Connecting Cavity Performance to Physics of the Surface

Martina Martinello - on behalf of the FNAL SRF team

CEC-ICMC 2019, Superconducting RF Cavity Materials
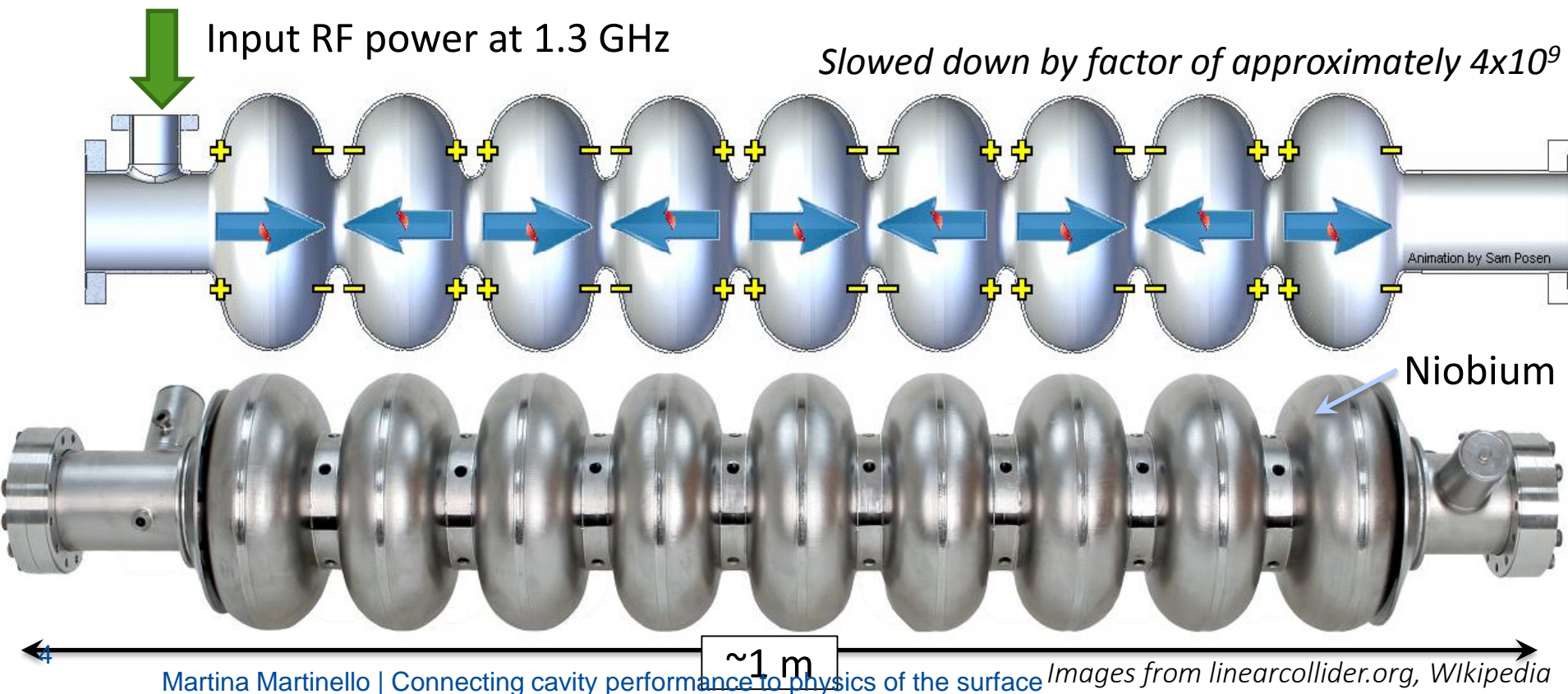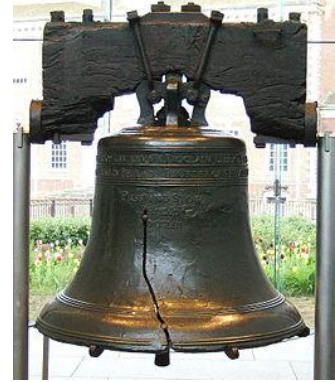
23 July 2019

Outline

- Introduction

- N-doping: the treatment for high-Q

- N-infusion: the treatment for high-Q at high-G

- Mild baking for high-G

- Conclusions
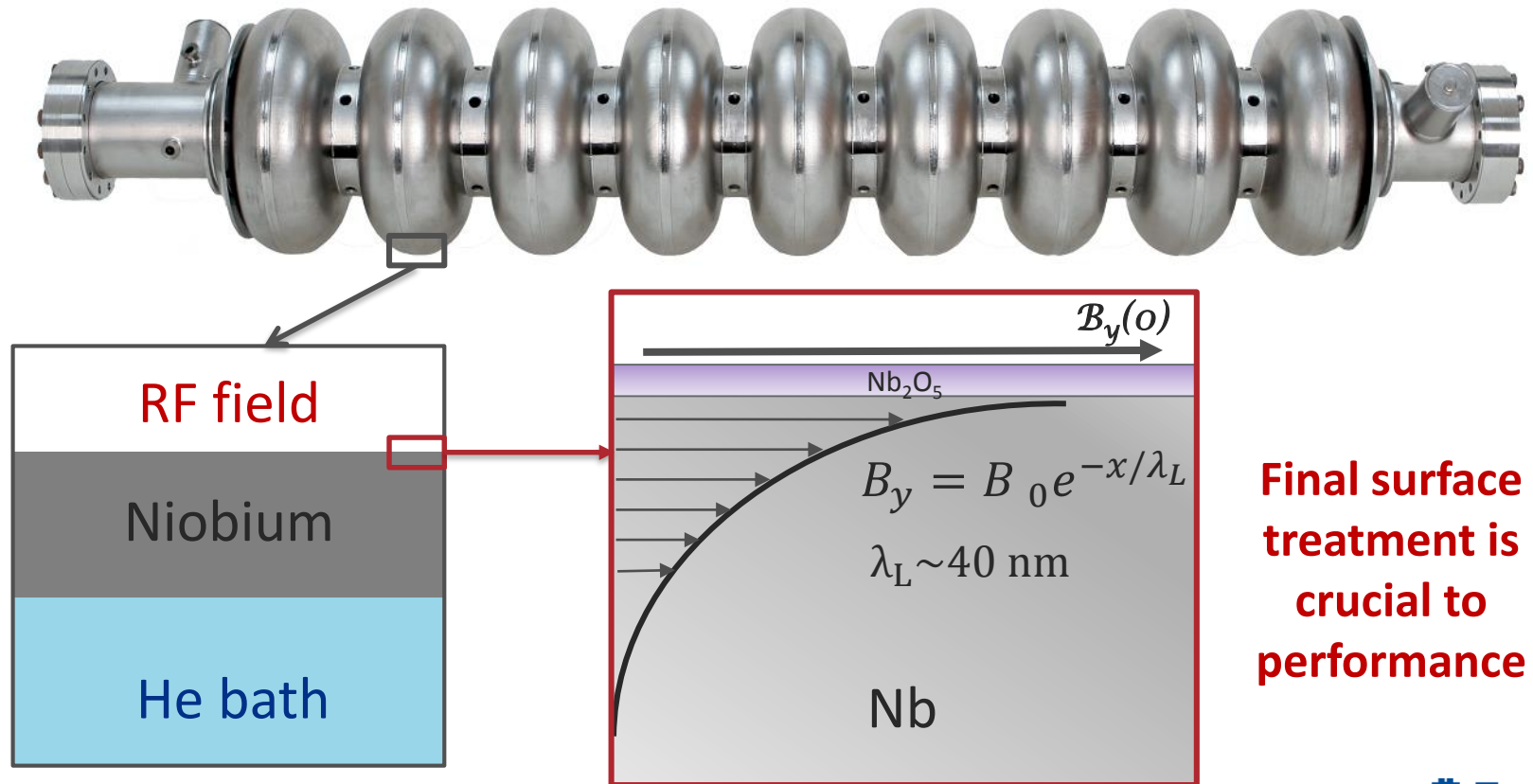
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Introduction

Particle Acceleration via SRF Cavities

- **Superconducting radiofrequency (SRF) cavities**
- High quality EM resonators: Typical $Q_0 > 10^{10}$
- Large electric field generated along the cavity axis
- Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

Slowed down by factor of approximately 4×10^9

Animation by Sam Posen

Niobium

~1 m

Martina Martinello | Connecting cavity performance to physics of the surface *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>

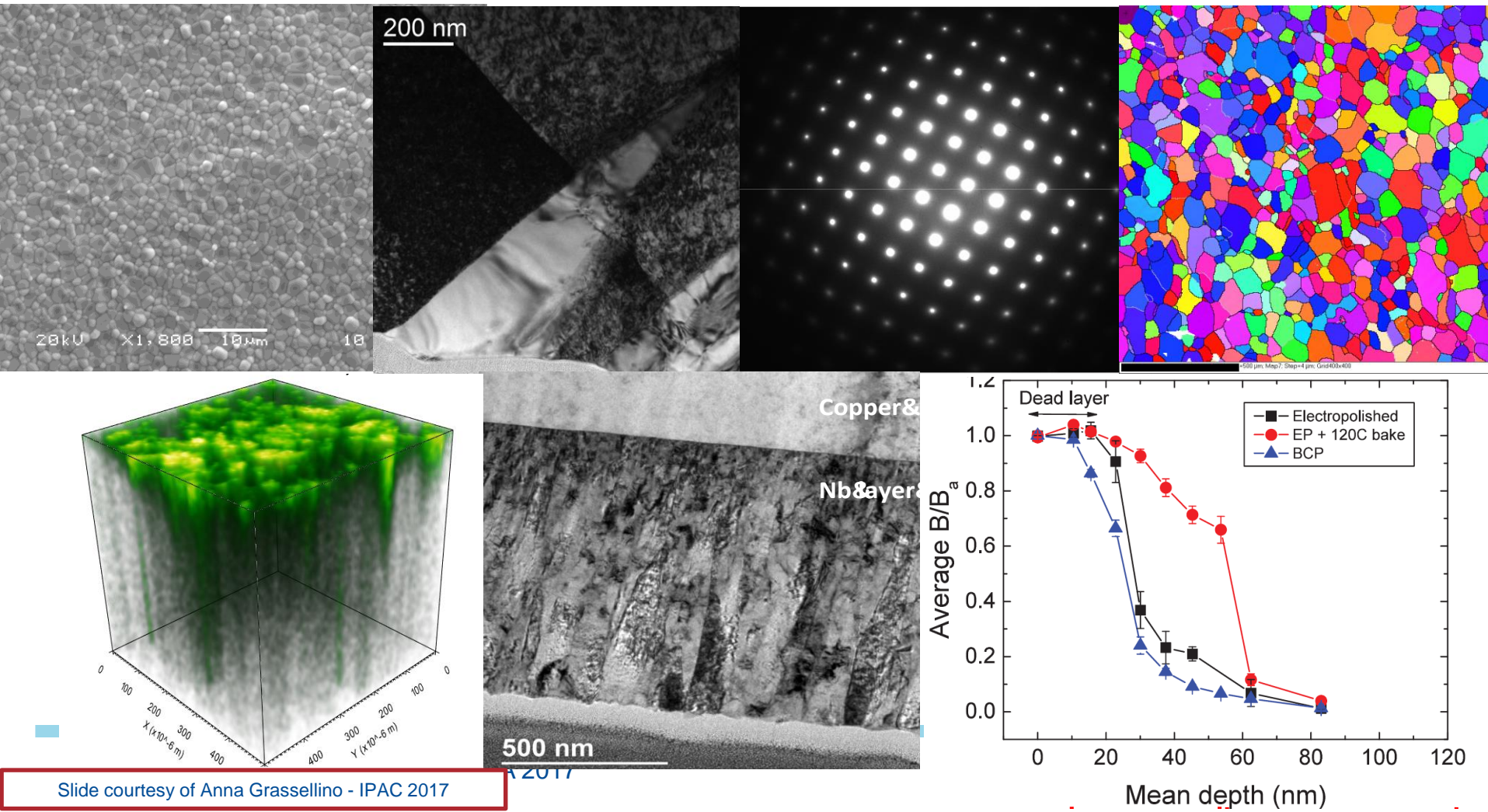- Losses concentrate on the first ~100 nm of the **inner surface**

RF field

Niobium

He bath

$\mathcal{B}_y(o)$

Nb$_2$O$_5$

$$B_y = B_0 e^{-x/\lambda_L}$$

$\lambda_L \sim 40$ nm

Nb

Final surface treatment is crucial to performance

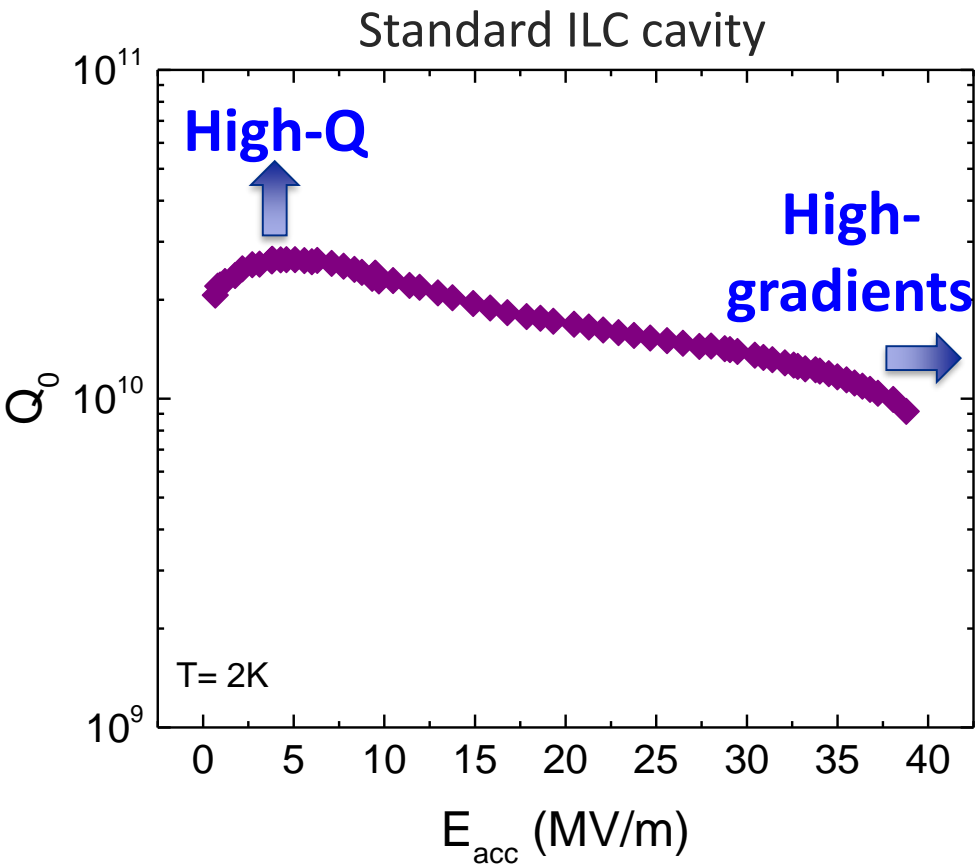🔷 **Fermilab**

Beam view, inside the cavity

Extreme attention to surface treatments and surface cleanliness are mandatory

2017

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Key to progress for superconducting RF cavities

