanoOhms

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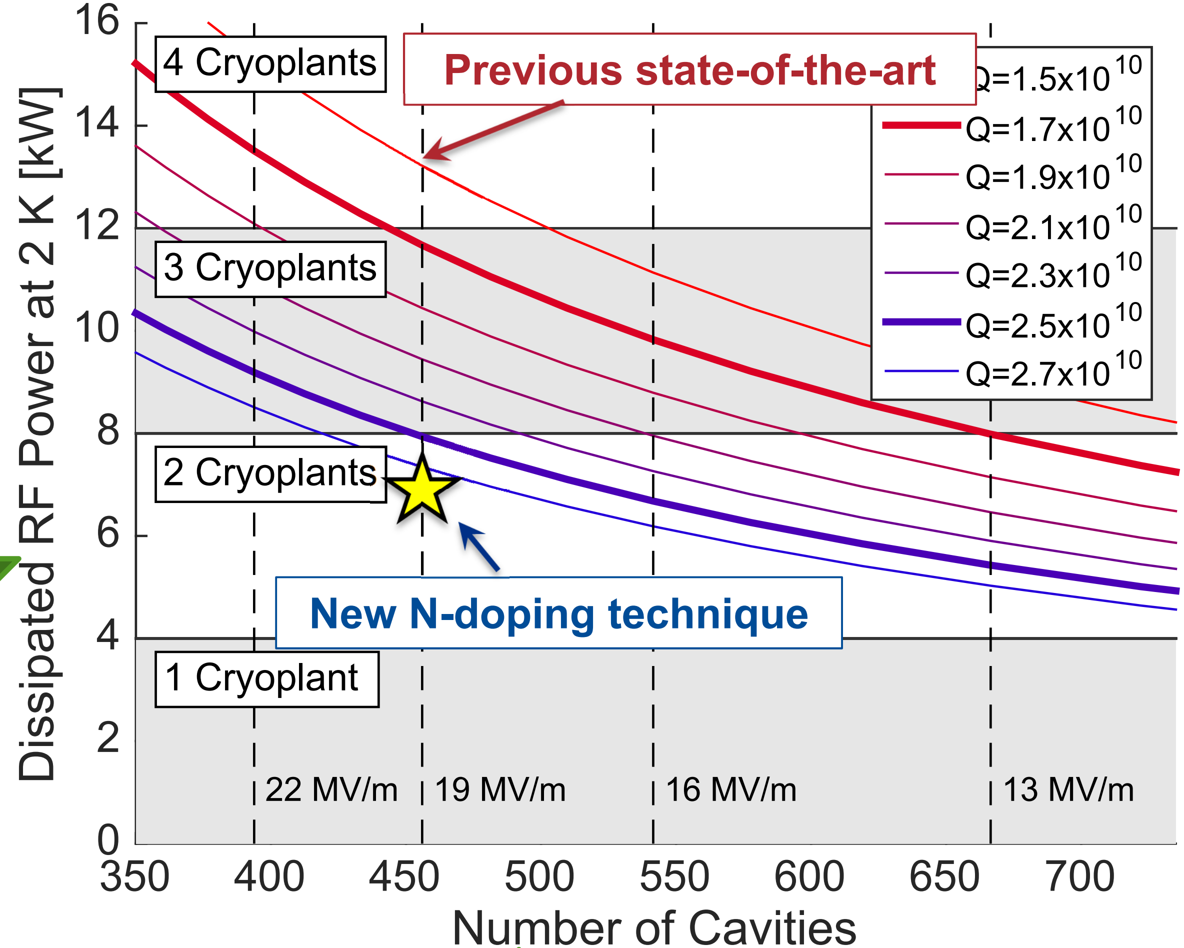
Factor of merit 1: Q_0 -> Cryogenic Infrastructure, Operating Cost

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

Lower cost

8 GeV CW SRF Linac



Lower cost

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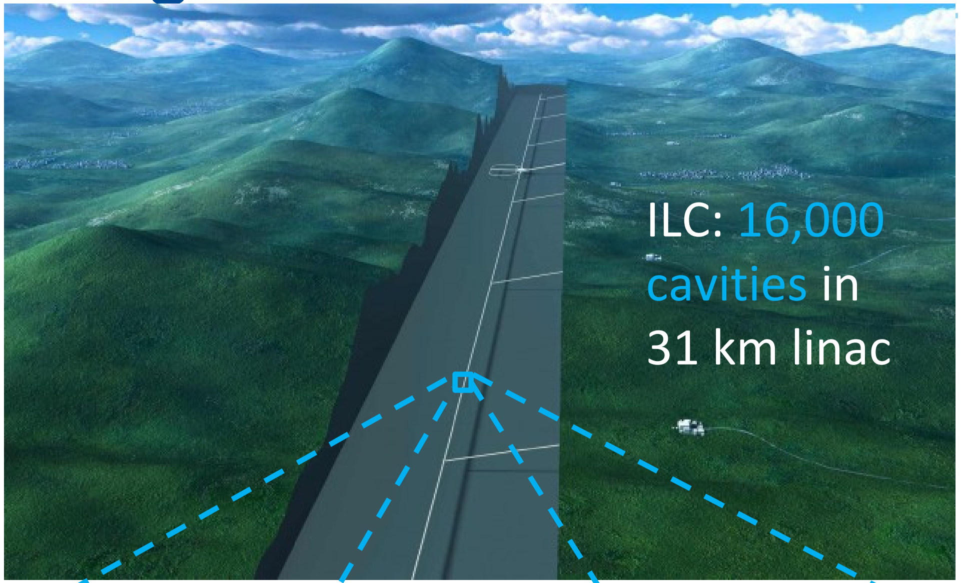
Factor of merit 2: Gradient -> Length for Linear Accelerator



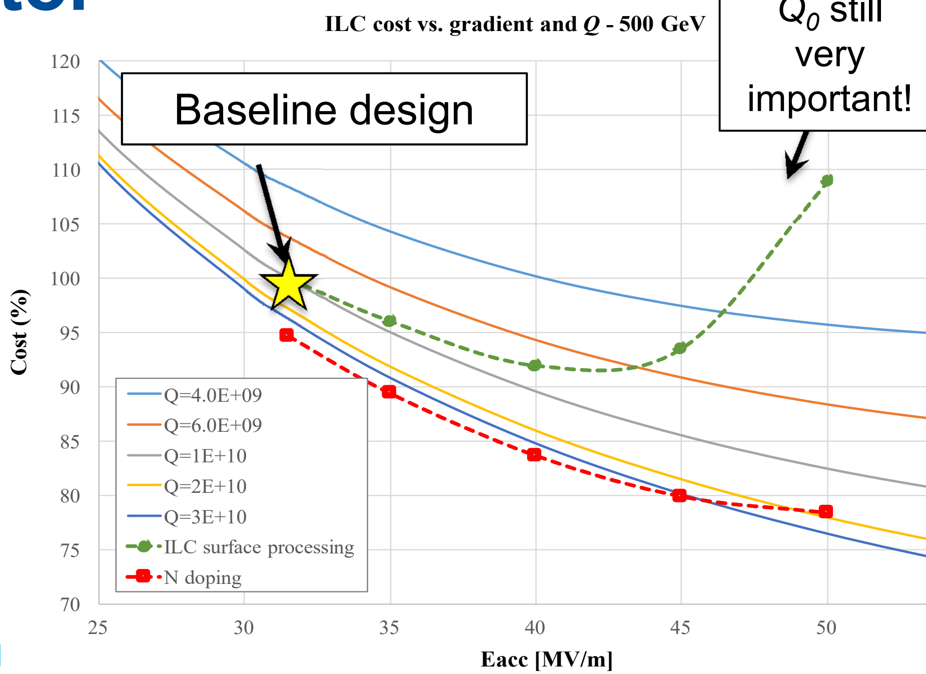


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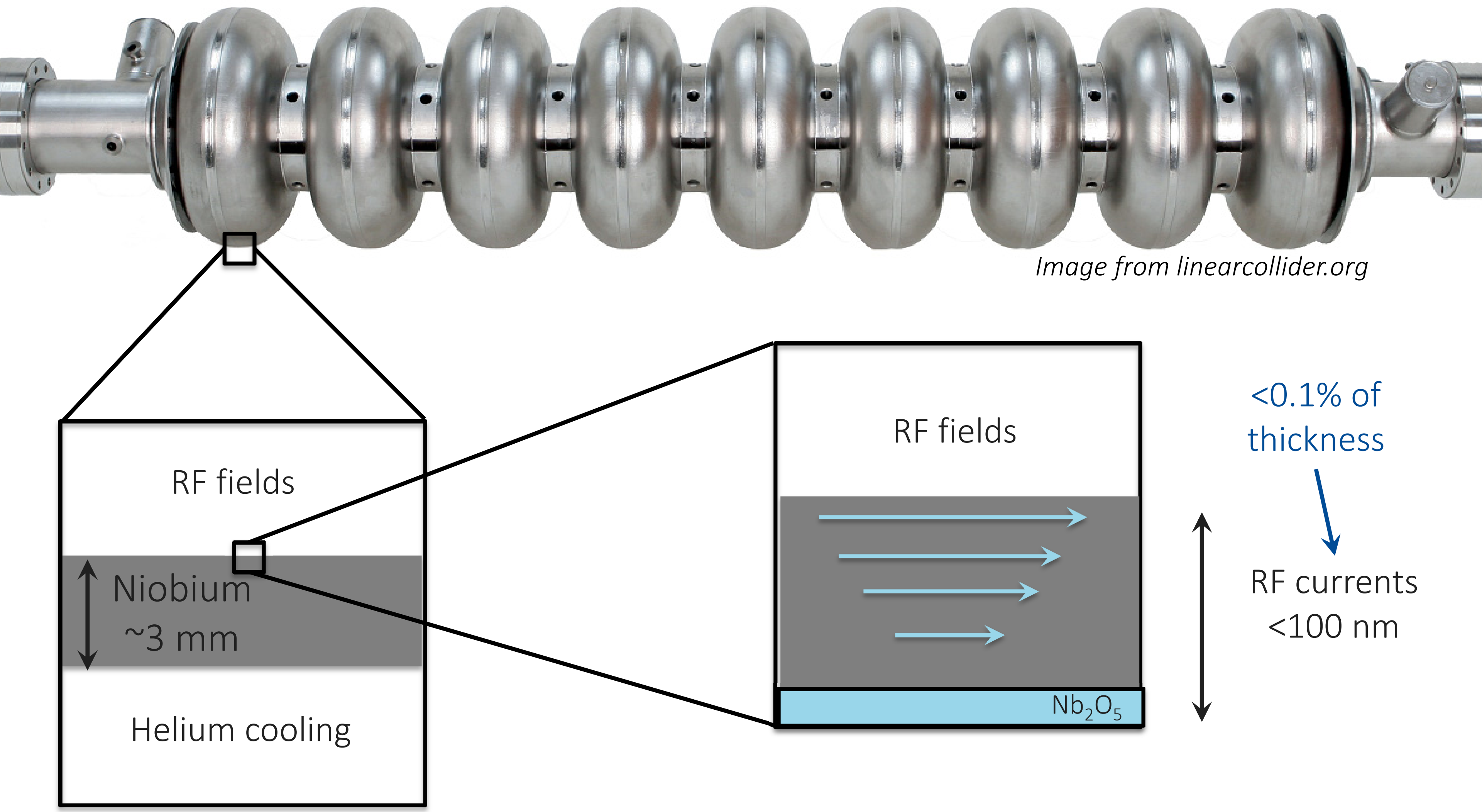
Image from linearcollider.org. Tunnelflug video by European XFEL. Cost analysis by N. Solyak

Performance are determined by nanometer scale structure of inner surface



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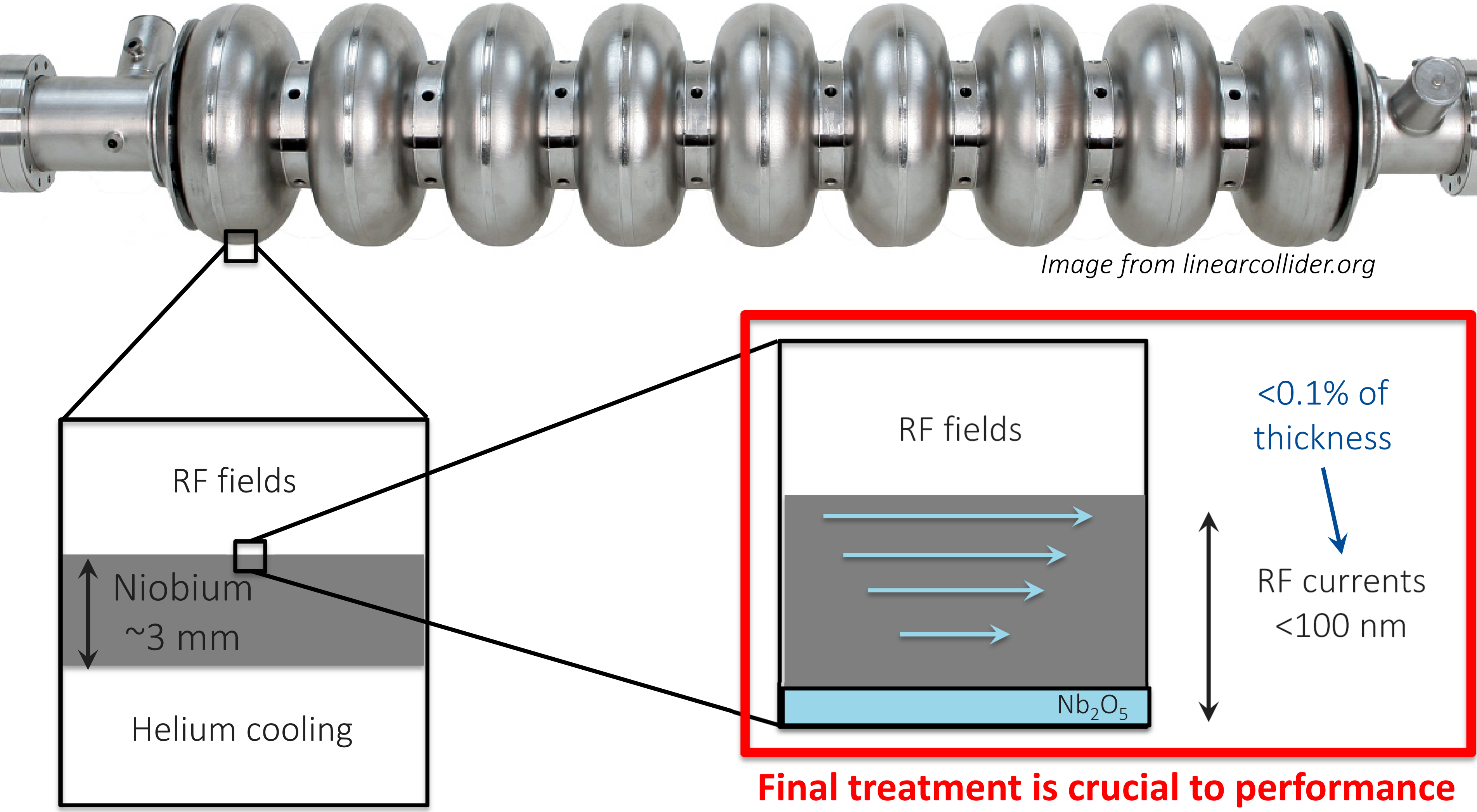


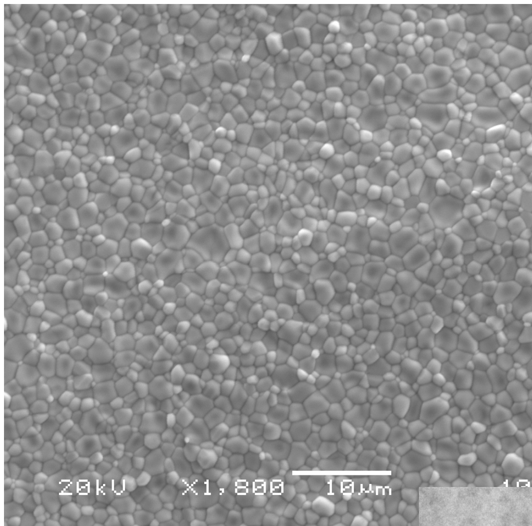
Final treatment is crucial to performance

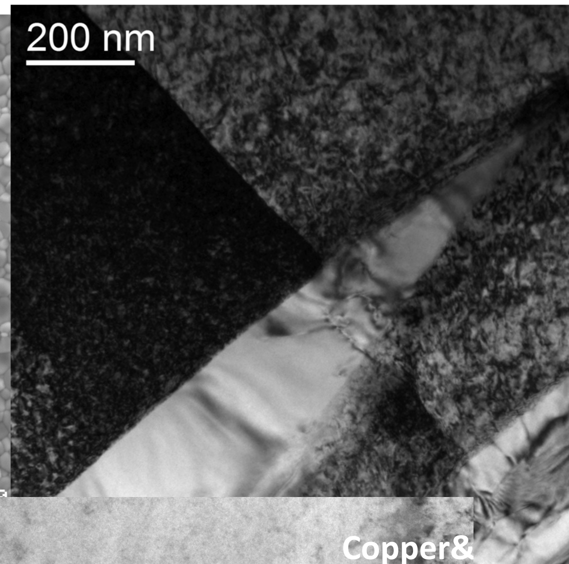
Beam view, inside the cavity

Extreme attention to surface treatments and surface cleanliness are mandatory

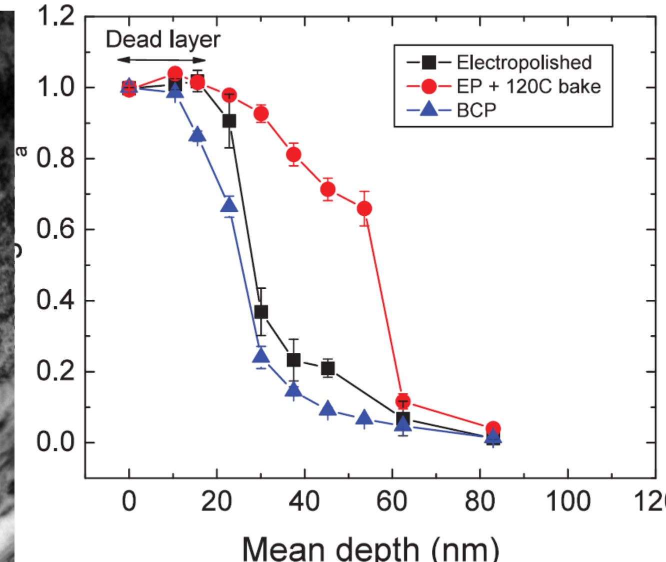
Key to progress for superconducting RF cavities

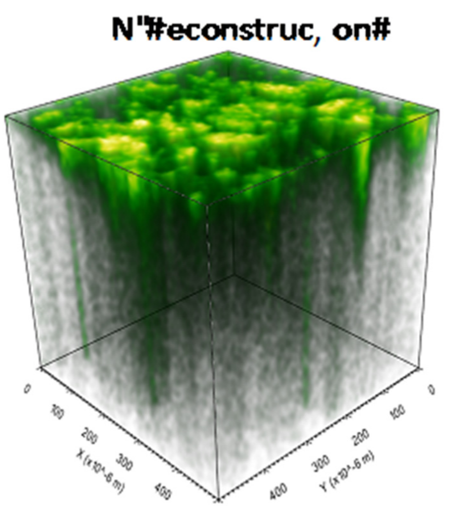
- Material science tools are <u>essential</u> to understand the surface nanostructural changes that lead to dramatic changes in performance

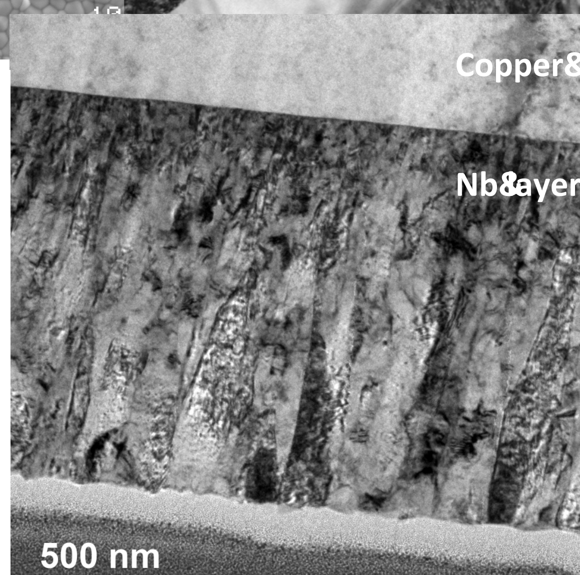


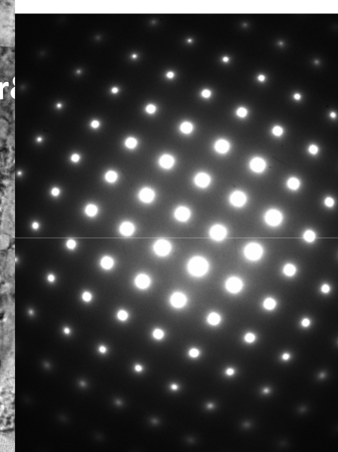


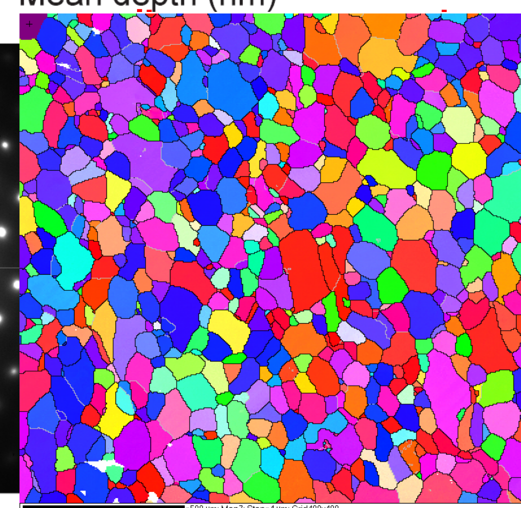
A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)



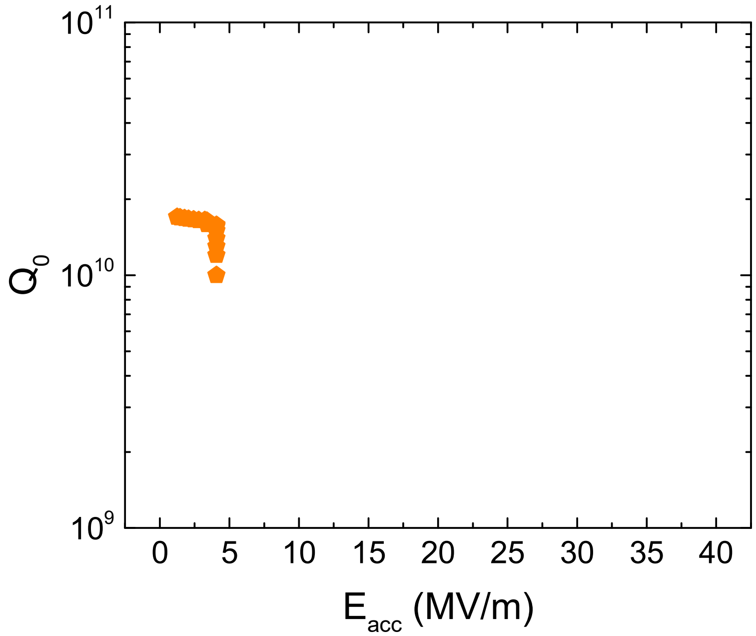








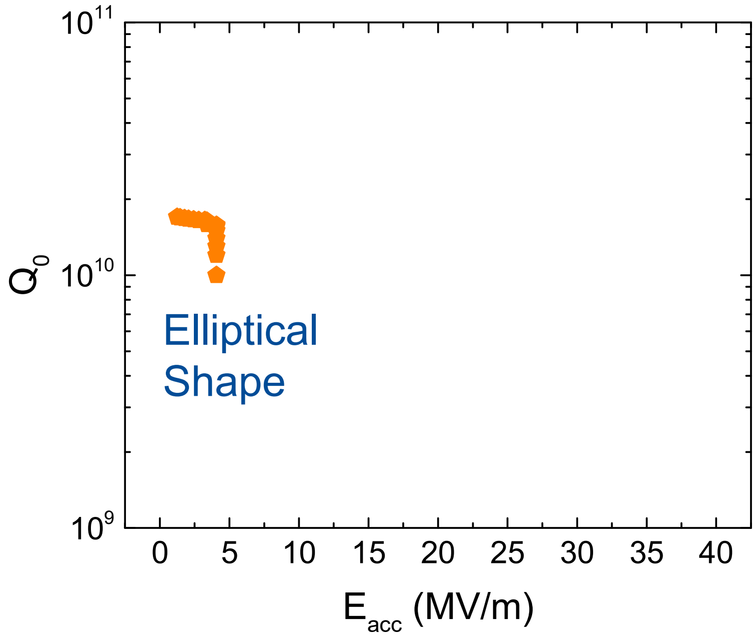
SRF Performance Evolution



1.3 GHz, 2K

3 – 4 MV/m
Multipacting

SRF Performance Evolution



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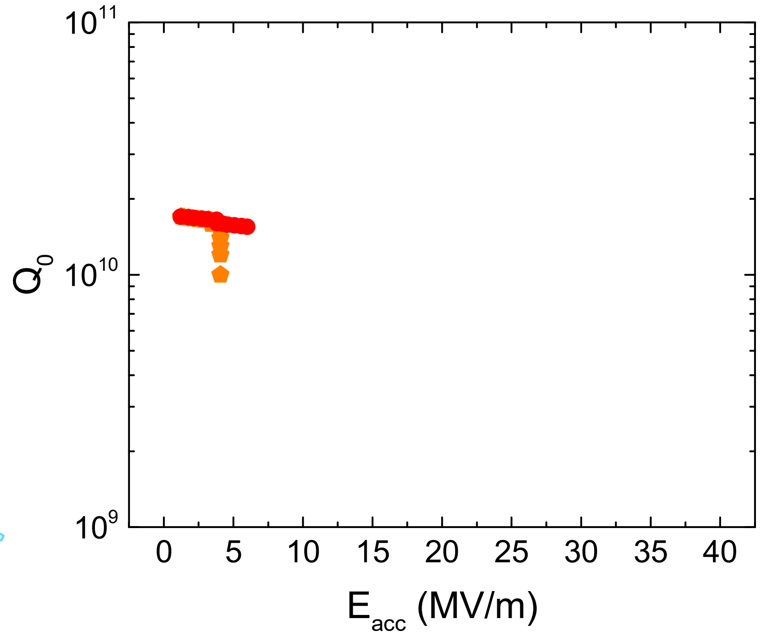

