

# WG4 summary talk

## ~Performance frontier~

2016/7/8

TTC meeting @ Saclay

WG4 S. Aull, A. Grassellino, K. Umemori

WG3 S. Belomestnykh, J. Hao, E. Jensen

(Joint session for High gradient and High-Q)

# Thin film and new materials

6 talks

- Nb<sub>3</sub>Sn

Daniel Hall 「Next generation Nb<sub>3</sub>Sn Cavities」

Charles Reece 「Nb<sub>3</sub>Sn development at JLab」

- Nb thin film etc

Guillaume Rosaz 「Production and R&D thin films activities at CERN for SRF applications」

Anne-Marie Valente-feliciano 「Towards high performance Nb thin films via energetic condensation」

Sebastian Aderhold / Genfa Wu 「Future thin film deposition efforts at FNAL」

Yoshihisa Iwashita 「Activities on SRF thin film study at KEK & Kyoto U.」

# High gradient / high-Q

7 talks

1. Summarize: what are the achievable gradients and Q at high gradients with state of the art ILC surface processing; where do we stand in terms of field emission
  - Nick Walker 「XFEL ILC-recipe VT results (RI)」
  - Rongli Geng 「Is current state of the art in FE an obstacle to 40MV/m (and beyond) operation?」
2. New results promising of very high gradients and high Q at very high gradients
  - Sebastian Aderhold / Anna Grassellino 「New low T nitrogen treatments cavity results with record gradients and Q」
3. New samples studies indicating potential pathway to higher gradients
  - Robart Laxdal 「New insights for reaching higher gradients from muSR sample studies」
4. Experimental max achievable gradients from Klystron measurements
  - James Maniscalco 「Estimated gradient limitation insights for different surface processing from klystron measurements」
5. Theoretical predictions/explanations for maximum achievable gradients in SRF cavities
  - Takayuki Kubo 「Reaching higher gradients in bulk Nb with nano-layer coating」
  - Mattia Checchin 「Ultimate gradient limitation in Nb SRF cavities」

Thin film and new material

# Film Development

Deposition parameters allow tuning the film properties - but have to be well controlled and fully understood

**ALL film properties are a direct consequence of the film structure, defect/impurity content... thus the technique, environment, substrate are key factors**

**Full control of the deposition process & tailored SRF performance**

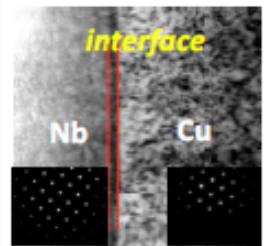
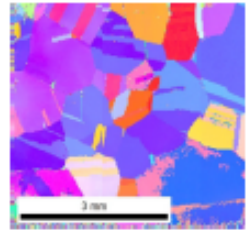
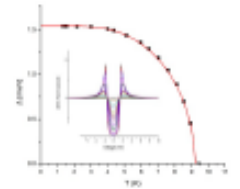
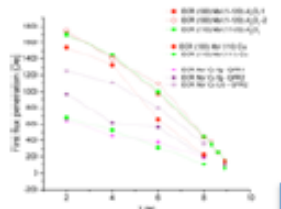
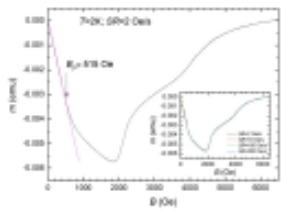
- UNDERSTANDING OF**
- The **chemistry** of the involved species
    - Reactivity**
    - Stoichiometric sensitivity**
  - Reaction process temperatures**
  - Final structure dependence on substrate structure**
  - Influence of deposition energy** on resulting structure
  - Sensitivity to the presence of contaminating species, defects**
  - Stability** of desired film against subsequent **degradation**

Careful **characterization of the attained composition and microstructure** (RHEED, STM, XRD, EBSD, AFM, optical profilometry, XPS, SIMS, TEM, FIB).



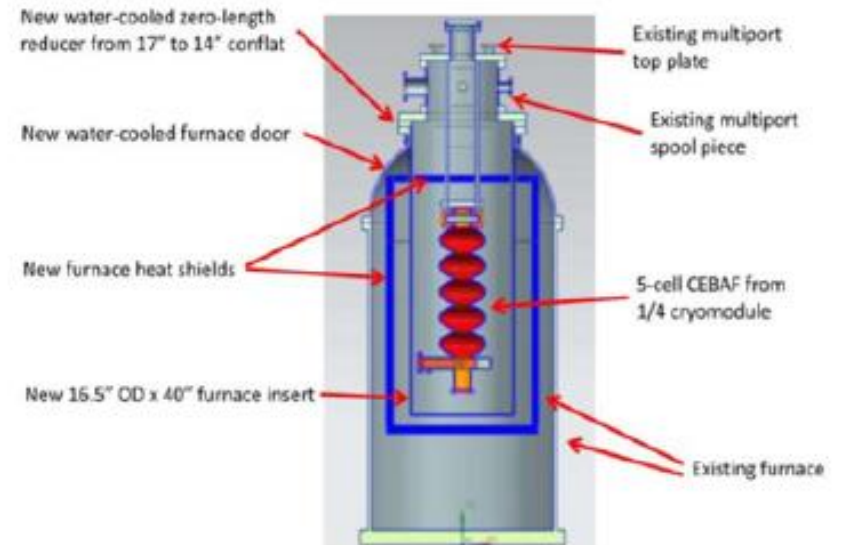
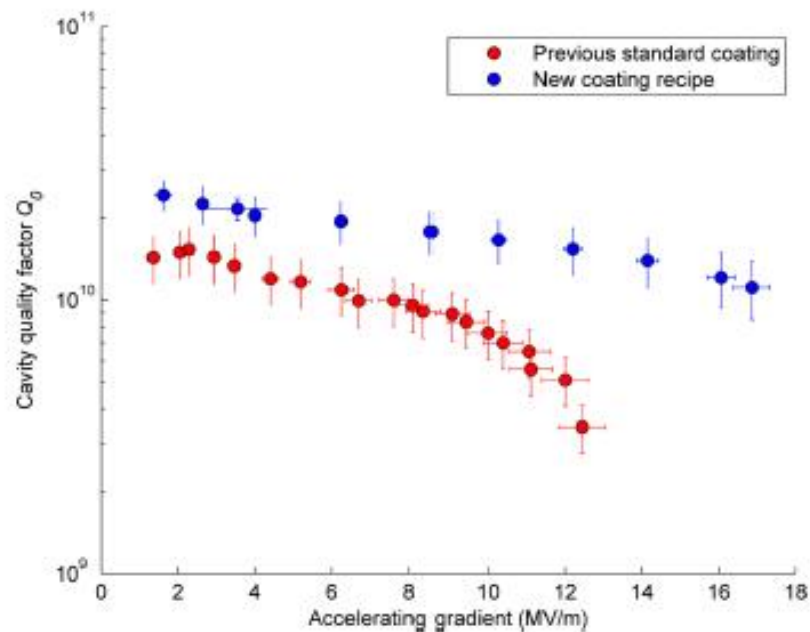
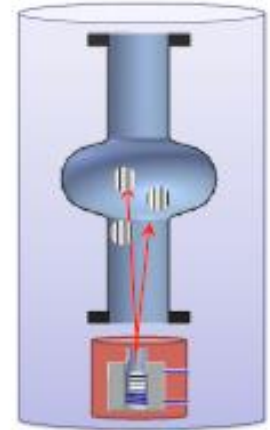
Close association with **resulting RF surface impedance & superconducting properties** ( $\lambda$ ,  $\Delta$ ,  $T_c$ ,  $H_c$ , RRR)

Towards high performance Nb thin films via energetic condensation



# Nb<sub>3</sub>Sn by reactive diffusion

- JLab joined the activities and prepares for coating 5-cell cavities.
- Cornell further improved recipe, increasing the quench field.