- Cavity surface undergoes a series of delicate chemical and heat treatments
- Material science tools are <u>essential</u> to understand the surface nano-structural changes that lead to dramatic changes in performance

SRF Cavities Figure of Merits

Standard ILC cavity

High-Q

High-gradients

Q_0

10^{11}

10^{10}

10^9

T= 2K

0   5   10   15   20   25   30   35   40

E_{acc} (MV/m)

Q-factor (Q_0):

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

$$R_s = R_{BCS}(T) + R_{res}$$
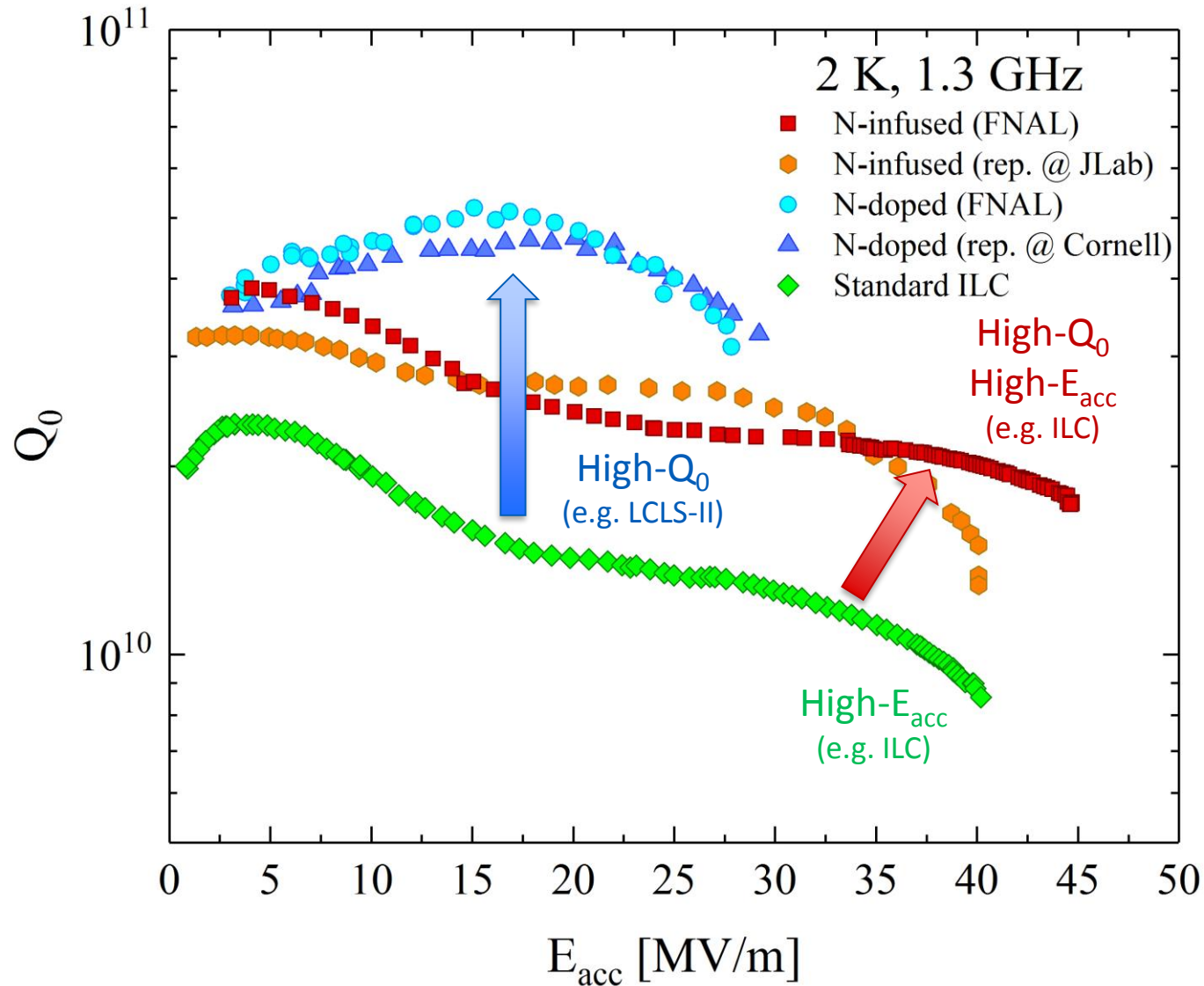
High $Q_0 \rightarrow$ lower power consumption

Accelerating field (E_{acc}):

Determine the energy transferred to charged particles

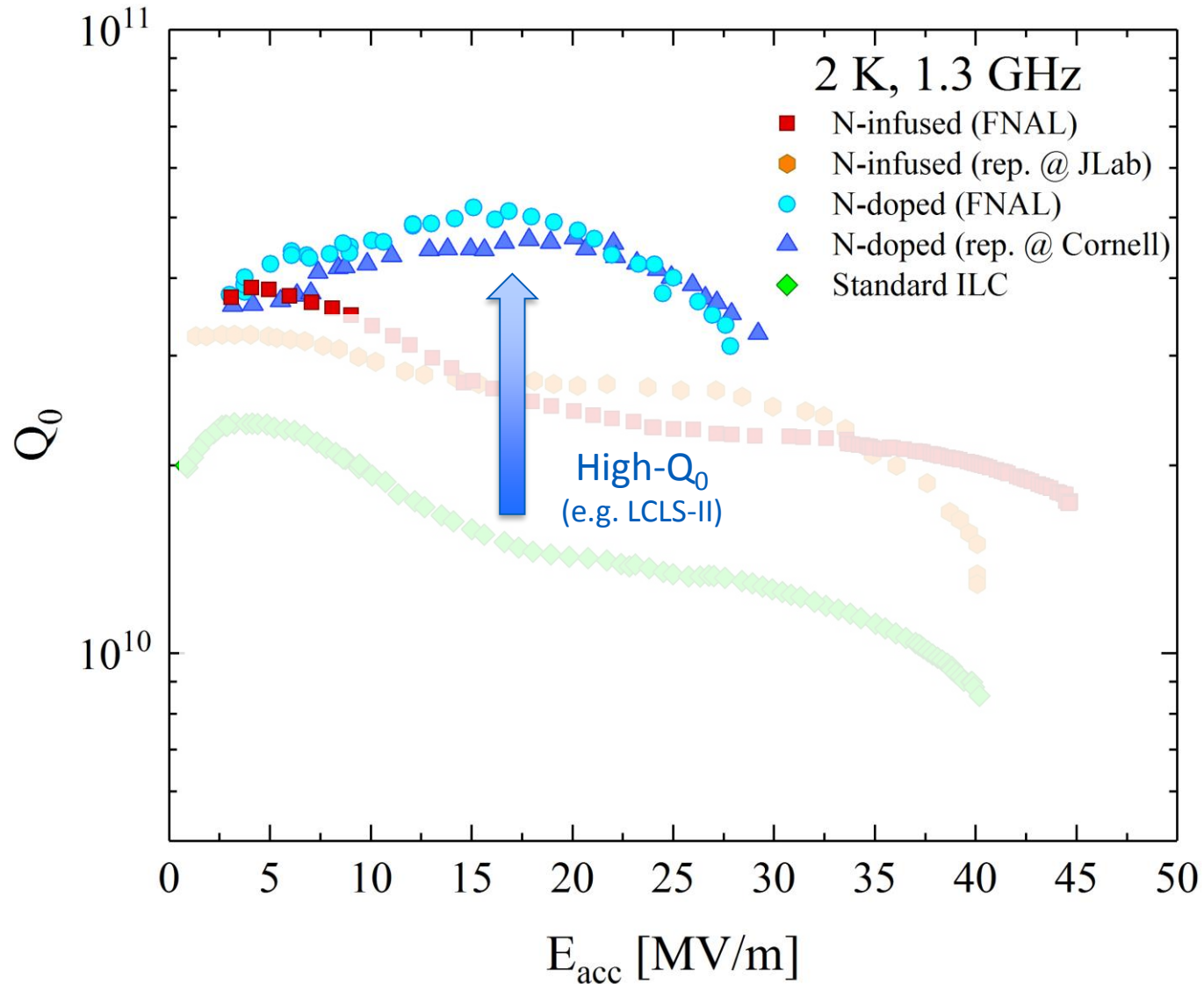High $E_{acc} \rightarrow$ lower accelerator length

High Q at large gradient may reduce both capital and operational costs of accelerators

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State-of-the-art treatments

hecting cavity performance to physics of the surface

Fermilab

N-doping: the treatment for high-Q

High-Q$_0$ treatments

2 K, 1.3 GHz

- N-infused (FNAL)
- N-infused (rep. @ JLab)
- N-doped (FNAL)
- N-doped (rep. @ Cornell)
- Standard ILC

High-Q$_0$
(e.g. LCLS-II)

Q$_0$

E$_{acc}$ [MV/m]

