



Recent Advance in SRF Cavity Technologies

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02-Sep-2019

NAPAC2019

Outline

- Introduction to SRF cavities
- State-of the art surface treatments
- Toward a better understanding
 - BCS surface resistance: new insights and optimization
 - Residual resistance: understanding and minimizing degradation due to trapped flux
- Technology improvement for SRF-based projects
- Conclusions

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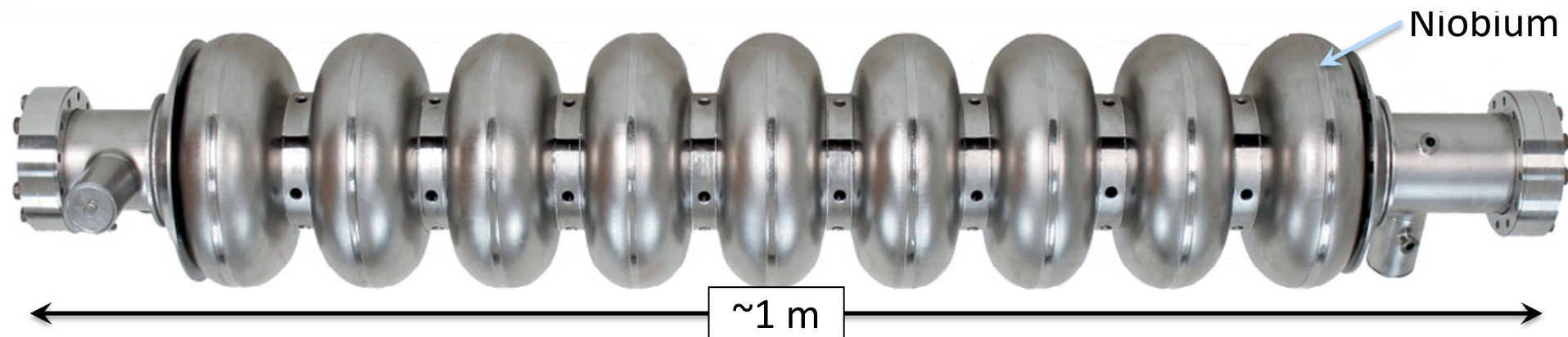
Particle Acceleration via SRF Cavities

- Superconducting Radio-Frequency (SRF) cavities are electro-magnetic resonators characterized by **very low power dissipation**
- The electric field provide acceleration to charged particles



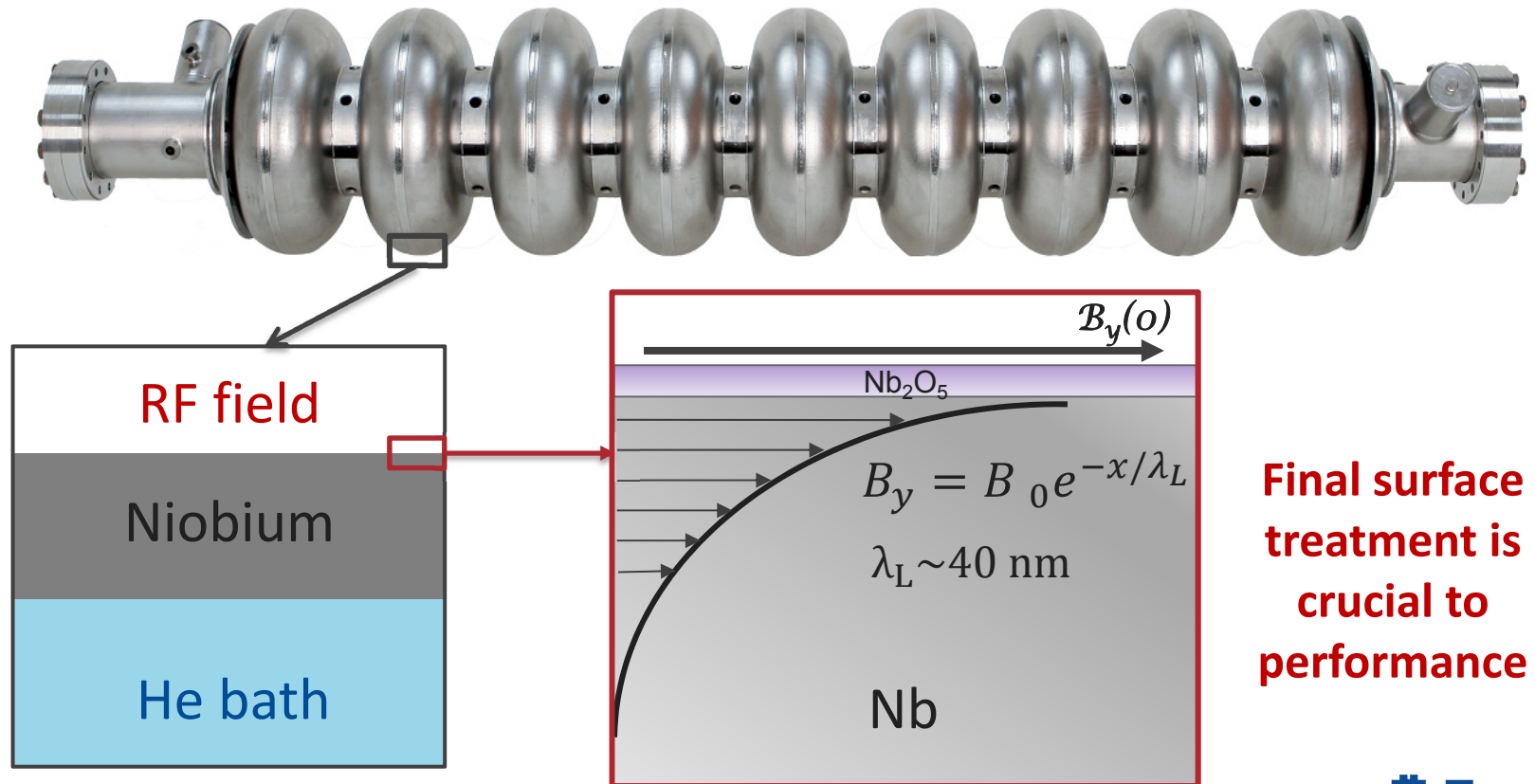
Input RF power at 1.3 GHz

Slowed down by factor of approximately 4×10^9

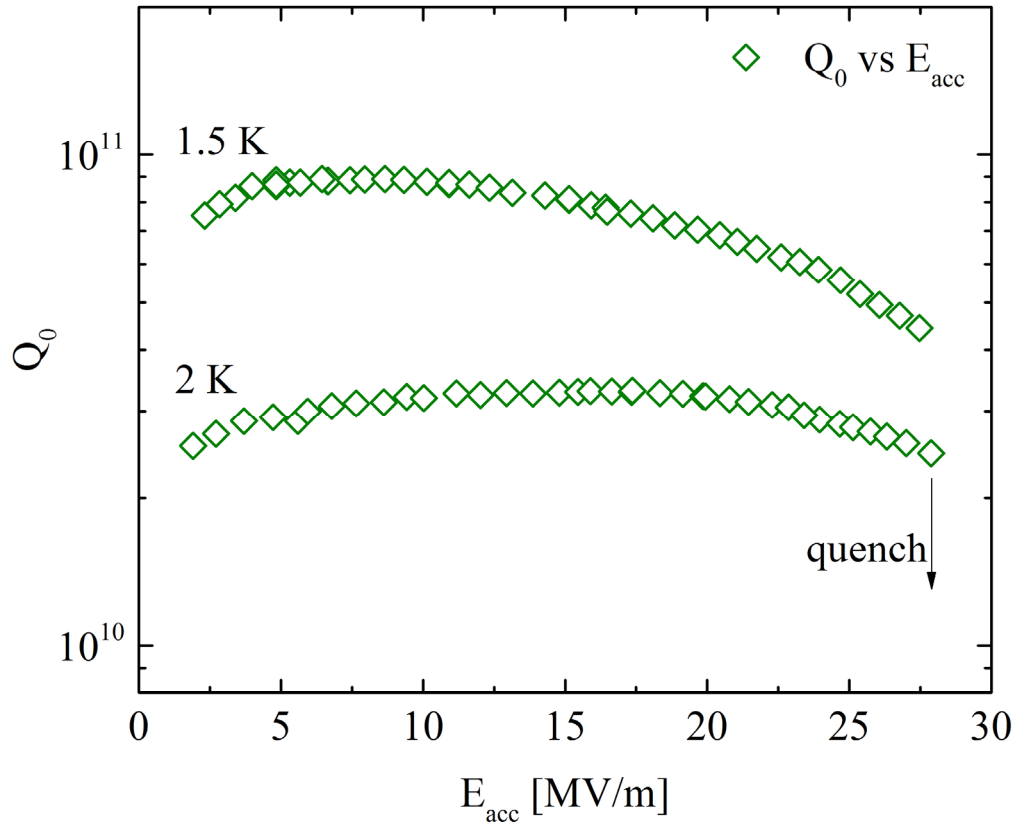


Superconducting RF Cavities

- Niobium ($T_c=9.2$ K), T operation 2 - 4.5 K
- RF surface resistance $\rightarrow$ fighting against $n\Omega$
- Losses concentrate on the first ~ 100 nm of the **inner surface**



SRF Cavities figure of merits: Q_0 vs E_{acc}



Q-factor (Q_0):

$$Q_0 = \frac{G}{R_s} = \frac{\omega_0 U}{P_d}$$

High $Q_0 \rightarrow$ lower power consumption.
Limited by $n\Omega$ of surface resistance.

Accelerating field (E_{acc}):

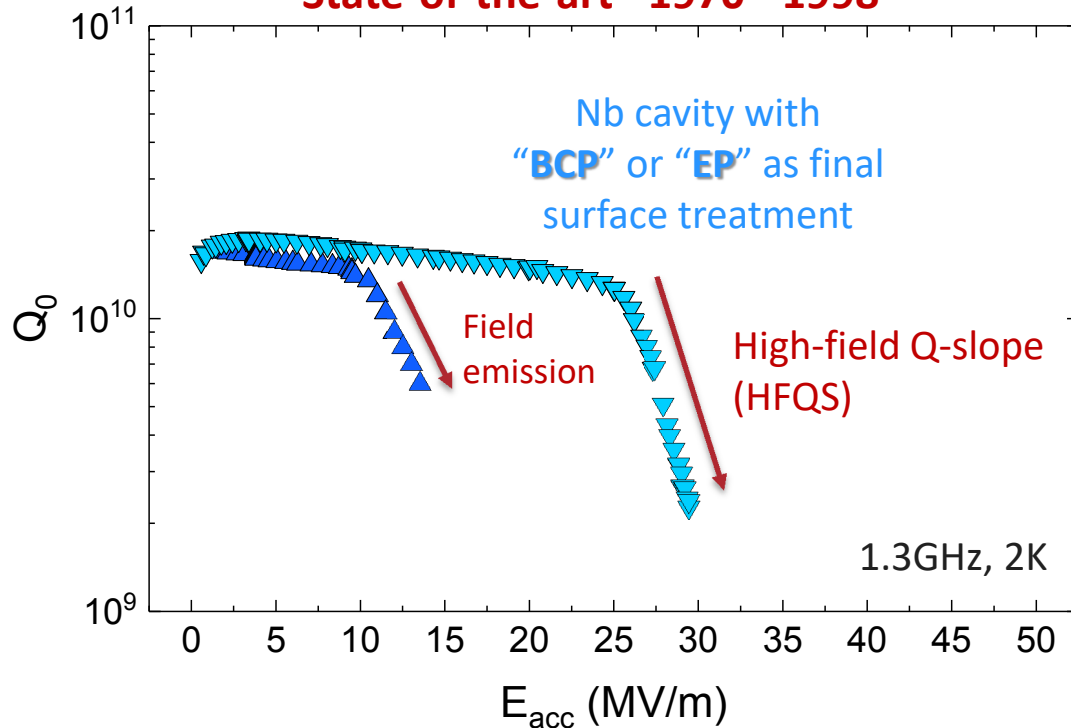
Determine the energy transferred to
charged particles.

High $E_{acc} \rightarrow$ lower accelerator length.
Limited by quench of the SC state.

High Q at high gradients may reduce both **capital and operational costs** of accelerators

Historical progress of SRF technology

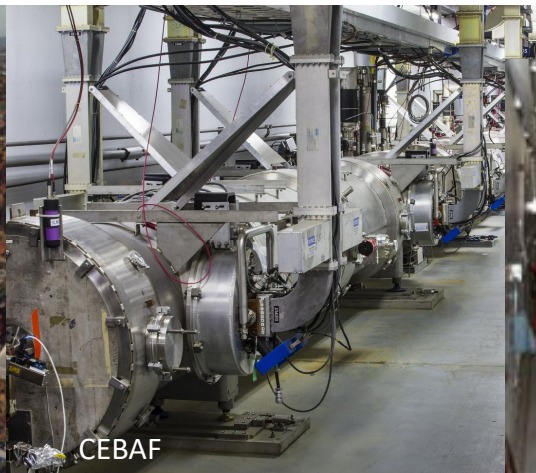
State-of-the-art ~1970 - 1998



BCP=Buffer chemical polishing
EP=Electro-polishing

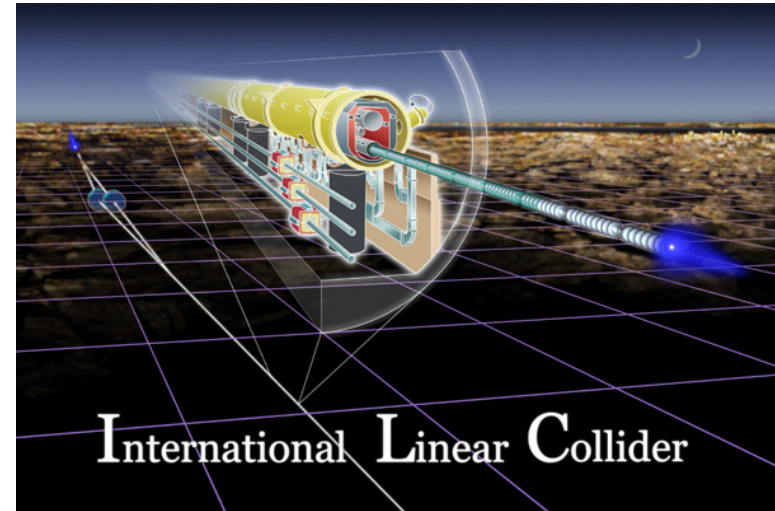
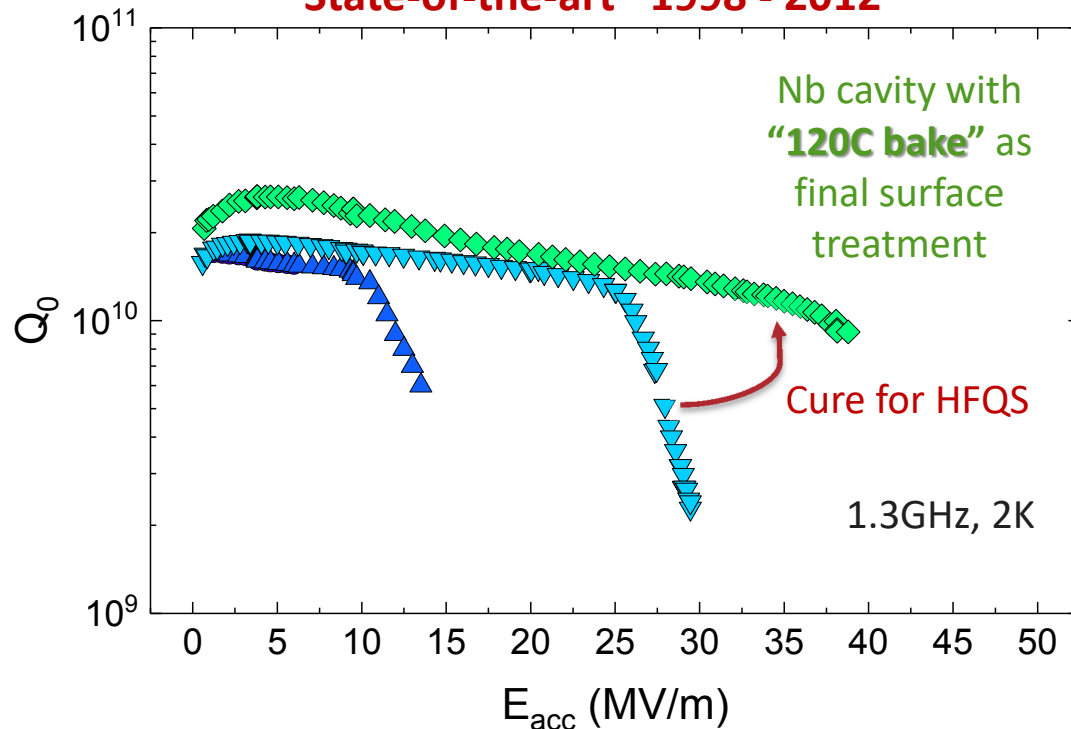
Enabled first SRF-based particle accelerators:

- **CEBAF**
- **CESR**
- **TRISTAN**
- **HERA**
- **SNS**
- ...



Historical progress of SRF technology

State-of-the-art ~1998 - 2012



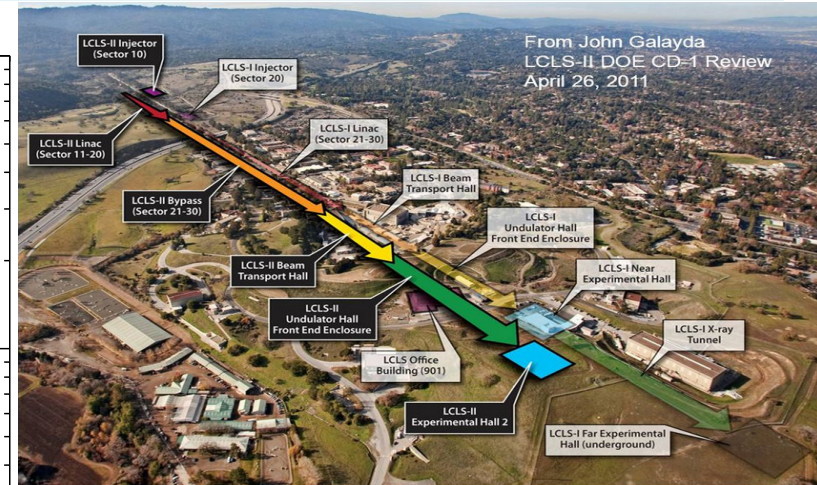
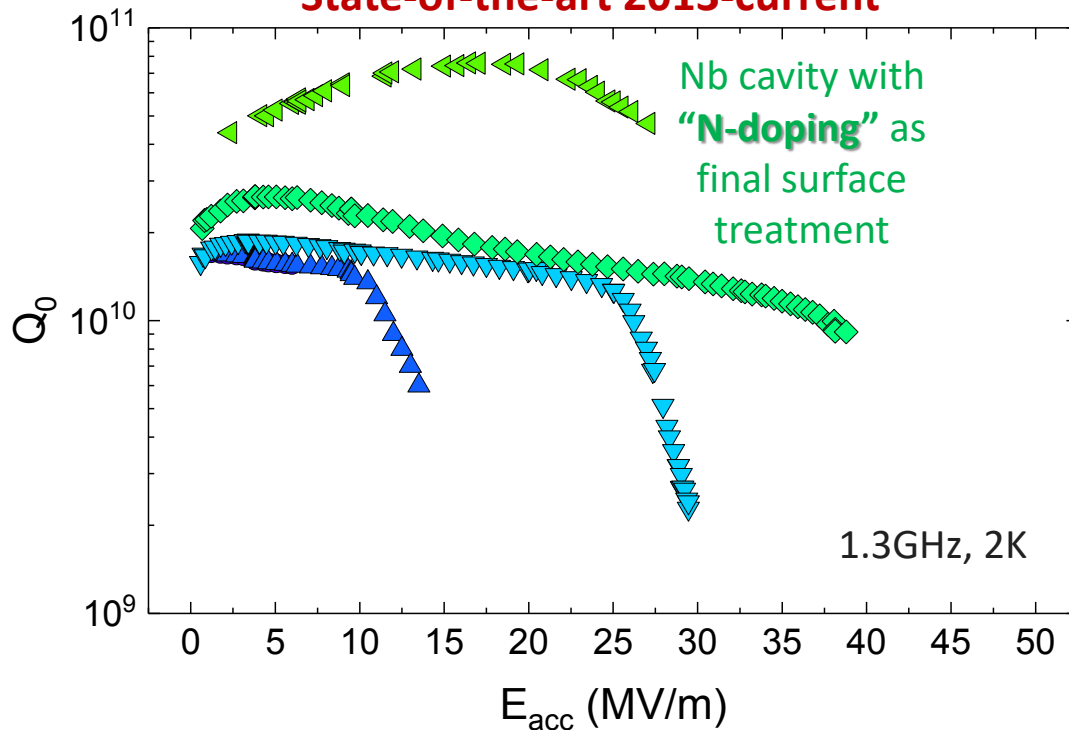
Enabled big SRF-based projects (LINAC):

- **ILC – 500 GeV** (16,000 Nb cavities)
 $Q = 1 \cdot 10^{10}$ at 31.5 MV/m
- **E-XFEL – 17.5 GeV** (816 Nb cavities)
 $Q = 1 \cdot 10^{10}$ at 23.6 MV/m

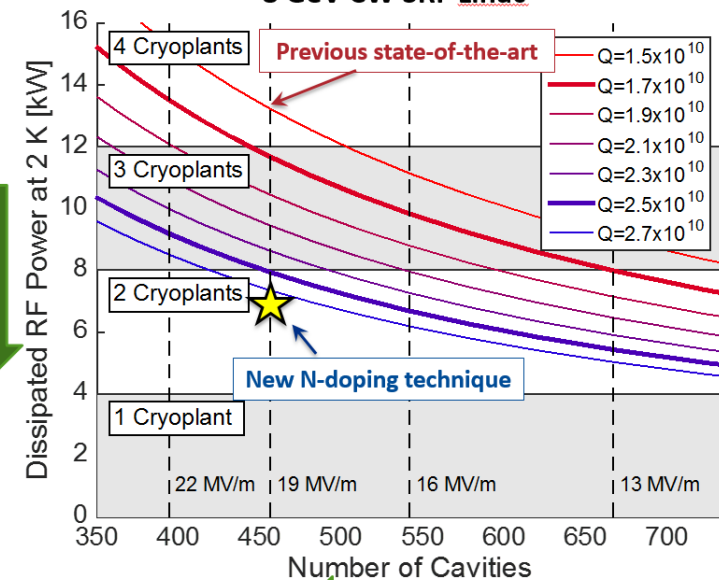


Historical progress of SRF technology

State-of-the-art 2013-current



8 GeV CW SRF Linac

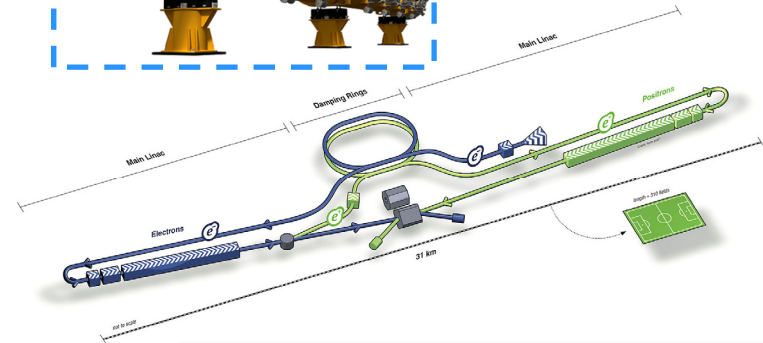
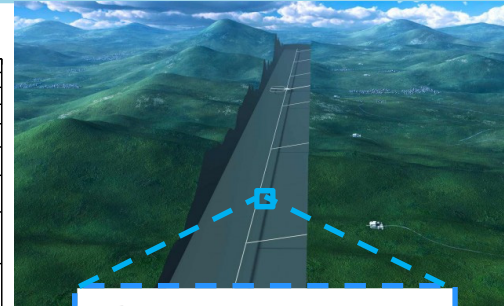
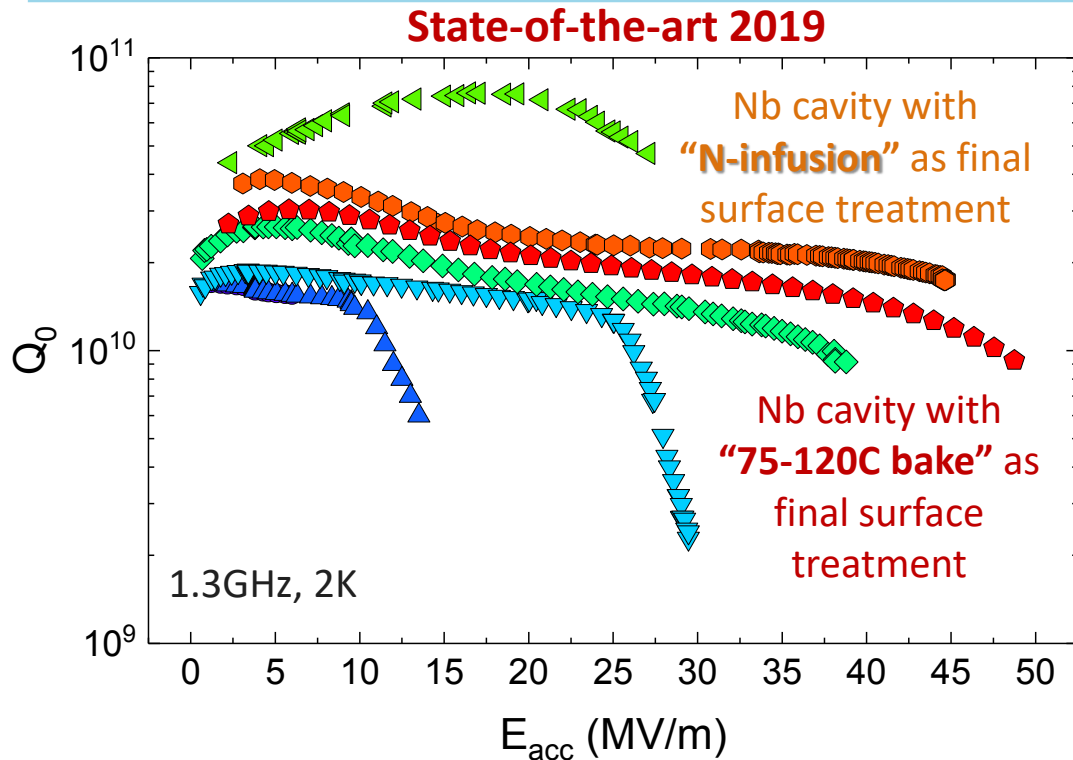


Enabled affordable CW operation:

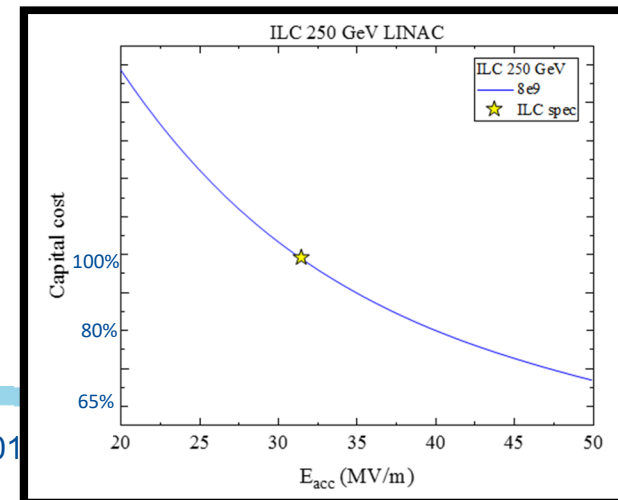
- LCLS-II
- LCLS-II HE
- PIP-II
- ...



