Recent advances and breakthrough for SRF cavities at FNAL

Martina Martinello

12 March 2021

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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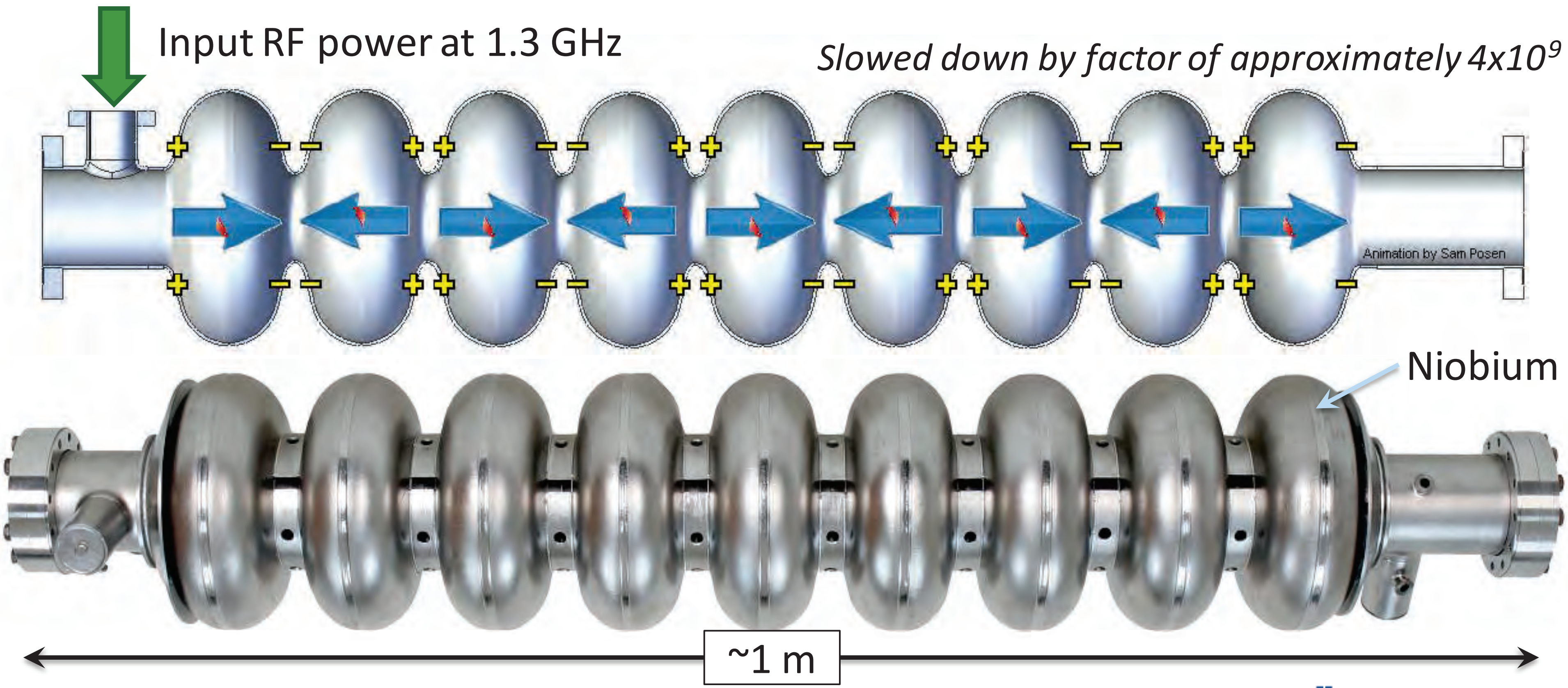
Particle Acceleration via SRF Cavities

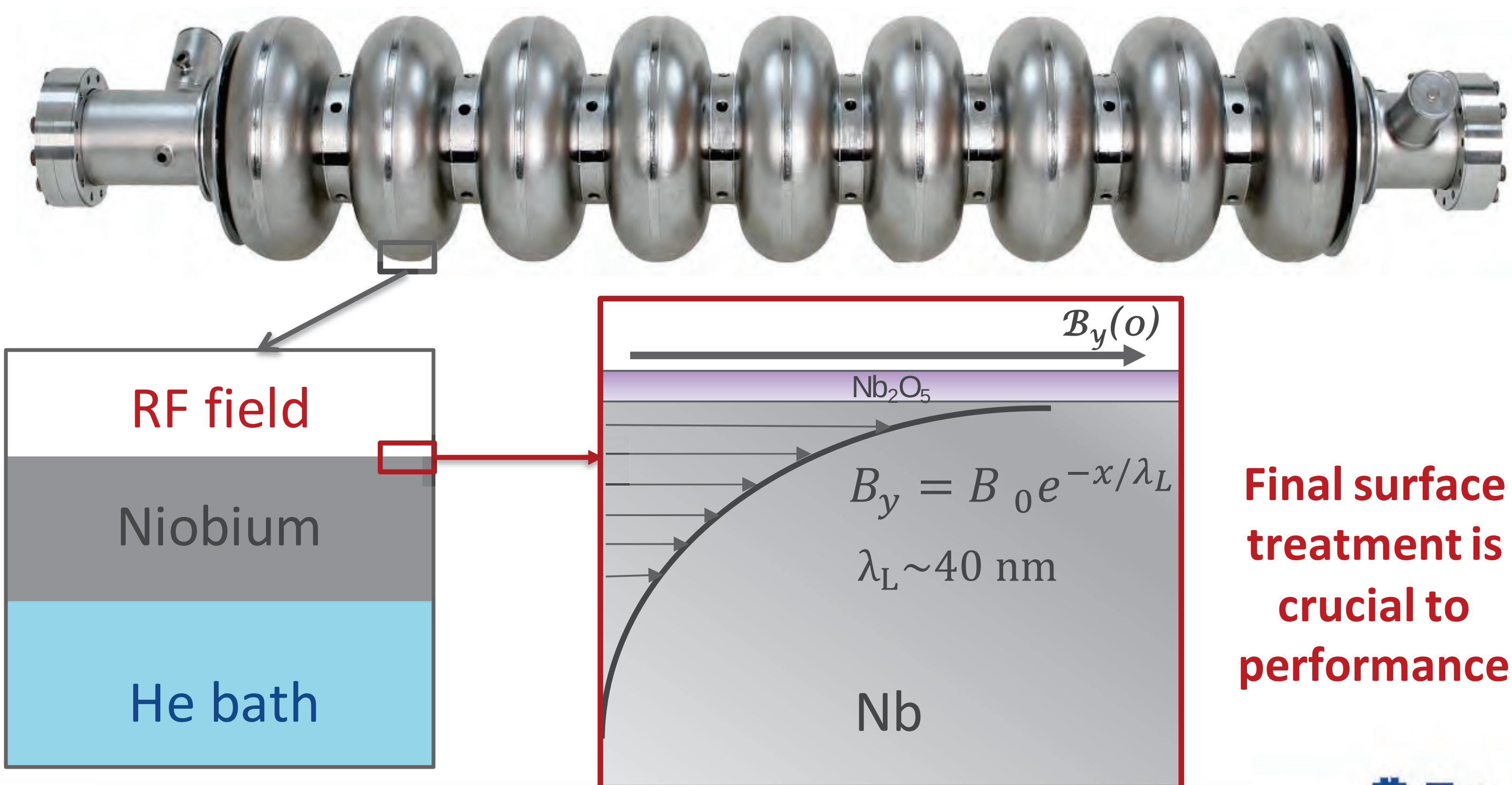
- Superconducting Radio-Frequency (SRF) cavities are electro-magnetic resonators characterized by **very low power dissipation**
- The electric field provide acceleration to charged particles



Images from linearcollider.org, WIkipedia

Superconducting RF Cavities

- Niobium (Tc=9.2 K), T operation 2 - 4.5 K
- RF surface resistance → <u>fighting against nΩ</u>
- Losses concentrate on the first ~100 nm of the **inner surface**

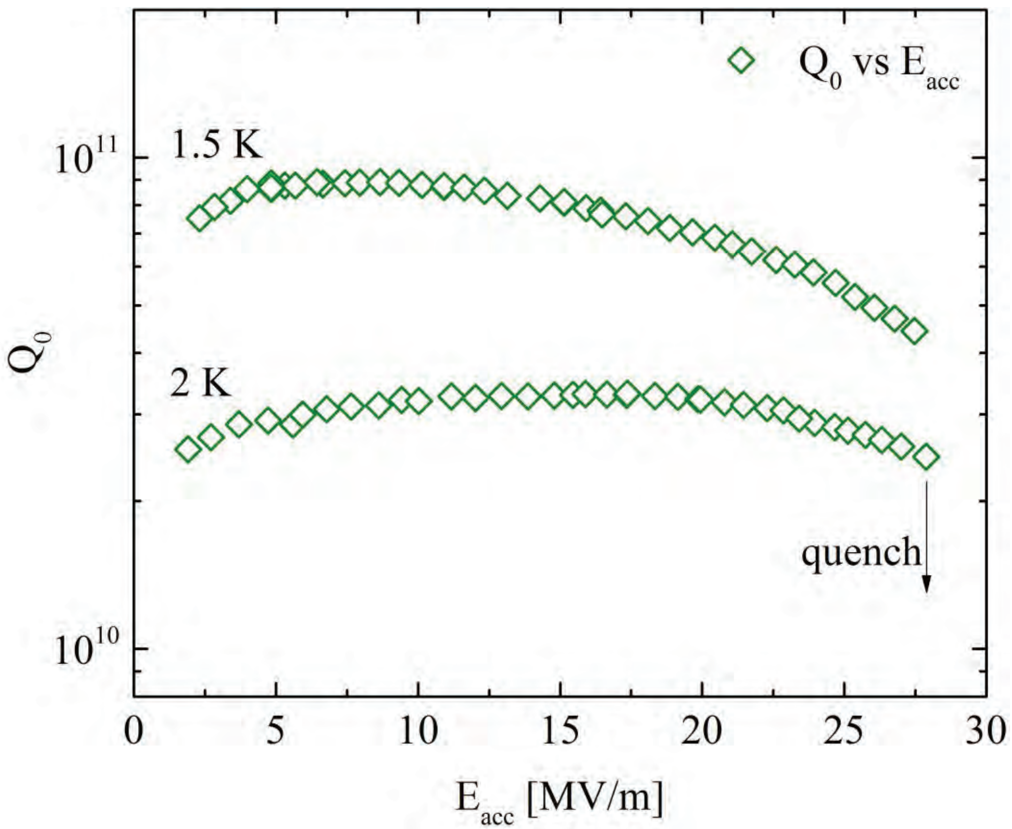


Final surface treatment is crucial to performance

Beam view, inside the cavity

Extreme attention to surface treatments and surface cleanliness are mandatory

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 → lower power consumption. Limited by nΩ of surface resistance.

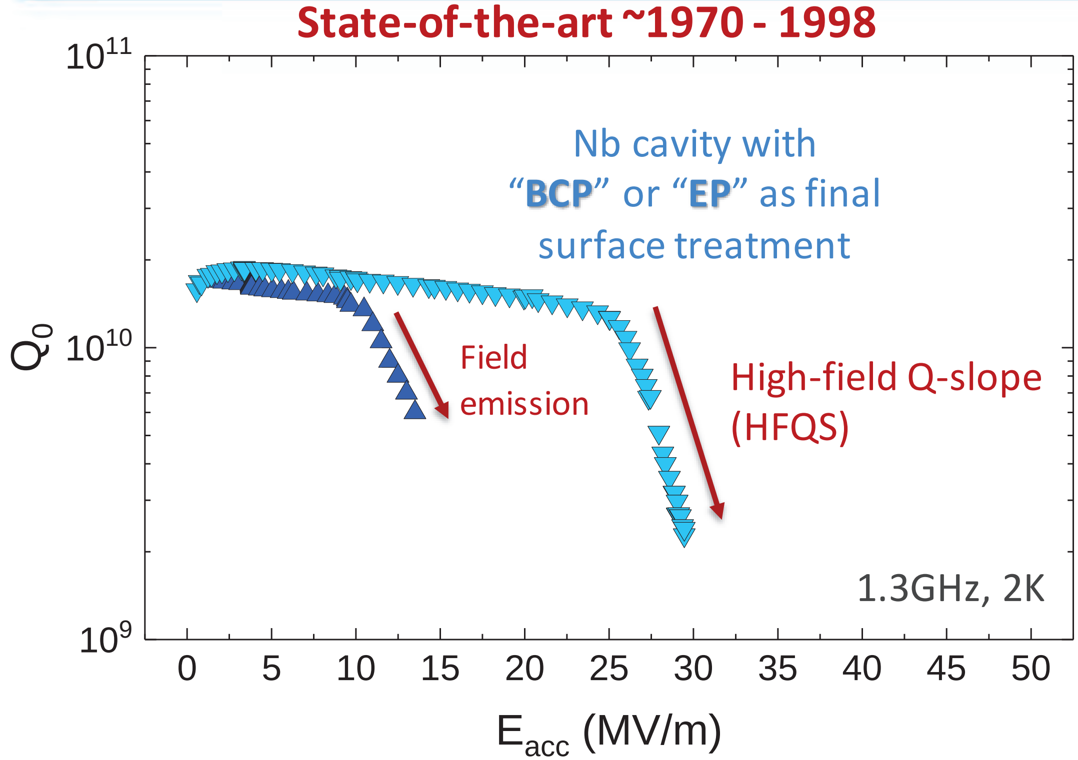
Accelerating field (E_{acc}):

Determine the energy transferred to charged particles.

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

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

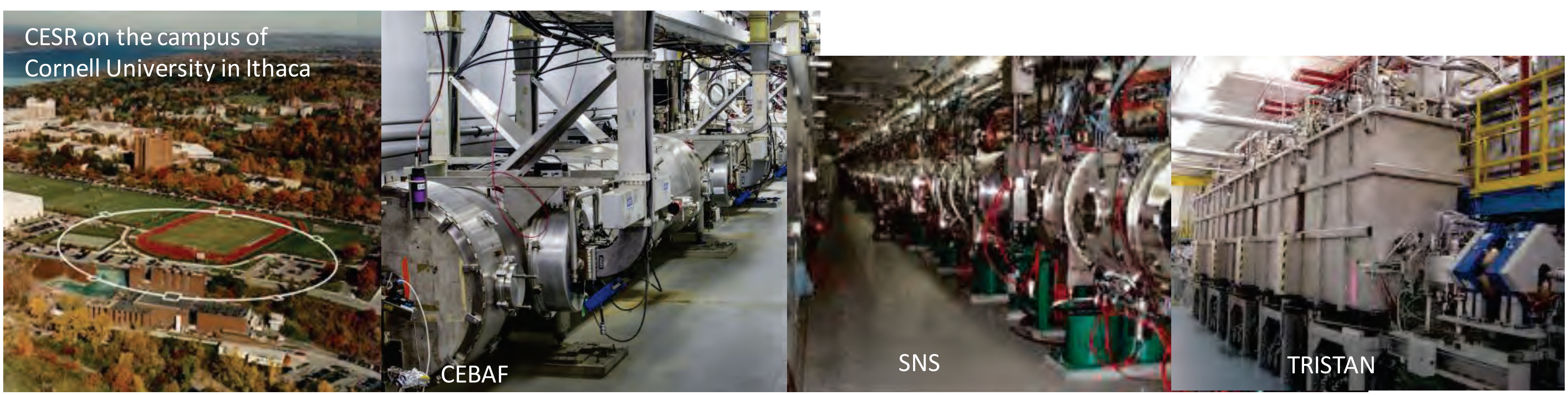
Historical progress of SRF technology



BCP=Buffer chemical polishing
EP=Electro-polishing

Enabled first SRF-based particle accelerators:

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



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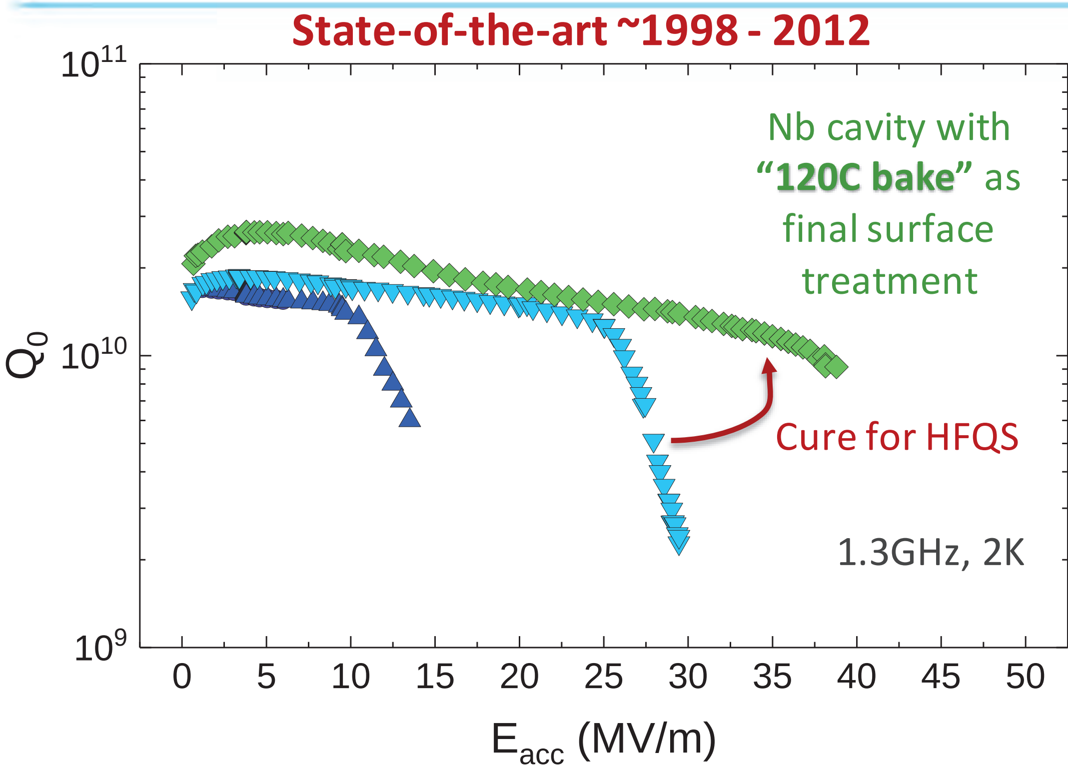
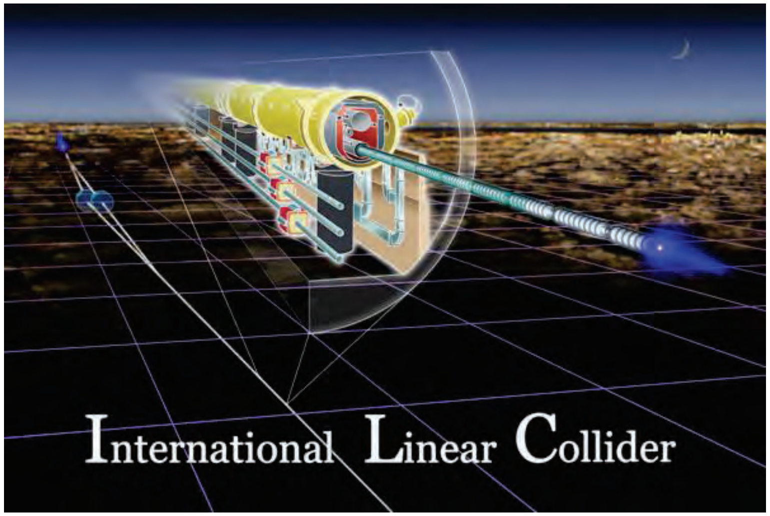


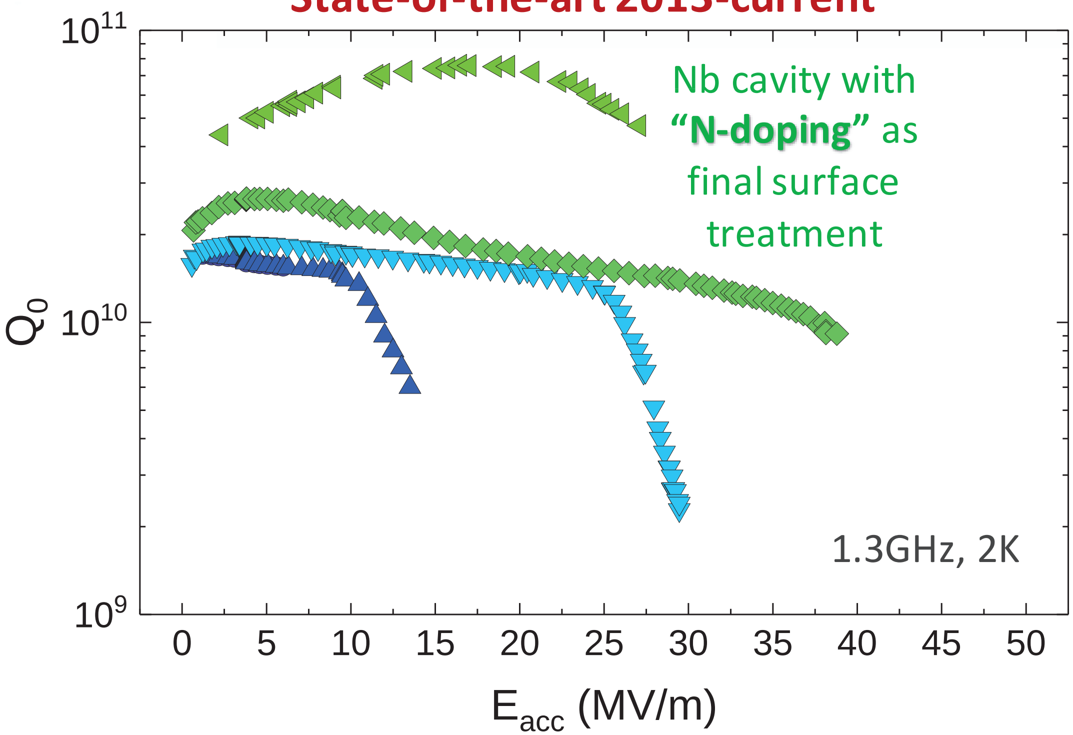


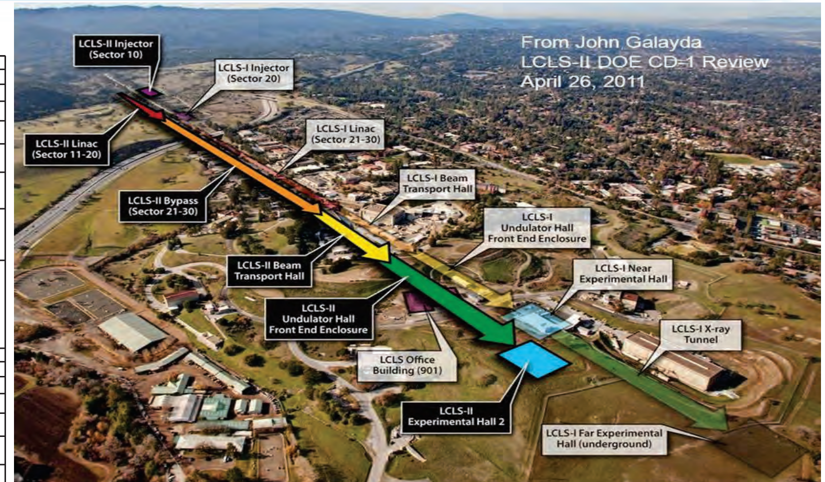
Enabled big SRF-based projects (LINAC):

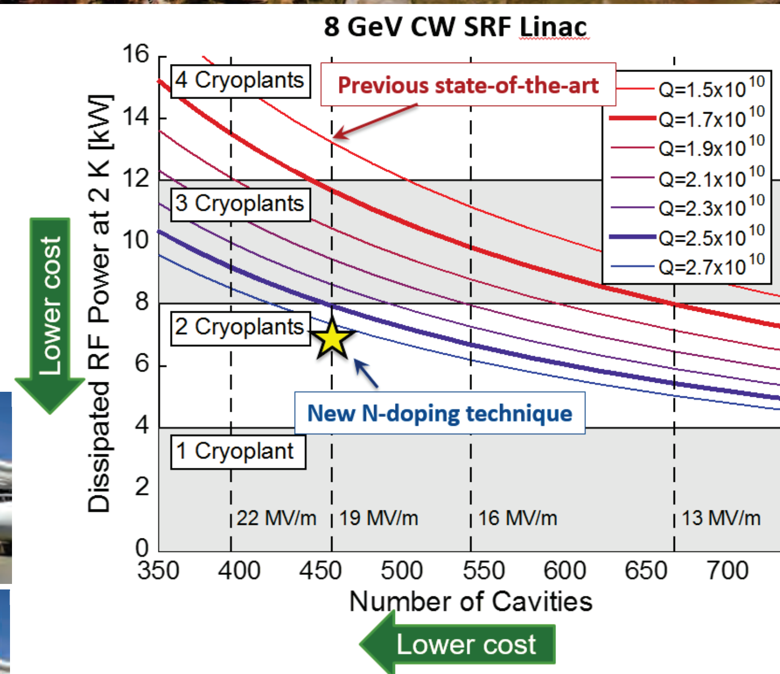
- **ILC – 500 GeV** (16,000 Nb cavities)
  $Q = 1 \cdot 10^{10}$ at 31.5 MV/m
- **E-XFEL – 17.5 GeV** (816 Nb cavities)
  $Q = 1 \cdot 10^{10}$ at 23.6 MV/m

Historical progress of SRF technology

State-of-the-art 2013-current

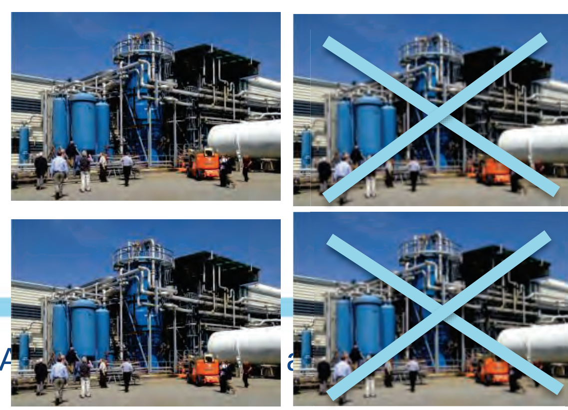




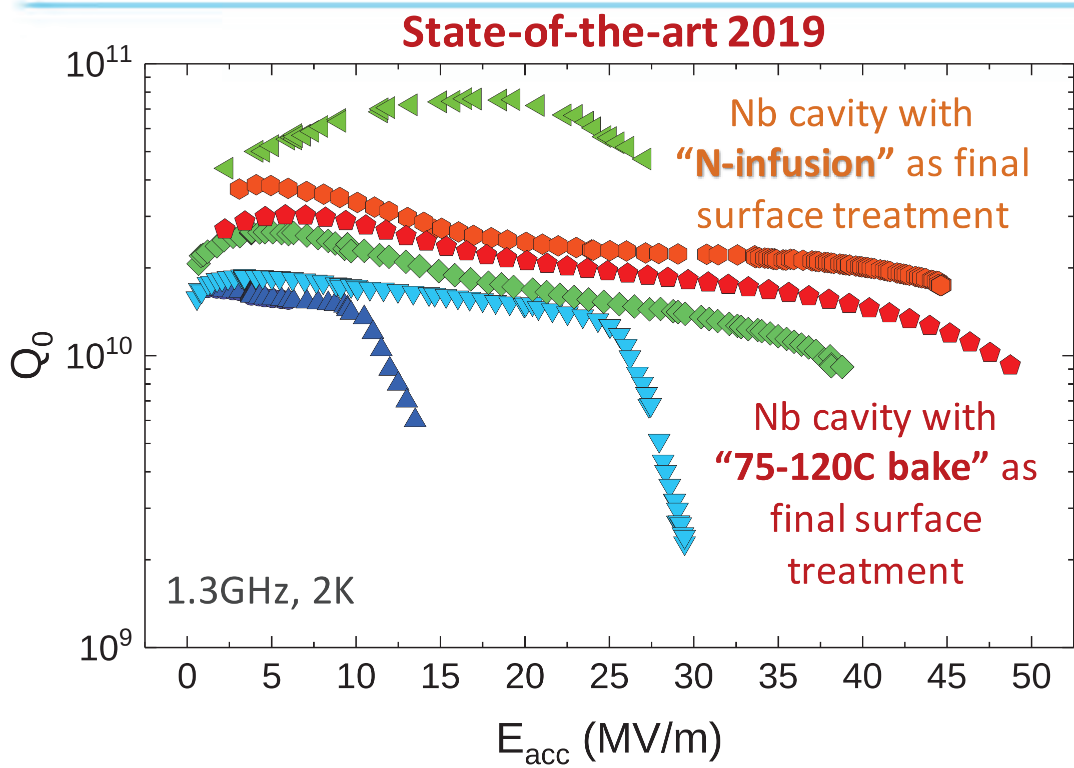


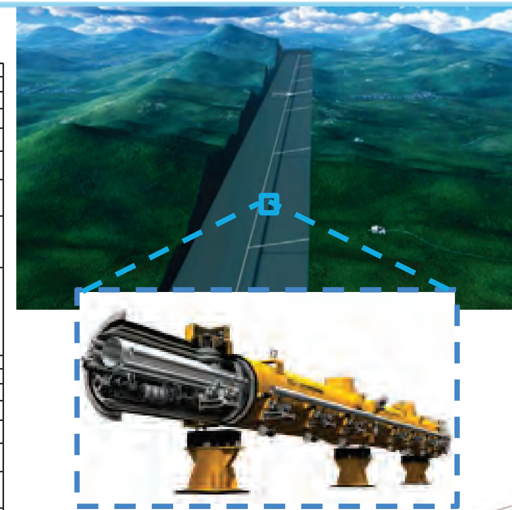
Enabled affordable CW operation:

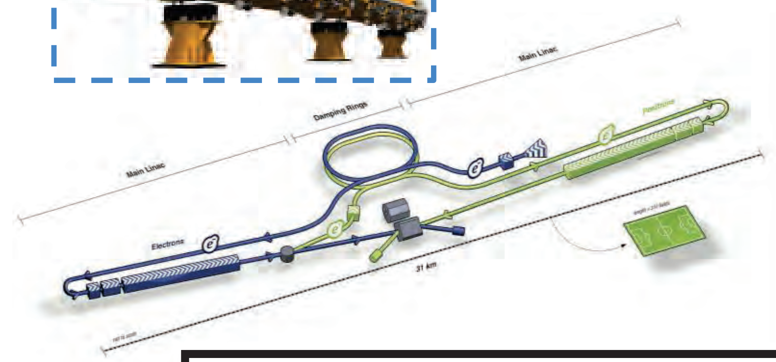
- **LCLS-II**
- **LCLS-II HE**
- **PIP-II**
- **...**