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N-doping treatment

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

Nb

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N-doping treatment

800C UHV, 3 hours → 800C N$_2$ injection p=25mTorr

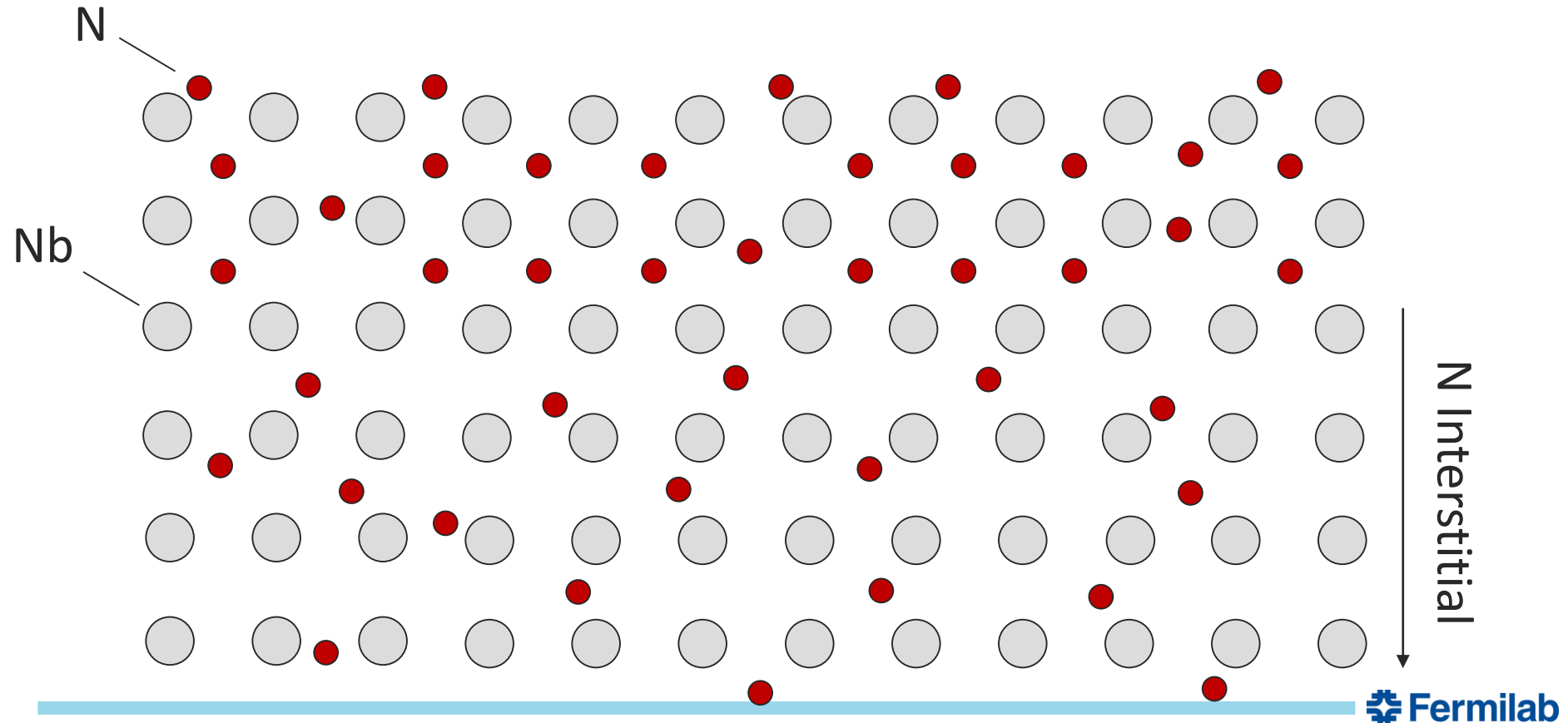800C N$_2$ 2 minutes

800C UHV, 6 minutes

UHV cooling

5 um EP

N$_2$

Nb

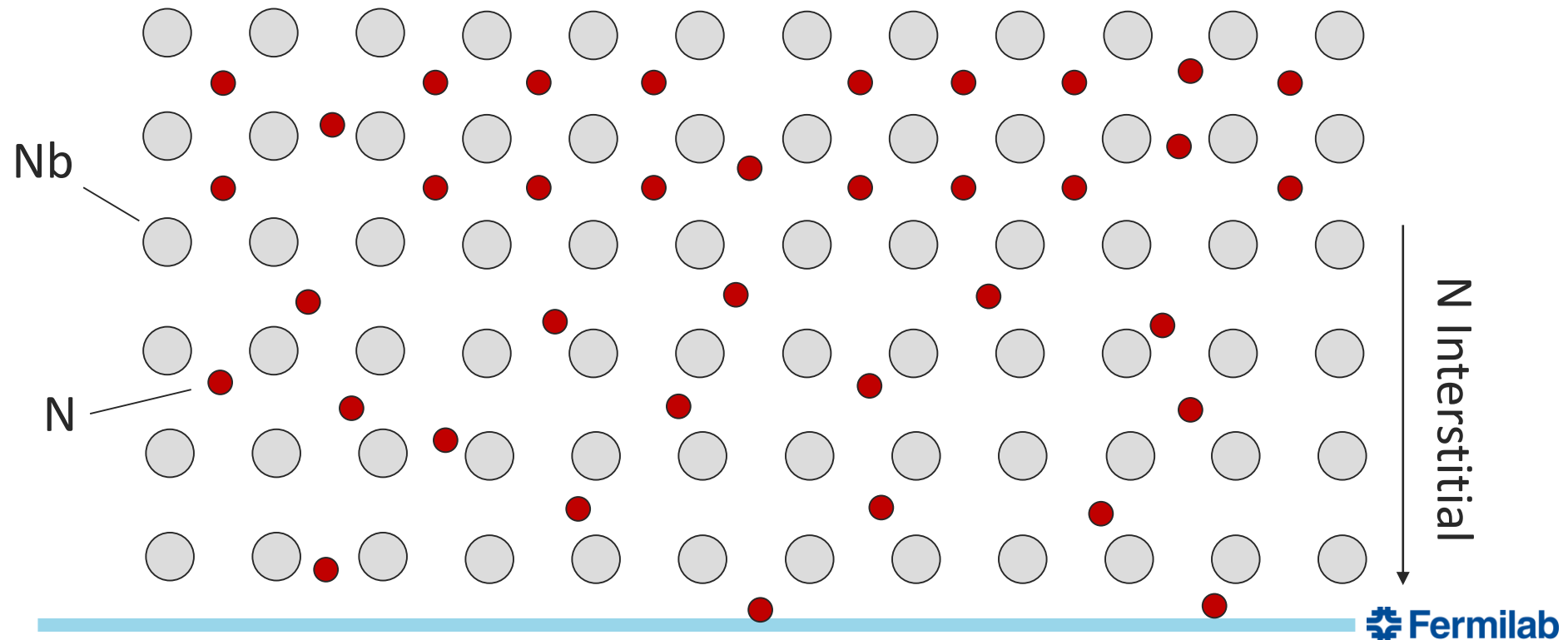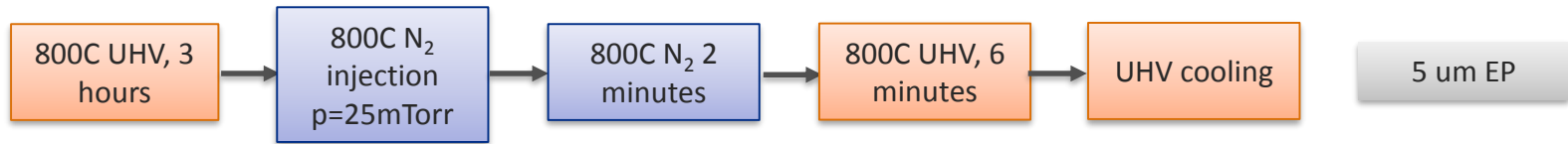Martina Martinello | Connecting cavity performance to physics of the surface

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N-doping treatment (example: the "2/6 recipe")

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

N_2

N

Nb

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N-doping treatment (example: the "2/6 recipe")

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N-doping treatment (example: the "2/6 recipe")

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

Nb

N

N Interstitial

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N-doping treatment (example: the "2/6 recipe")

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

Nb_xN_y
$\sim 2\ \mu m$

Nb

N

20' @ 800 C with 25 mTorr N_2
— Sample
— H3
— H7
— C4
— C5

N atoms density [cm^{-3}]

depth [μm]

1.000 µm

Pt layer

~0.2 µm

0.1 µm

Nb [113]+Nb$_2$N [210]+?

Y. Trenikhina et al, Proc. of SRF 2015

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N-doping treatment (example: the "2/6 recipe")
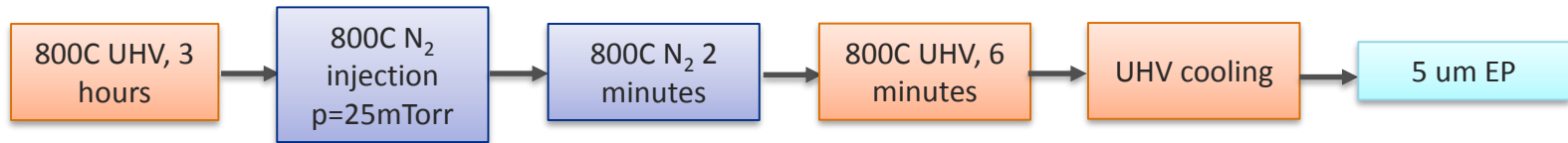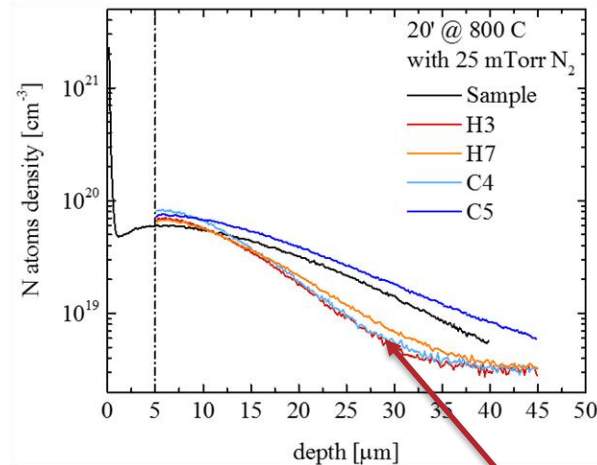
800C UHV, 3 hours → 800C N_2 injection p=25mTorr → 800C N_2 2 minutes → 800C UHV, 6 minutes → UHV cooling → 5 um EP

Final RF Surface

Nb

N

N Interstitial

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N-doping treatment (example: the "2/6 recipe")

```
[800C UHV, 3 hours] → [800C N₂ injection p=25mTorr] → [800C N₂ 2 minutes] → [800C UHV, 6 minutes] → [UHV cooling] → [5 um EP]
```
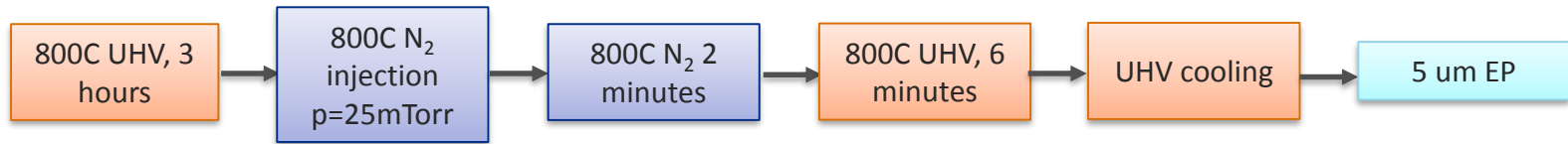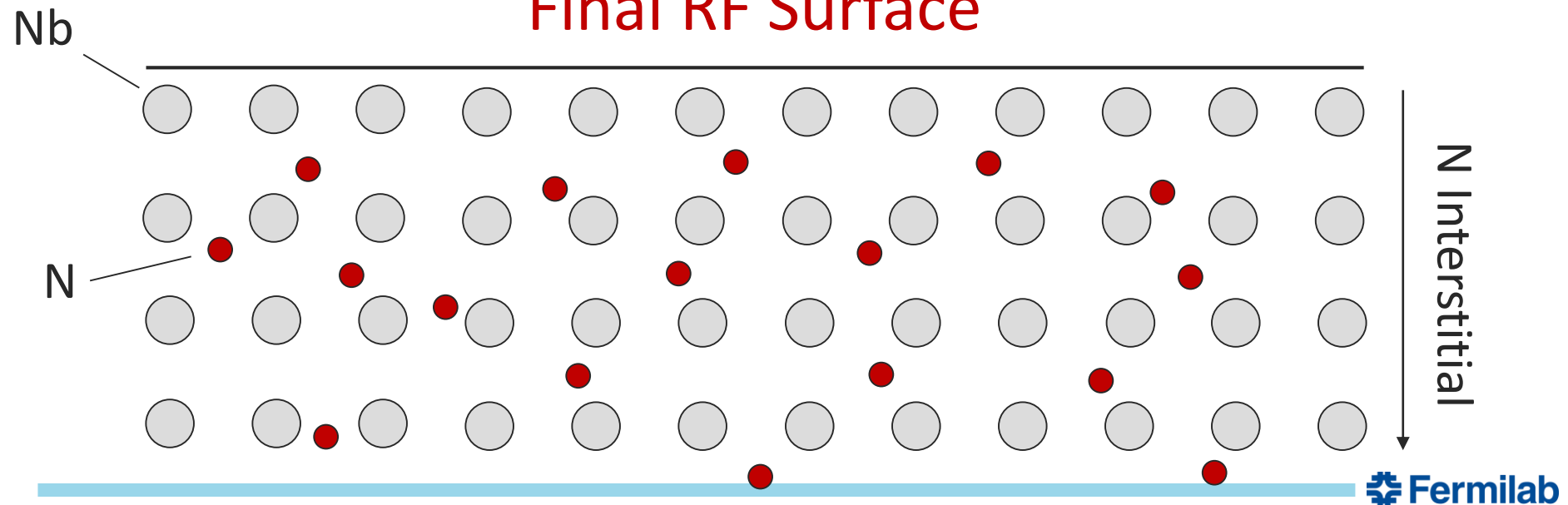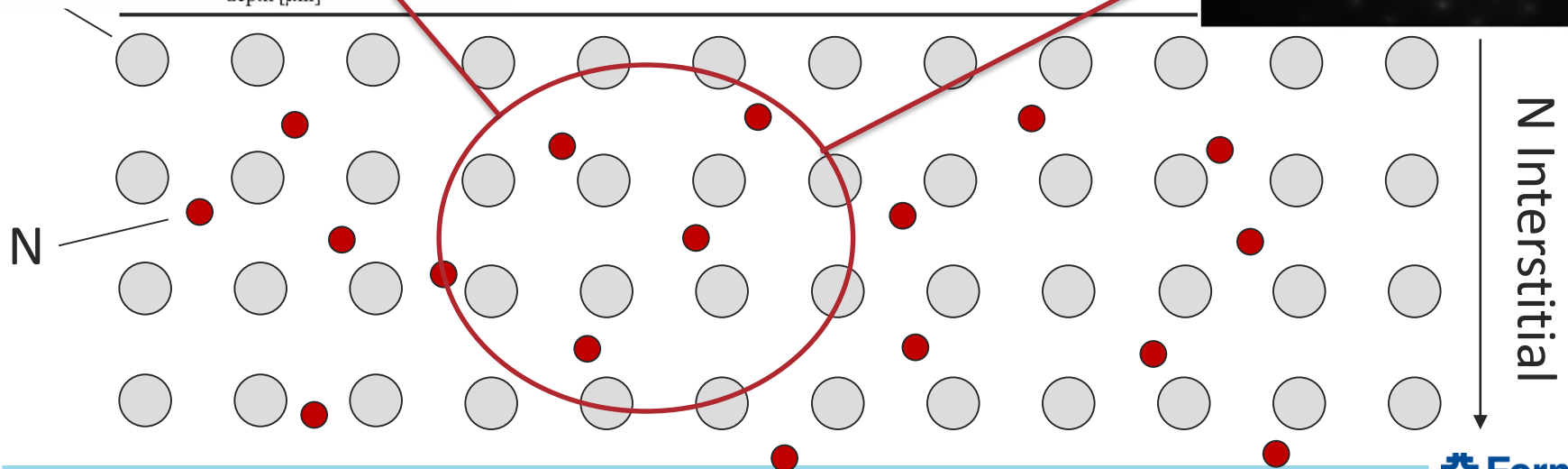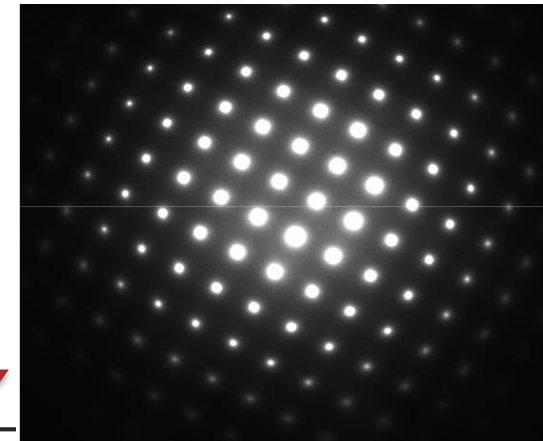

Y. Trenikhina et Al, Proc. of SRF 2015

Only Nb from TEM/NED spectra:
N must be interstitial

Final RF Surface

N Interstitial

N

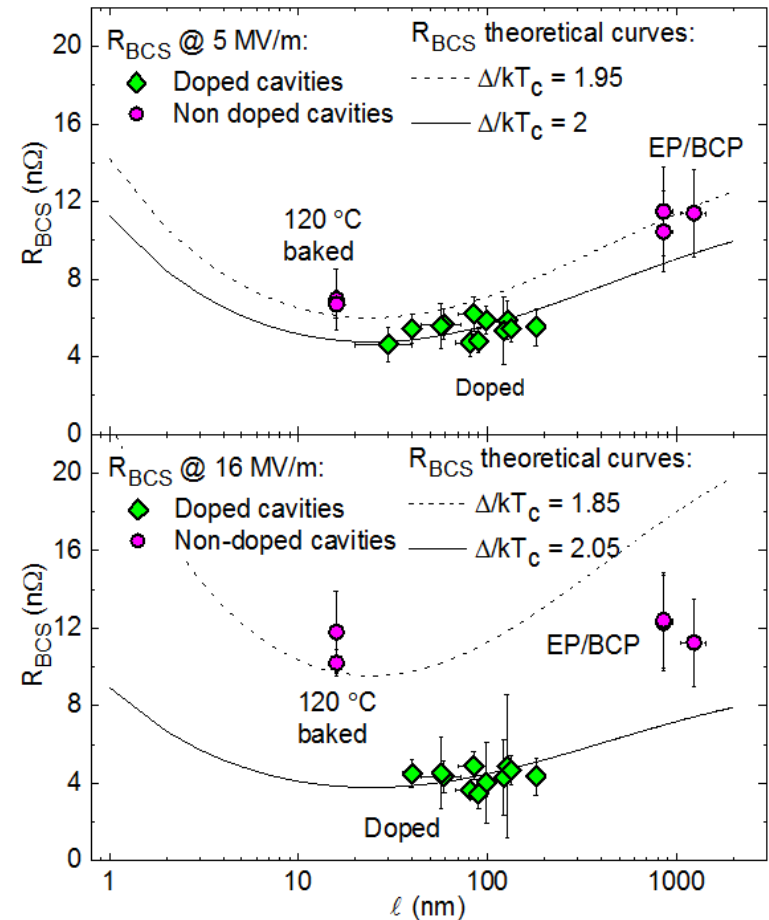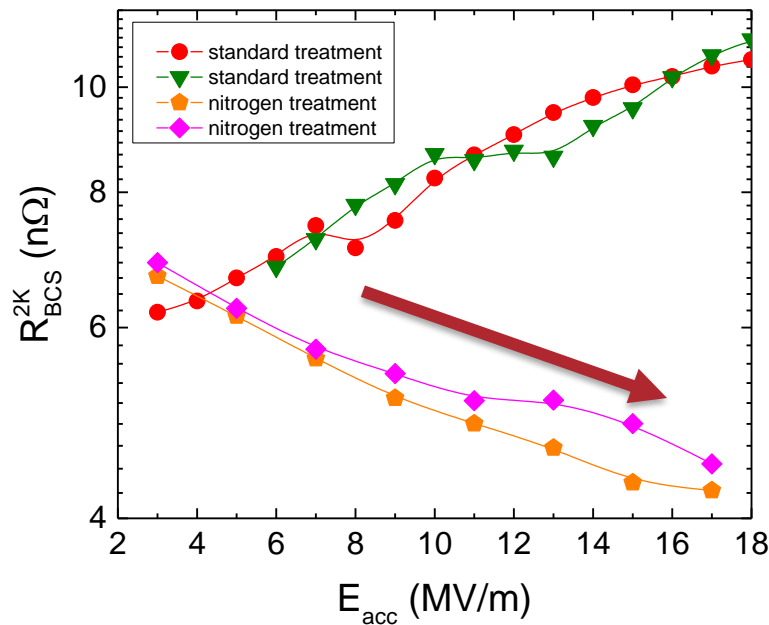Martina Martinello | Connecting cavity performance to physics of the surface