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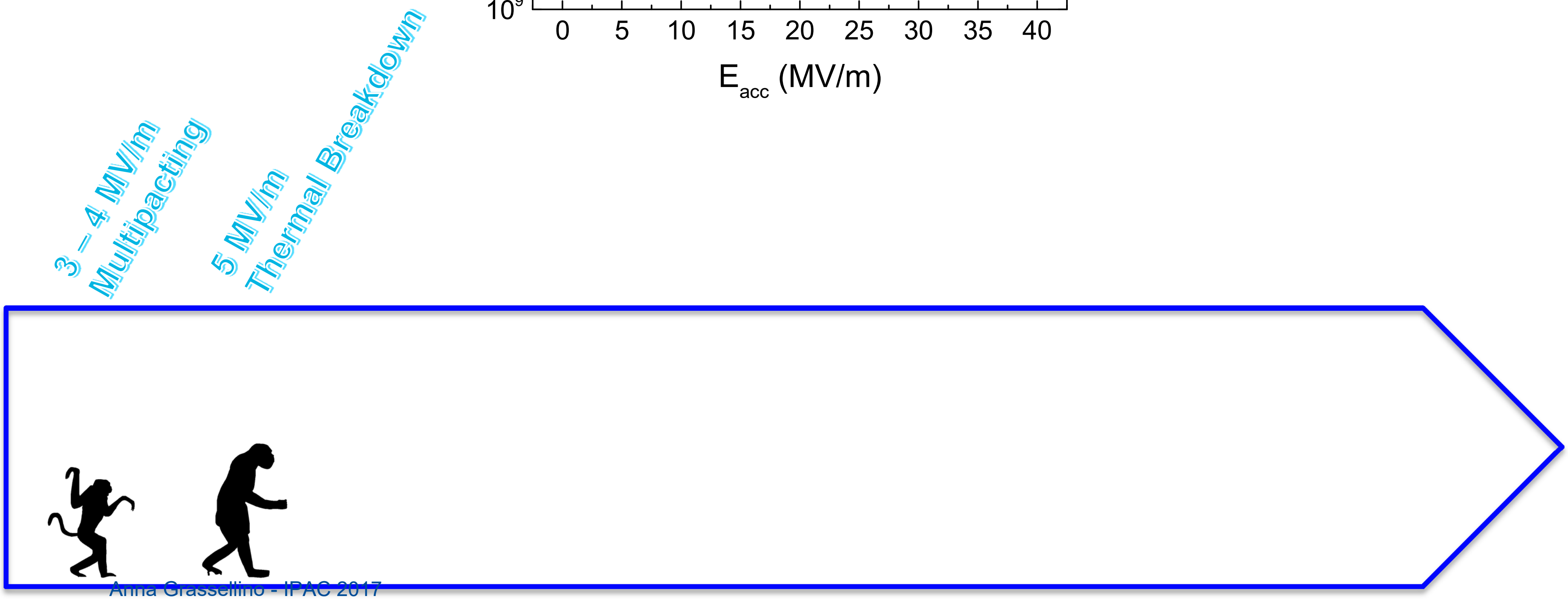

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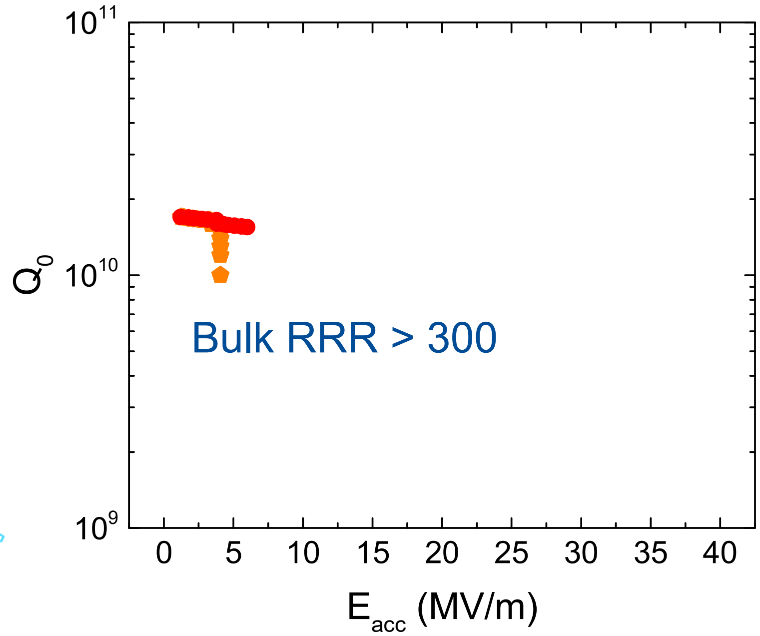

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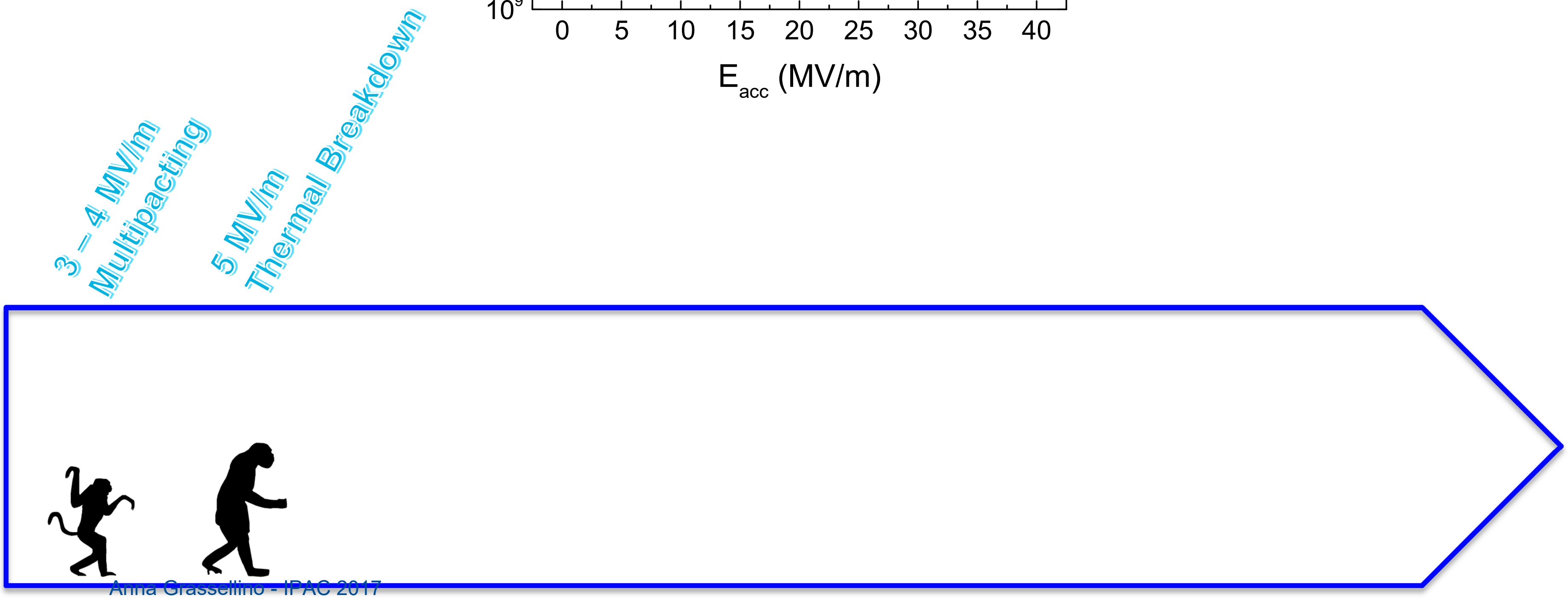

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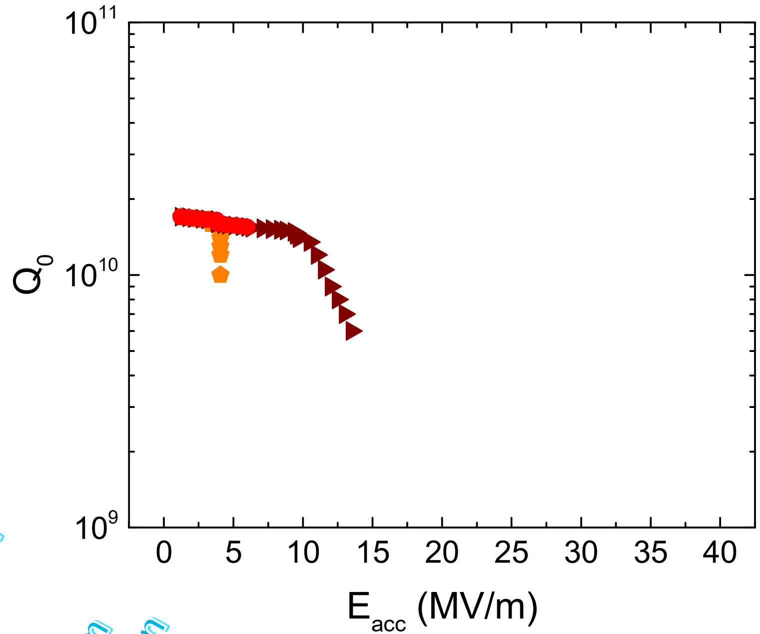

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Field Emission

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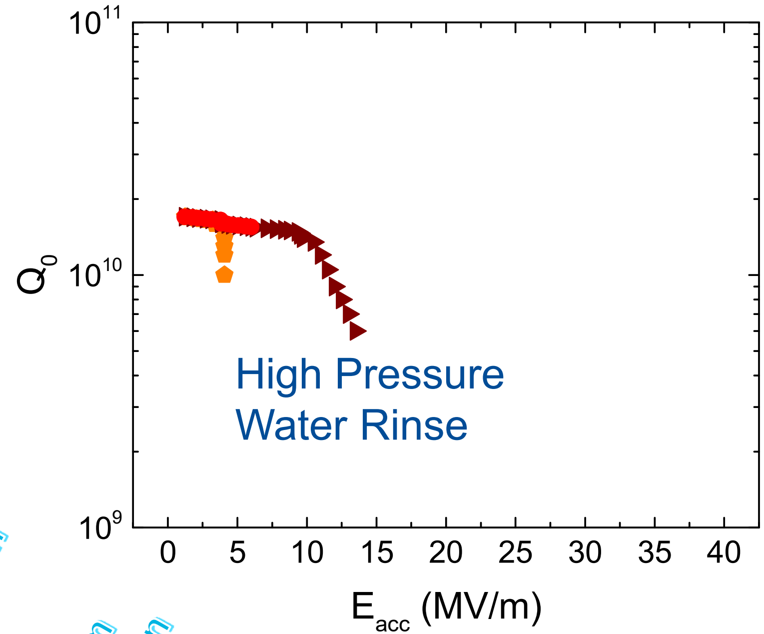

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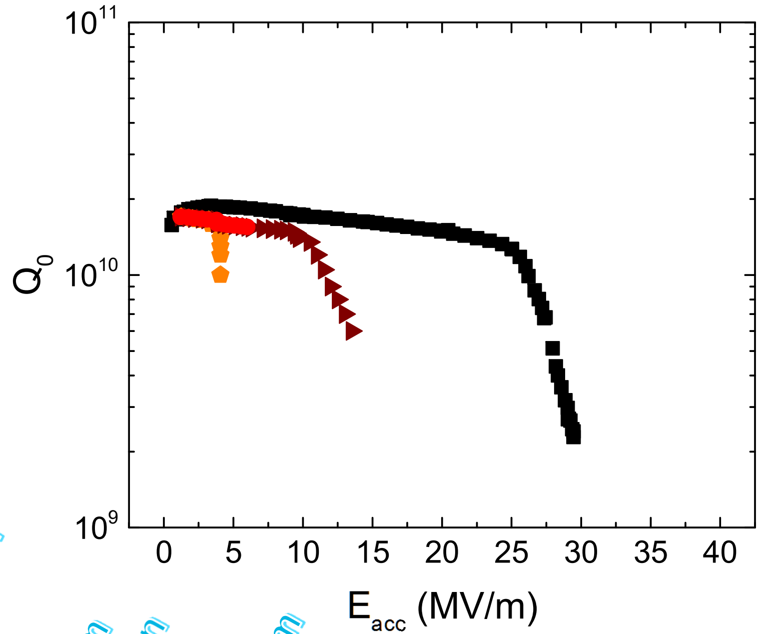

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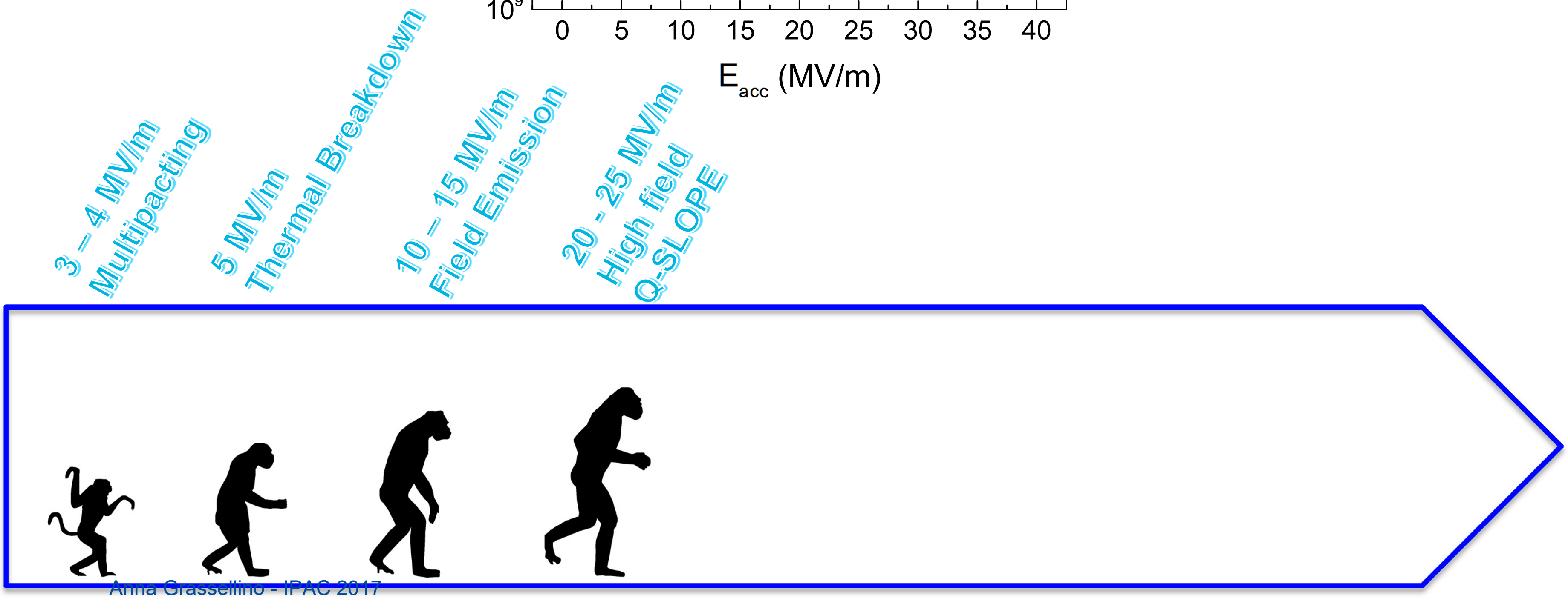

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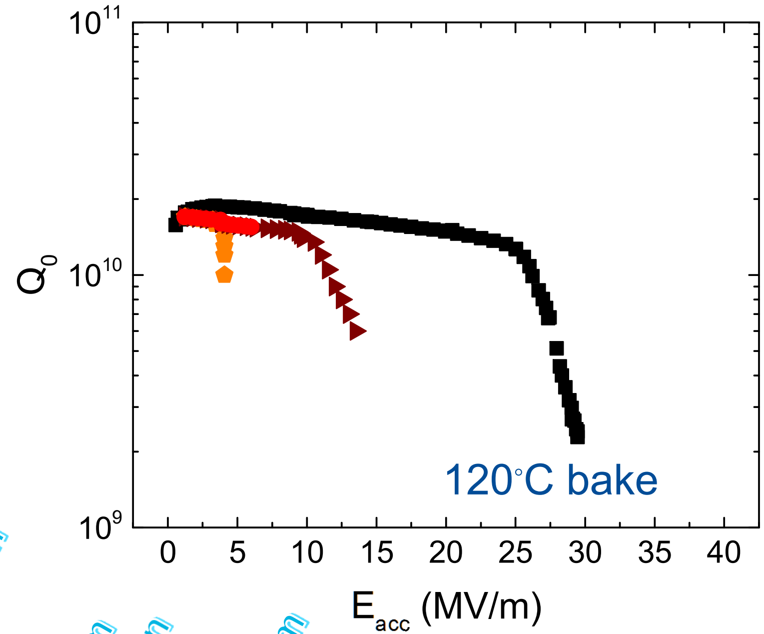

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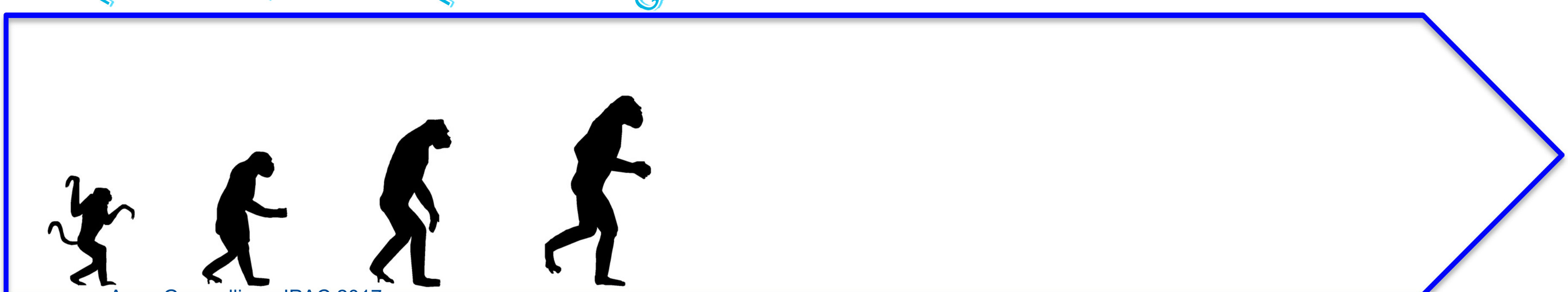

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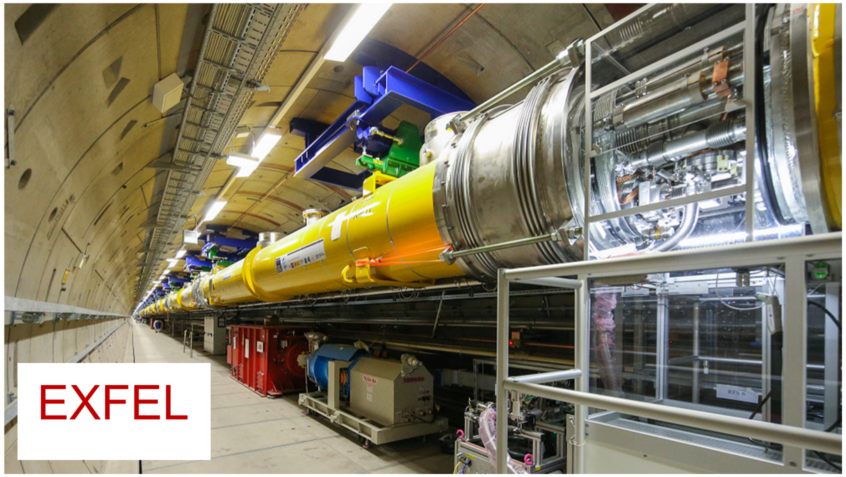