Historical progress of SRF technology



N-infusion and *75-120C bake* enable significant cost reduction for high gradient machines like **ILC**, **E-XFEL upgrade**, etc

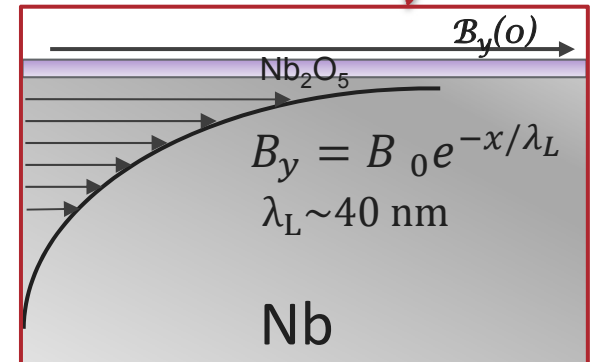
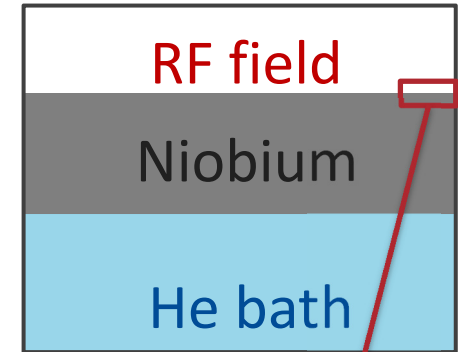
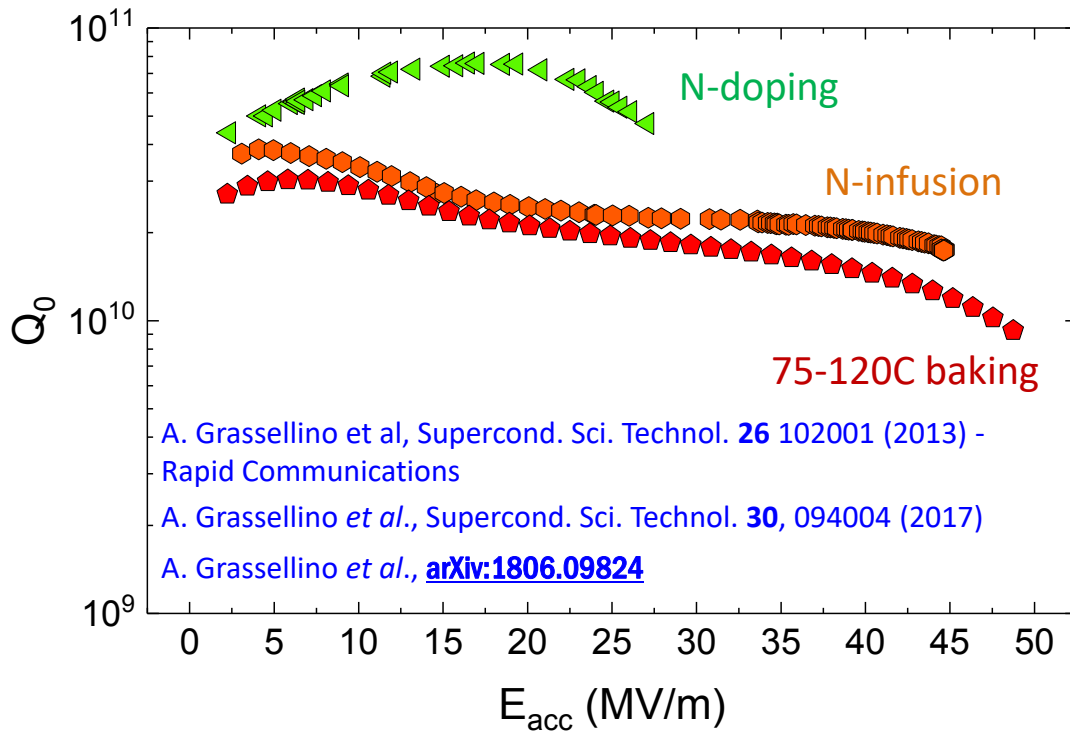


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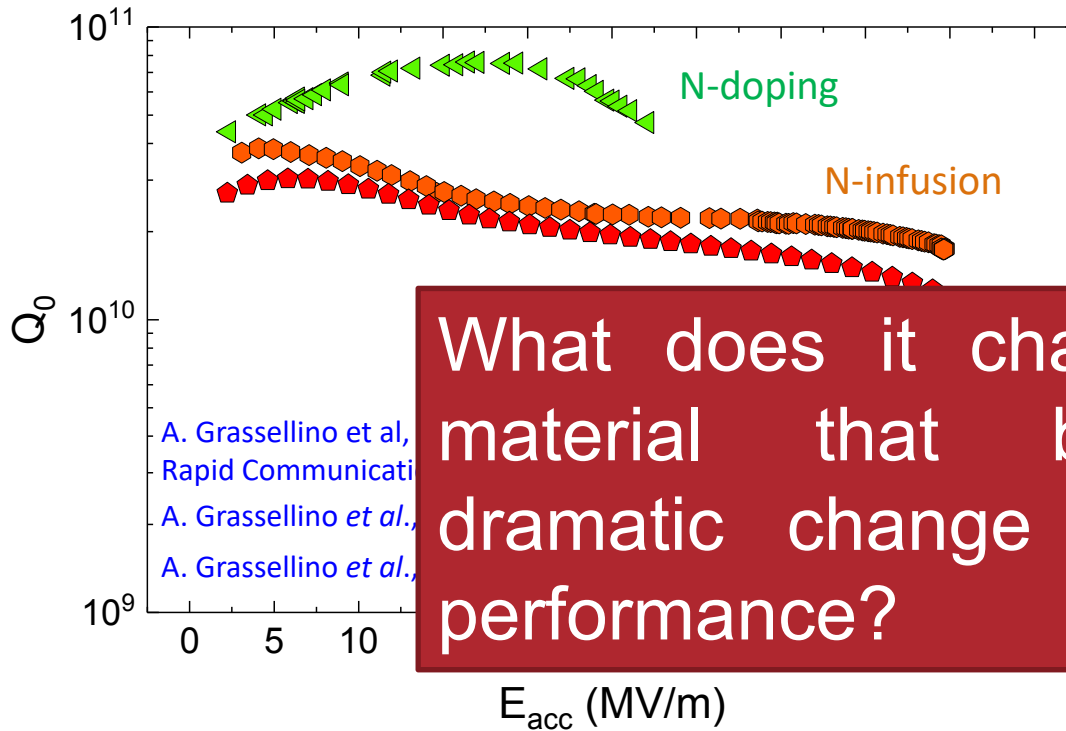
Historical progress of SRF technology

Current state-of-the-art

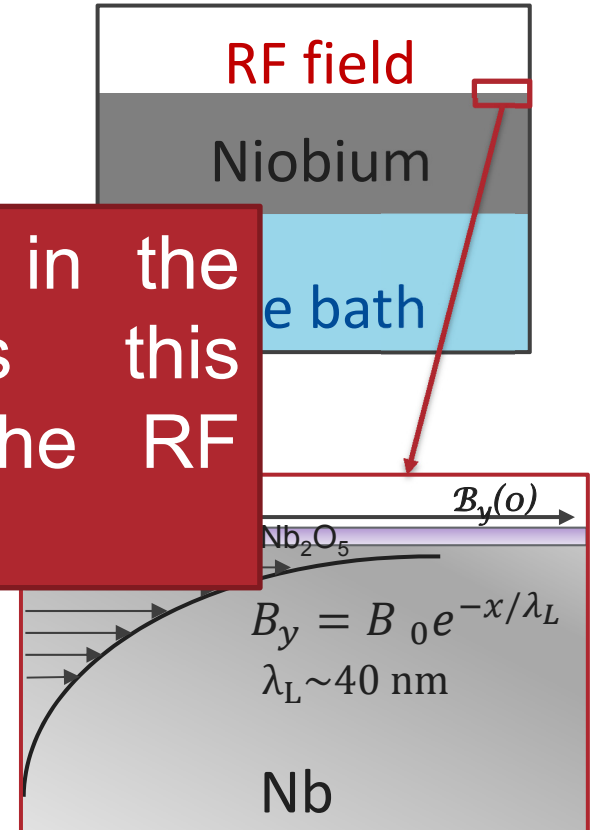


Historical progress of SRF technology

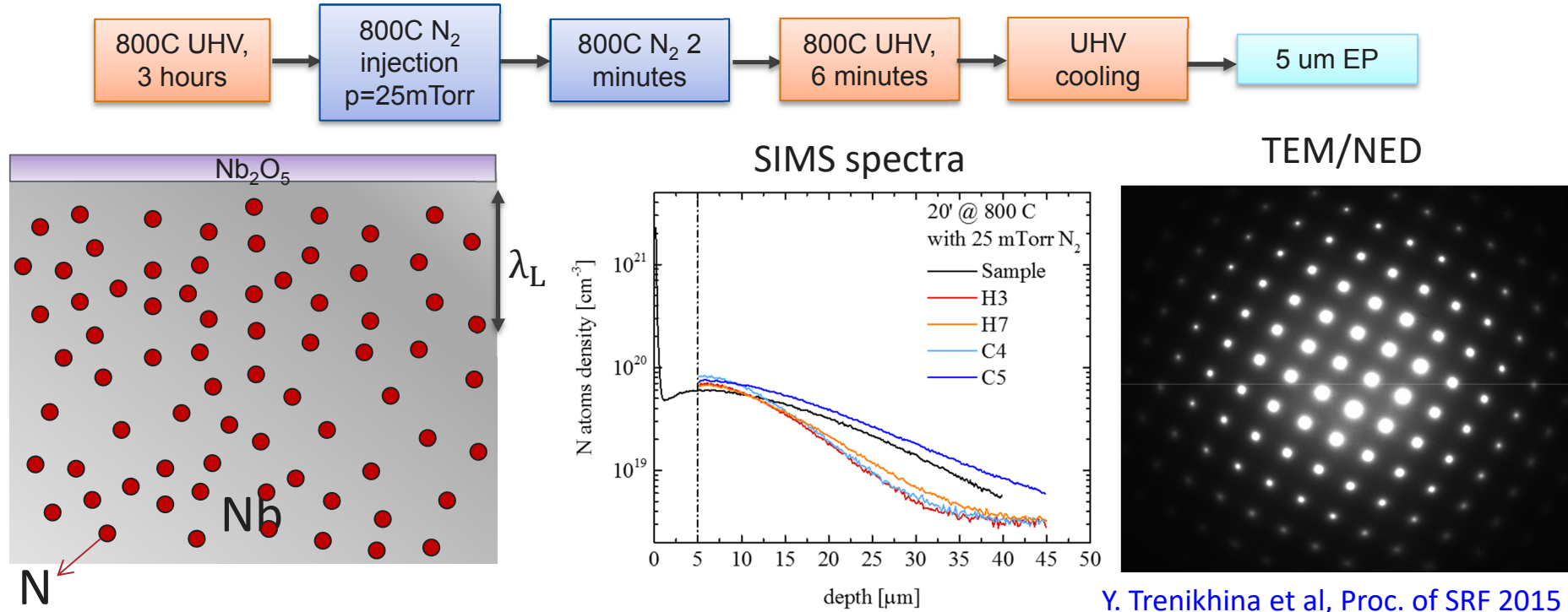
Current state-of-the-art



What does it change in the material that brings this dramatic change in the RF performance?



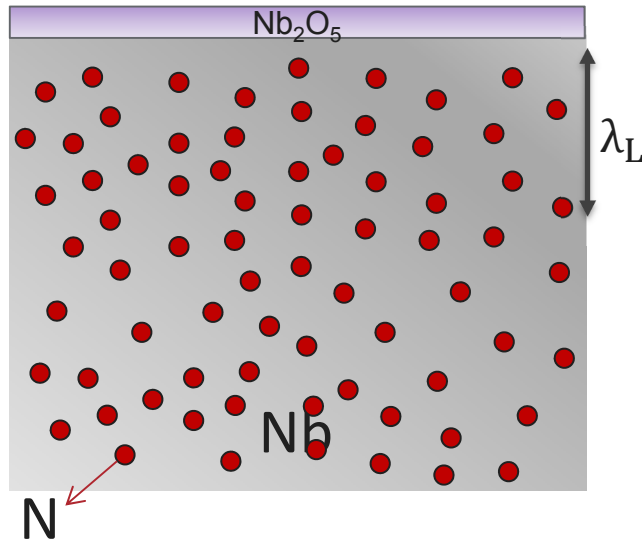
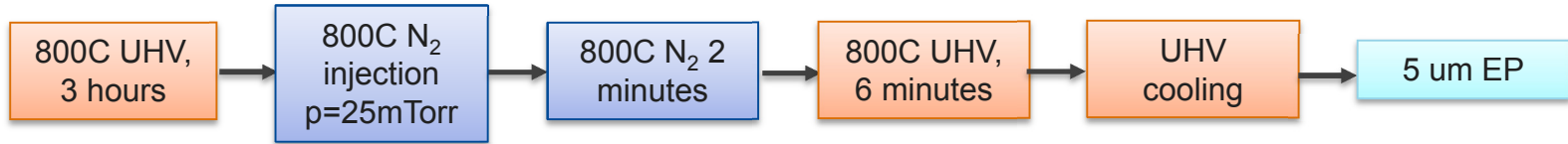
N-doping



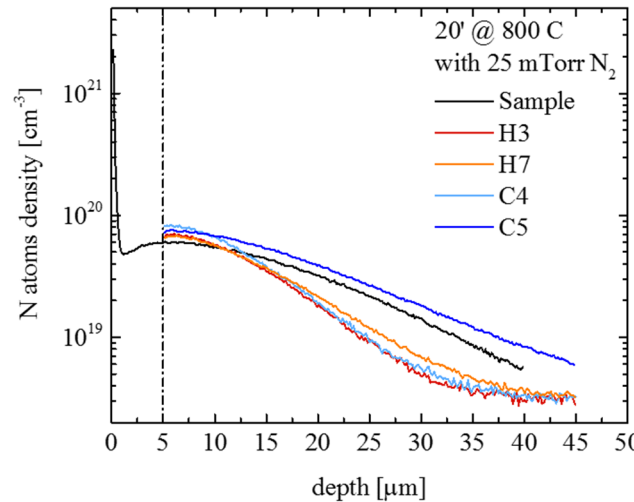
Y. Trenikhina et al, Proc. of SRF 2015

- SIMS spectra: nitrogen in the material for about tens of micrometers
- TEM/NED: only Nb signal from diffraction pattern

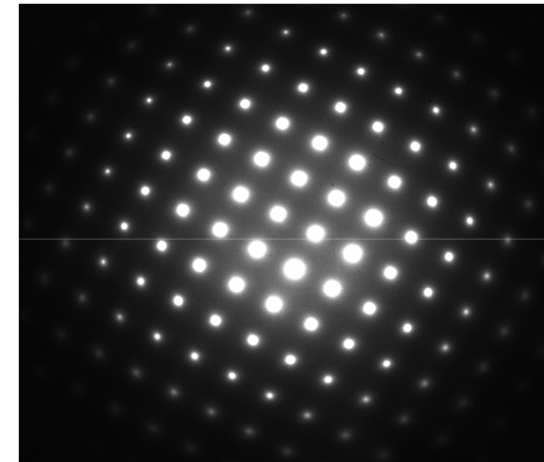
N-doping



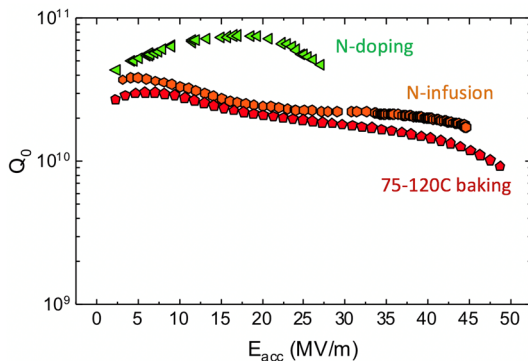
SIMS spectra



TEM/NED

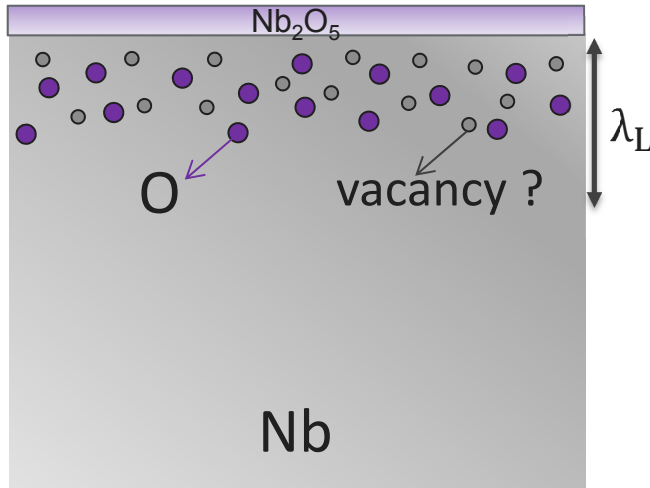


Y. Trenikhina et al, Proc. of SRF 2015

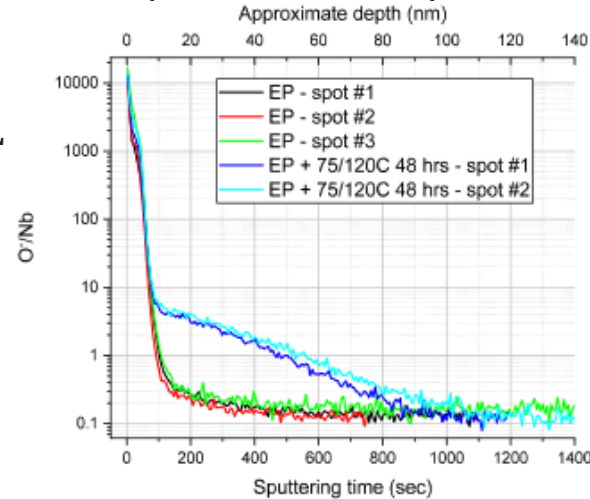


Boost in Q-factors due to presence of interstitial N, constant through the penetration depth

75-120C baking



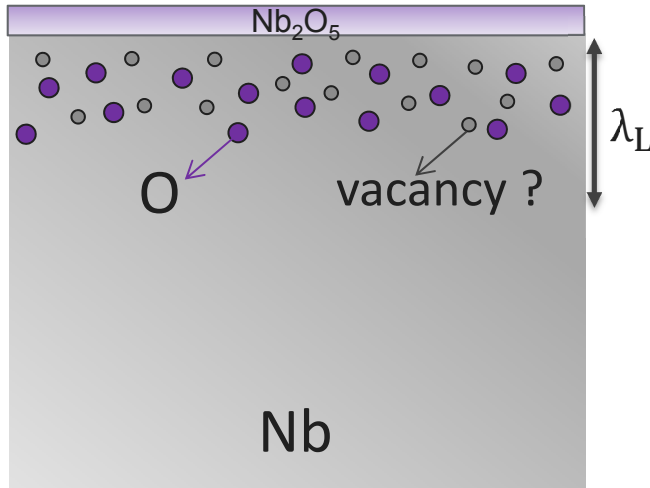
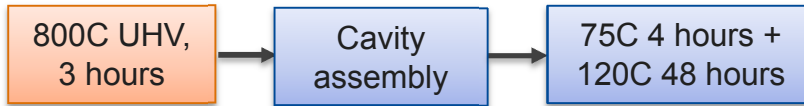
SIMS spectra of cavity cut-outs



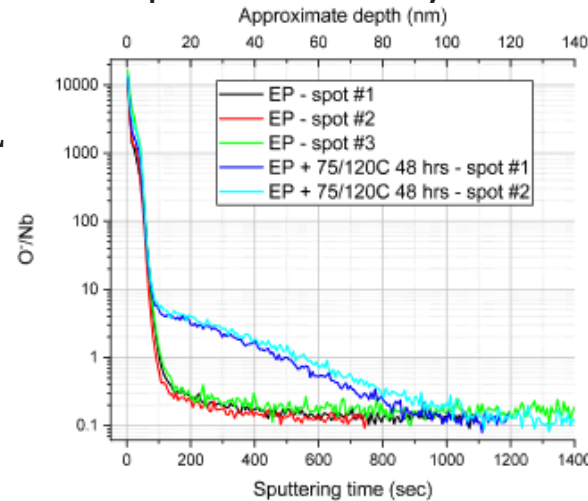
A. Romanenko *et al.*, Proc. of SRF 2019

- SIMS spectra: oxygen in the material for about tens of nanometers

75-120C baking

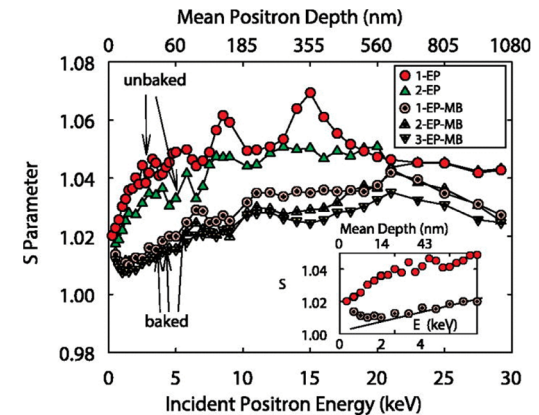


SIMS spectra of cavity cut-outs



A. Romanenko *et al.*, Proc. of SRF 2019

Positron annihilation in 120C baked samples

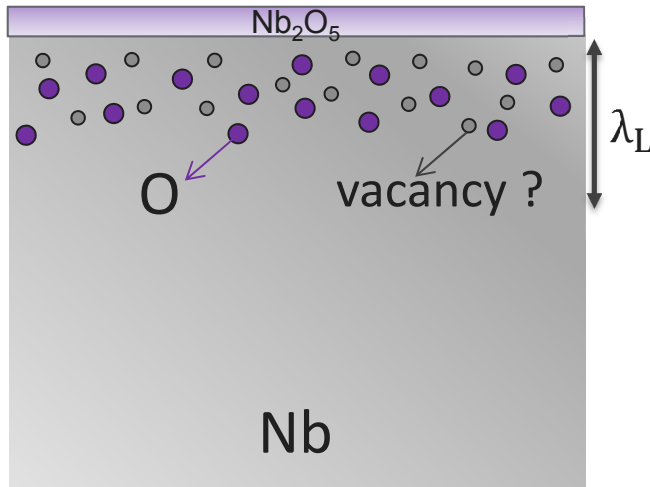


A. Romanenko *et al.*, Appl. Phys. Lett. 10, 232601 (2013)

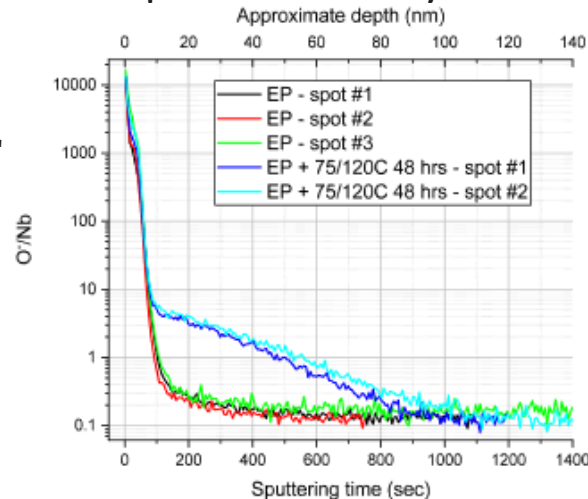
- SIMS spectra: oxygen in the material for nanometers