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N-doping: reversal of BCS surface resistance

$$R_s(T) = \boxed{R_{BCS}(T)} + R_{res}$$

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

A. Grassellino *et al.*, Supercond. Sci. Technol. **26** 102001 (2013) - Rapid Communications
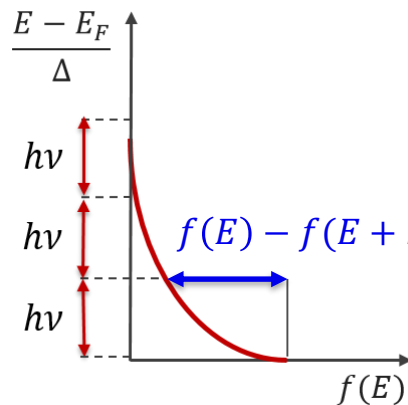A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)
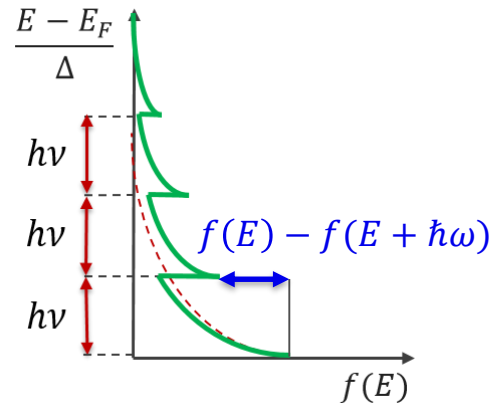M. Martinello *et al.*, App. Phys. Lett. **109**, 062601 (2016)

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Qualitative description of the R_{BCS} reversal

QP are driven out-of-equilibrium by microwave absorption eventually reaching a steady state

Equilibrium distribution of QPs
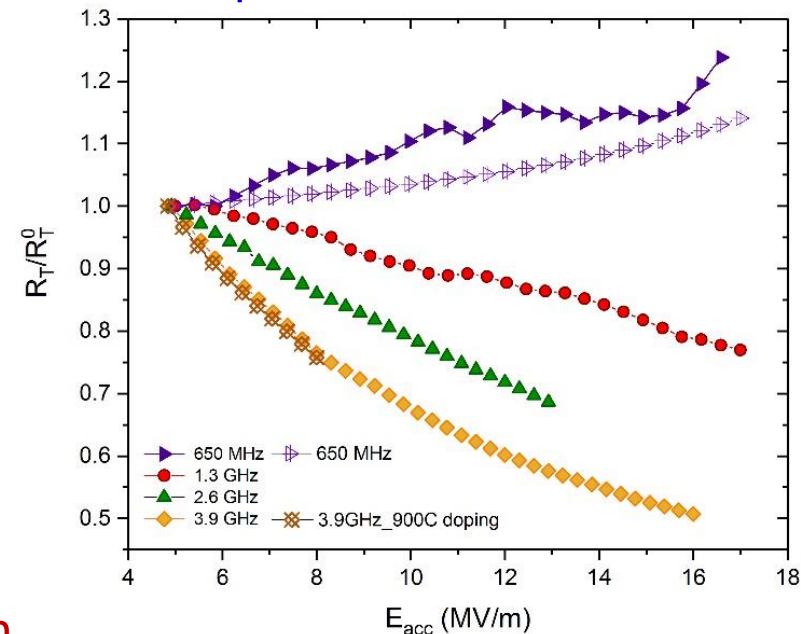
Non-equilibrium distribution of QPs

Strong "non-BCS" frequency dependence is observed

$\frac{E - E_F}{\Delta}$

$h\nu$

$h\nu$ $f(E) - f(E + \hbar\omega)$

$h\nu$

$f(E)$

$\frac{E - E_F}{\Delta}$

$h\nu$

$h\nu$ $f(E) - f(E + \hbar\omega)$

$h\nu$

$f(E)$

$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega} \int_{\Delta}^{\infty} [f(E) - f(E + \hbar\omega)] g_1(E) dE$$

- ▶ 650 MHz ▷ 650 MHz
- ● 1.3 GHz
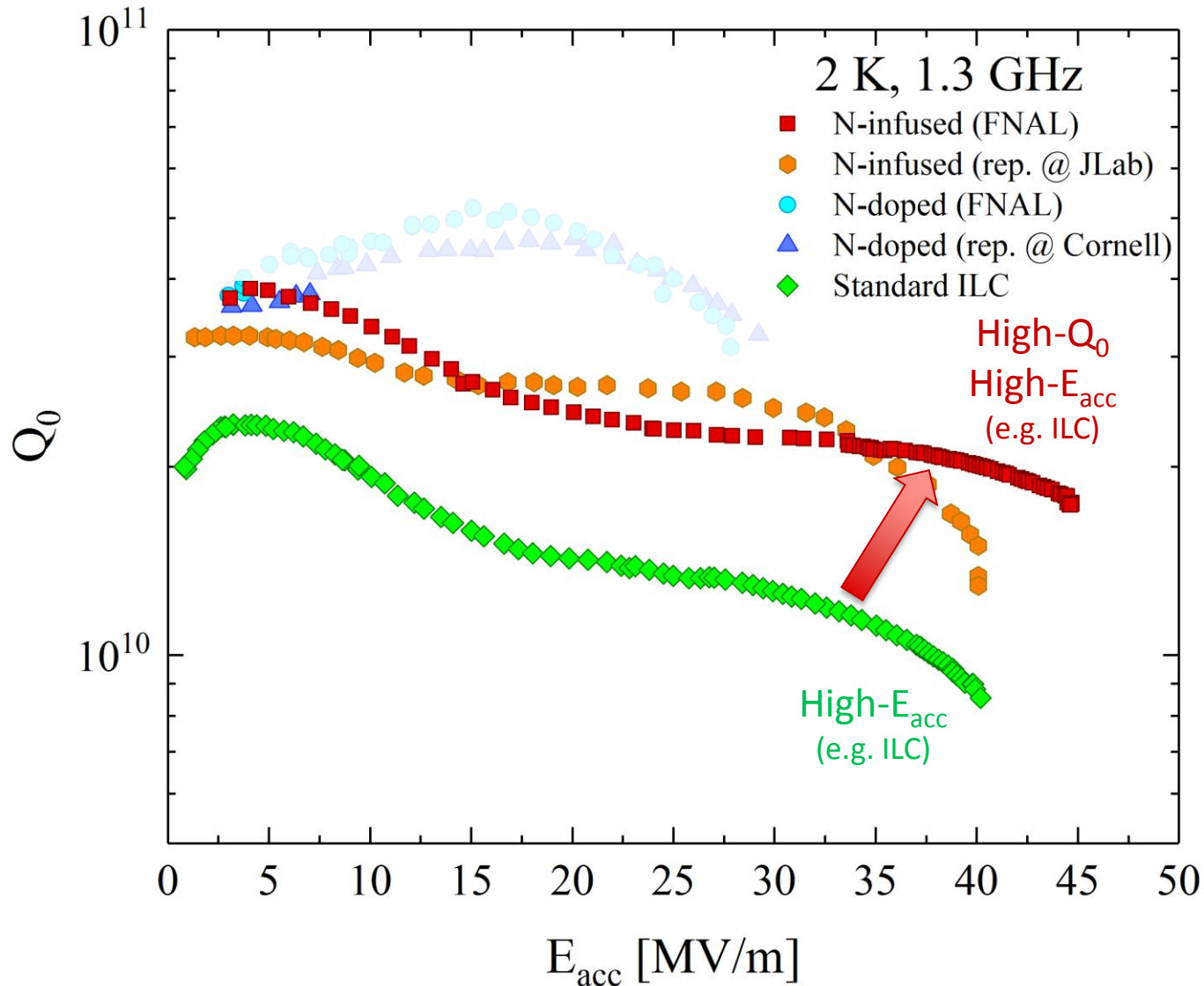- ▲ 2.6 GHz
- ◆ 3.9 GHz ✳ 3.9GHz_900C doping

R_T/R_T^0 vs E_{acc} (MV/m)

Smaller with non-equilibrium QPs distribution

M. Martinello *et al.*, Phys. Rev. Lett. 121, 224801 (2018)
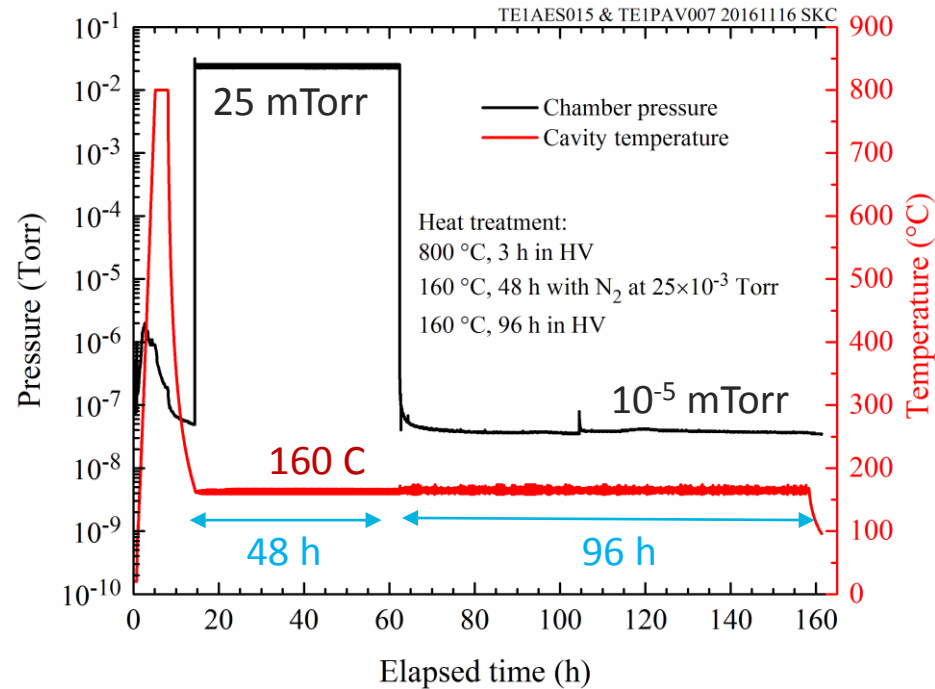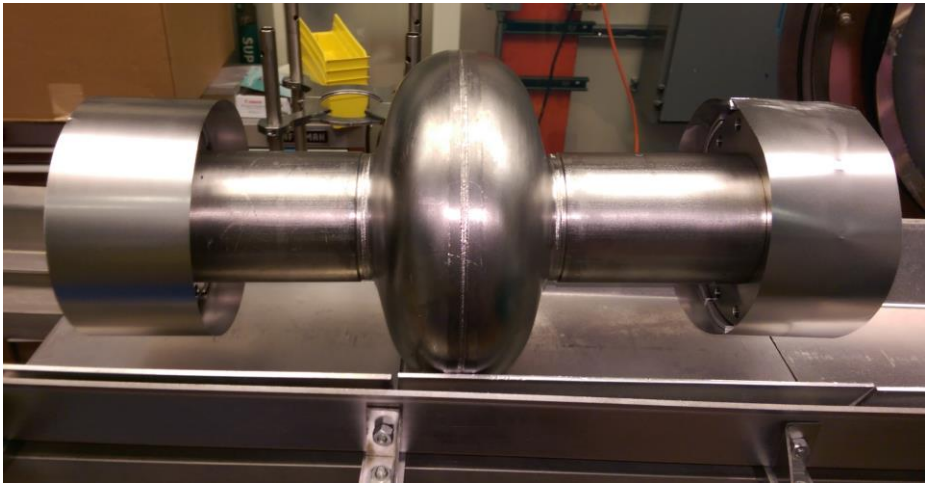
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N-infusion: the treatment for high-Q at high-G

High-E$_{acc}$ and high-Q$_0$/high-E$_{acc}$ treatments

Example of N-infusion processing sequence

- Bulk electro-polishing
- High T furnace (with caps to avoid furnace contamination):
  - 800C 3 hours HV
  - 120C 48 hours with N_2 (25 mTorr)
- NO chemistry post furnace
- HPR, VT assembly

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

A. Grassellino *et al.*, **arXiv:1305.2182**
A. Grassellino et al 2017 Supercond. Sci. Technol. **30** 094004

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From N-doping to N-infusion

By N-doping Nb cavities at lower temperatures (N-infusion) we can tune the Q-factor:
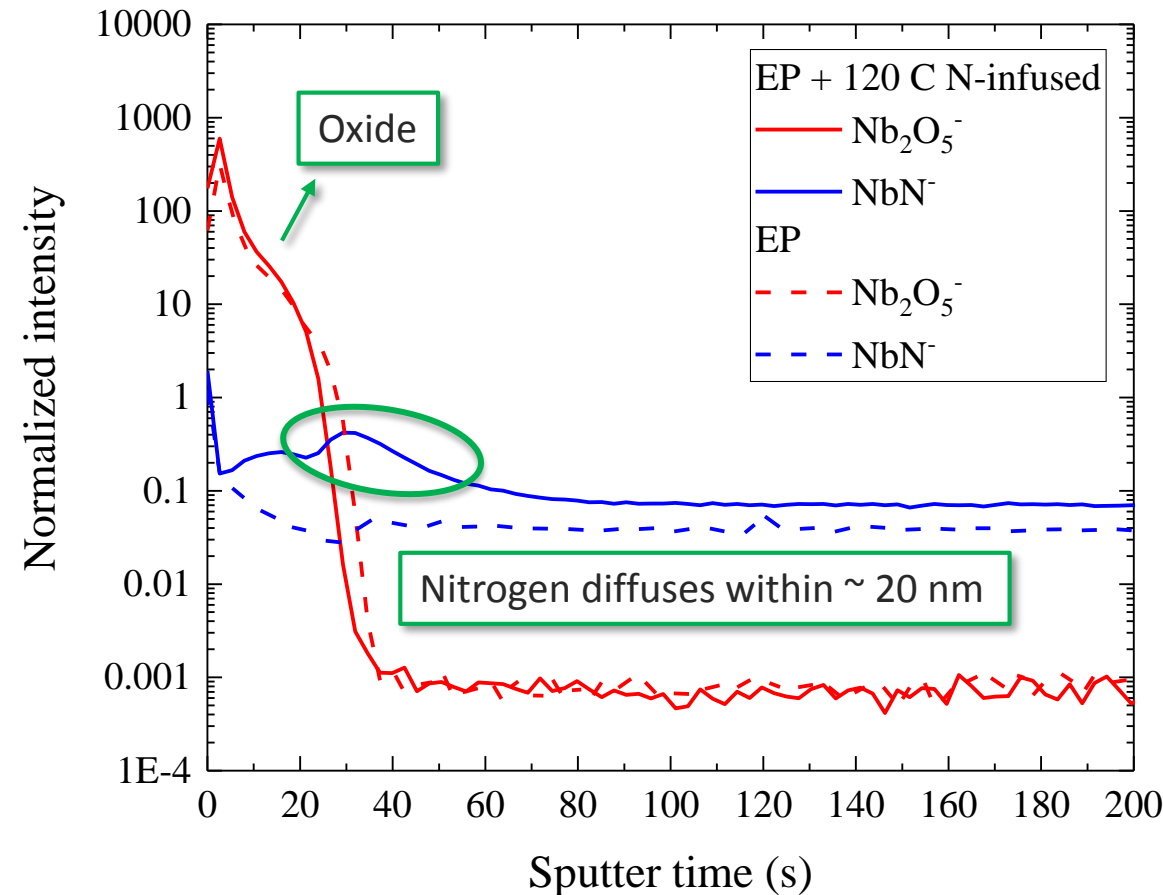⇒ strong effects on the BCS and residual resistance