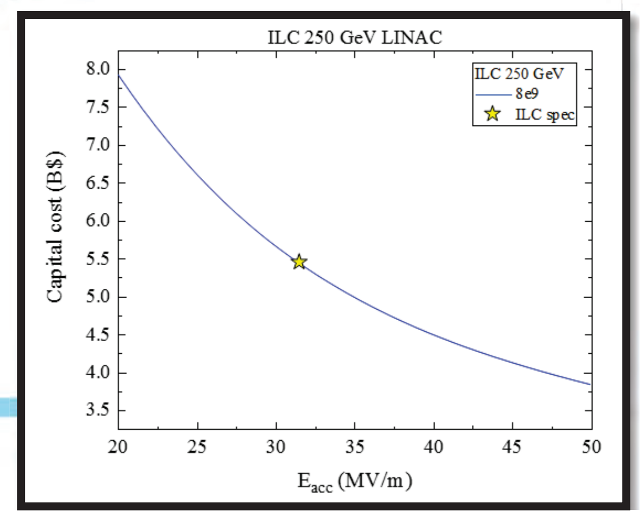
Historical progress of SRF technology







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



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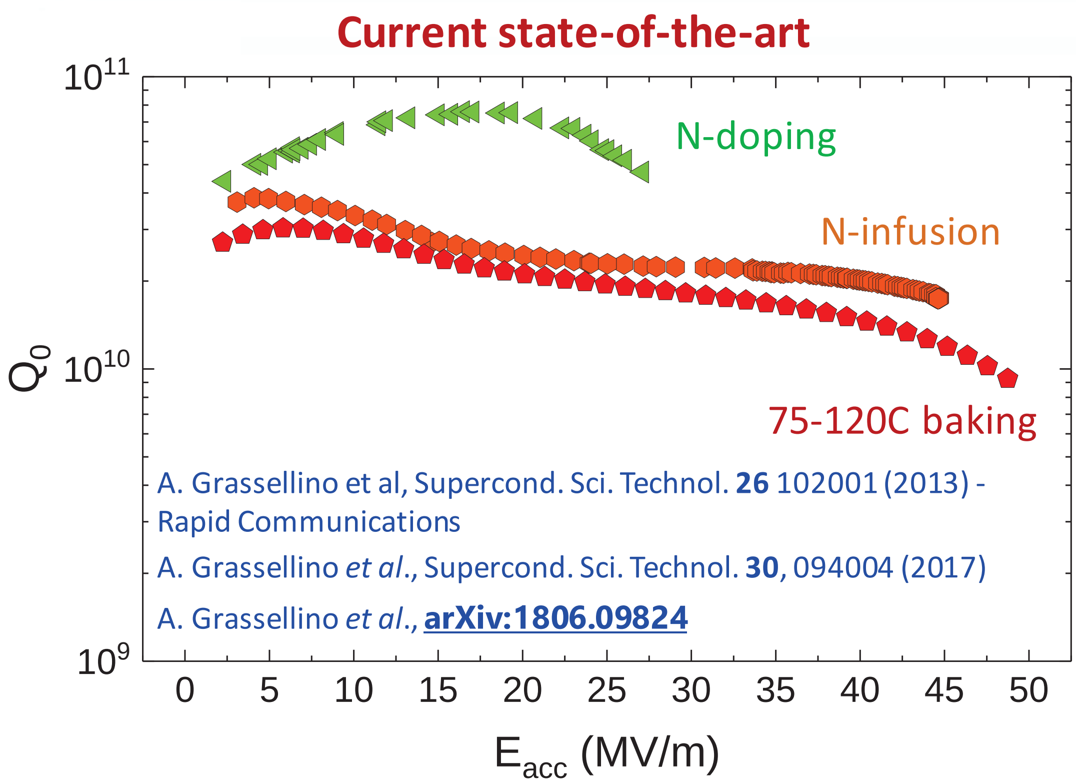
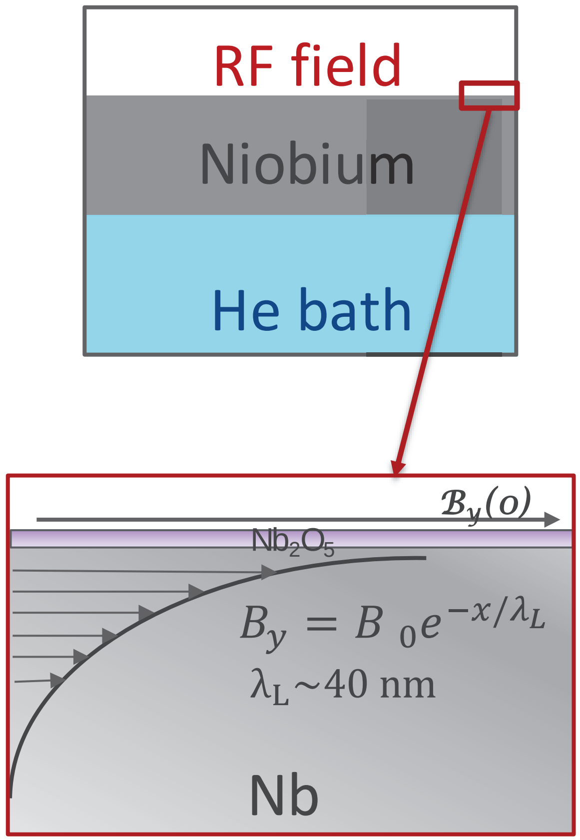
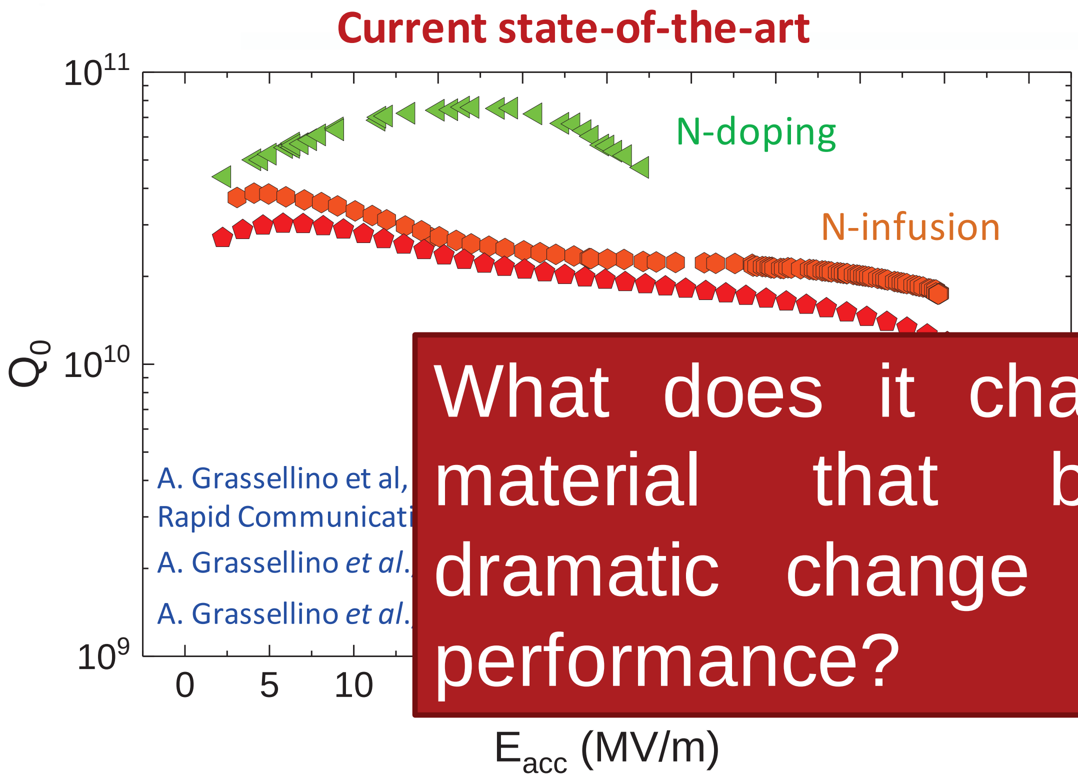
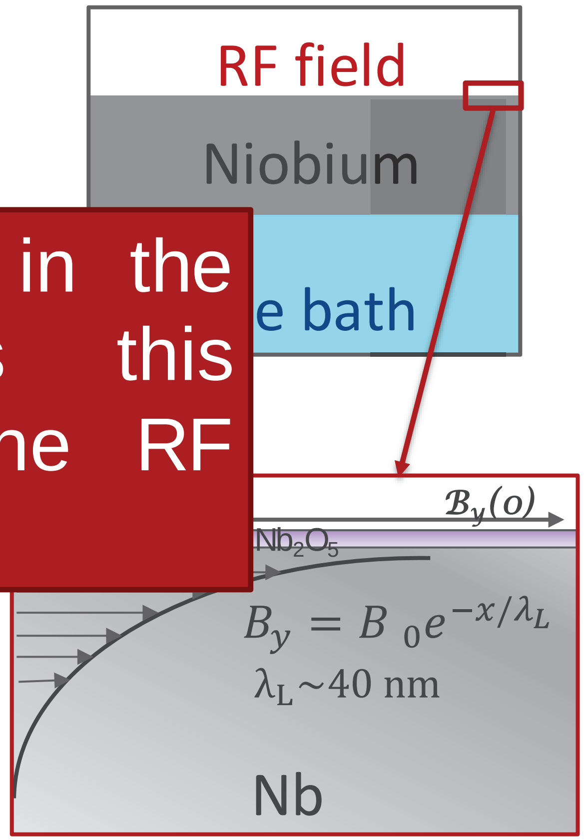




Fermilab

Historical progress of SRF technology



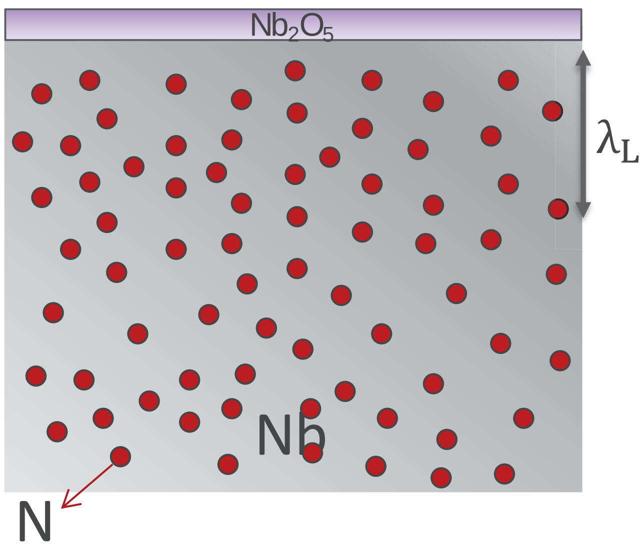


What does it change in the material that brings this dramatic change in the RF performance?

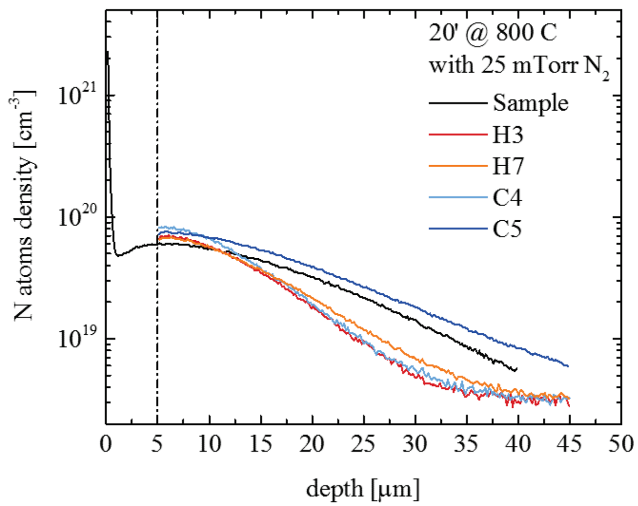
Fermilab

N-doping

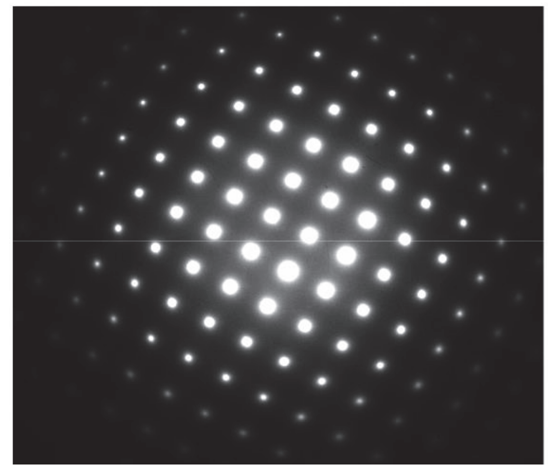
800C UHV, 3 hours → 800C N_2 injection p=25mTorr → 800C N_2 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP



SIMS spectra



TEM/NED

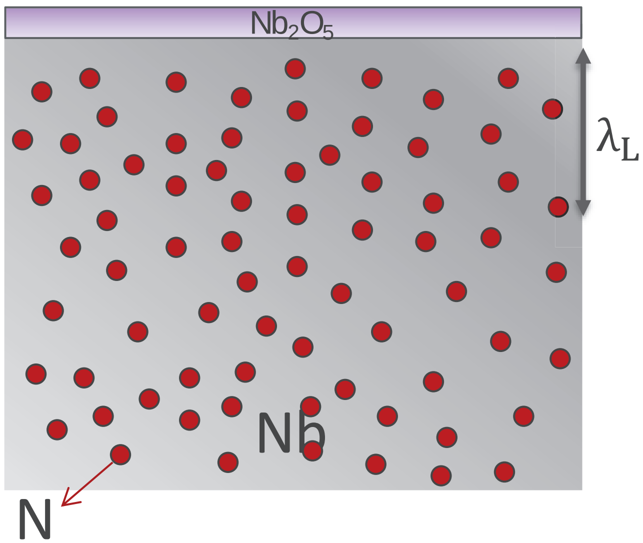


Y. Trenikhina et al, Proc. of SRF 2015

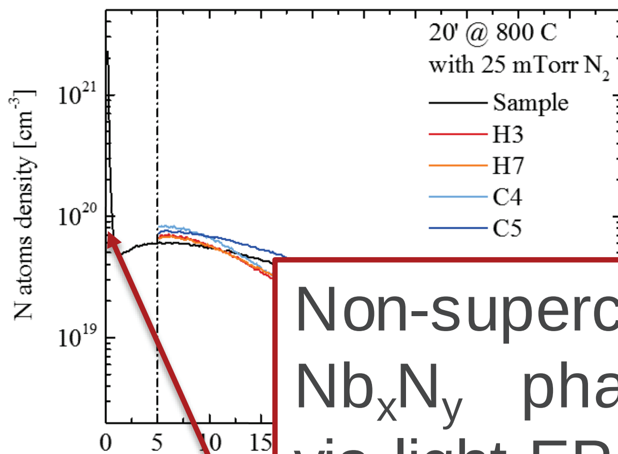
- SIMS spectra: nitrogen in the material for about tens of micrometers
- TEM/NED: only Nb signal from diffraction pattern → N is interstitial

N-doping

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

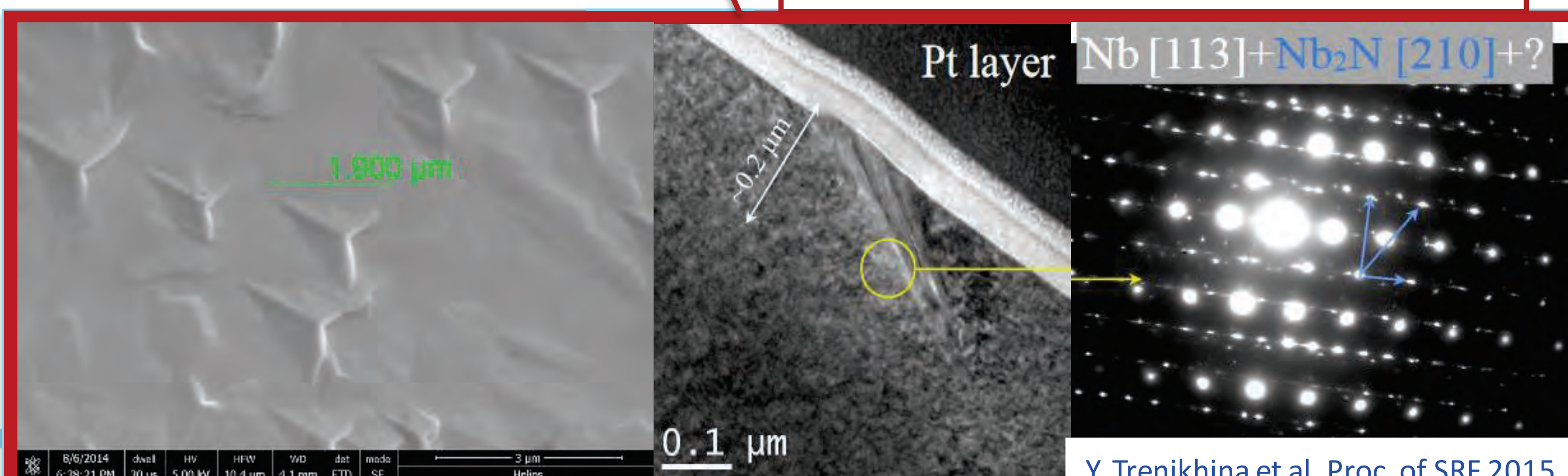


SIMS spectra



TEM/NED

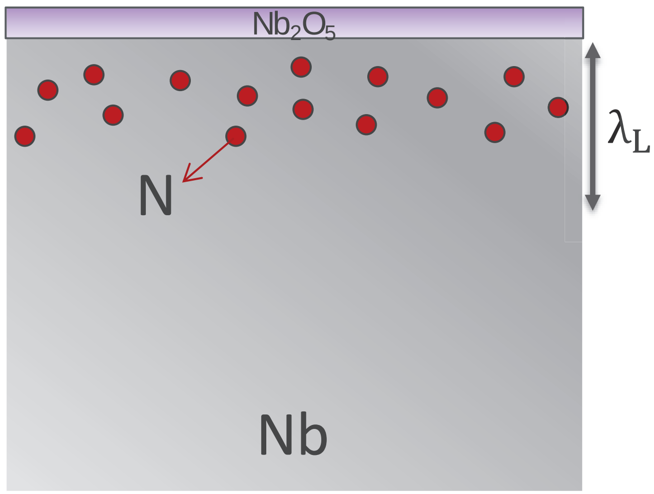
Non-superconducting Nb_xN_y phase removed via light EP



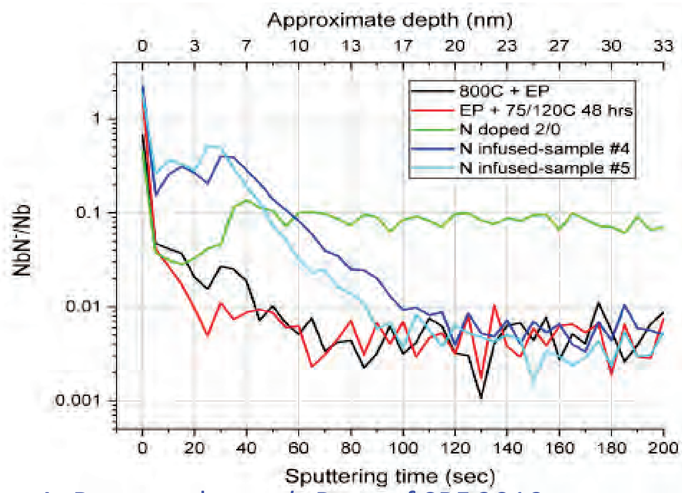
Y. Trenikhina et al, Proc. of SRF 2015

120C N-infusion

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



SIMS spectra of cavity cut-outs

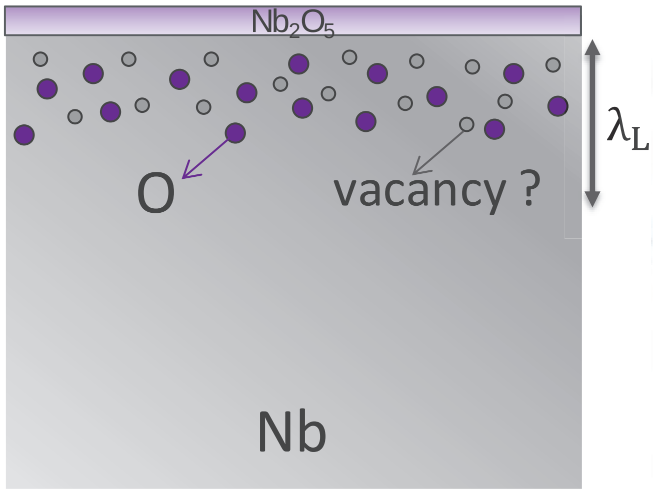


A. Romanenko *et al.*, Proc. of SRF 2019

- SIMS spectra: nitrogen in the material for about 10-15 nanometers

75-120C baking

800C UHV, 3 hours → Cavity assembly → 75C 4 hours + 120C 48 hours



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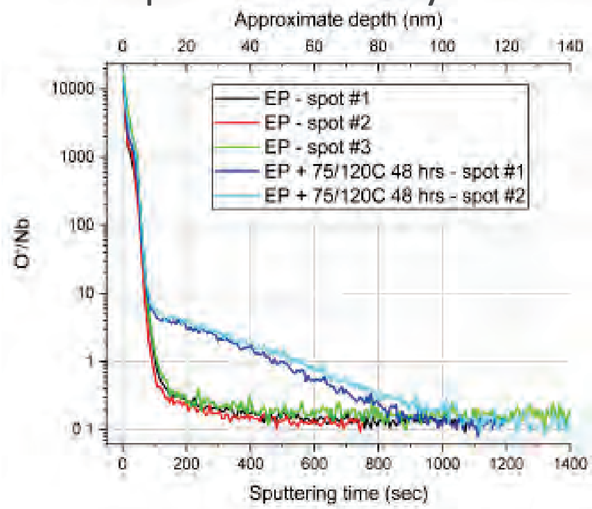

A. Romanenko *et al.*, Proc. of SRF 2019

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Fermilab

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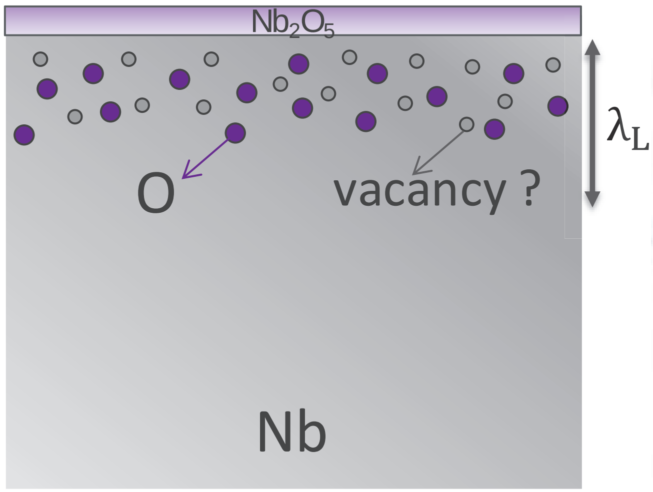

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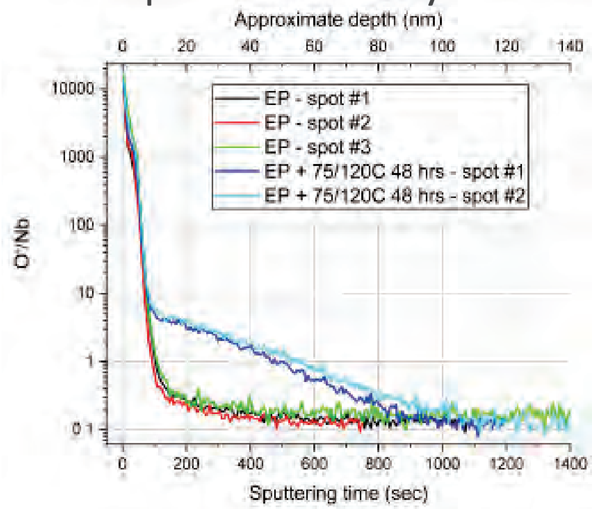
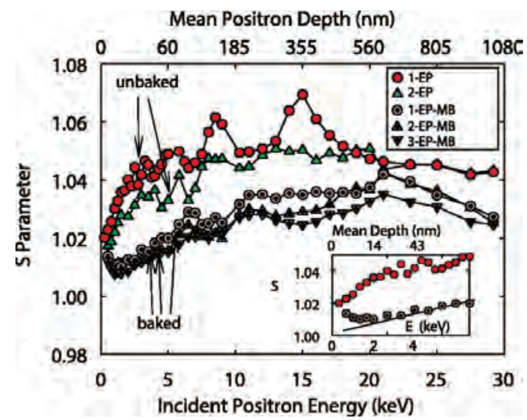


A. Romanenko *et al.*, Proc. of SRF 2019

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

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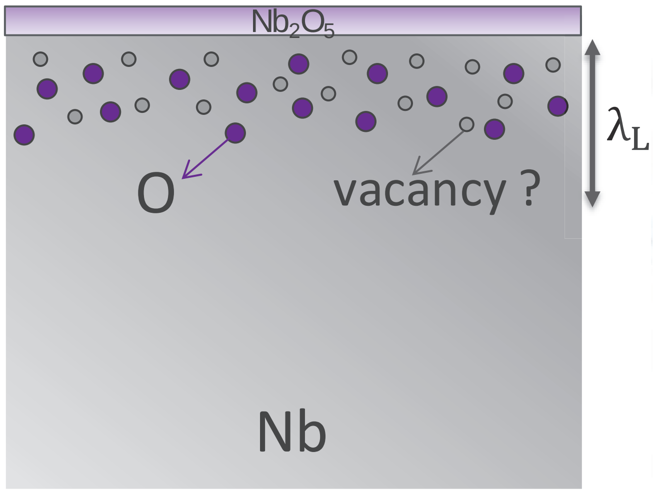

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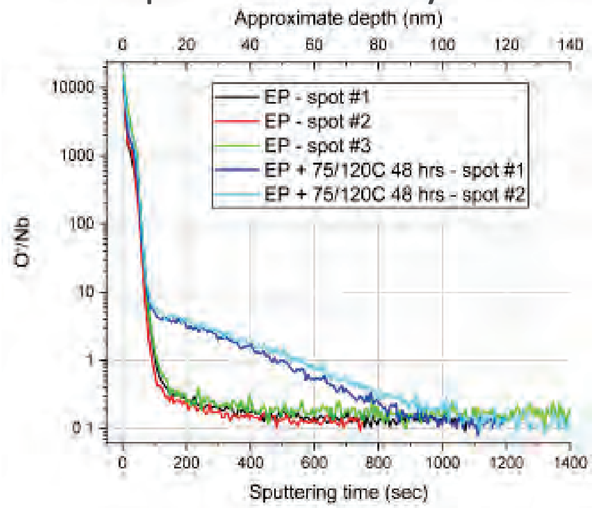
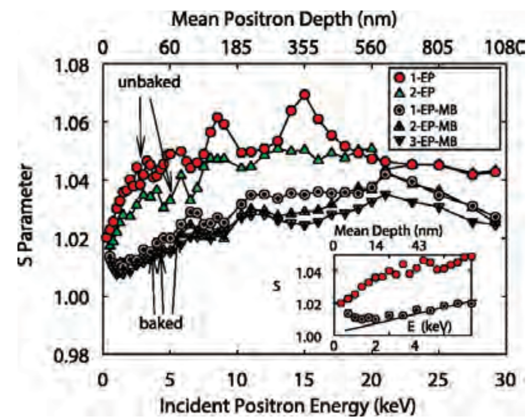


A. Romanenko *et al.*, Proc. of SRF 2019

Positron annihilation in 120C baked samples



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

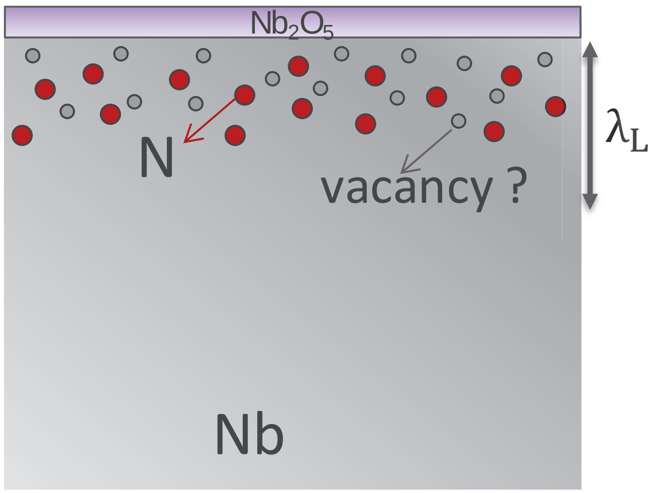
- SIMS spectra: oxygen in the material for nanometers
- Possibility of having vacancy-hydrogen complexes also after the 75-120C baking

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

Fermilab

120C N-infusion

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



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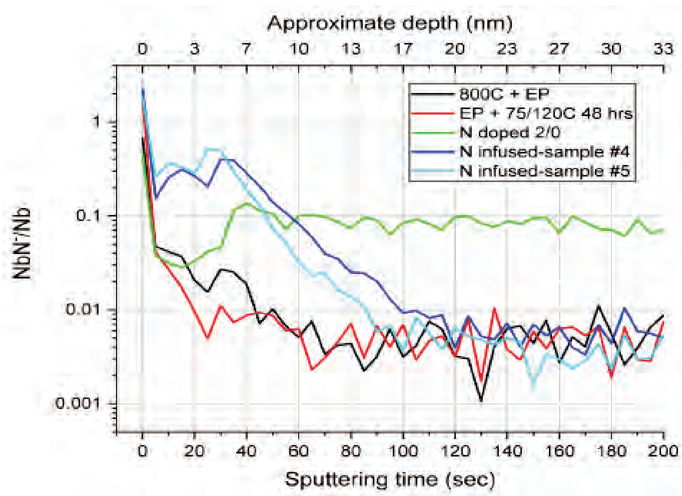

A. Romanenko *et al.*, Proc. of SRF 2019

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

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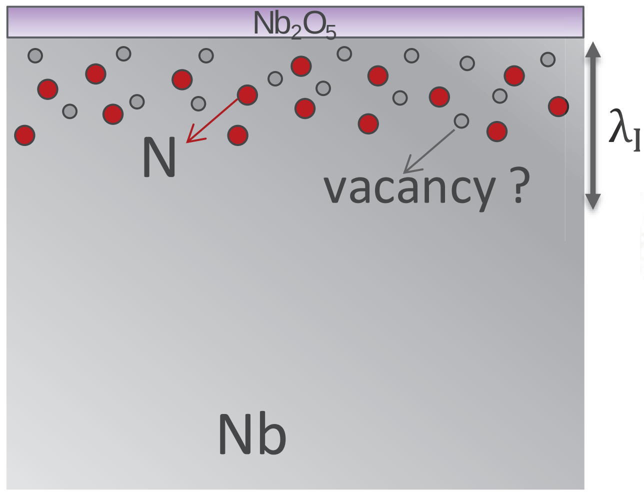
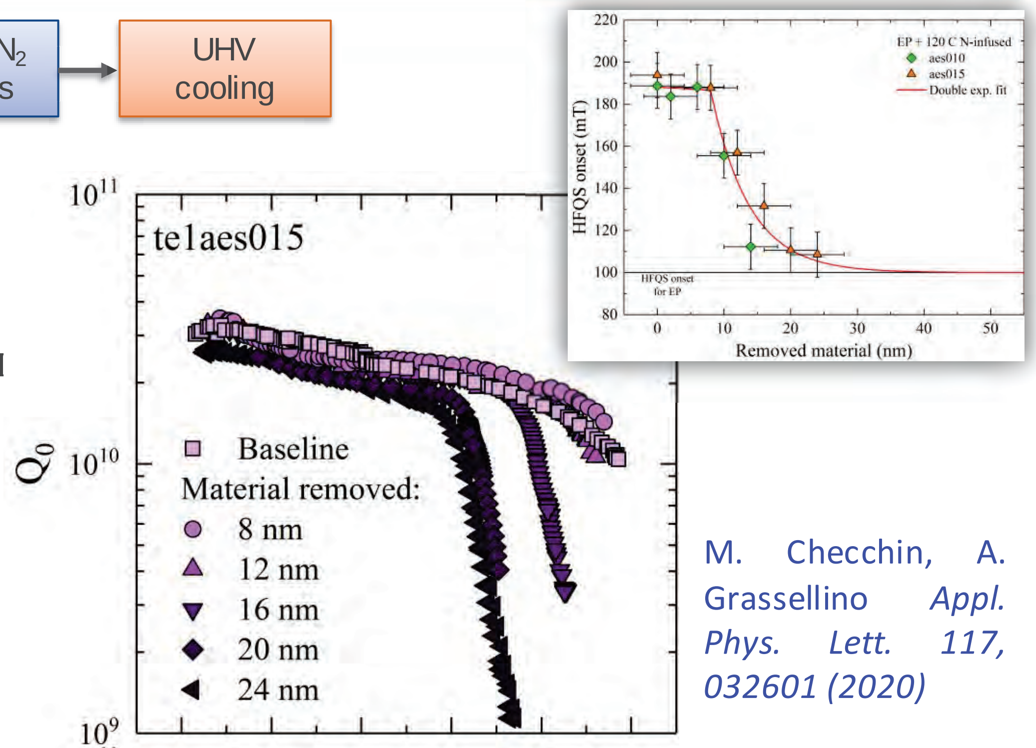


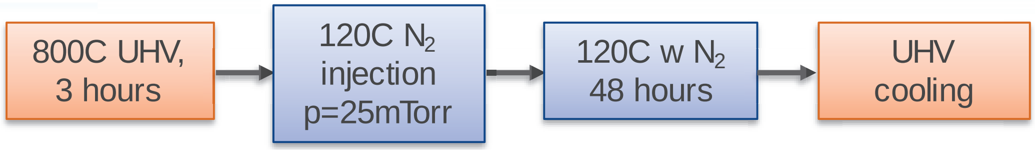


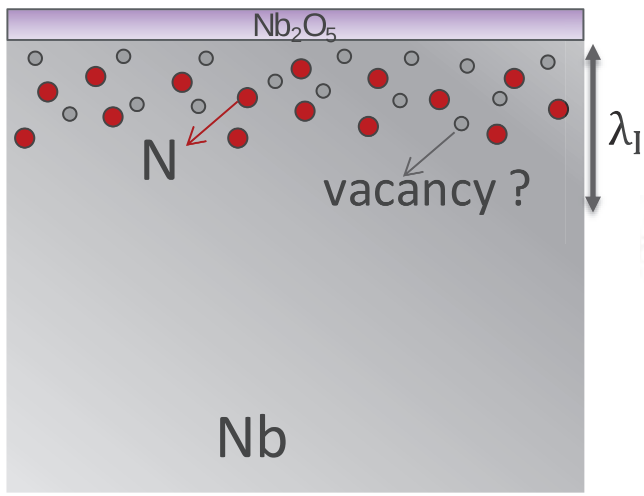
M. Checchin, A. Grassellino *Appl. Phys. Lett. 117, 032601 (2020)*

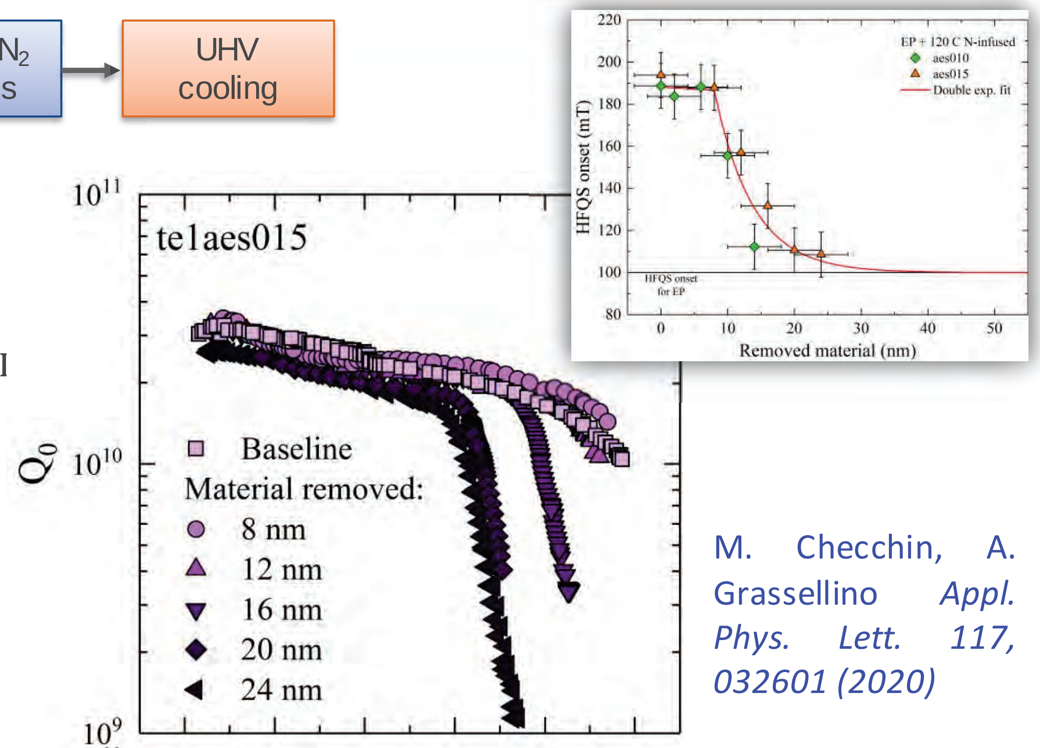
- HF rinses studies shows that the N-infusion process modifies only the surface of the material
- HFQS behavior is totally re-established after removing ~ 20 nm