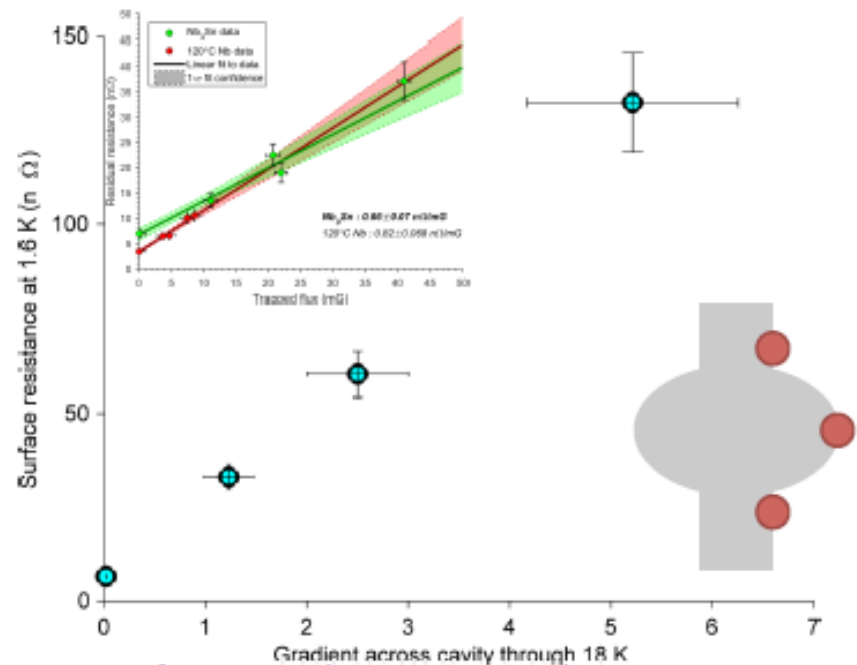
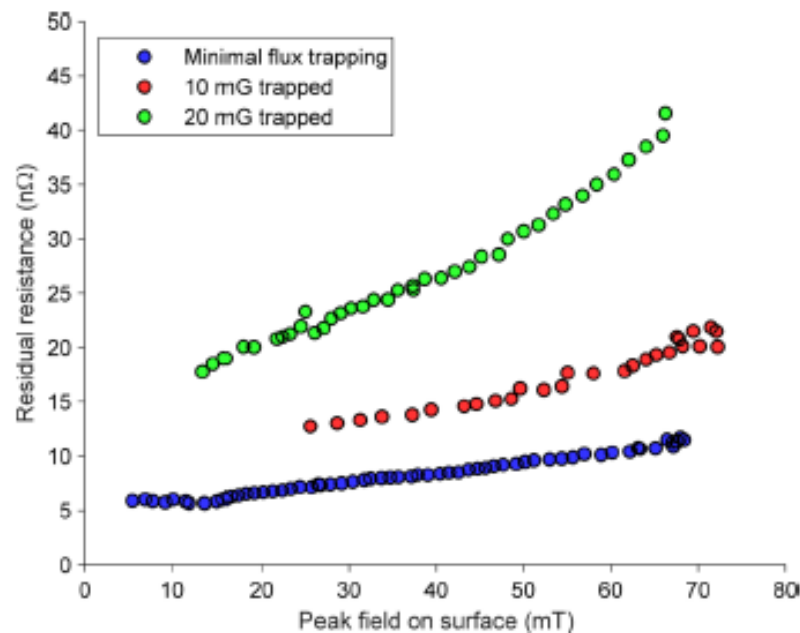


Next Generation Nb<sub>3</sub>Sn cavities: Current performance, limitations, and considerations for practical use,  
D. Hall/M. Liepe (Cornell)

Nb<sub>3</sub>Sn Developments at JLab,  
C. Reece/ G. Ereemeev (JLab) & U. Pudasaini/  
M. Kelley (W&M)

# Nb<sub>3</sub>Sn: Trapped Flux Sensitivity

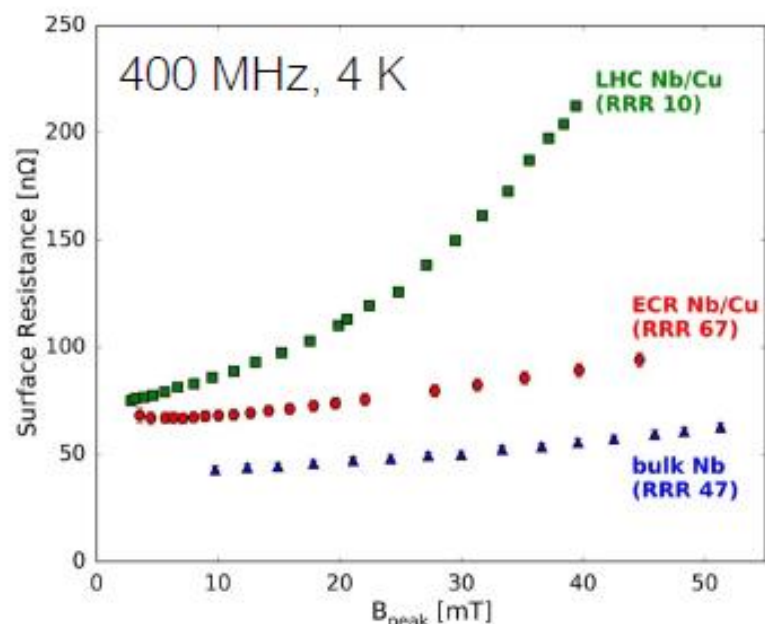
- Surface resistance increase with trapped magnetic field similar to 120C baked bulk Nb
- Strong surface resistance increase with temperature gradient — similar to Nb/Cu —> thermal electric currents at the metal-metal interface?



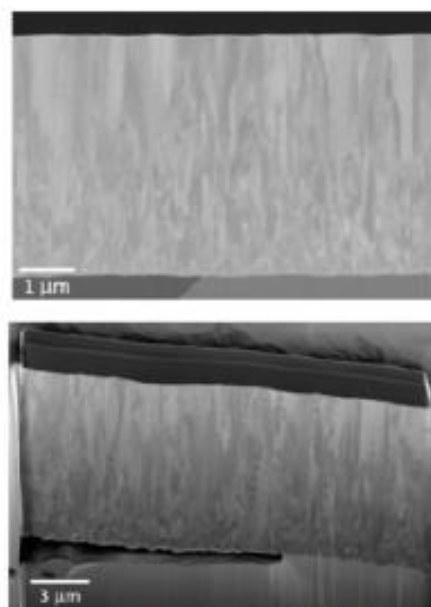
Next Generation Nb<sub>3</sub>Sn cavities: Current performance, limitations, and considerations for practical use, D. Hall/M. Liepe (Cornell)