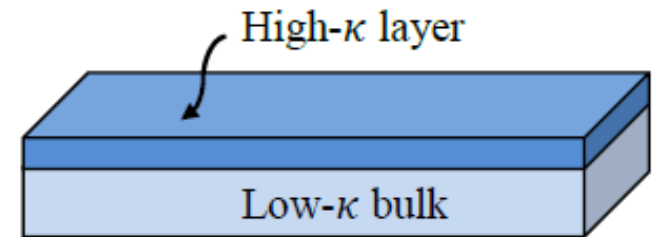A. Grassellino *et al.*, Supercond. Sci. Technol. **30**, 094004 (2017)

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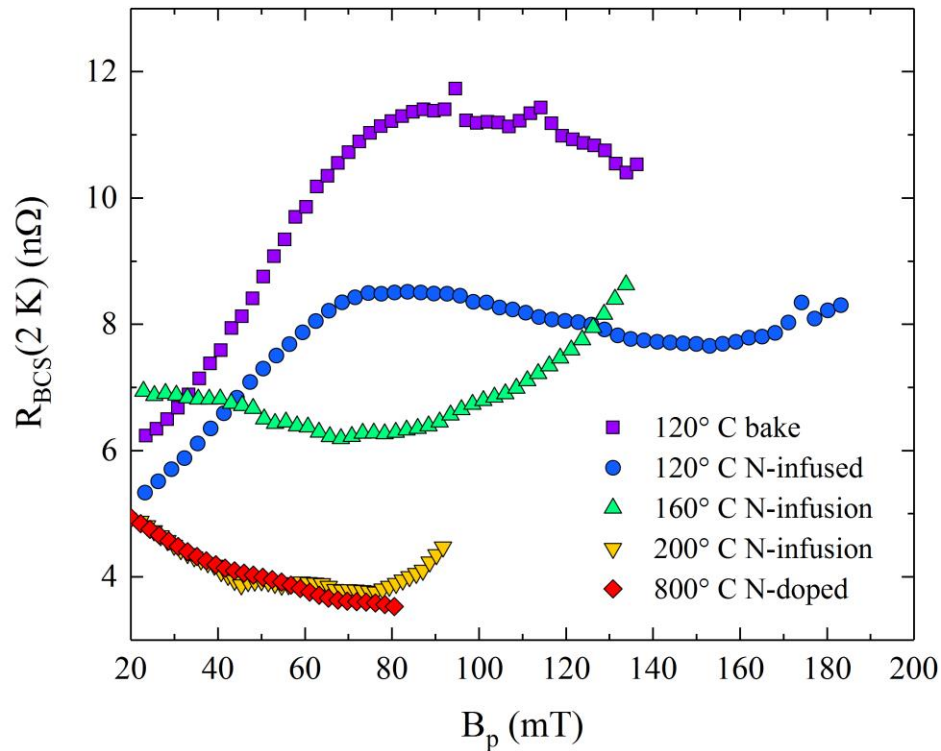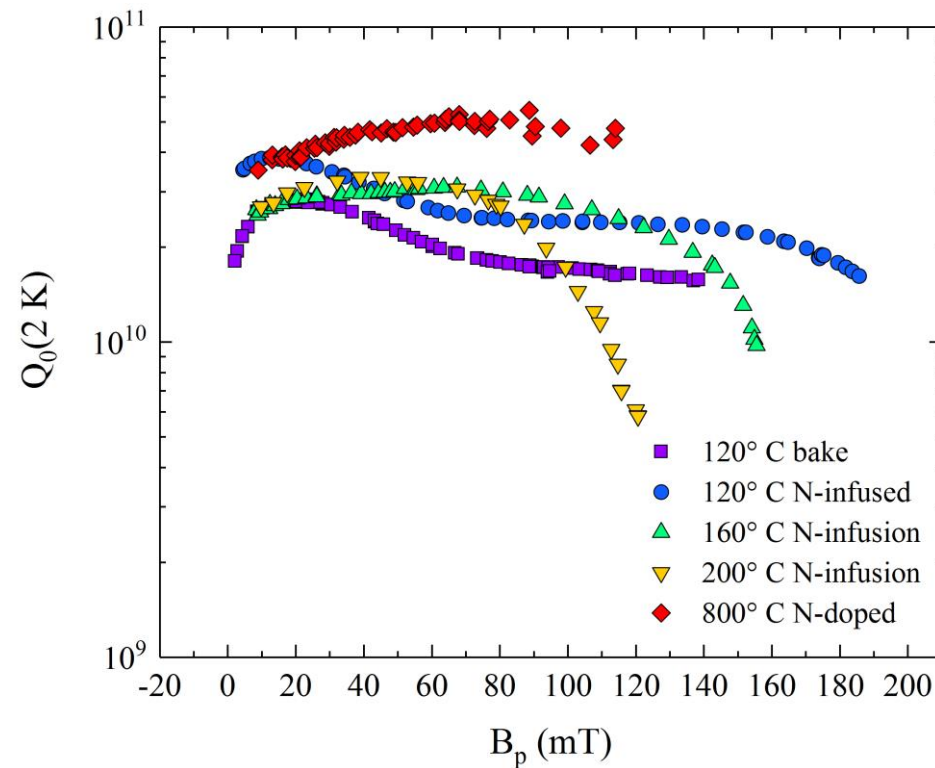
Impurity profiles in cavity cutouts by TOF-SIMS

Comparing EP cavity **cutout** with EP + 120 C 48h N-infused cavity **cutout**

N-infused cavities are an example of **layered superconductors**
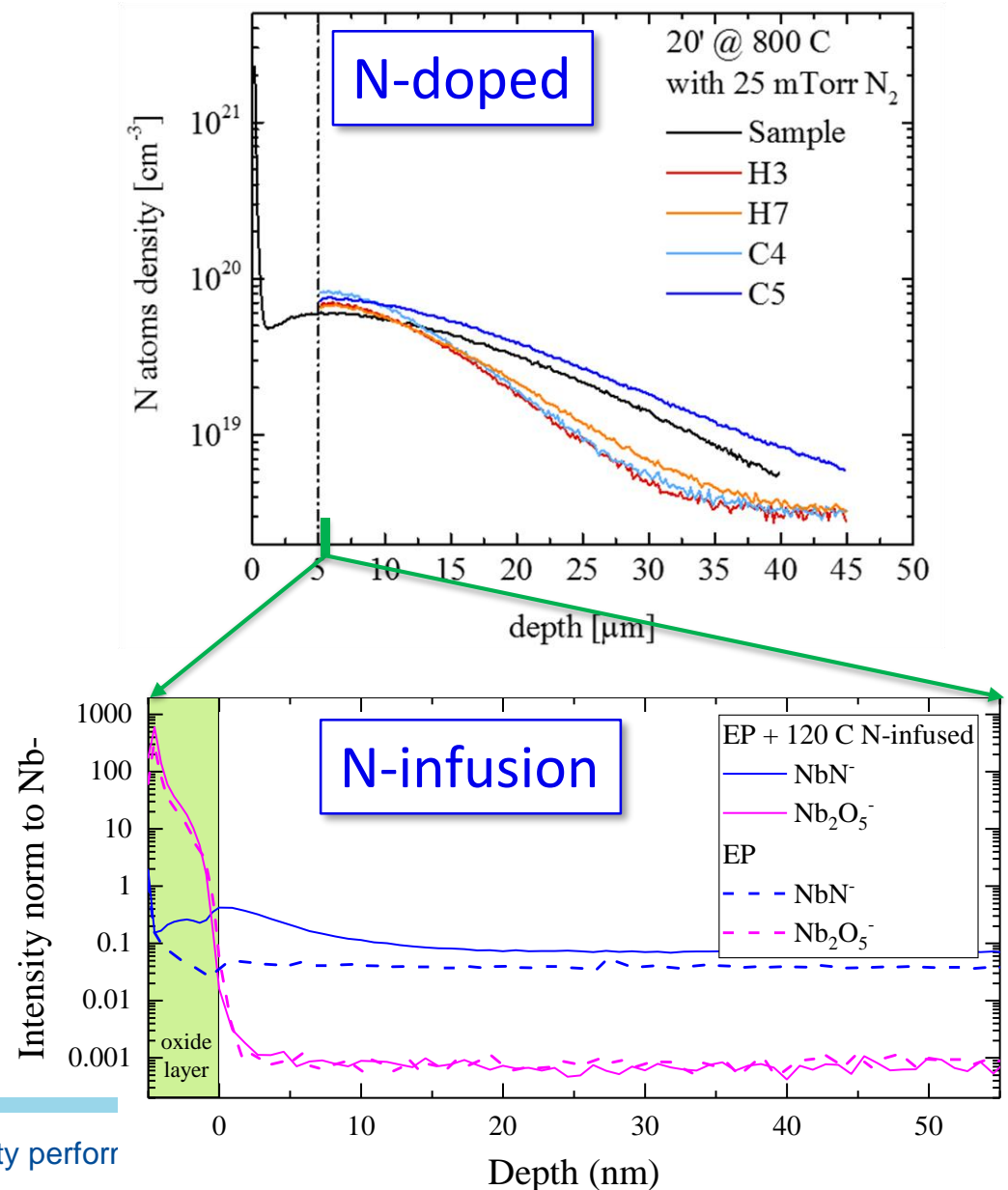
- N-enriched layer in the first ~ 20 nm

A. Romanenko *et al.*, IPAC 2018
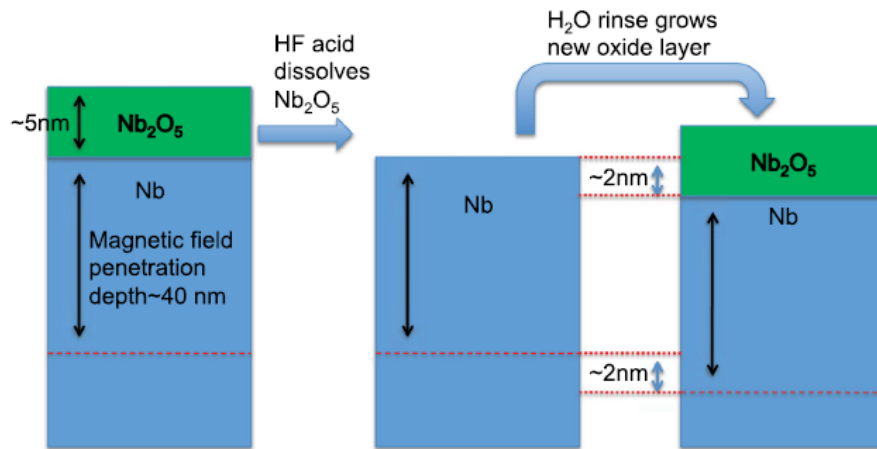M. Checchin *et al.*, IPAC 2018

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Comparison N-doped vs N-infusion

- N-doped N profiles are up to $\sim 50\ \mu m$ deep

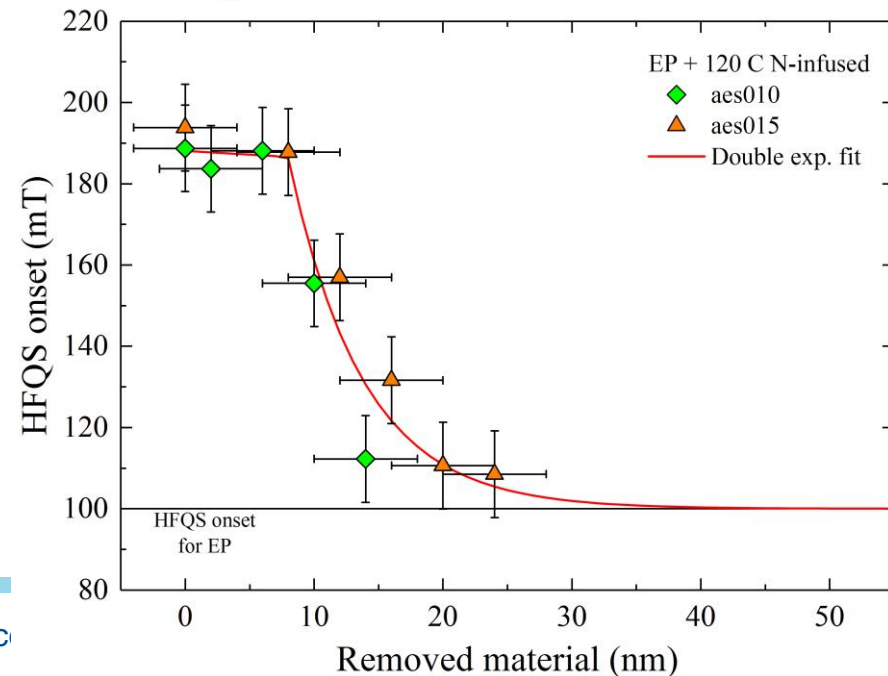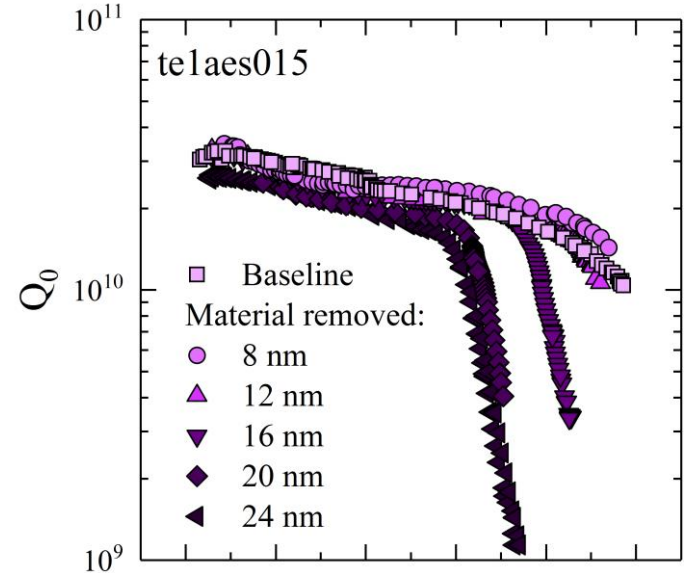- N-infused N profiles are $\sim 20\ nm$ deep