Positron annihilation studies show possible presence of vacancy-hydrogen complexes in 120C bake samples, in the first nanometers

75-120C baking

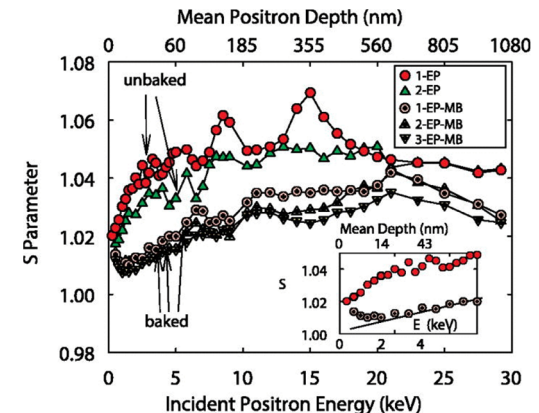


SIMS spectra of cavity cut-outs



A. Romanenko *et al.*, Proc. of SRF 2019

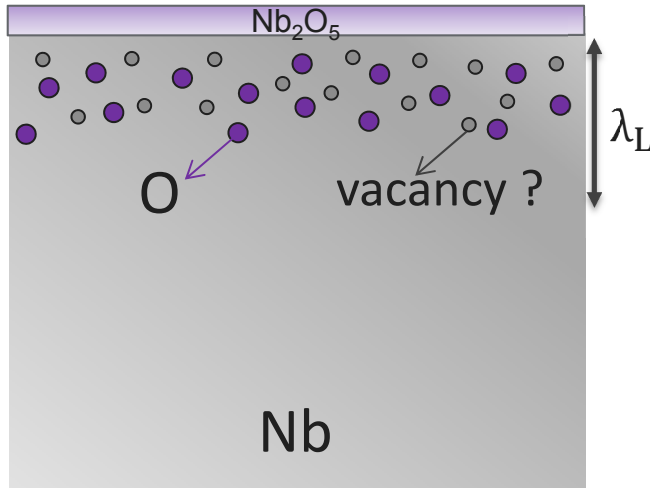
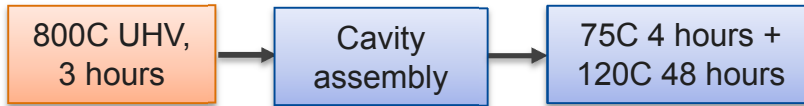
Positron annihilation in 120C baked samples



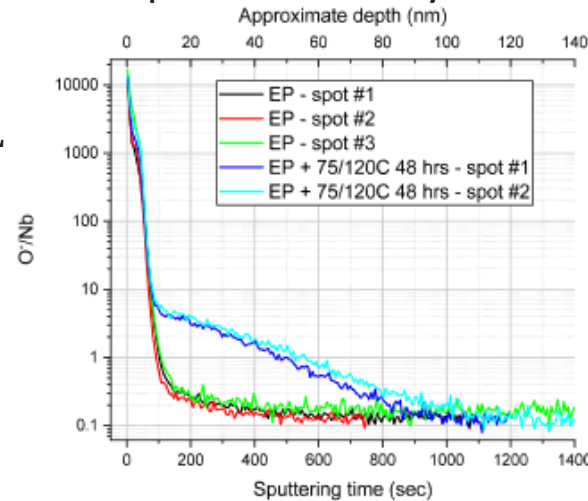
A. Romanenko *et al.*, Appl. Phys. Lett. 10, 232601 (2013)

- SIMS spectra: oxygen in the material for nanometers
 - Possibility of having vacancy-hydrogen complexes also after the 75-120C baking
- Positron annihilation studies show possible presence of vacancy-hydrogen complexes in 120C bake samples, in the first nanometers

75-120C baking

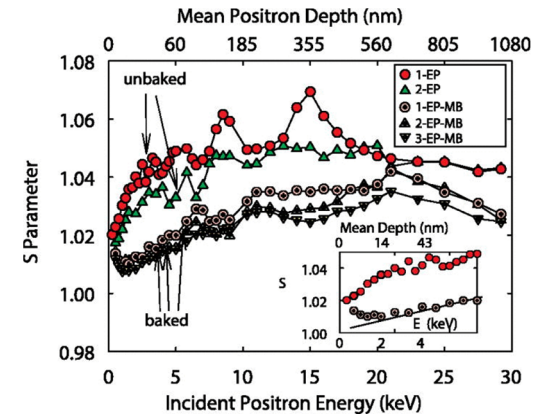


SIMS spectra of cavity cut-outs

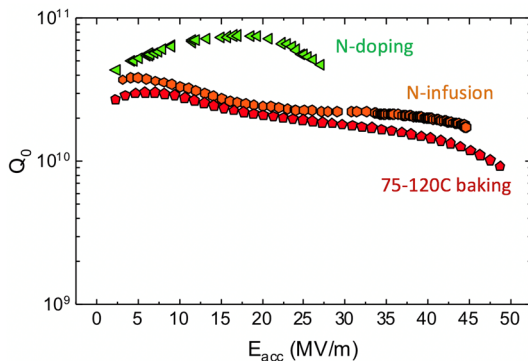


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Positron annihilation in 120C baked samples

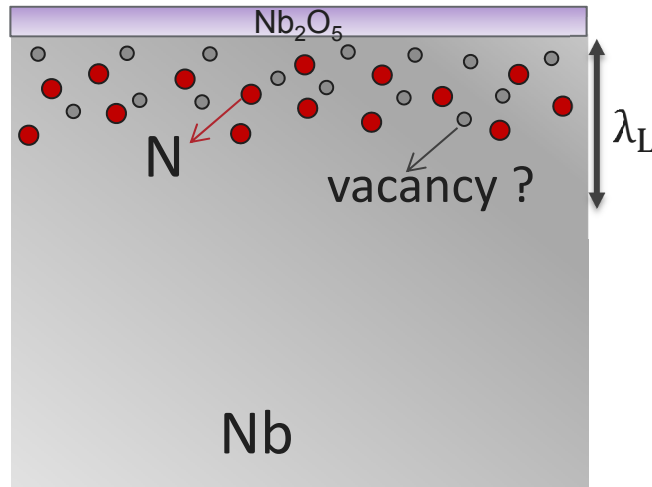
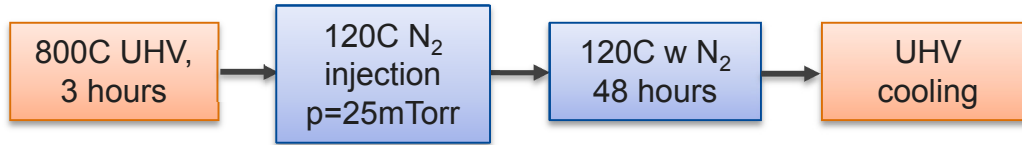


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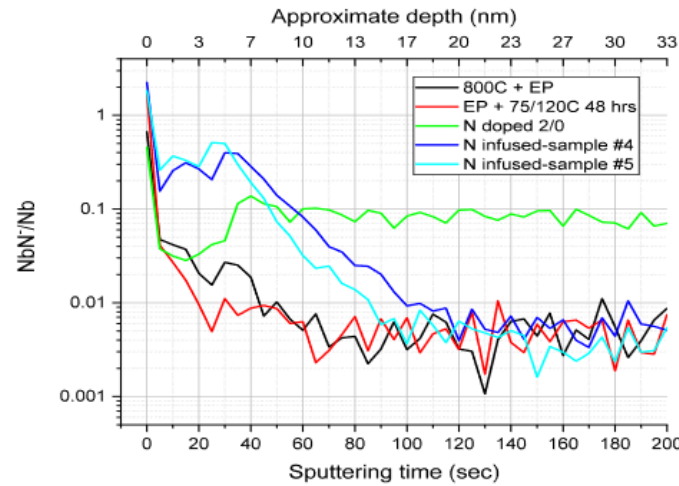


The E_{acc} improvement in 75-120C baked cavities most likely due to presence of impurities for a depth lower or comparable to the one of the penetration depth

120C N-infusion



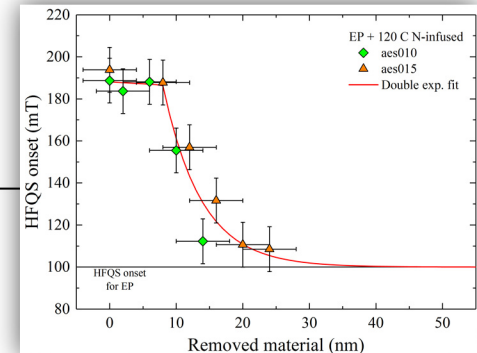
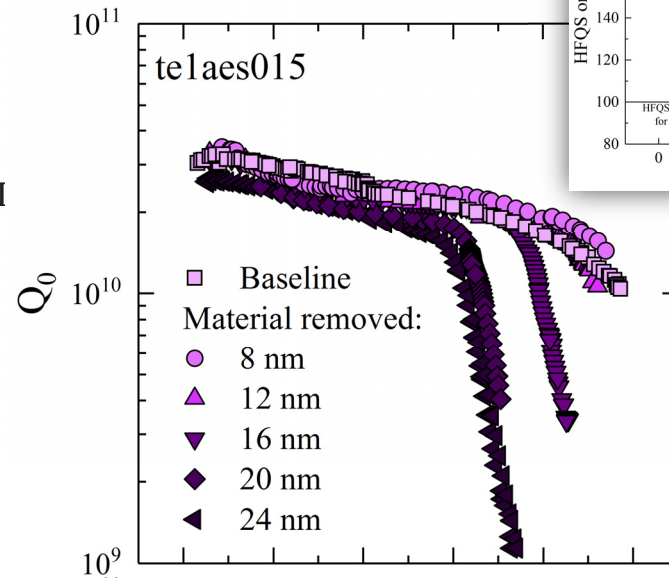
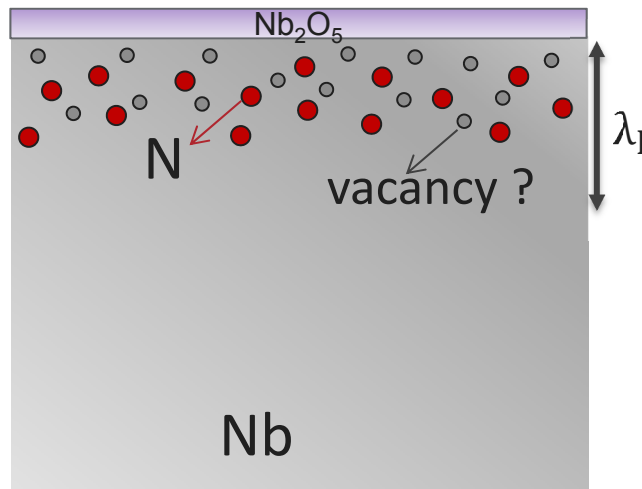
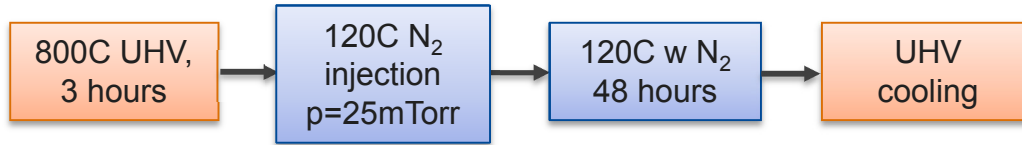
SIMS spectra of cavity cut-outs



A. Romanenko et al., Proc. of SRF 2019

- SIMS spectra: nitrogen in the material for about 10-15 nanometers
- Vacancy-hydrogen complexes present also after 120C N-infusion?

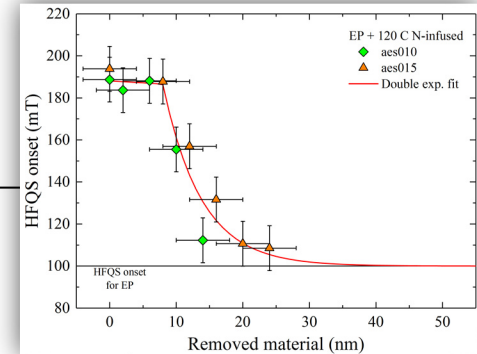
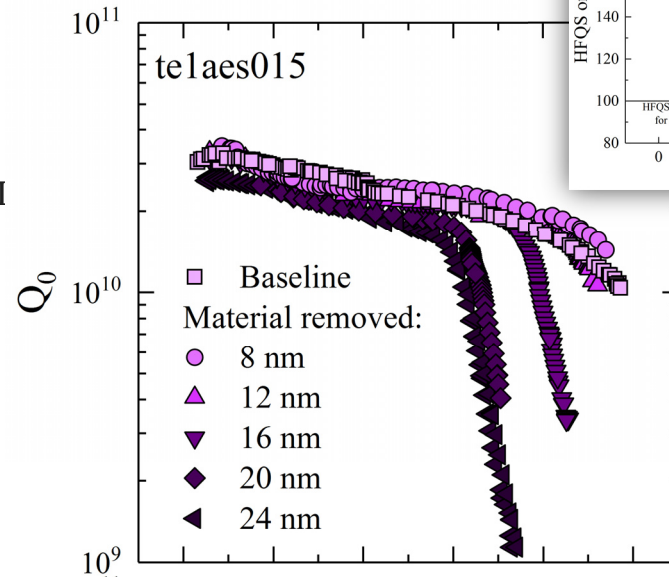
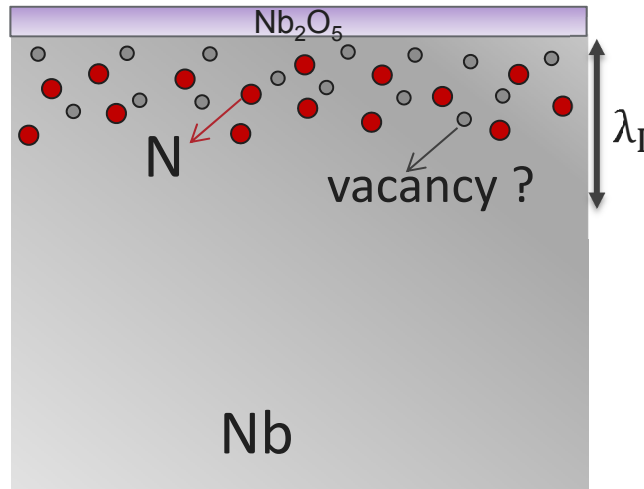
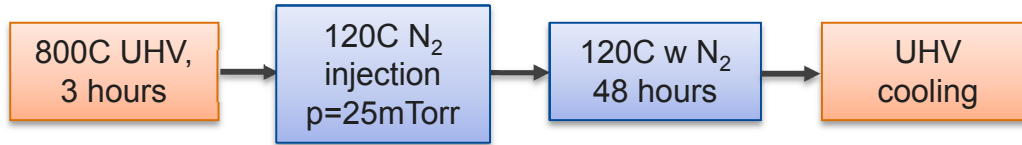
120C N-infusion



M. Checchin *et al.*,
Proc. of IPAC 2018

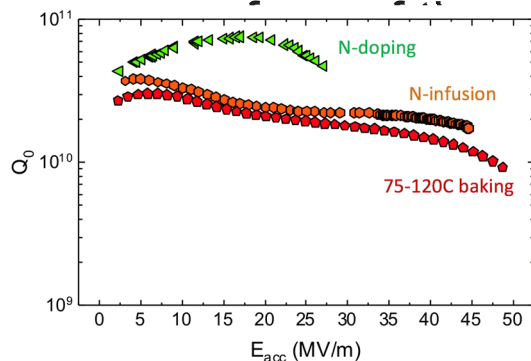
- HF rinses studies shows that the N-infusion process modifies only the surface of the material
- HFQS behavior is totally re-established after removing ~ 20 nm

120C N-infusion



M. Checchin *et al.*,
Proc. of IPAC 2018

- HF rinses studies shows that the N-infusion process modifies only the



The Eacc improvement of N-infused cavities must be connected to impurities within the first 15-20 nm (depth < penetration depth)

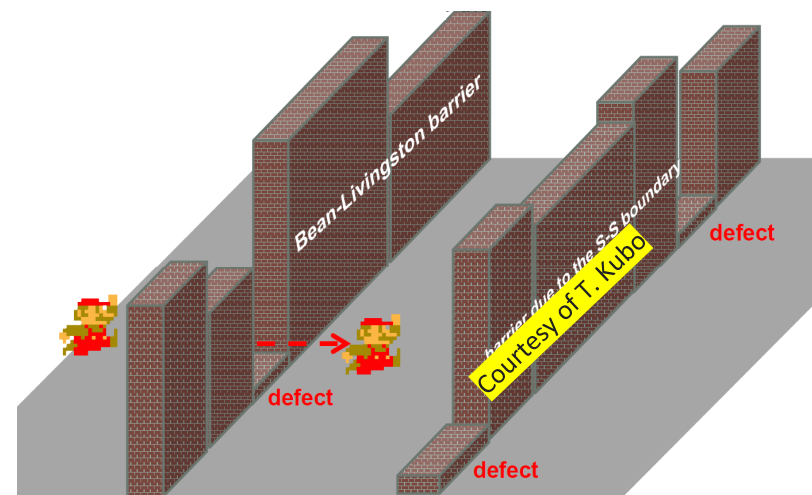
Theoretical explanation for quench field improvement

1. Calculations of the max field sustainable by the cavity in case of a layered S-S structure (dirty superconductor on top of a clean bulk superconductor):

- W. Ngampruetikorn et al., TTC Workshop, Fermilab, USA (2017)
- T. Kubo, TTC Workshop, CEA-Saclay, France (2016)
- T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017)
- M. Checchin et al., IPAC 2017

In all these theories, layered S-S structures may either add an energy barrier or enhance the Bean-Livingston barrier depending on the thickness:

- Vortex penetration is less favorable
- Vortex nucleation is less sensitive to defects at the surface

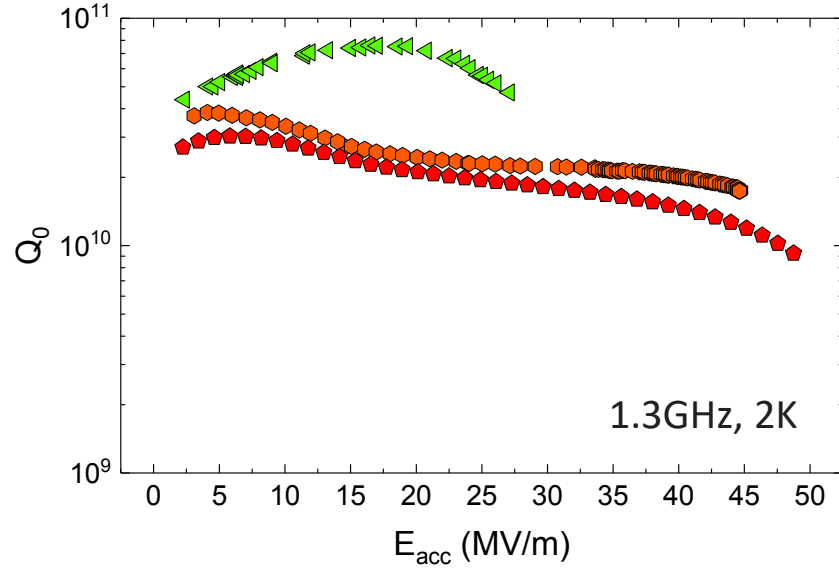


2. New idea: Vortex nucleation is governed by the characteristic time scale of order parameter changes, so-called τ_{Δ} . Presence of impurities may slower the e-ph scattering time (A. Romanenko et. Al, IPAC 2018 and SRF 2019)

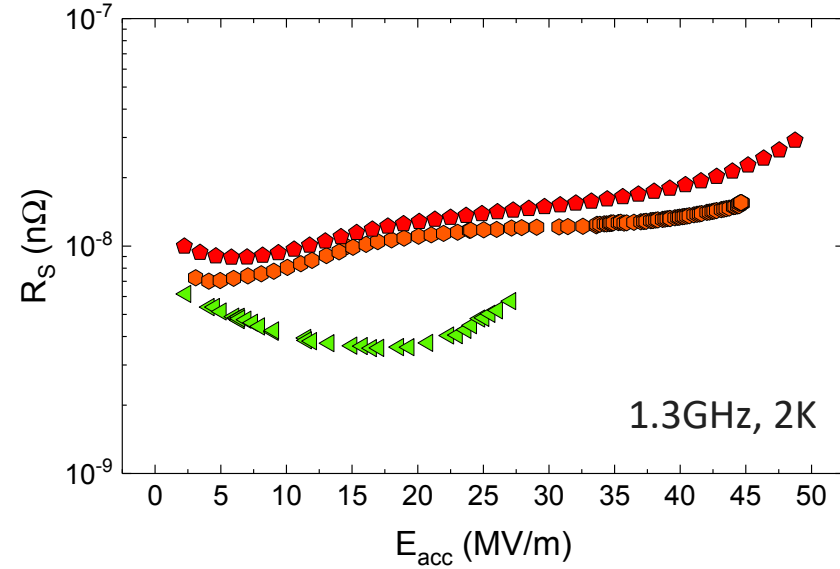
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The surface resistance



$$Q_0 = \frac{G}{R_s}$$

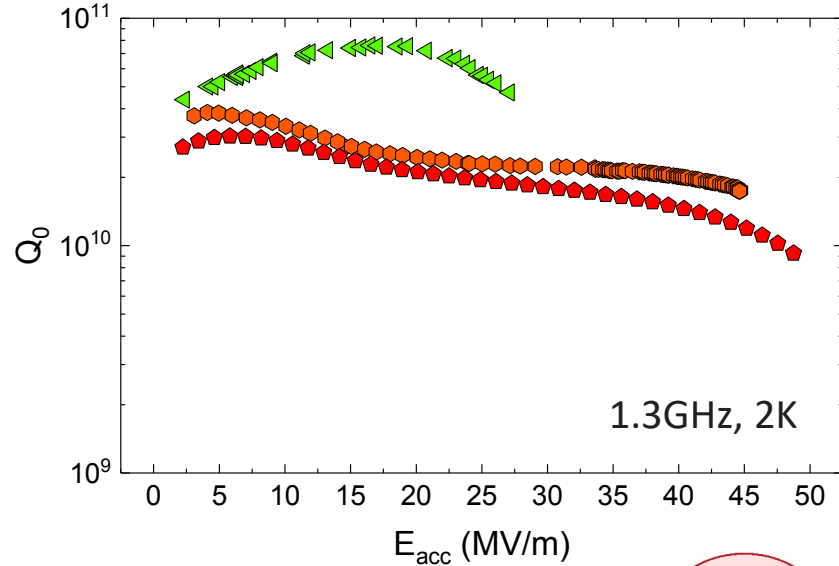


$$R_s = R_{BCS} + R_{fl} + R_0$$

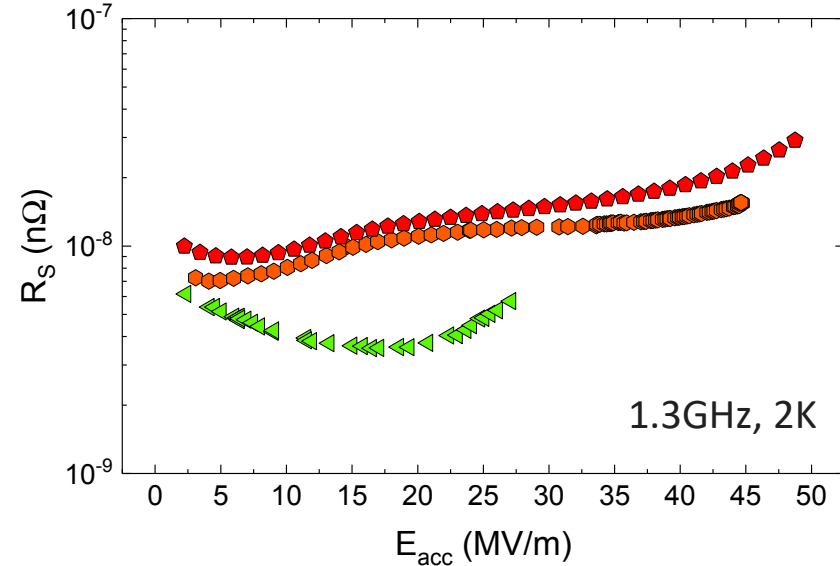
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The surface resistance