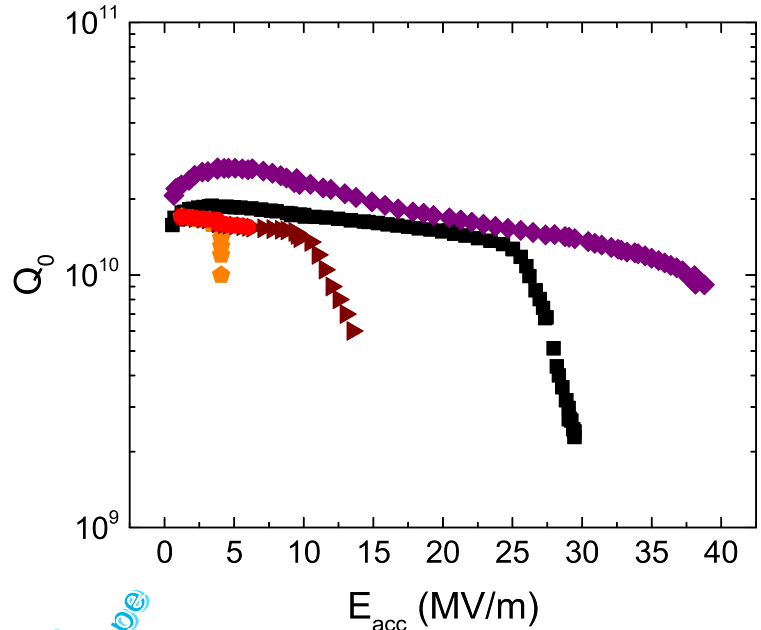

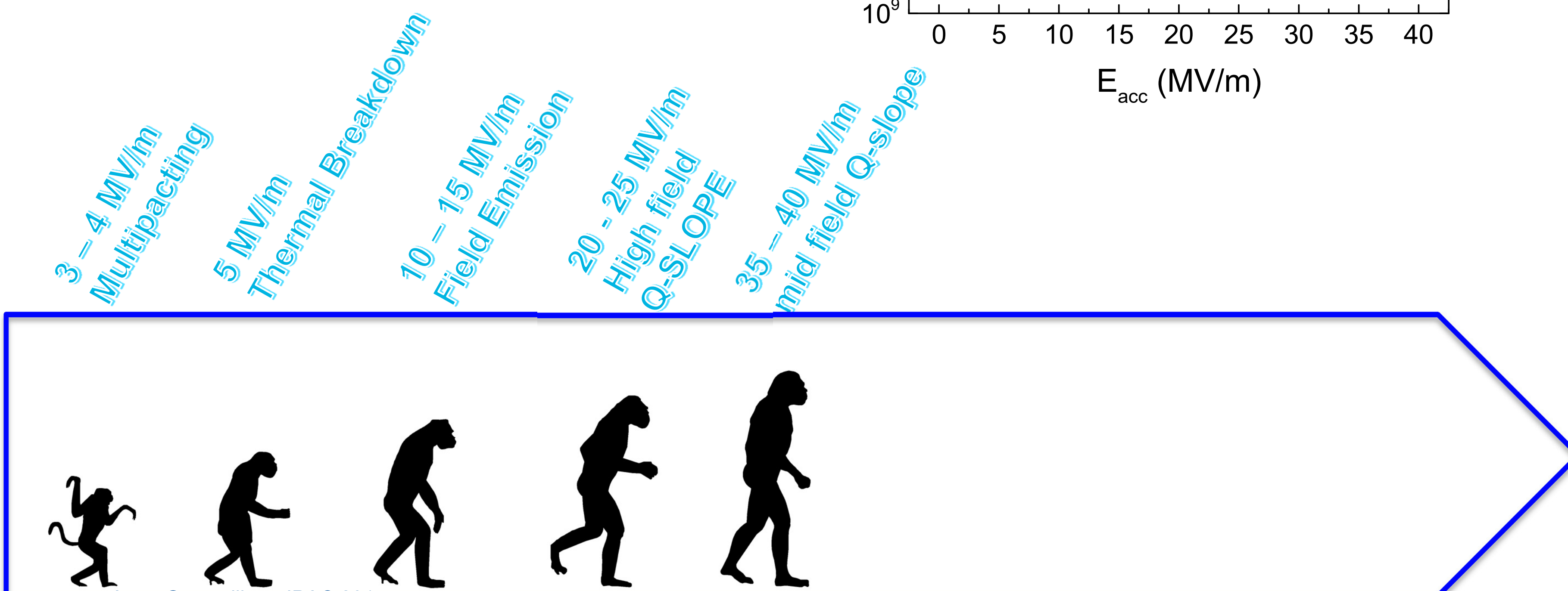

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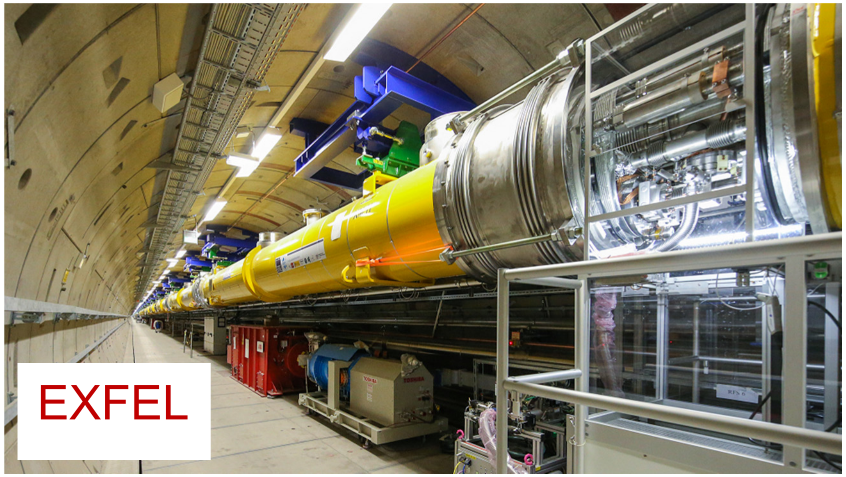

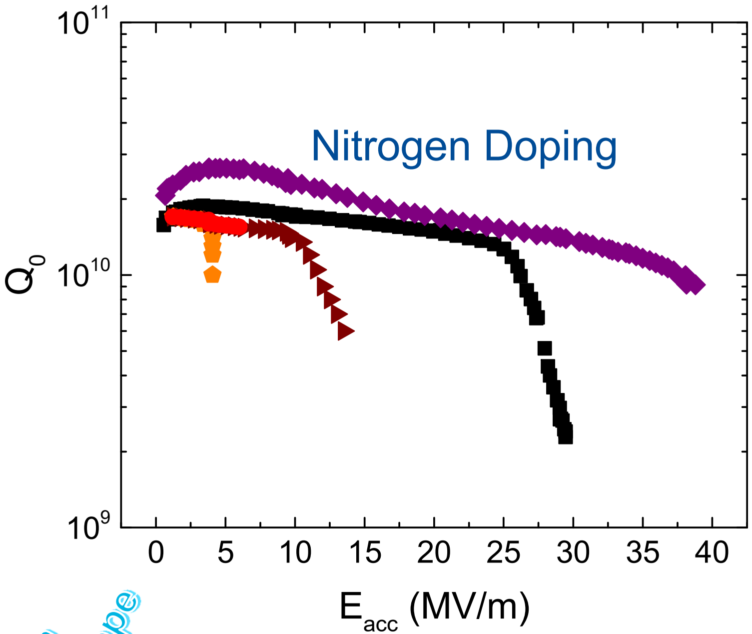

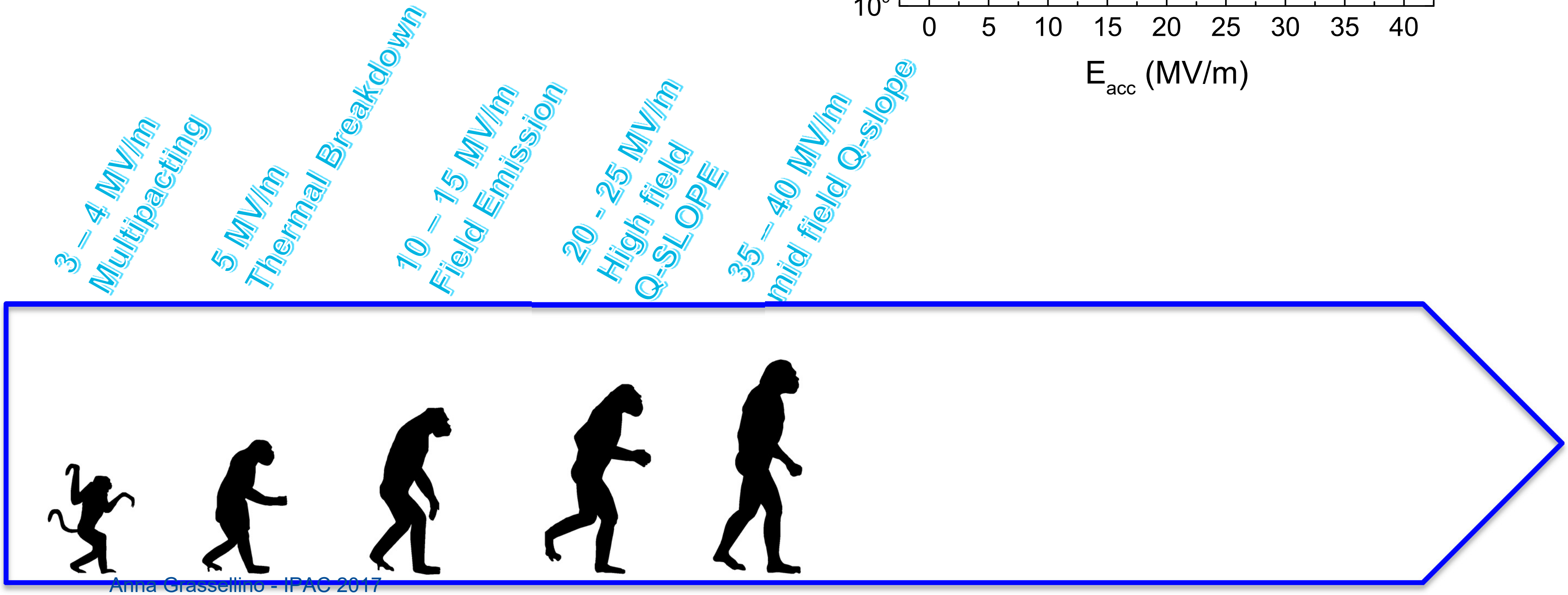

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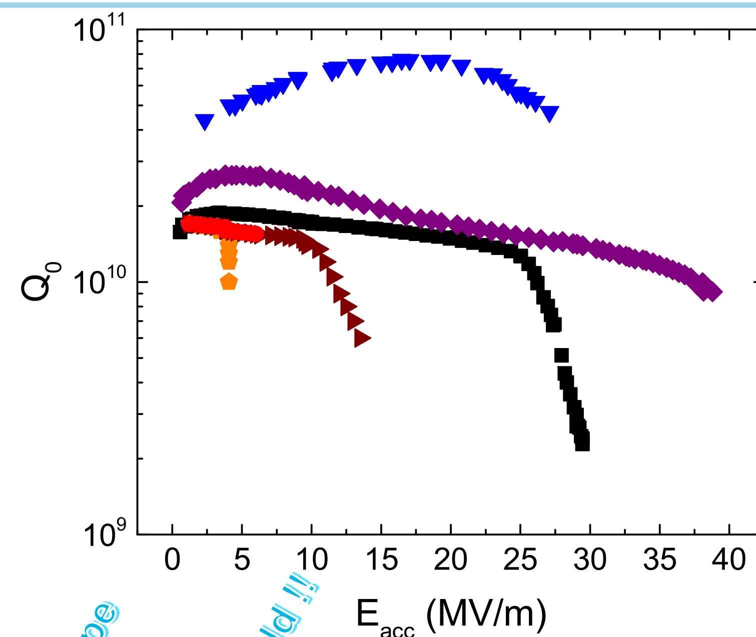

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Multipacting

5 MV/m
Thermal Breakdown

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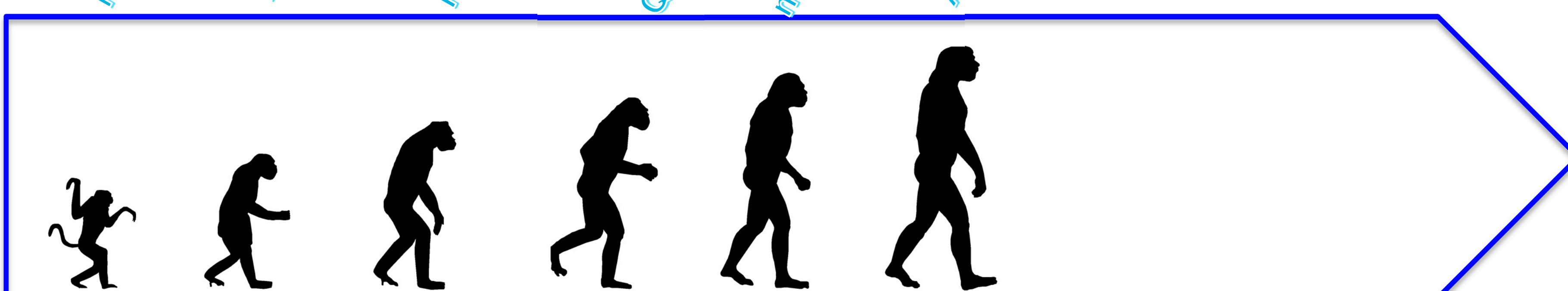
Field Emission

20 - 25 MV/m
High field
Q-SLOPE

35 – 40 MV/m
mid field Q-slope

Q > 5e10
At medium field !!



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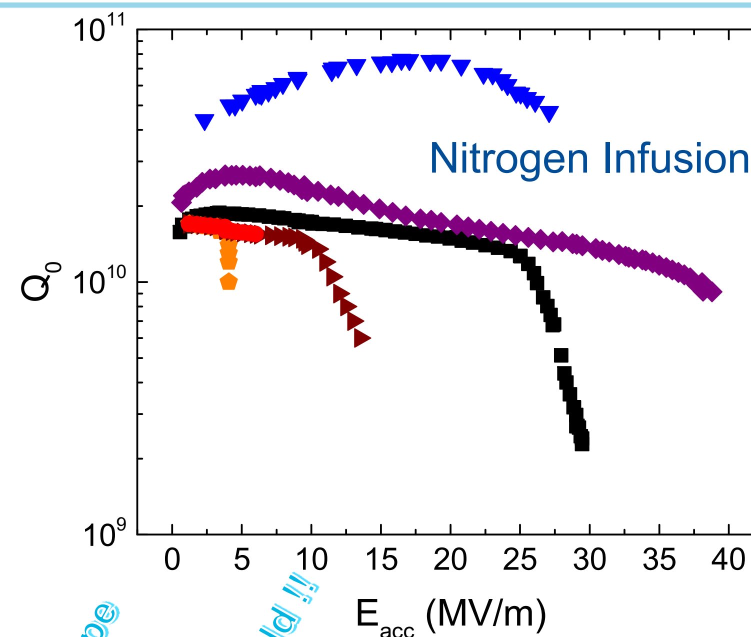

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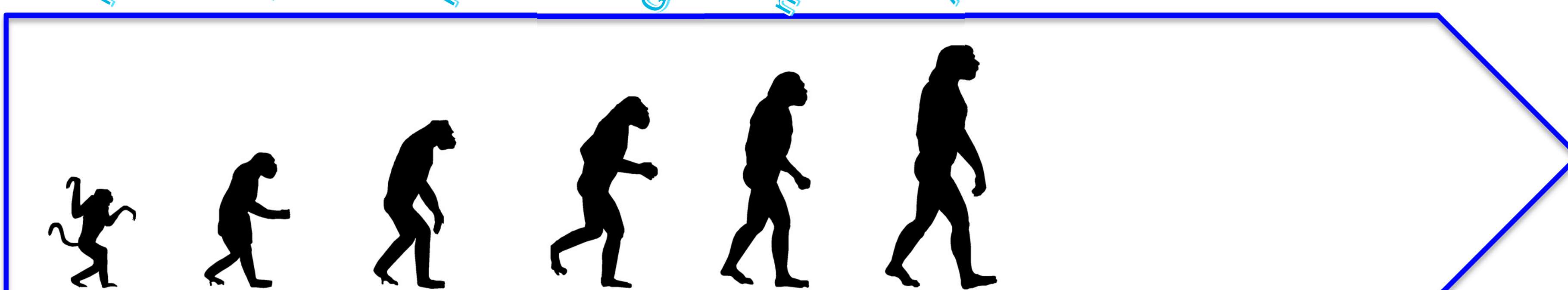
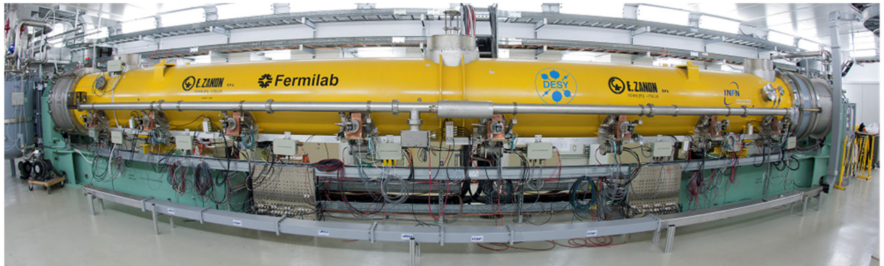
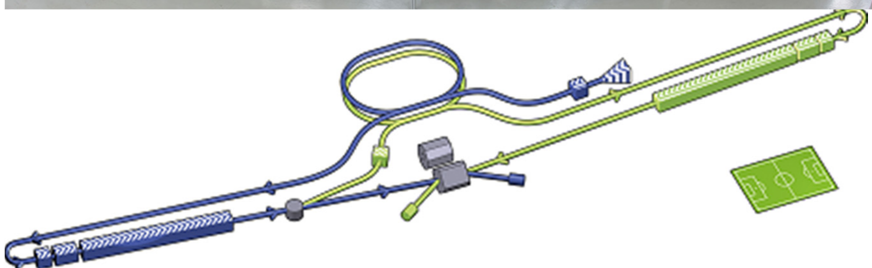


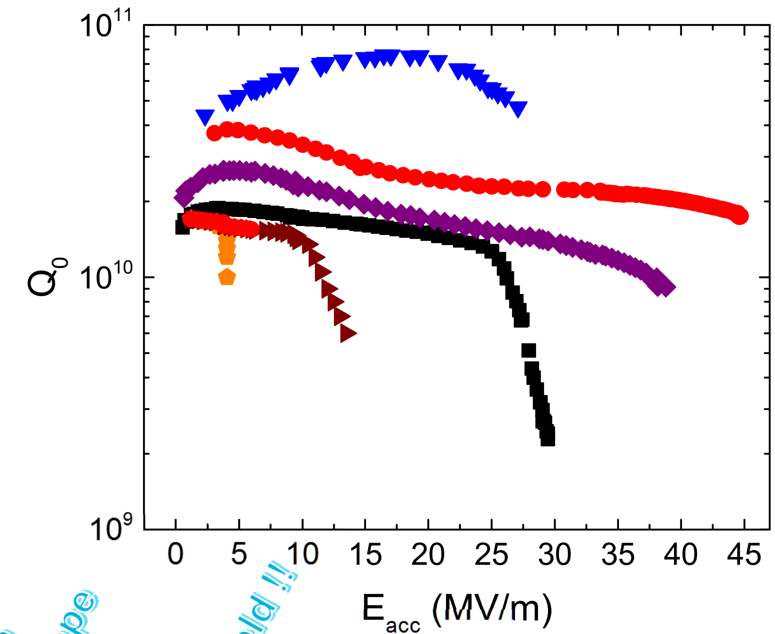
SRF Performance Evolution

1.3 GHz, 2K

ILC cost reduction







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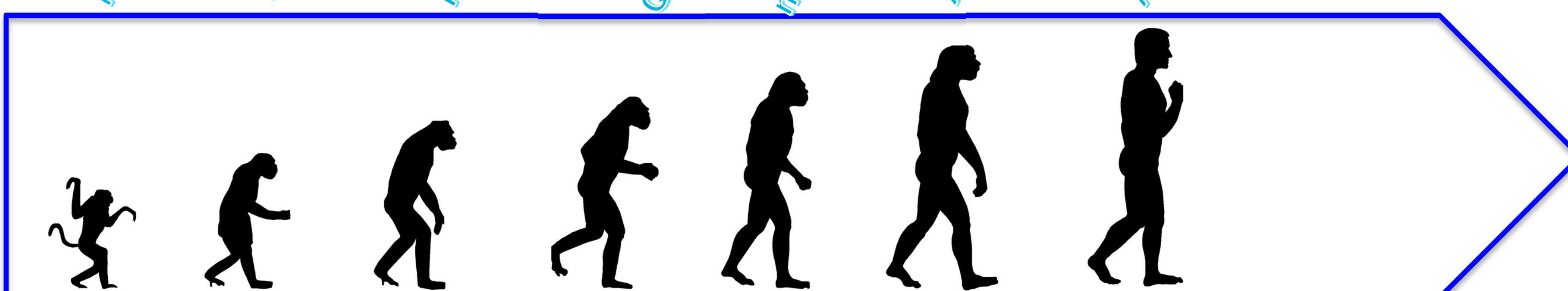
Q > 5e10 At medium field !!

Q > 2e10 At high field



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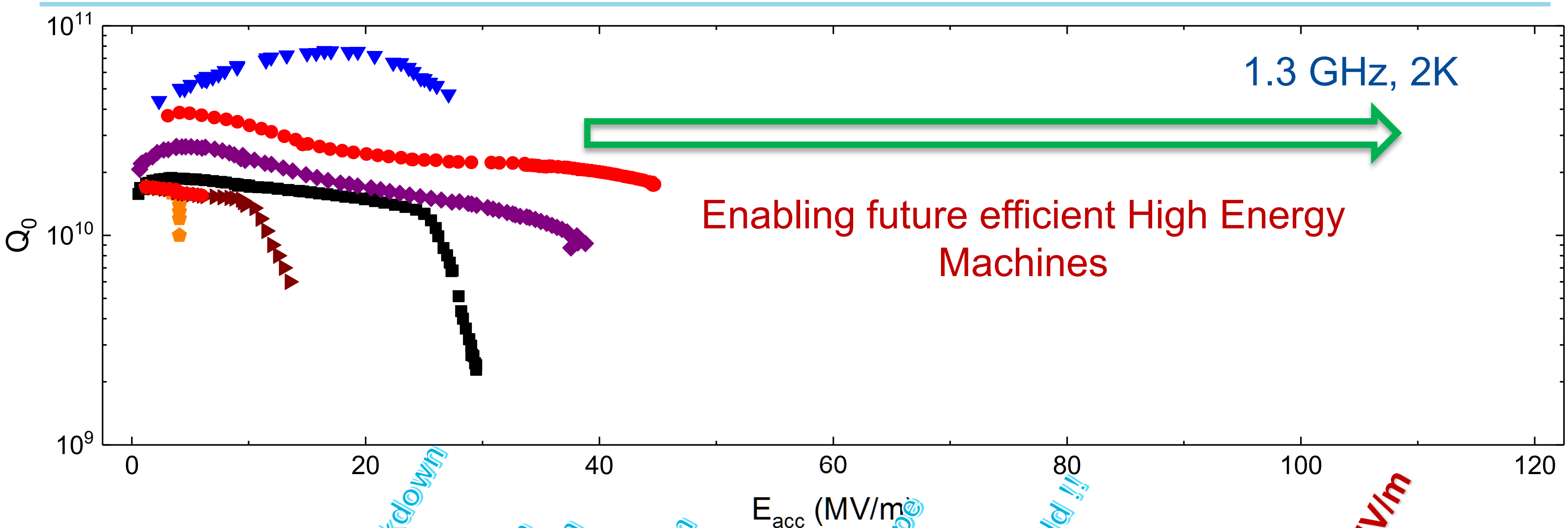
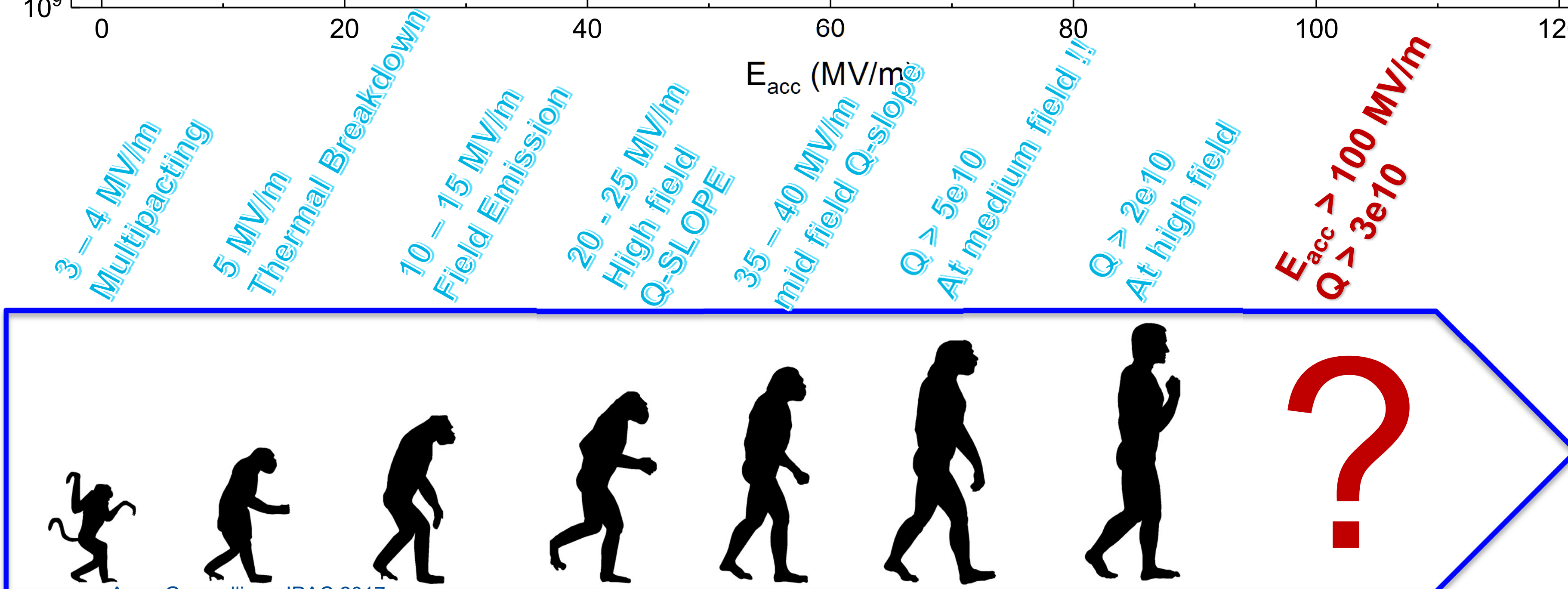
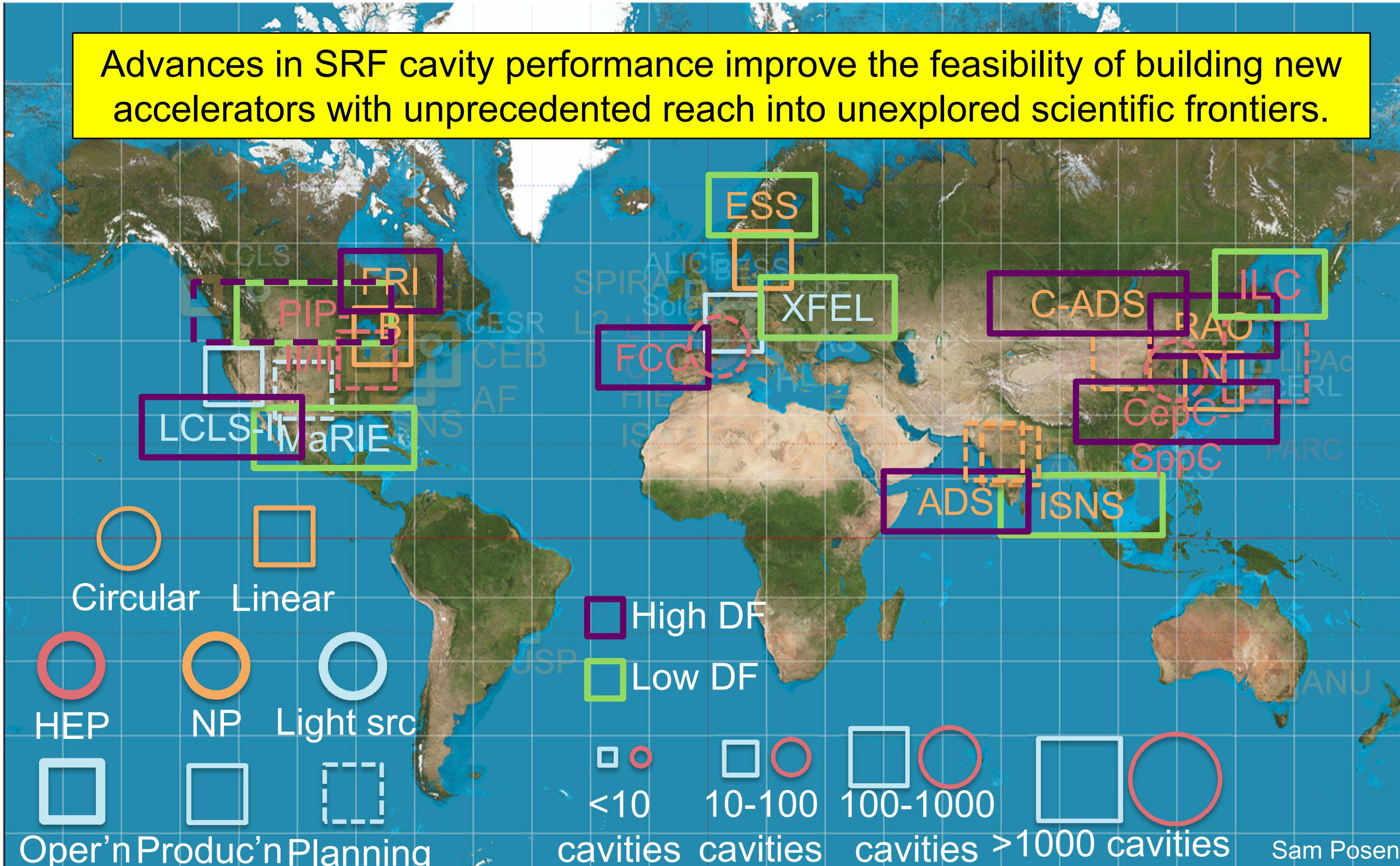