HF rinse studies on 120 C N-infused cavities

- HF rinses studies shows that the N-infusion process modifies only the surface of the material, the bulk is not affected

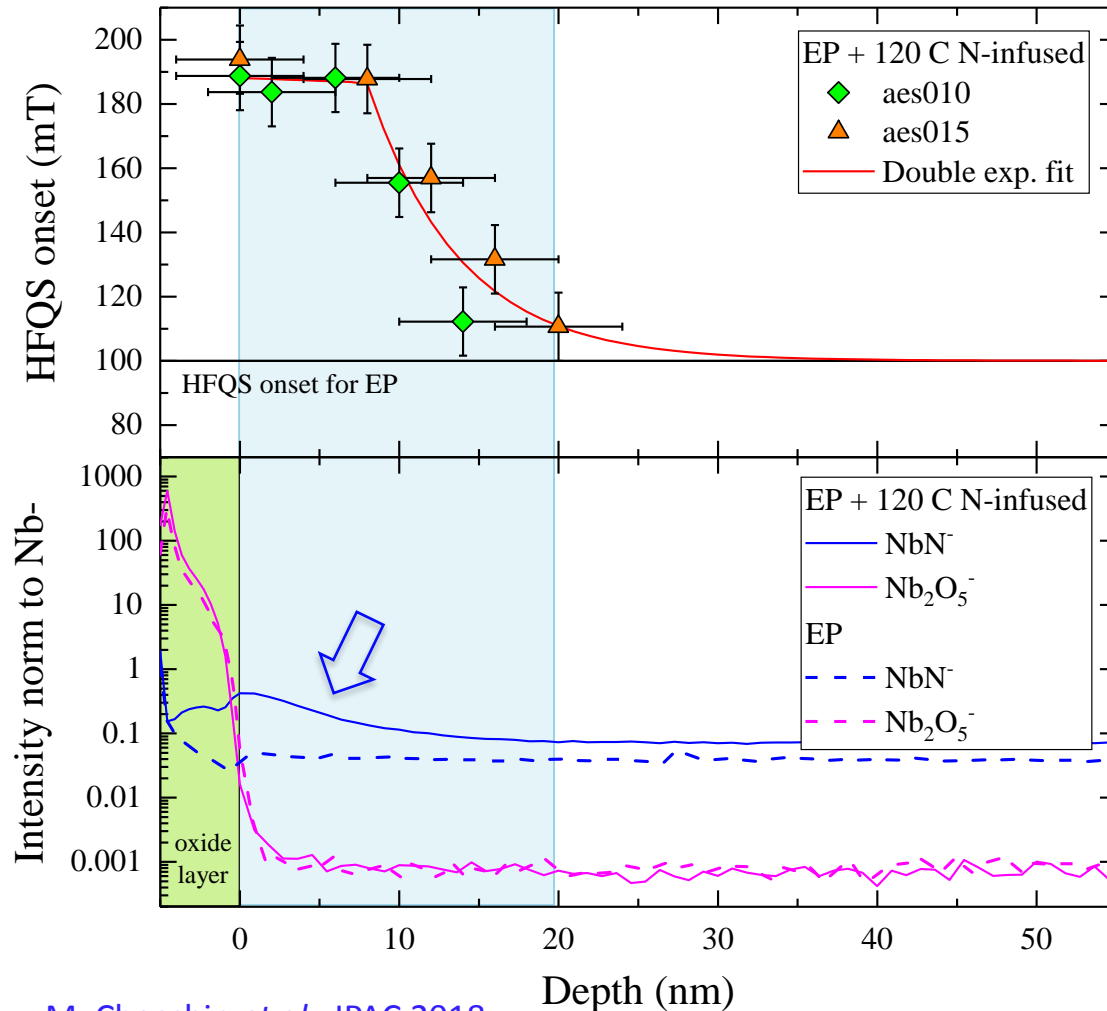- HFQS behavior is re-established after removing enough material

M. Checchin *et al.,* IPAC 2018

RF and TOF-SIMS data comparison

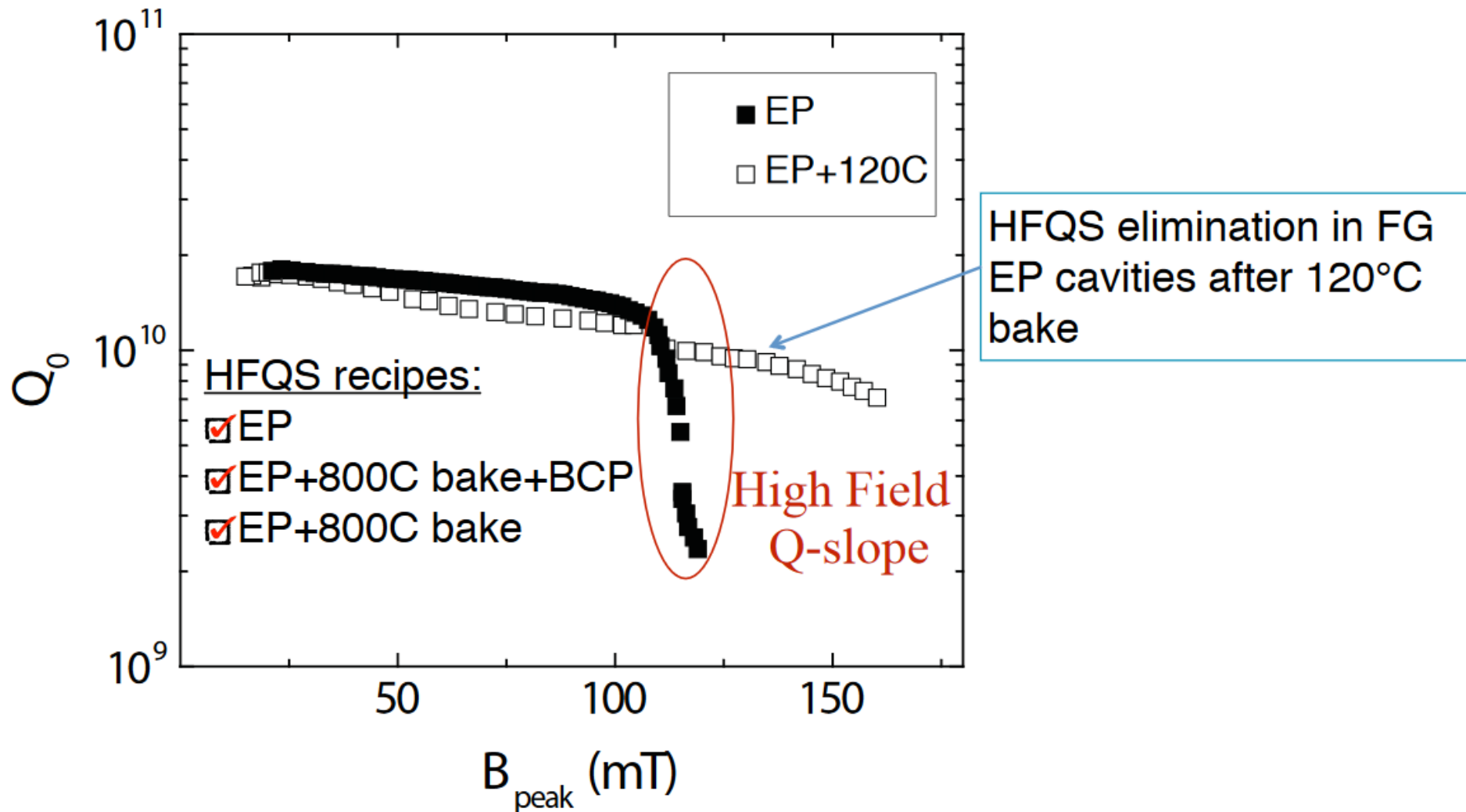## N-infusion performance dictated by the nitrogen profile

- Onset of HFQS in 120 C N-infused cavities in *agreement with the diffusion profile of* **nitrogen**

- Oxygen and carbon are changing in a scale length not relevant for HFQS

M. Checchin *et al.*, IPAC 2018

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Mild baking for high-G

HFQS-producing treatments

HFQS elimination in FG EP cavities after 120°C bake

HFQS recipes:
☑ EP
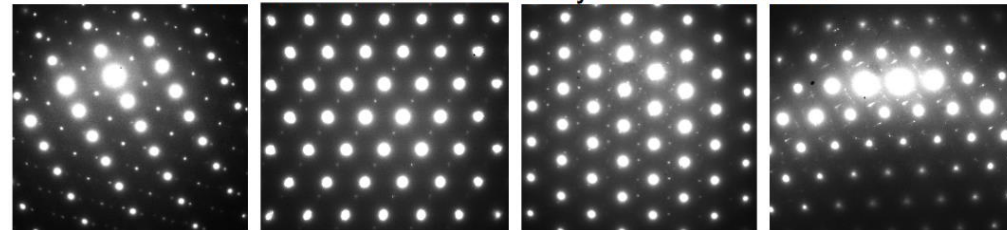☑ EP+800C bake+BCP
☑ EP+800C bake

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Hypothesis of HFQS and mild baking effect

- HFQS most likely due to nano-hydrides at the surface of EP and BCP cavities (A. Romanenko et.al., Supercond. Sci. Technol. 26, 035003 (2013))
- Mild T (120C) baking allows for vacancies precipitation -> creation of vacancy-hydrogen complexes rather than NbH precipitates (A. Romanenko et.al., Appl. Phys. Lett. 10, 232601 (2013))
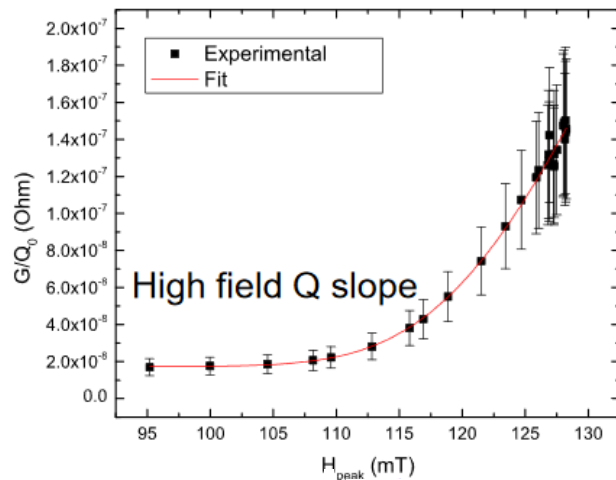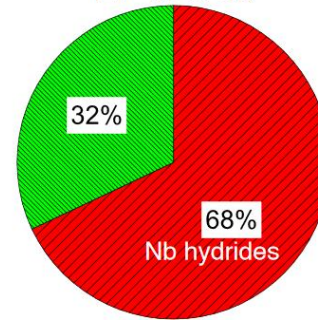

Normal conducting hydrides of size d are <u>superconducting by proximity effect up to the breakdown field</u> $H_b \sim 1/d$
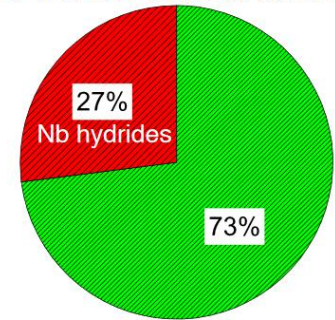
NED: Nb hydrides precipitation in **all cutouts**, amount and/or size of Nb hydrides is different
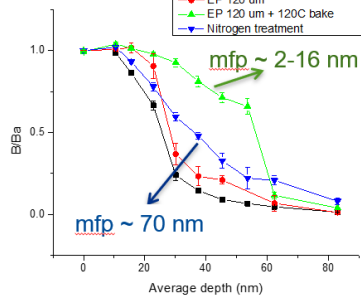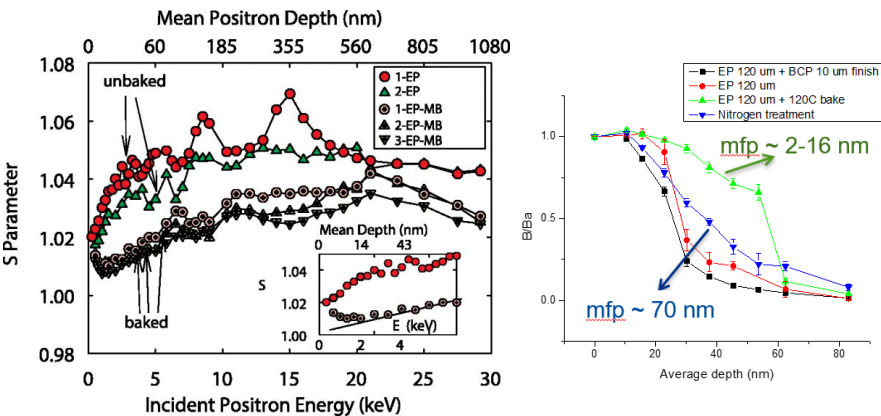
EP at 94K

EP+120C baked at 94K

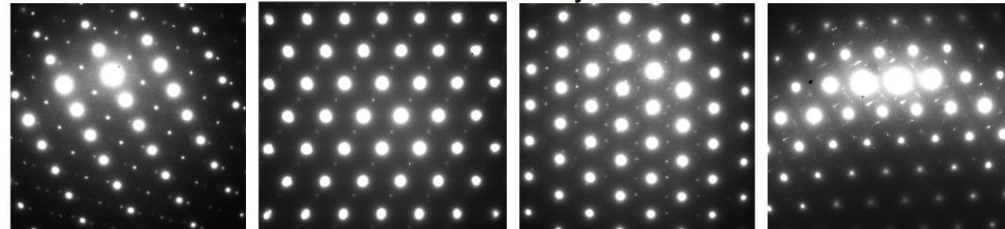Y. Trenikhina et al., Journ. of App. Phys. 117, 154507 (2015);

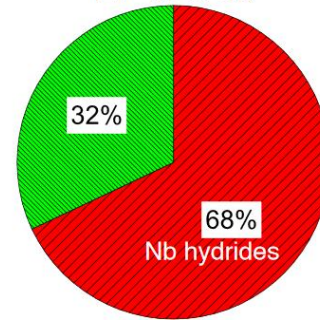🔷 **Fermilab**

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- Mild T (120C) baking allows for vacancies precipitation -> creation of vacancy-hydrogen complexes rather than NbH precipitates (A. Romanenko et.al., Appl. Phys. Lett. 10, 232601 (2013))

- Positron annihilation studies show possible presence of vacancy-hydrogen complexes in 120C bake cut-outs
- Low-energy uSR shows reduced mean-free-path in the near surface region

NED: Nb hydrides precipitation in **all cutouts**, amount and/or size of Nb hydrides is different

EP at 94K — 32%, 68% Nb hydrides
EP+120C baked at 94K — 27% Nb hydrides, 73%

Y. Trenikhina et al., Journ. of App. Phys. 117, 154507 (2015);

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120 C modified

UP TO ~ 49 MV/m

Q_0

10^{11}

10^{10}

10^9

120 C N-infused
- ■ aes015
- ● pav007

120 C standard
- ▲ acc003
- ▼ acc005

120 C modified
- ◆ aes009
- ◀ 1de3

~1.3 times higher gradient

E_{acc} (MV/m)

A. Grassellino *et al.*, to be published (2018)

nnecting cavity performance to physics of the surface

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New finding: 50 MV/m in TESLA shape cavities can be systematically achieved!