# Energetic Condensation: the Pathway to Denser Films

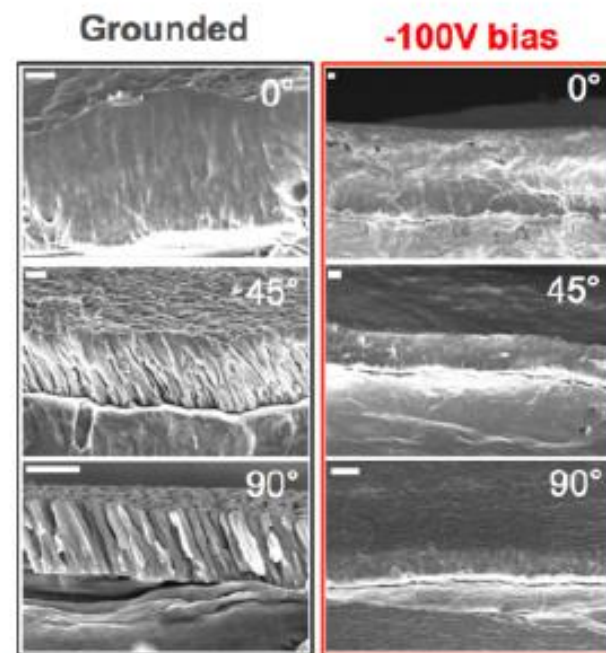
- Energetic condensation techniques (ECR, HIPIMS,...) show improved Nb film microstructure.
- First RF measurements on samples show significantly mitigated Q-slope



A.-M. Valente (JLab) & S. Aull (CERN)



Production and R&D thin films activities at CERN for SRF applications, G. Rosas (CERN)





# Nb/Cu: Cavity Deposition

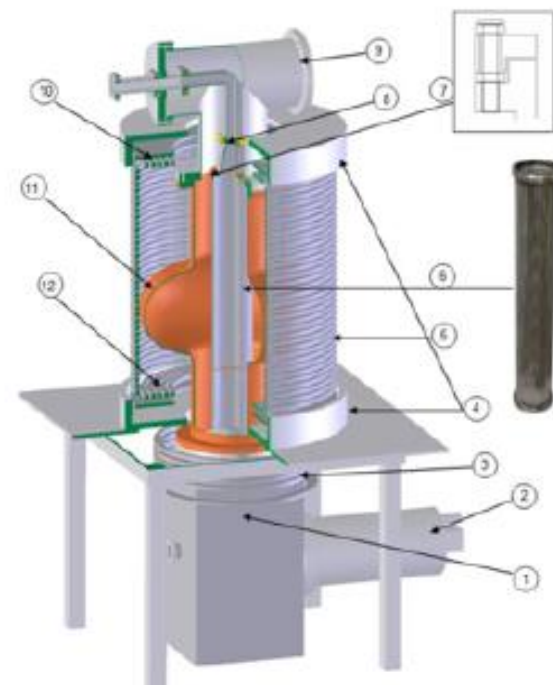
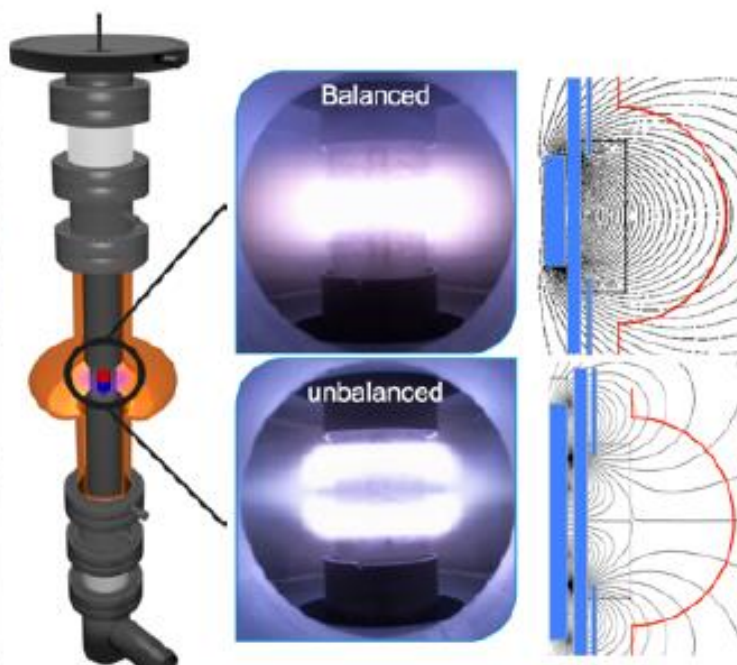


Towards high performance Nb thin films via energetic condensation

A.-M. Valente (JLab)



Production and R&D thin films activities at CERN for SRF applications, G. Rosas (CERN)



Future thin film deposition efforts at FNAL, G. Wu/M. Checchin (FNAL)

# Conclusion

- the new material/thin film community is growing, understanding of recipes are advancing, performance is improving
- Synergies between Nb<sub>3</sub>Sn and Nb/Cu could speed up understanding the relation between material properties and SRF performance

The screenshot shows the Jefferson Lab website header with the logo "Jefferson Lab" and the tagline "EXPLORING THE NATURE OF MATTER". Below the header is a navigation menu with links: Circular, Registration, Abstract Submission, Program, Lodging, Travel, Visa, Participants List, and Child Care Program. The main content area is titled "Thin Films 2016" and features a "print version" icon. The text describes the 7th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, held from July 27-29, 2016, at the Thomas Jefferson National Accelerator Facility in Newport News, VA. It includes a "Circular" section with two paragraphs of text.

**Jefferson Lab**  
EXPLORING THE NATURE OF MATTER

LINKS print version

[Circular](#)

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**Thin Films 2016**

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July 27-29, 2016  
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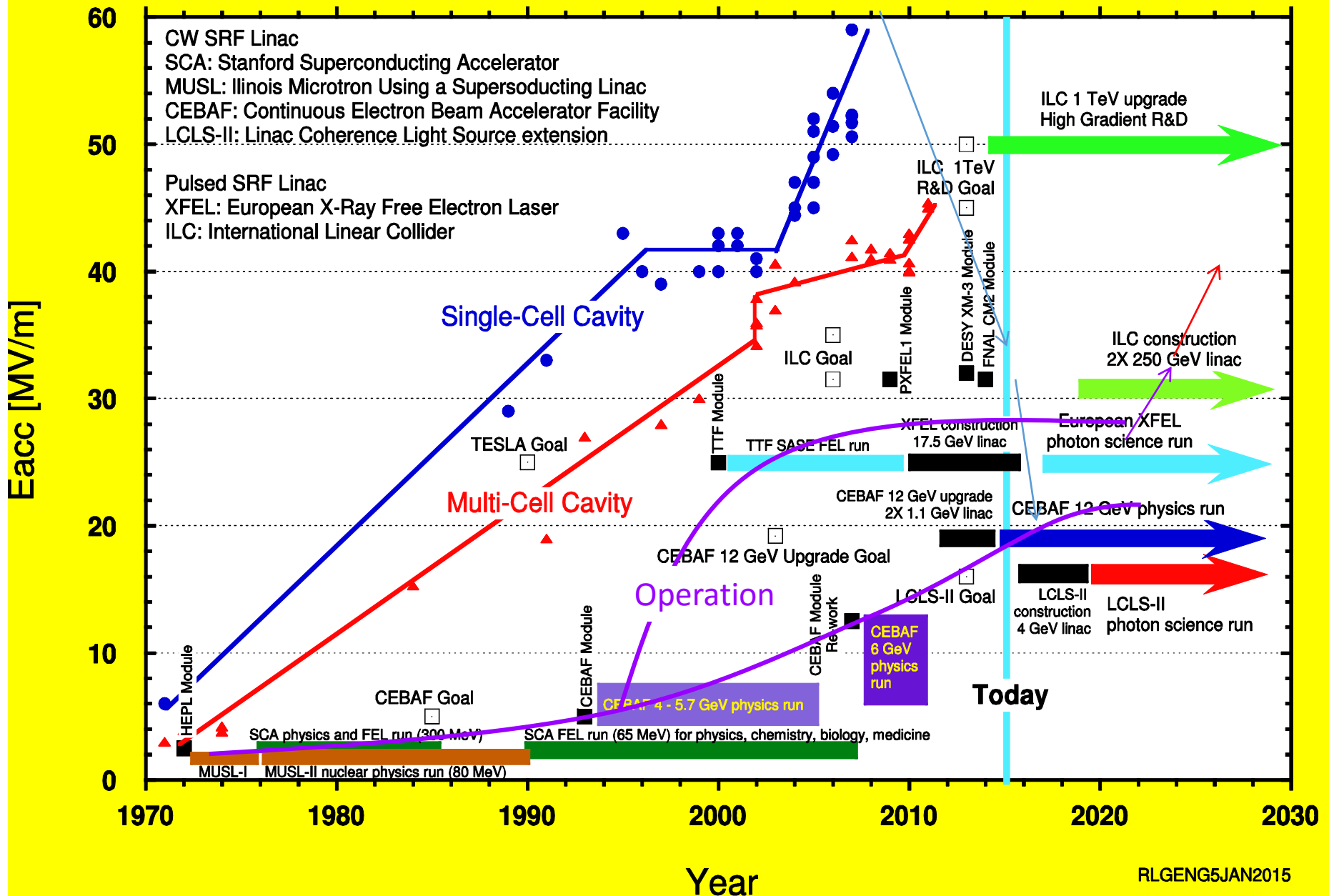
**Circular**