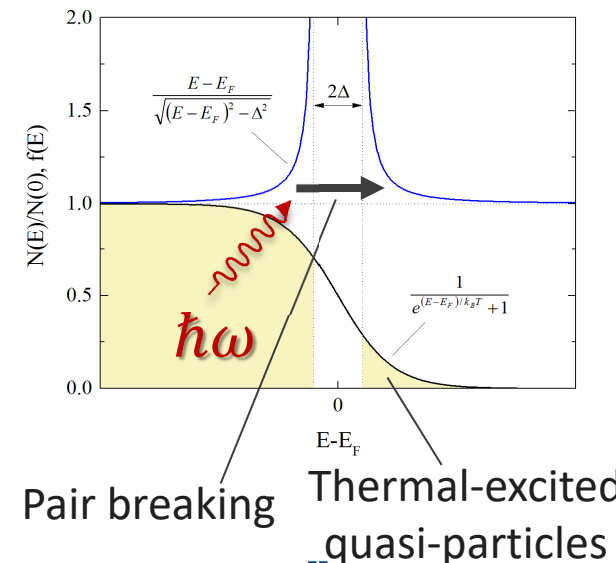


$$Q_0 = \frac{G}{R_s}$$



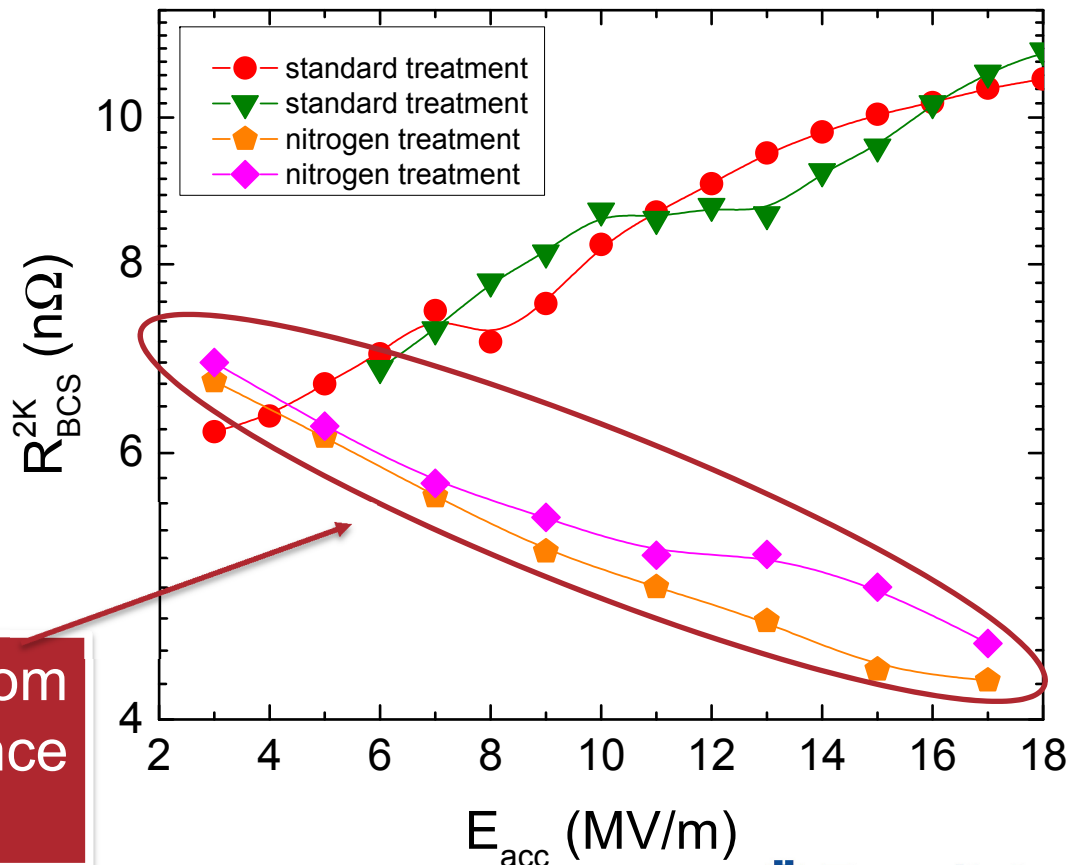
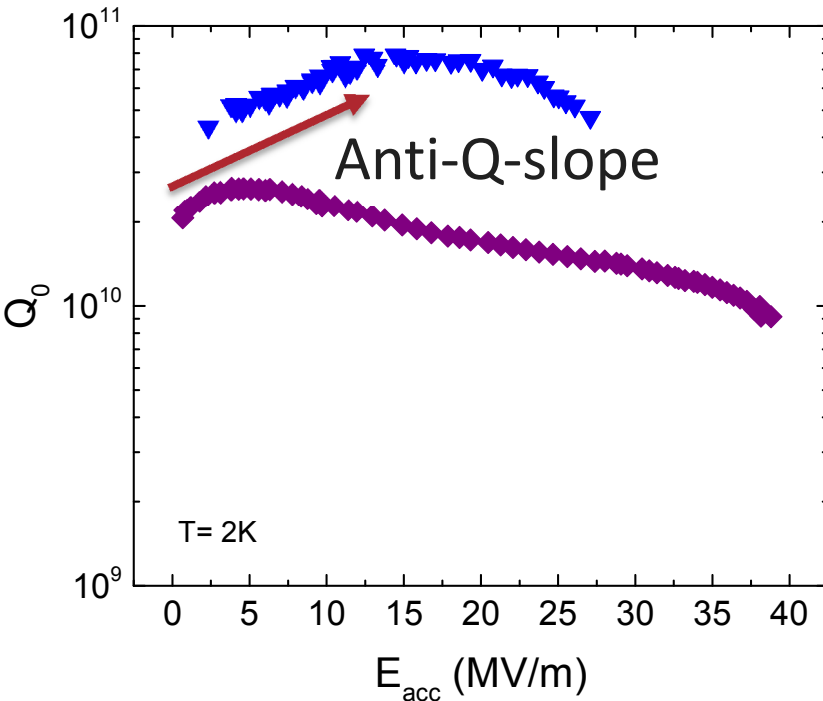
$$R_s = \underbrace{R_{BCS}}_{\text{BCS surface resistance}} + R_{fl} + R_0$$

- Dissipation due to thermally-excited quasi-particles (“normal-electrons”)
- Depends on temperature, normal-conducting and superconducting material parameters (mean-free-path, energy gap, penetration depth, etc)



First observation of R_{BCS} decreasing with field

$$R_S(2\text{ K}) = R_{BCS}(2\text{ K}) + R_0 + R_{fl}$$



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

Study of Cavities at Different Frequency

650 MHz



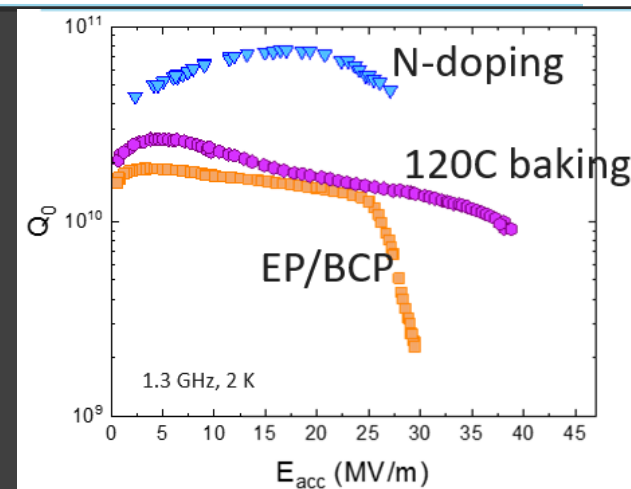
1.3 GHz



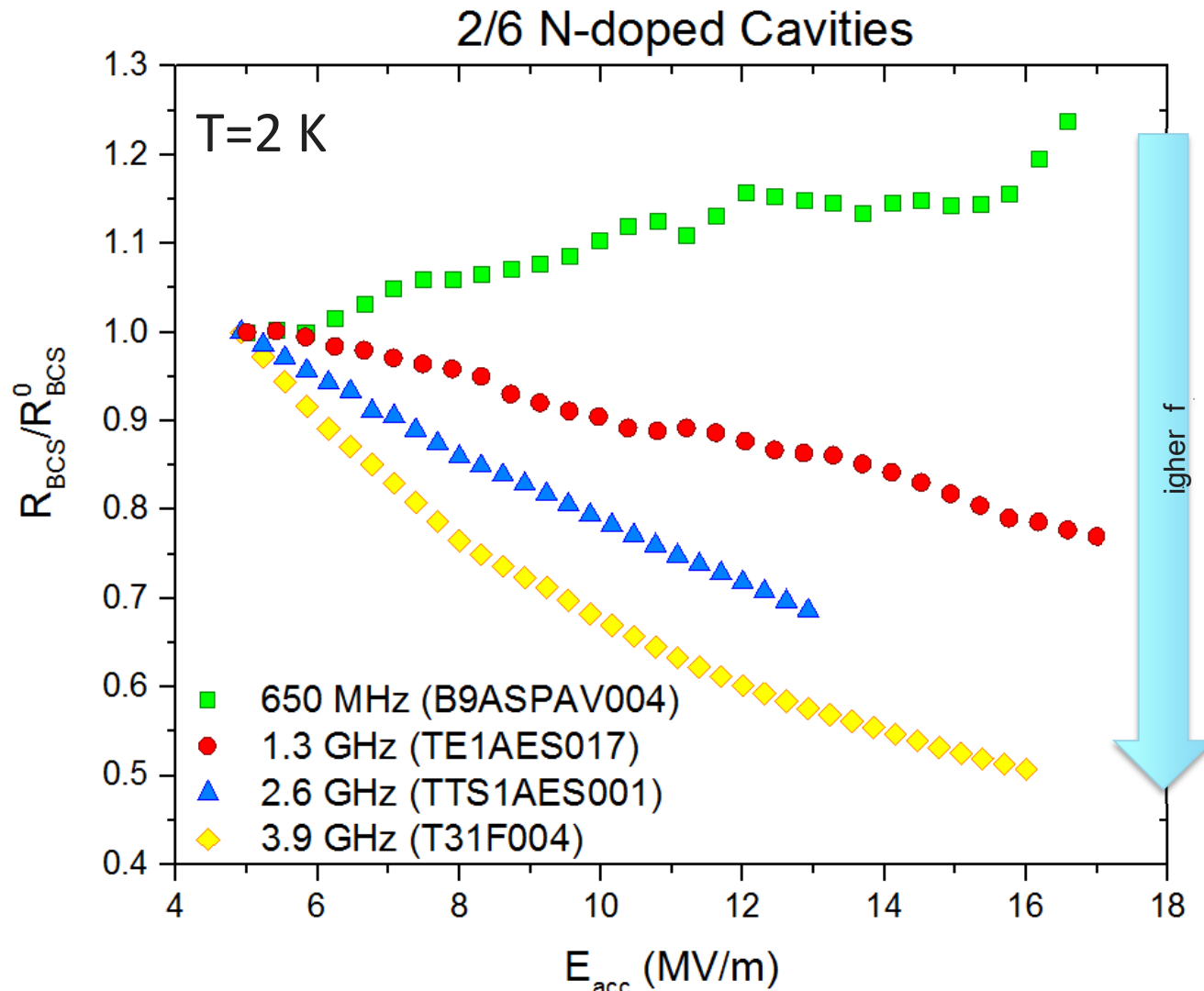
2.6 GHz



3.9 GHz

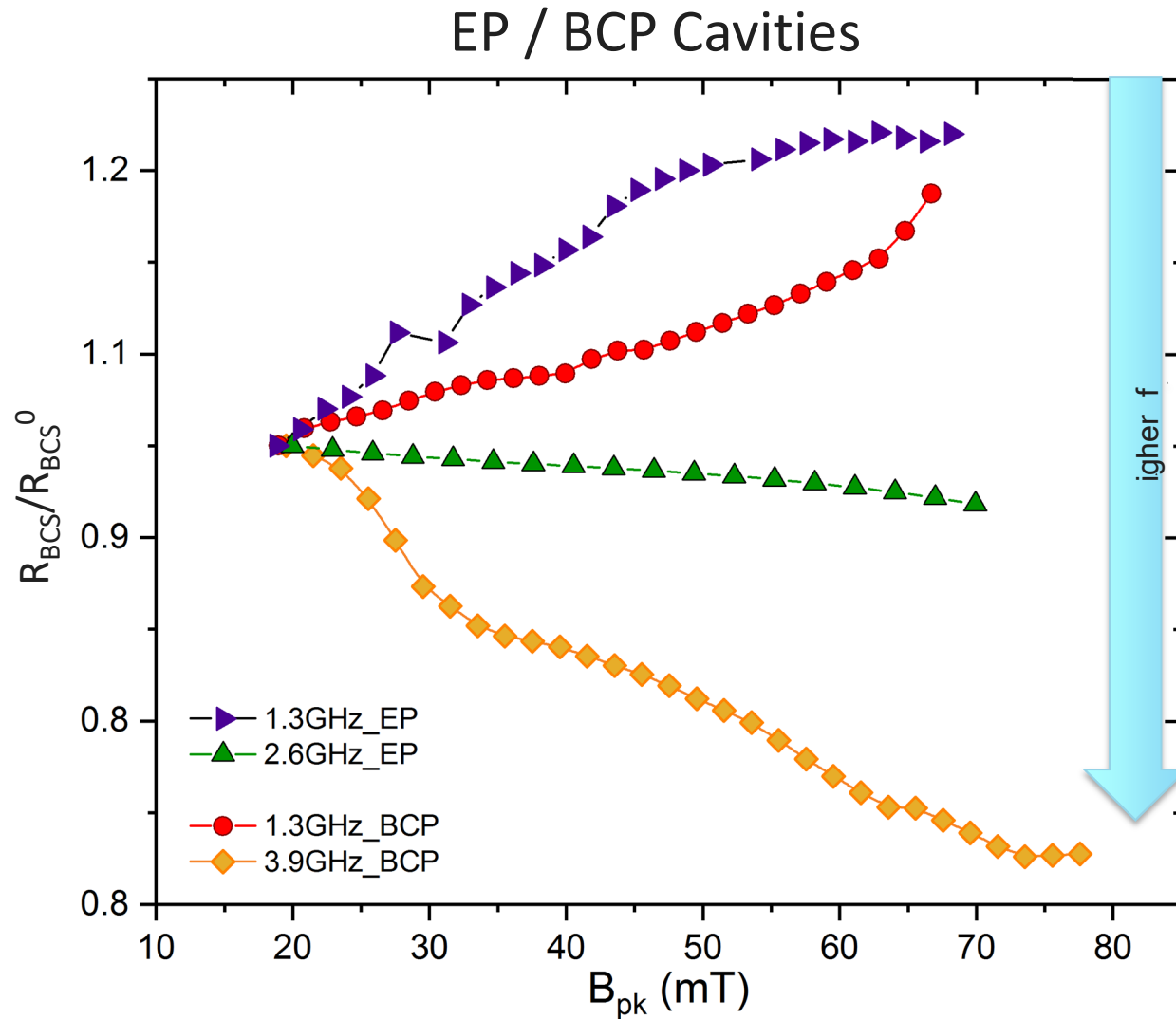


Frequency dependence of $R_{\text{BCS}}(E_{\text{acc}})$: toward a better understanding



M. Martinello *et al.*, Phys. Rev. Lett. 121, 224801 (2018)

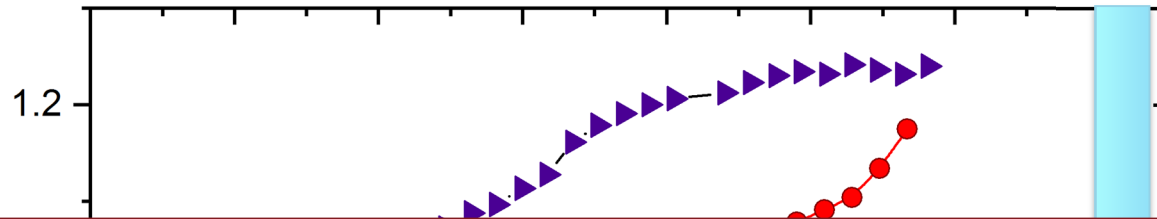
Summary of the Frequency Dependence of $R_{BCS}(E_{acc})$



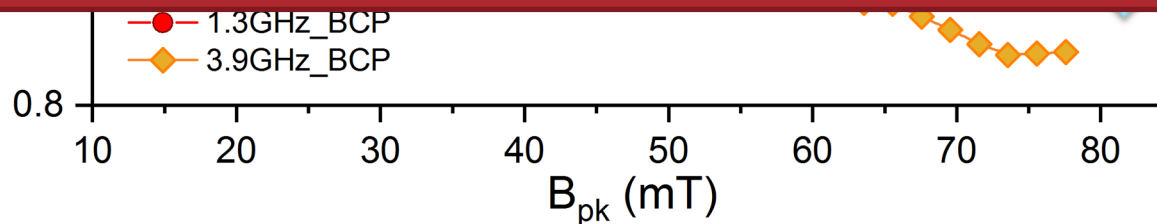
M. Martinello *et al.*, Phys. Rev. Lett. 121, 224801 (2018)

Summary of the Frequency Dependence of $R_{BCS}(E_{acc})$

EP / BCP Cavities

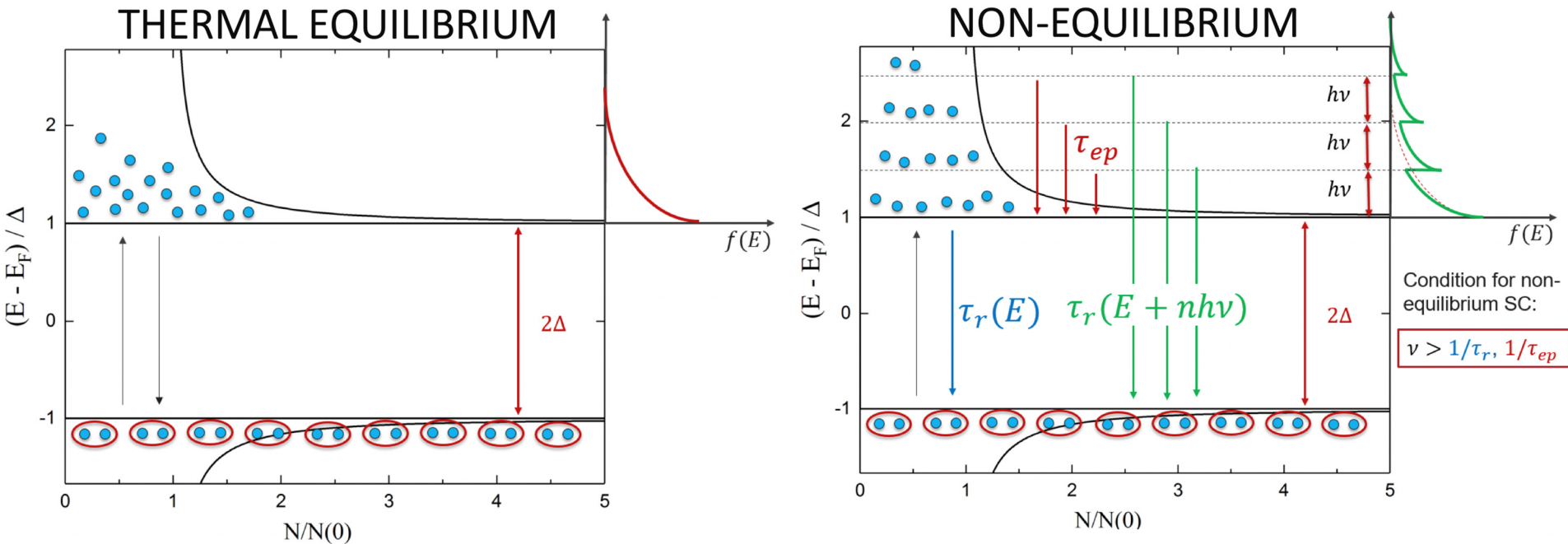


- The R_{BCS} decreasing with the field is an INTRINSIC behavior of Nb cavities resonating at high frequencies
- The N-doping allows to observe this effect at lower frequencies



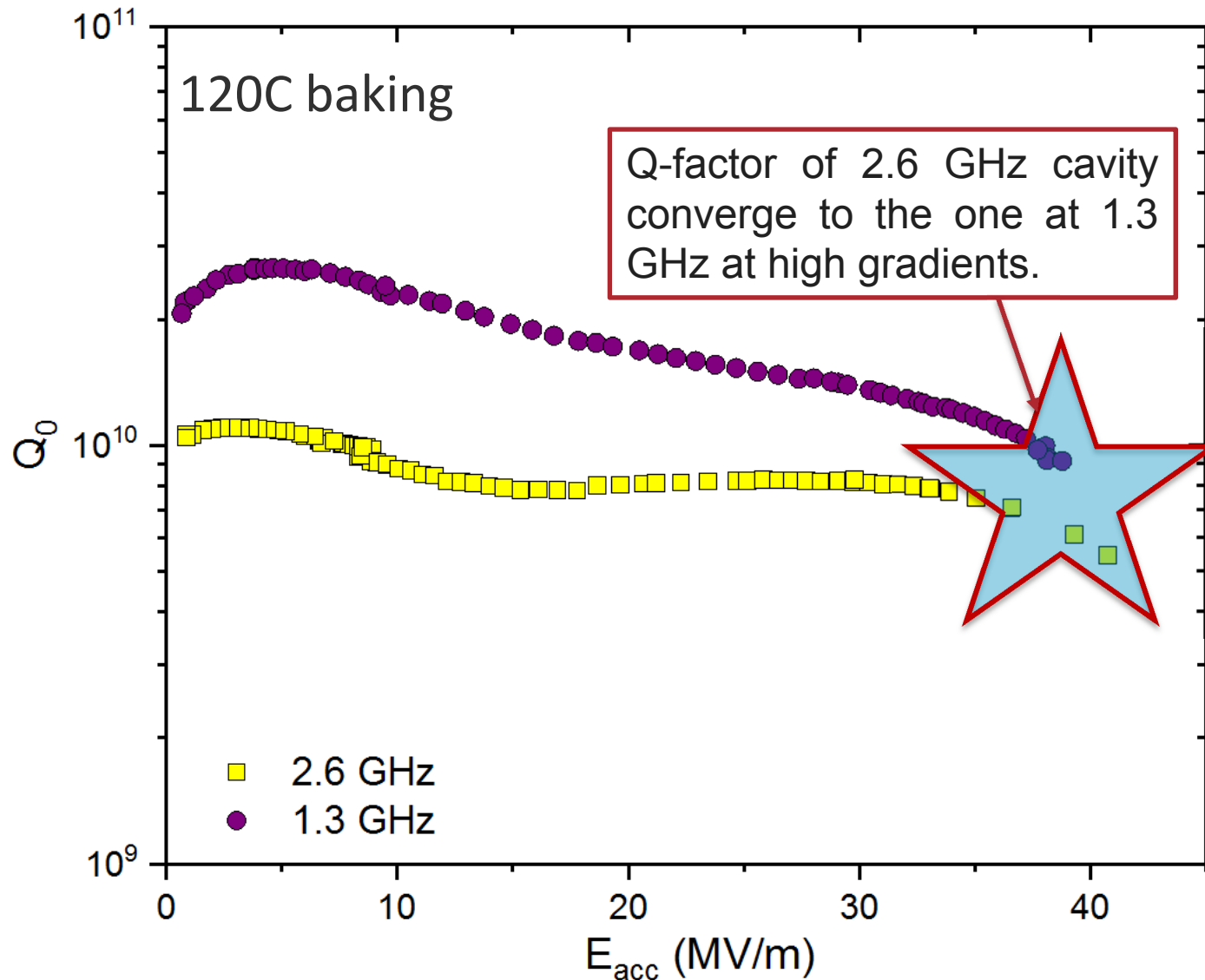
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Doping and Frequency Effect on the QPs Distribution

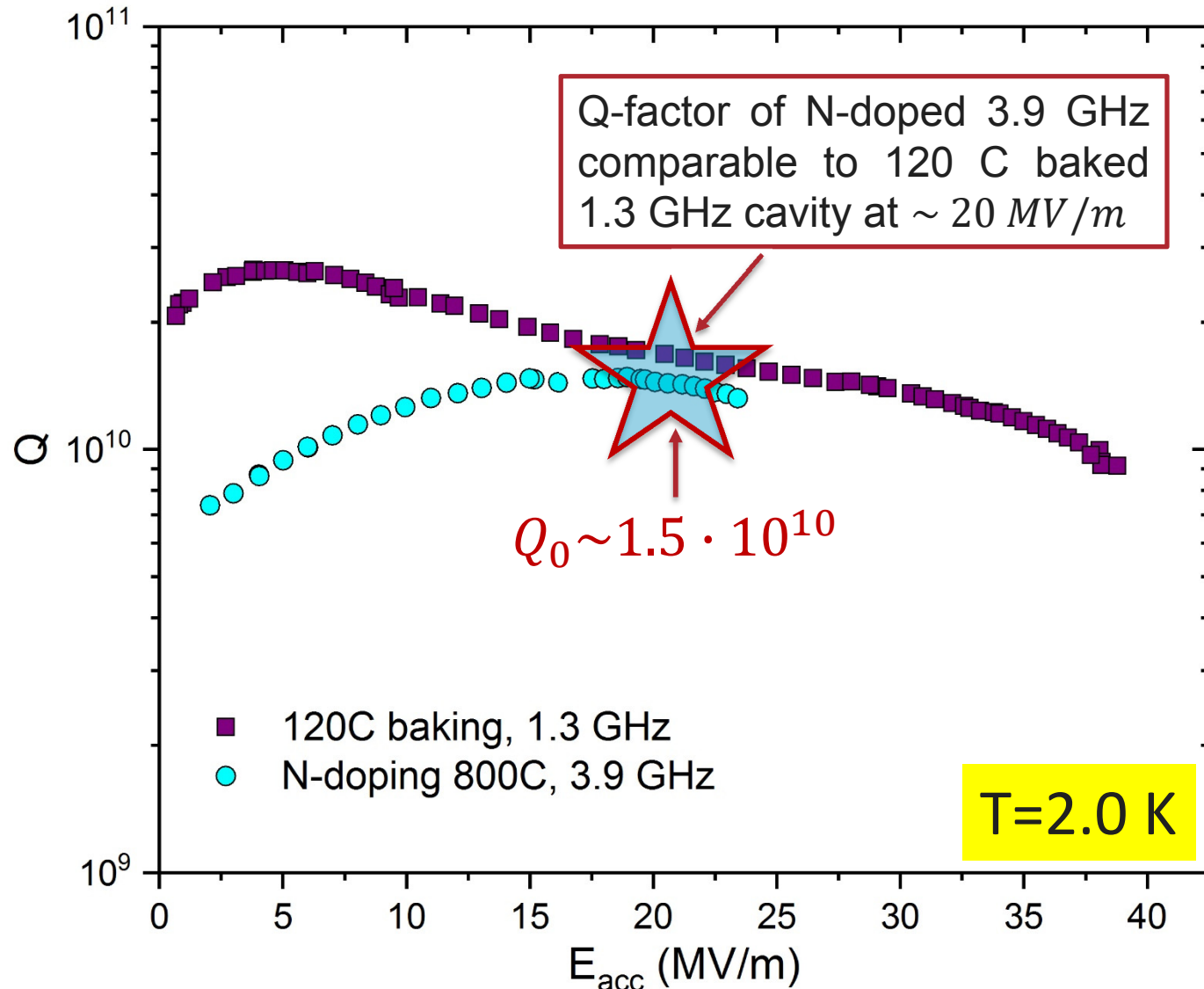


- Higher the frequency, higher the probability to match the condition for non-equilibrium
- N-doping (surface treatments in general) may modifies τ_{ep} and τ_r enhancing non-equilibrium effects