- We have recently focused our attention to the systematic achievement of unprecedented accelerating gradients ~48-50 MV/m (~ 210 mT, TESLA shape) in low temperature baked cavities

- One peculiarity of these cavities surface preparation is a pre-120C bake step at ~75C

- Another peculiarity is a surface with a very cold final EP preparation

f=1.3GHz
T=2K

75C 2hr/120C 48hr
▶ 1DE3
75C 4hr/120C 48hr
■ AES009
● PAV011
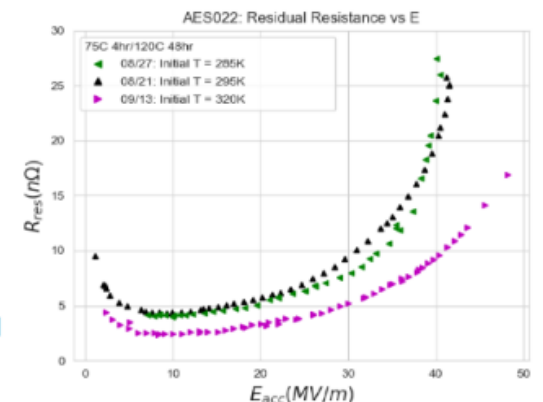◆ RI001
· AES011
★ RI002
◀ AES022

Q_0 vs E_{acc}(MV/m)
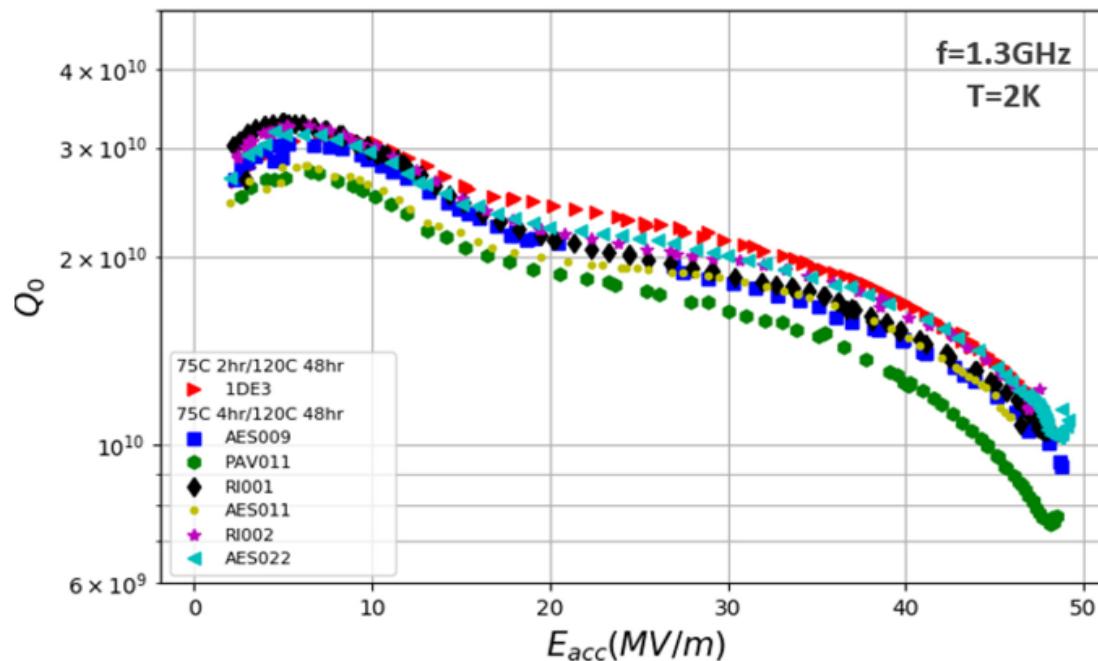
See Grassellino et al
arXiv:1806.09824

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7/2/2019

New finding: 50 MV/m in TESLA shape cavities can be systematically achieved!

- On dozens of tests and several cavities now, we see switch in performance for same cavity with no retreatment in between (always under vacuum)
- Effects of magnetic fields, dewars, cables, top plates have been excluded
- Some correlation has been found with cooldown speed near room T and starting T ~320-340K

Bafia, Grassellino, to be published

New finding: 50 MV/m in TESLA shape cavities can be systematically achieved!

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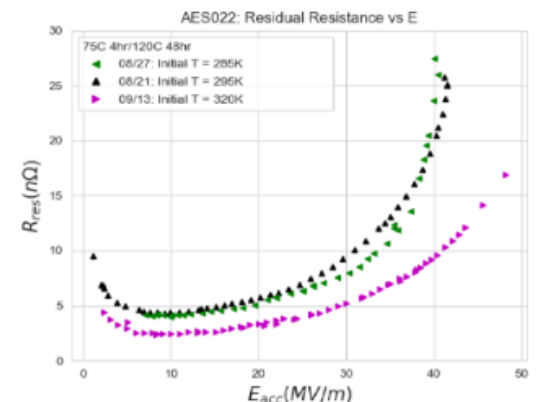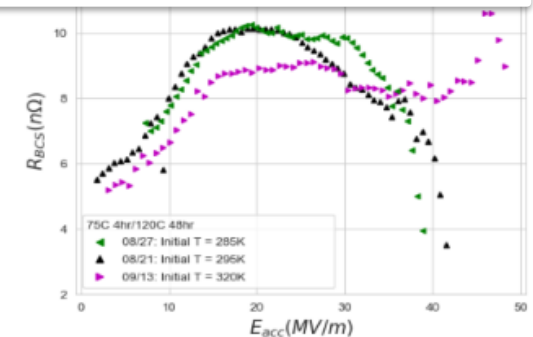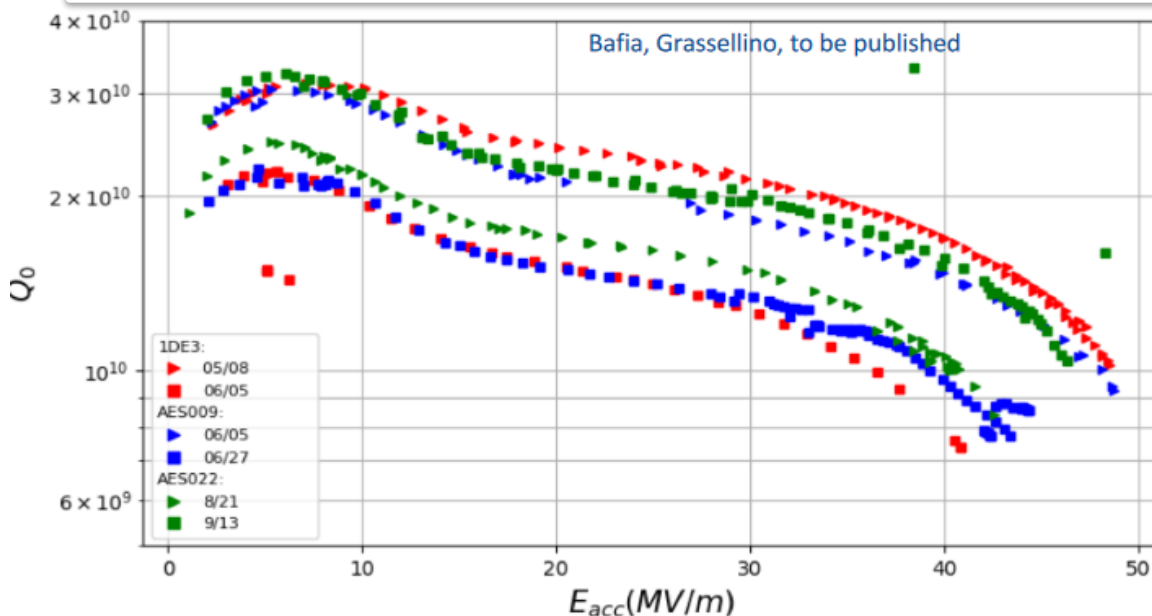Switch in performance connected to different formation of NbH ?-> On-going study by A. Grassellino and D. Bafia. See also Z. Sung (FNAL) talk

Bafia, Grassellino, to be published

1DE3:
▶ 05/08
■ 06/05
AES009:
▶ 06/05
■ 06/27
AES022:
▶ 8/21
■ 9/13

75C 4hr/120C 48hr
◀ 08/27: Initial T = 285K
▲ 08/21: Initial T = 295K
▶ 09/13: Initial T = 320K

AES022: Residual Resistance vs E

75C 4hr/120C 48hr
◀ 08/27: Initial T = 285K
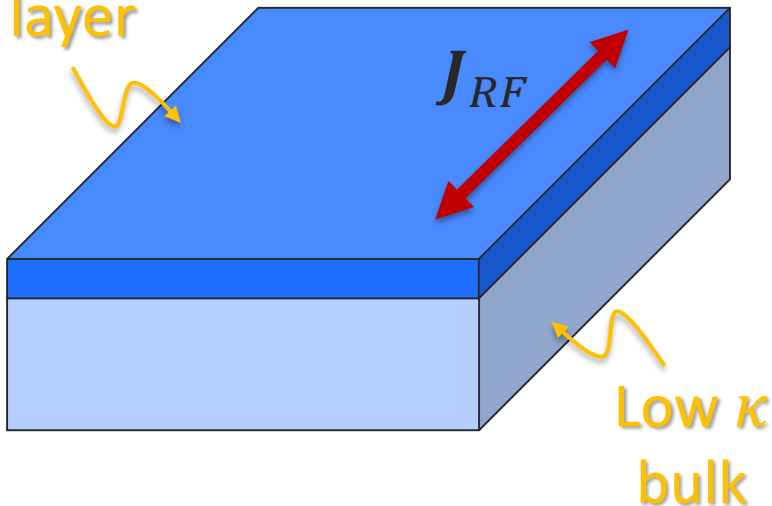▲ 08/21: Initial T = 295K
▶ 09/13: Initial T = 320K

Summary material properties for high-gradient

➤ Material analysis suggest that cavities that leads to high-gradients shows a high κ layer at the surface

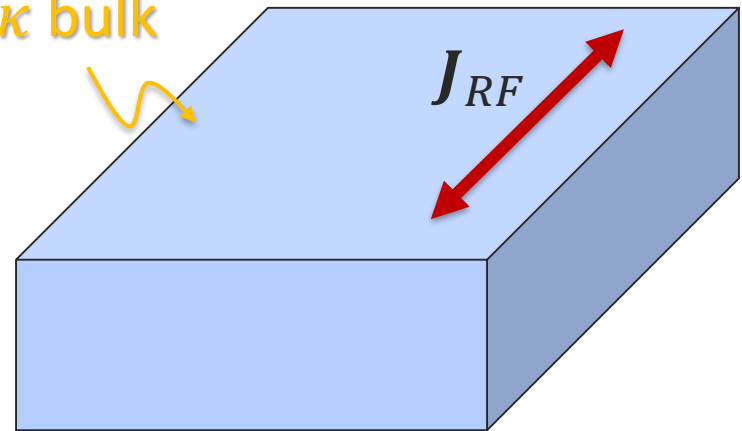❑ Higher T infusion and modified 120 C baking are still being investigated

- • 120 C baking
- • 120 C N-infusion

- • EP/BCP
- • N-doped

High κ layer

J_{RF}

Low κ bulk

Constant κ bulk

J_{RF}

...necting cavity performance to physics of the surface

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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.*, to be published (2018)

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

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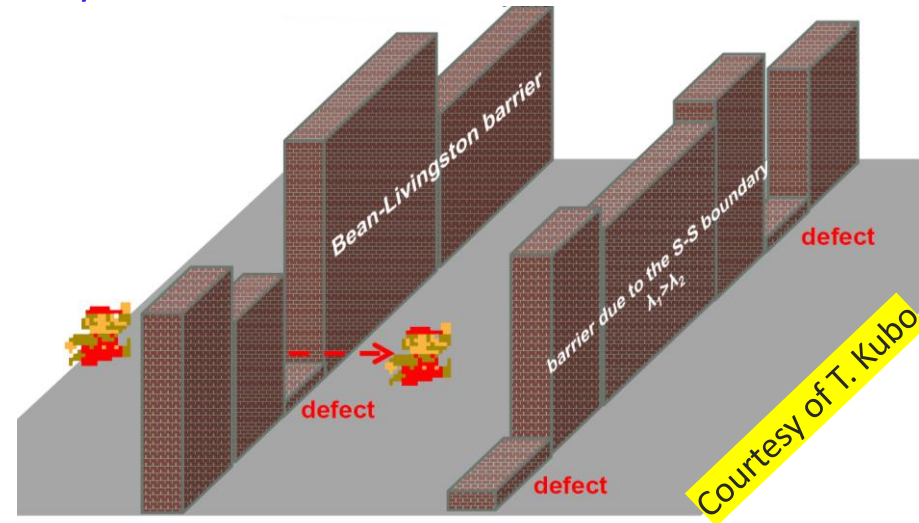
2. New idea: Vortex nucleation is governed by the characteristic time scale of order parameter changes, so-called τ_Δ. Presence of impurities may slower the e-ph scattering time (A. Romanenko et. Al, IPAC 2018 and SRF 2019)

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Conclusions

Conclusions

- Constant profile of N (and perhaps other impurities) within the penetration depth of the SC allow to obtain the highest Q at medium field

- Small dirty layer of N within first nanometers help to achieve systematically 45 MV/m