Fermilab

120C N-infusion







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- 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

The performance improvement of the N-infusion treatment must be connected to impurities within the first 15-20 nm

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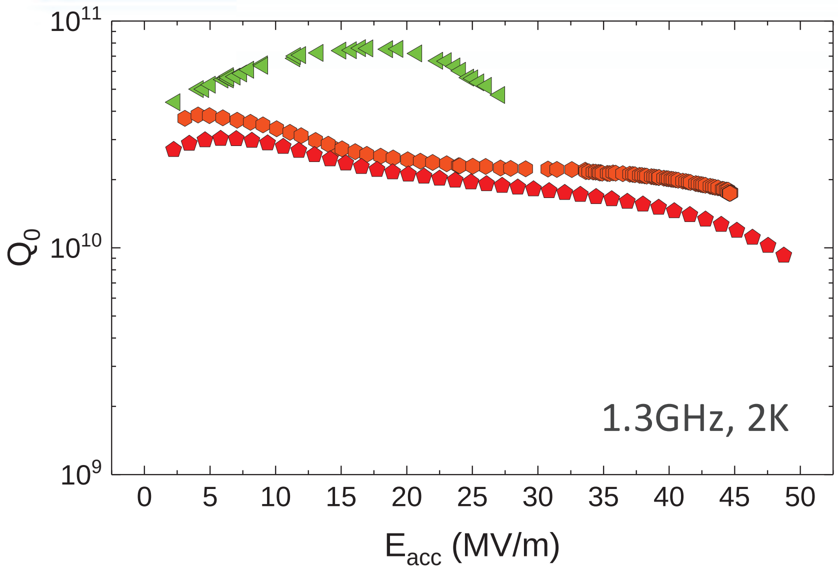
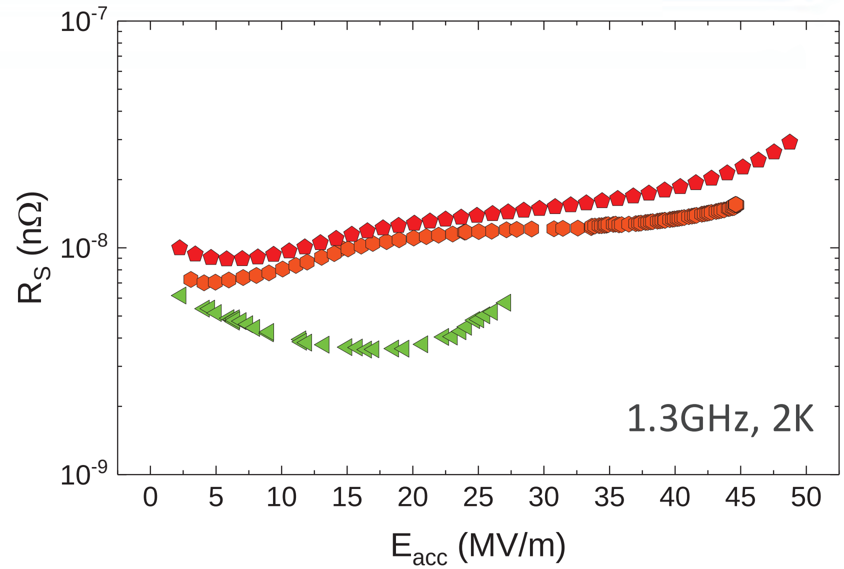
The surface resistance



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



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

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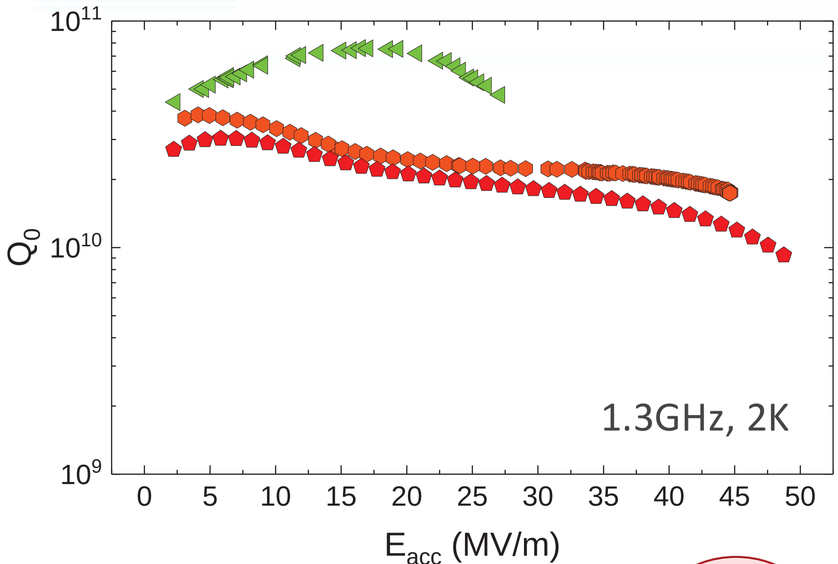

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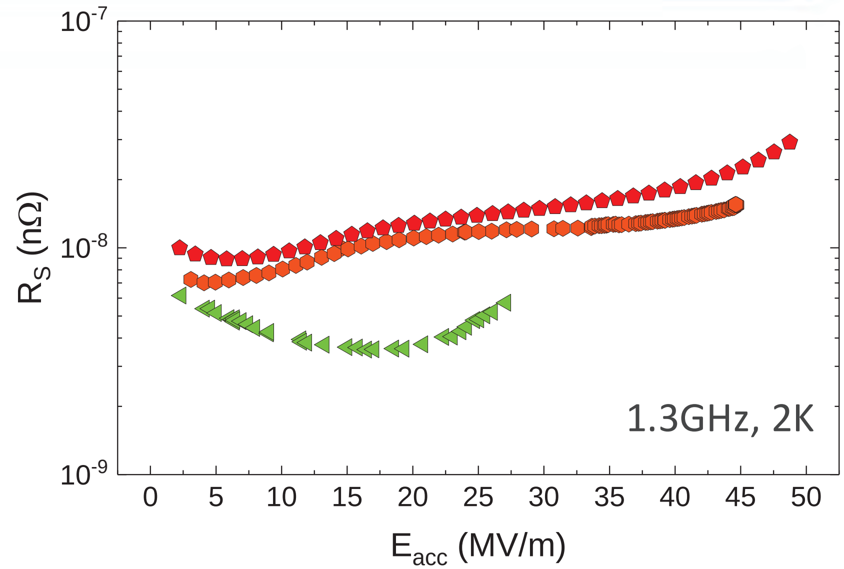
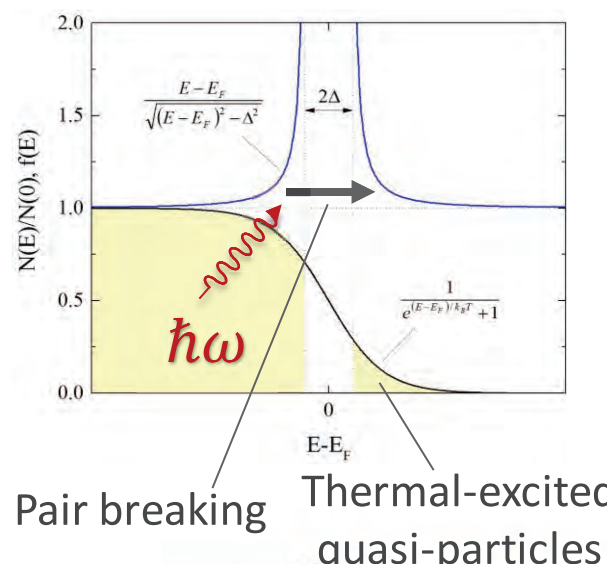


$$R_s = R_{BCS} + R_{fl} + R_0$$

BCS surface resistance

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



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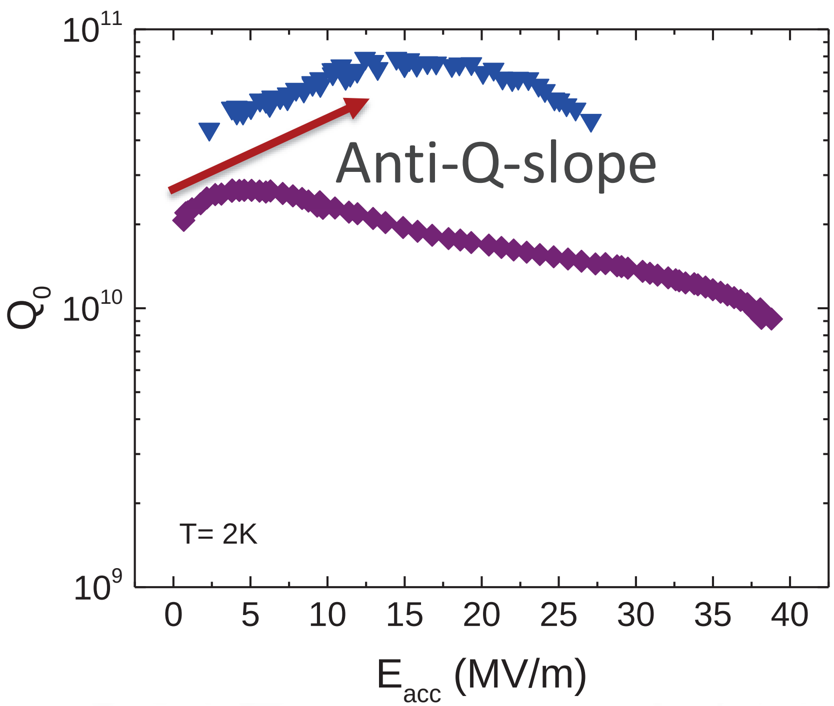
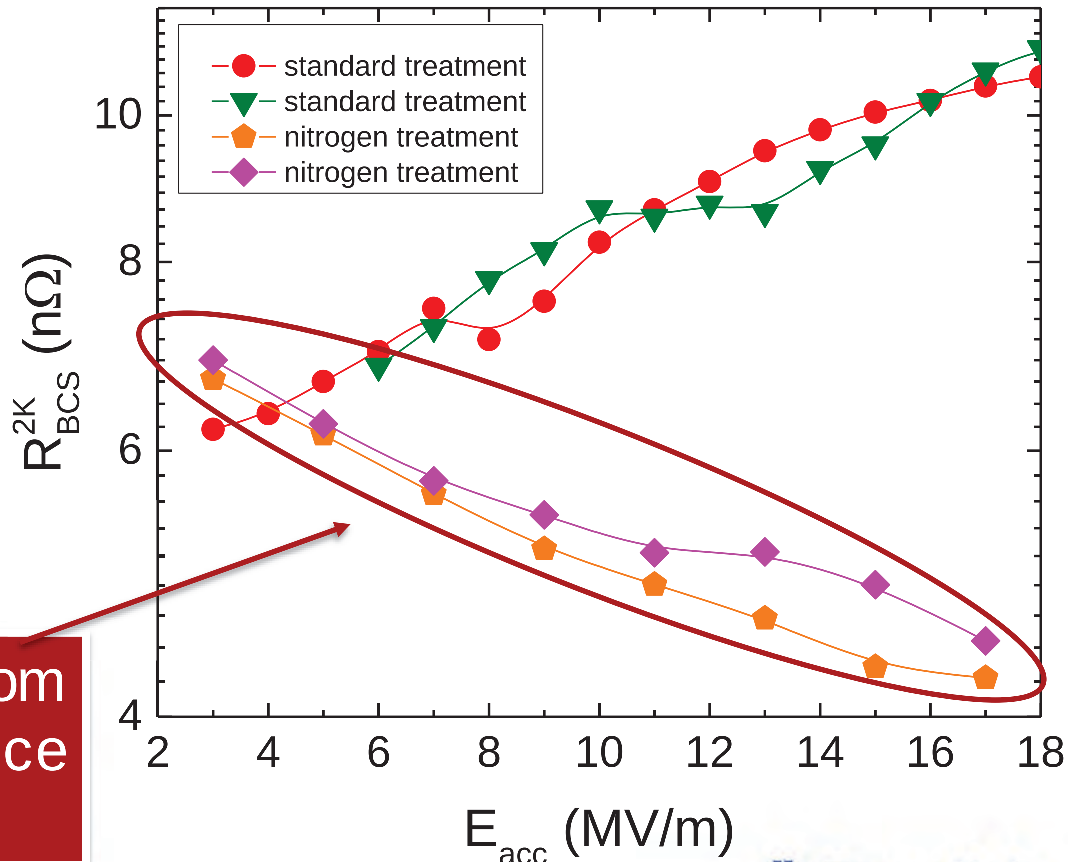
First observation of R_{BCS} decreasing with field

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





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

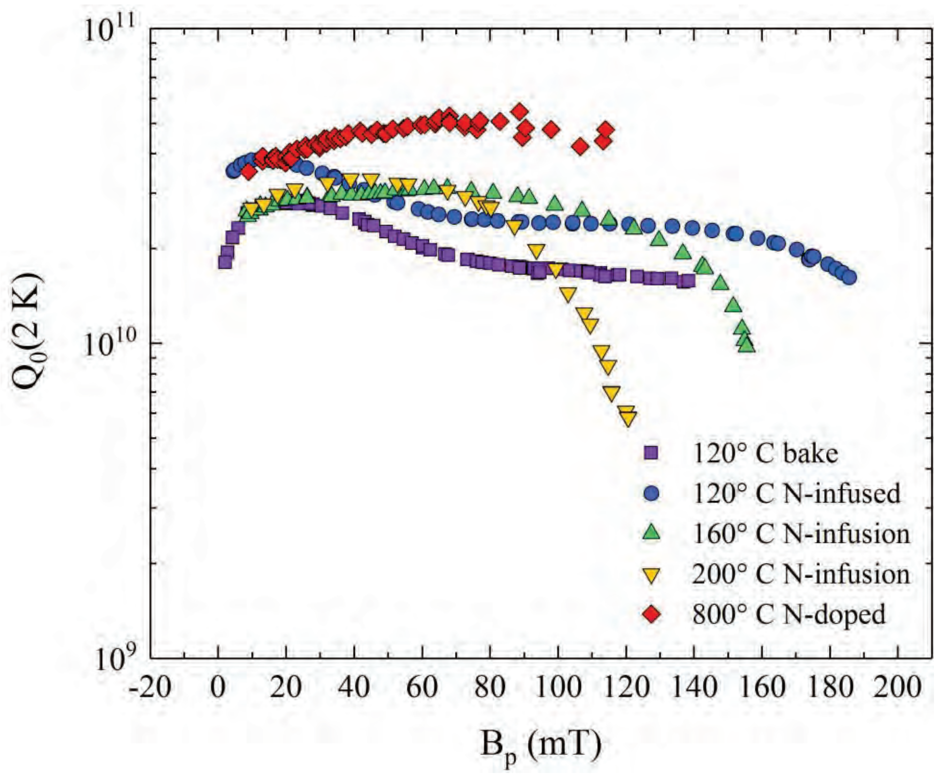
A. Grassellino et al, Supercond. Sci. Technol. **26** 102001 (2013) - Rapid Communications

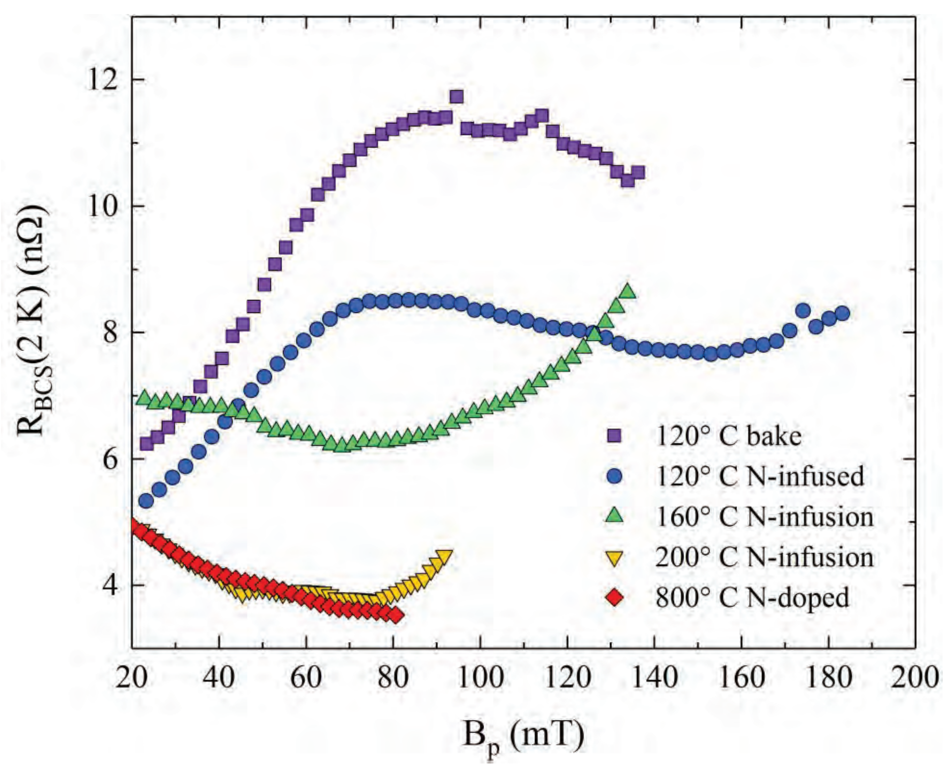
A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

R_{BCS} tuning with N-infusion at different T

By N-doping Nb cavities at lower temperatures (N-infusion) we can tune the Q-factor:

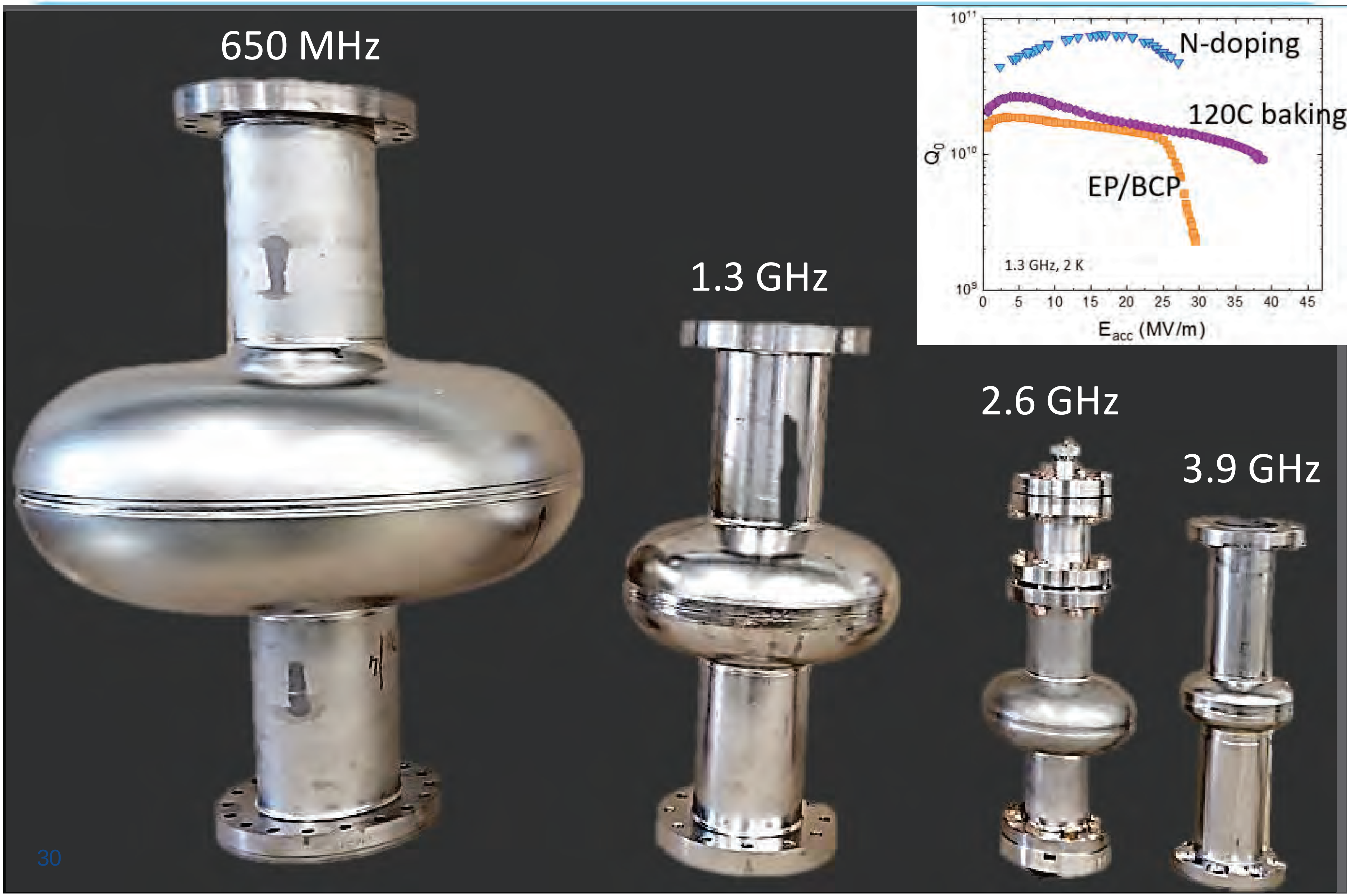
⇒ strong effects on the BCS and residual resistance



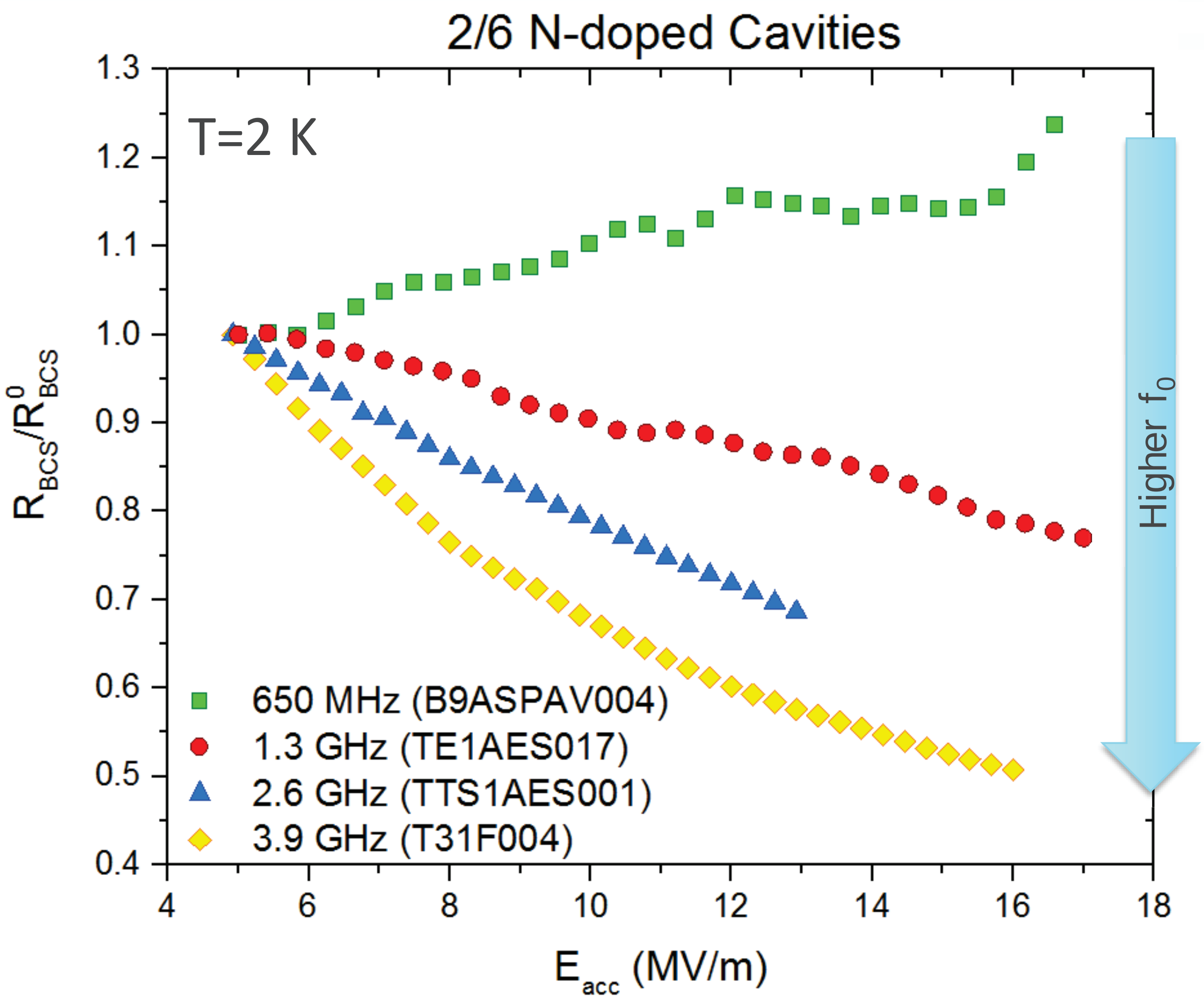


A. Grassellino *et al.*, Supercond. Sci. Technol. **30**, 094004 (2017)

Study of Cavities at Different Frequency



Frequency dependence of R_{BCS}(Eacc): toward a better understanding



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

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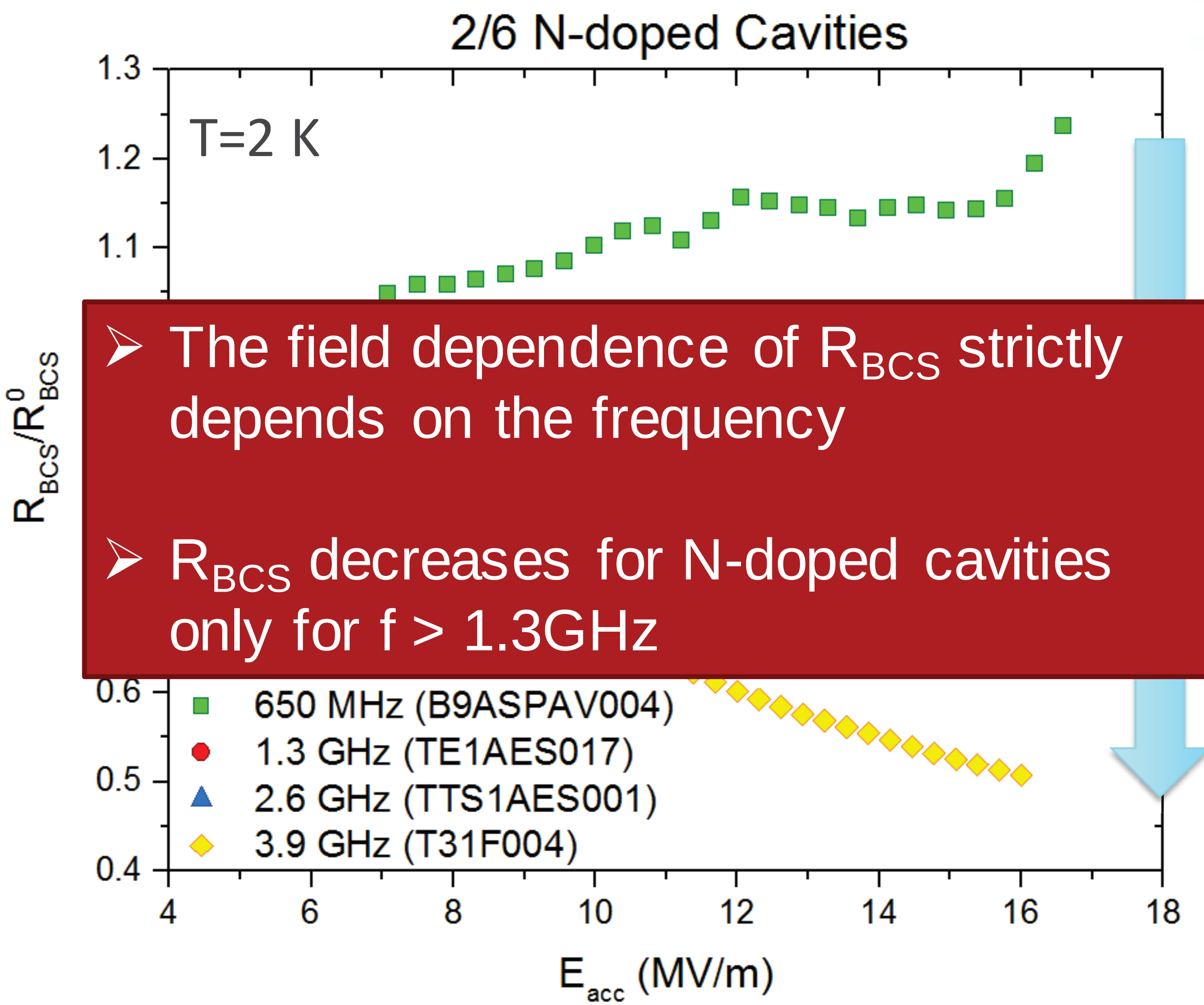
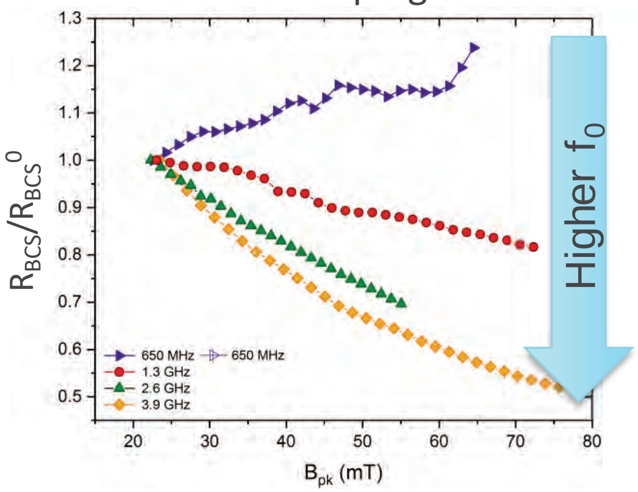


- The field dependence of R_{BCS} strictly depends on the frequency
- R_{BCS} decreases for N-doped cavities only for f > 1.3GHz

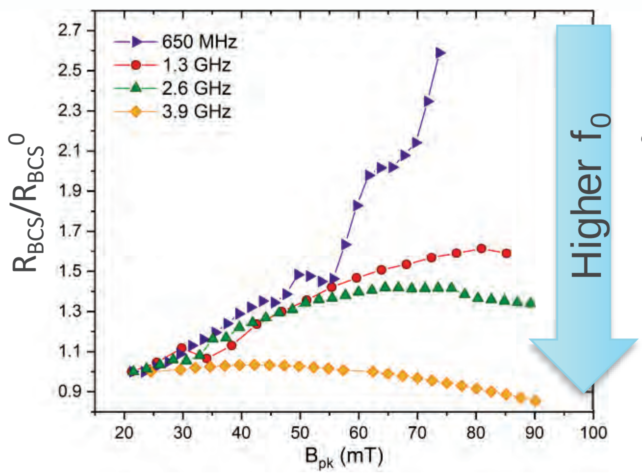
M. Martinello *et al.*, Phys. Rev. Lett. 121, 224801 (2018)

Summary of the Frequency Dependence of R_{BCS}(Eacc)

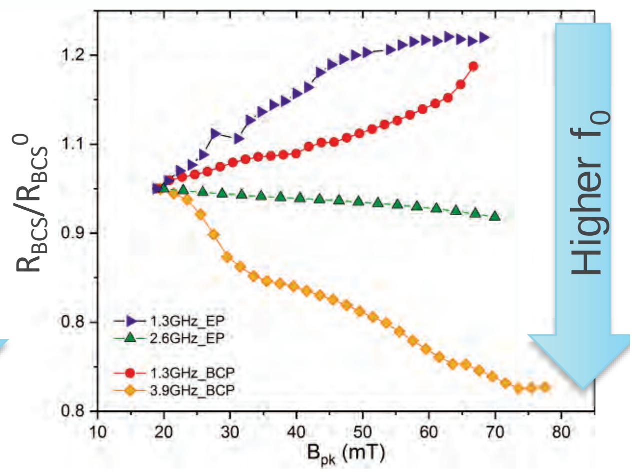
N-doping



120C baking

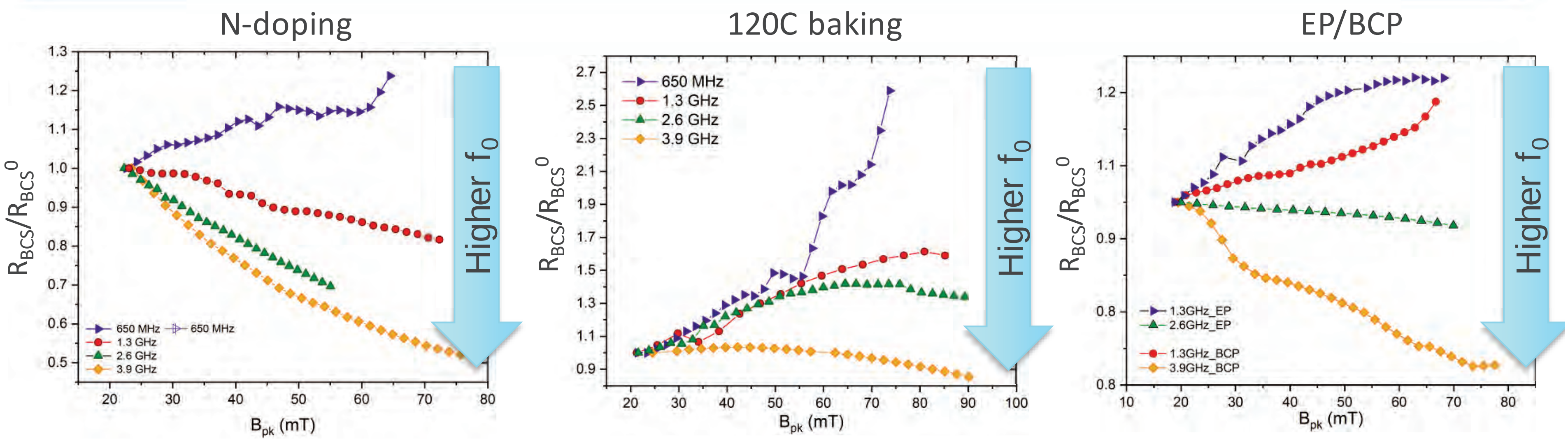


EP/BCP



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

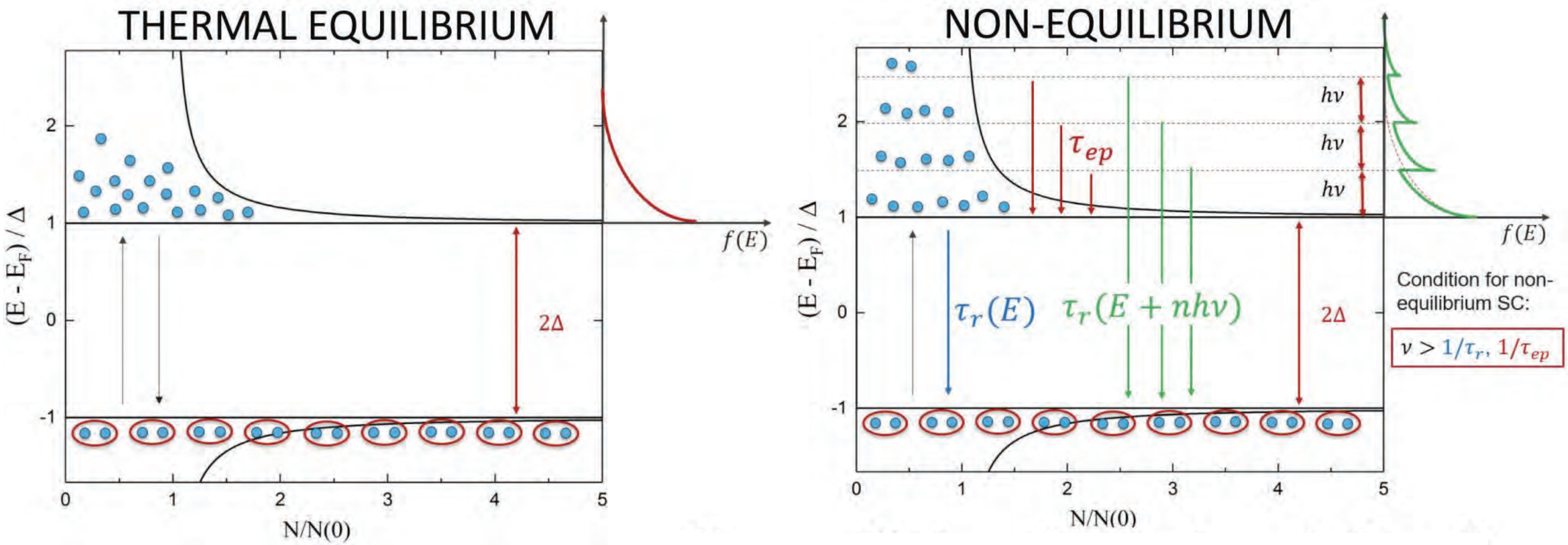
Summary of the Frequency Dependence of R_{BCS}(Eacc)