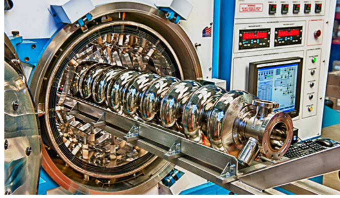
Motivation State-of-the-Art SRF Technology

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.

First breakthrough for Q: N doping of Nb cavities



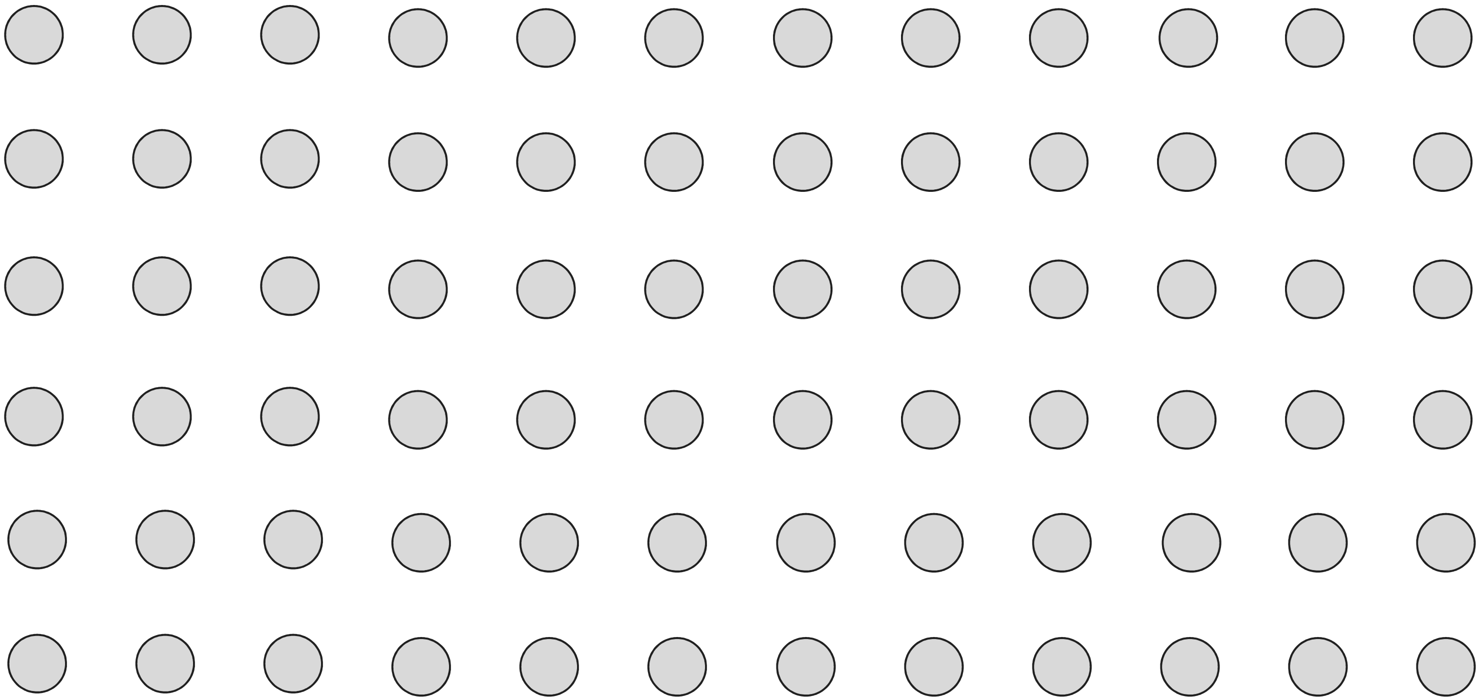
800C UHV, 3 hours

800C N_2 p = 25 mTorr 2 minutes

800C UHV, 6 minutes

UHV cooling

5 um EP



Slides adapted from M. Martinello

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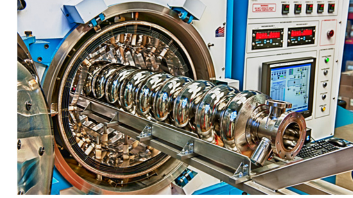
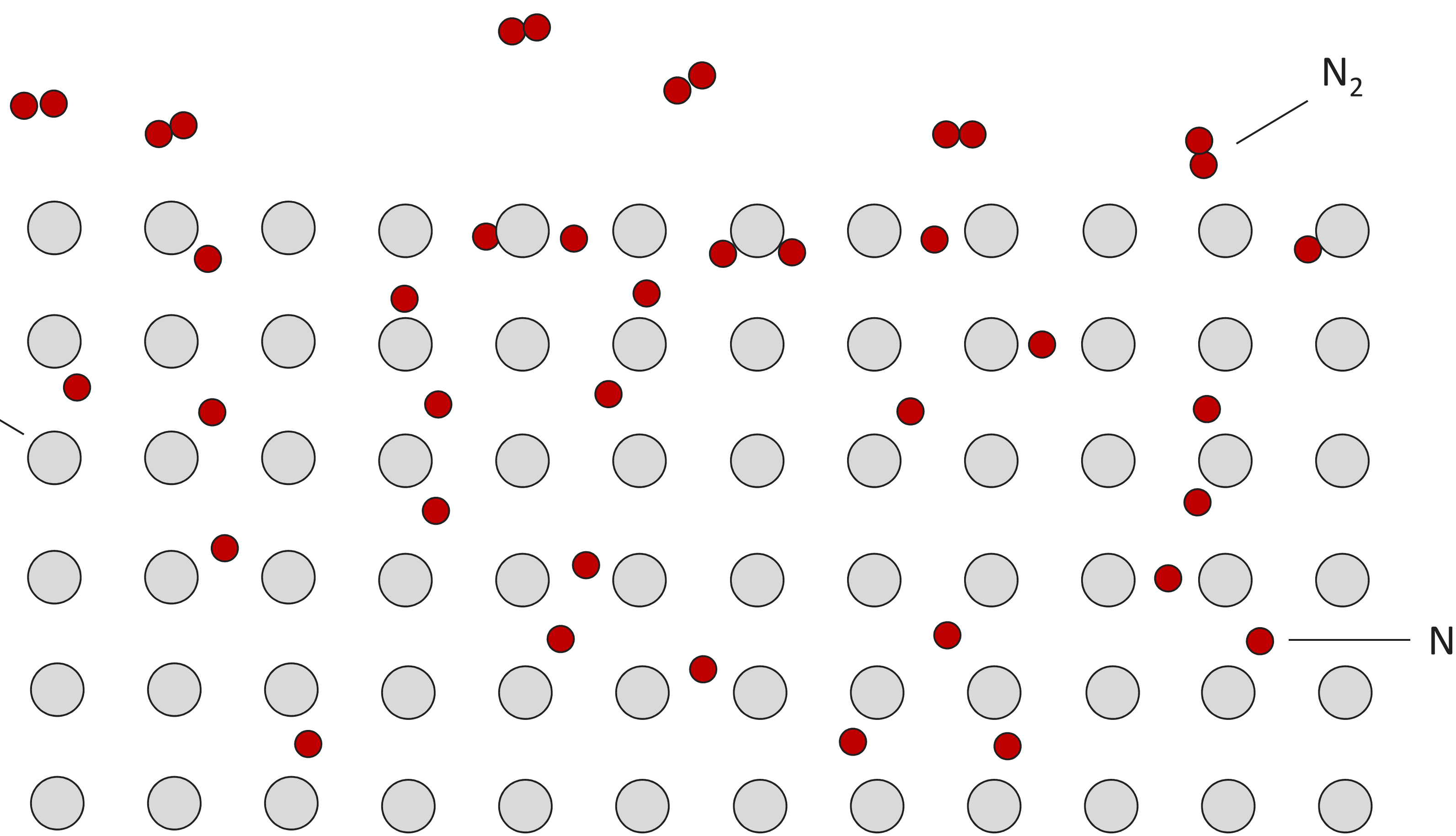


800C UHV, 3 hours → 800C N_2 p = 25 mTorr 2 minutes | 800C UHV, 6 minutes | UHV cooling | 5 um EP



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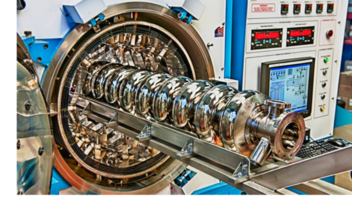

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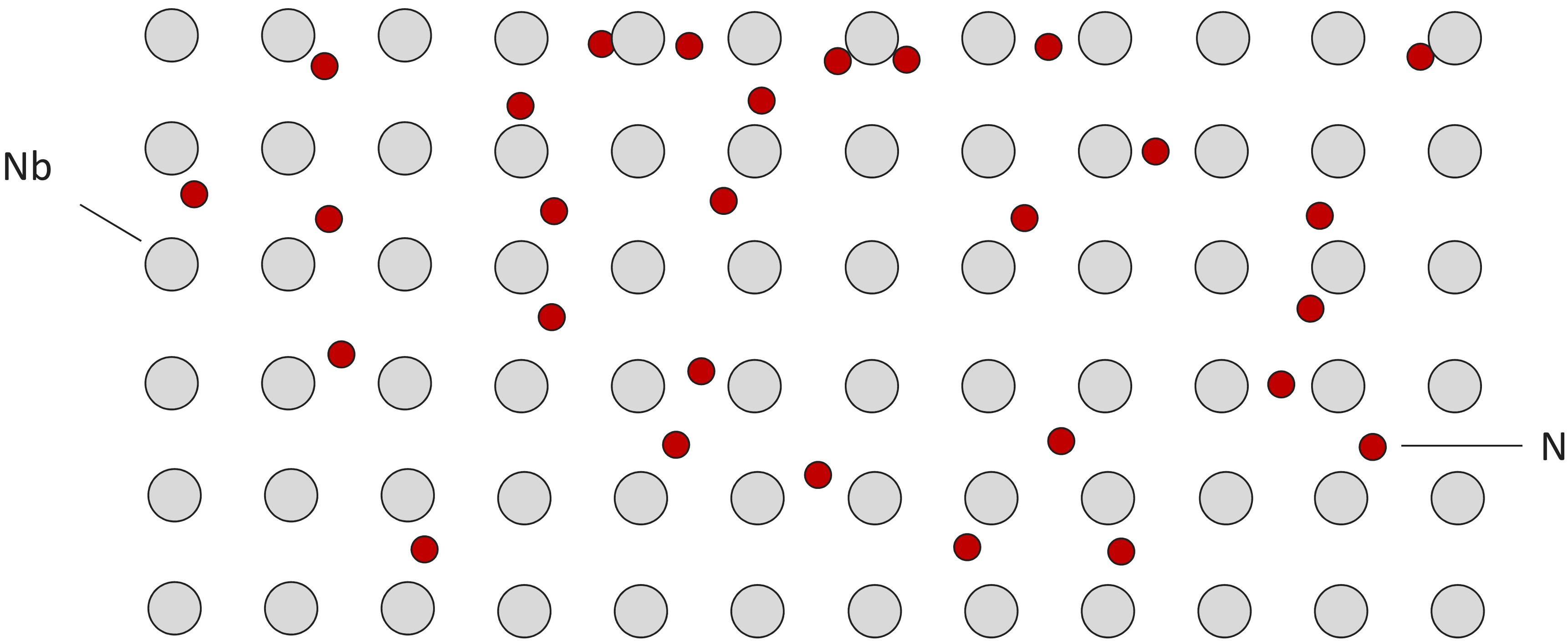

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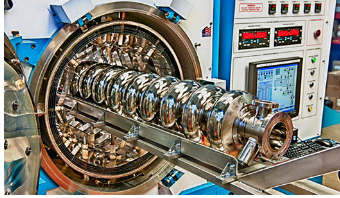

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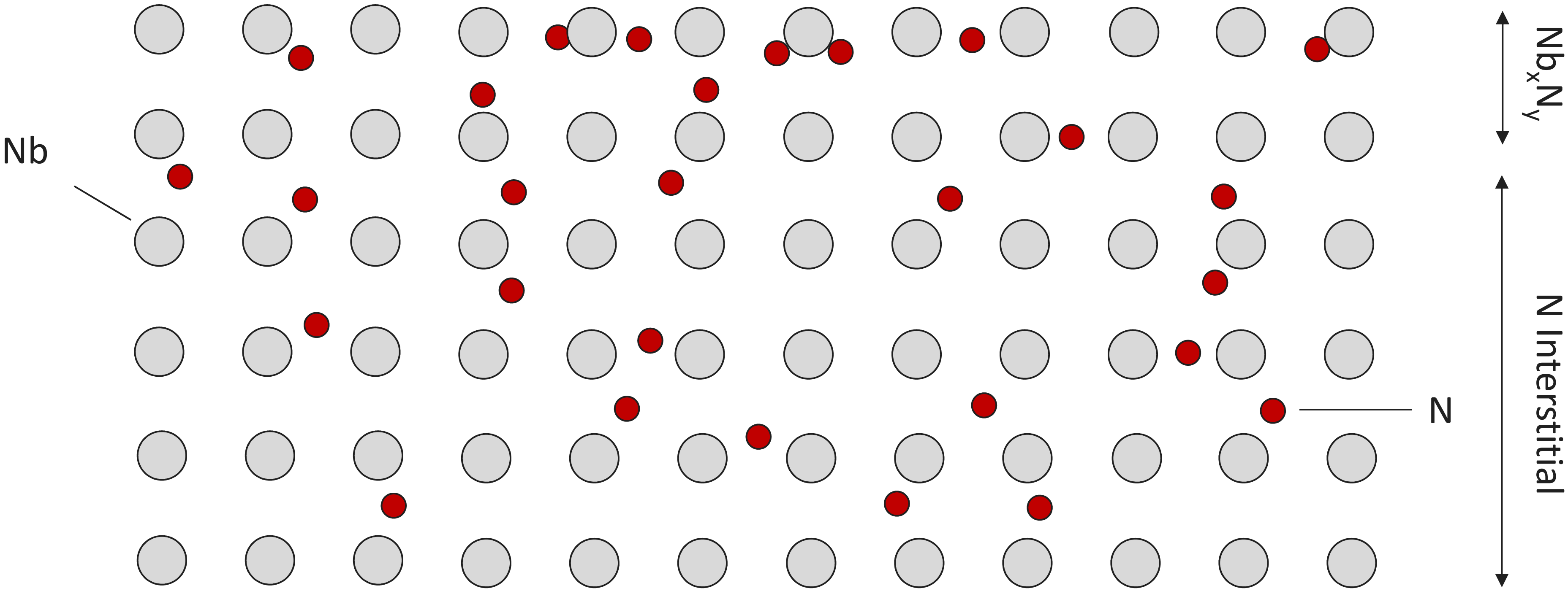

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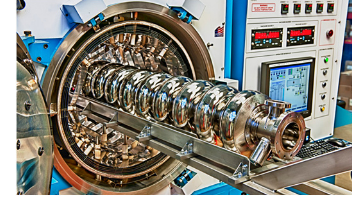

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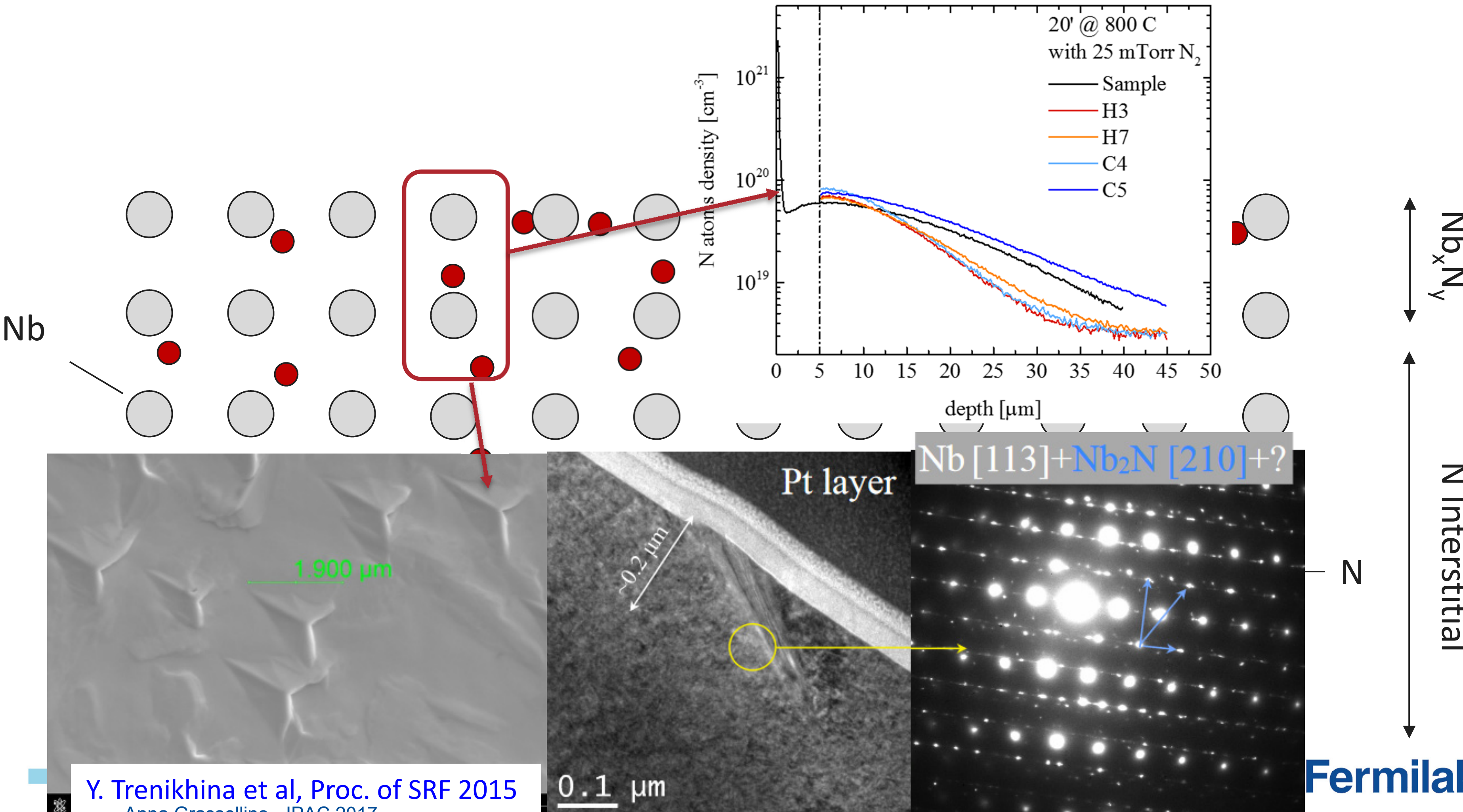

Y. Trenikhina et al, Proc. of SRF 2015

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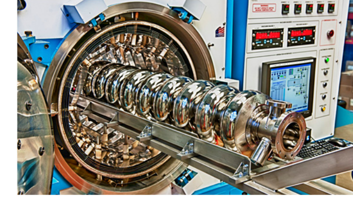

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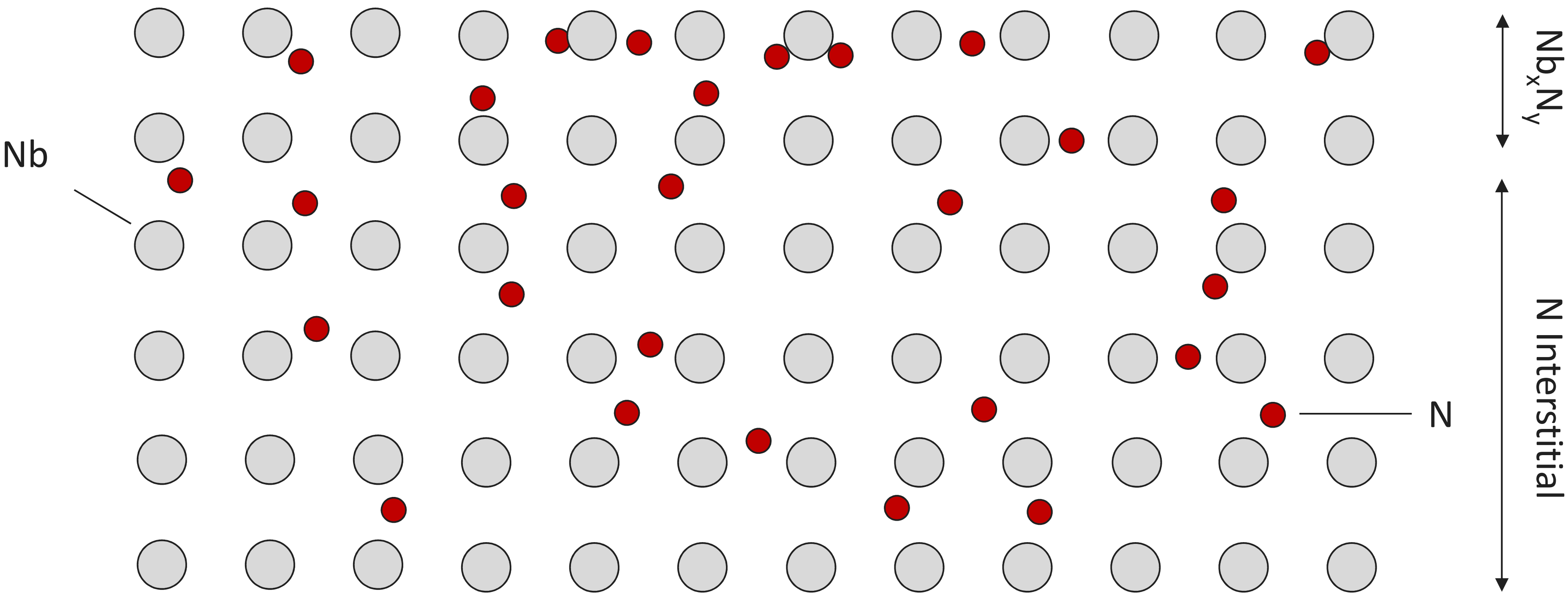