The seventh workshop in this series will continue the goal of providing a forum for new initiatives in innovative thin films and related technology to advance future generations of superconducting RF accelerators. Present superconducting RF accelerator technology is based on predominately bulk niobium, for which the state of the art in performance is reaching the theoretical limit. Thin film technology offers the prospect of considerable savings in fabrication costs and opens the way with innovative technologies to the use of alternative superconducting materials with enhanced intrinsic properties such as critical temperature and critical field. Intensive and coordinated R&D effort is of decisive importance for the scientific Community.

The primary aim of the workshop is to support this initiative by providing an opportunity to bring together individuals and institutions working in this effort and infusing expertise of specialists from related disciplines (superconductivity, plasma physics, material science, nanotechnology, RF engineering and industry. Reports on work from each participating group and extensive discussions on existing problems, new ideas and programs for the future will constitute the primary focus of the program.

High gradient / High-Q

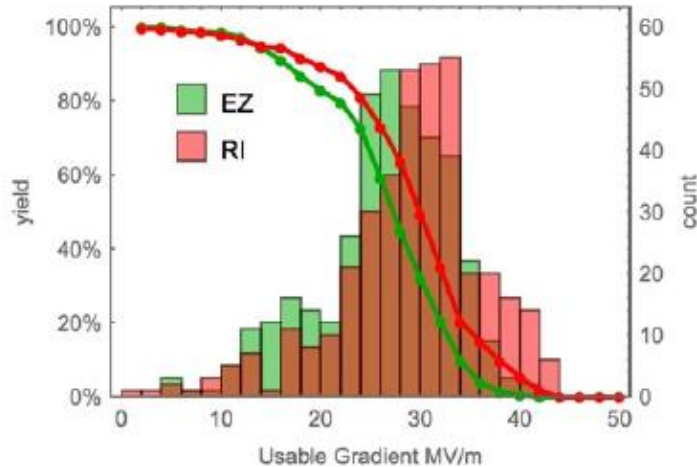
# L-band SRF Linear Accelerator Technology and Impact to Nuclear, Elementary Particle, and Photon Sciences



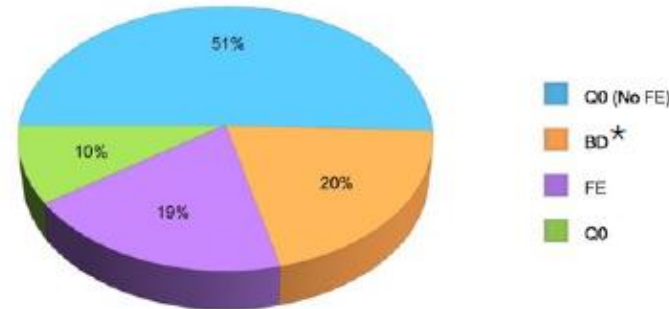
RLGEN5JAN2015

Rongli Geng 「Is current state of the art in FE an obstacle to 40MV/m (and beyond) operation?」

European XFEL **Test results: USABLE GRADIENT** 

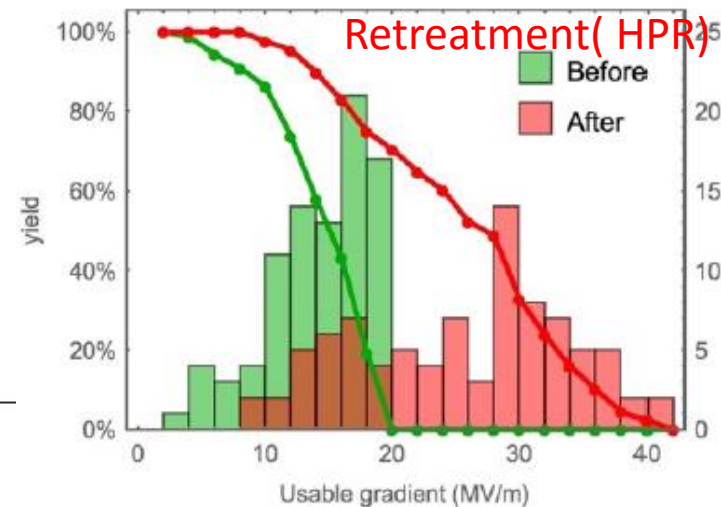


“As received” test



\* few cases of power limitation, HOM coupler heating etc.

	RI	EZ	Total
Tests	375	367	742
$G_{AVG}$ (MV/m)	29.1	26.4	27.8
$G_{RMS}$ (MV/m)	7.4	6.6	7.1
yield @ 20MV/m	89%	83%	86%
yield @ 26MV/m	73%	59%	66%
yield @ 28MV/m	63%	45%	54%



XFEL cavity results • ECFA LC 2016 • Santander - Spain • 31-05-2016  
 Nicholas Walker • DESY • nicholas.walker@desy.de

Retreatment (additional HPR) is effective to recover performance. From some model analysis, including retreatment of cavity, ~50% of cavity can be operated at 35 MV/m

# Summary of Achieved High Gradient

- 36 MV/m one 9-cell without beam (HTC @ FNAL)
  - 57hours
- 31.5 MV/m, 7 9-cell without beam (ASTA @ FNAL)
  - unknown hours
- > 30 MV/m, several 9-cells with beam (FLASH)
  - 15 hours at 3 mA
  - Several hours close to 9 mA

- There is some operation experiment at 30 -35 MV/m, but not for > 40MV/m.
- Propose test operation of cavity > 40 MV/m