The R_{BCS} decreasing with the field, that has been considered the signature of the N-doped treatment, is actually visible also in clean Nb (EP/BCP) but at higher frequency (> 1.3 GHz)

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

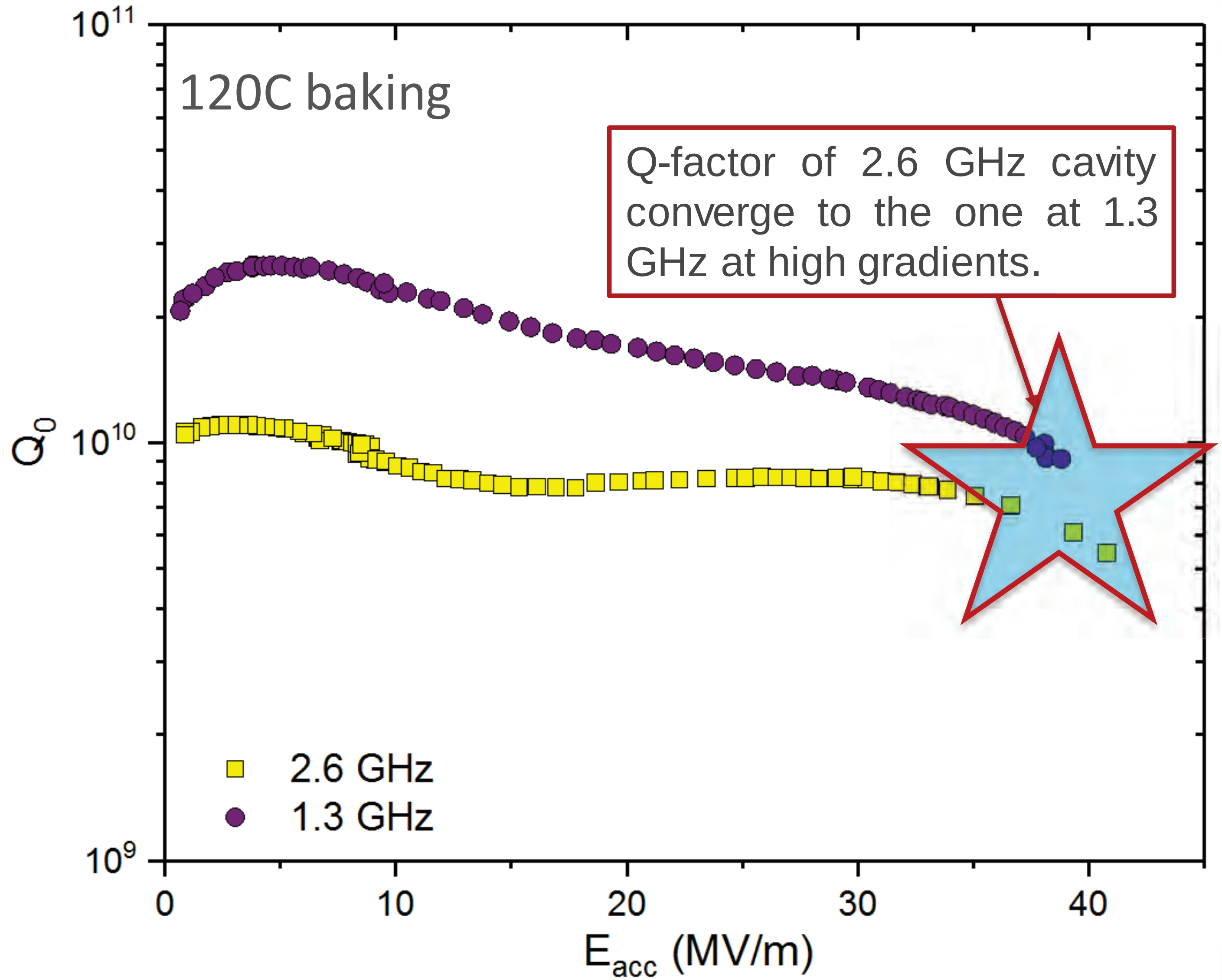
Doping and Frequency Effect on the QPs Distribution



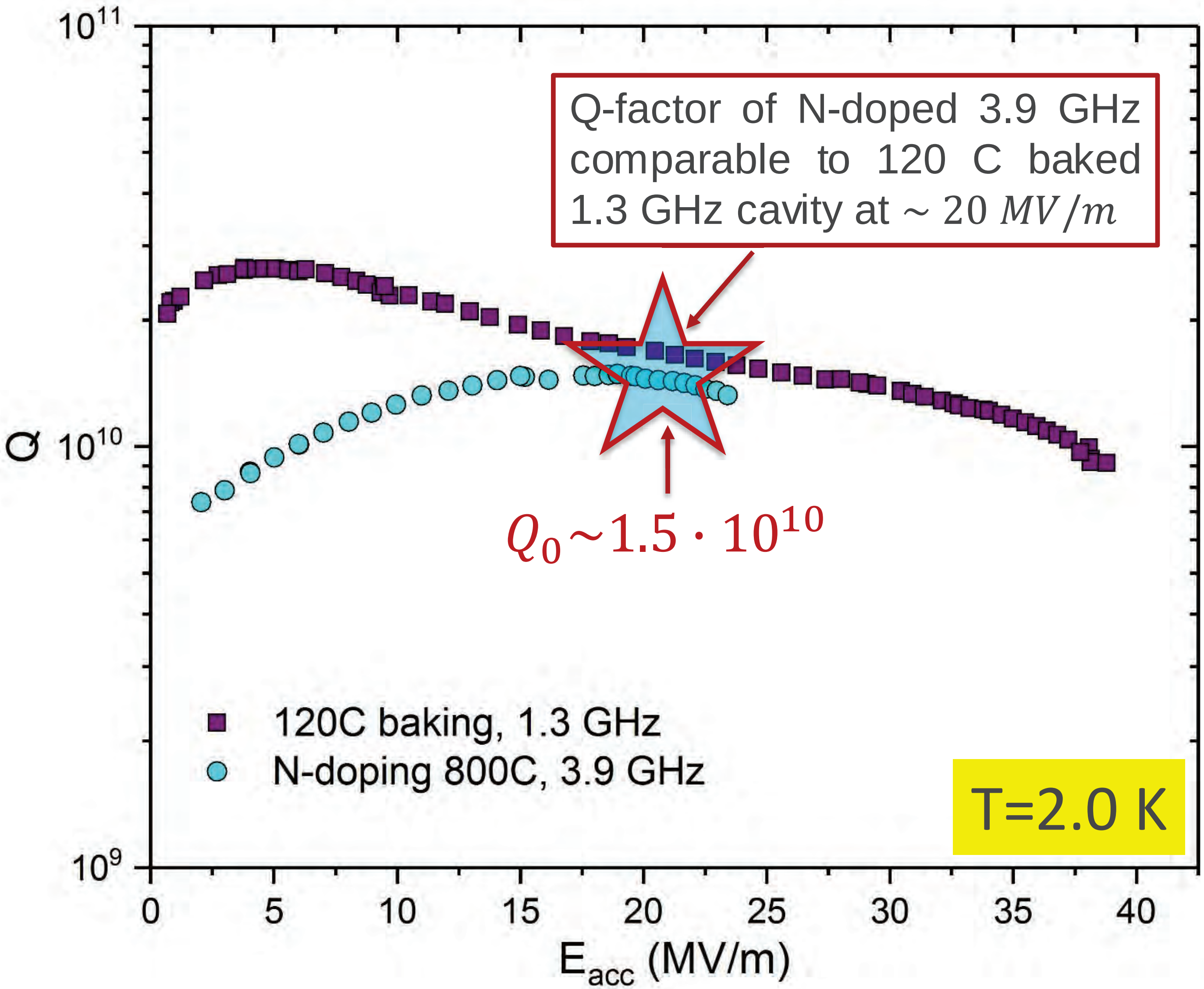
- Higher the frequency, higher the probability to match the condition for non-equilibrium
- N-doping (surface treatments in general) may modify τ_{ep} and τ_r enhancing non-equilibrium effects

A. Romanenko, LINAC 2014

High Frequency Cavities Favorable at High Field



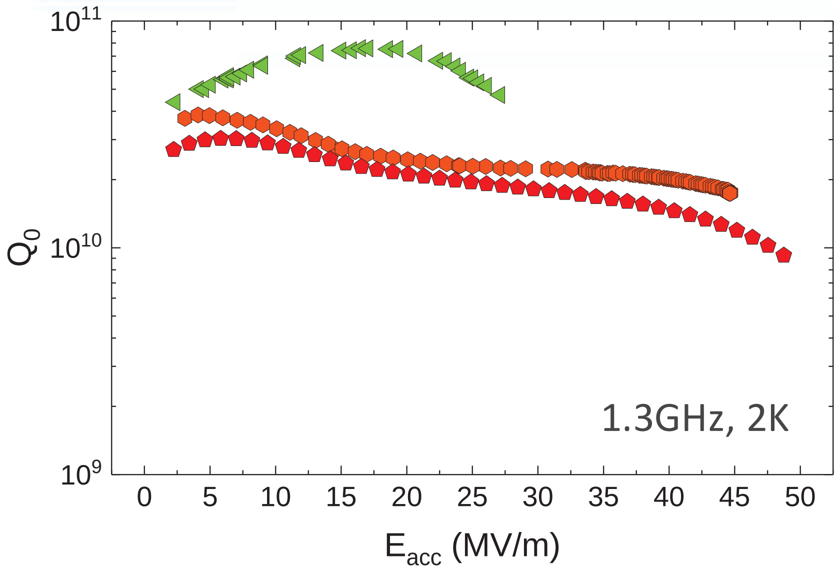
Unprecedented Medium Field Q_0 at 3.9 GHz



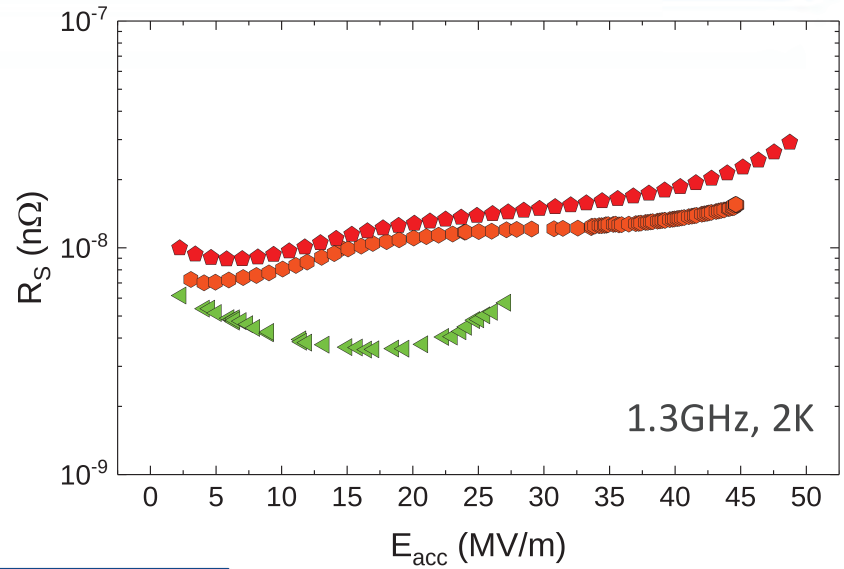
Outline

- 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**
- Technology improvement for SRF-based projects
- Conclusions

The surface resistance

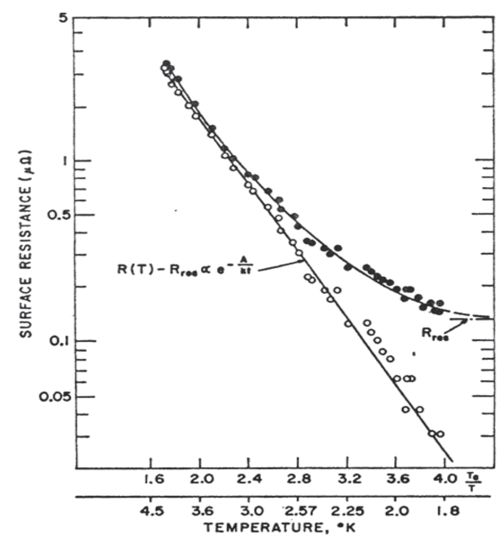


$$Q_0 = \frac{G}{R_s}$$



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

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

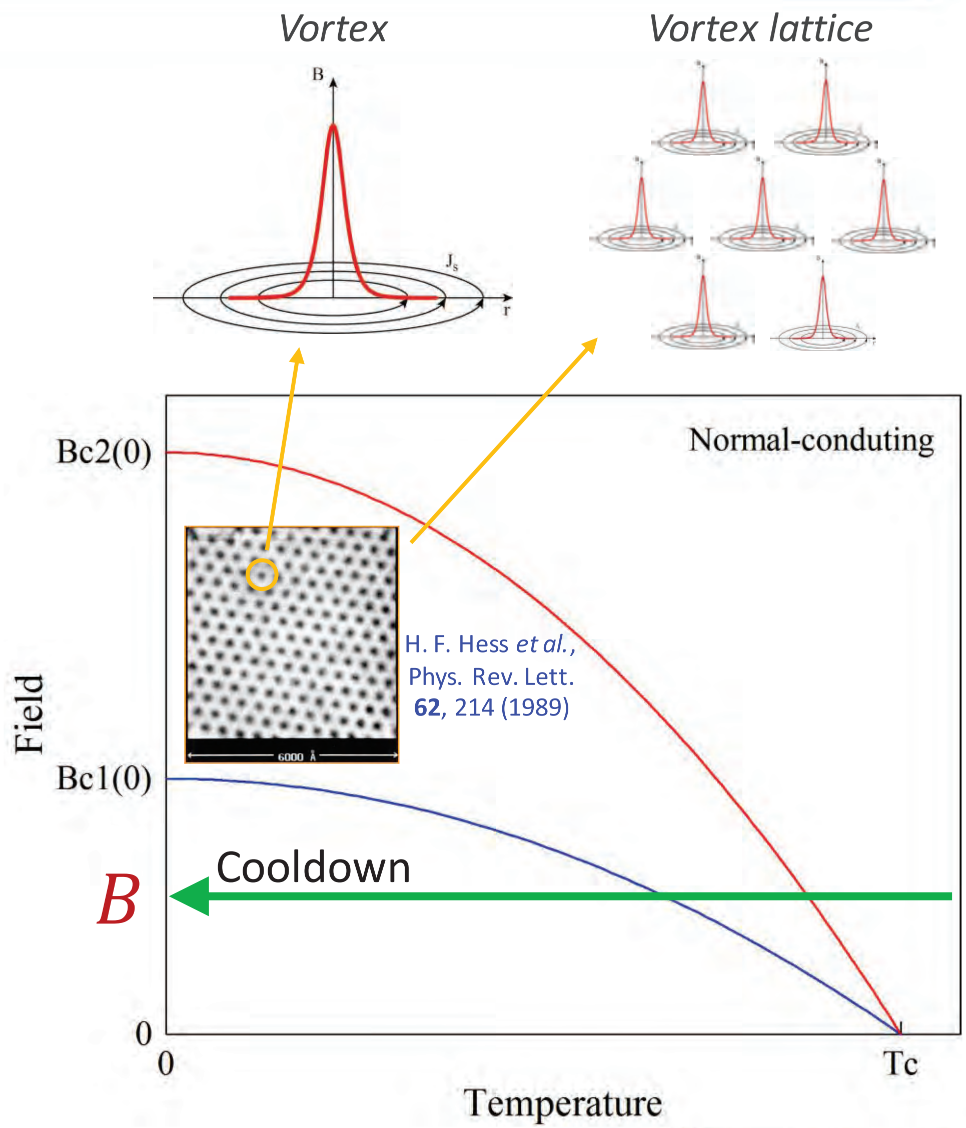
If pinned, vortices may survive in the Meissner state introducing dissipation:

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

η_t—flux trapping efficiency

S—trapped flux sensitivity

B—external magnetic field



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Trapped flux surface resistance

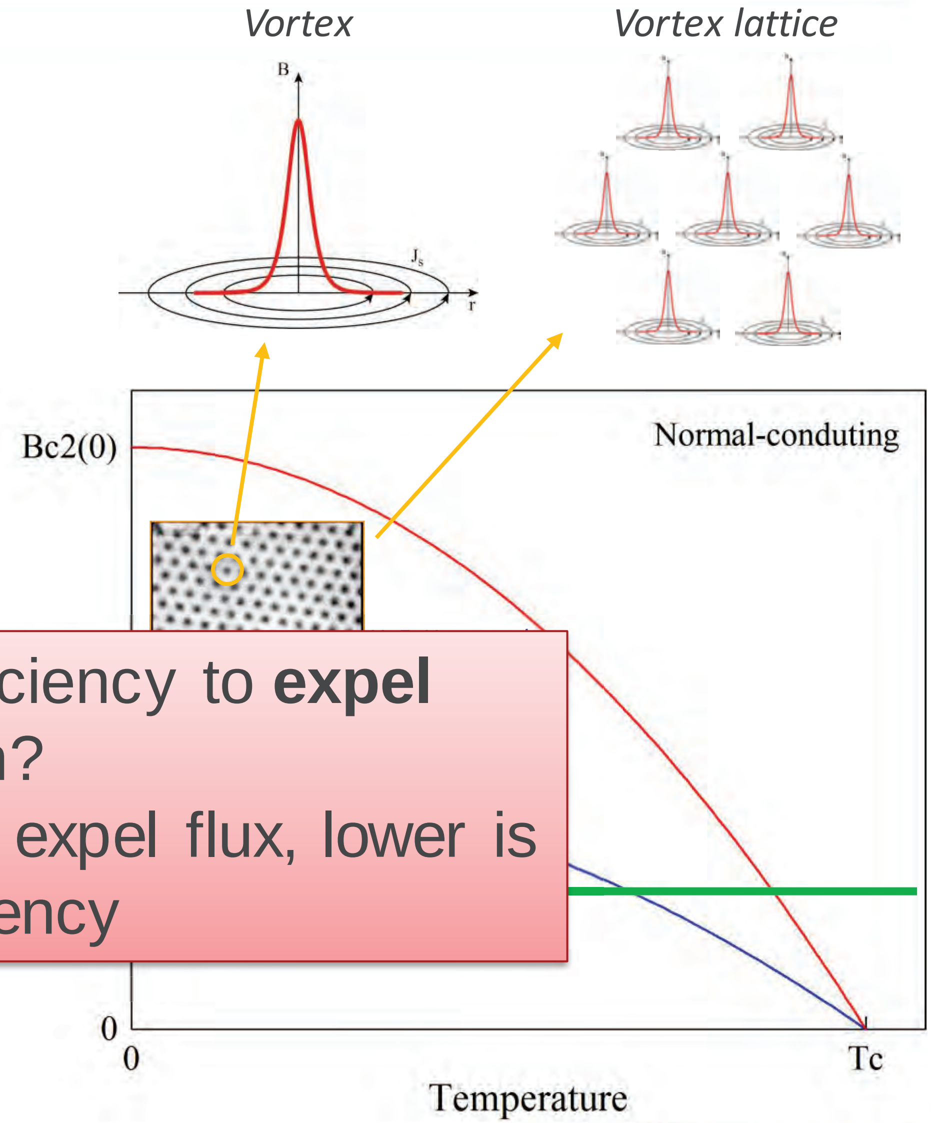
If pinned, vortices may survive in the Meissner state introducing dissipation:

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

η_t—flux trapping efficiency

S—

B—



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

- Higher is the ability to expel flux, lower is the flux trapping efficiency

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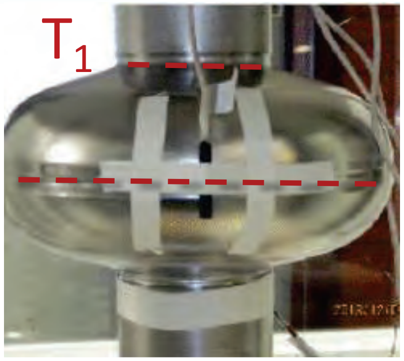
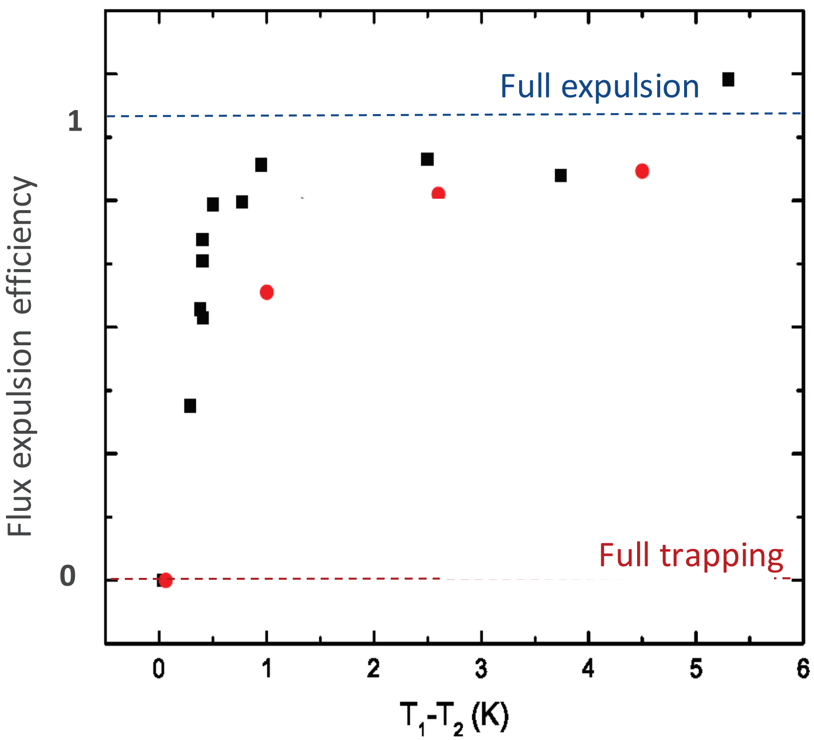
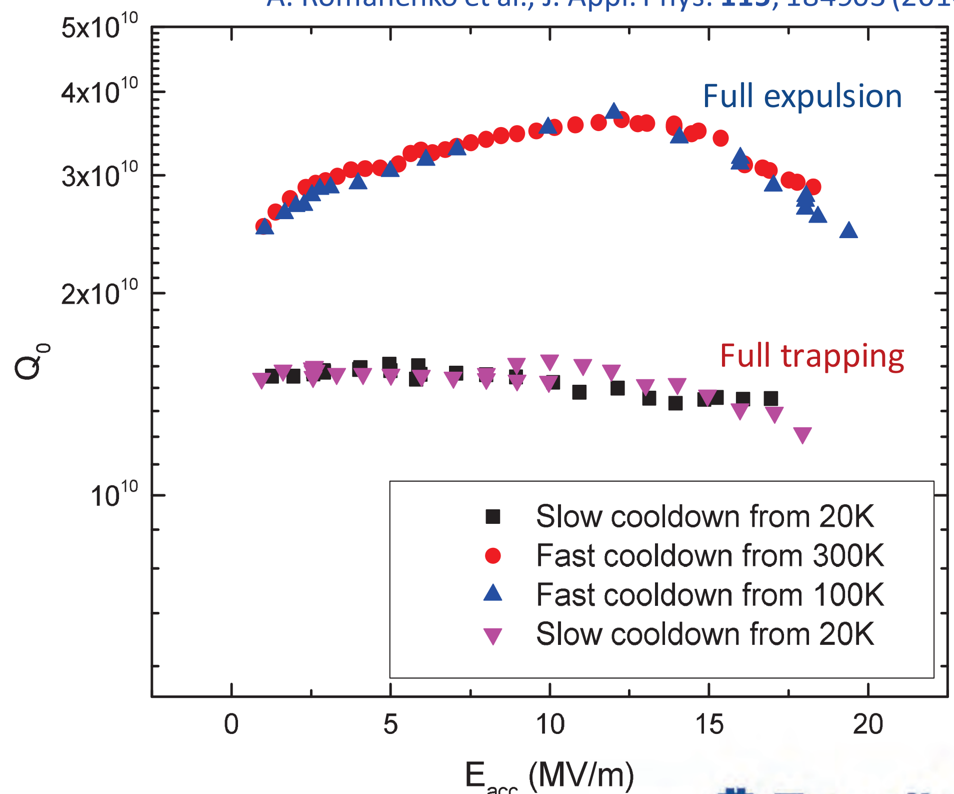
Fast cooldown helps flux expulsion



- 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)





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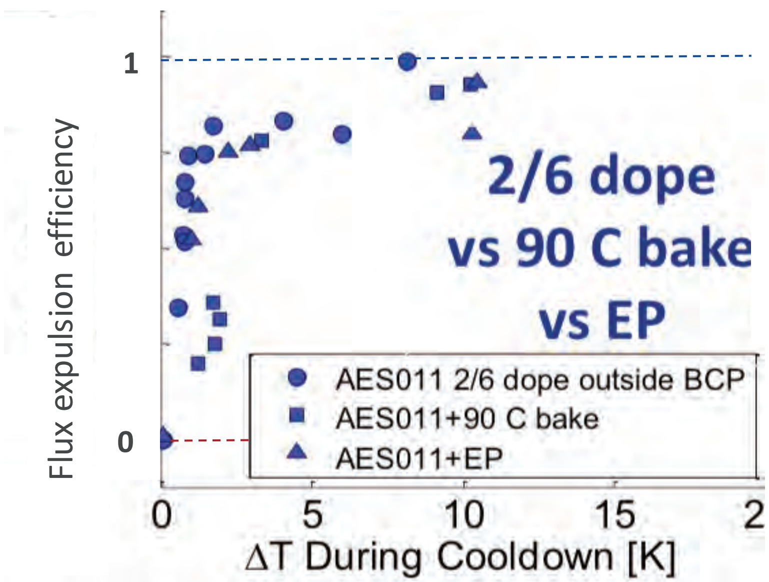
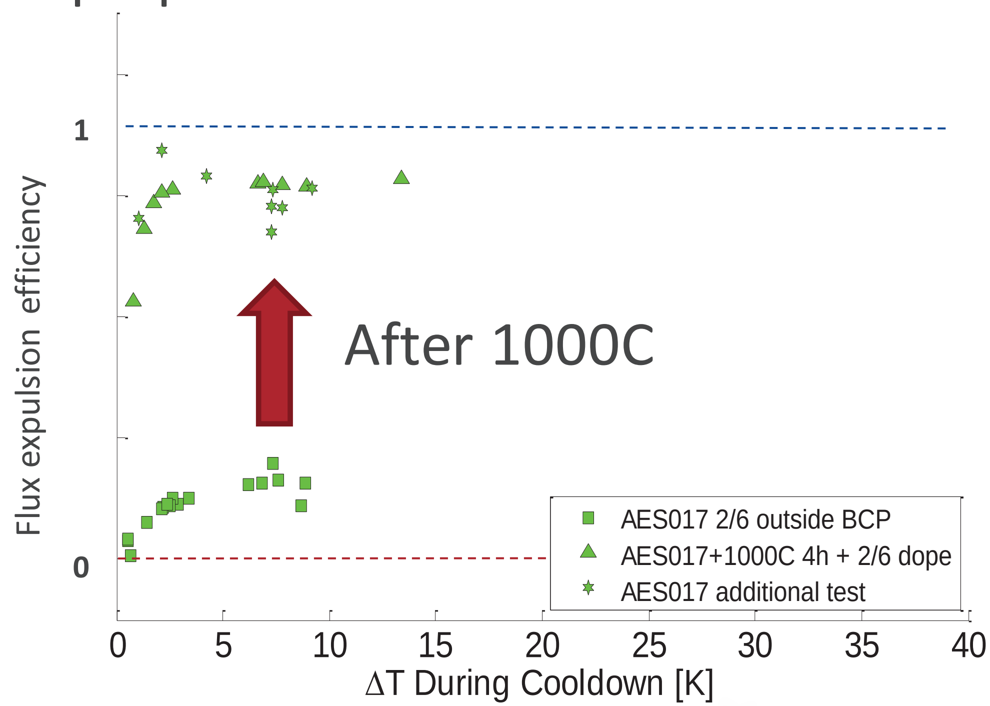
Flux expulsion depends on bulk properties of Nb cavities

- 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)

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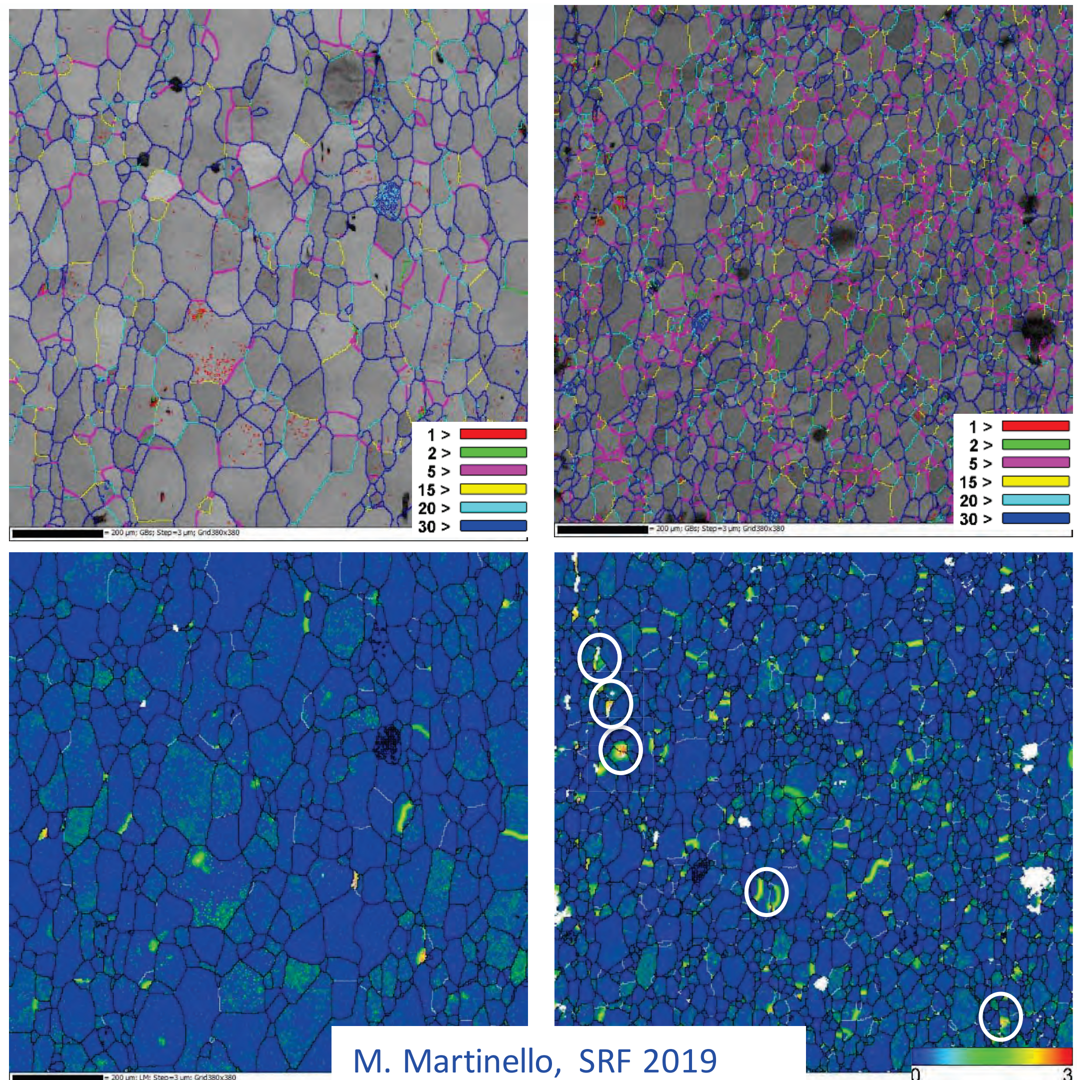
Analysis of “as received” materials