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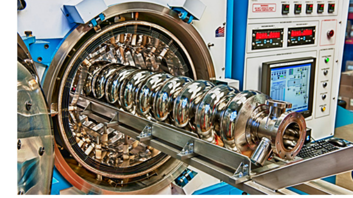

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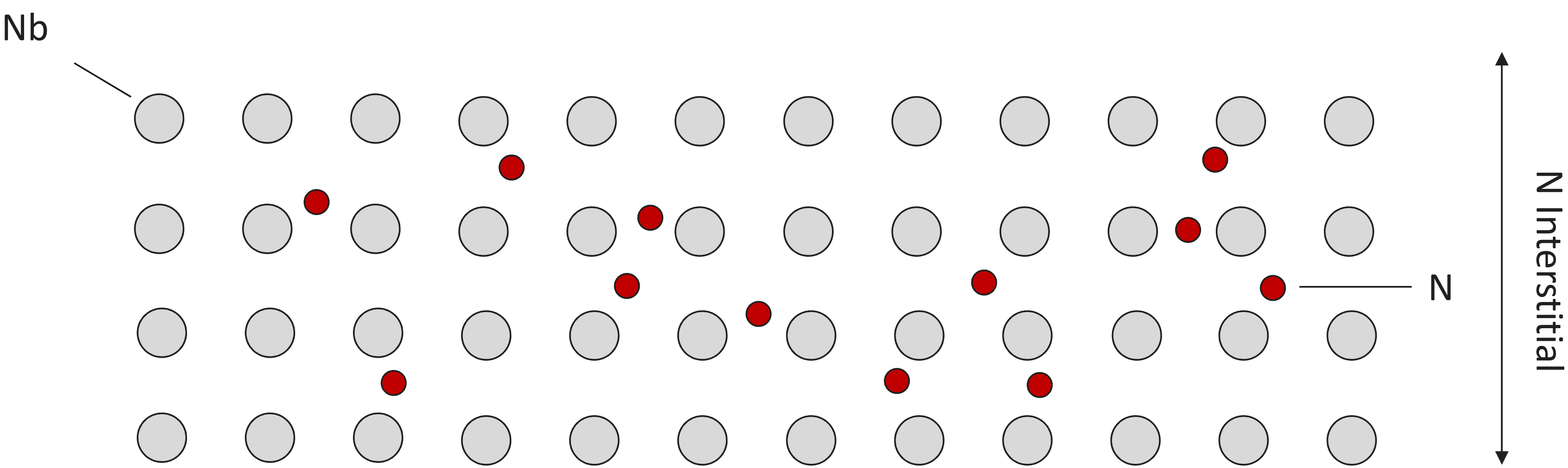

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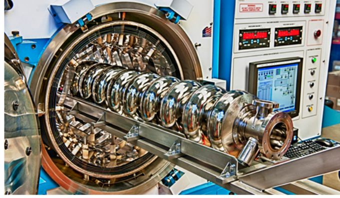

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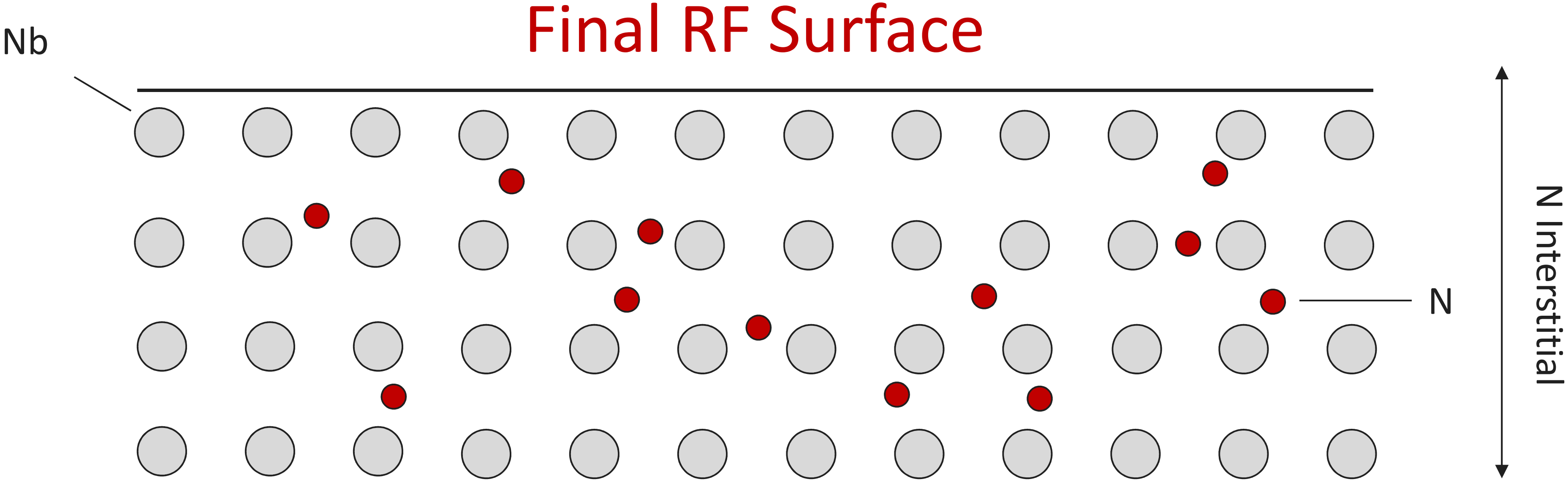
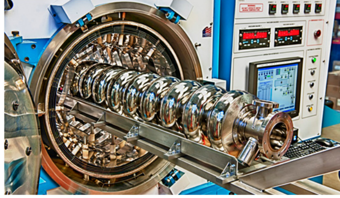
Final RF Surface



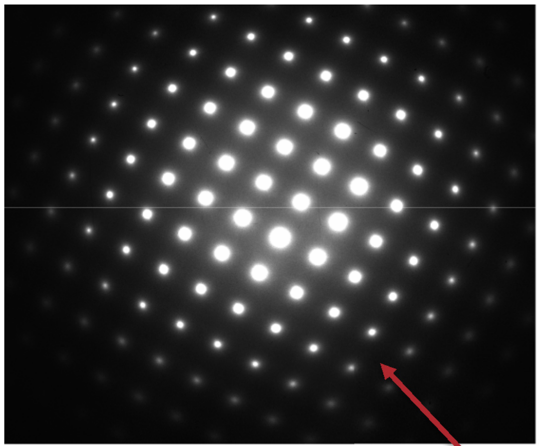
Slides adapted from M. Martinello

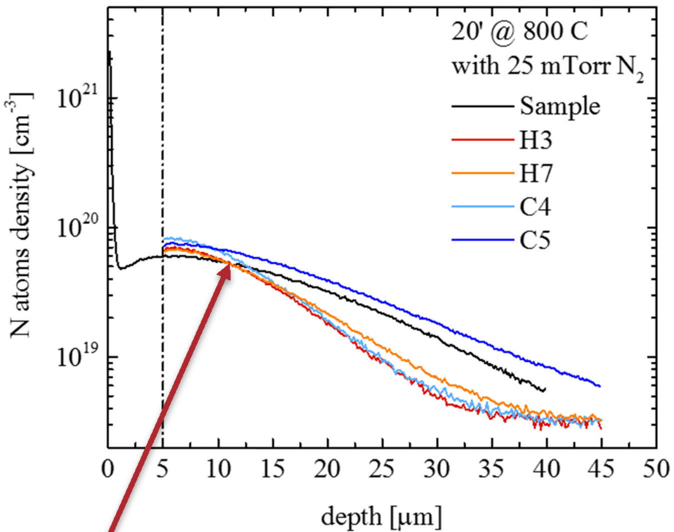


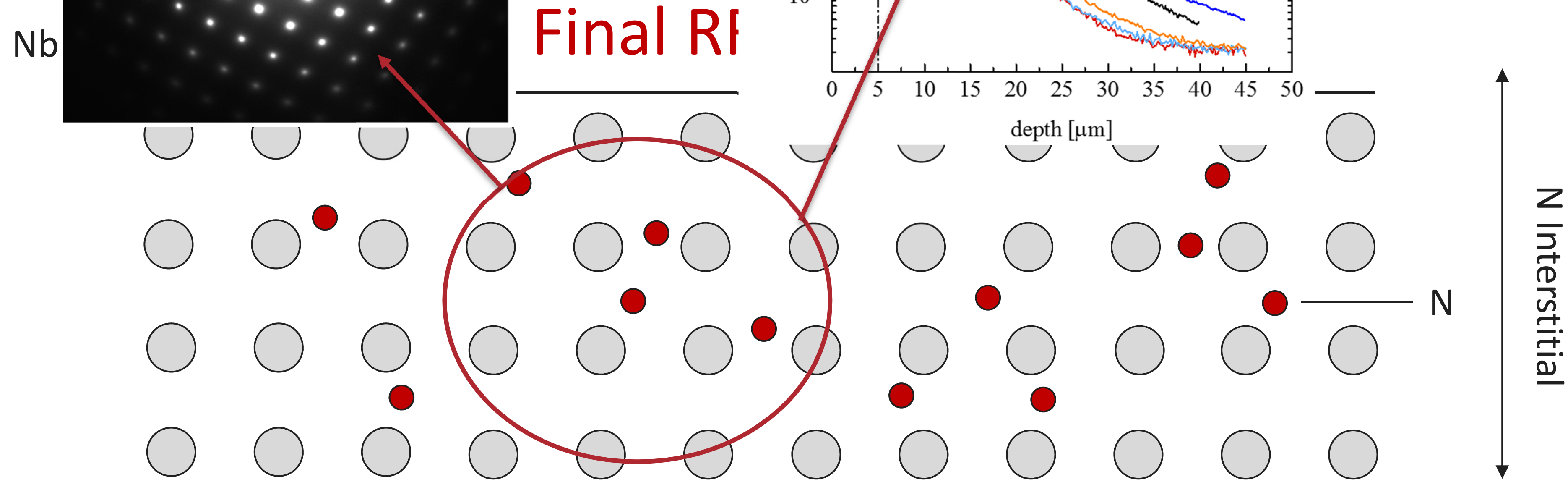
First breakthrough for Q: N doping of Nb cavities

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

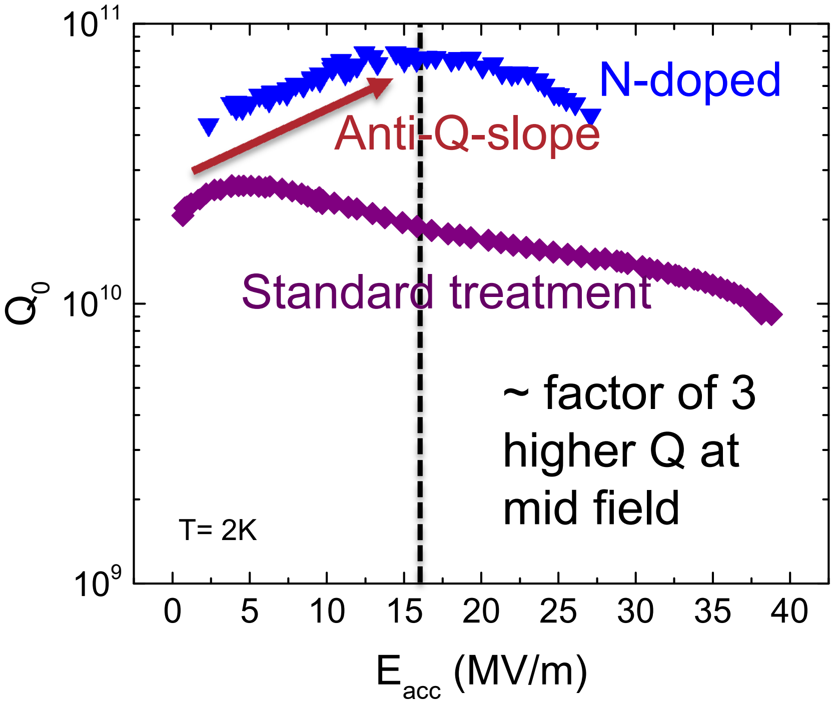


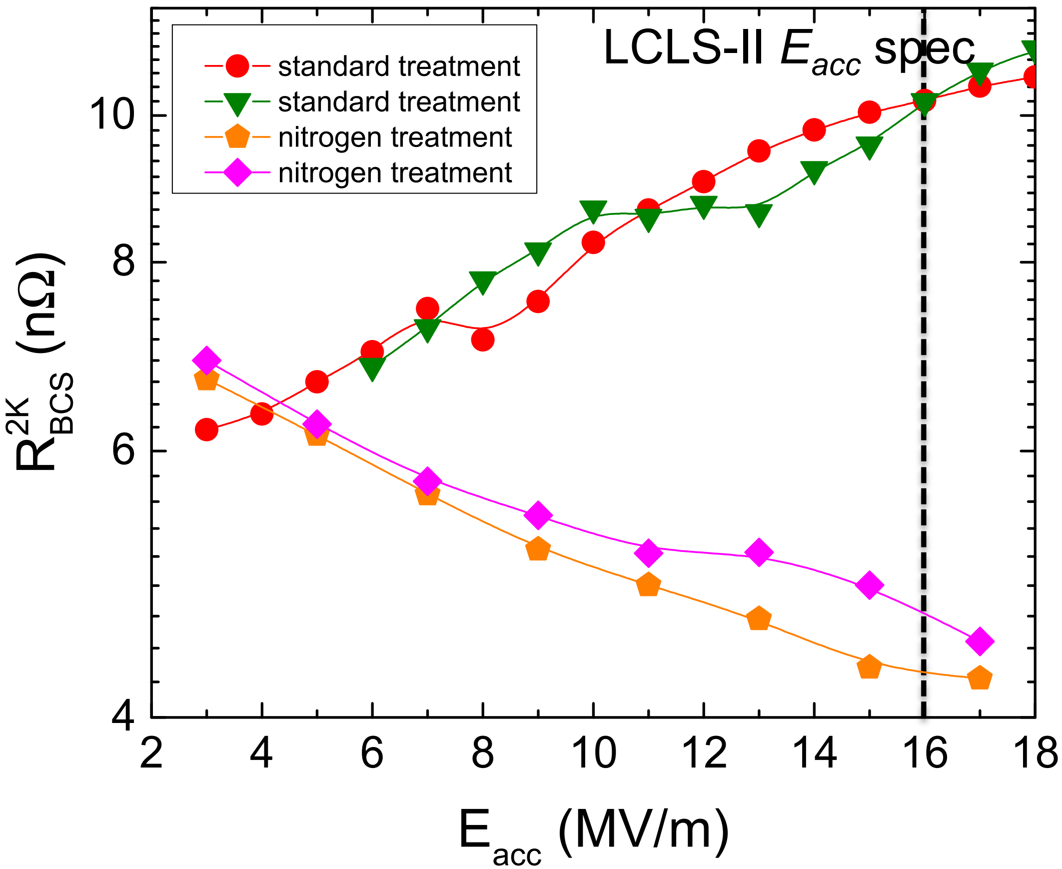




Slides adapted from M. Martinello

Effect on Surface Resistance: the curious anti-Q slope effect





Anti-Q-slope emerges from the BCS surface resistance decreasing with field

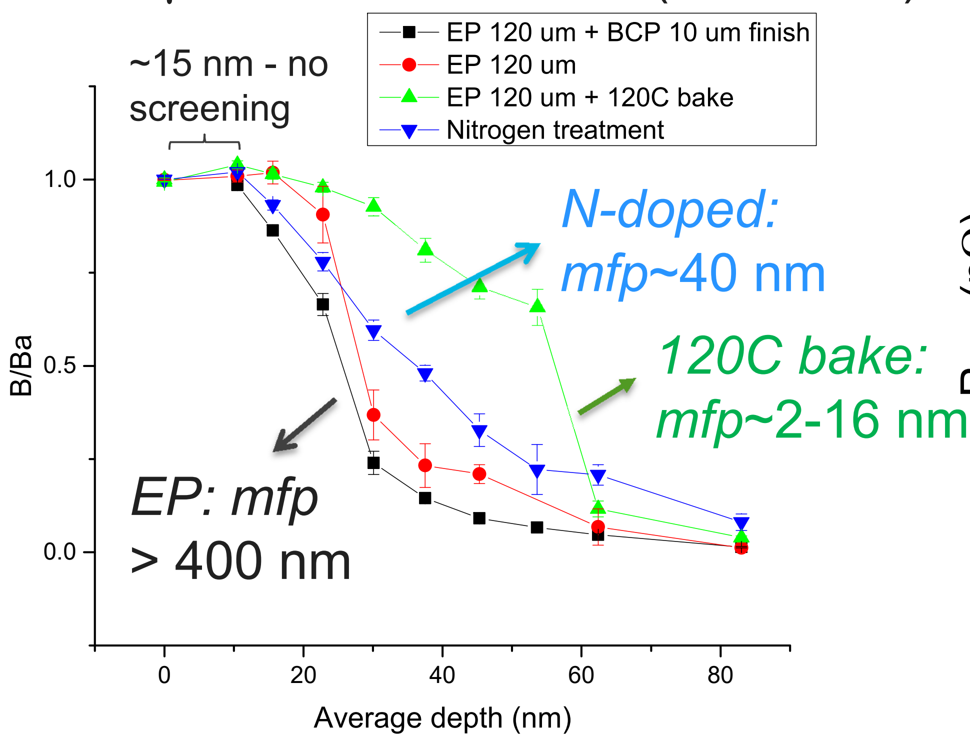
→ **Unexpected, unprecedented**

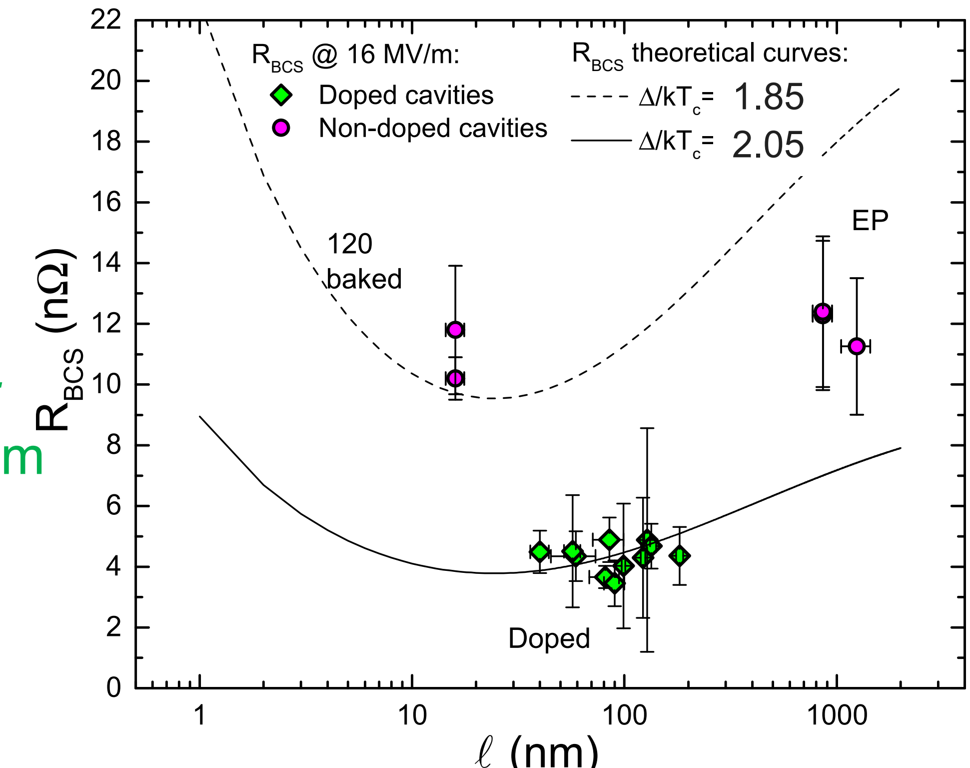
- >2x R_{BCS} improvement at 2 K, 16 MV/m
- 2-4 times higher quality factors achieved

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

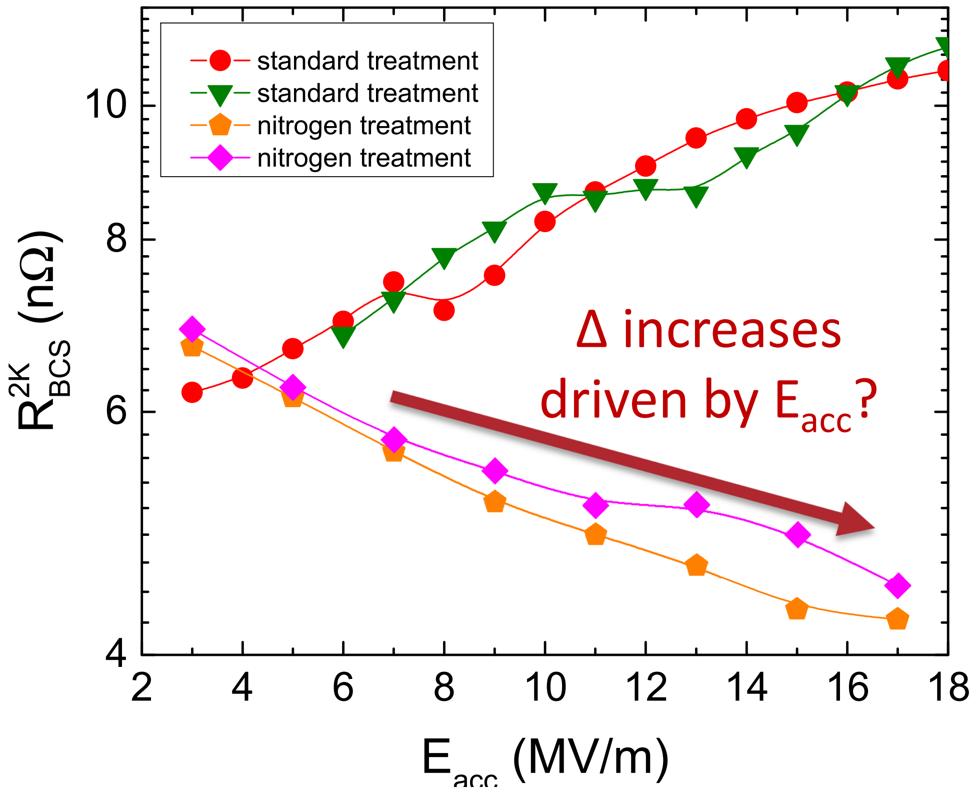
Slide adapted from M. Martinello

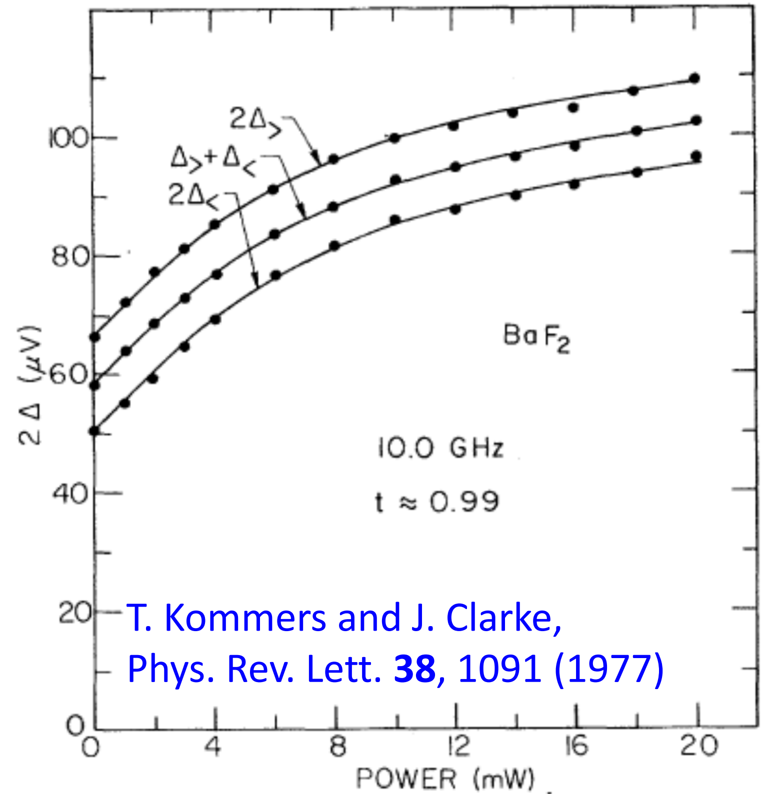
Understanding the reversal of R_{BCS} with the RF field