- Presence of vacancies/hydrogen-vacancy complexes within the first nanometers help to increase the maximum achievable gradient up to 50 MV/m
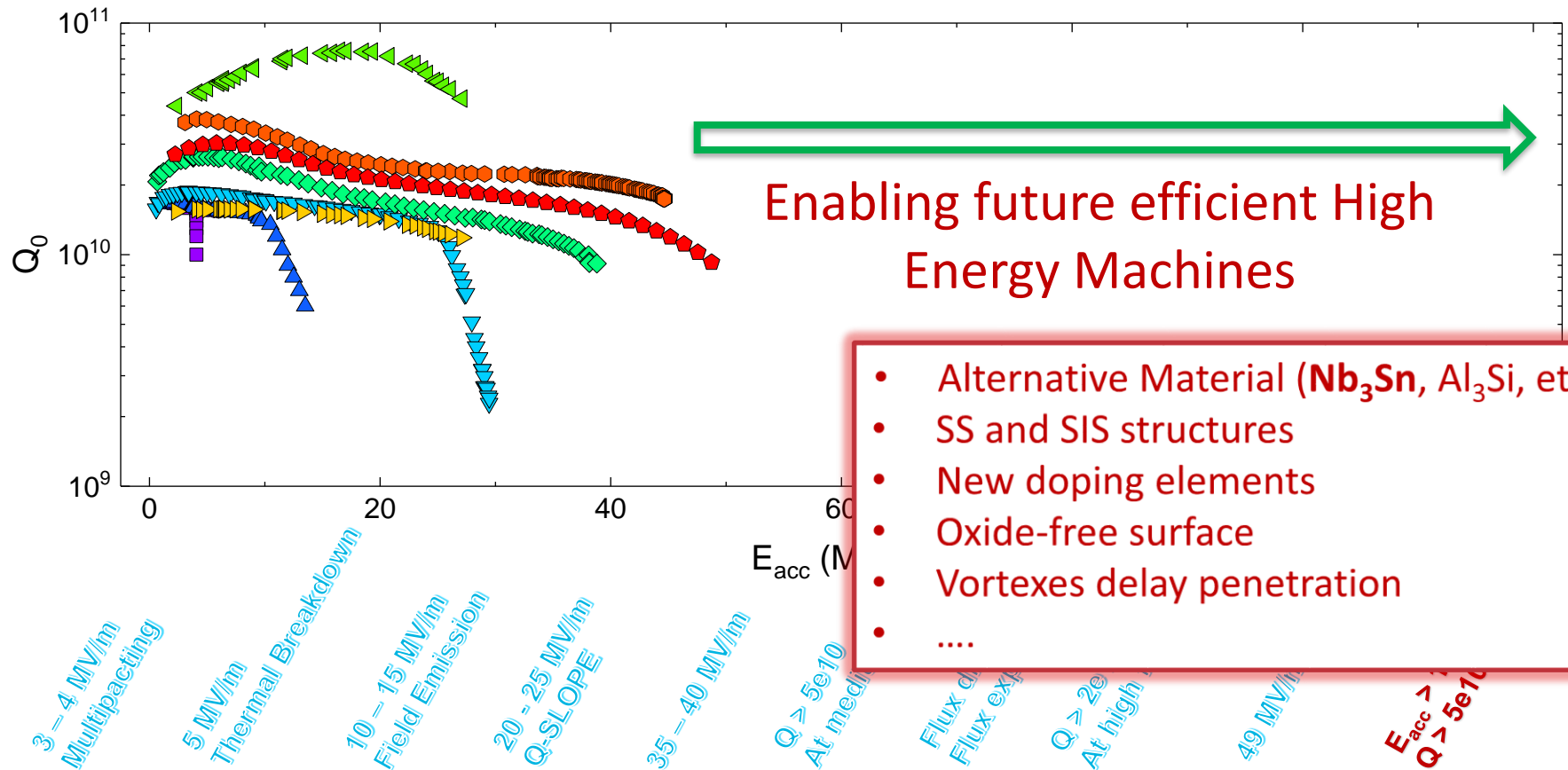
- Characteristic of material within the first tens of nanometers is crucial to determine cavity performance

- <u>Material science is the key to make progress in SRF</u>

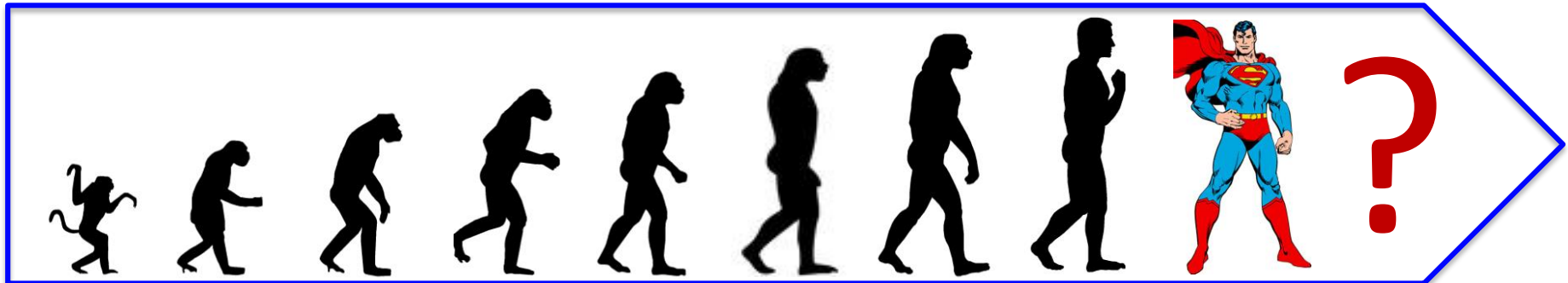# SRF performance: past, present and future
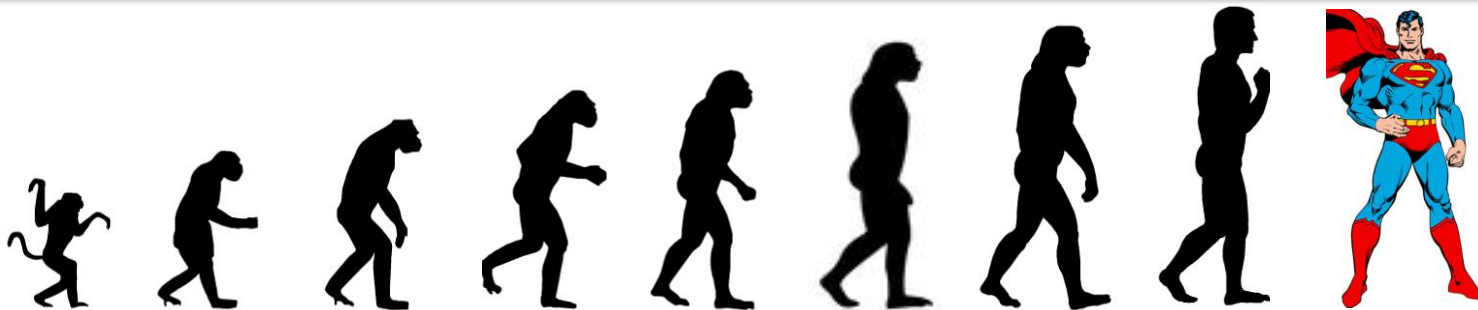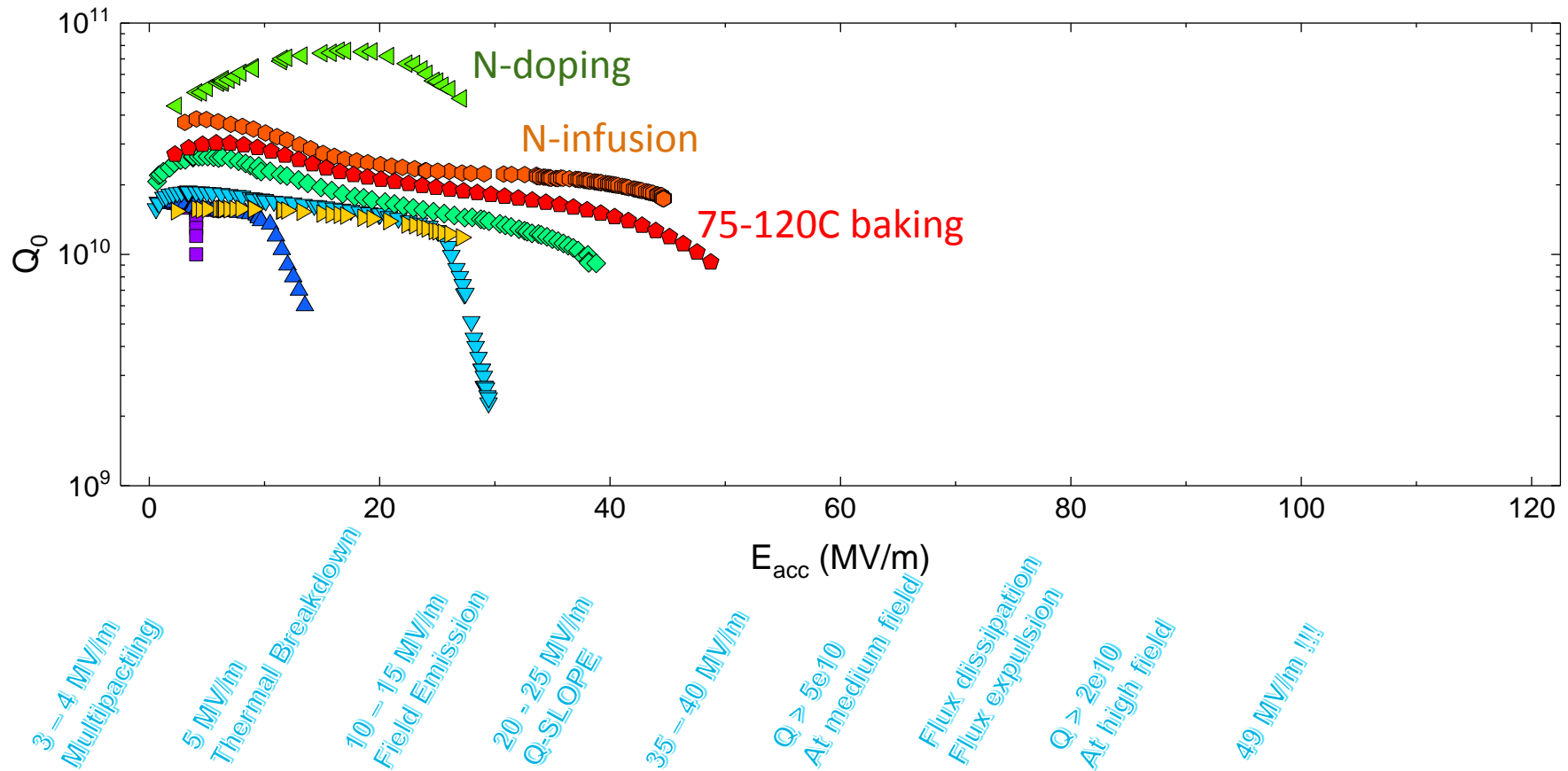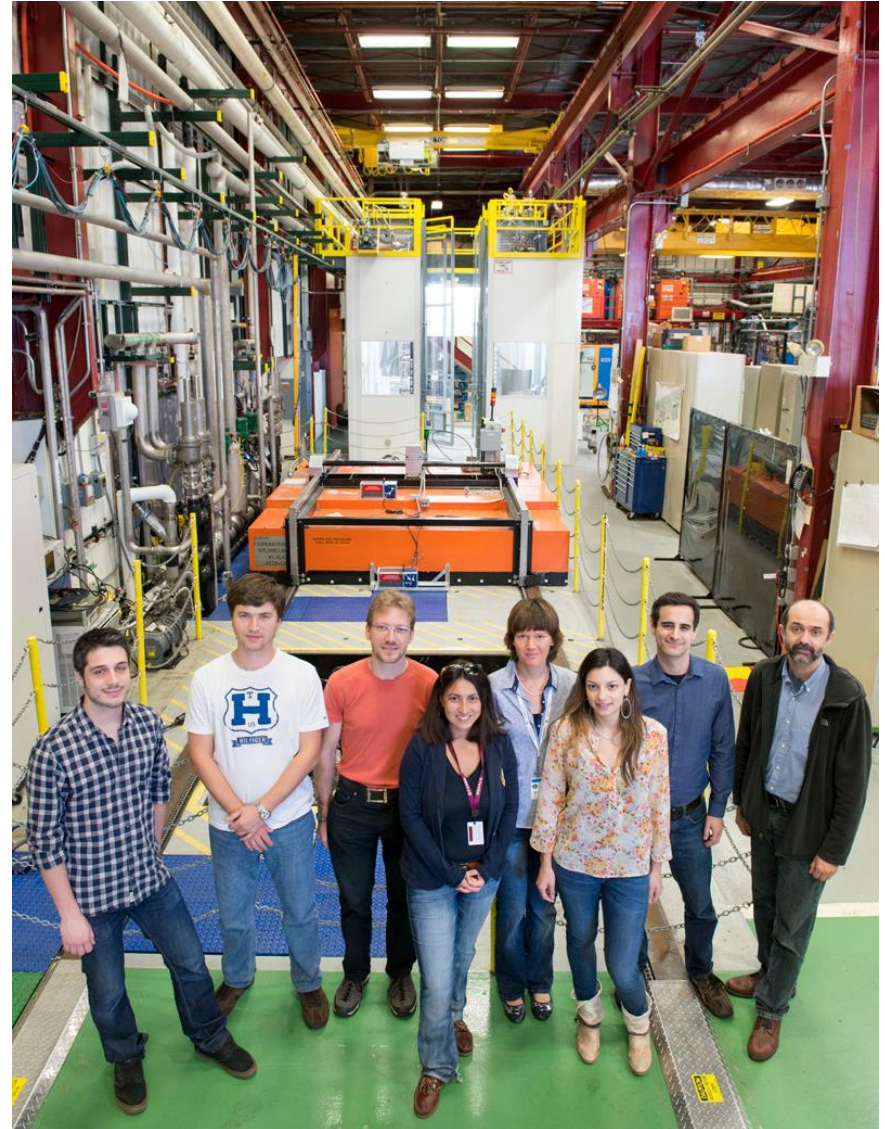
SRF performance: past, present and future

Enabling future efficient High Energy Machines

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

Q_0

E_{acc} (M...

10^{11}

10^{10}

10^9

0   20   40   60

3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown

10 – 15 MV/m
Field Emission

20 - 25 MV/m
Q-SLOPE

35 – 40 MV/m

Q > 5e10
At medi...

Flux d...
Flux exp...

Q > 2e...
At high ...

49 MV/m...

E_{acc} > ...
Q > 5e10...

?

Acknowledgements

Thanks to Fermilab SRF Measurement and Research Department for contributions with graphs, slides, etc.

Martina Martinello | Connecting cavity performance to physics of the surface

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Thank you for your attention!