- 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°)
- 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

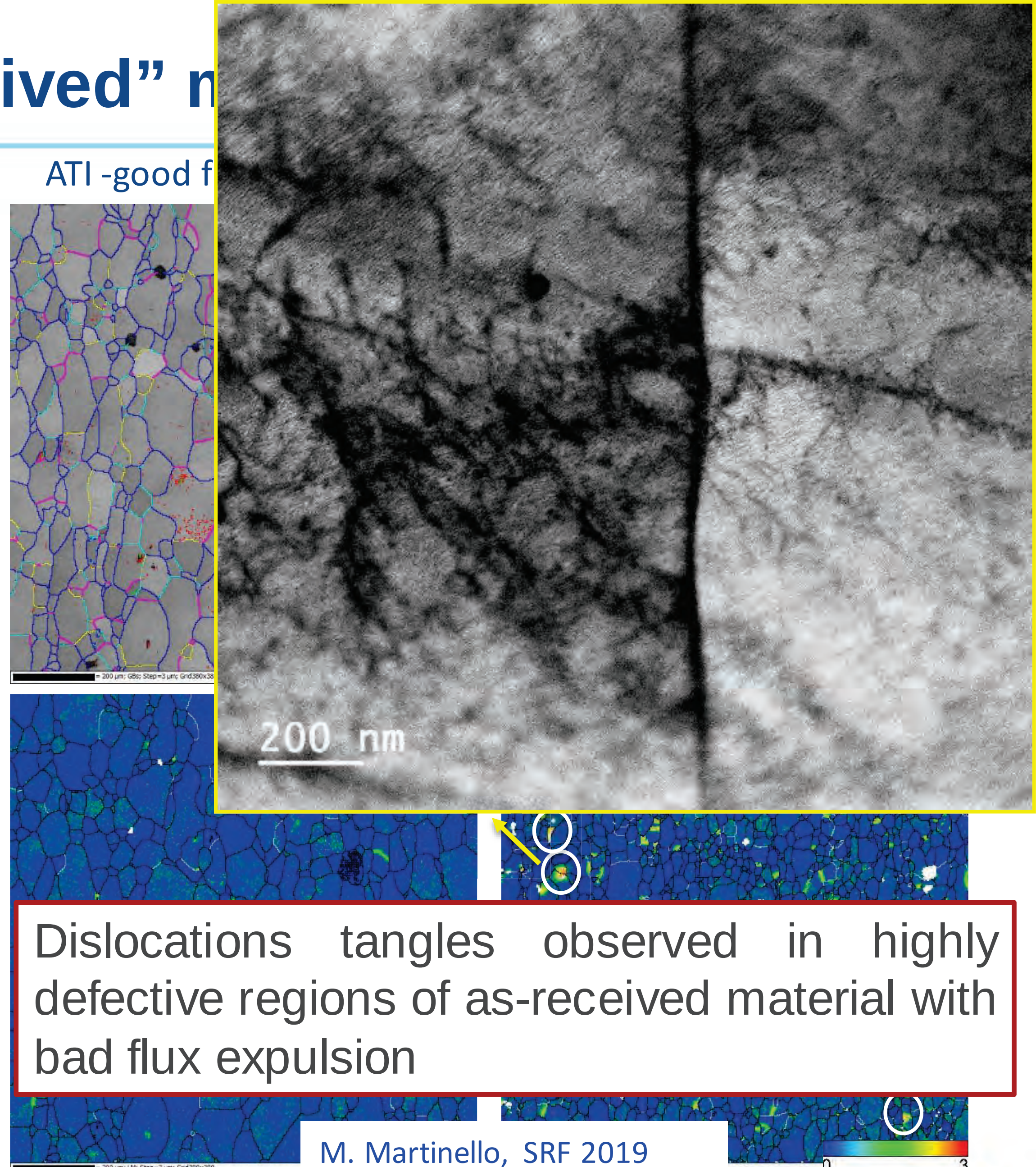
Analysis of “as received” n

- 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°)

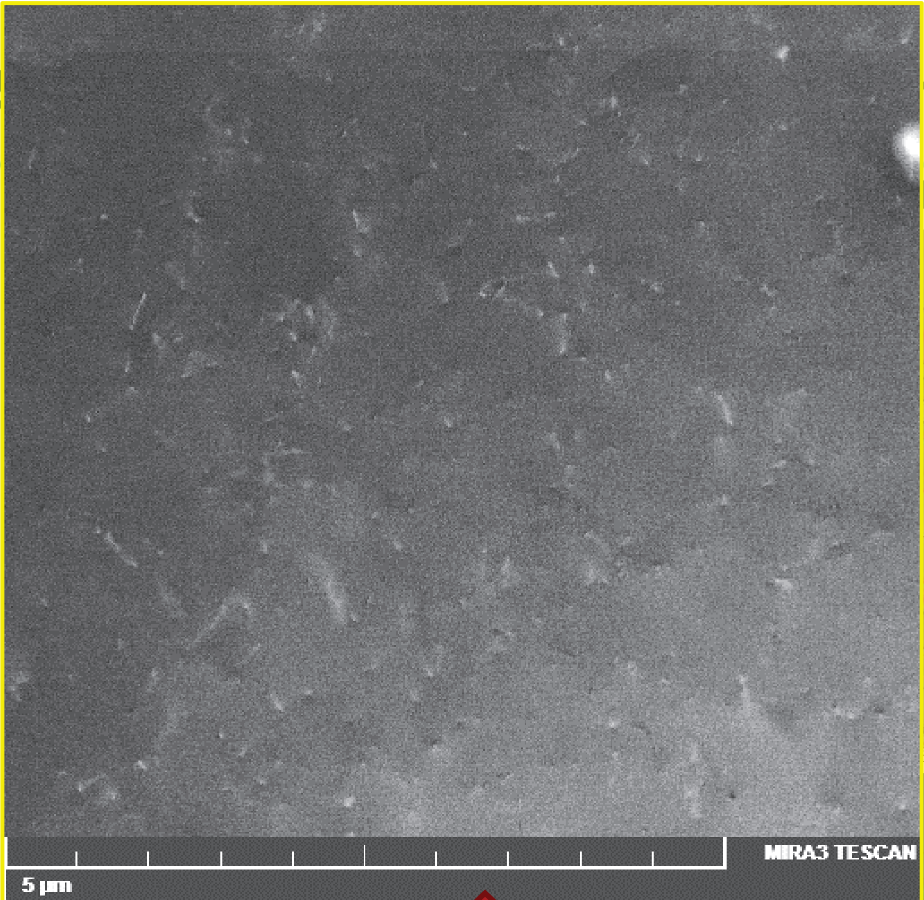
- Material with bad flux expulsion properties shows larger density of regions with very high local misorientation
  -> **dislocations tangles**

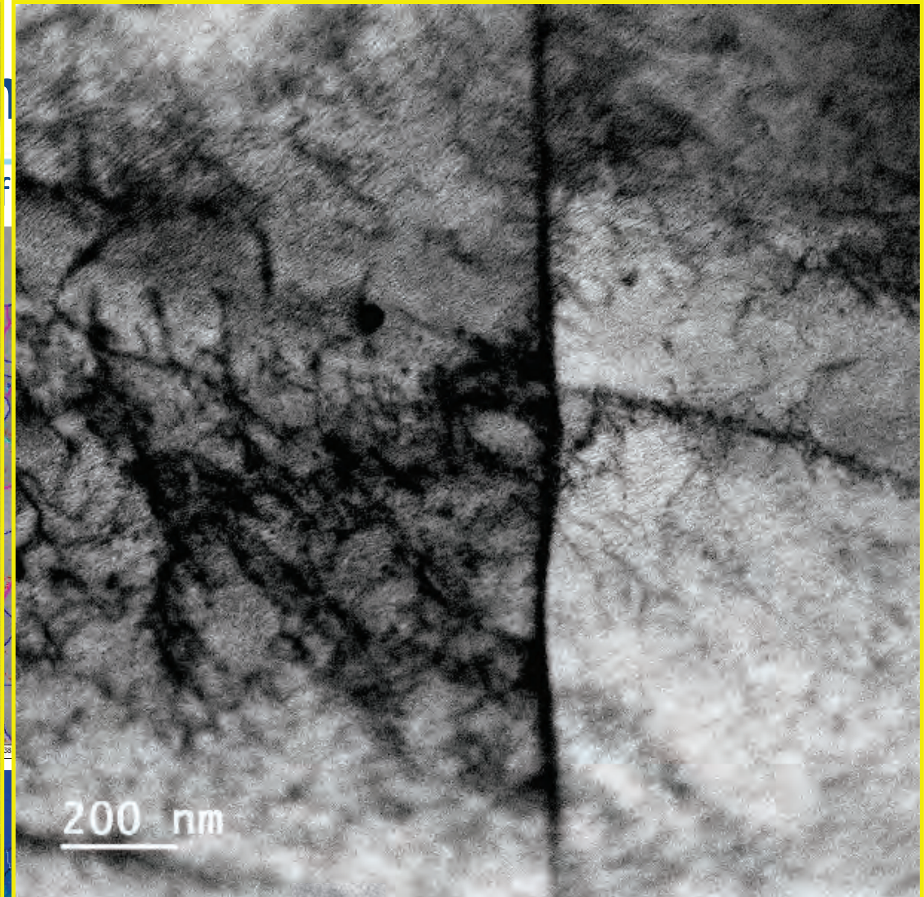
ATI -good f



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

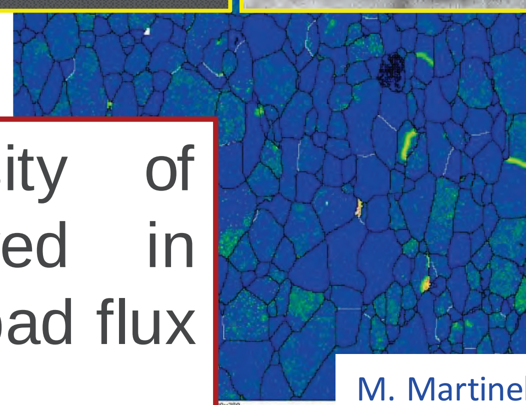
M. Martinello, SRF 2019

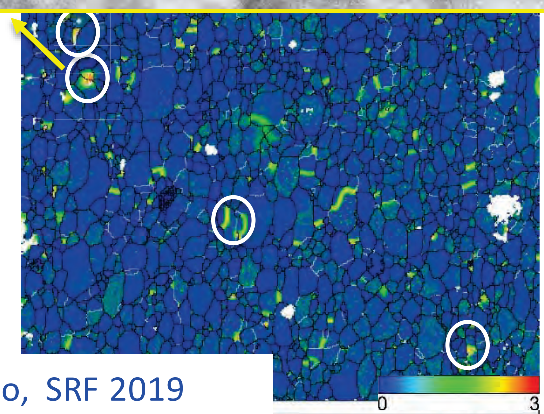




- Material with … flux expulsion propertie… shows … lar… wi… mi…

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





M. Martinello, SRF 2019

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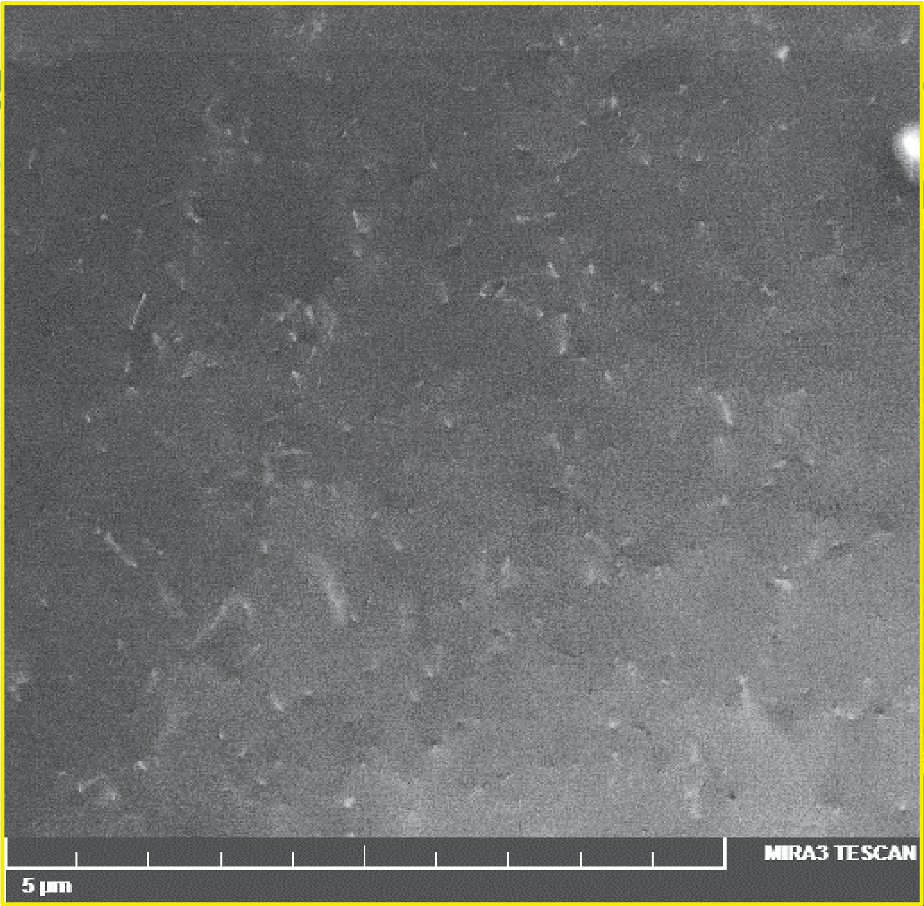
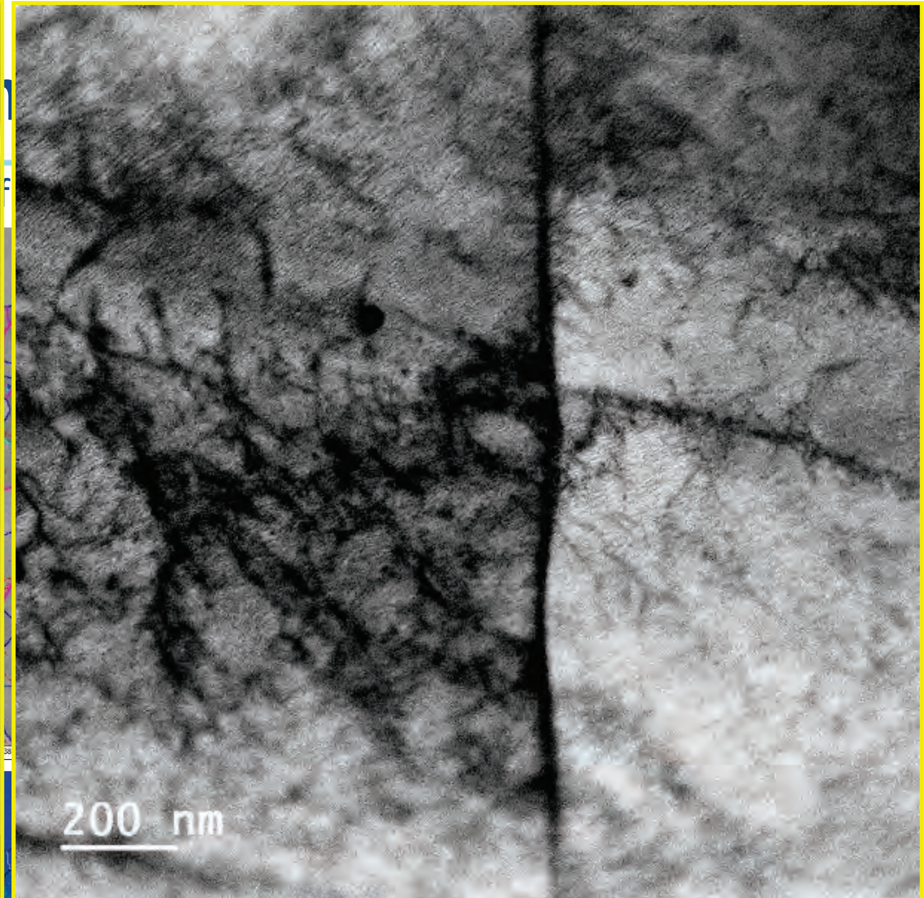
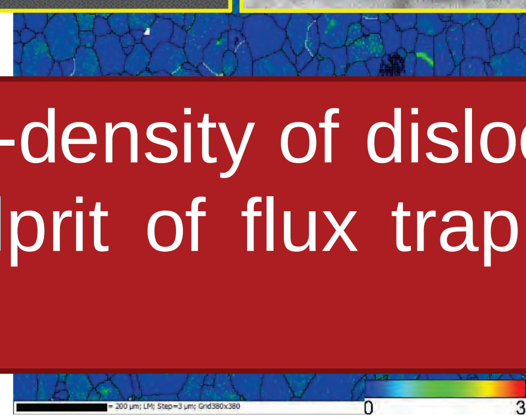
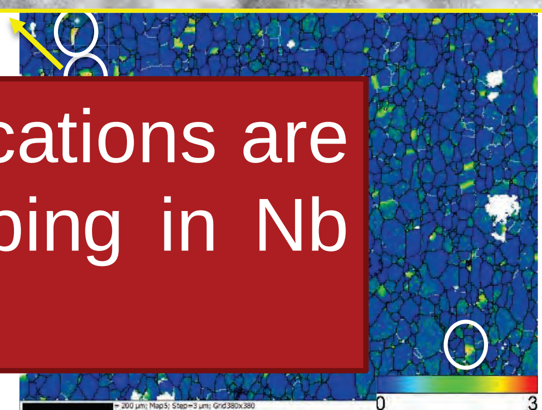




- Material with bad flux expulsi… larger … with … misorie…
  -> **disl… tangles**





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

Trapped flux surface resistance

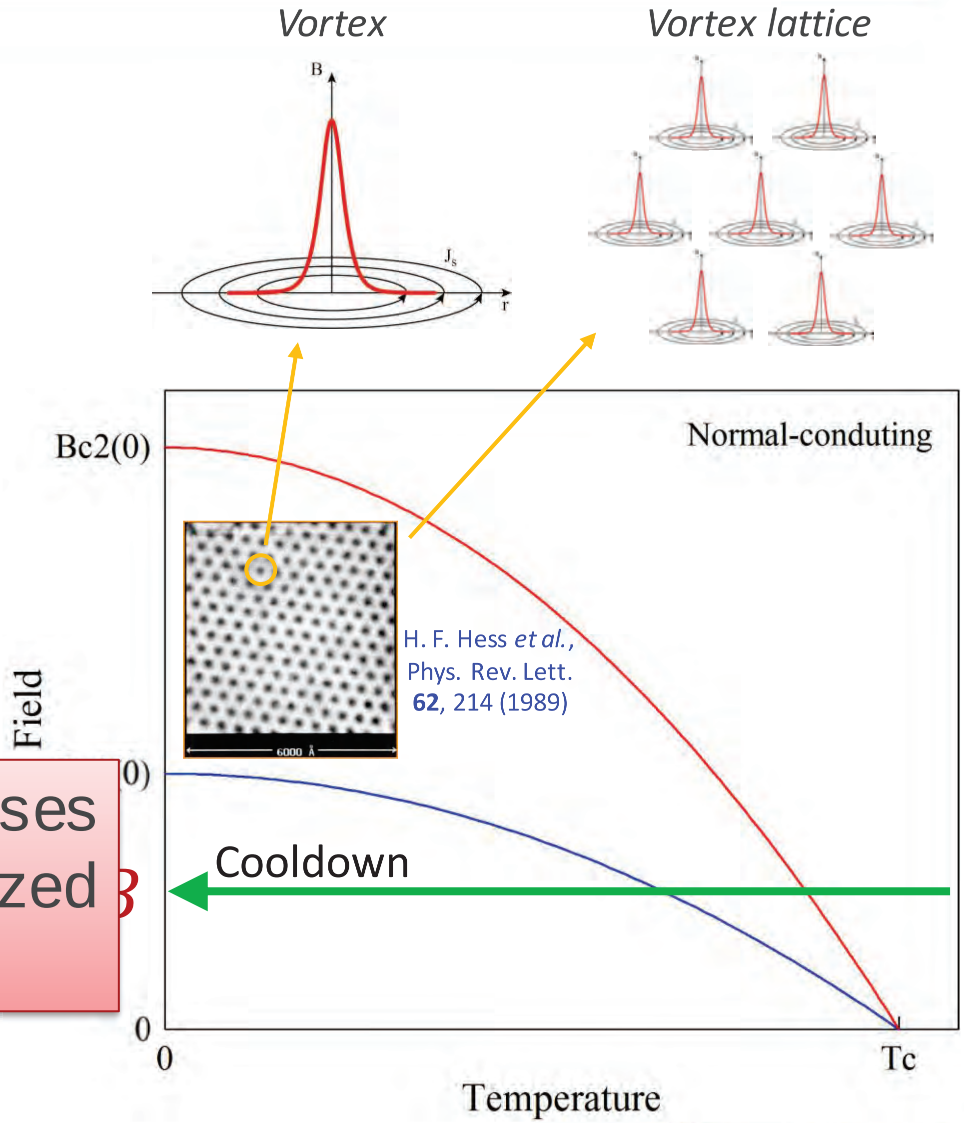
If pinned, vortices may survive in the Meissner state introducing dissipation:

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

η_t—flux trapping efficiency

S—trapped flux sensitivity

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



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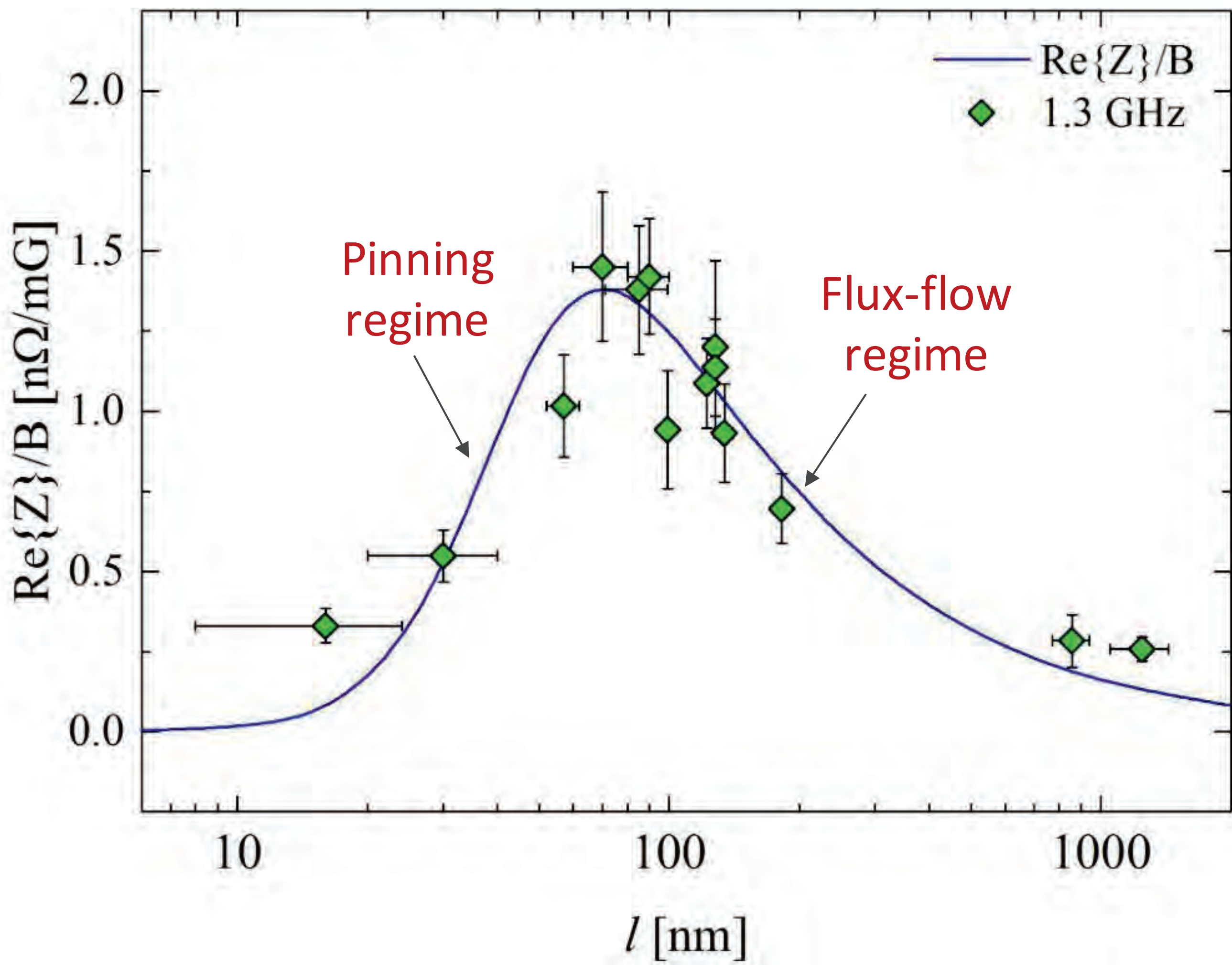
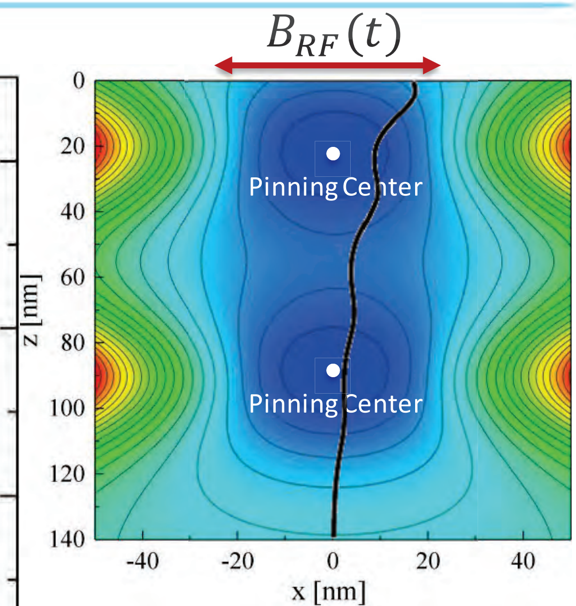
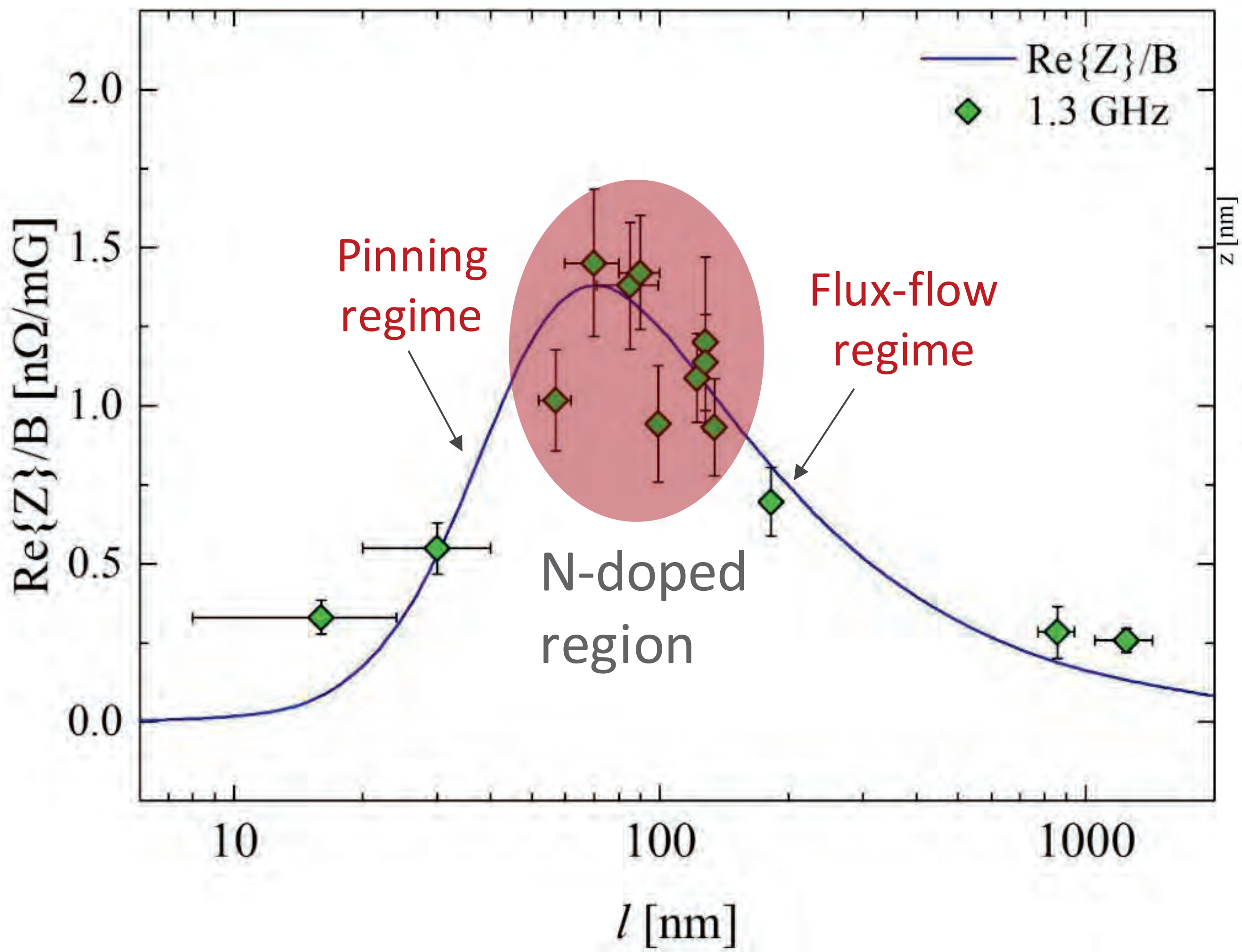
Sensitivity versus mean-free-path

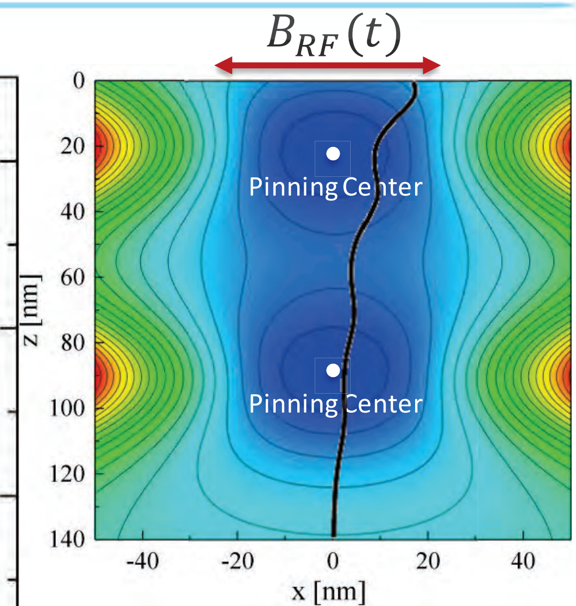




M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
M. Checchin et al., Supercond. Sci. Technol. 30, 034003 (2017)

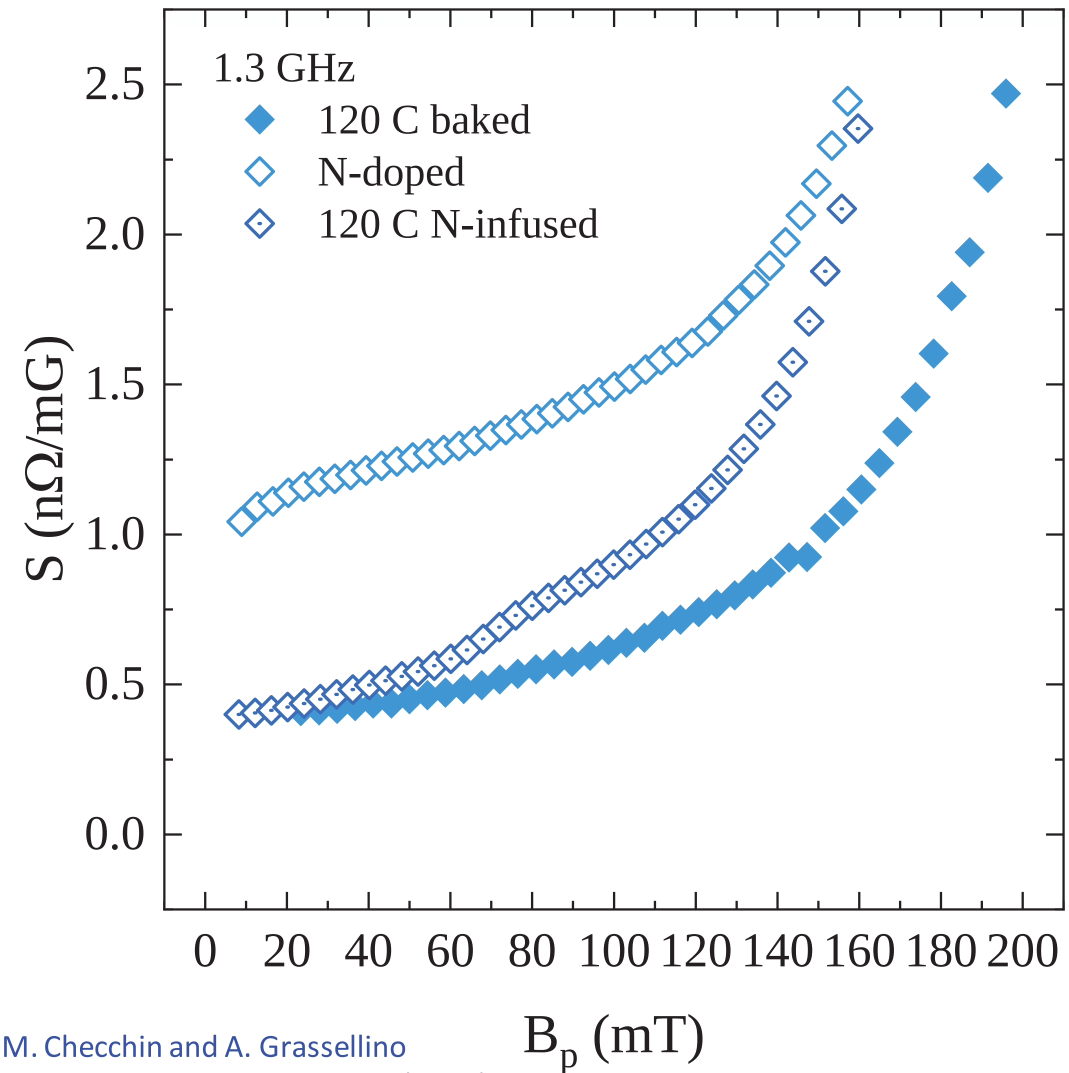
Sensitivity versus mean-free-path





M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
M. Checchin et al., Supercond. Sci. Technol. 30, 034003 (2017)