High Frequency Cavities Favorable at High Field



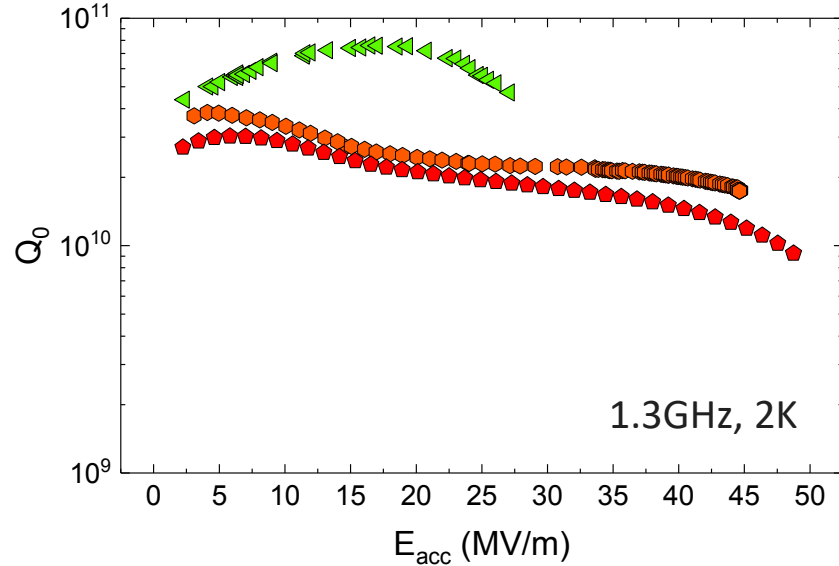
Unprecedented Medium Field Q_0 at 3.9 GHz



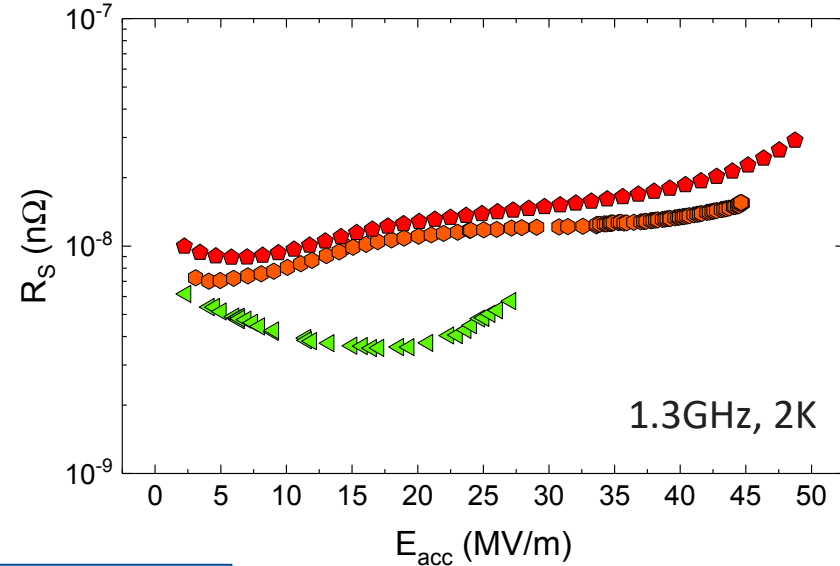
Outline

- Introduction to SRF cavities
- State-of the art surface treatments
- **Toward a better understanding**
 - BCS surface resistance: new insights and optimization
 - **Residual resistance: understanding and minimizing degradation due to trapped flux**
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- Conclusions

The surface resistance



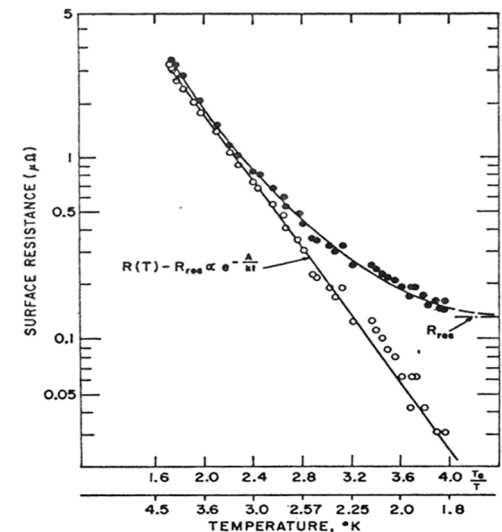
$$Q_0 = \frac{G}{R_s}$$



$$R_s = R_{BCS} + R_{fl} + R_0$$

Residual resistance

- Constant contribution which does not depends on temperature
- R_{fl} (trapped flux surface resistance) depends on magnetic field trapped during SC transition
- R_0 depends on defects, precipitates, etc..



Trapped flux surface resistance

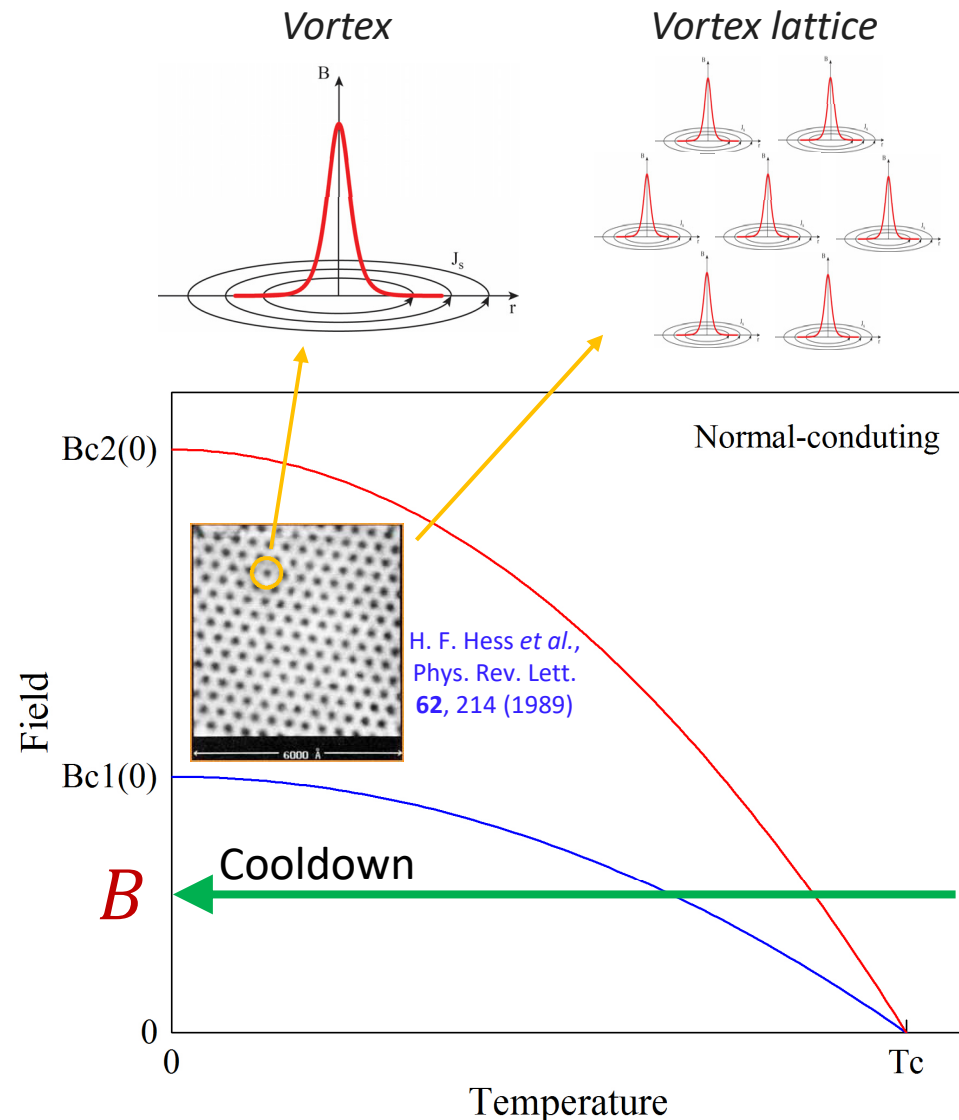
If pinned, vortices may survive in the Meissner state introducing dissipation:

$$R_{fl} = \eta_t \cdot S \cdot B$$

η_t —flux trapping efficiency

S —trapped flux sensitivity

B —external magnetic field



Trapped flux surface resistance

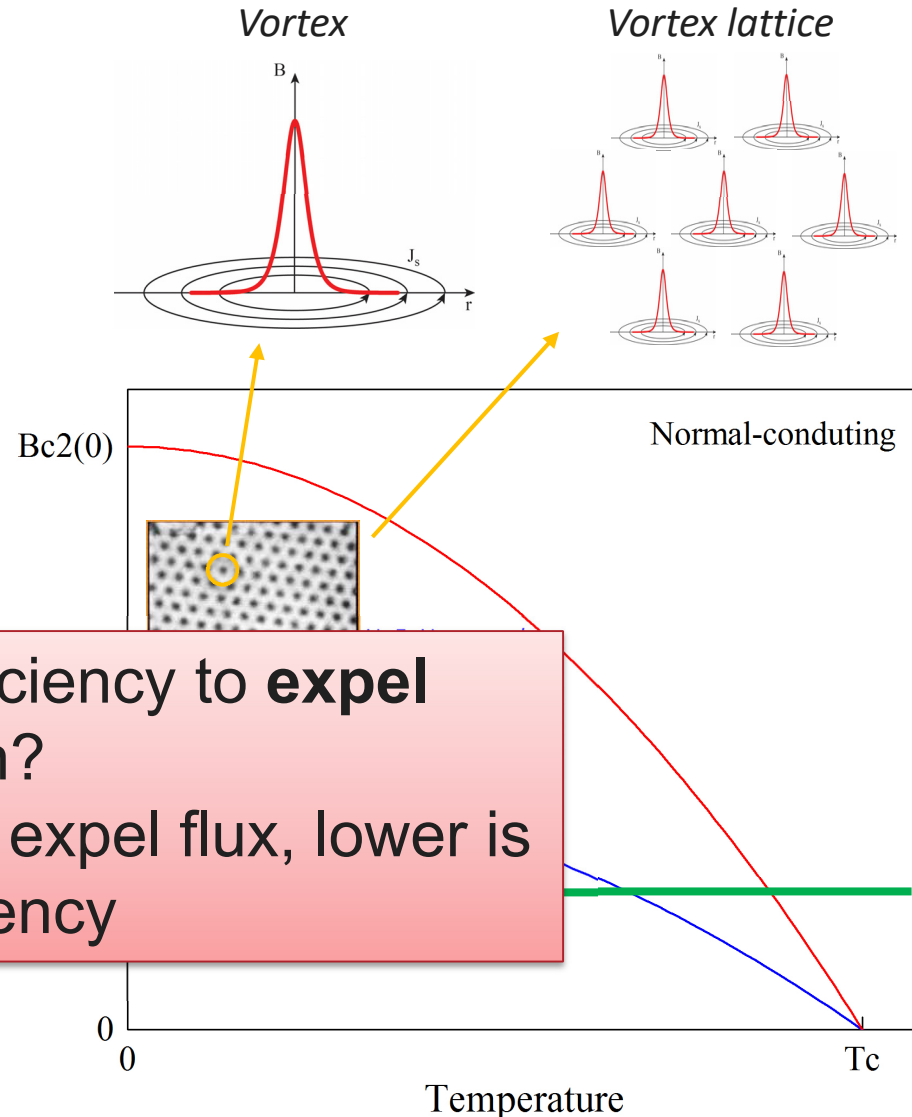
If pinned, vortices may survive in the Meissner state introducing dissipation:

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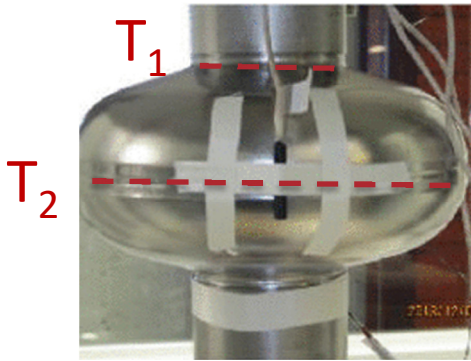
η_t —flux trapping efficiency

S —What is the cavity ability/efficiency to **expel flux** during the SC transition?

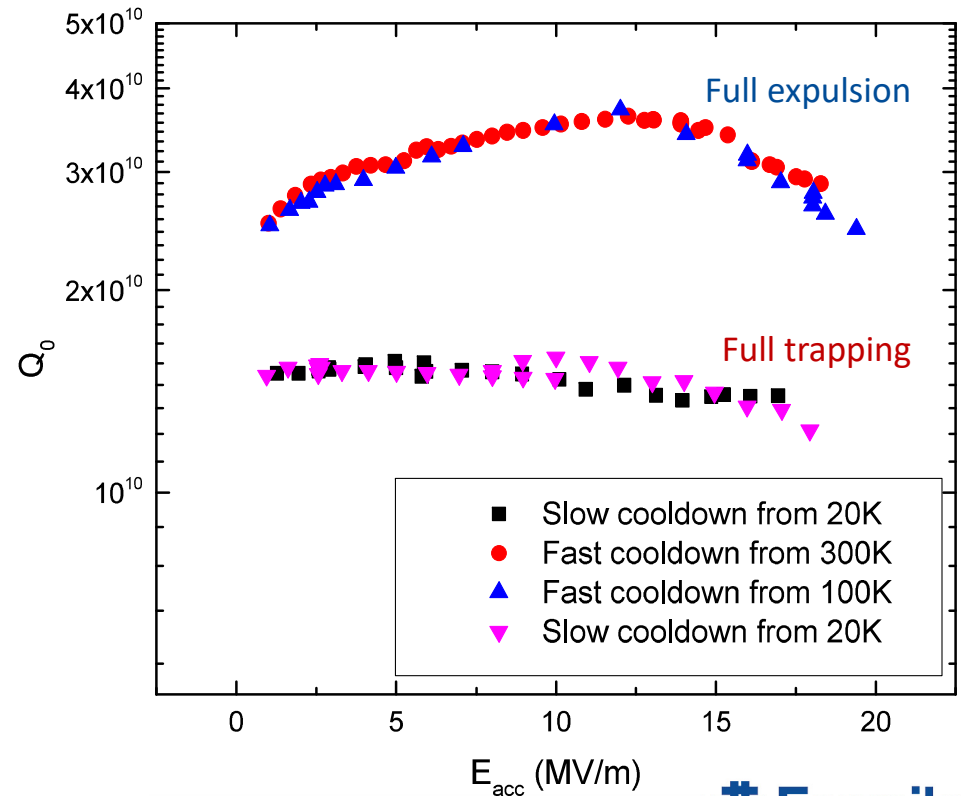
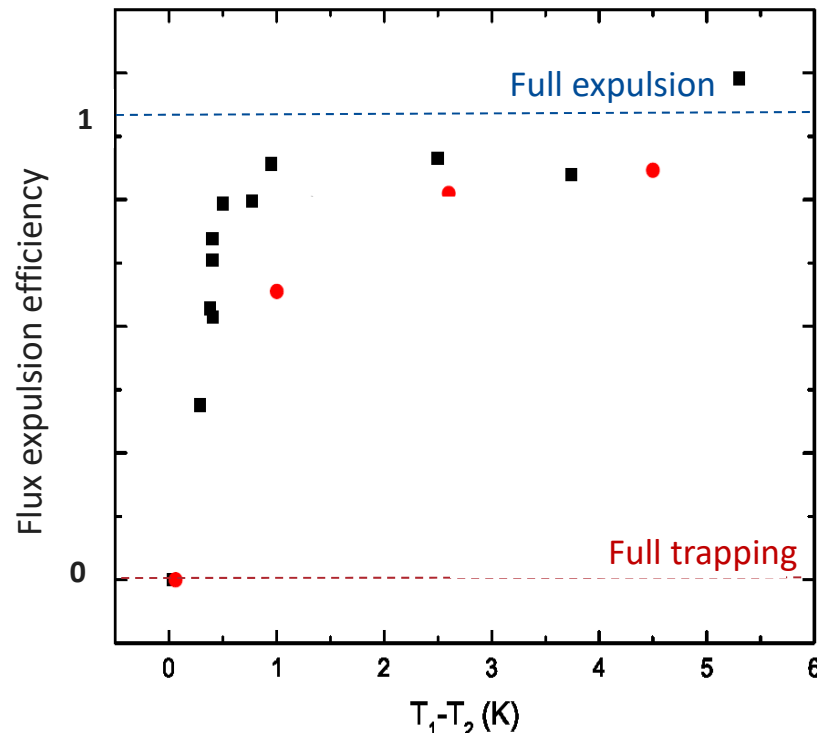
B —
➤ Higher is the ability to expel flux, lower is the flux trapping efficiency



Fast cooldown helps flux expulsion



- **Fast cool-down** leads to large thermal gradients
→ efficient flux expulsion
- **Slow cool-down** leads to small thermal gradients
→ poor flux expulsion

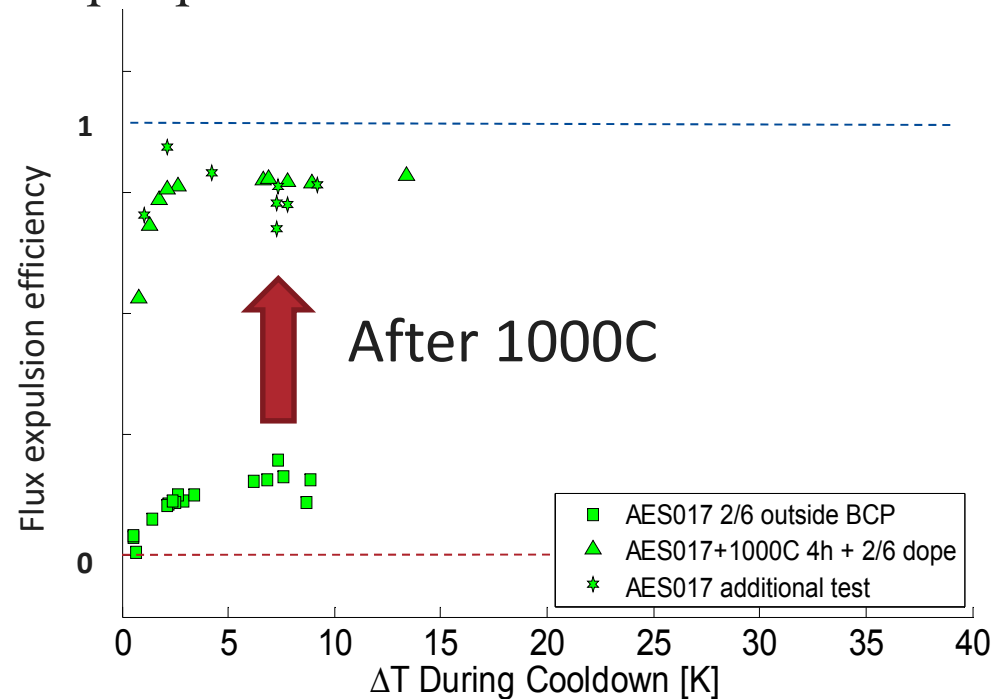
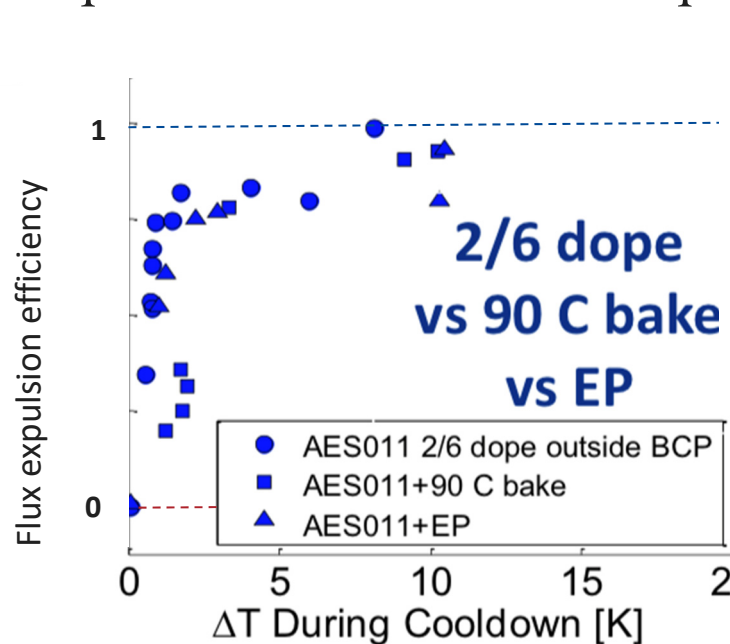


A. Romanenko et al., Appl. Phys. Lett. **105**, 234103 (2014)

A. Romanenko et al., J. Appl. Phys. **115**, 184903 (2014)

Flux expulsion depends on bulk properties of Nb cavities

- Flux expulsion is a bulk property → does not depend on surface treatment
- Not all materials show good flux expulsion, even with large thermal gradient during the SC transition → high T treatments allow to improve materials flux expulsion properties

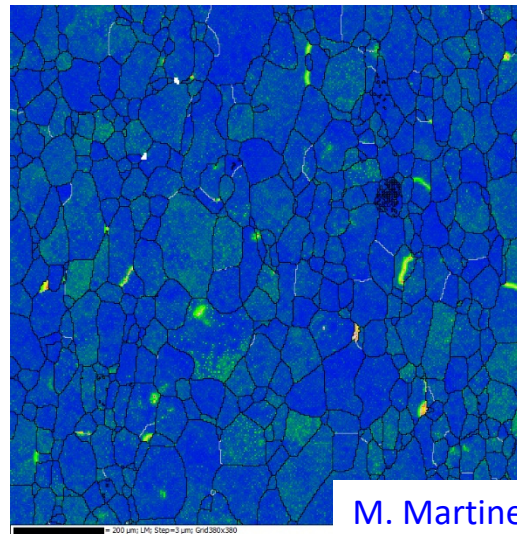
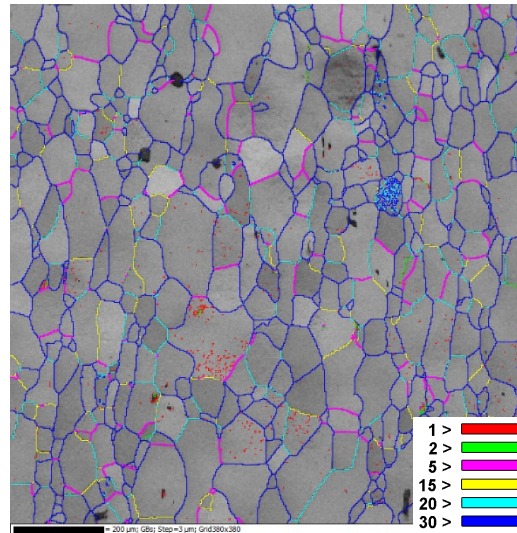


S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

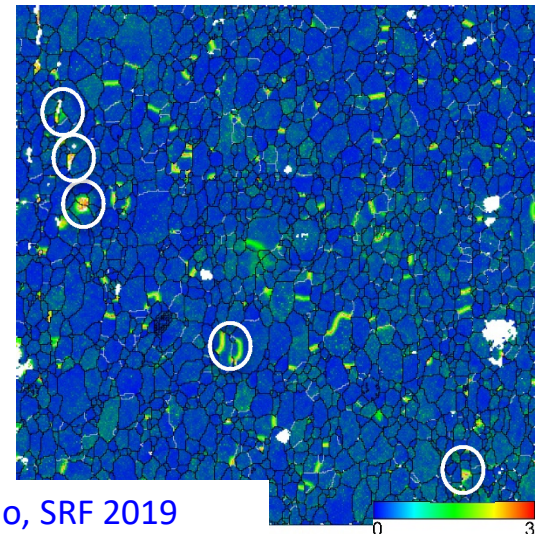
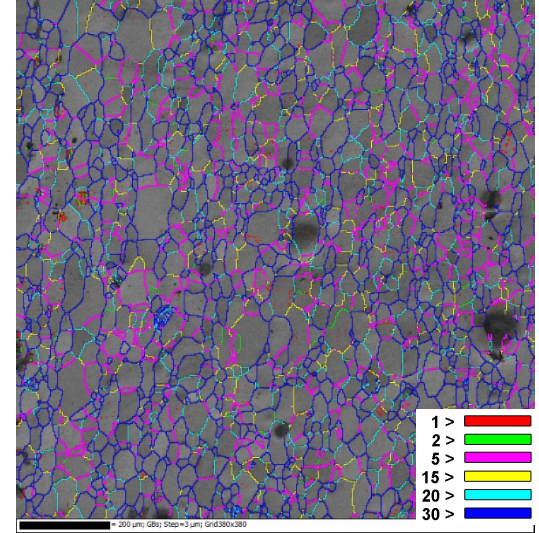
Analysis of “as received” materials