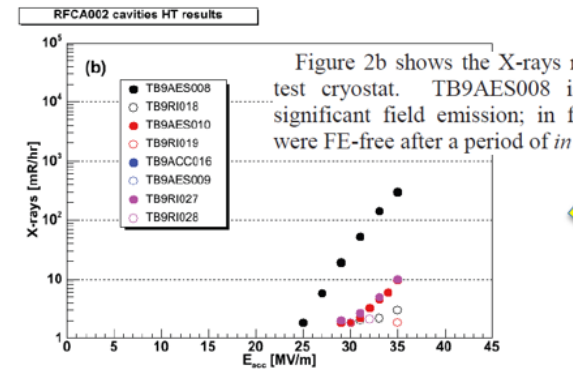
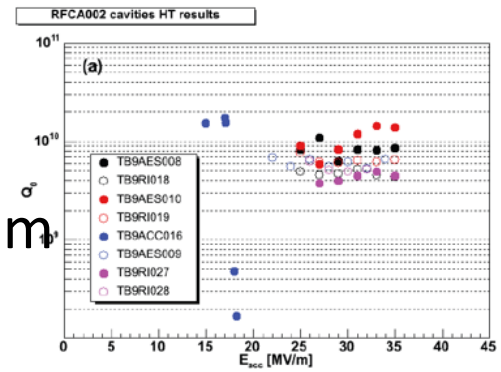
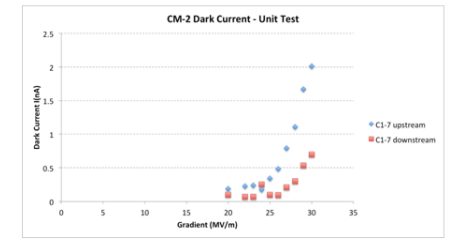
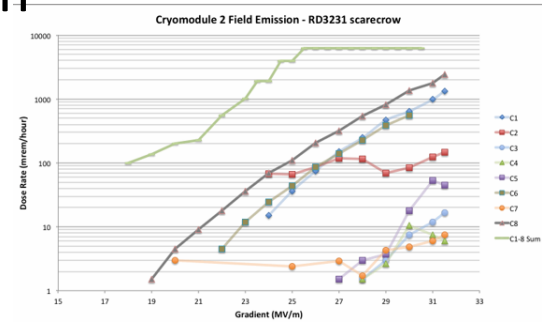
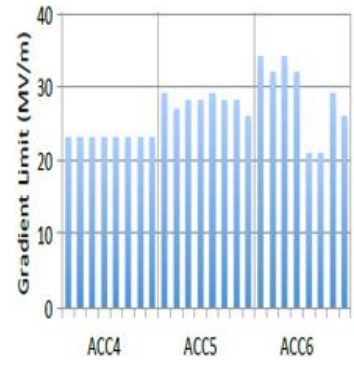


Figure 2: (a)  $Q_0$  vs.  $E_{acc}$  from the last horizontal test of the RFA002 cavities. (b) X-rays vs.  $E_{acc}$  from the last horizontal test of the RFA002 cavities. Note the y-axis range differs from Figure 1b.

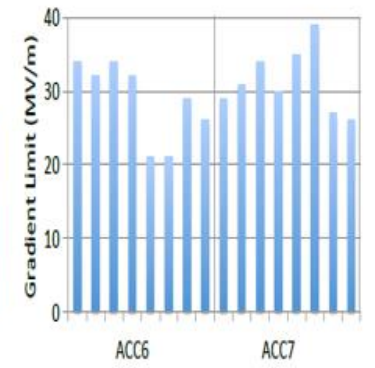


E. Harms, TTC 2014 at KEK

Figure 3.2 Measured cavity-gradient limits for the cavities in the FLASH Accelerator cryomodules for the 9mA studies

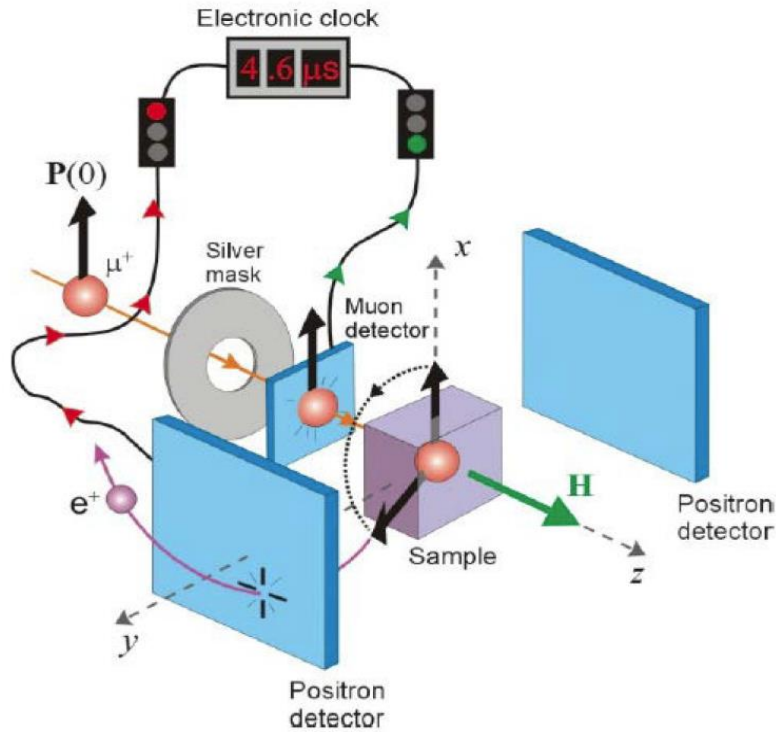


(a) Modules ACC4,5,6 (2008-2009)

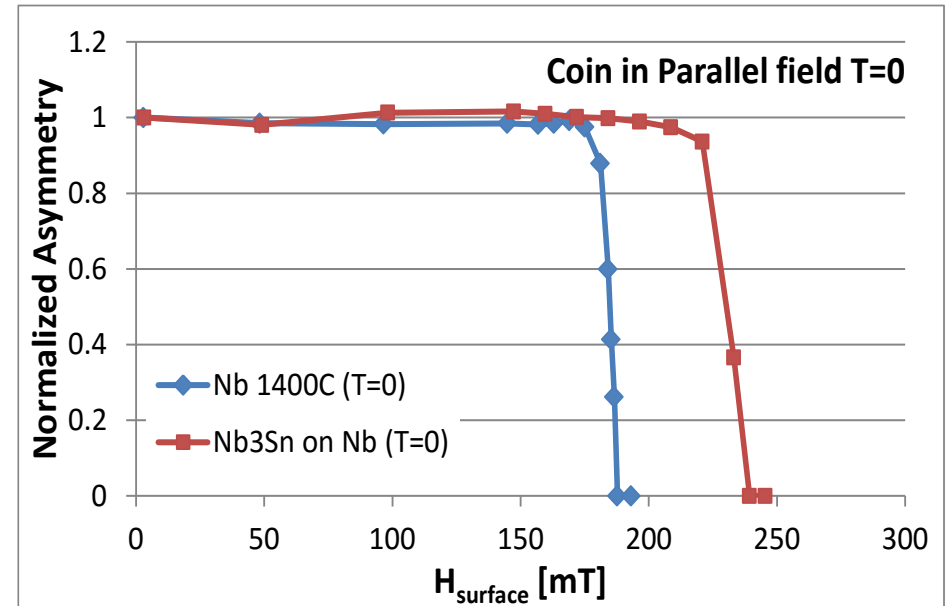


(b) Modules ACC6,7 (2010-2012)