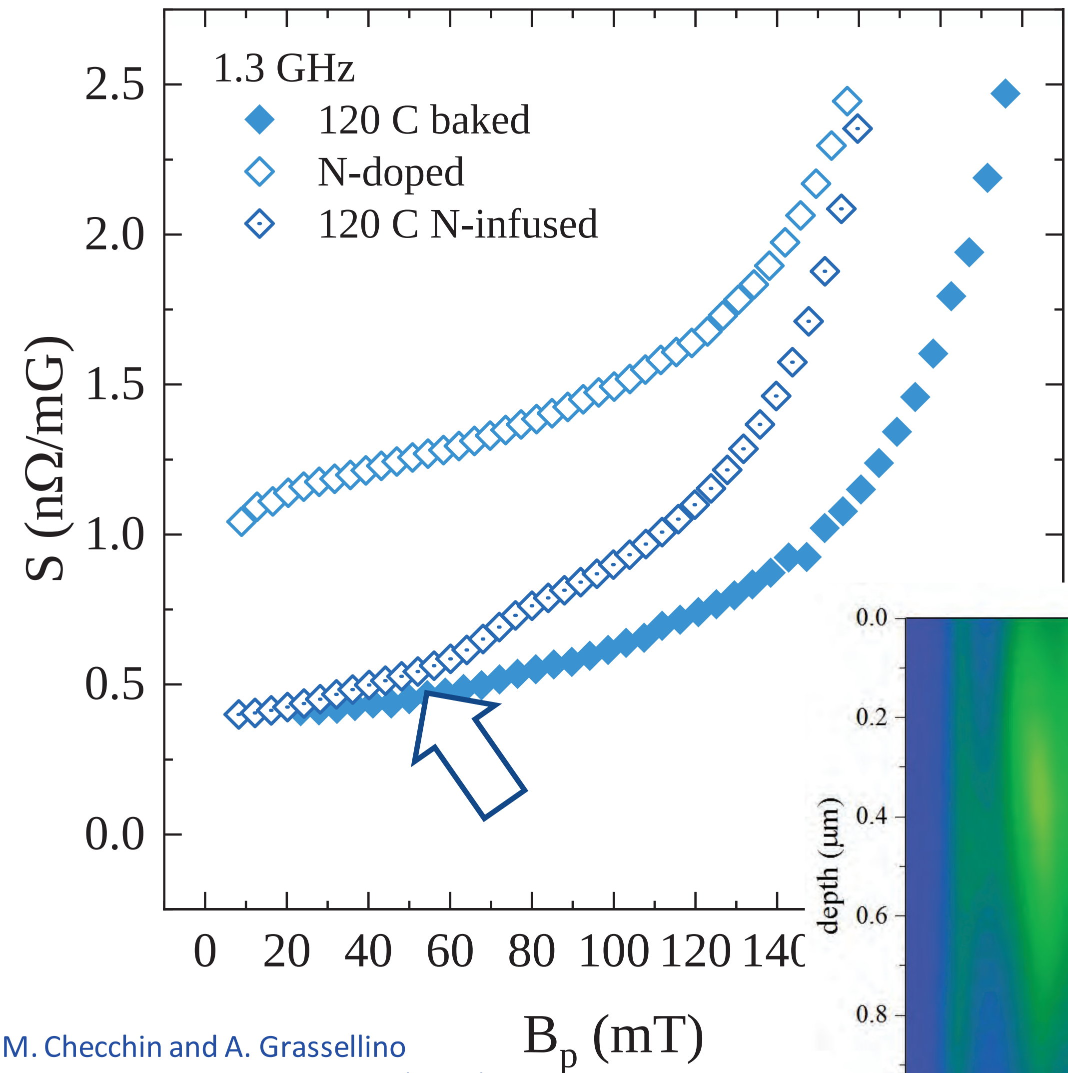
Sensitivity as a function of the field



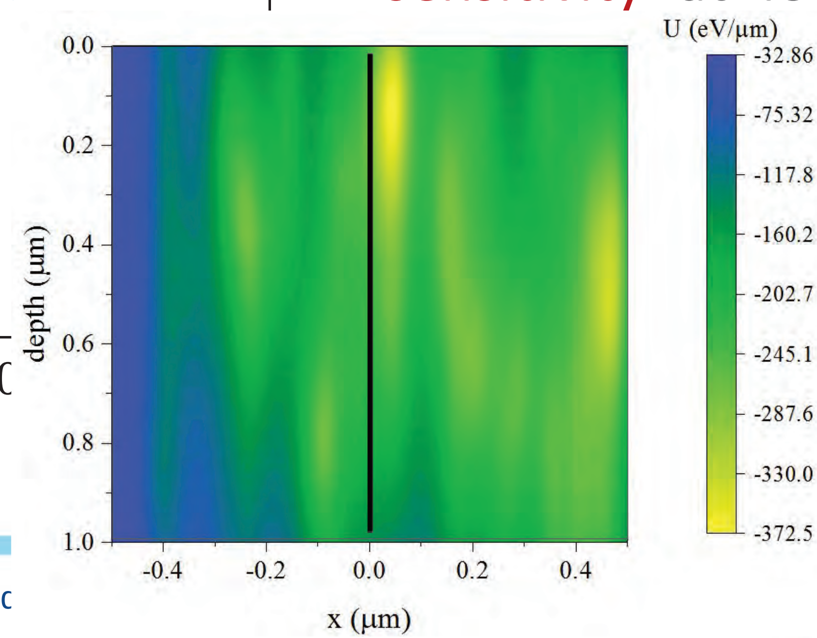
M. Checchin and A. Grassellino
Phys. Rev. Applied 14, 044018 (2020)

- 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 fir high-field applications!

Sensitivity as a function of the field

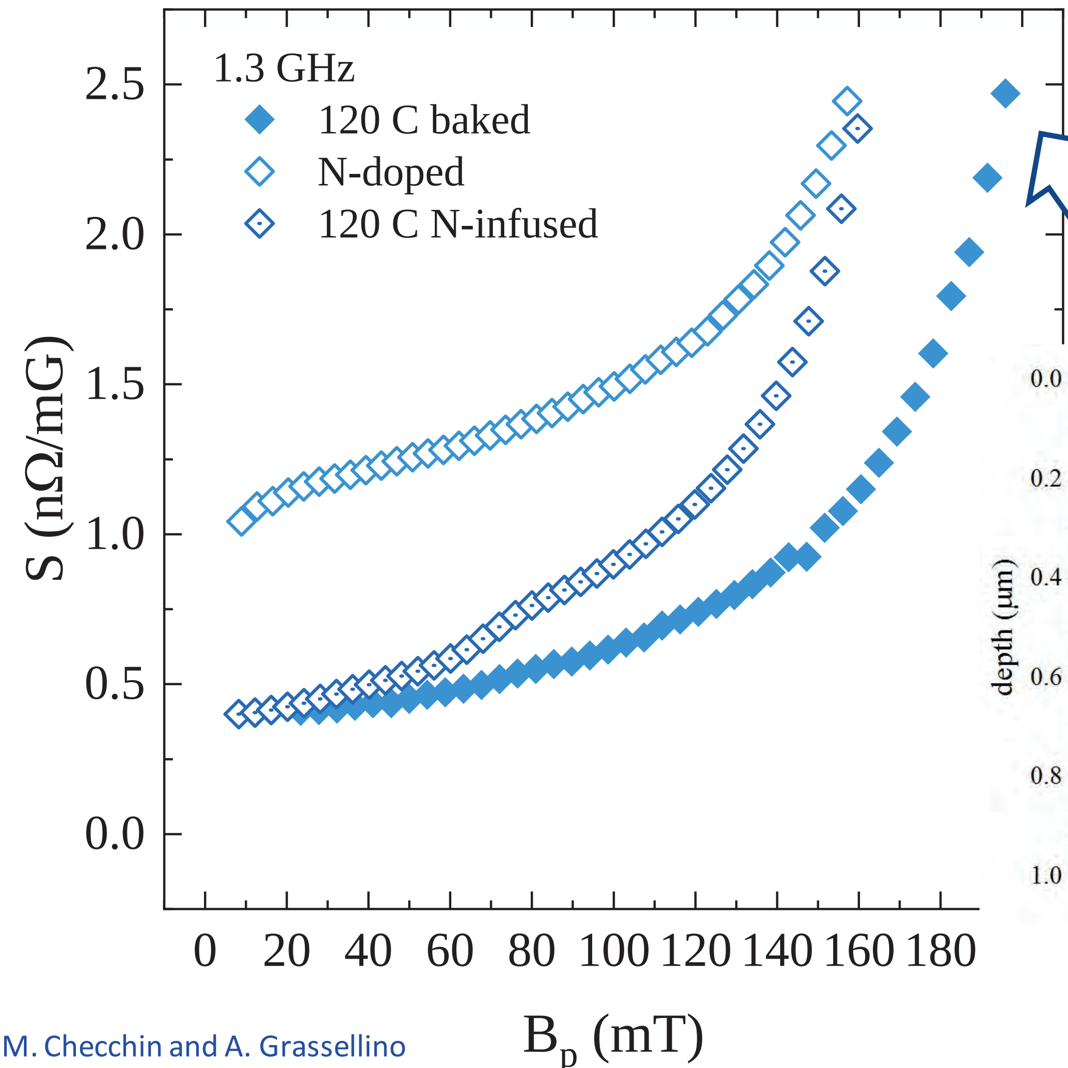


- At high field the trapped flux sensitivity increases exponentially
- 120C baked and N-infused cavities have very low values of sensitivity at low field … gh at … that … high-



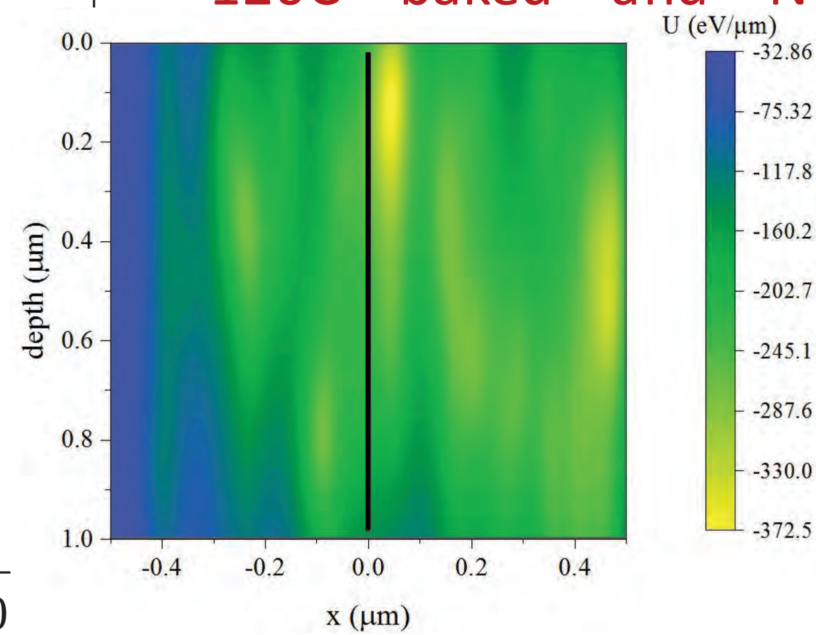
M. Checchin and A. Grassellino
Phys. Rev. Applied 14, 044018 (2020)

Sensitivity as a function of the field



- At high field the trapped flux sensitivity increases exponentially

- 120C baked and N-



field applications!

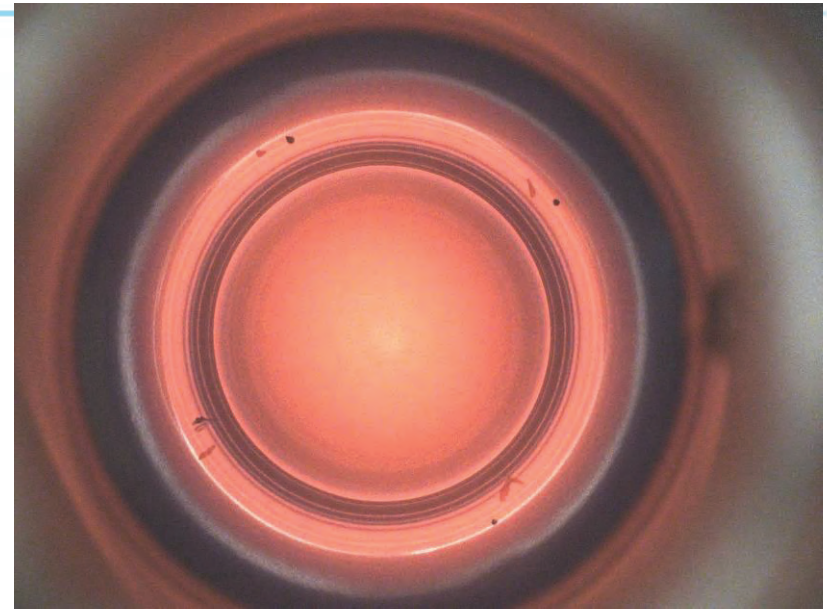
M. Checchin and A. Grassellino
Phys. Rev. Applied 14, 044018 (2020)

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

Plasma processing R&D for LCLS-II cavities

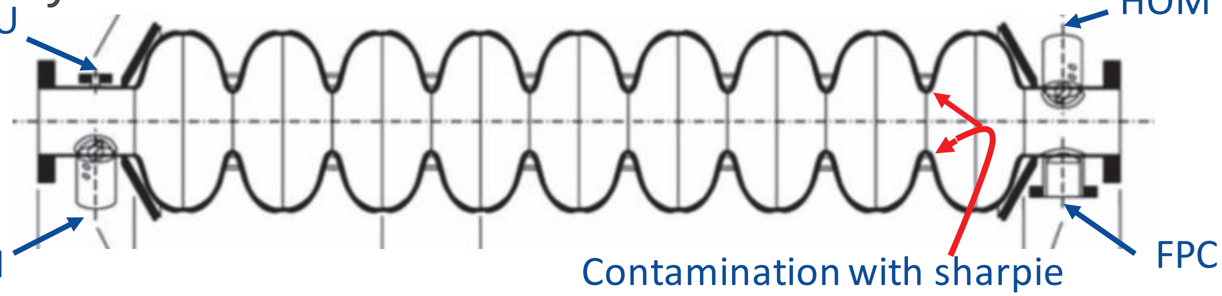
Work performed in collaboration with SLAC and ORNL

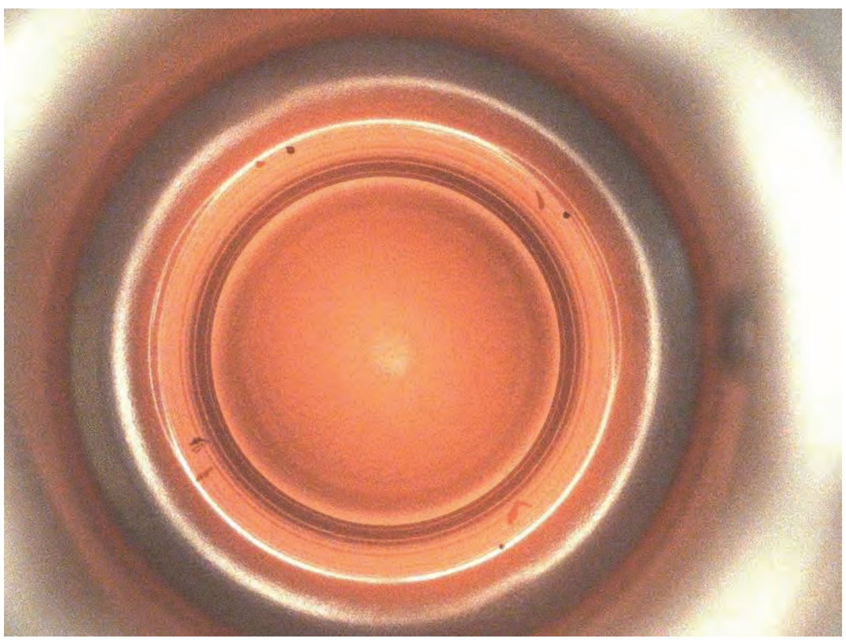


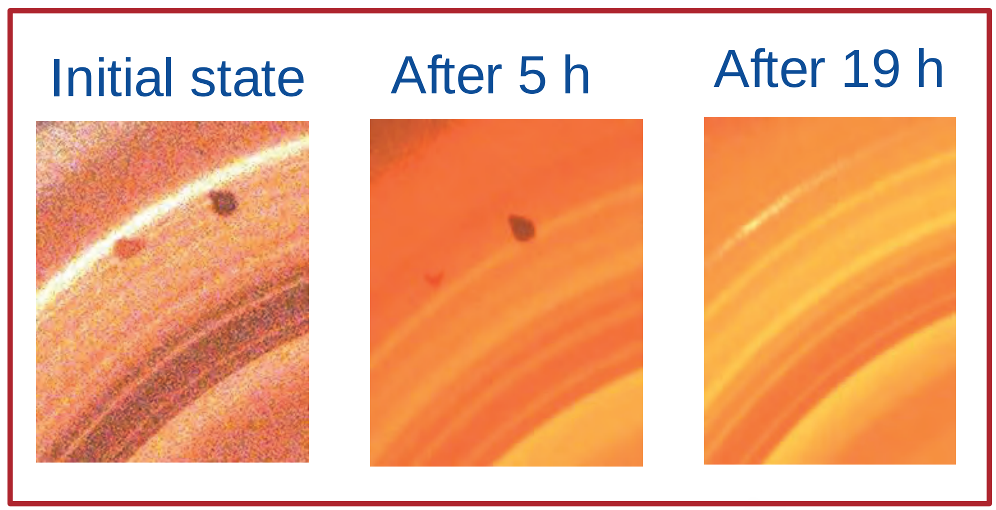
- Ne-O gas mixture (few % of O_2, mostly Ne) at p ~ 75-150mTorr
- Plasma ignition sequentially cell-by-cell using HOMs antenna (10-50 W for ignition, few W for sustain plasma) P. Berrutti et al., J. App. Phys. **126**, 023302 (2019)
- Approximately 1-2 hours processing per cell
- On-going R&D to optimize parameters and understand rate of success in naturally FE cavities B. Giaccone, M. Martinello et al. Phys. Rev. Accel. Beams 24, 022002(2021)

First study in a 9-cell contaminated cavity

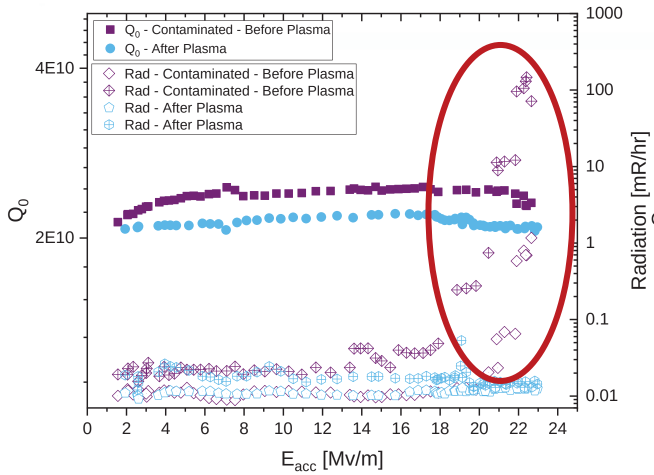
- **<u>Scope</u>: remove hydrocarbon contamination with plasma cleaning**
- 8 "dots" of permanent markers around the iris of the first cell of a 9-cell LCLS-II cavity

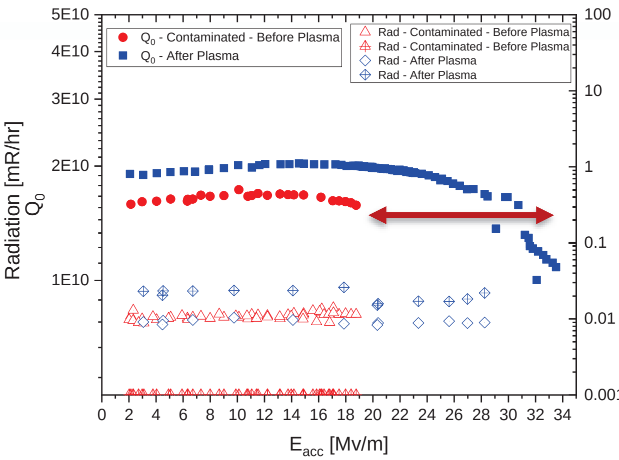


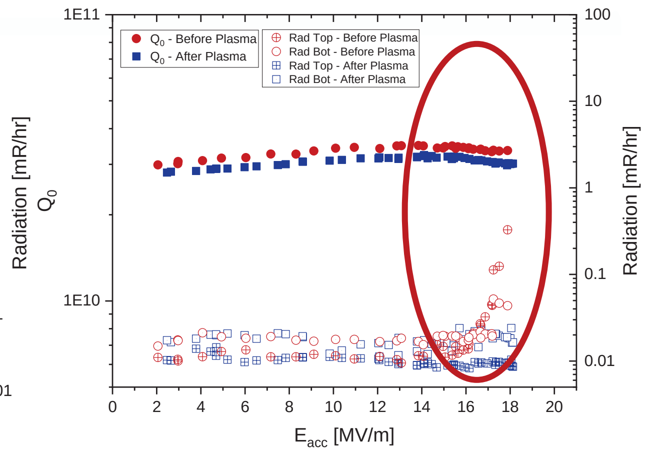




Summary results of plasma processed cavities





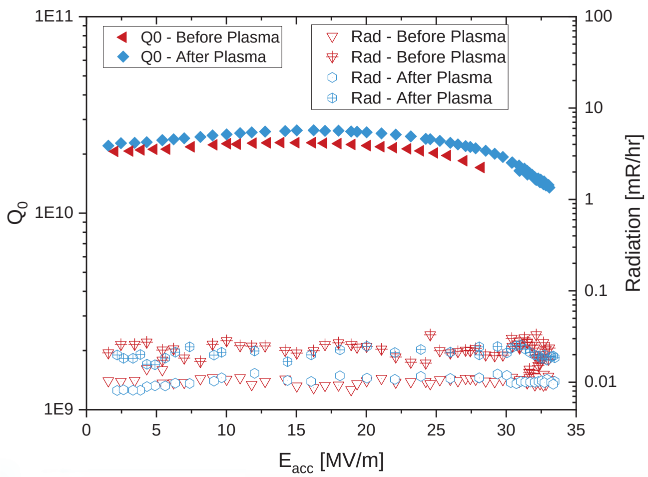


No radiation detected after plasma processing!

15 MV/m gained after plasma processing!

No radiation detected after plasma processing!

B. Giaccone, M. Martinello et al. Phys. Rev. Accel. Beams 24, 022002(2021)



- 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

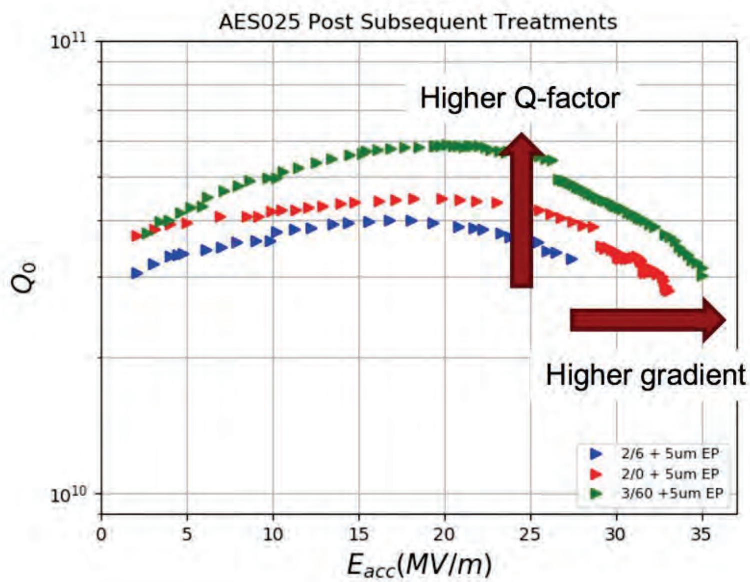
LCLS-II production at FNAL is completed,
now time to look at what's next

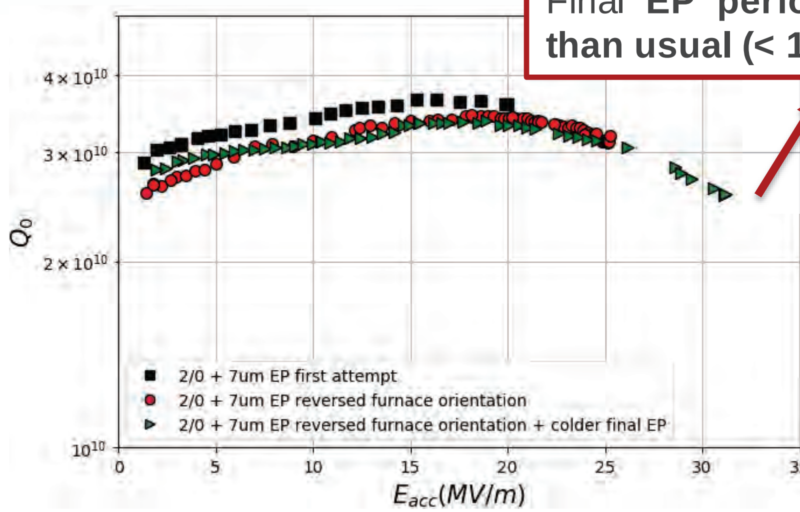
LCLS-II - High Energy

The LCLS-II-HE project will **increase the energy of the CW-SCRF linac to 8 GeV**, enabling the photon energy range to be extended to at least 13 keV and potentially up to 20 keV at 1 MHz repetition rates

Parameter	LCLS-II	LCLS-II HE
# 1.3 GHz CMs	35	20
Operating Gradient	16 MV/m	20.8 MV/m for new CMs 18 MV/m for old CMs
Required Q_0 at Operating Gradient	2.7×10^{10}	2.7×10^{10}

N-doping optimization for LCLS-II HE

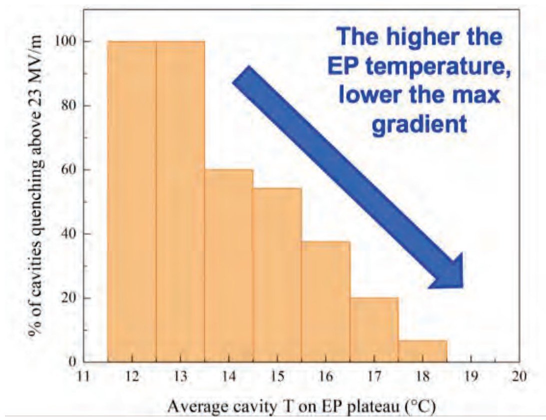


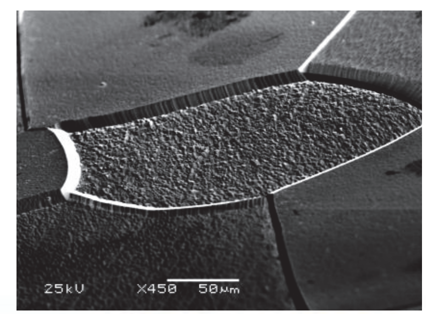


Final **EP performed colder than usual (< 13 C)**

Higher density of Nb_xN_y precipitates promote preferential etching during EP forming recessed grains

- 2N0 recipe studied in single-cell cavities showed higher gradient compare to 2N6 (LCLS-II) recipe
- Cold EP prevents preferential etching around nitrides leading to a smoother surface finishing -> higher gradients





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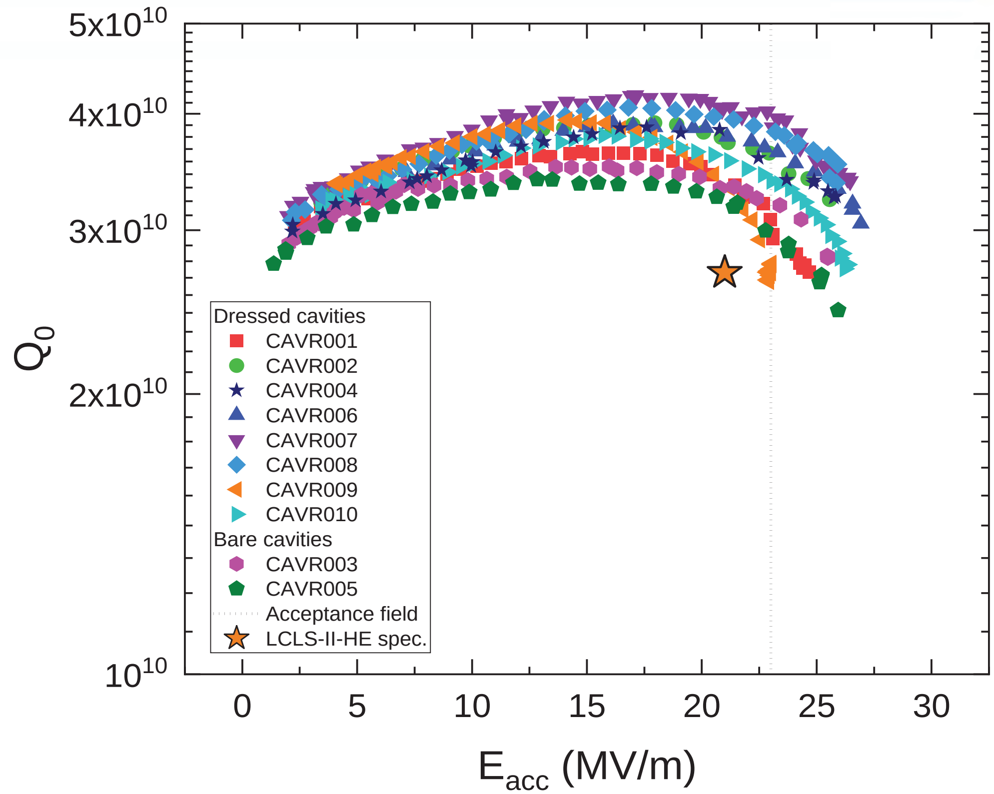
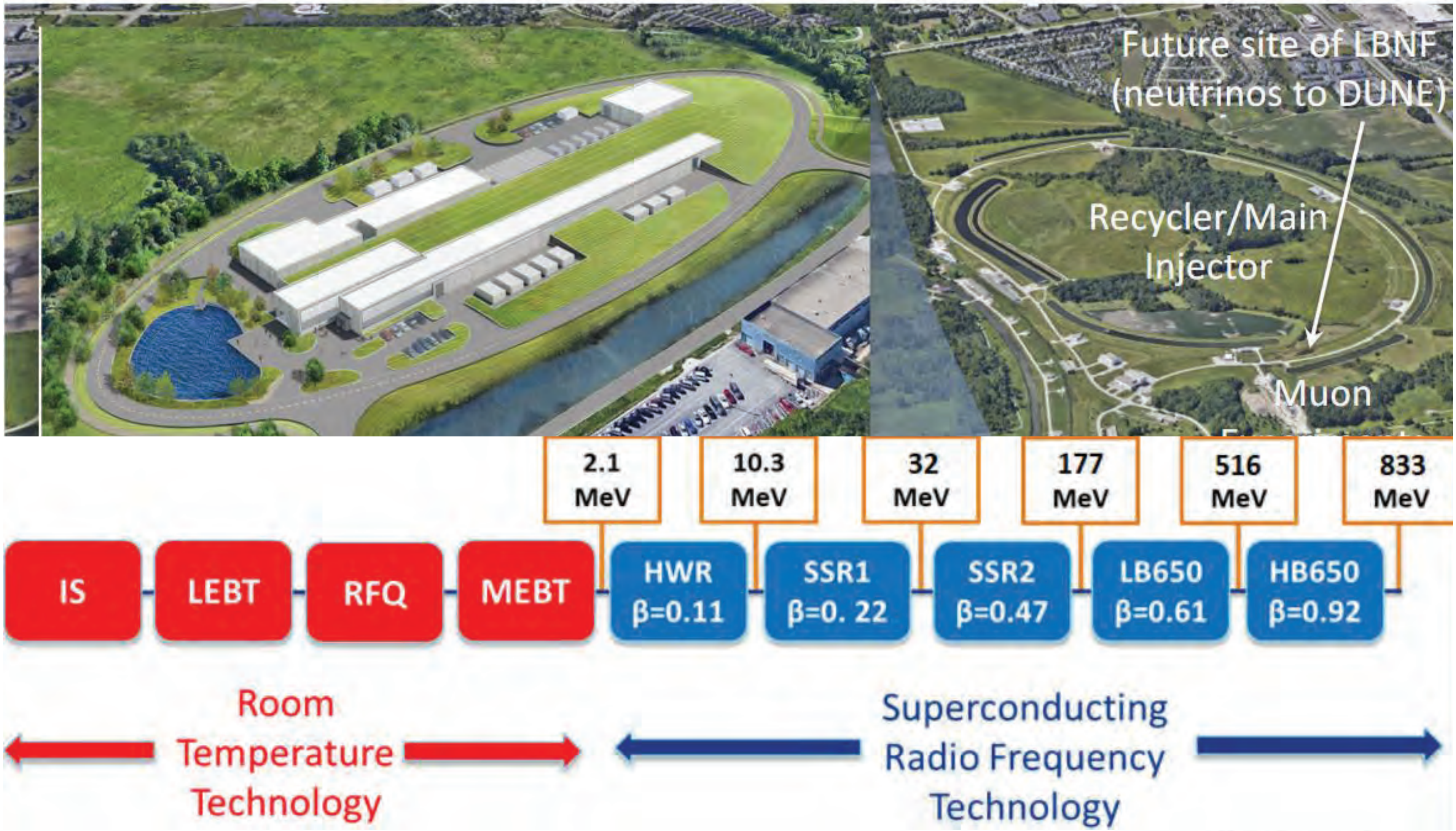
Verification-CM 9-cell cavities results