The non-equilibrium quasiparticle distribution driven by microwave fields is shown to stimulate the superconductivity[1,2,3]:

Δ increases with the RF field amplitude (absorbed power)

R_{BCS} decreases with the RF field amplitude (absorbed power)



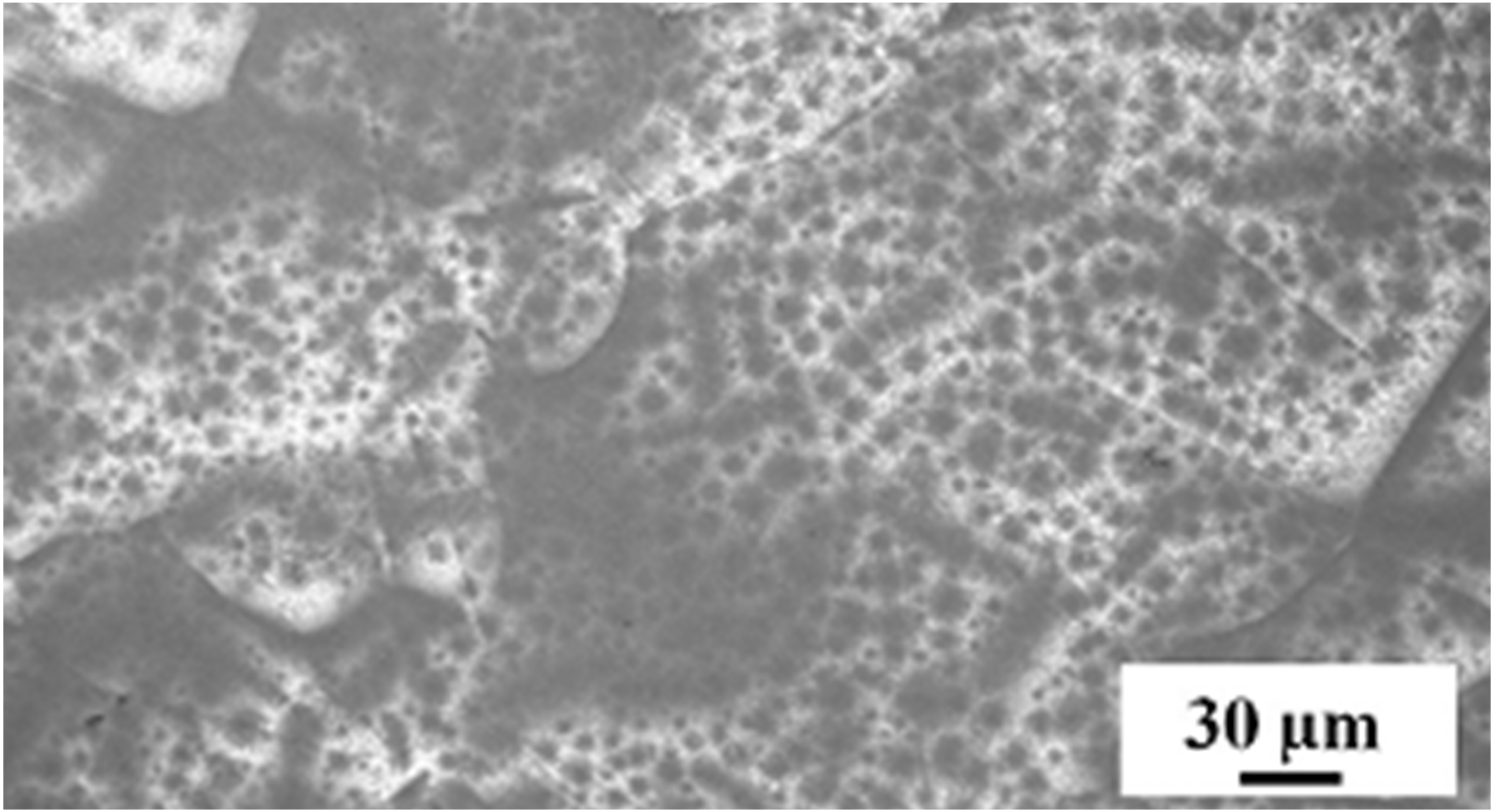


T. Kommers and J. Clarke, Phys. Rev. Lett. **38**, 1091 (1977)

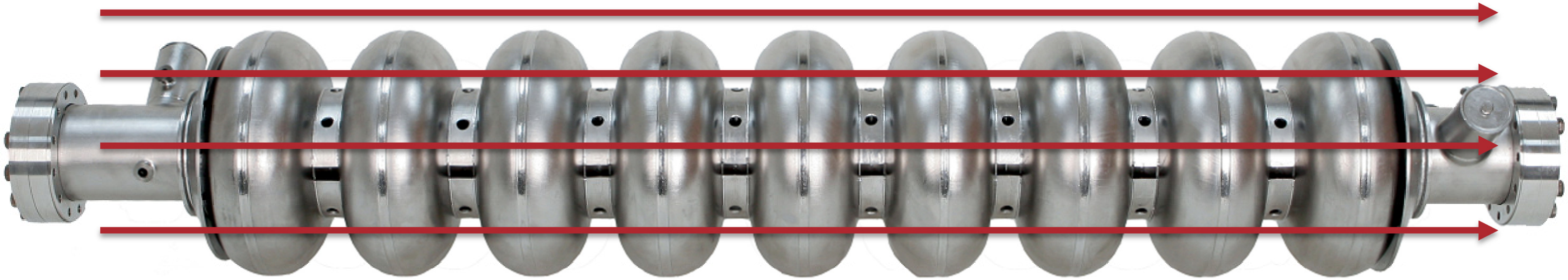
[1] G.M. Eliashberg, ZhETF Pis. Red. **11**, 186 (1970)
[2] J.-J. Chang and D. J. Scalapino, Phys. Rev. B **15**, 2051 (1977)
[3] D. J. Goldie and S. Withington, Supercond. Sci. Technol. **26,** 015004 (2013)

Magnetic flux lines can be trapped and cause large RF losses

Trapped vortices imaged via Bitter Decoration



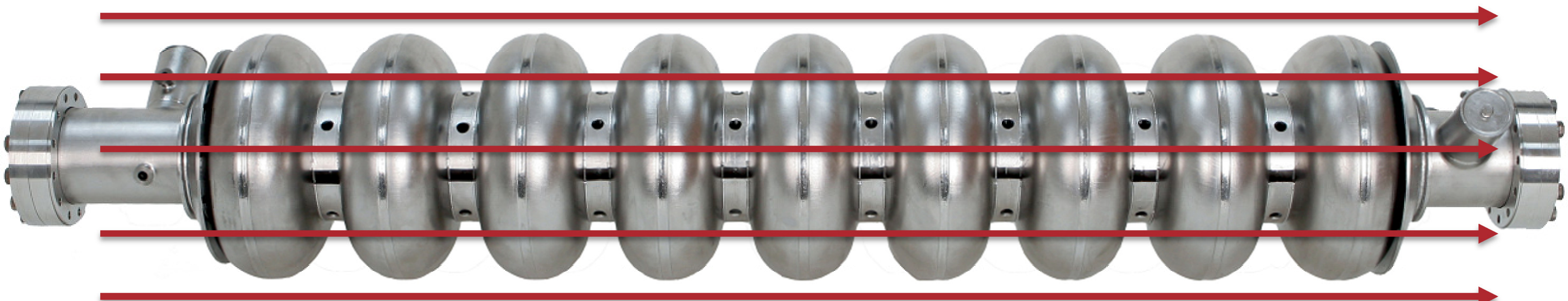
Cooldown through Critical Temperature for maximum magnetic flux expulsion and preservation of Q



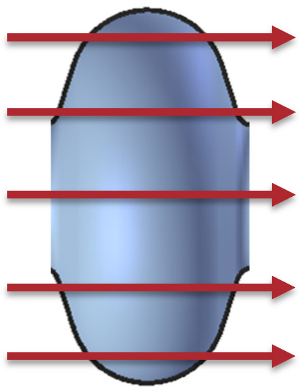
$H_{shielded}$ ~ 5 mOe ~ 1% of Earth's field

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

Cooldown through Critical Temperature for maximum magnetic flux expulsion and preservation of Q



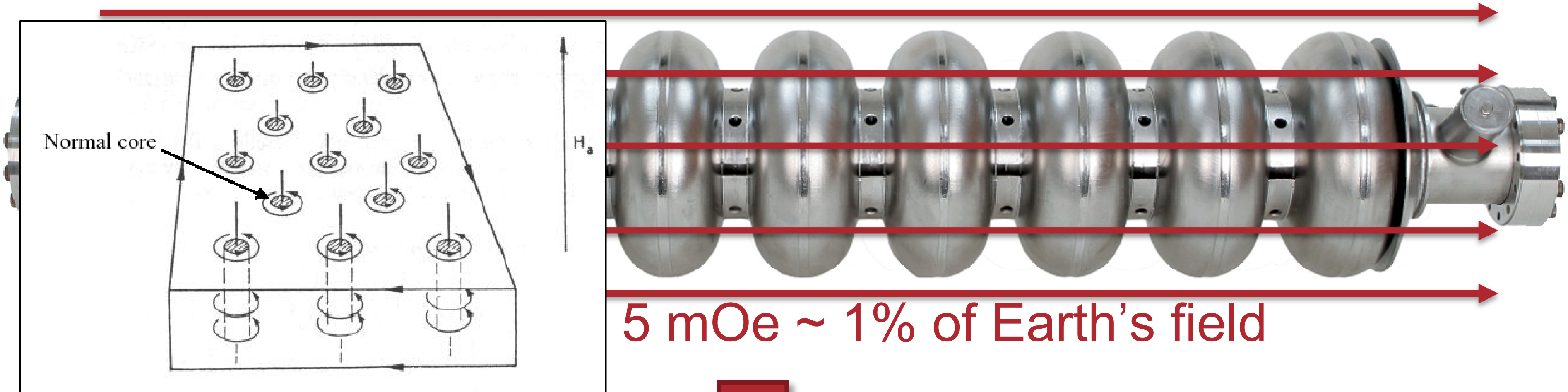
$H_{shielded}$ ~ 5 mOe ~ 1% of Earth's field



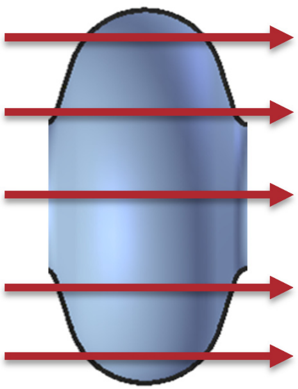
Magnetic Flux Trapping

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

Cooldown through Critical Temperature for maximum magnetic flux expulsion and preservation of Q



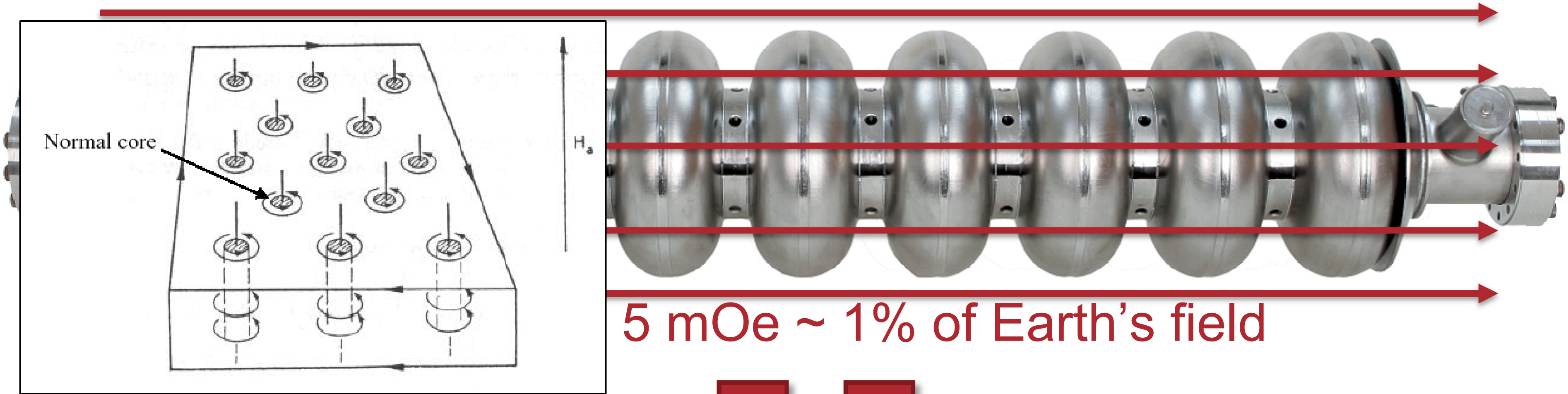
5 mOe ~ 1% of Earth's field



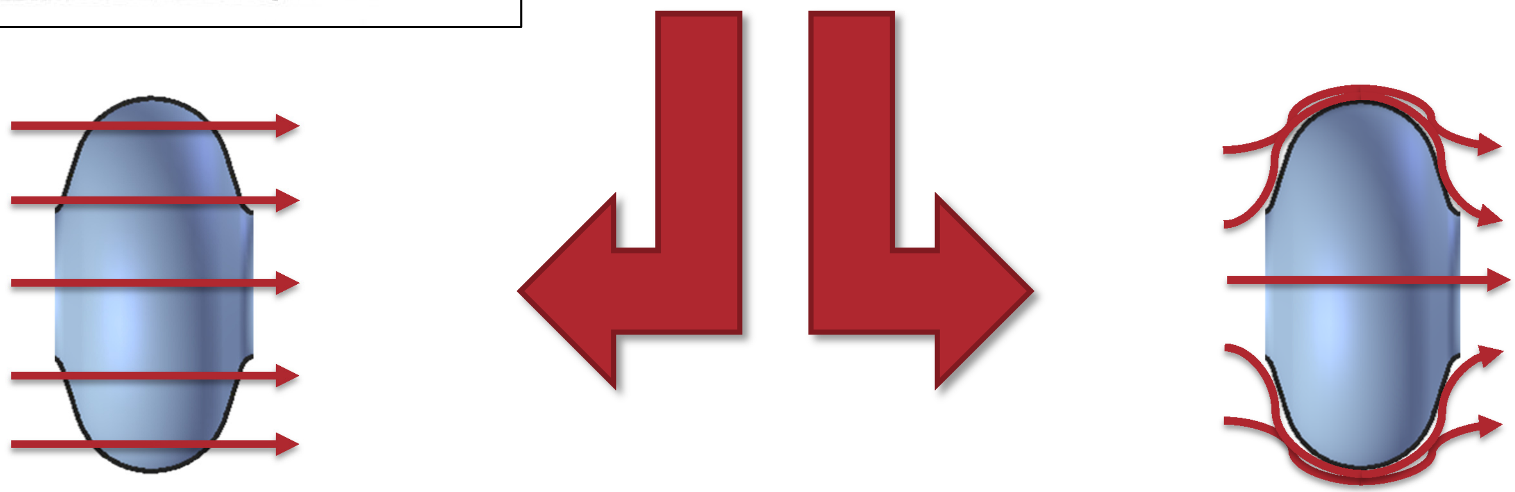
Magnetic Flux Trapping

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

Cooldown through Critical Temperature for maximum magnetic flux expulsion and preservation of Q



5 mOe ~ 1% of Earth's field

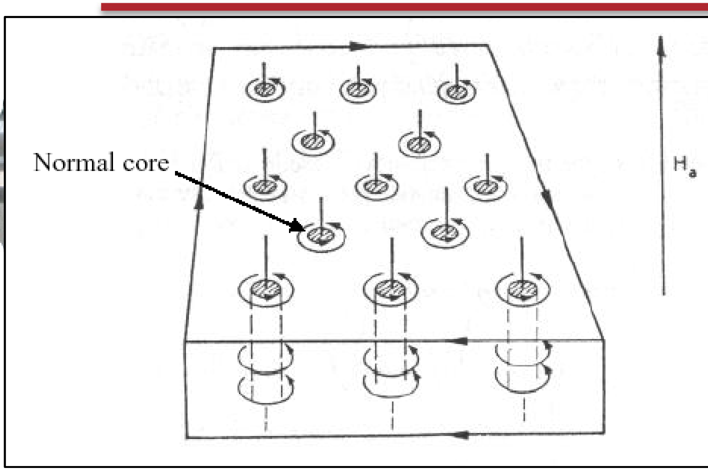


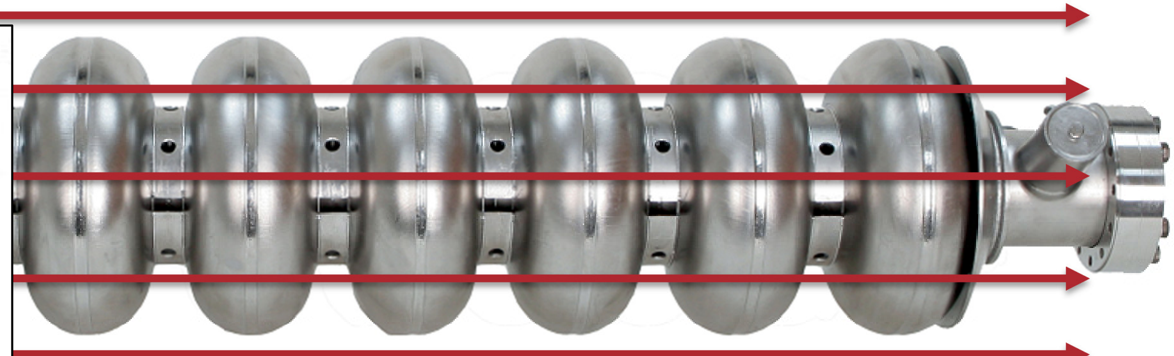
Magnetic Flux Trapping

Magnetic Flux Expulsion

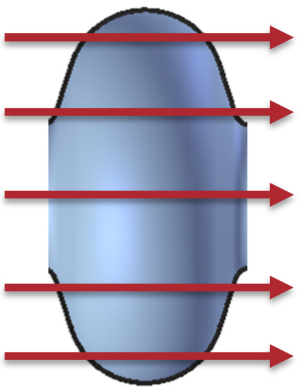
Flux image from Rose-Innes and Roderick, Introduction to Superconductivity

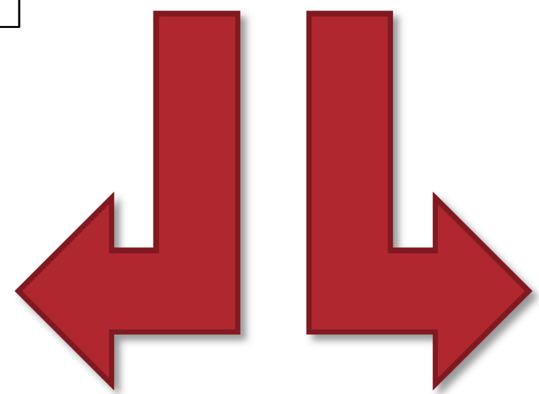
Cooldown through Critical Temperature for maximum magnetic flux expulsion and preservation of Q





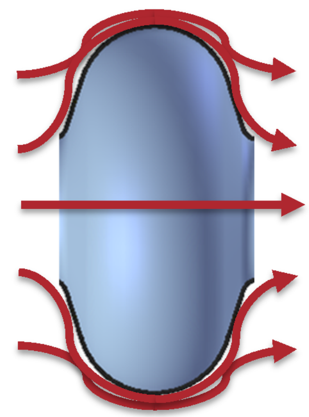
5 mOe ~ 1% of Earth's field





Trapped flux increases

R_{res}

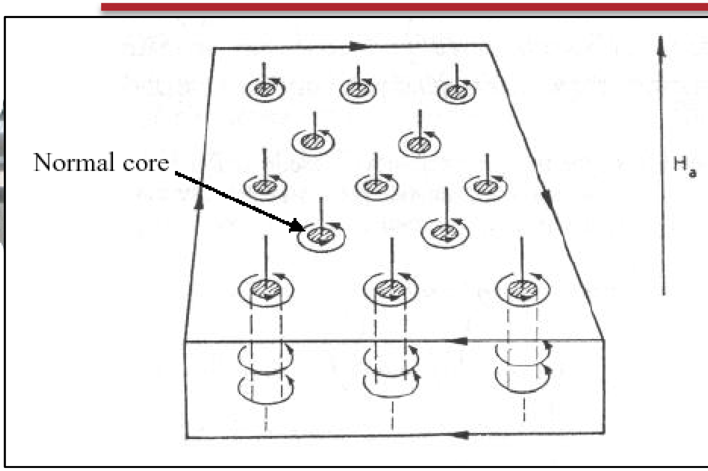


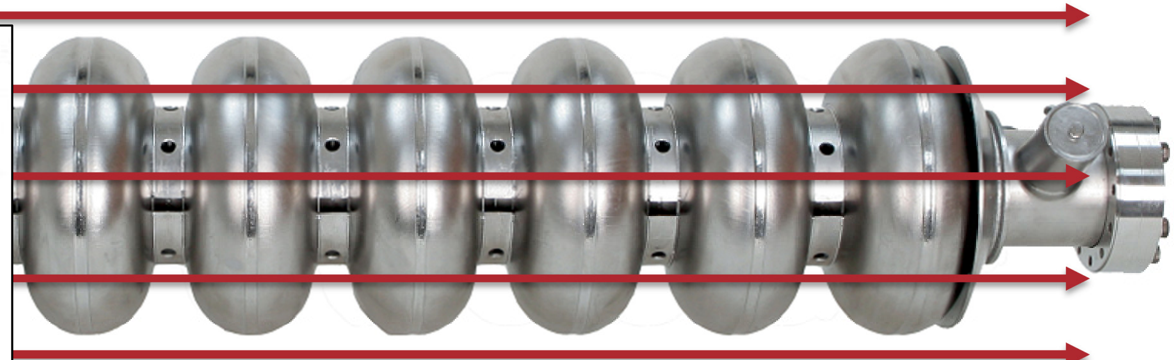
Magnetic Flux Trapping

Magnetic Flux Expulsion

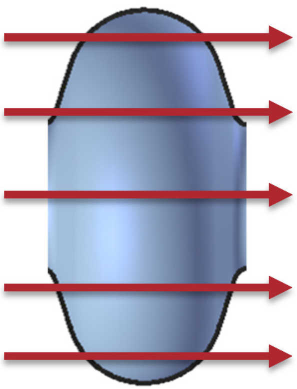
Flux image from Rose-Innes and Roderick, Introduction to Superconductivity

Cooldown through Critical Temperature for maximum magnetic flux expulsion and preservation of Q