# Muon Spin Rotation – muSR



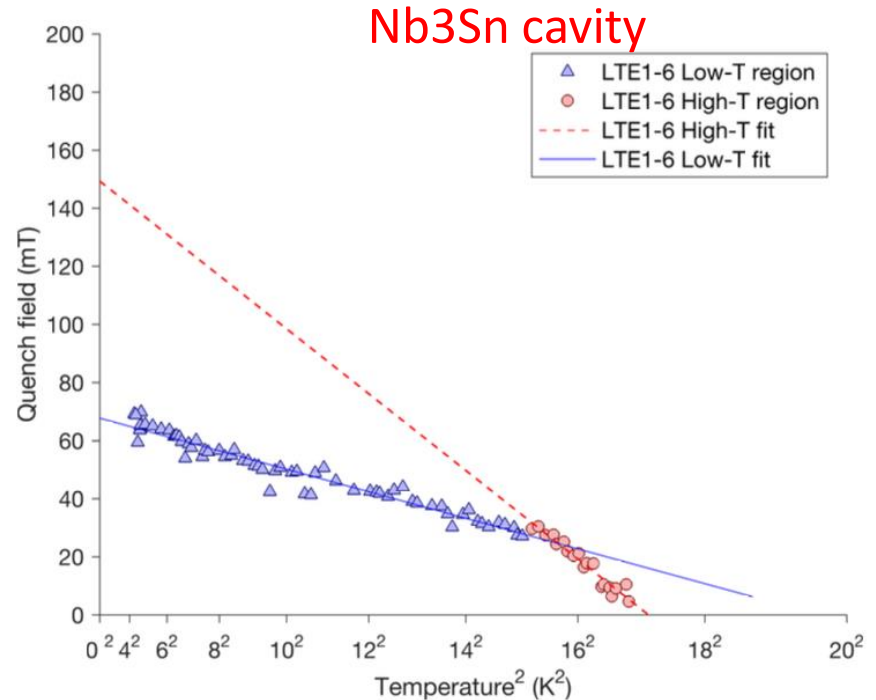
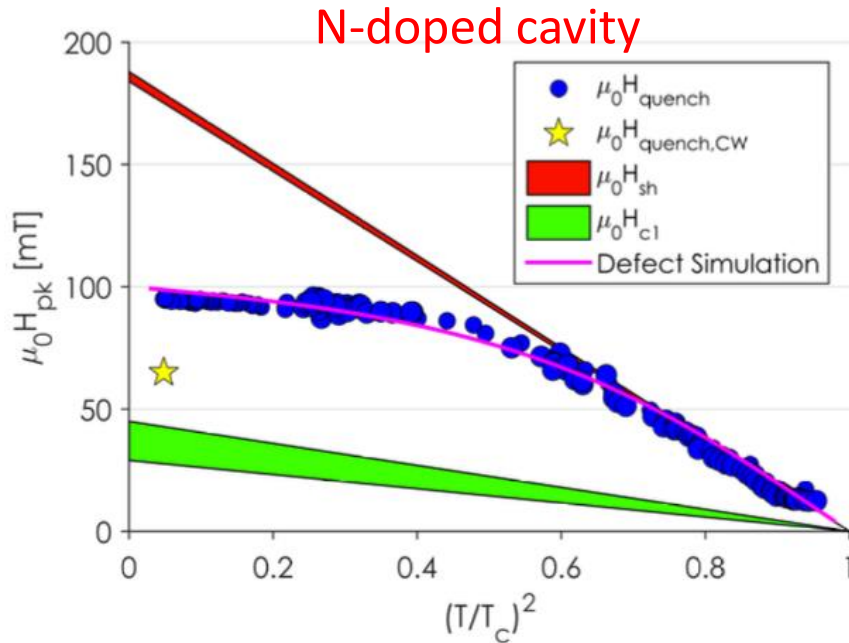
- The time evolution of the asymmetry in the two signals gives a measure of the local field in the sample



- An uncoated Nb sample in parallel geometry has flux breaking in at 180mT (at T=0) – consistent with  $H_{c1}$
- A Nb coin coated with Nb3Sn has flux breaking in at 230mT (at T=0) consistent with  $H_{sh}$  of Nb

*A layer of higher  $T_c$  material on niobium can push the field of first flux entry from a field consistent with  $H_{c1}$  to a field consistent with  $H_{sh}$*

## Motivation: Klystron test can escape from global thermal effects

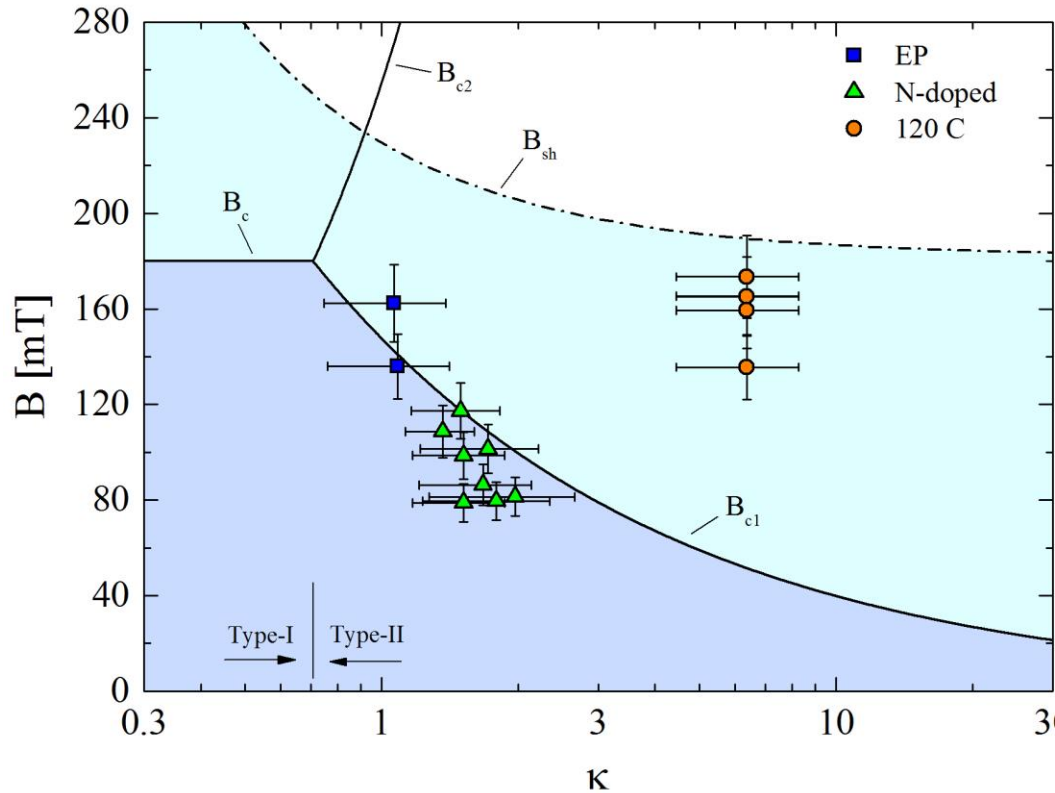


- High T: limited by flux entry at Bsh
- As T decreases, Bpk diverges, indicating thermal effects

Two slope can clearly be seen from klystron analysis



# CW quench field data



N-doped cavities so far quench **below**  $B_{c1}$

→ statistically, N-doped cavities are quenching close or below the lower critical field