- New N-doping protocol (2N0 + cold EP) successfully transferred to industry
- Vertical test completed for 10 vCM cavities fabricated and processed in industry
- Performance exceeded specification with average Q0=3.6e10 and Eacc=25.6 MV/m
- 8 fully dressed cavities have been assembled in the vCM



Proton Improvement Plan at FNAL: PIP-II

Proton Improvement Plan at FNAL: PIP-II



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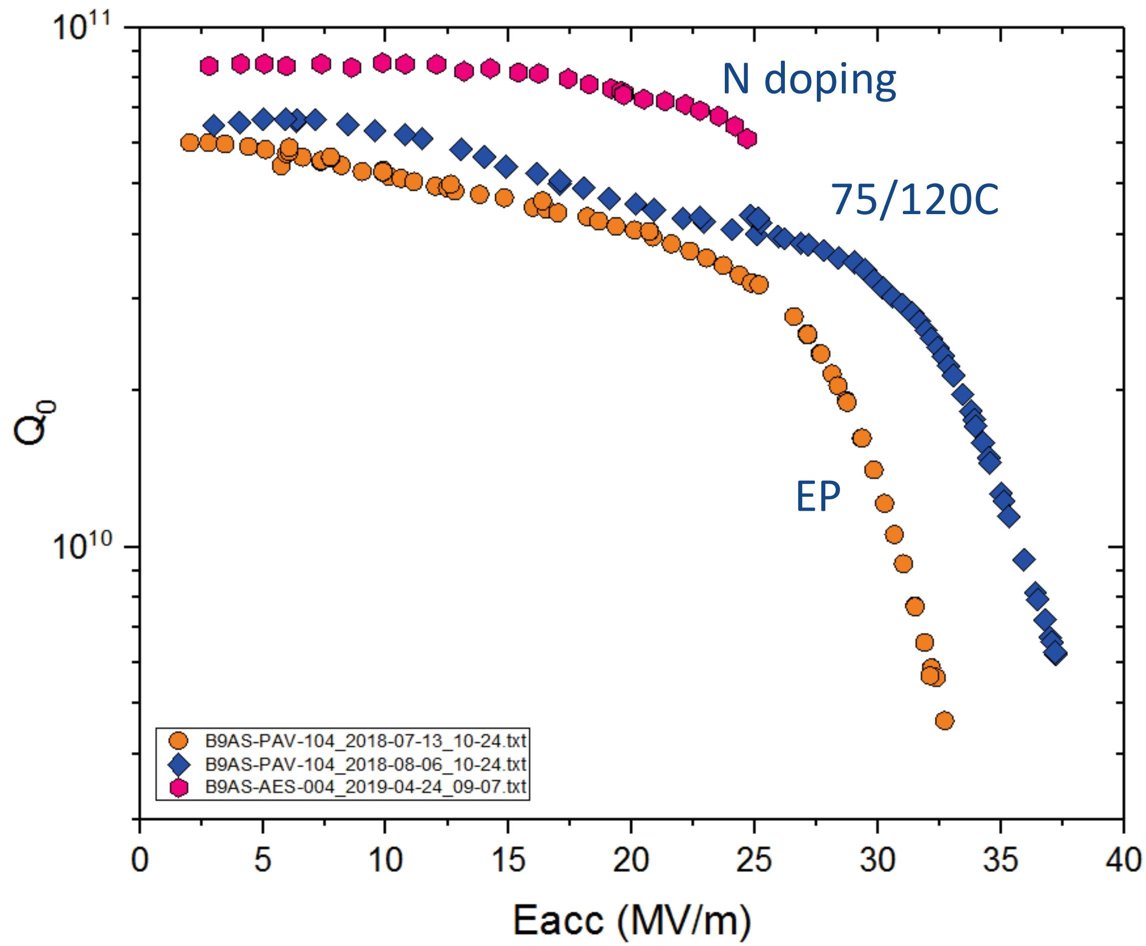
State-of-the-art surface treatments in HB650 cavities

Single-cell HB650, 2K



- All these treatments may exceed PIP-II specs:

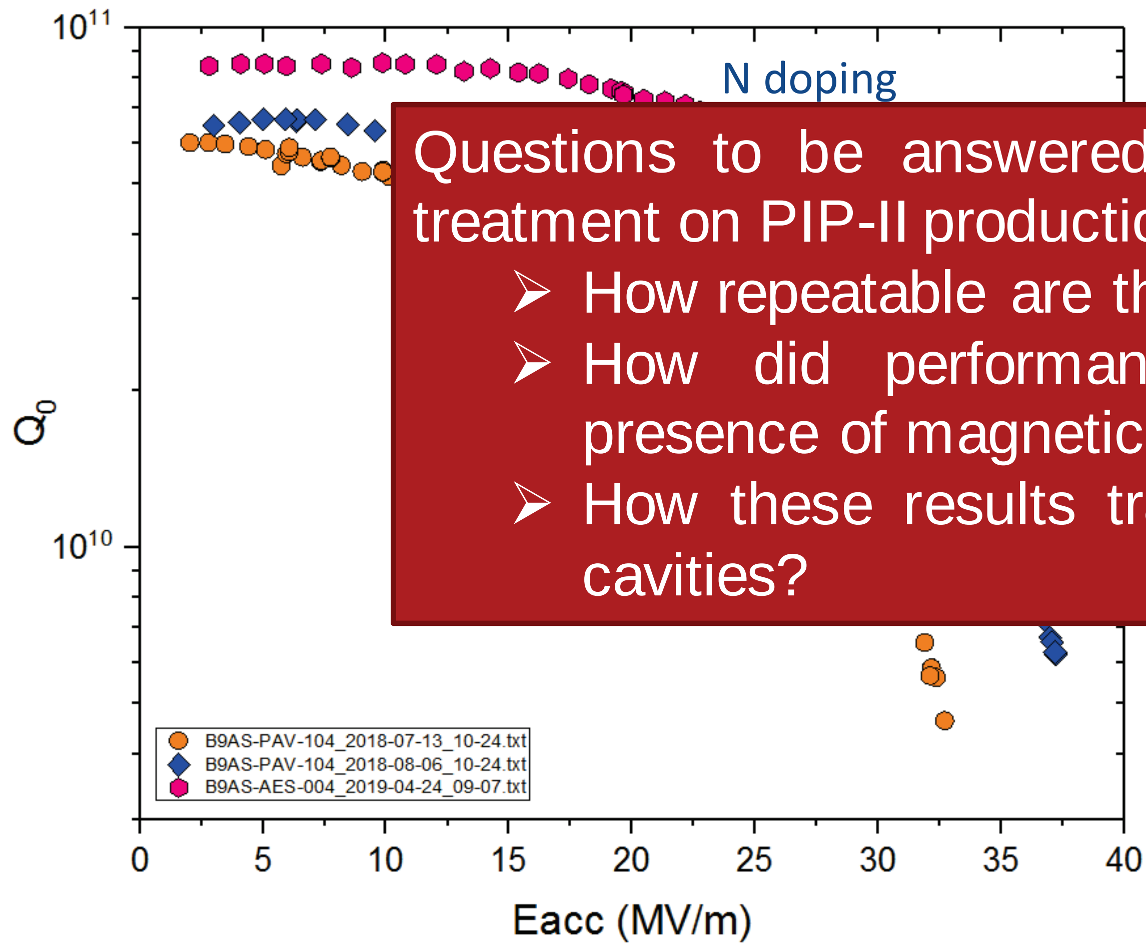
N-doping	7.6e10
75-120C baking	4.7e10
EP	4e10

- N-doping gives the highest Q-factor at medium field

Fermilab

State-of-the-art surface treatments in 650 MHz cavities

Single-cell HB650, 2K



Questions to be answered to finalize the treatment on PIP-II production cavities:

- How repeatable are these results?
- How did performance degrade in presence of magnetic field?
- How these results translate in 5-cell cavities?

- All these treatments may exceed PIP-II specs:

7.6e10
4.7e10
4e10

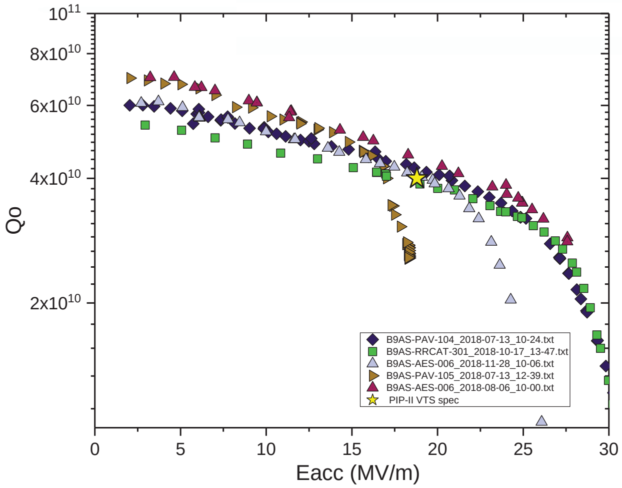
gives the highest Q-factor at medium field

Fermilab

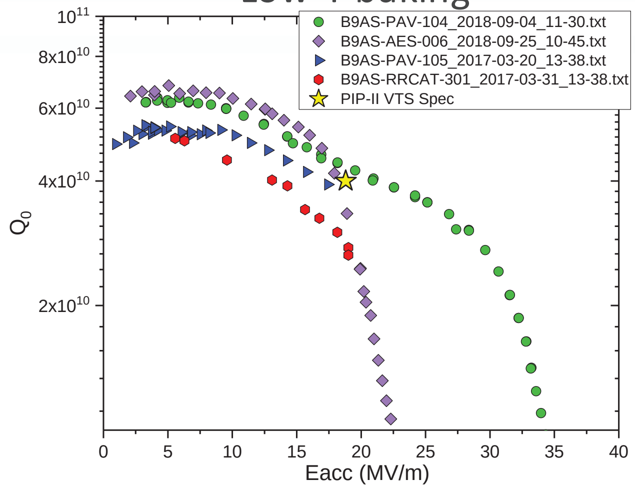
All test done in compensated magnetic field

Surface treatments comparison in single-cell cavities

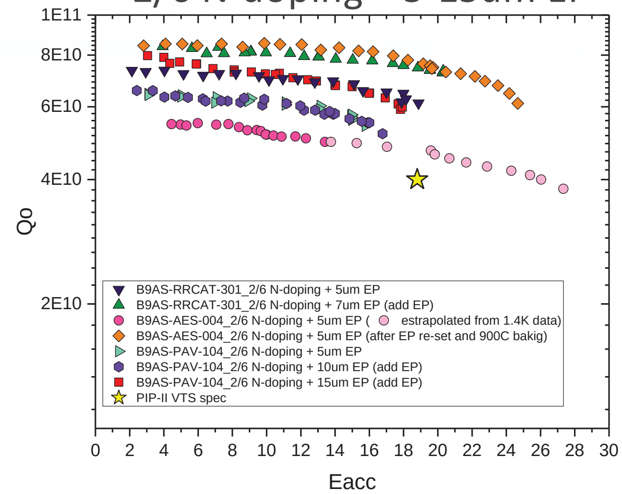
EP



Low-T baking



2/6 N-doping + 5-15um EP



Q_0 at 20 MV/m between ~ 3.7e10 and 4.2e10

Q_0 at 20 MV/m between ~ 2.5e10 and 4.2e10

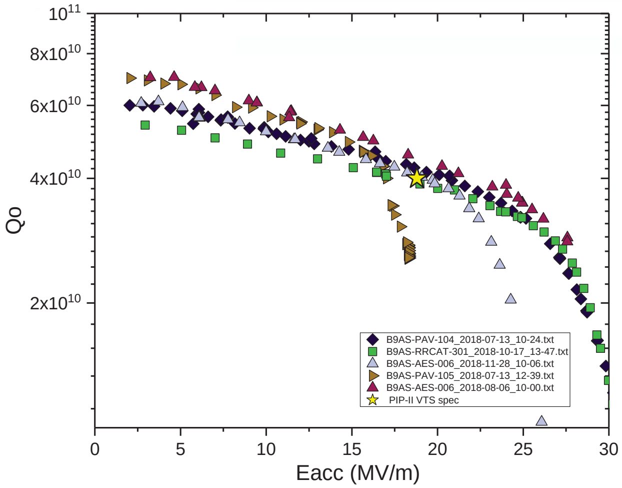
Q_0 at 20 MV/m between ~ 4.5e10 and 7.5e10

Fermilab

All test done in compensated magnetic field

Surface treatments comparison in single-cell cavities

EP



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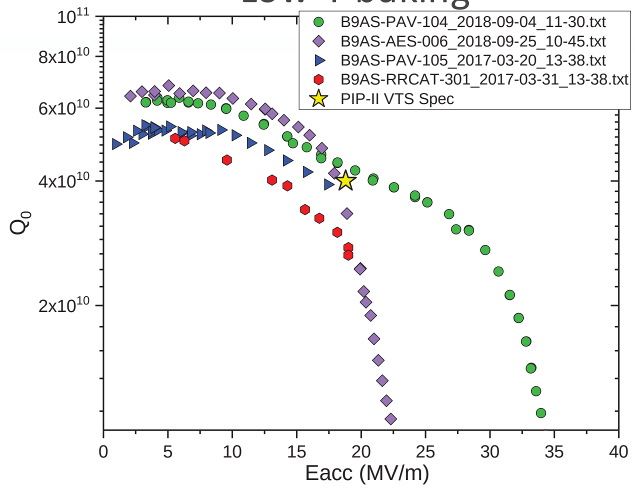

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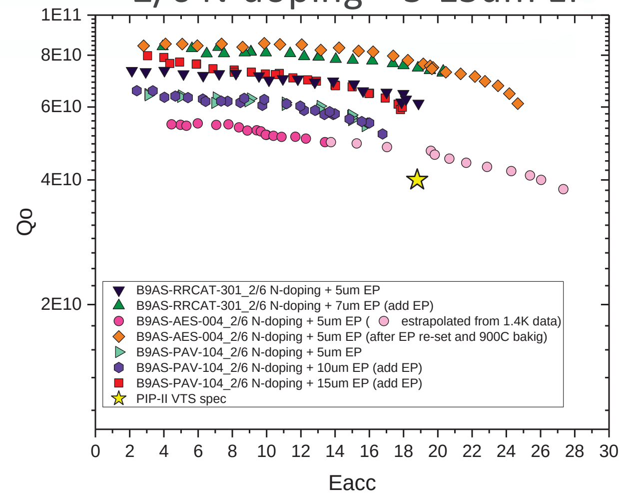


Q_0 at 20 MV/m between ~ 3.7e10 and 4.2e10

Q_0 at 20 MV/m between ~ 2.5e10 and 4.2e10

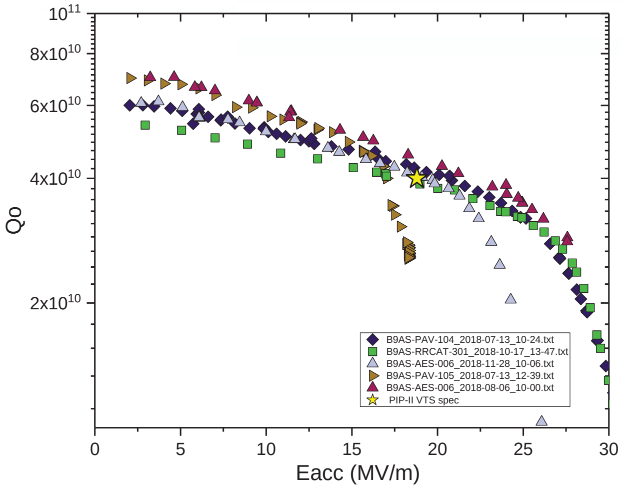
Q_0 at 20 MV/m between ~ 4.5e10 and 7.5e10

Only N-doped cavities consistently exceed Q_0 spec

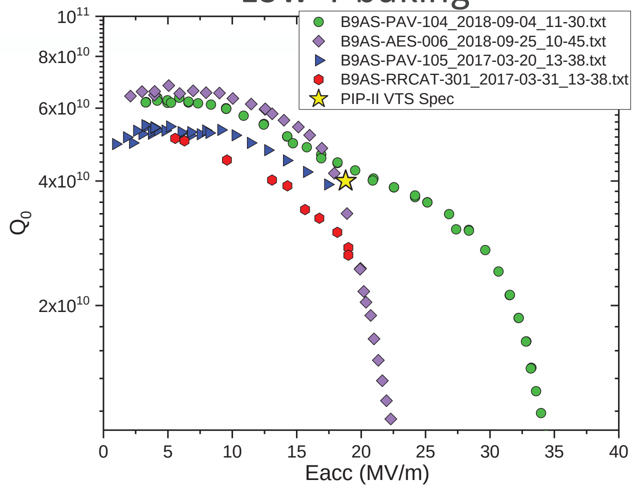
All test done in compensated magnetic field

Surface treatments comparison in single-cell cavities

EP



Low-T baking



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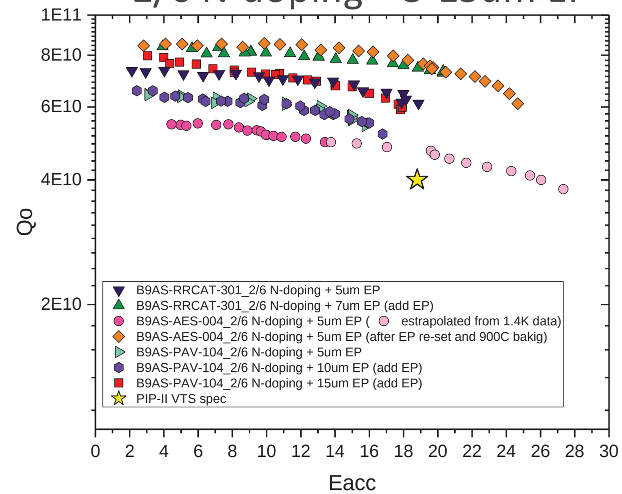


EP

- Quench field between 17 and 30 MV/m
- HFQS onset starting from 16 MV/m to 27 MV/m

Low-T baking

- Quench field between 18 and 35 MV/m
- HFQS onset starting from 17 MV/m to 27 MV/m

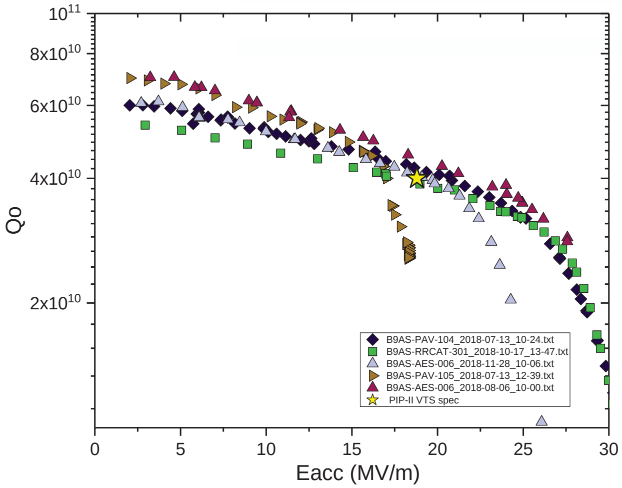
2/6 N-doping + 5-15um EP

- Quench field between 16 and 28 MV/m
- No HFQS

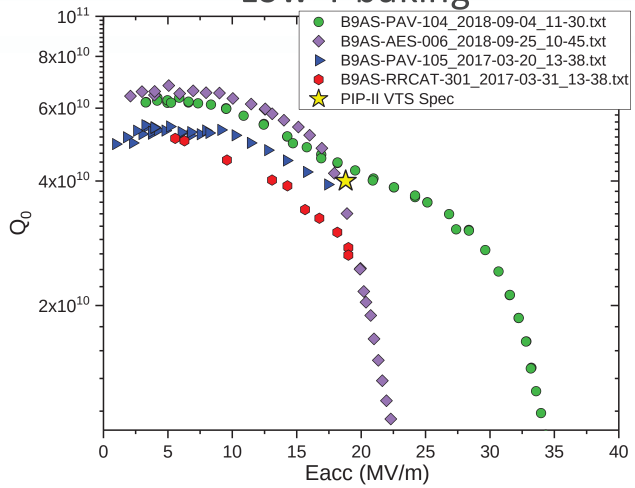
All test done in compensated magnetic field

Surface treatments comparison in single-cell cavities

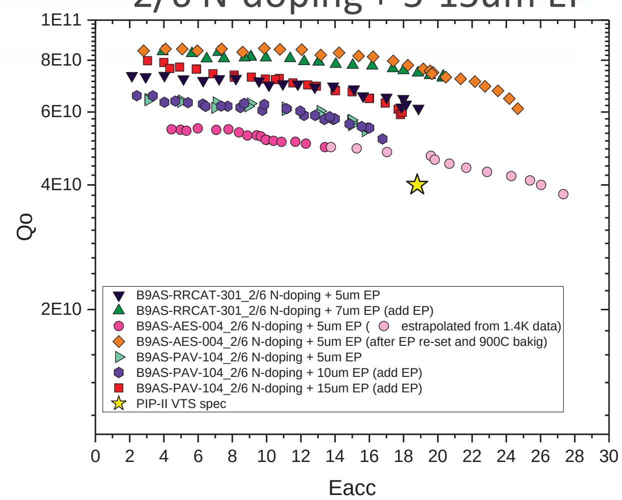
EP



Low-T baking



2/6 N-doping + 5-15um EP



EP:

- Quench field between 17 and 30 MV/m
- HFQS onset starting from 16 MV/m to 27 MV/m

Low-T baking:

- Quench field between 18 and 35 MV/m
- HFQS onset starting from 17 MV/m to 27 MV/m

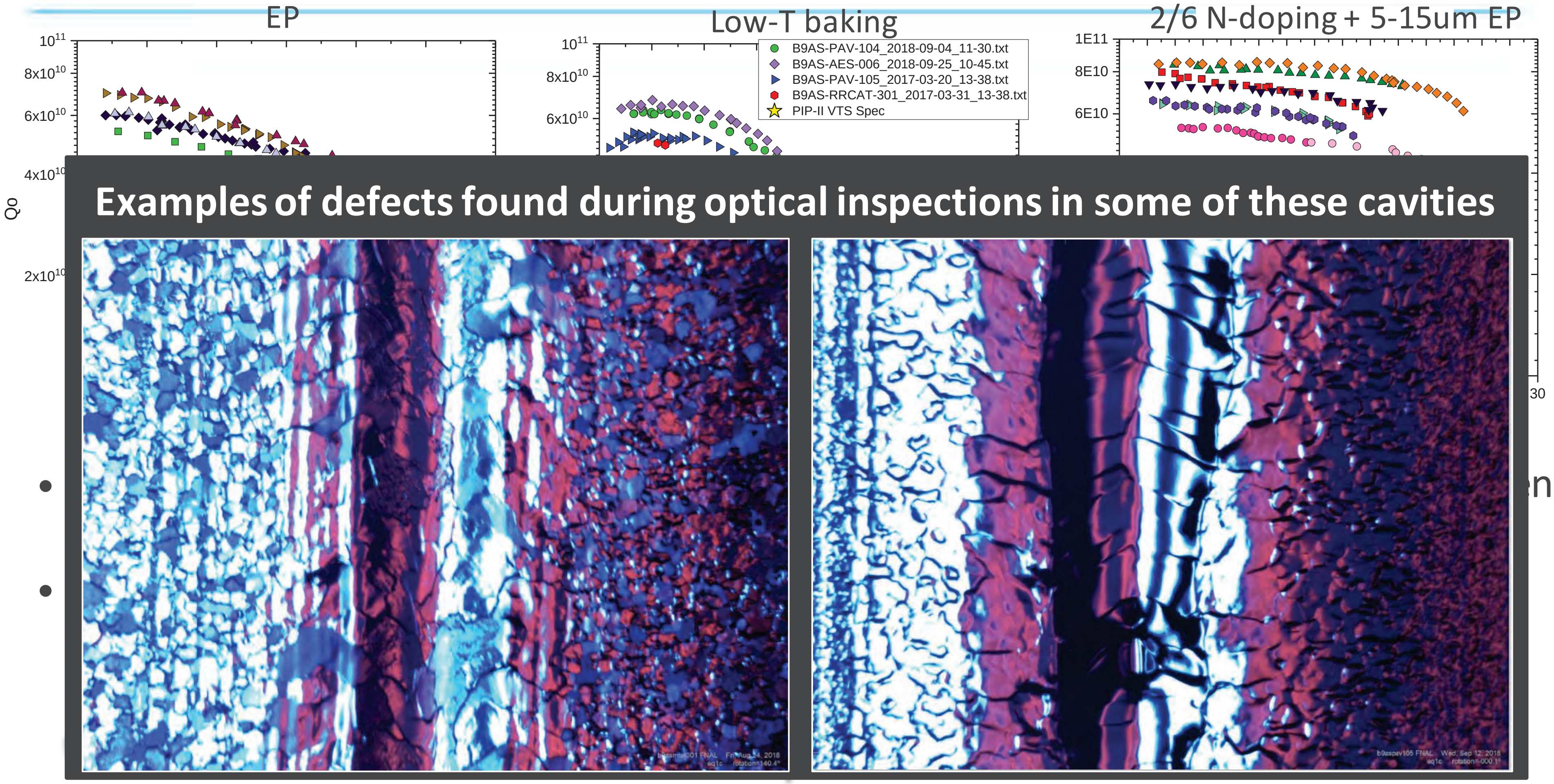
2/6 N-doping + 5-15um EP:

- Quench field between 16 and 28 MV/m
- No HFQS

In most cases early quench and/or HFQS onset is related to defects in the cavity, it is not a fundamental limitation

All test done in compensated magnetic field

Surface treatments comparison in single-cell cavities



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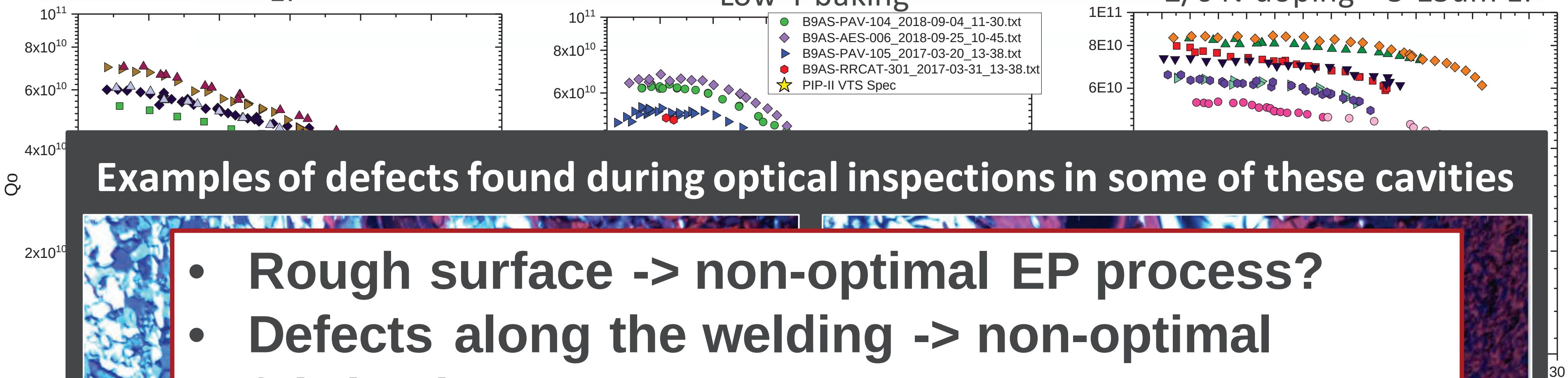
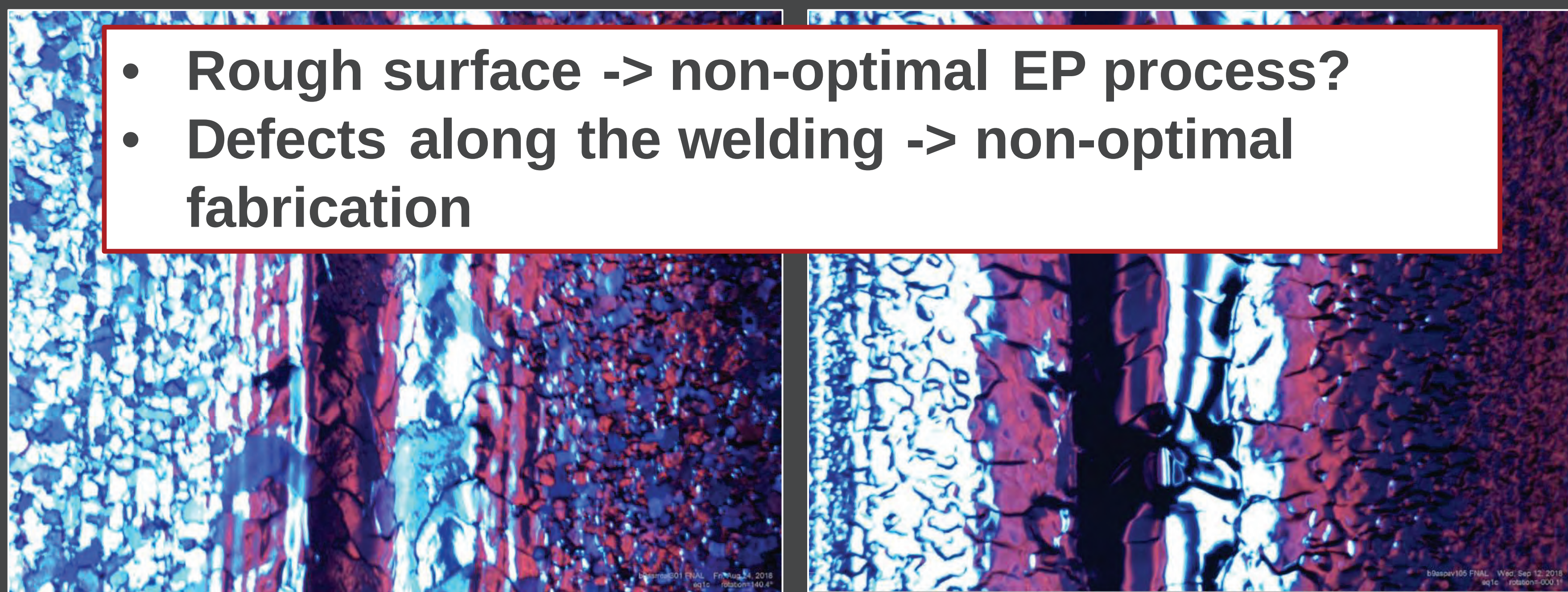
Surface treatments comparison in single-cell cavities



Examples of defects found during optical inspections in some of these cavities



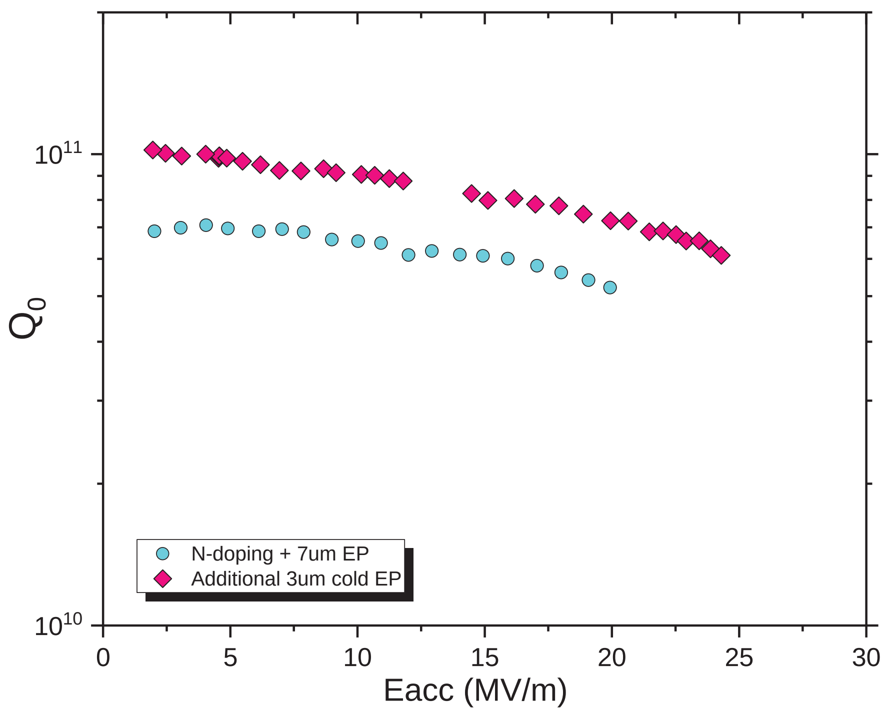
- **Rough surface -> non-optimal EP process?**
- **Defects along the welding -> non-optimal fabrication**

In most cases early quench and/or HFQS onset is related to defects in the cavity, it is not a fundamental limitation