- Material that shows **good flux expulsion** properties after annealing at 800C has bigger grain size in the “as received” condition
- Material with **bad flux expulsion** properties shows larger density of low-angle GBs (misorientation $< 15^\circ$)
- Material with bad flux expulsion properties shows larger density of regions with very high local misorientation

ATI -good flux expulsion-



Ningxia -bad flux expulsion-

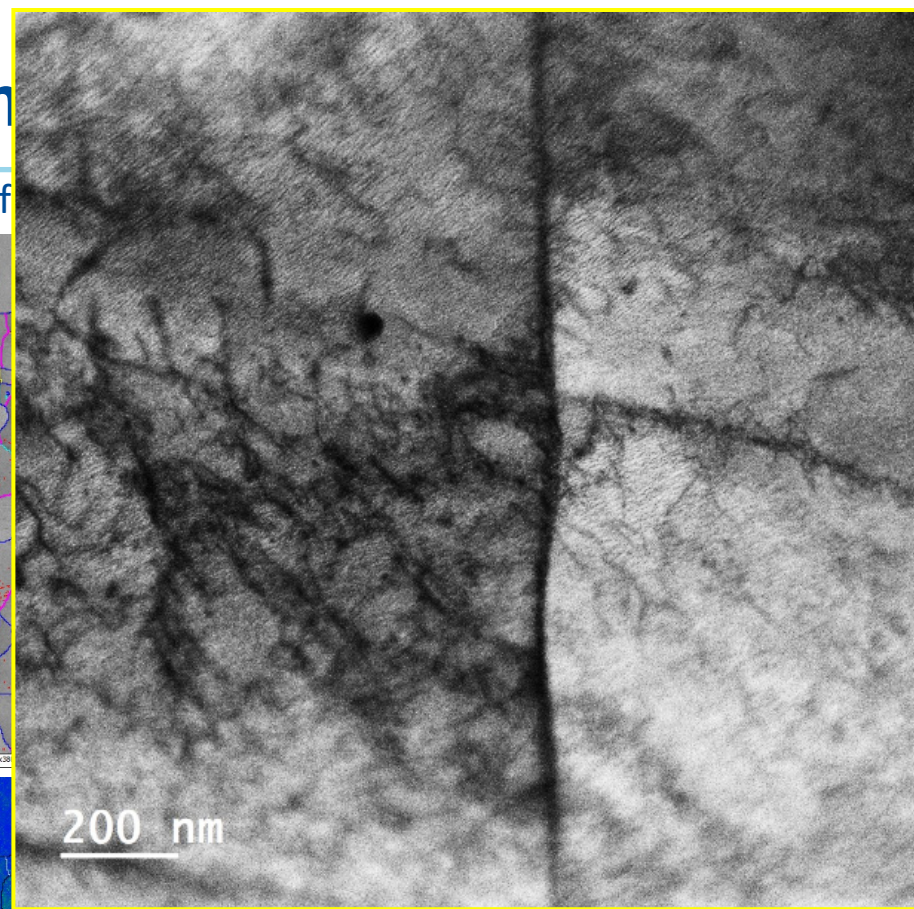
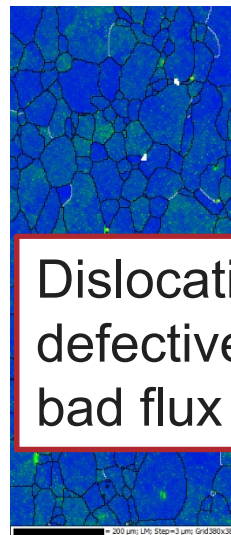
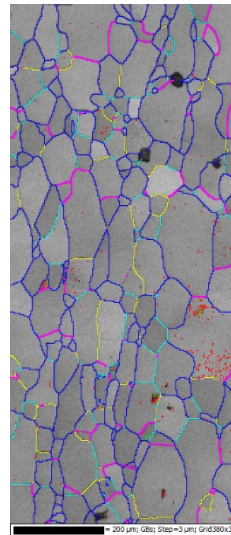


M. Martinello, SRF 2019

Analysis of “as received” n

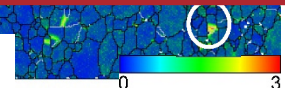
- Material that shows **good flux expulsion** properties after annealing at 800C has bigger grain size in the “as received” condition
- Material with **bad flux expulsion** properties shows larger density of low-angle GBs (misorientation $< 15^\circ$)
- Material with bad flux expulsion properties shows larger density of regions with very high local misorientation
-> **dislocations tangles**

ATI -good f

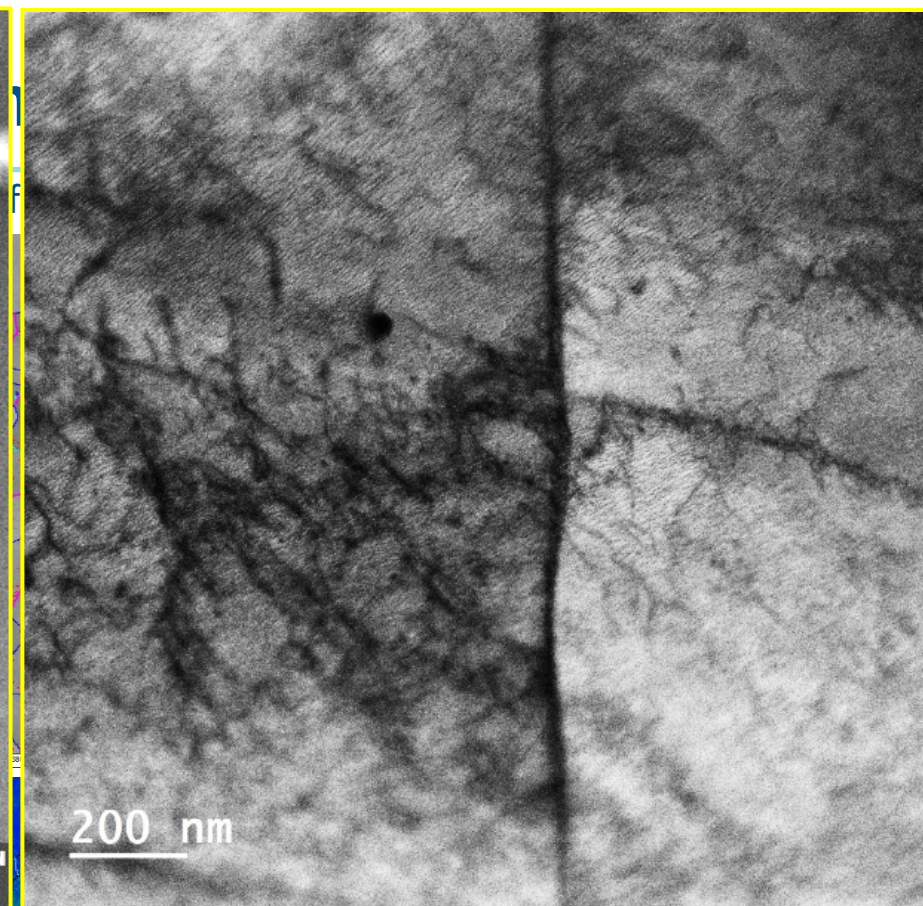


Dislocations tangles observed in highly defective regions of as-received material with bad flux expulsion

M. Martinello, SRF 2019

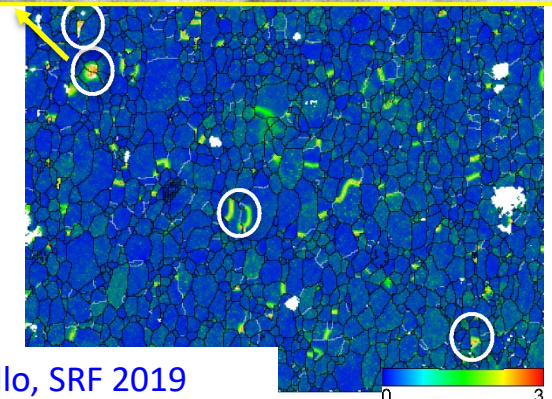
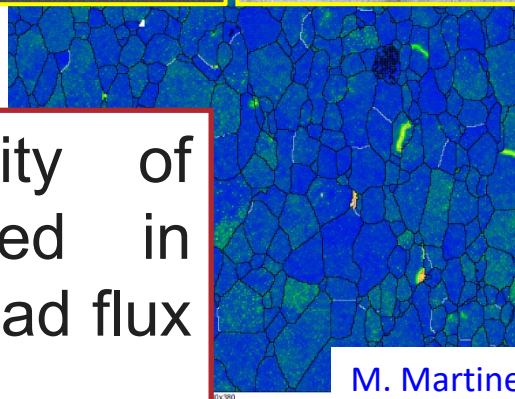


Fermilab

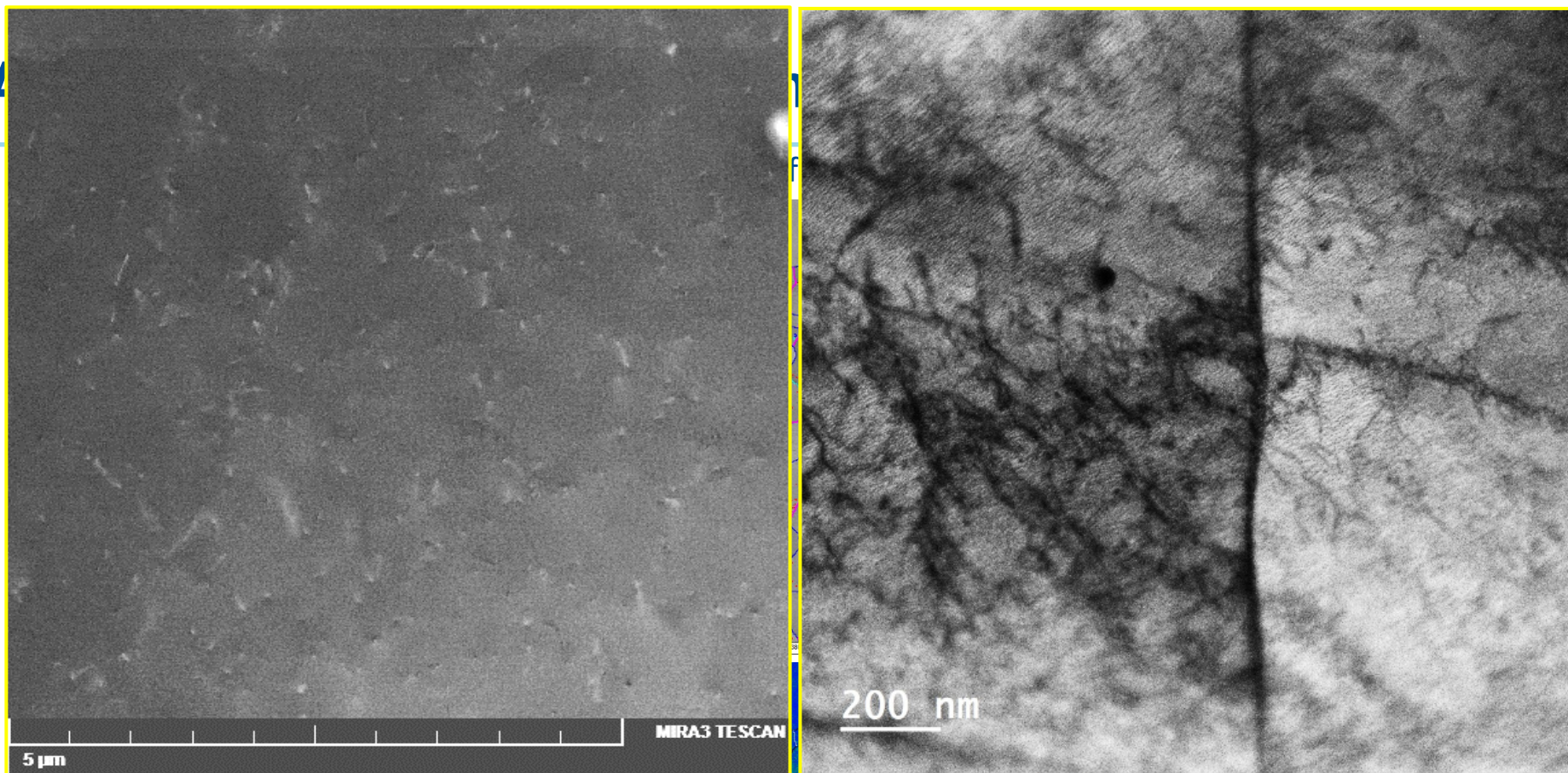


Material with flux expulsion properties shows

Lots of high-density of dislocations observed in **cavity cut-out** with bad flux expulsion



M. Martinello, SRF 2019



Material with bad flux

expulsion

larger

with

misorientation

-> dislocations tangles

Area with high-density of dislocations are most likely culprit of flux trapping in Nb cavities



Trapped flux surface resistance

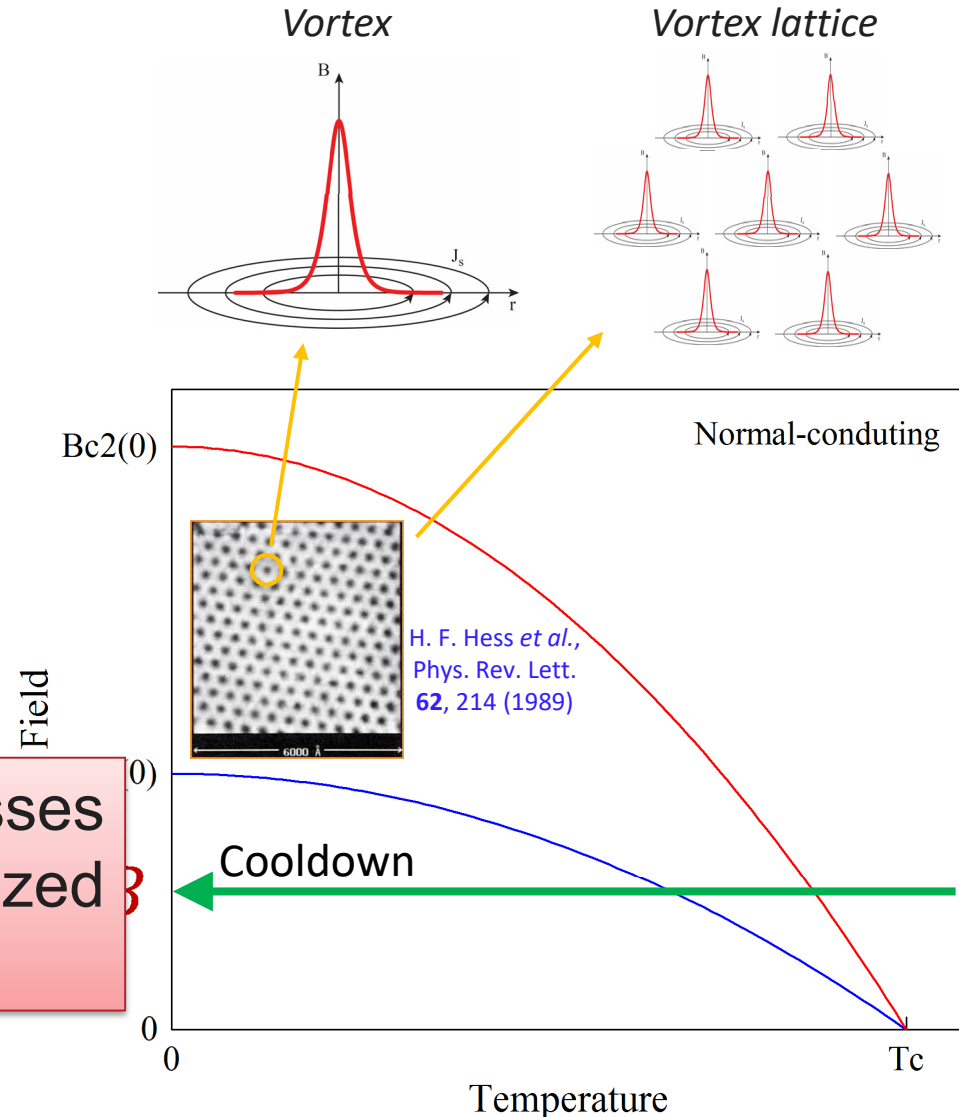
If pinned, vortices may survive in the Meissner state introducing dissipation:

$$R_{fl} = \eta_t \cdot S \cdot B$$

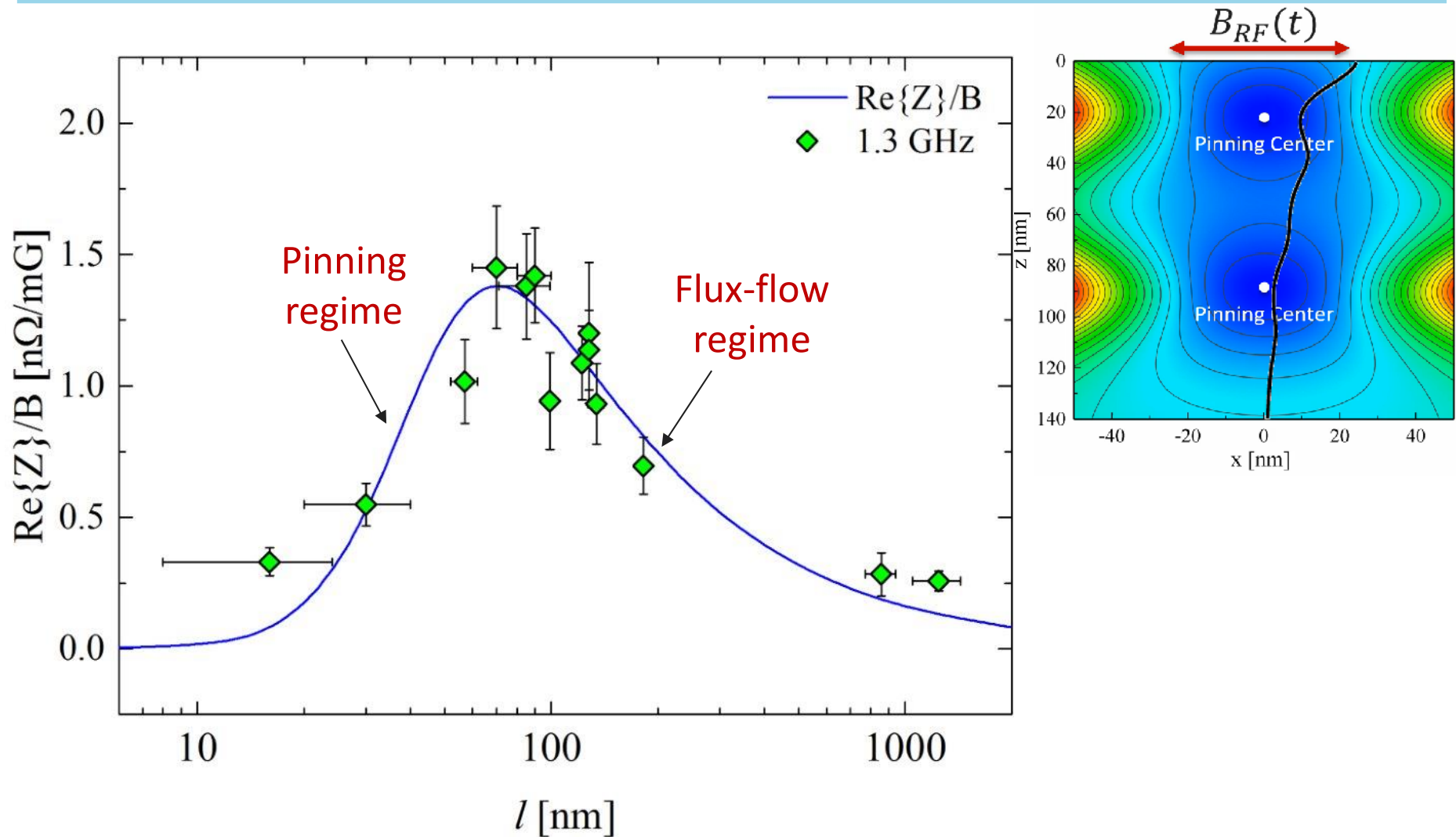
η_t —flux trapping efficiency

S —trapped flux sensitivity

Trapped flux sensitivity = losses (due to trapped flux) normalized for the amount of flux trapped