120 C baked cavities quench always **above**  $B_{c1}$

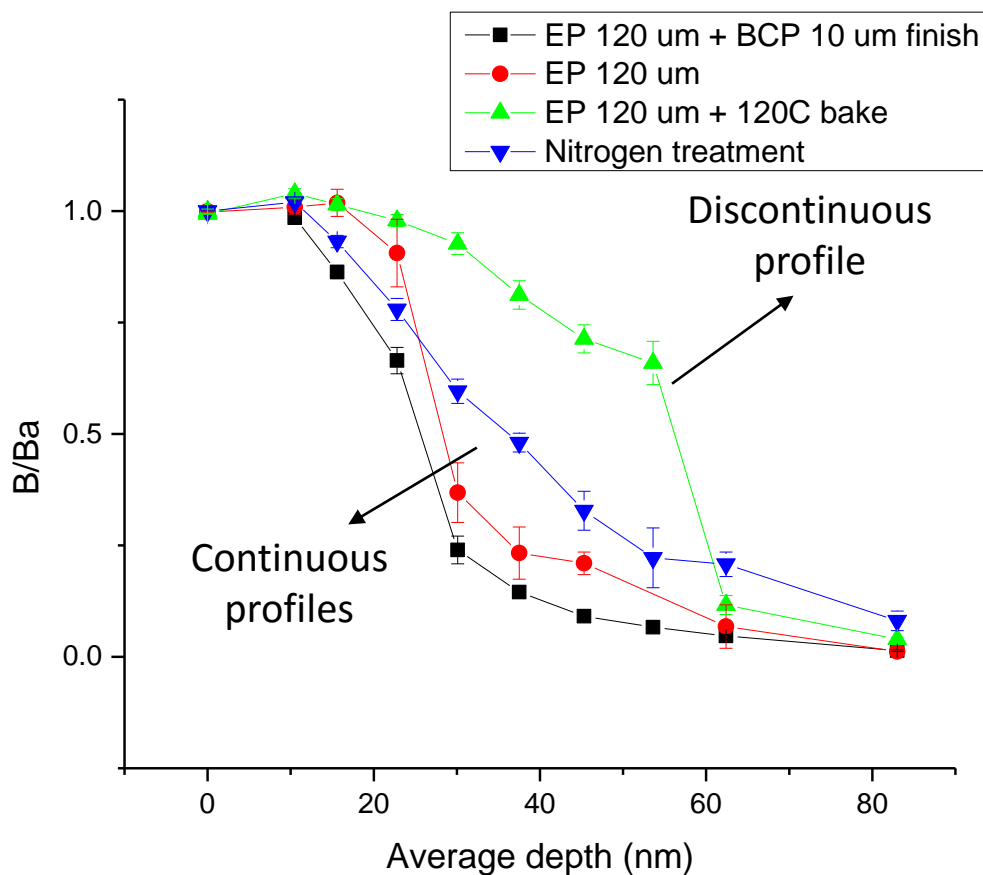
→ 120 C baked cavities can reach the metastable Meissner state above the lower critical field

$$H_c(0) = 180 \text{ mT}^1 \quad \lambda_0 = 39 \text{ nm}^2 \quad \xi_0 = 38 \text{ nm}^2$$

<sup>1</sup> S. Casalbuoni *et al.*, Nucl. Instr. Meth. Phys. Res. A 583, 45 (2005)

<sup>2</sup> B. W. Maxfield and W. L. McLean, Phys. Rev. 139, A1515 (1965)

# Surface of 120C bake vs N doping vs EP, via LE-muSR

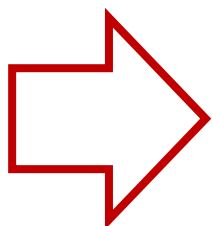


N-doped, EP and BCP do not show discontinuous field penetration profile

→ constant concentration profile

Standard 120 C baked does present discontinuous field penetration profile

→ dirty layer!