Fermilab

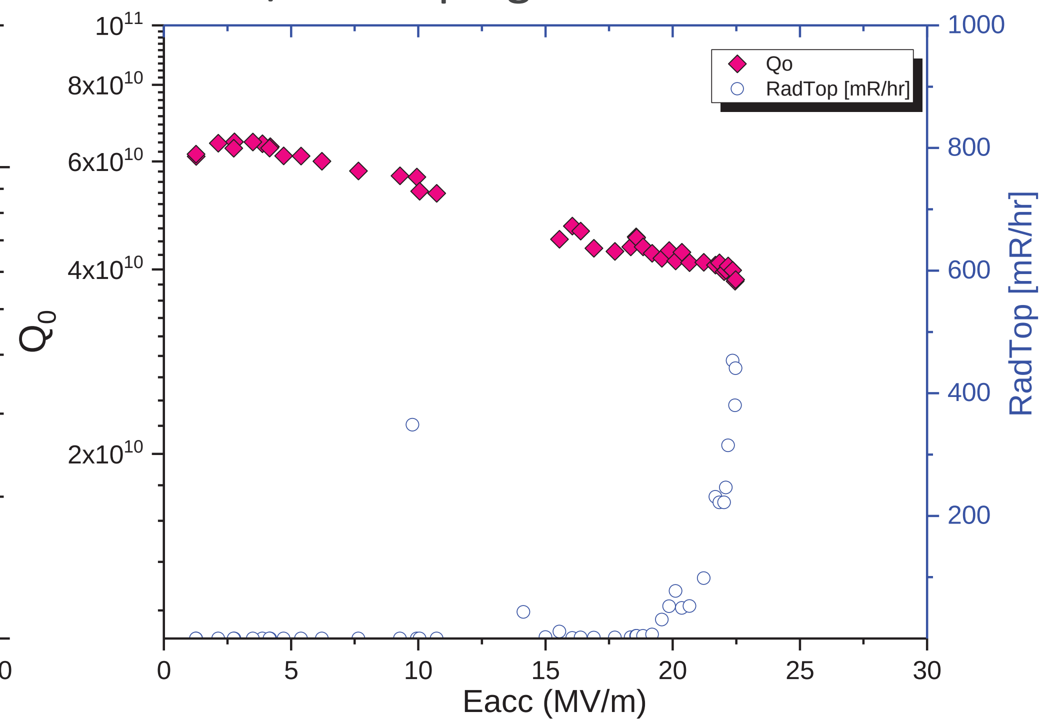
Cold EP on HB650 5-cell cavities

2/6 N-doping + 7um EP + 3um **cold** EP



Quench field improved from 20 to 24 MV/m by adding 3um of cold EP

2/6 N-doping + 7um **cold** EP



Cavity limited by FE at ~23MV/m, quench field may be higher

Fermilab

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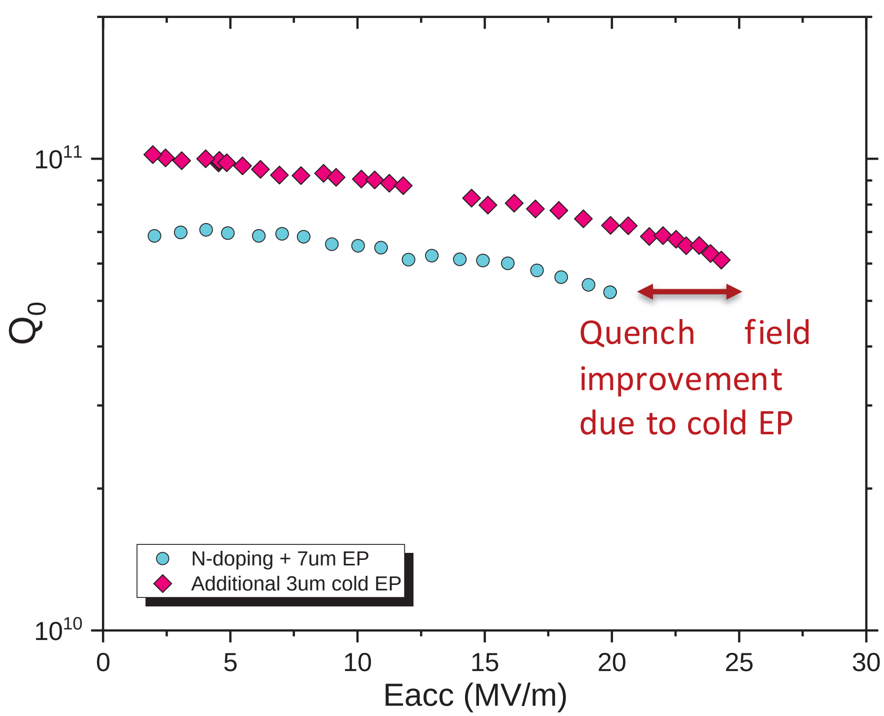
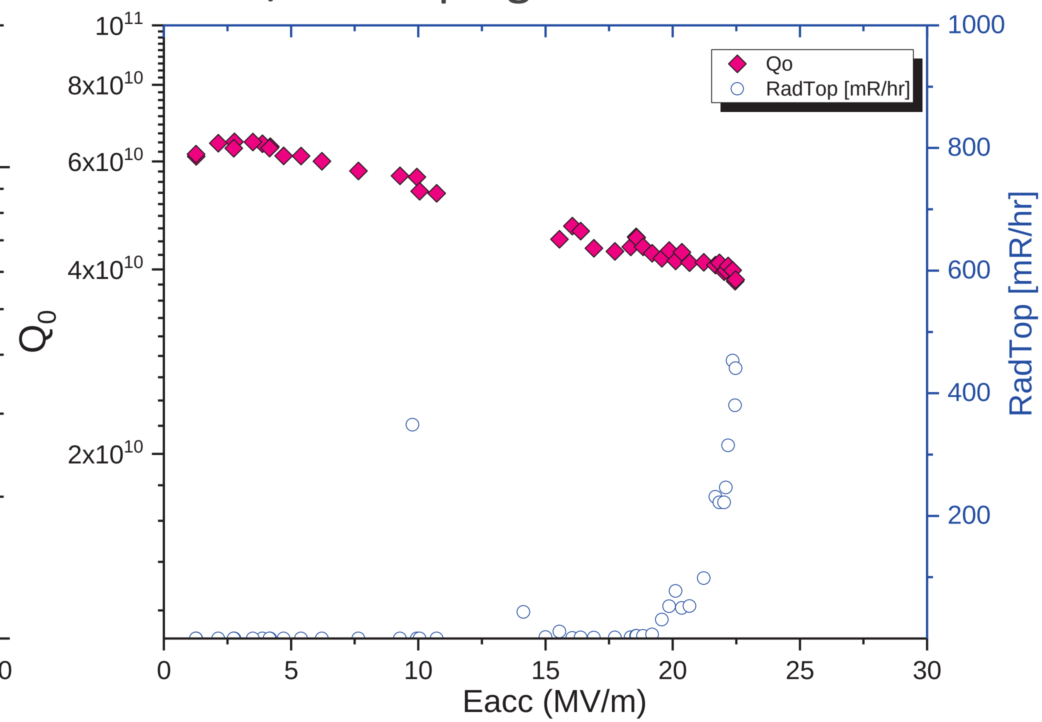


2/6 N-doping + 7um **cold** EP



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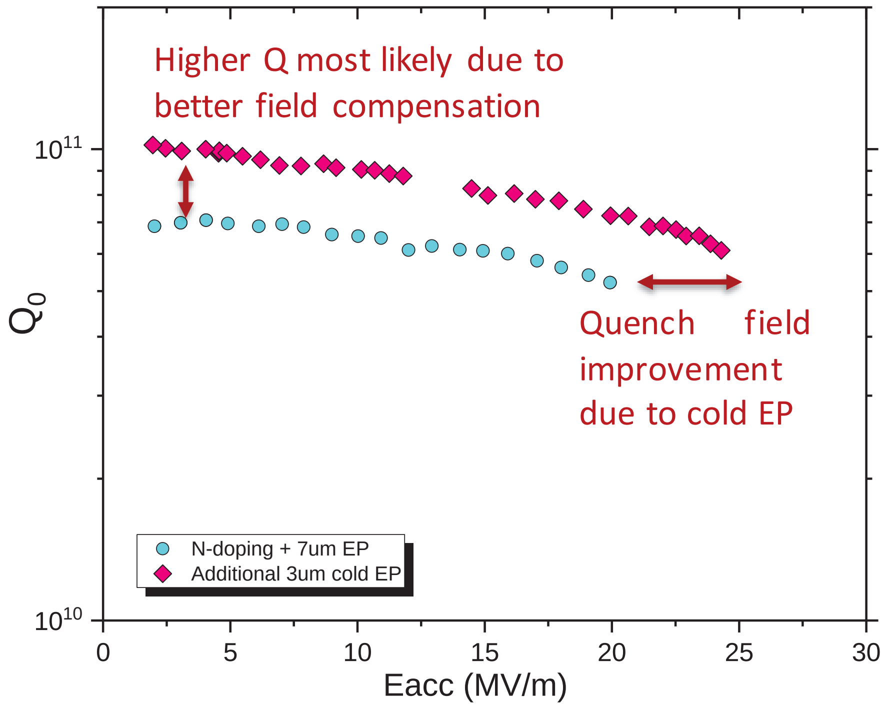

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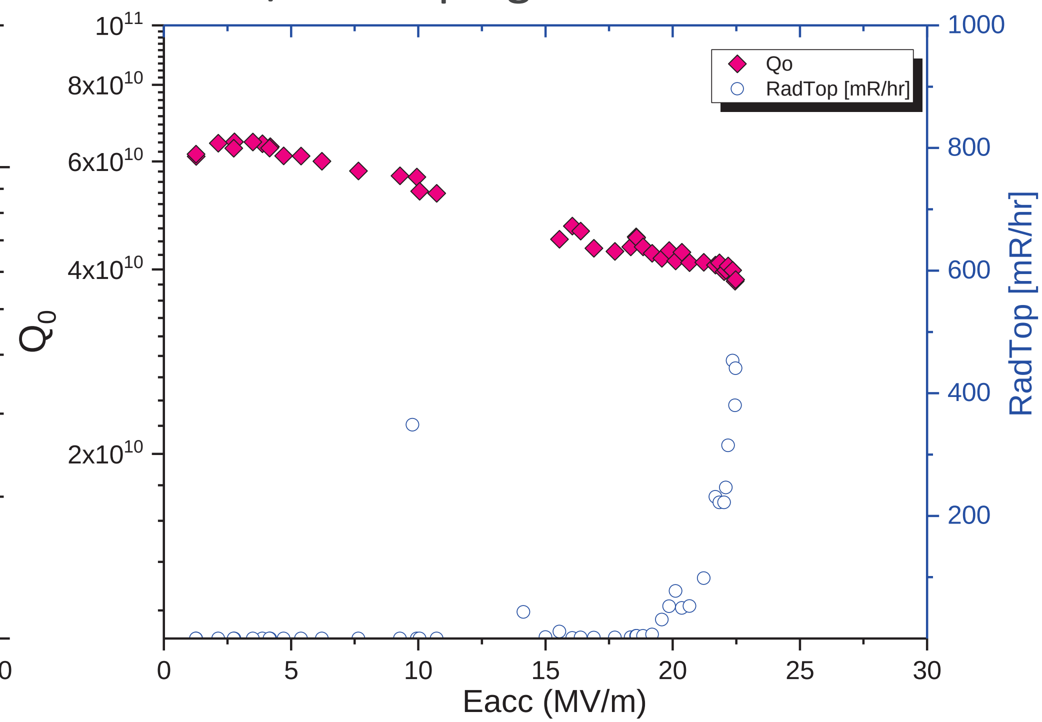

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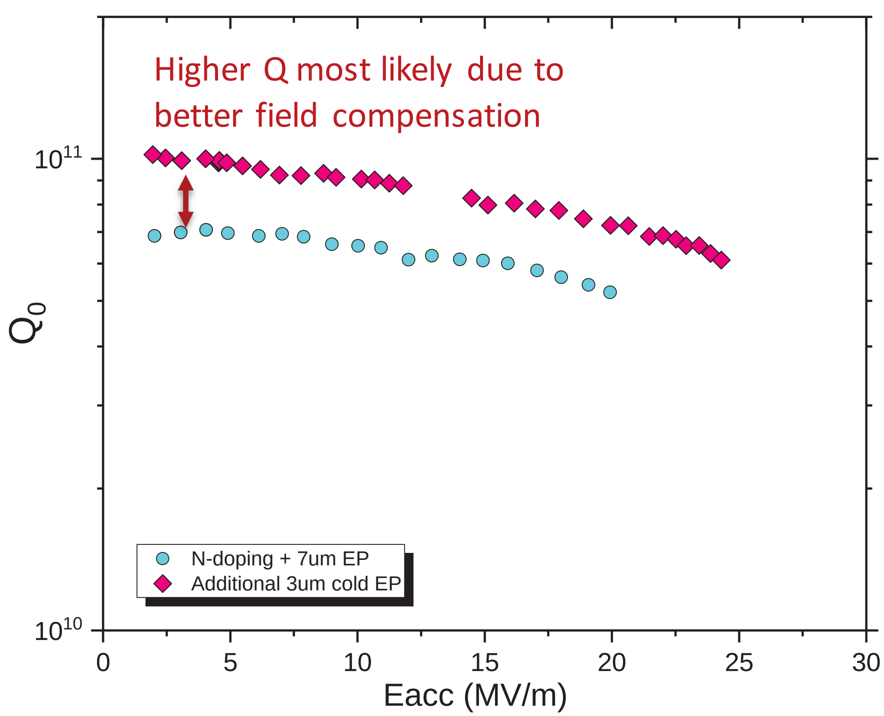

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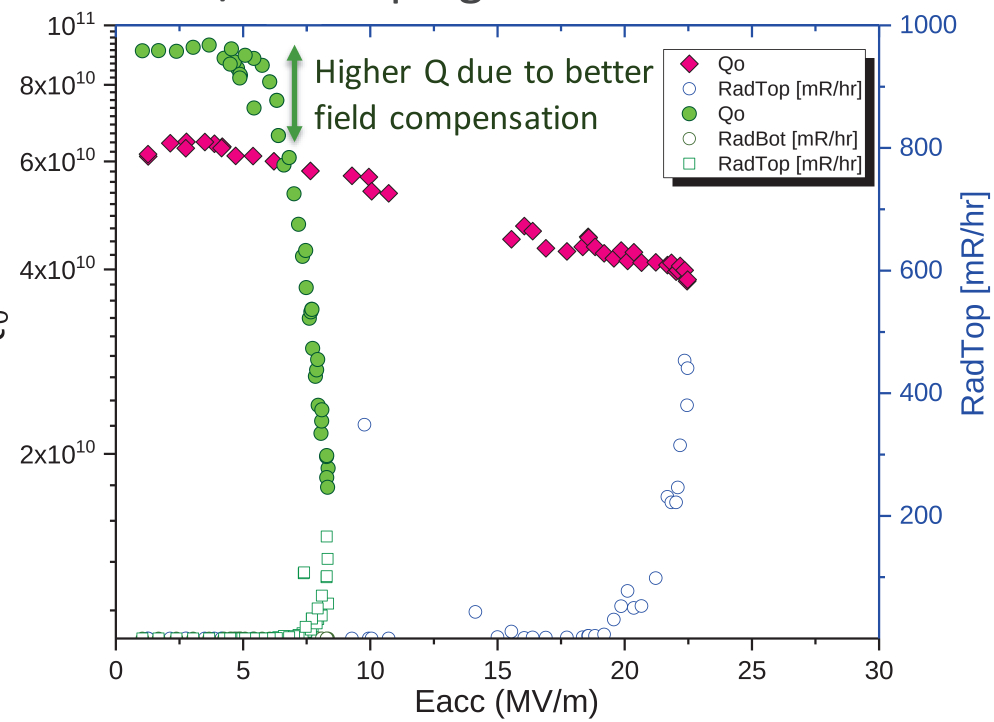
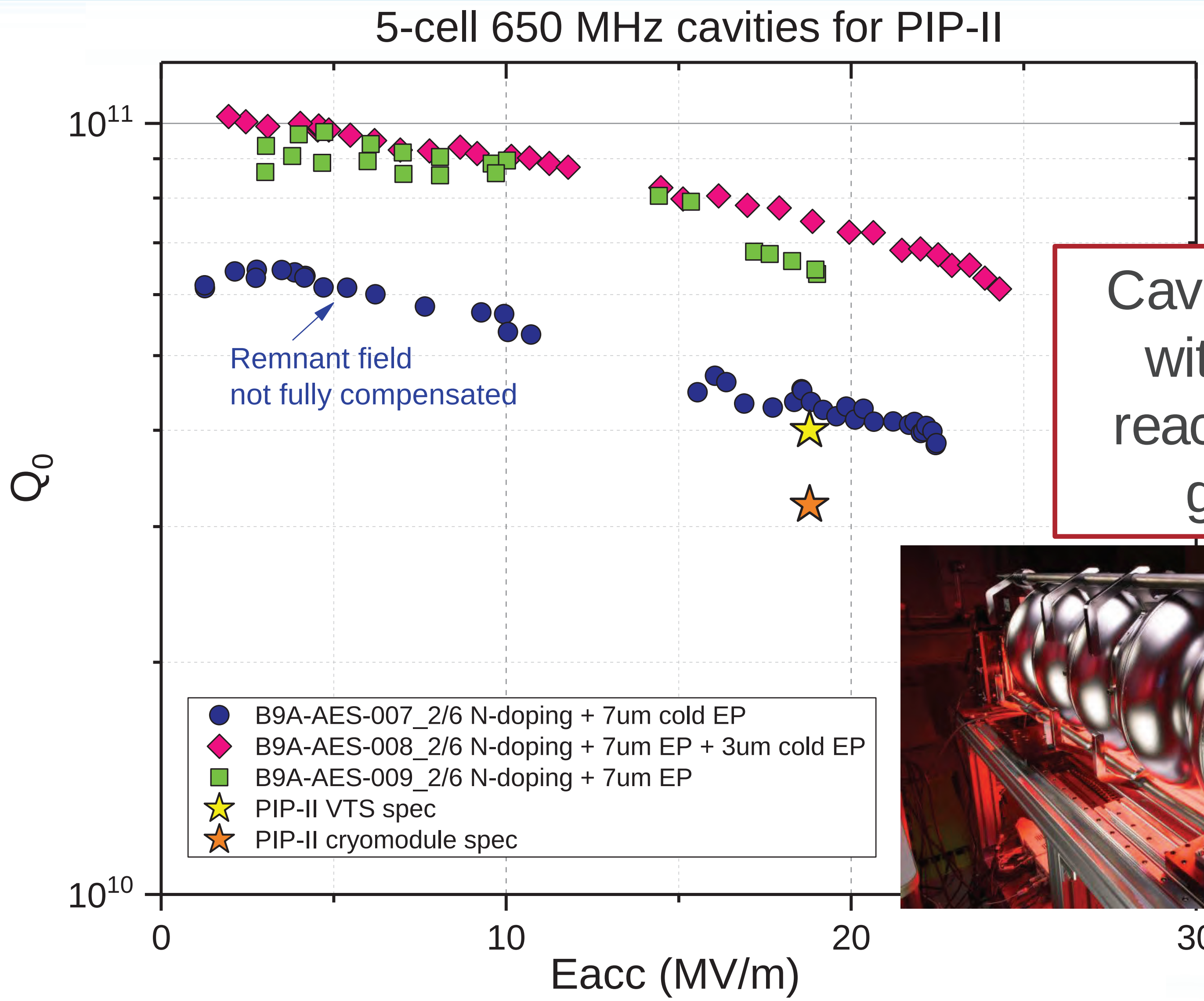


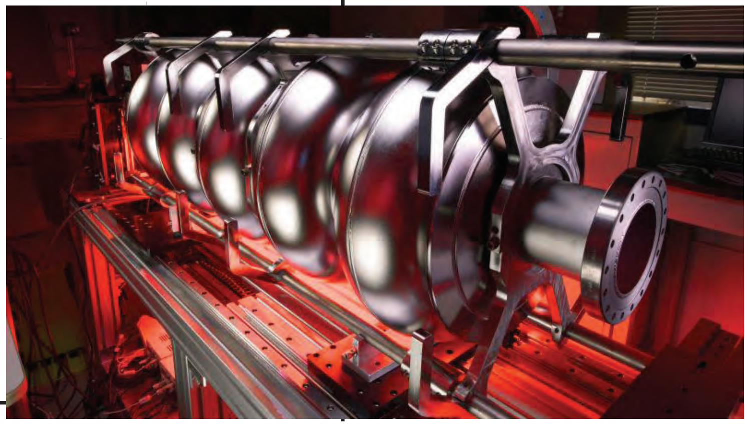
Cavity re-tested after HPR at Lab2 showed large FE starting from low field

Fermilab

Summary results on HB650 5-cell cavities



Cavities treated with cold EP reached higher gradients



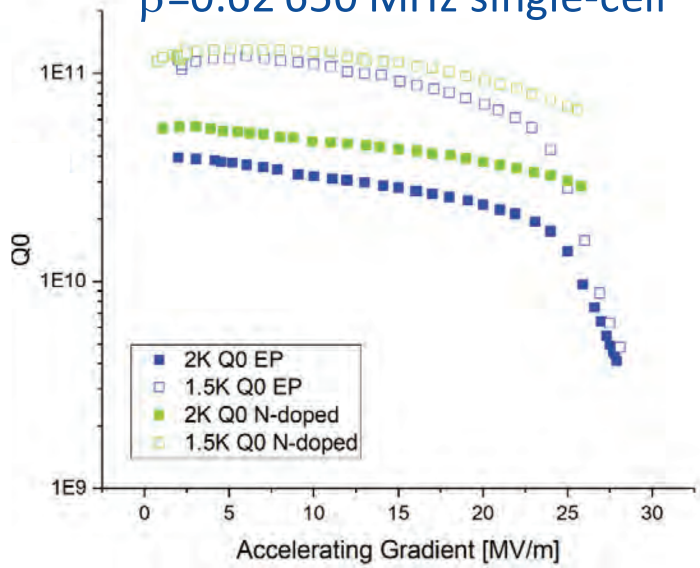
Fermilab

LB650 and 644 MHz cavities studies

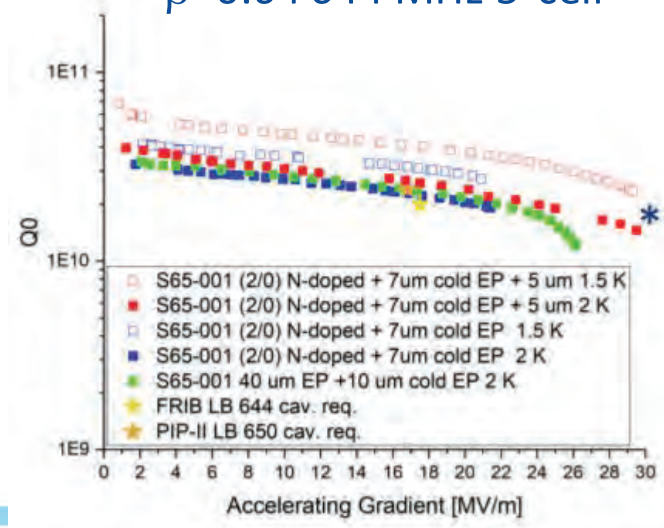
- Collaboration between FNAL and INFN to optimize Q-factor on PIP-II LB650 (b=0.62) cavities, first results in N-doped single-cell cavity very promising

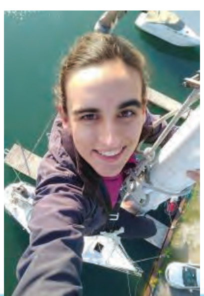
- Collaboration between FNAL, MSU and ANL through an Accelerator Stewardship Award focused on transferring the doping technology to 5-cell LB 644MHz cavities. Results also very promising!

β=0.62 650 MHz single-cell



β=0.64 644 MHz 5-cell





Kellen McGee
PhD student from MSU now working at FNAL
Recipient of DOE Office of Science Graduate Student Research Fellowships

HWR and SSR1 pCM assembly

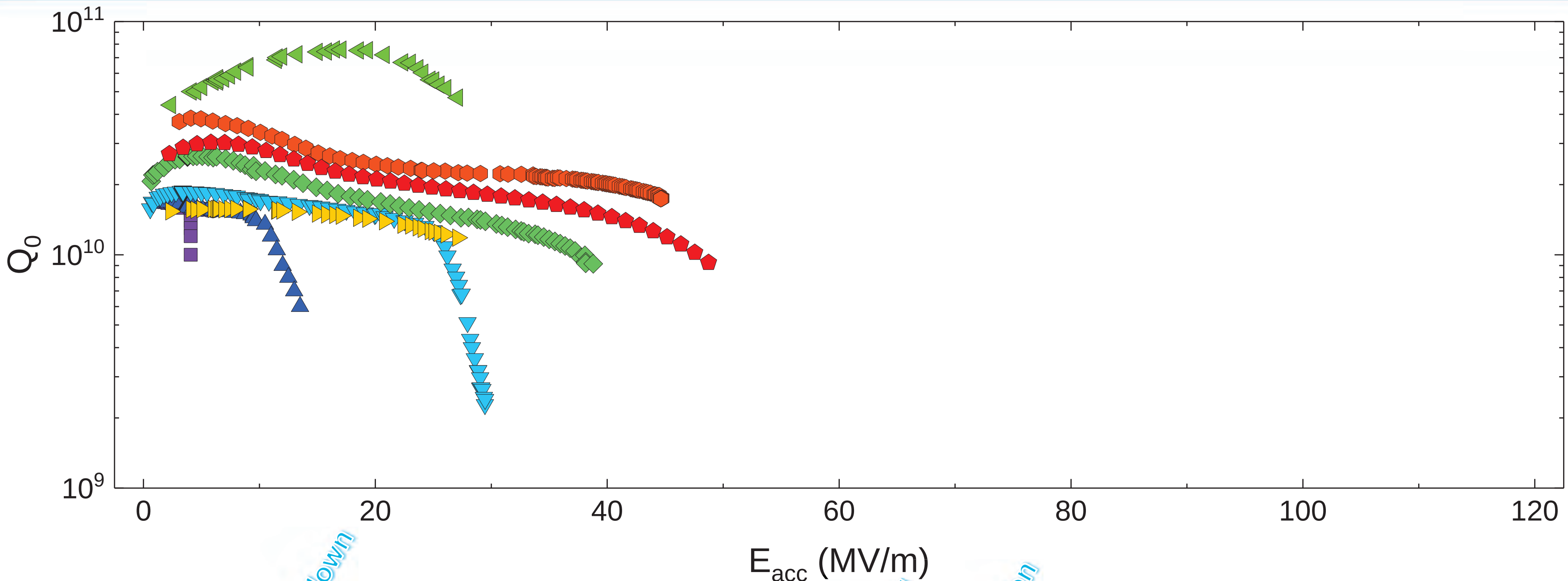
HWR cryomodule cold mass assembly

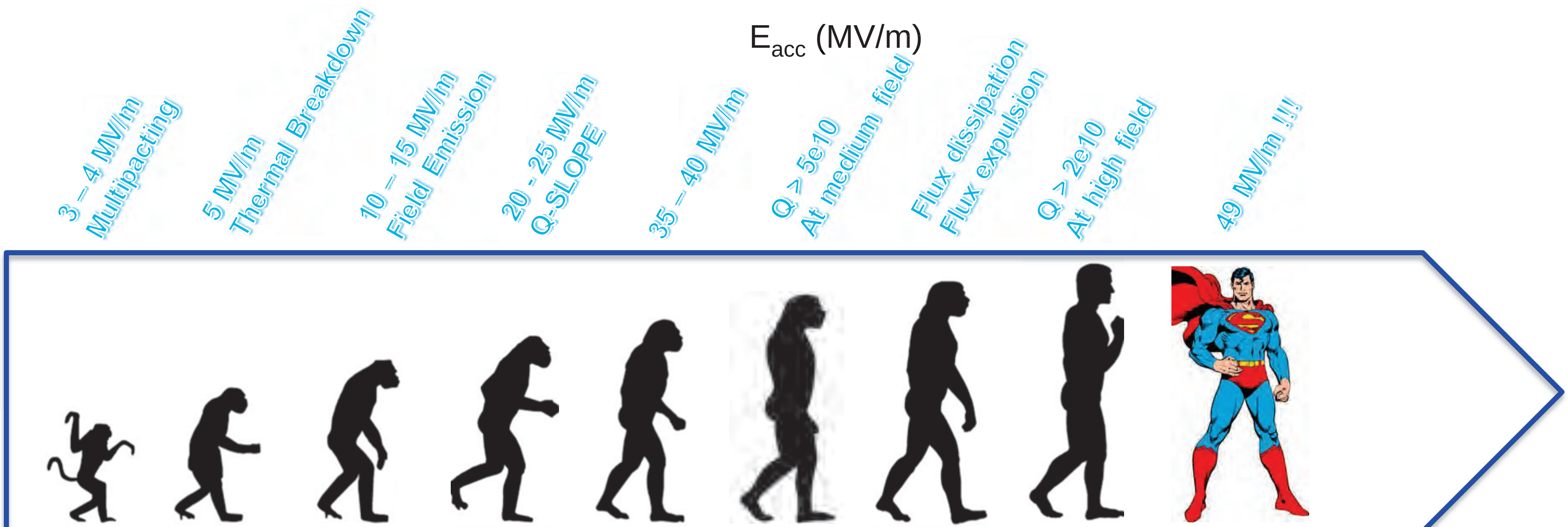
SSR1 cryomodule cold mass assembly

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**

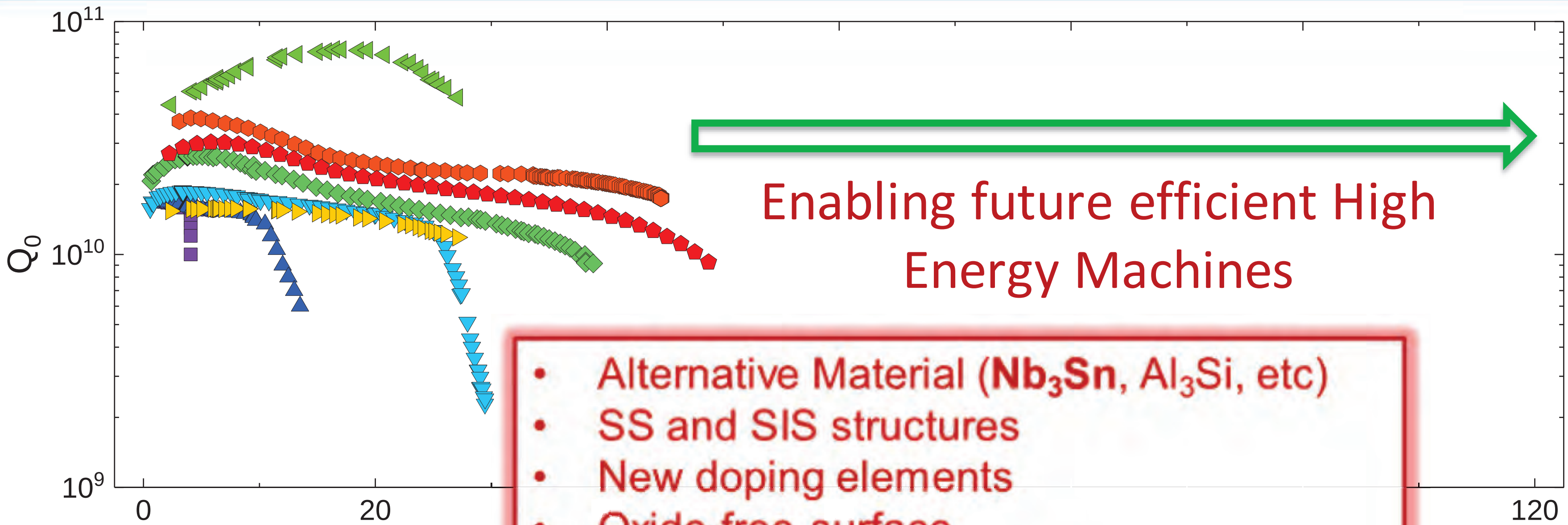
SRF performance: past, present and future



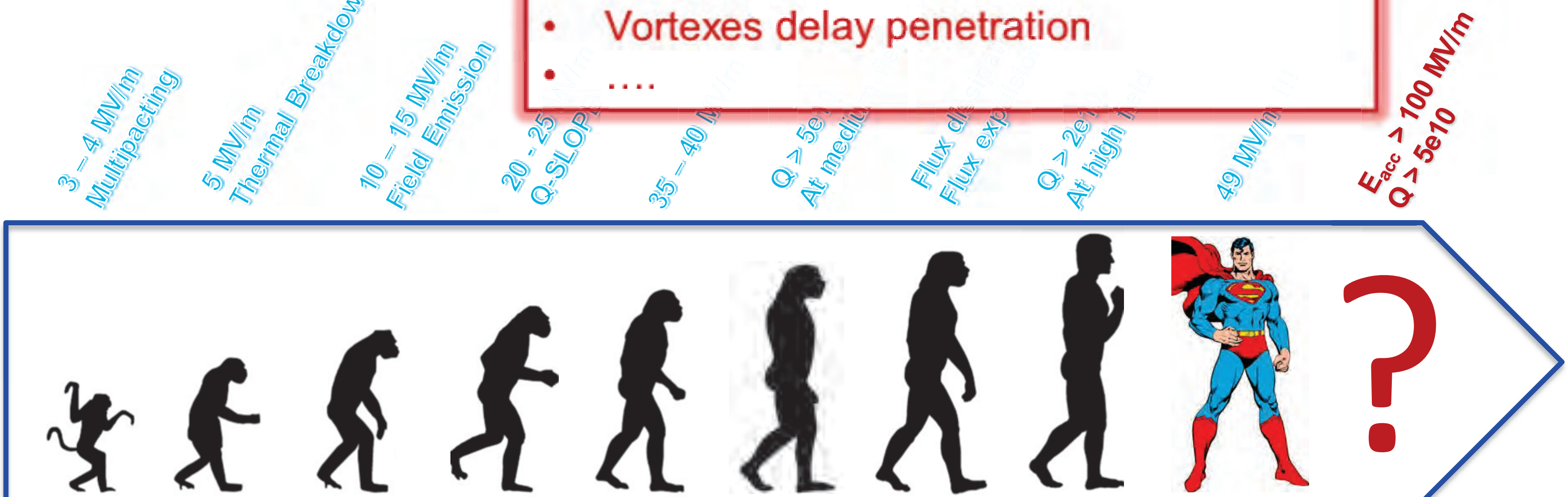


Slide adapted from Mattia Checchin

SRF performance: past, present and future



- Alternative Material (**Nb_3Sn**, Al_3Si, etc)
- SS and SIS structures
- New doping elements
- Oxide-free surface
- Vortexes delay penetration
- ….



Slide adapted from Mattia Checchin


Thanks to the whole FNAL SRF team!

Thank you for your attention!