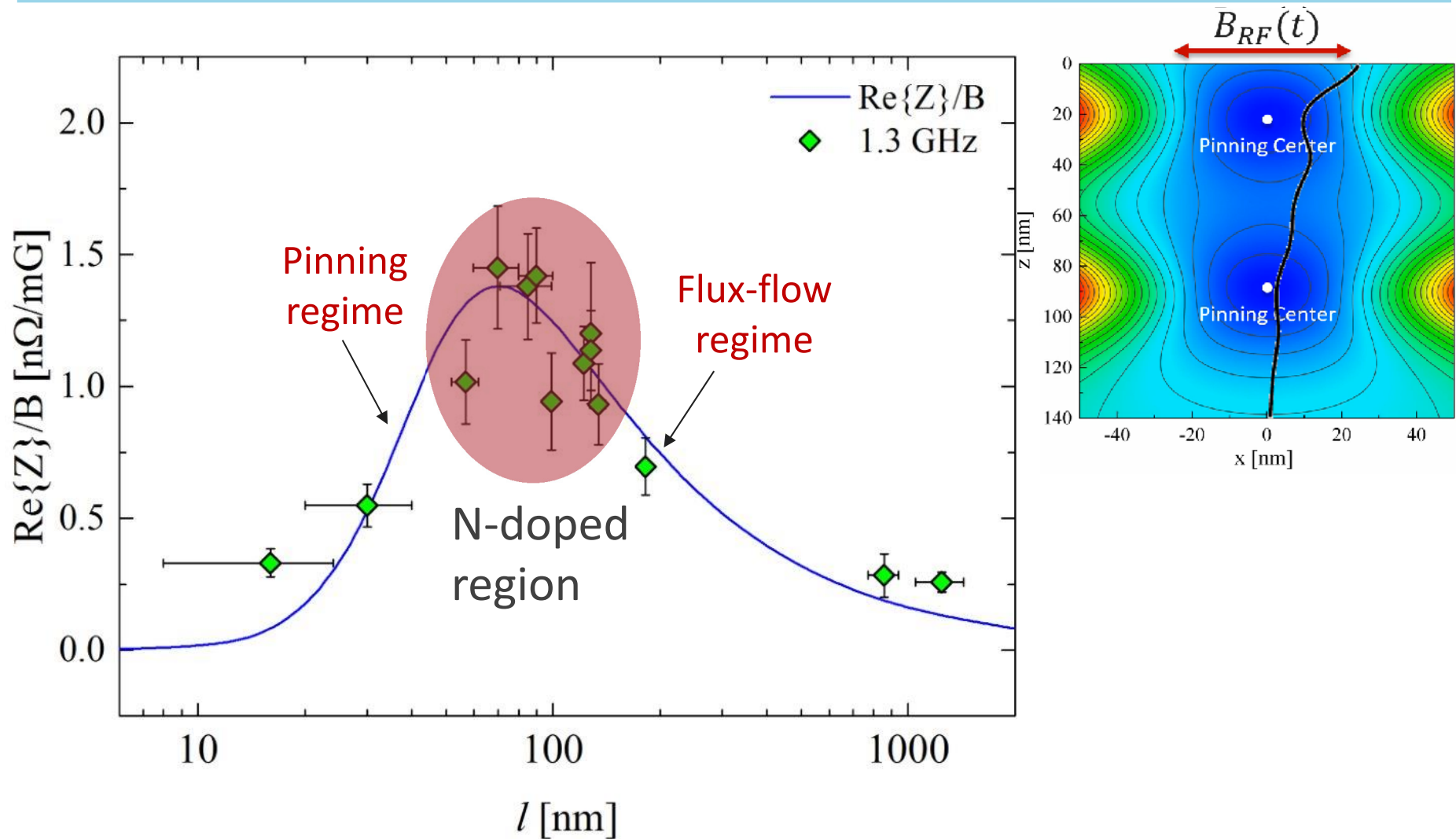
Sensitivity versus mean-free-path



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

M. Checchin et al., Supercond. Sci. Technol. **30**, 034003 (2017)

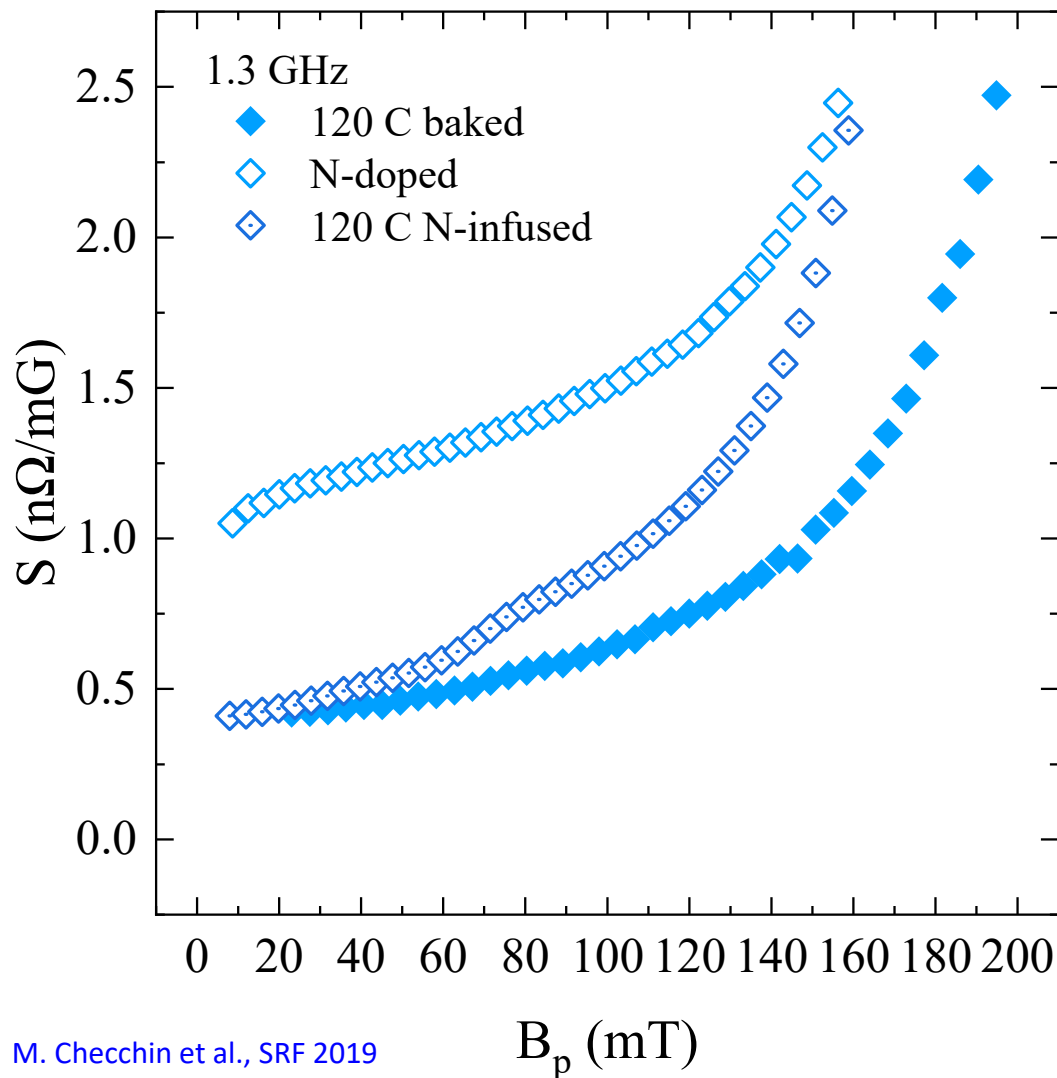
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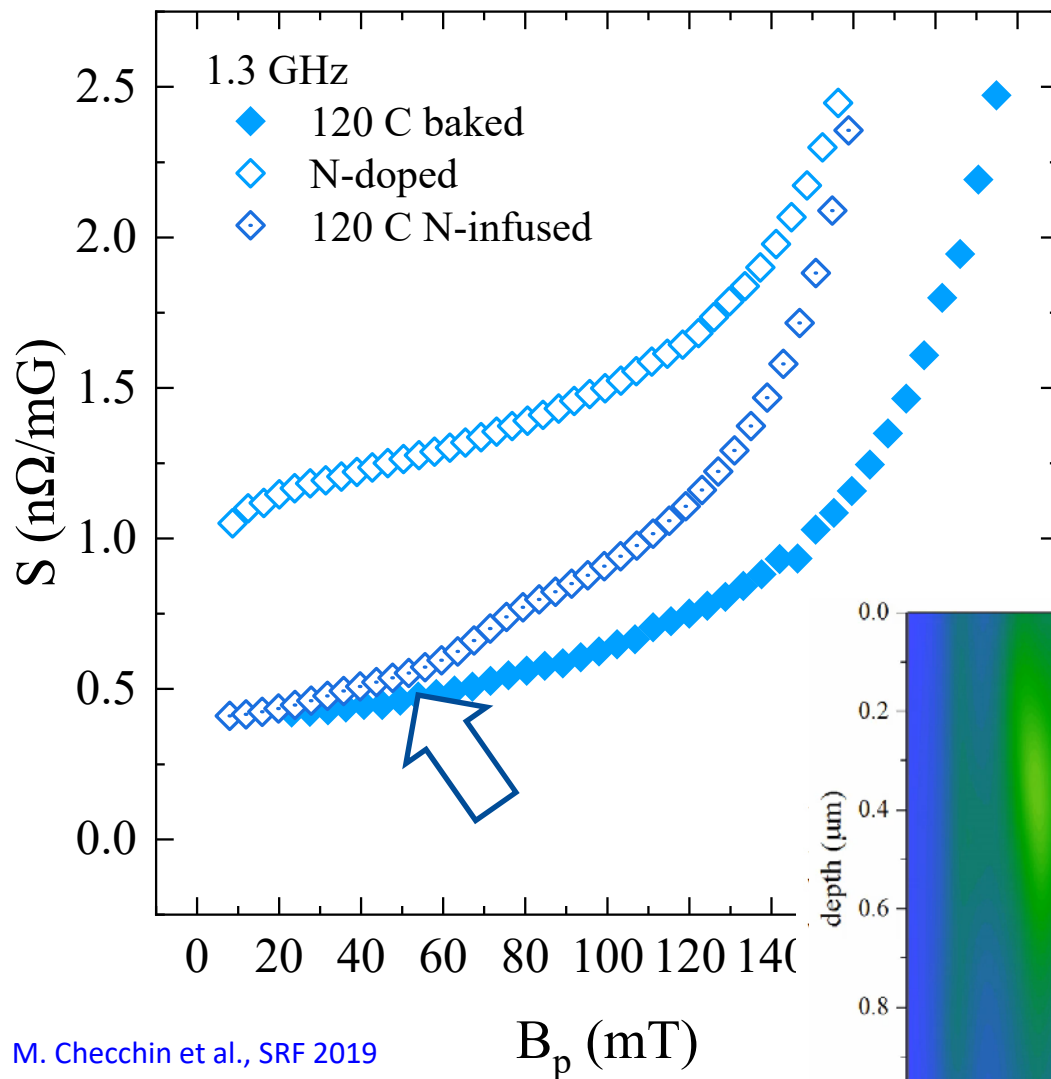
Sensitivity as a function of the field



M. Checchin et al., SRF 2019

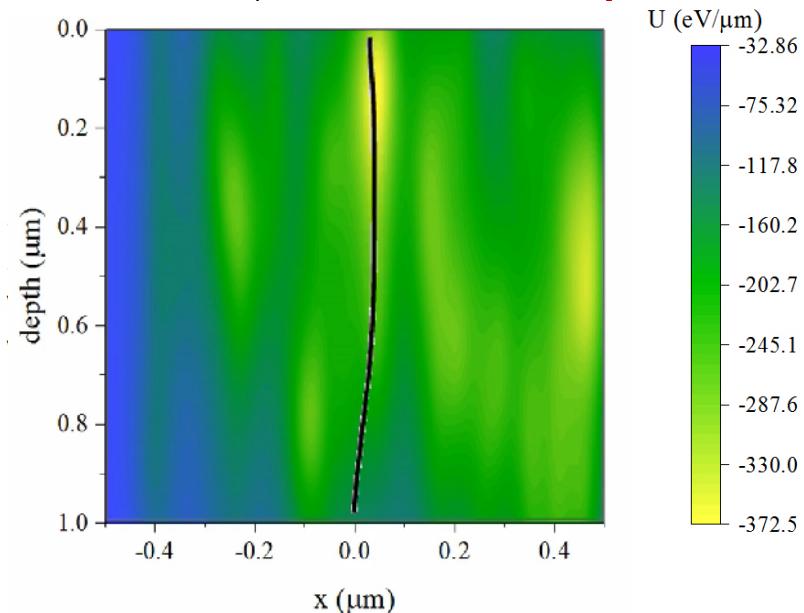
- At high field the trapped flux sensitivity increases exponentially
- 120C baked and N-infused cavities have very low values of sensitivity at low field but significantly high at high field
- Important to take that into account for high-field applications!

Sensitivity as a function of the field



M. Checchin et al., SRF 2019

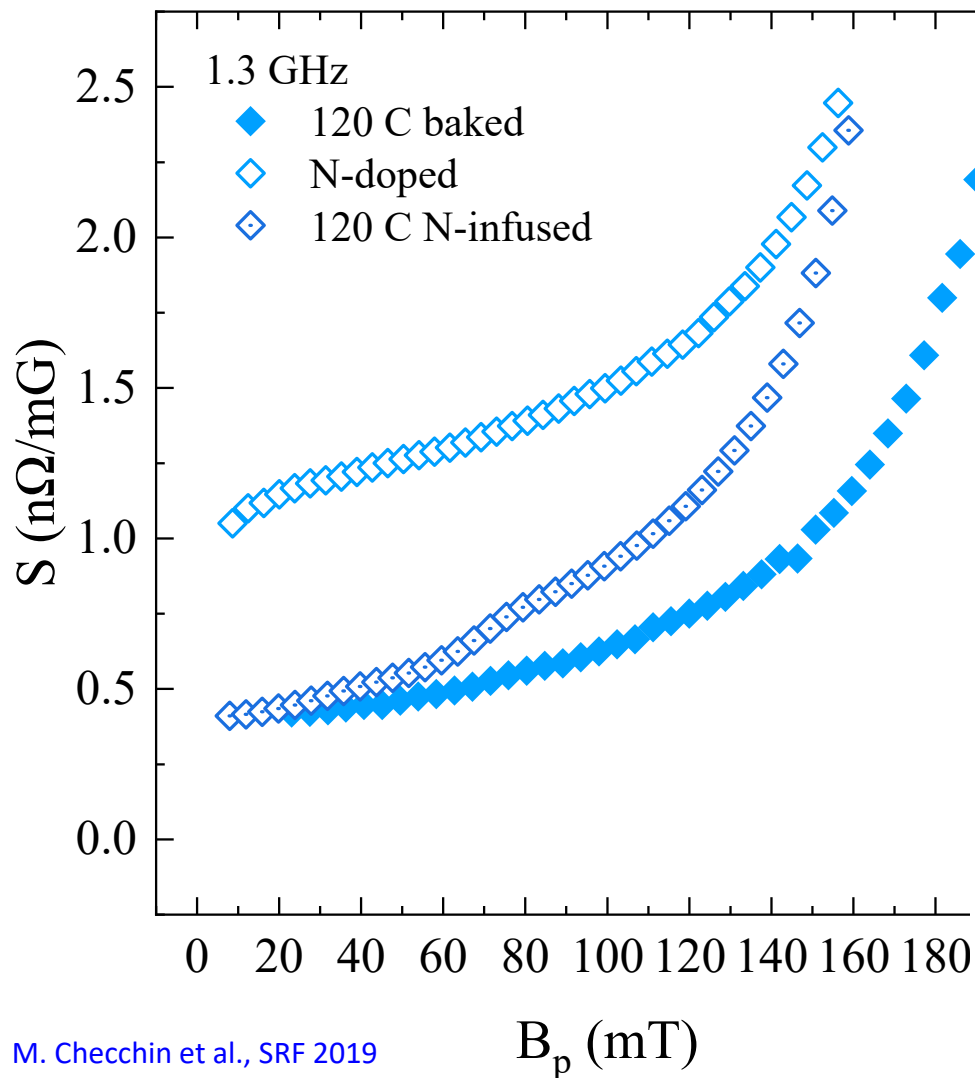
- At high field the trapped flux sensitivity increases exponentially
- 120C baked and N-infused cavities have very low values of sensitivity at low field



that
high-

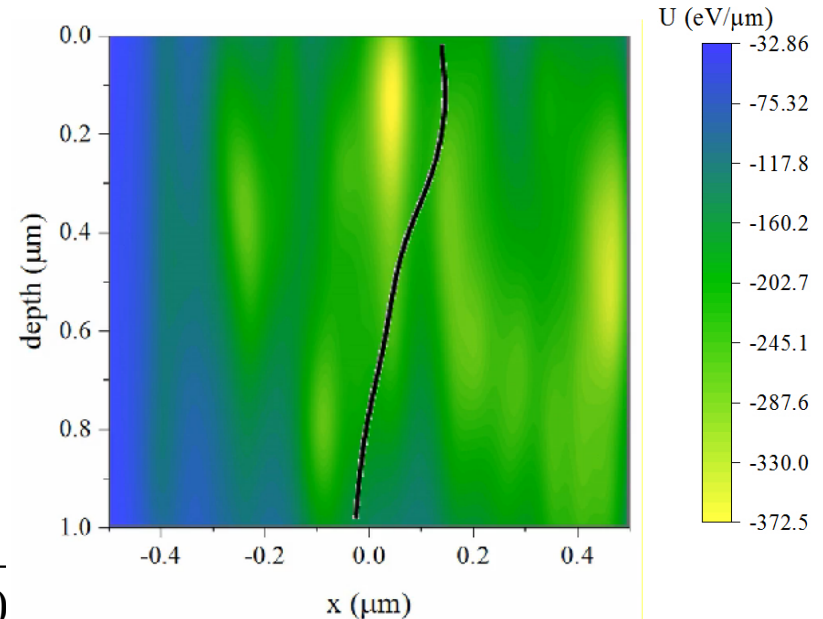
milab

Sensitivity as a function of the field



- At high field the trapped flux sensitivity increases exponentially

- 120C baked and N-



field applications!

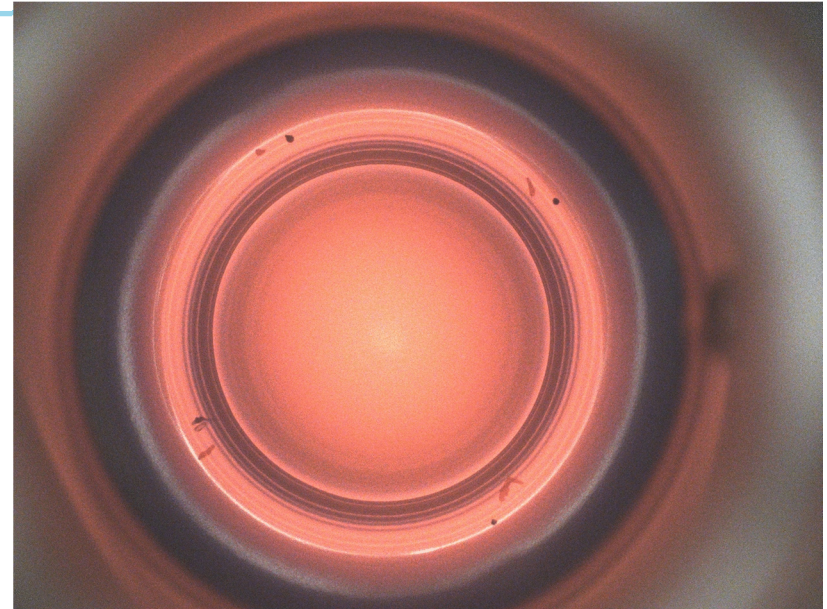
M. Checchin et al., SRF 2019

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Plasma processing R&D for LCLS-II cavities

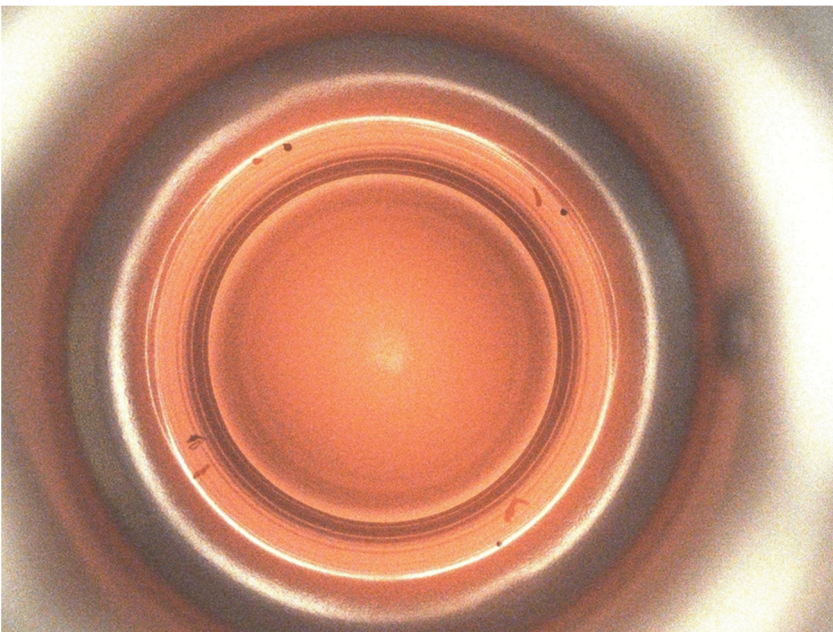
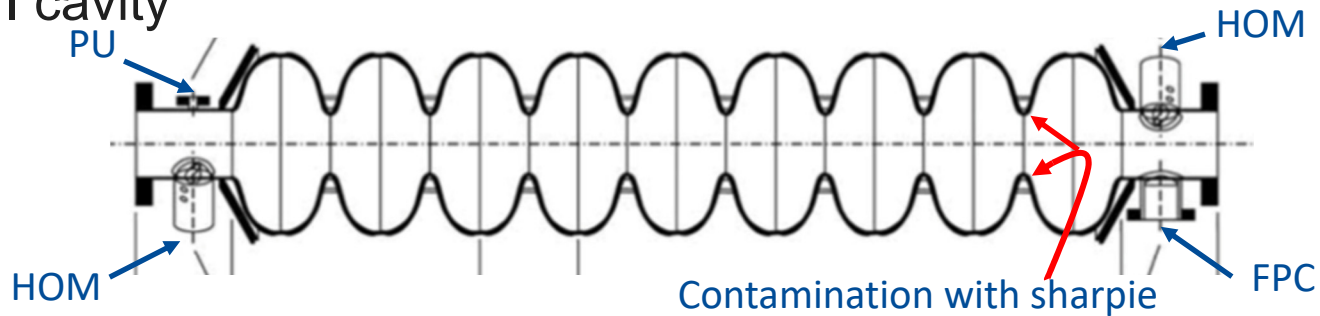
Work performed in collaboration with SLAC and ORNL



- Ne-O gas mixture (few % of O₂, mostly Ne) at $p \sim 75\text{-}150\text{mTorr}$
- Plasma ignition sequentially cell-by-cell using HOMs antenna (10-50 W for ignition, few W for sustain plasma) [P. Berrutti et al., J. App. Phys. **126**, 023302 \(2019\)](#)
- Approximately 1-2 hours processing per cell
- On-going R&D to optimize parameters and understand rate of success in naturally FE cavities [B. Giaccone, M. Martinello, to be published](#)

First study in a 9-cell contaminated cavity

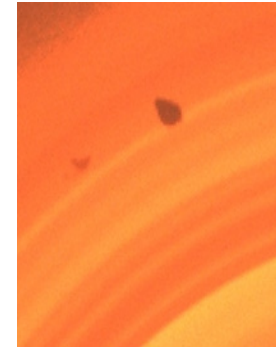
- **Scope:** remove hydrocarbon contamination with plasma cleaning
- 8 “dots” of permanent markers around the iris of the first cell of a 9-cell LCLS-II cavity



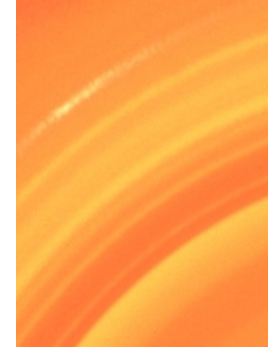
Initial state



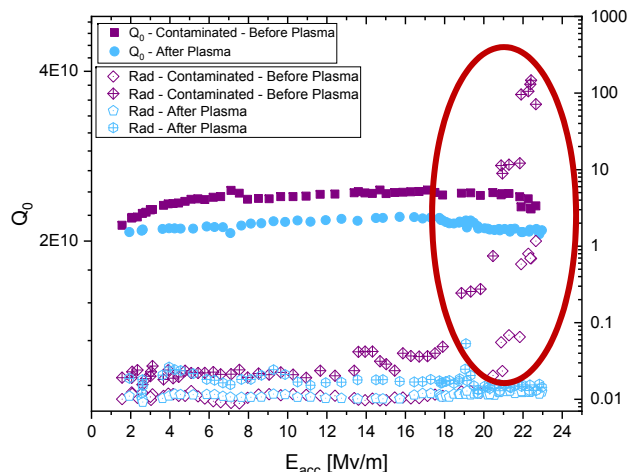
After 5 h



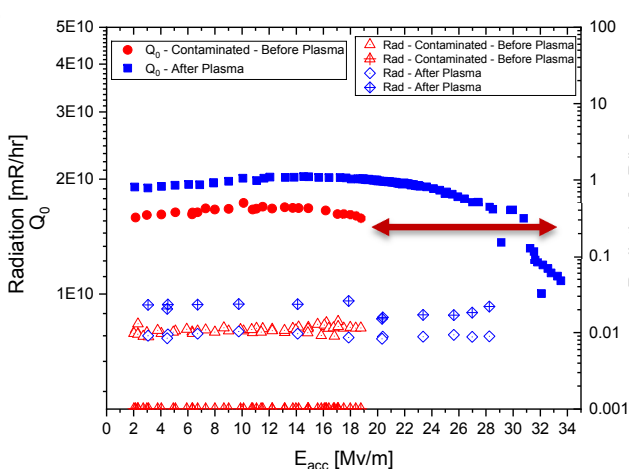
After 19 h



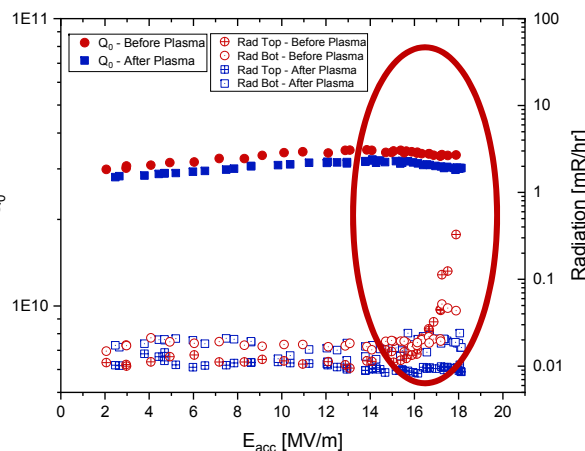
Summary results of plasma processed cavities



No radiation detected after plasma processing!

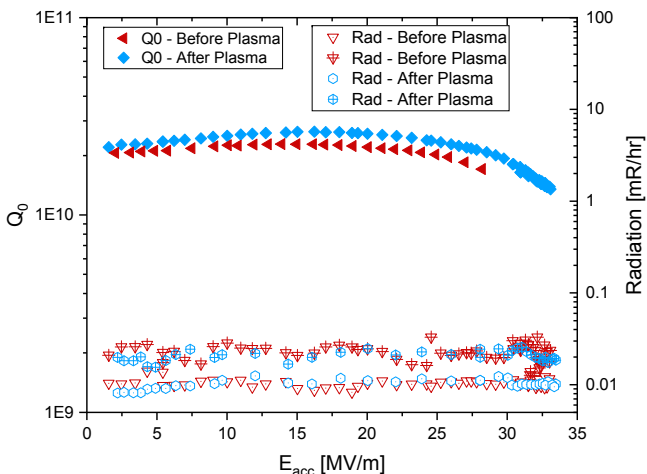


15 MV/m gained after plasma processing!



No radiation detected after plasma processing!