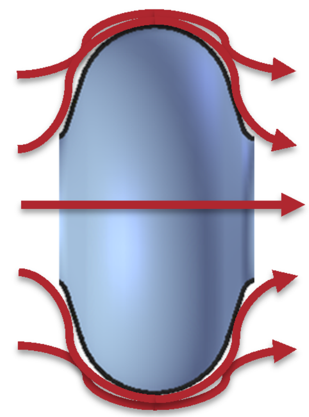
5 mOe ~ 1% of Earth's field



Magnetic Flux Trapping

Trapped flux increases R_{res}

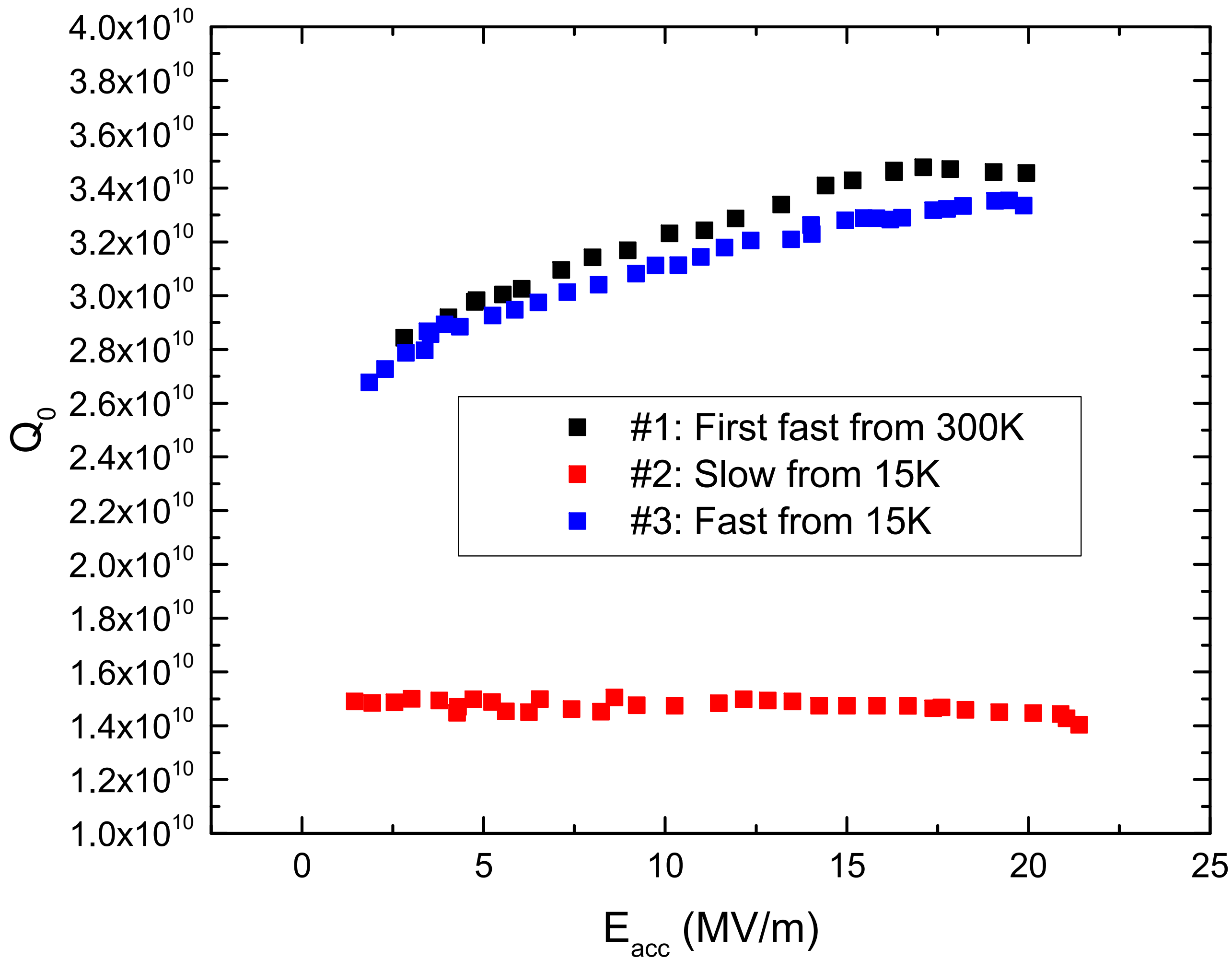
Closer to intrinsic R_{res}



Magnetic Flux Expulsion

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

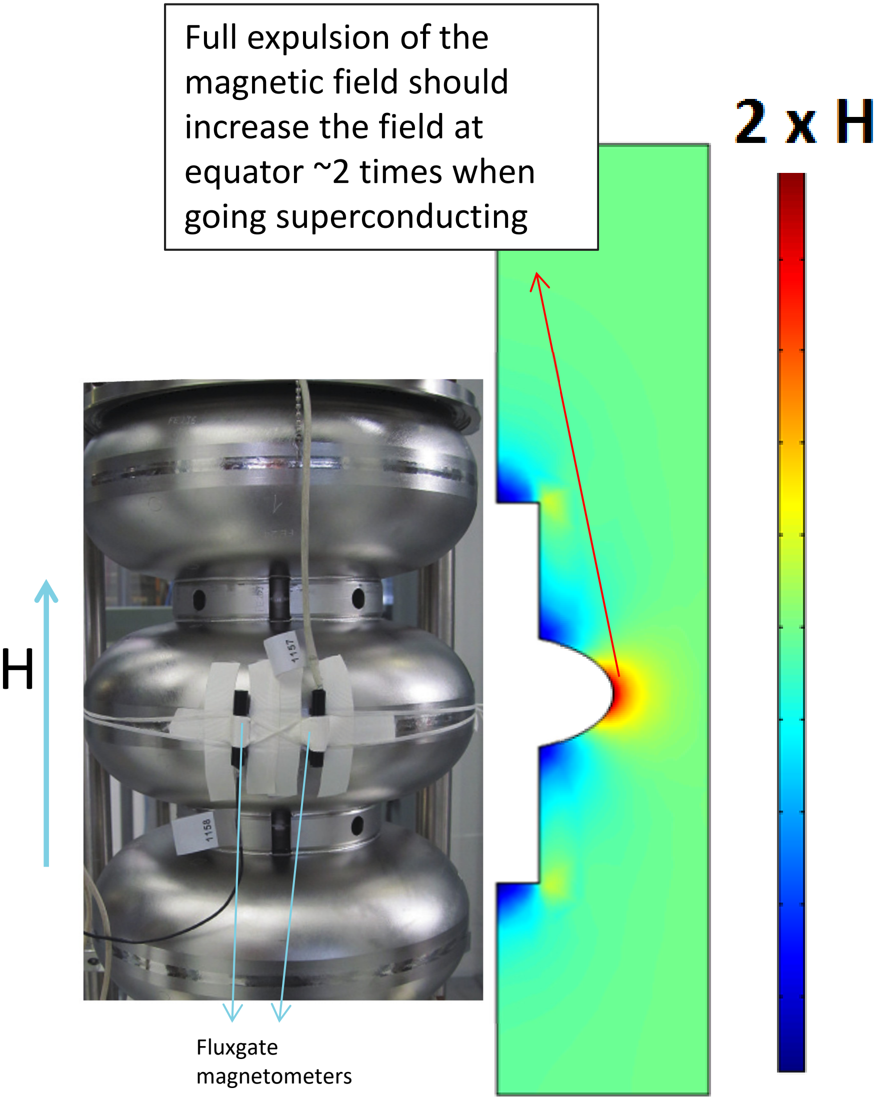
At FNAL, found that slow cooldown can kill high Q



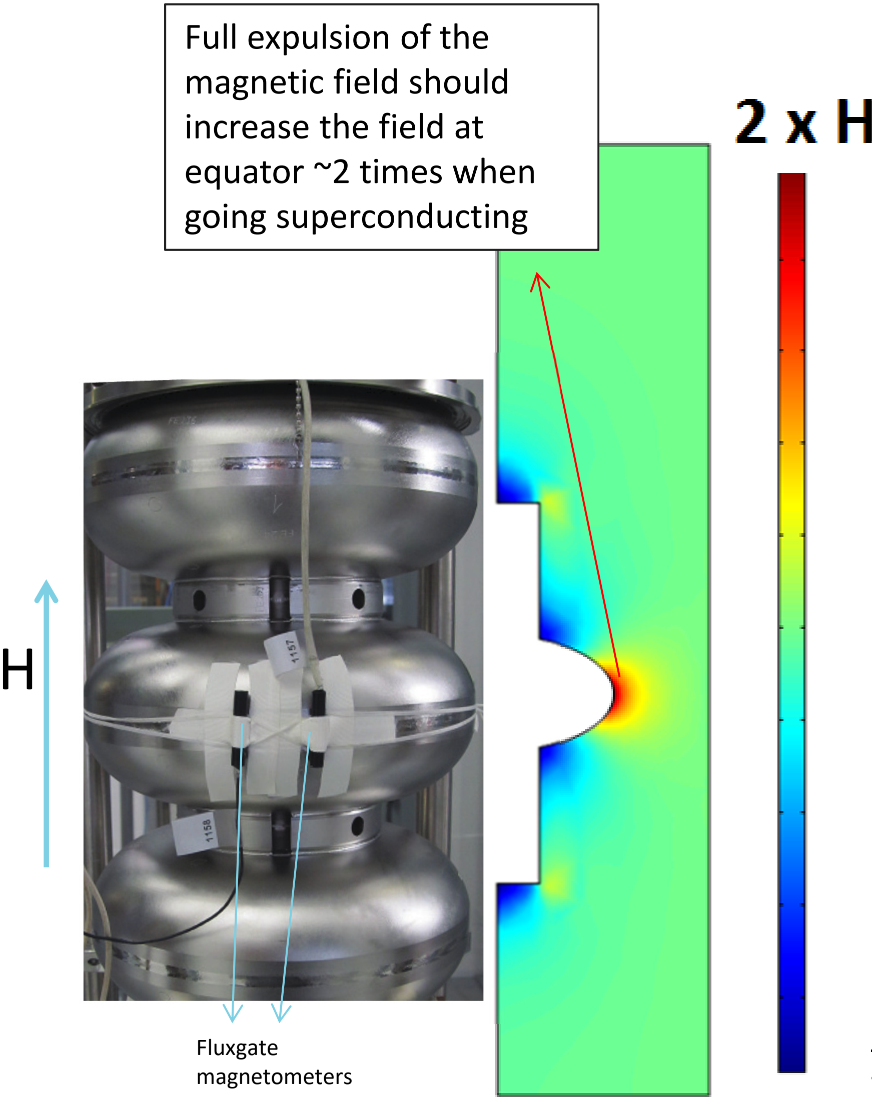
N doped nine cell in 5 mGauss!

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

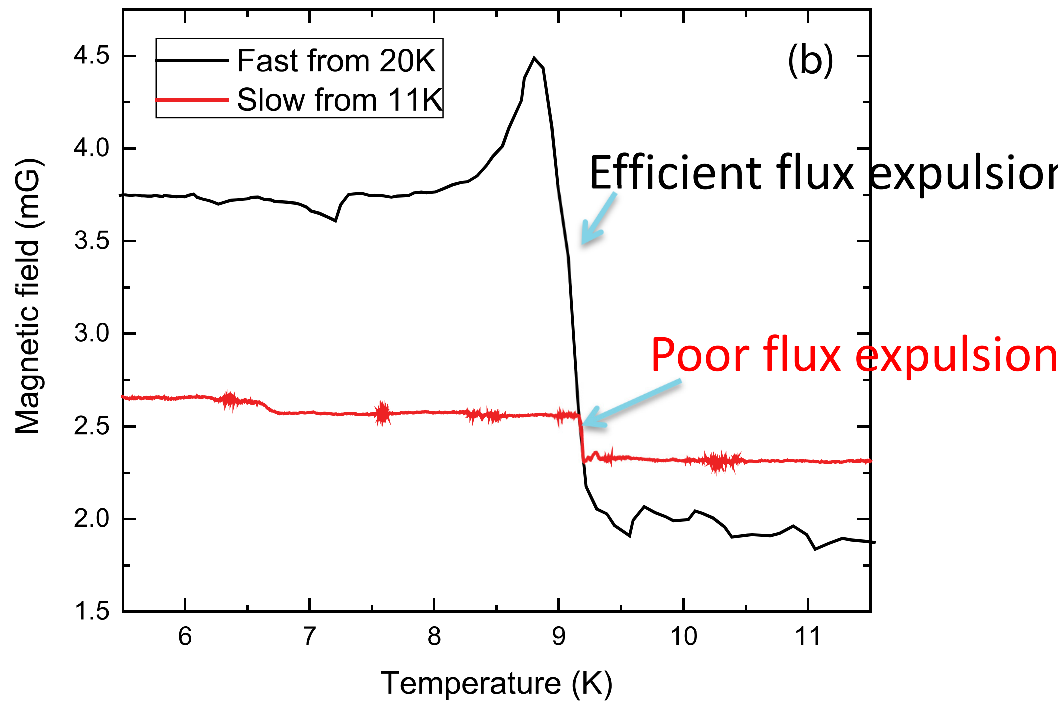
Magnetic probes revealed the new physics – flux gets trapped or detrapped depending on cooling



Magnetic probes revealed the new physics – flux gets trapped or detrapped depending on cooling



It turns out the expulsion efficiency can be controlled by the cooldown procedure through Tc=9.2K (fast/slow, uniform or not)



Same Meissner behavior for EP, EP+120C, N doping, fine/single grain, cooling is what matters

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

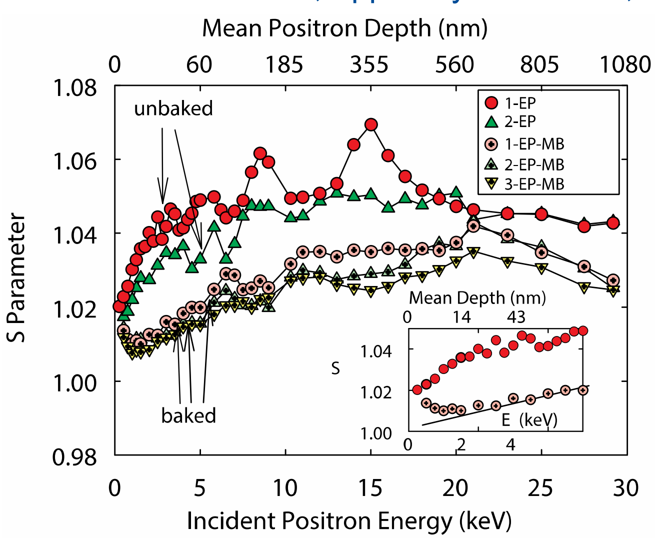
Spec: 2.7×10^{10}

World record cryomodule with twice efficiency

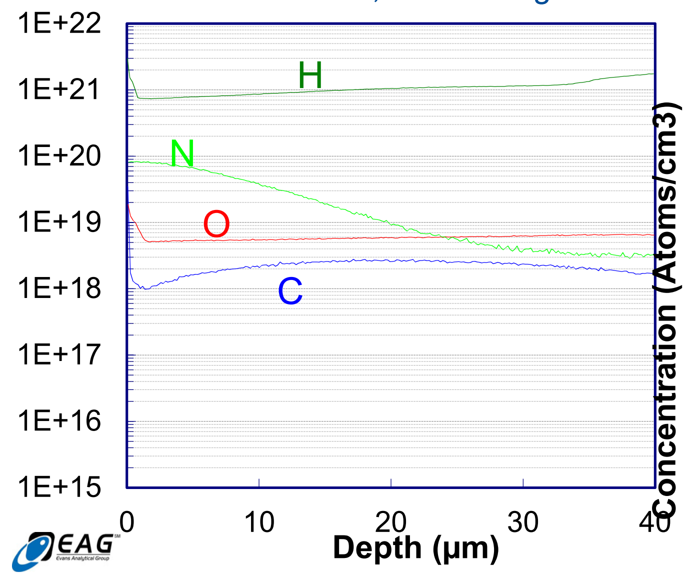
Extending High Q to high gradients: motivation behind experiments

- Composition and mean free path in first nanometers of cavity surface have been shown to be crucial for both Q and gradient performance
- **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. Romanenko et al, Appl. Phys. Lett. **102**, 232601 (2013)



A. Grassellino et al, Proceedings of SRF 2015



120C bake, vacancies in first ~ 60 nanometers N doping, nitrogen throughout several micro

Motivation behind experiments

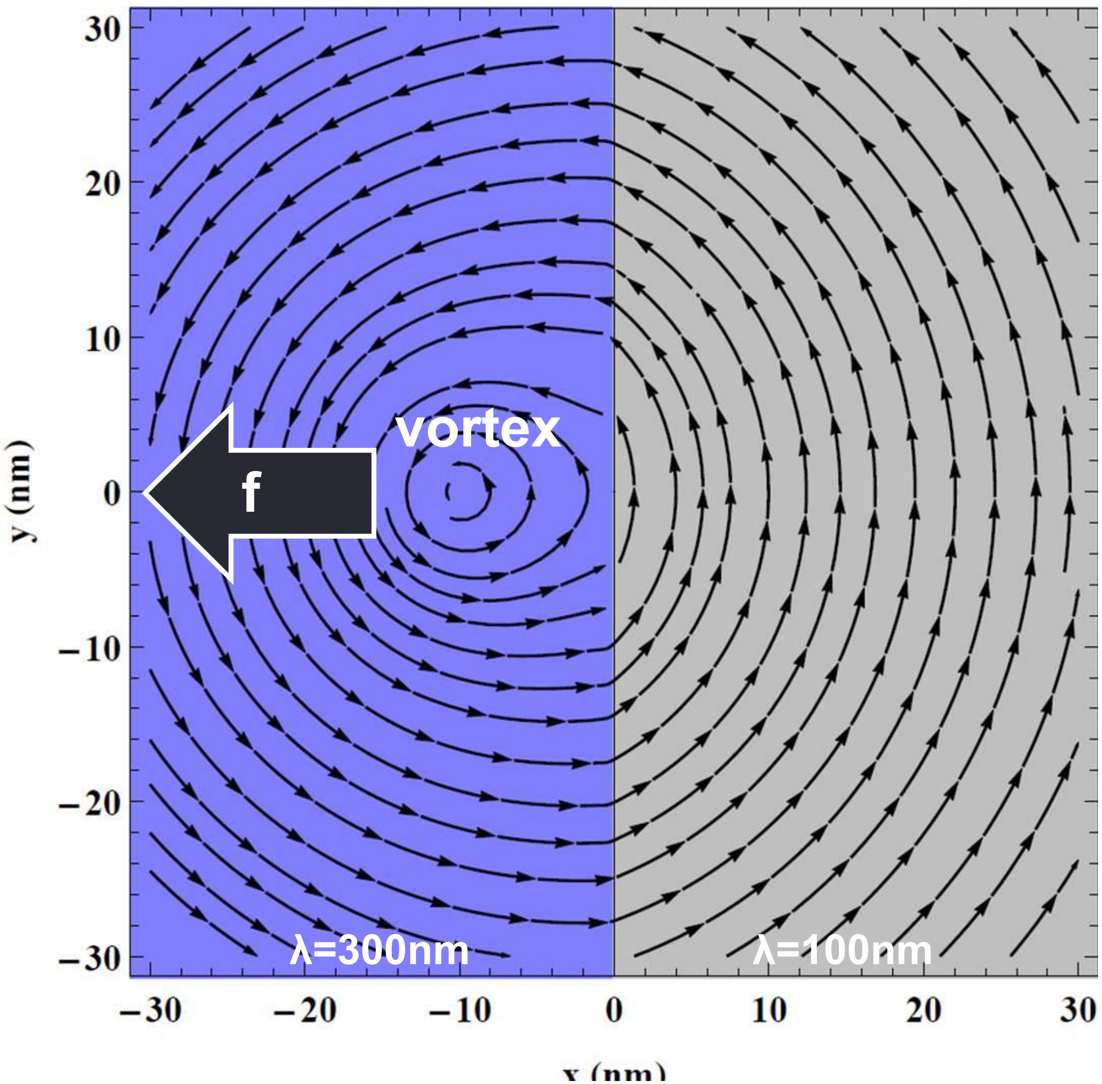
- Therefore, we decided to study how to better **"engineer"** a dirty layer on top a clean bulk, using low T nitrogen treatments → aim to **create few to several nanometers of nitrogen enriched layer** on top of clean EP bulk, to attempt to bring together the benefit of the Q and gradient

- 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

Intuitive picture of 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.



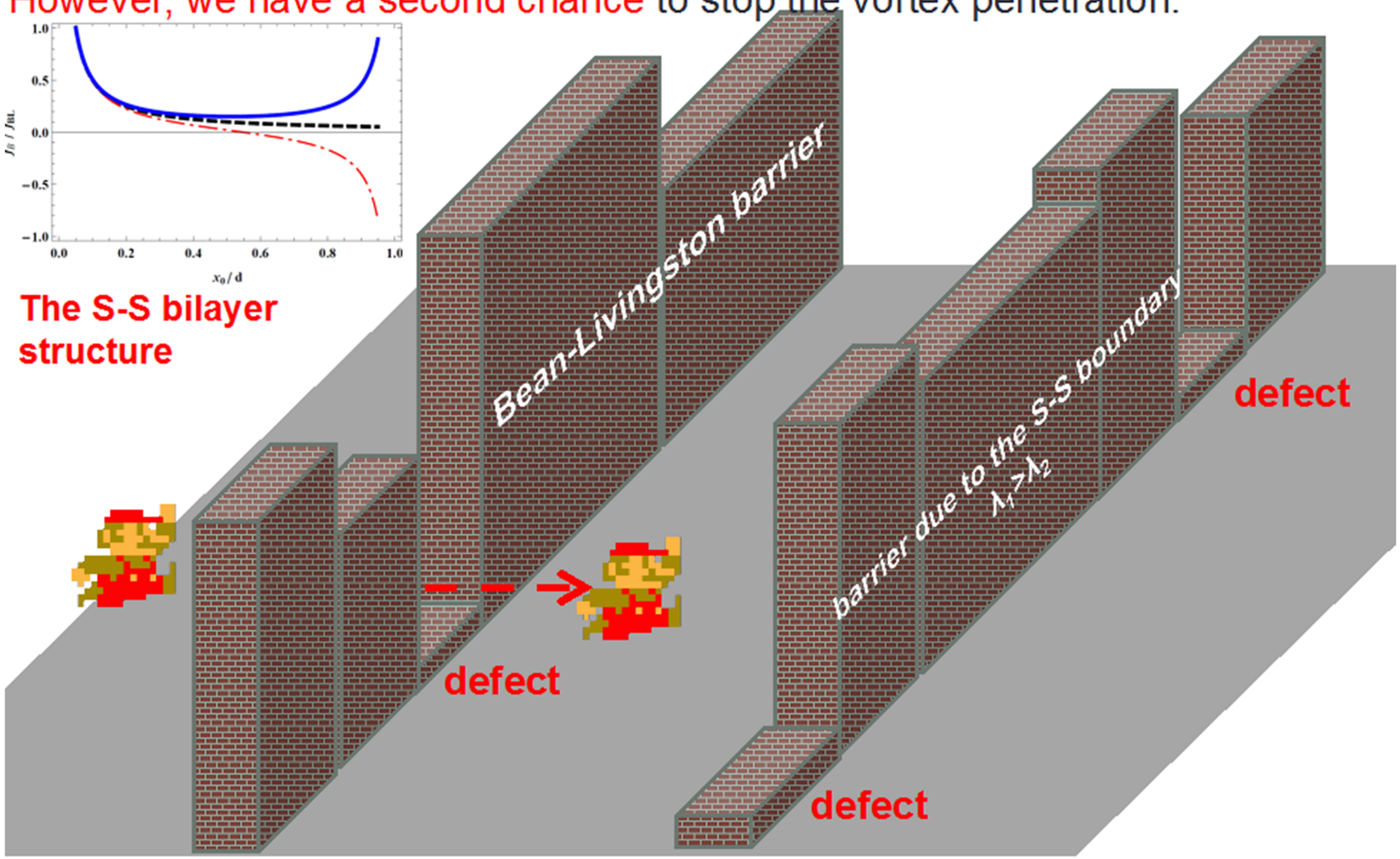
T.Kubo, in proceedings of LINAC14, Geneva, Switzerland (2014), p. 1026, THPP074

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

Intuitive picture of trick to delay flux penetration - layering

TTC@Saclay 40

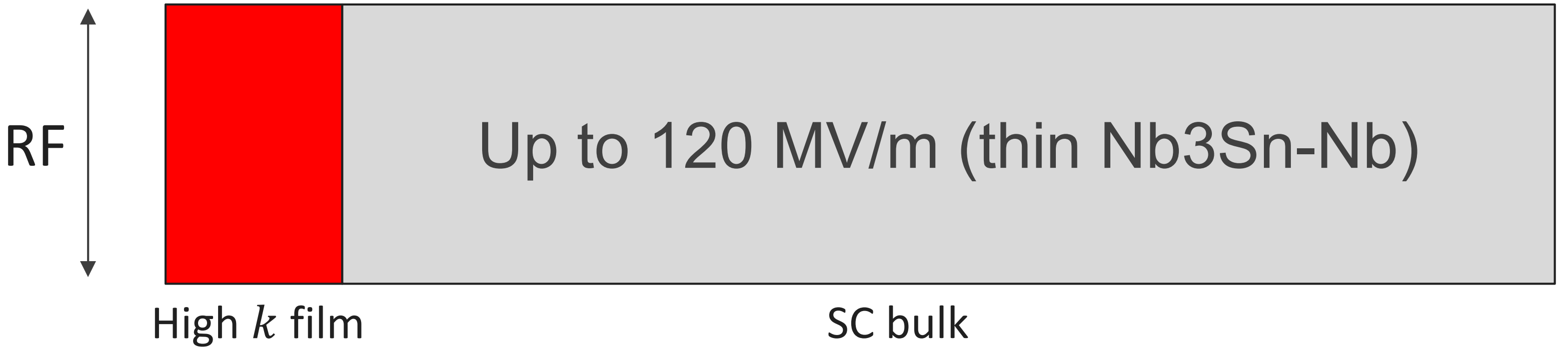
In addition to the BL barrier, we have the second barrier due to the S-S boundary. The second barrier is also imperfect: easily weakened by defects. However, we have a second chance to stop the vortex penetration.