B. Giaccone et al., Proc. of SRF 2019



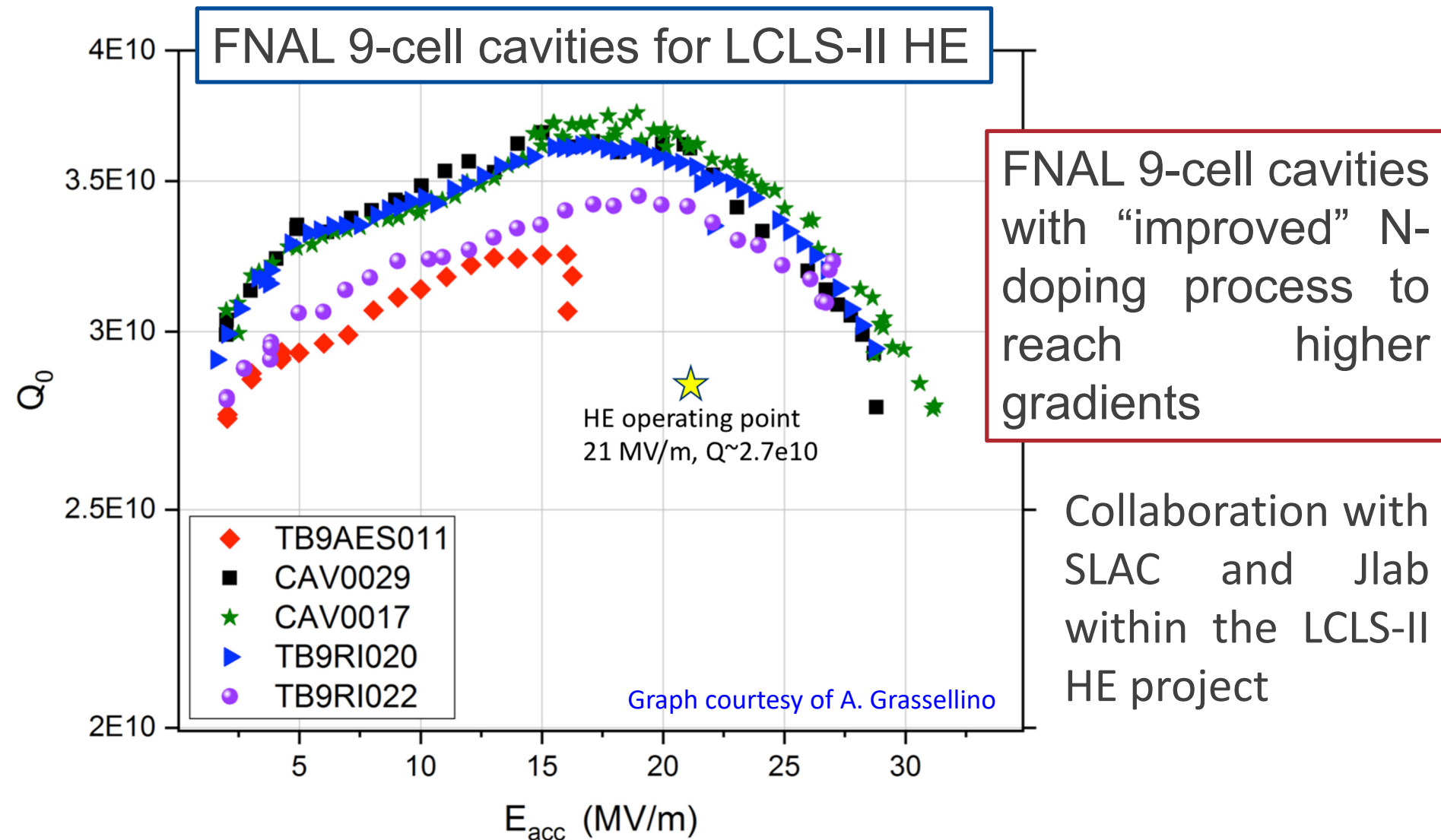
No Q degradation observed in N-doped cavities after plasma process
Increasing of performance observed in 3 cavities treated with plasma processing

LCLS-II CM production at FNAL



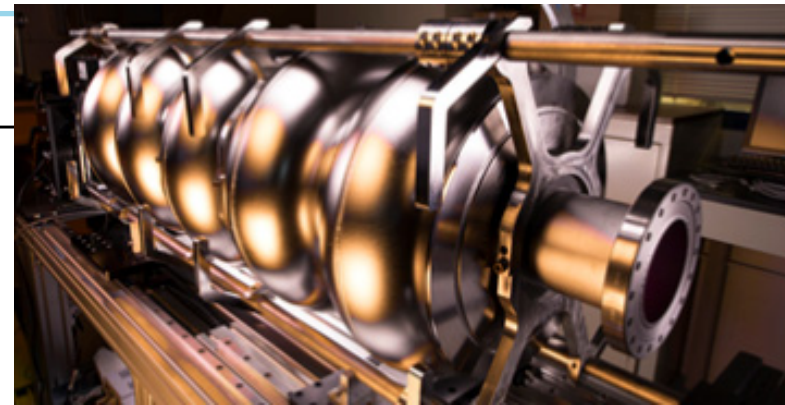
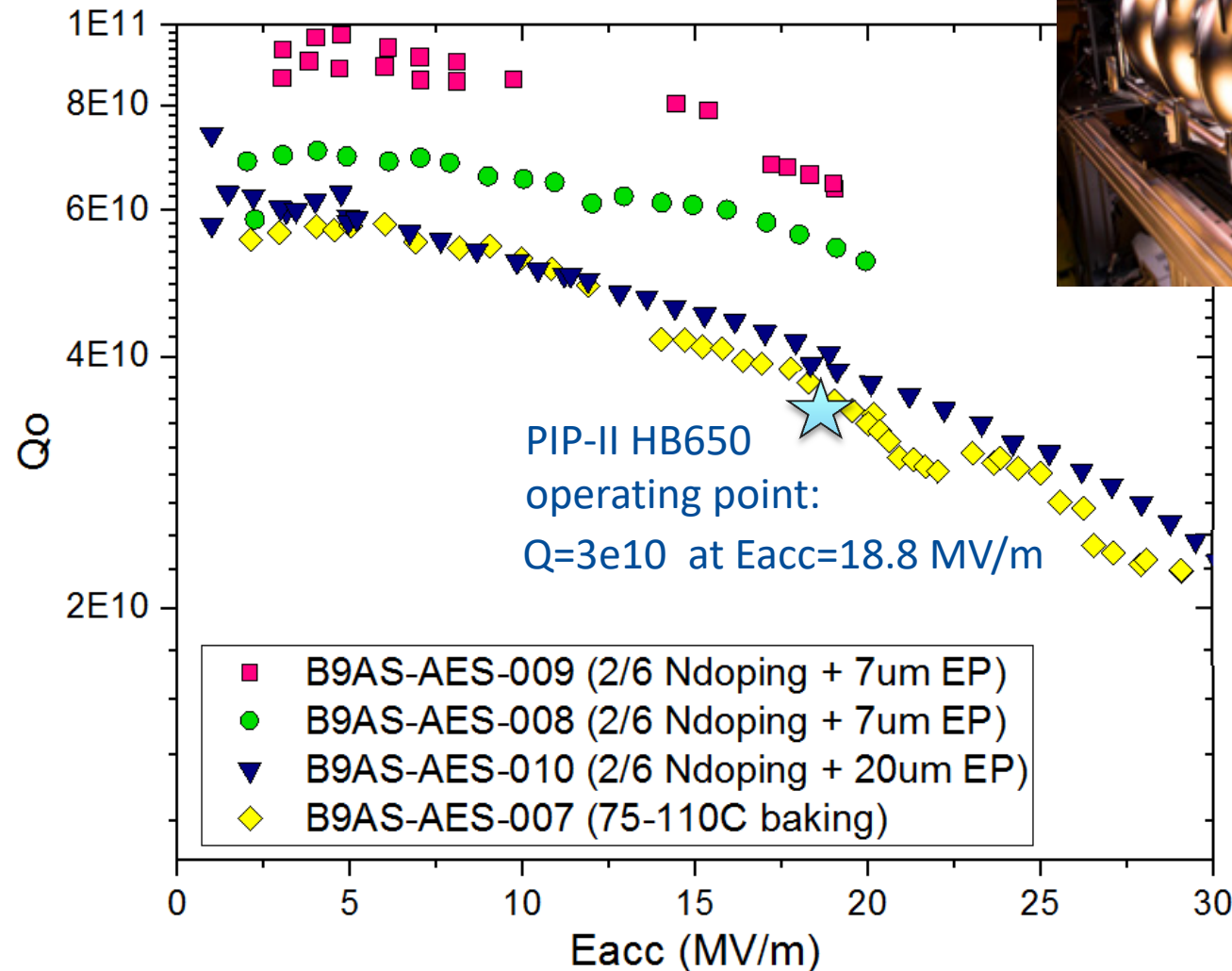
LCLS-II production at FNAL is almost completed, now time to look at what's next

N-doping optimization for LCLS-II HE



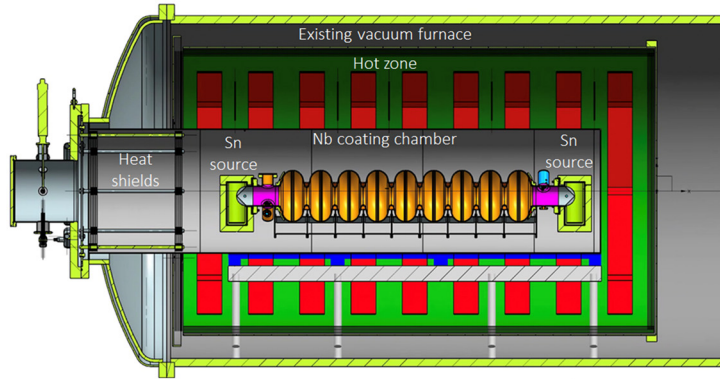
N-doping optimization for PIP-II

5-cell HB 650 MHz cavities



- N-doping is being optimized for 650 MHz cavities
- **Record Q-factors** obtained even in 5-cell cavities!
- 1st cavity has been dressed with He jacket

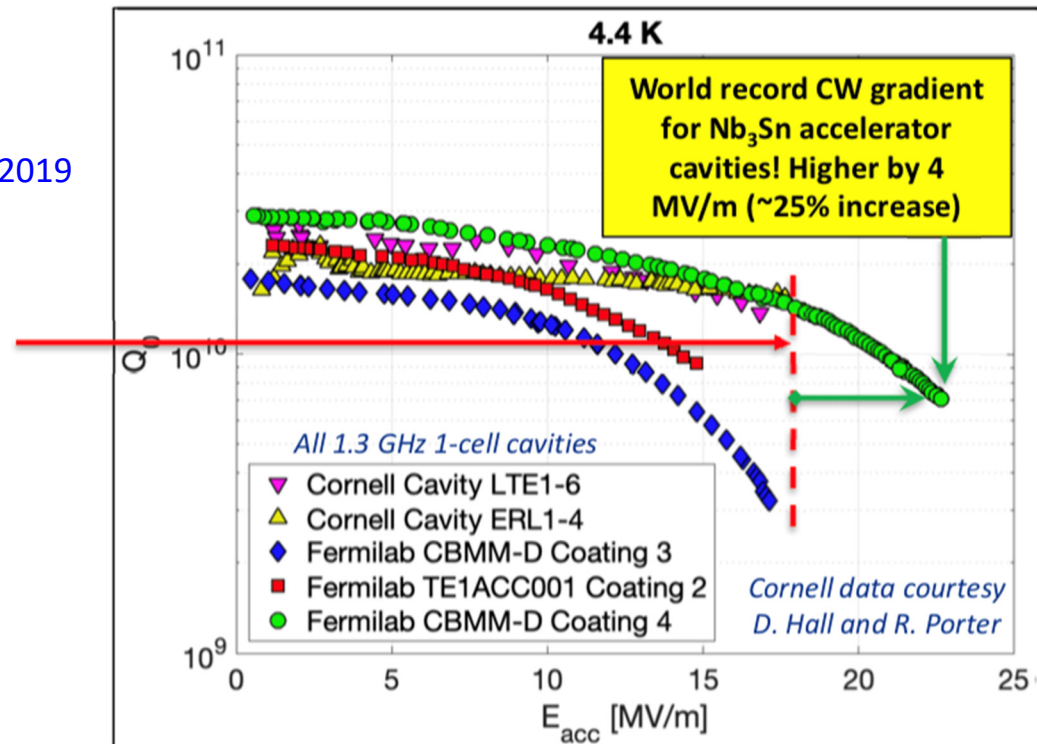
New progress with Nb₃Sn



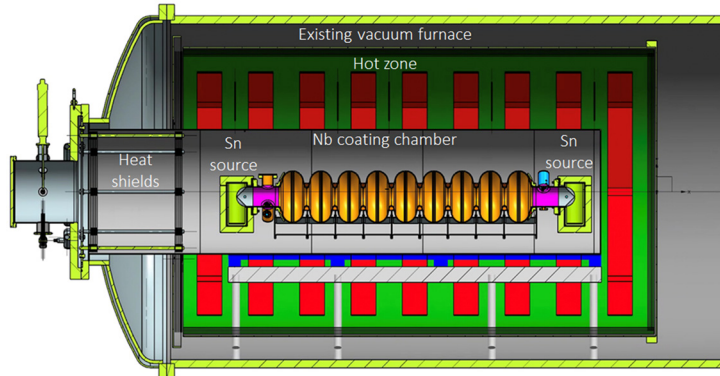
- Nb₃Sn is a superconductor with $T_c=18K$
- Allows for efficient operation at 4.4K
 - Compact SRF accelerator!

S. Posen, TTC 2019

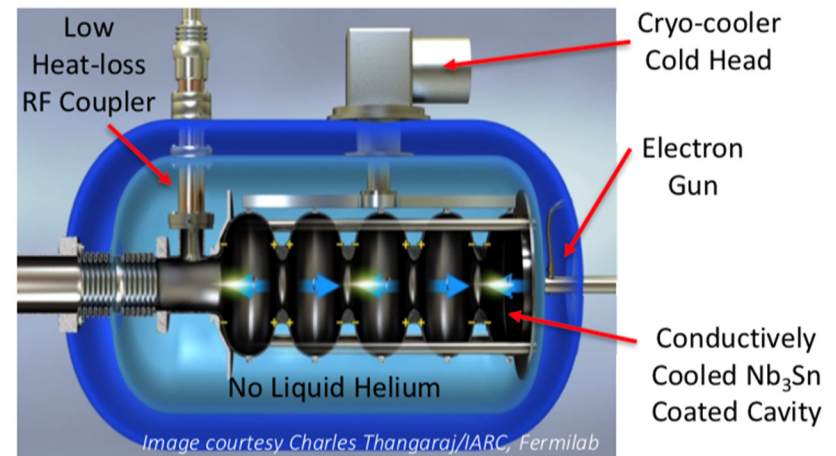
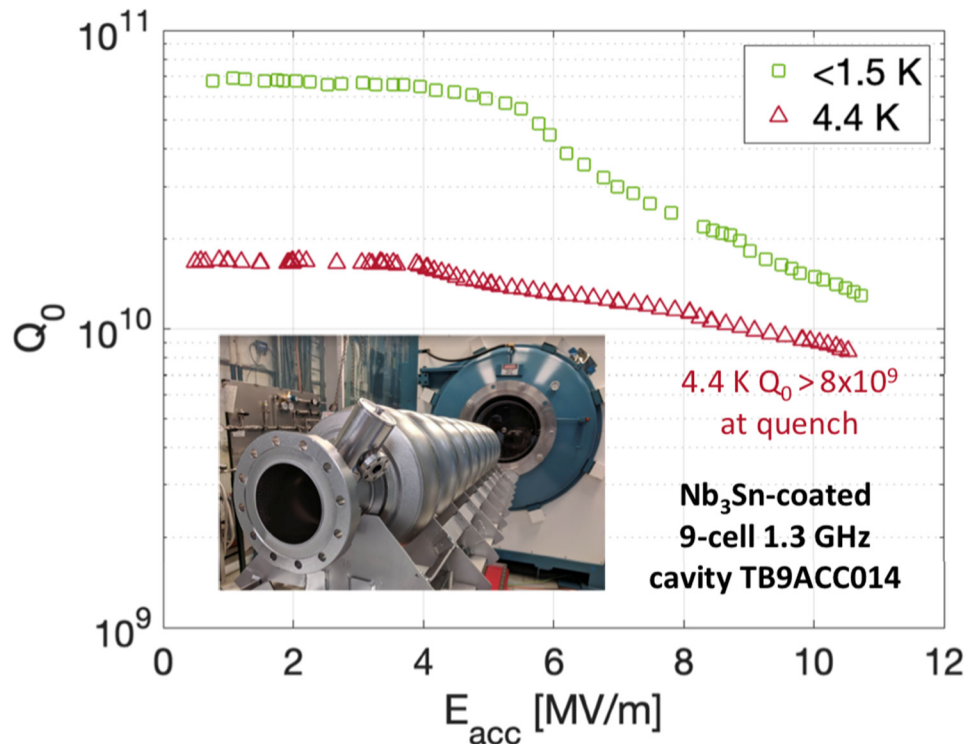
Previous CW
accelerating
gradient limit
~17-18 MV/m



New progress with Nb₃Sn



- Nb₃Sn is a superconductor with T_c=18K
- Allows for efficient operation at 4.4K
 - Compact SRF accelerator!

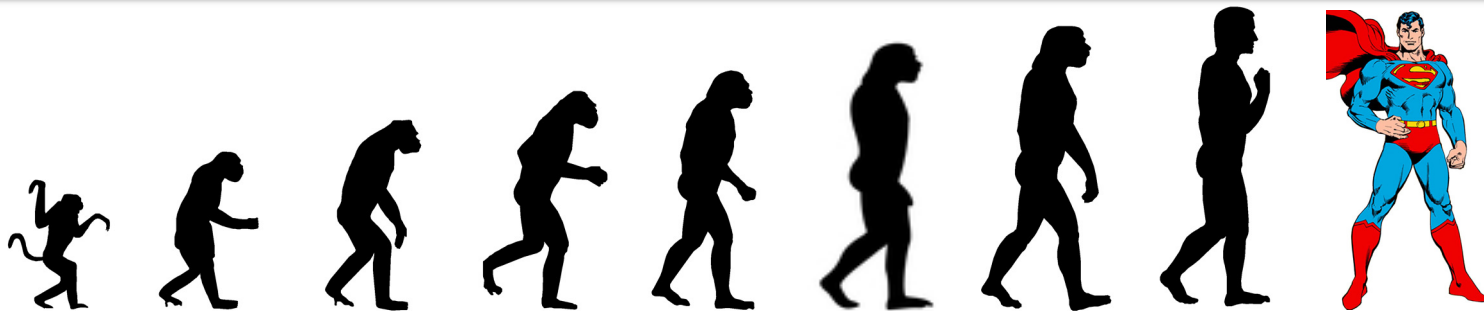
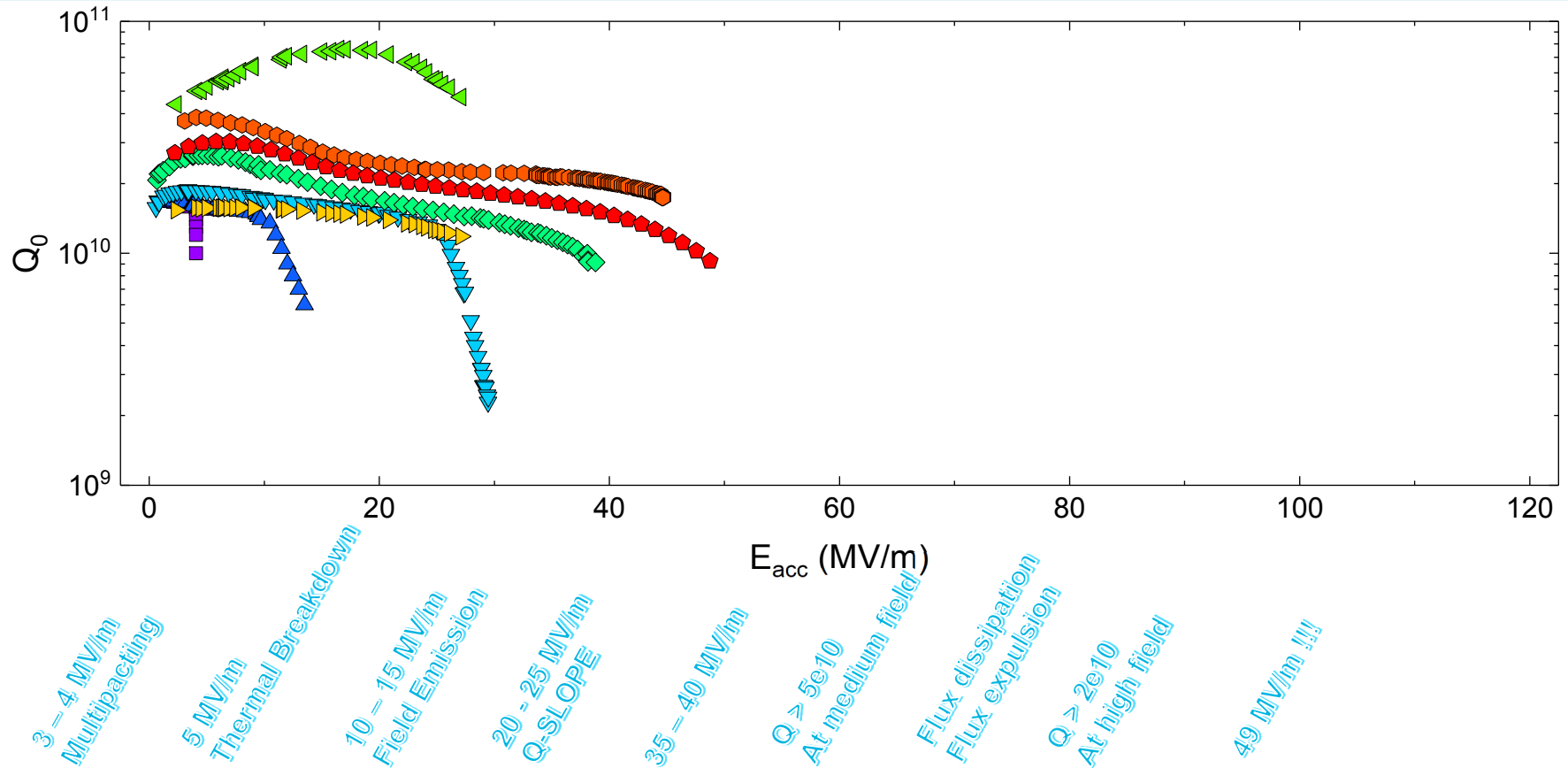


S. Posen et al., Proc. of SRF 2019

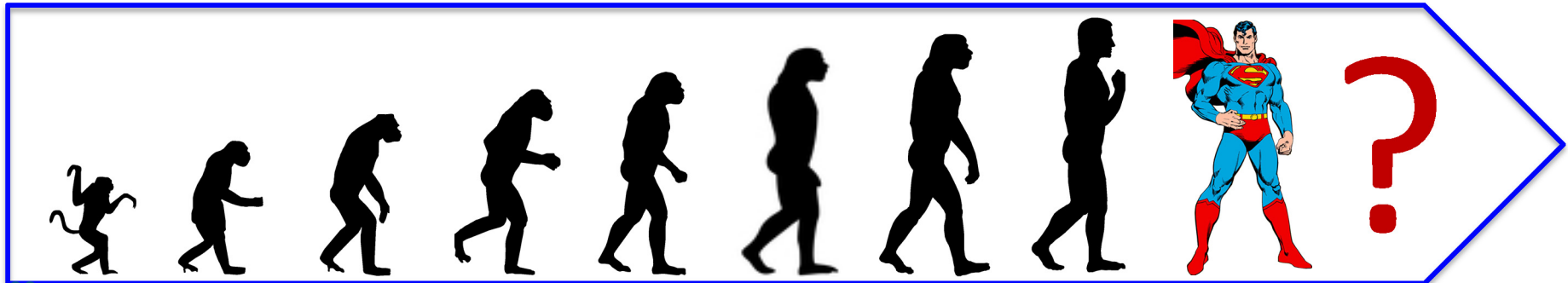
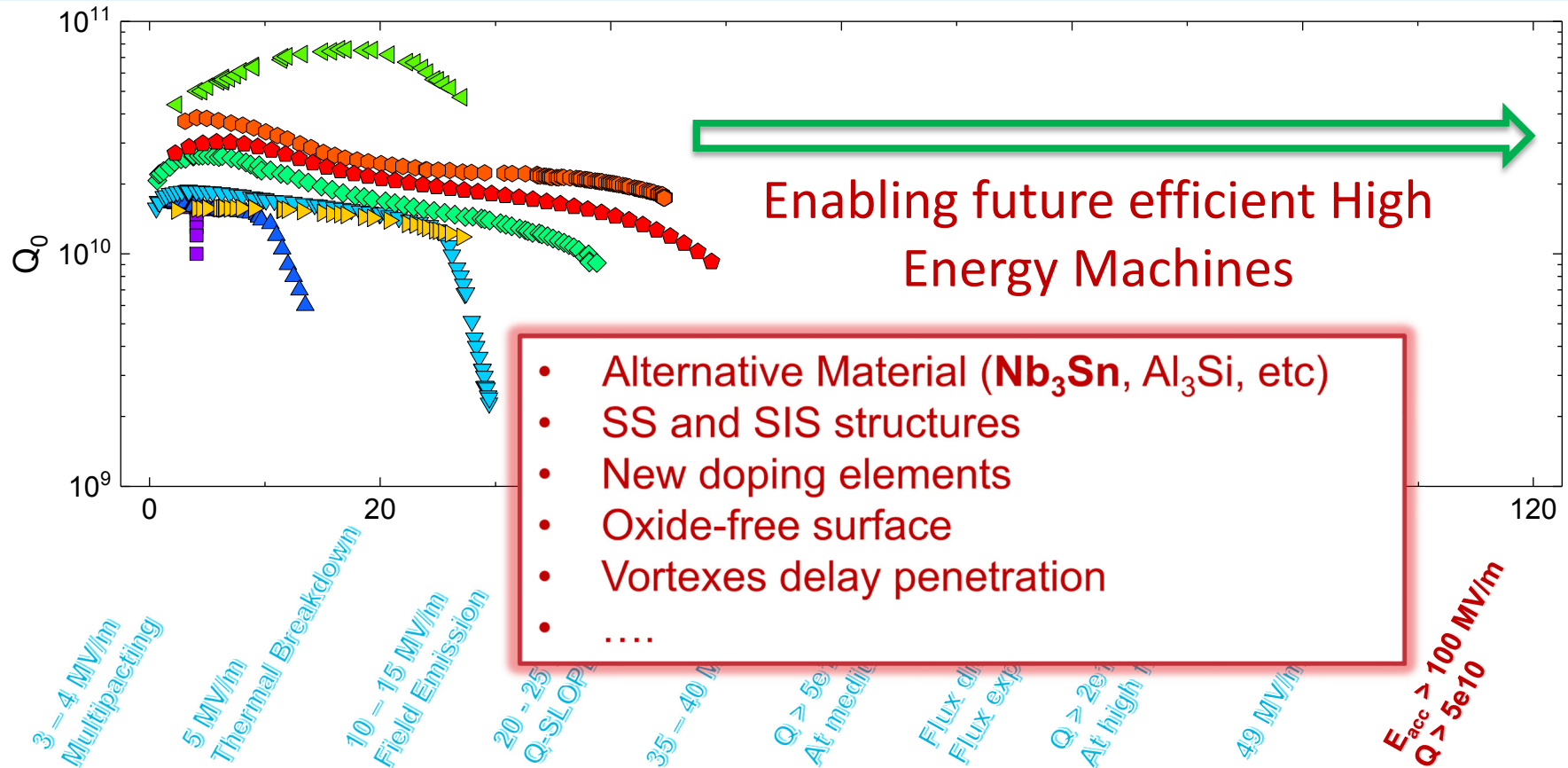
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SRF performance: past, present and future



SRF performance: past, present and future



Thanks to the whole FNAL SRF team!



Thank you for your
attention!