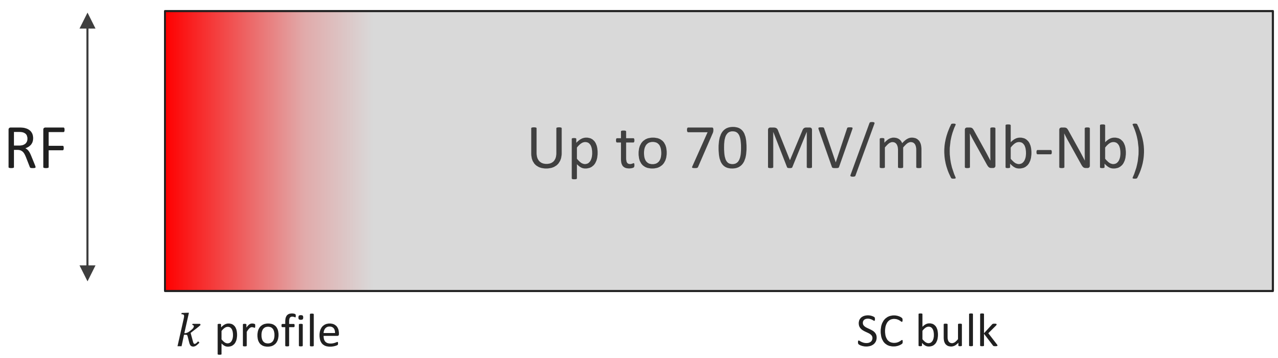
Fermilab

Superconductor-Superconductor (Dirty Layer) Potential

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

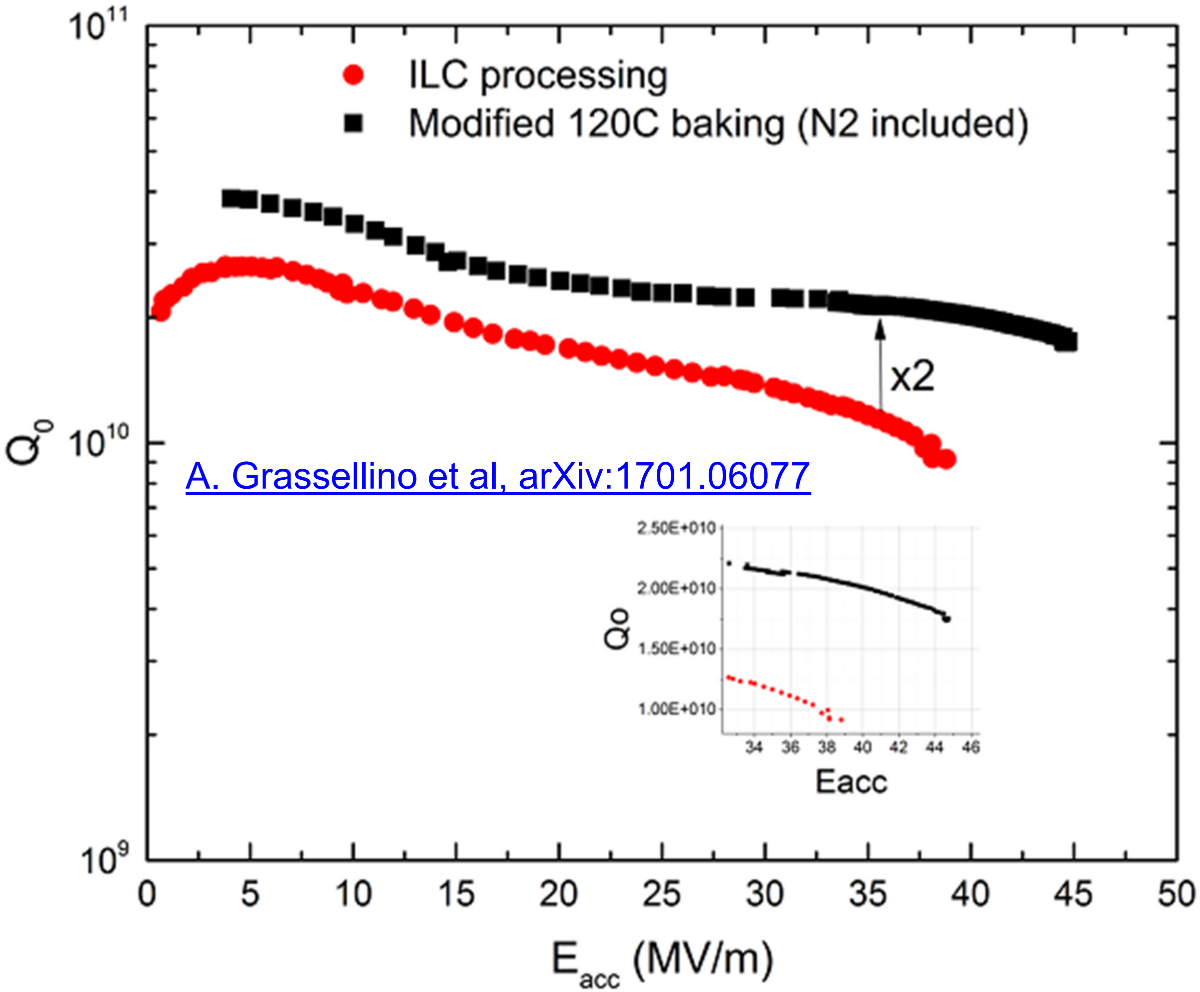


- Diffused κ profile: numerical from Ginzburg-Landau eqs.
  M. Checchin *et al.*, IPAC 2016 & LINAC 2016



Can be produced by thermal diffusion!

New breakthrough at FNAL: N infusion (dirty SC on clean SC) produces very high Q at very high gradient



- 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
- First nine cell results confirm the findings
- Working on applying to higher frequencies

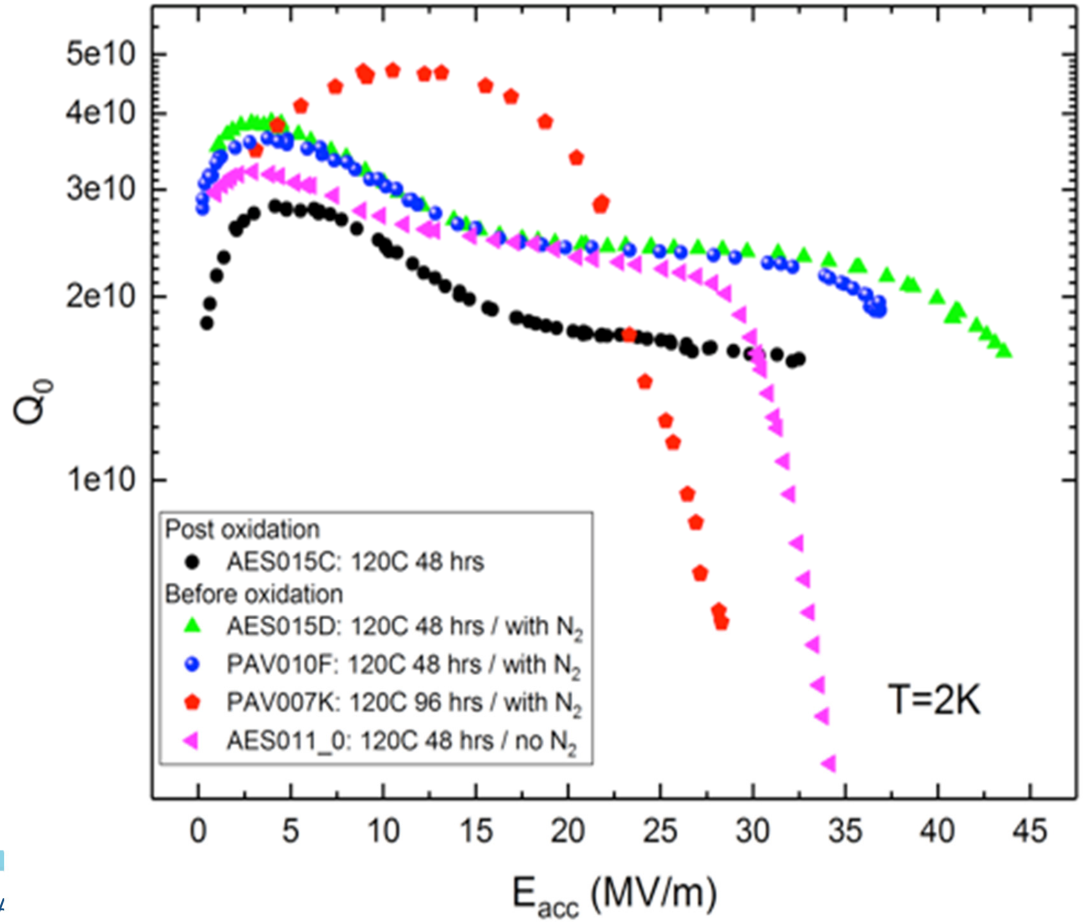
Increase in Q factor of two, increase in gradient ~20%

Slide from A. Grassellino

120C with N for twice time (96 hours)

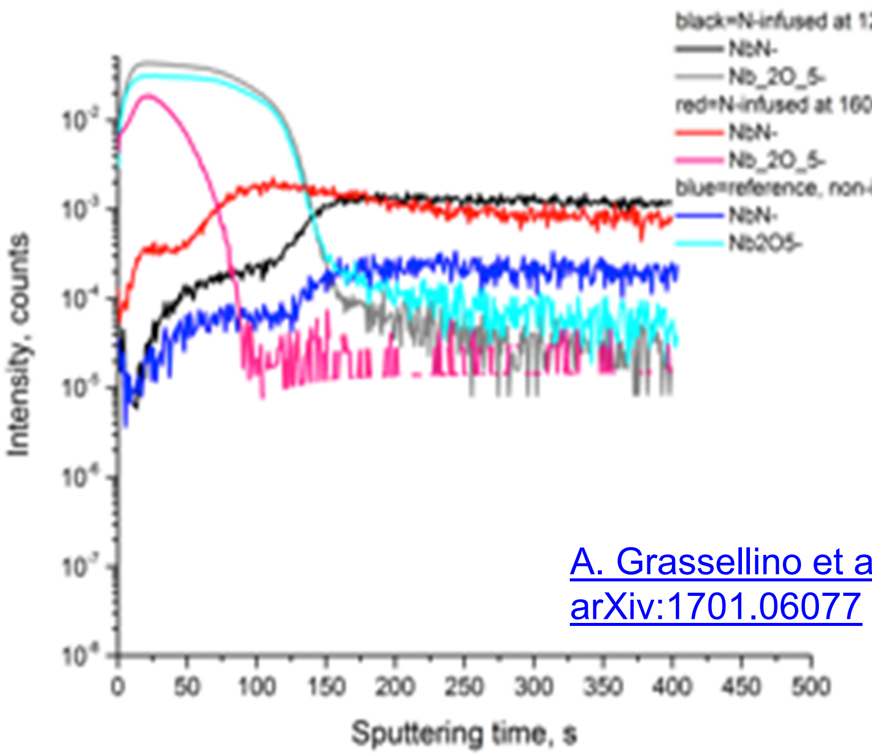
- Doubling the time with N2 at 120C reverses the BCS resistance – so the diffusion depth between 48 and 96 hours is the crucial one of the BCS reversal (~ 10-20 nm)

A. Grassellino et al, arXiv:1701.06077

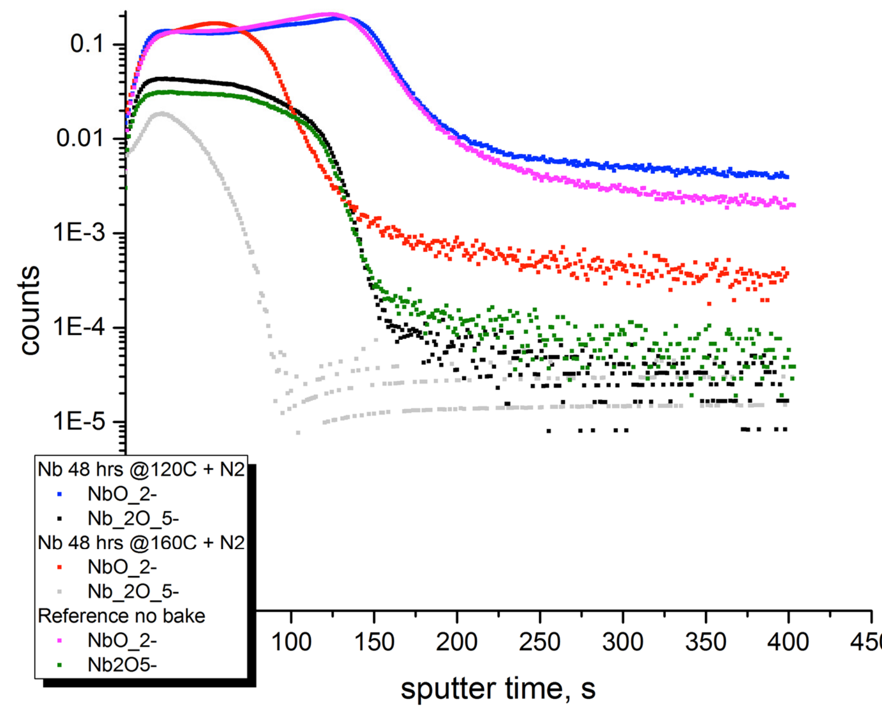


Why is nitrogen giving this improvement?

- There is nitrogen diffusion seen with TOF-SIMS > 10 nm, same level above background as per high T doping (factor of 10-20)
- Interesting – systematically observe different oxide thickness for 160C N infused sample
- Nb_2O_5 and NbO_2 about half of the size of standard undoped and 120C infused…could it be that part of improvement comes from better oxide or lack of lossy oxides as NbO2? Nitrogen favors growth of better quality oxide?



A. Grassellino et al, arXiv:1701.06077



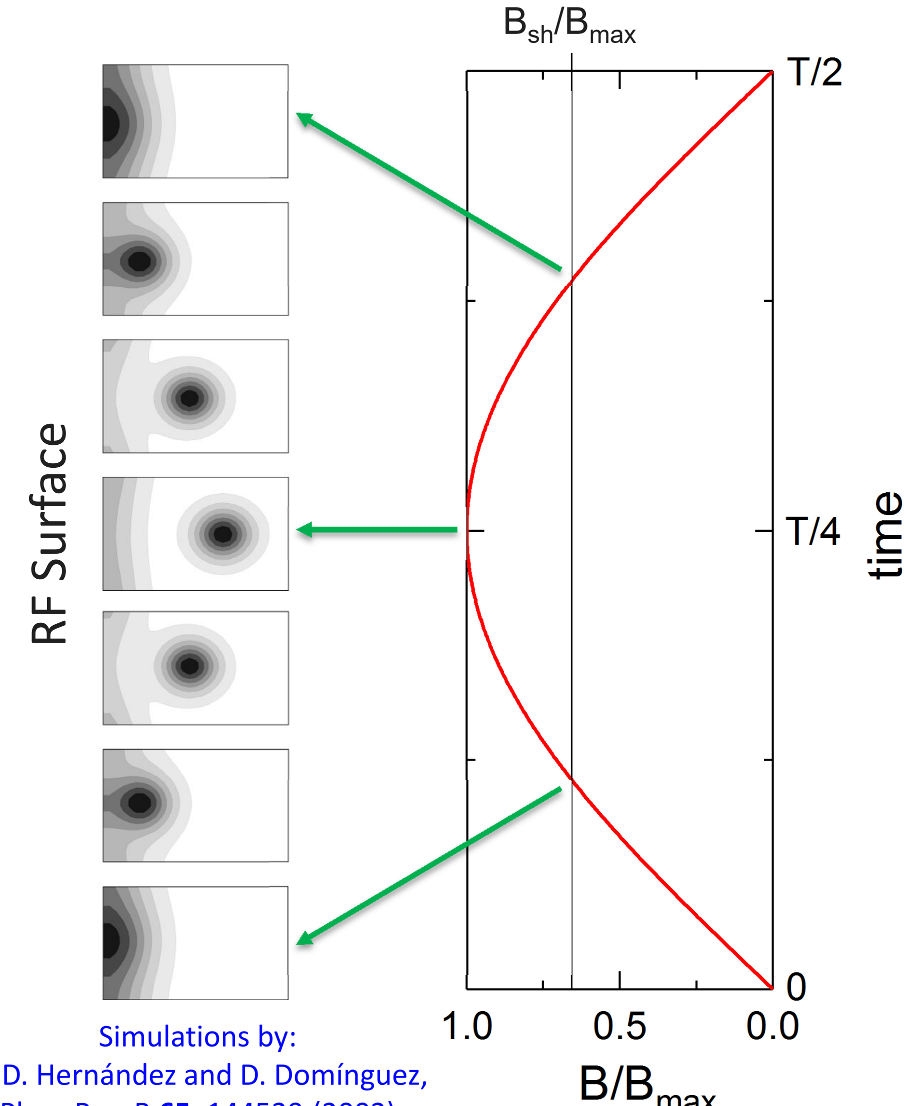
Vortex Nucleation Time – can we beat DC superheating field?

DC regime: magnetic flux vortices can nucleate when the magnetic field amplitude is larger than B_{sh}

RF regime: we should consider that $B(t)$ oscillates. The vortex nucleation may depend on the field frequency f:

- The vortex nucleation happens in a certain characteristic time τ_n
- If the frequency is high enough so that $1/f \gg \tau_n$ then the vortex should not have enough time to nucleate

Can the field be sustained above the superheating field in such a regime?

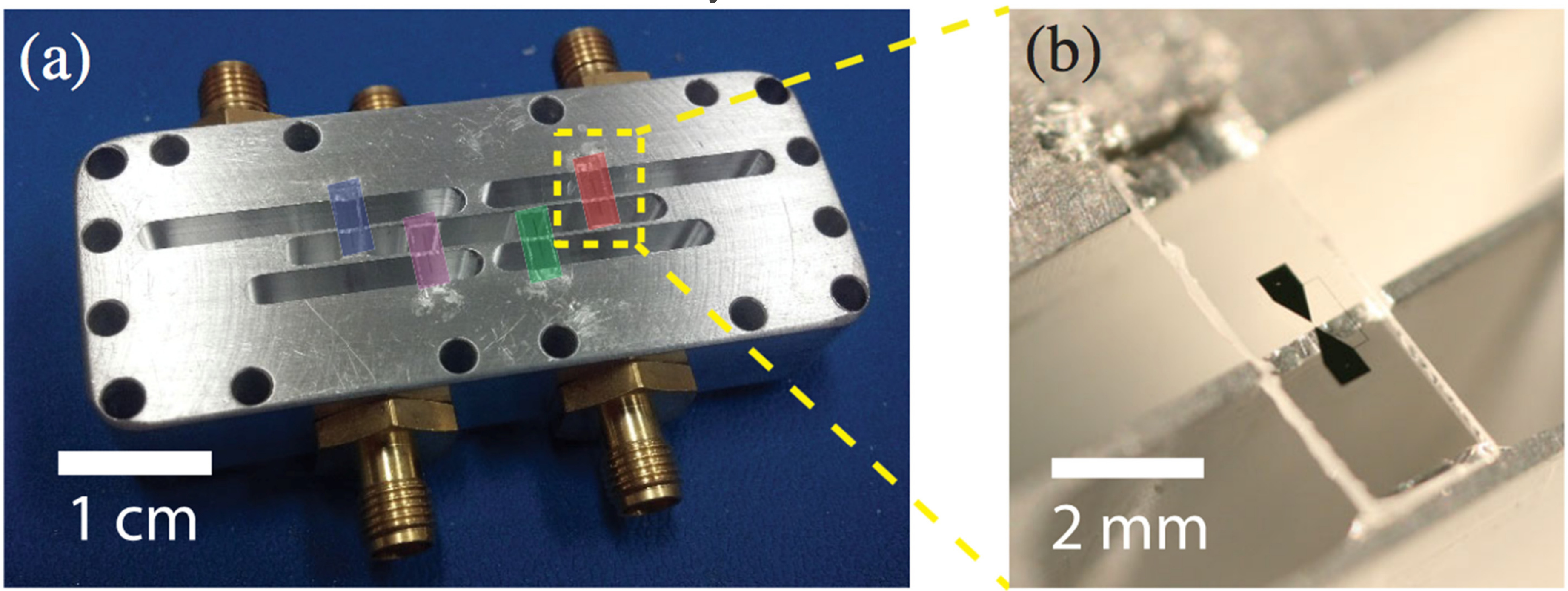


Simulations by:
A. D. Hernández and D. Domínguez,
Phys. Rev. B **65**, 144529 (2002)

3D circuit QED architecture

State-of-the-art quality factors Q in ‘quantum computing’ are ~10^8

Machined Aluminum host cavity



H. Paik et al, Phys. Rev. Lett. 117, 251502 (2016)

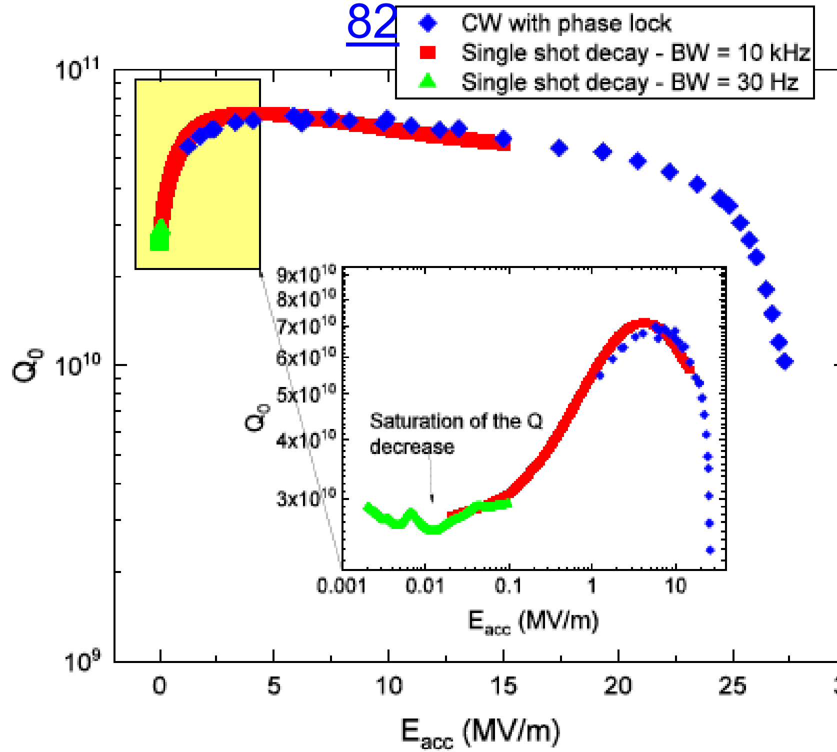
Towards quantum computing regime at FNAL SRF

- Need to demonstrate T = 20 mK and <N> ~ 1 photon high Q

BlueFors specialized refrigerator example

Now measured down to <N> ~ 10^{10} photons

A. Romanenko
https://arxiv.org/abs/1705.05982



Good news: low field Q saturates at Q~**3 x 10^{10}**

Conclusions

- Superconducting RF technology for particle accelerators have come a long way but still have huge and unexplored potential
- SRF technology state of the art cavities have gradients up to 50 MV/m and quality factors exceeding 5e10 at 2K, 1.3 GHz, 2e11 at 1.5K, 2e10 at 4.2K (Nb3Sn)
- SRF is now at the beginning of a new phase. The next factor of 2-3 will require a strong focus on:
  - Physics of SRF surface (material science tools)
  - As much involvement as possible of superconductivity theory experts with strong ties to technology centers/labs (ex. FNAL-Northwestern Univ CAPST)
- Long term to focus on: what is the ultimate limit for achievable gradients and Q? Can we go to 100 MV/m or more? We need to understand the ultimate limitations and explore pathways forward
- Pathway forward will be challenging, but rewarding

Thanks to Fermilab SRF Team Effort

- > 100 people with world leading SRF expertise, techs, engineers, scientists
- World class SRF facilities
- International collaborations with several institutions