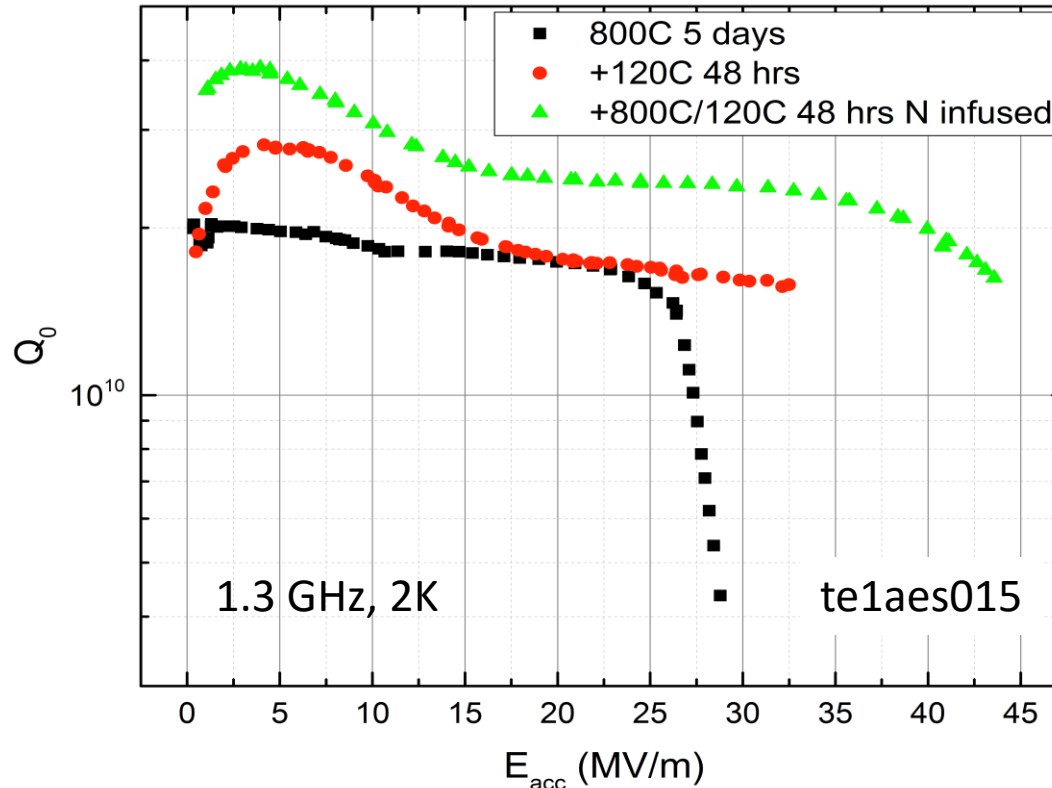


120 C baked cavities quench above  $B_{c1}$  likely because of the dirty layer.

**Nitrogen-infused cavities may exploit the same phenomenon, but bringing also benefit for the Q!**

# Nitrogen Infusion

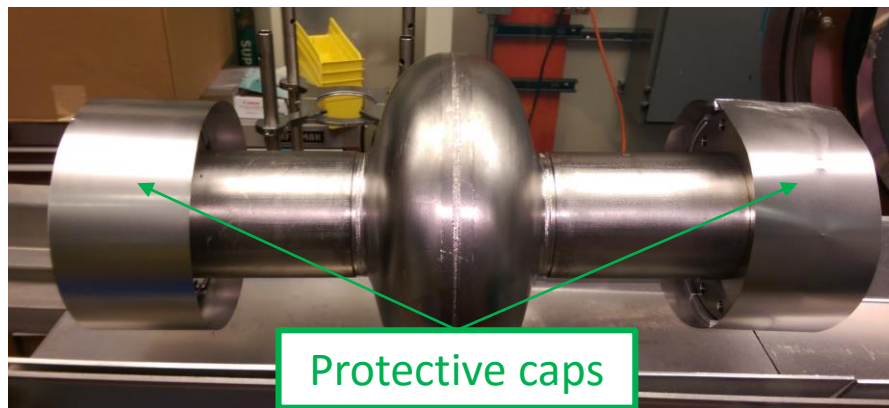
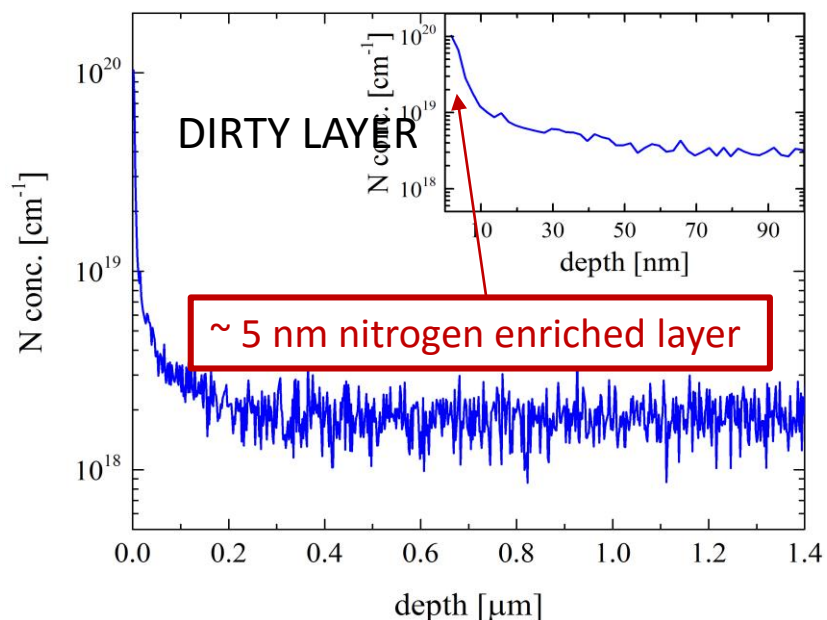
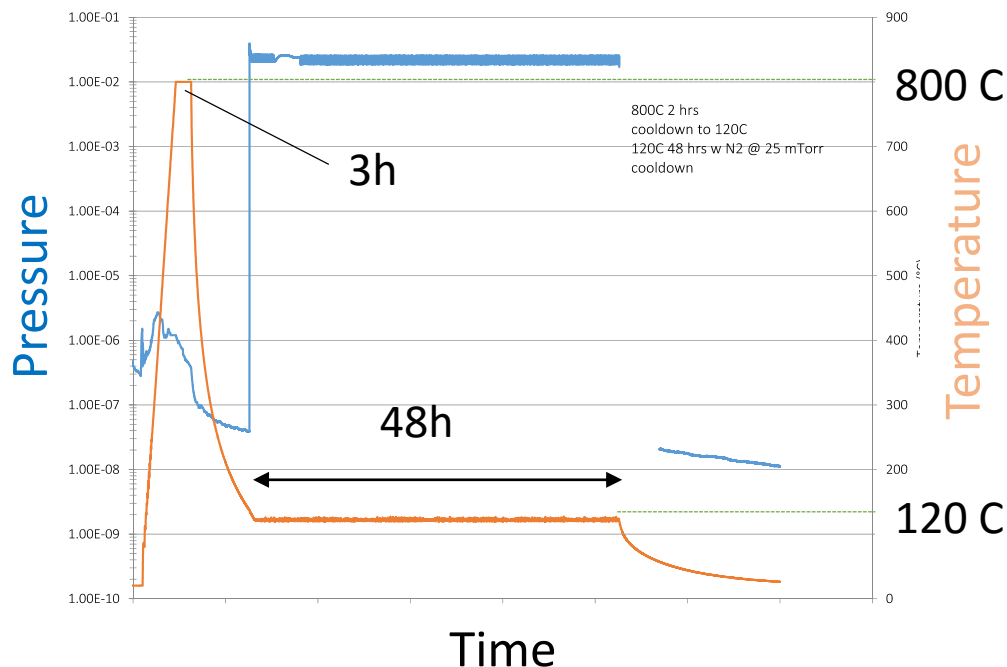
## systematic improvement in Q and quench fields



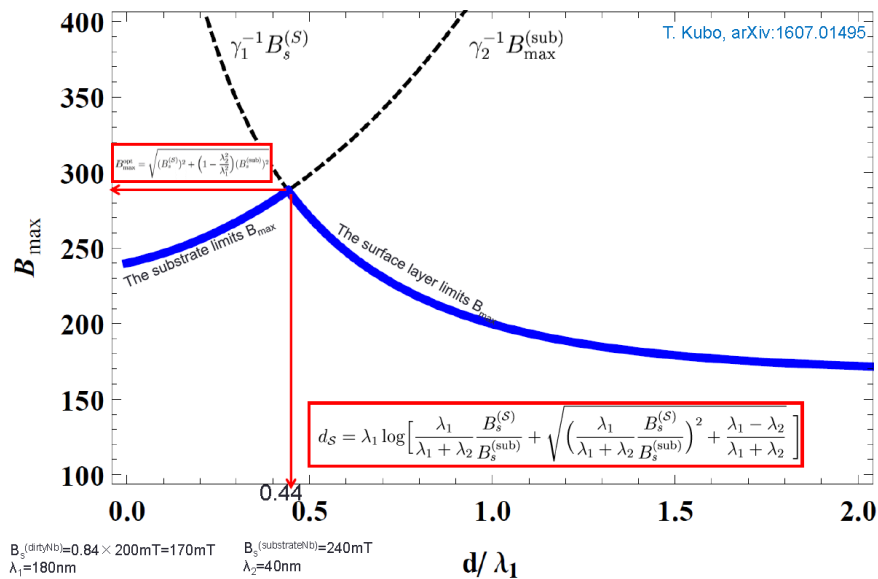
- Clear evolution trend confirming **improvement in Q and quench field**
- NO EP between furnace treatments: comparing same morphological surface, just different impurity content

## Example of nitrogen infusion treatment - engineering a thin dirty layer with N<sub>2</sub>, on a clean bulk

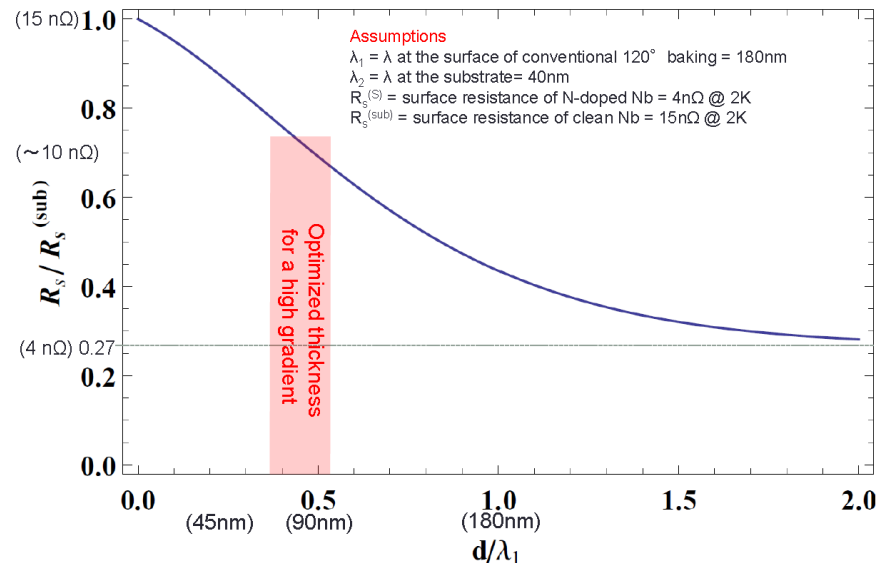
- Bulk electro-polishing
- High T furnace with caps to avoid contamination:
  - 800C 3 hours HV
  - 120C 48 hours with N<sub>2</sub> (25 mTorr)
- NO chemistry post furnace
- HPR, VT assembly



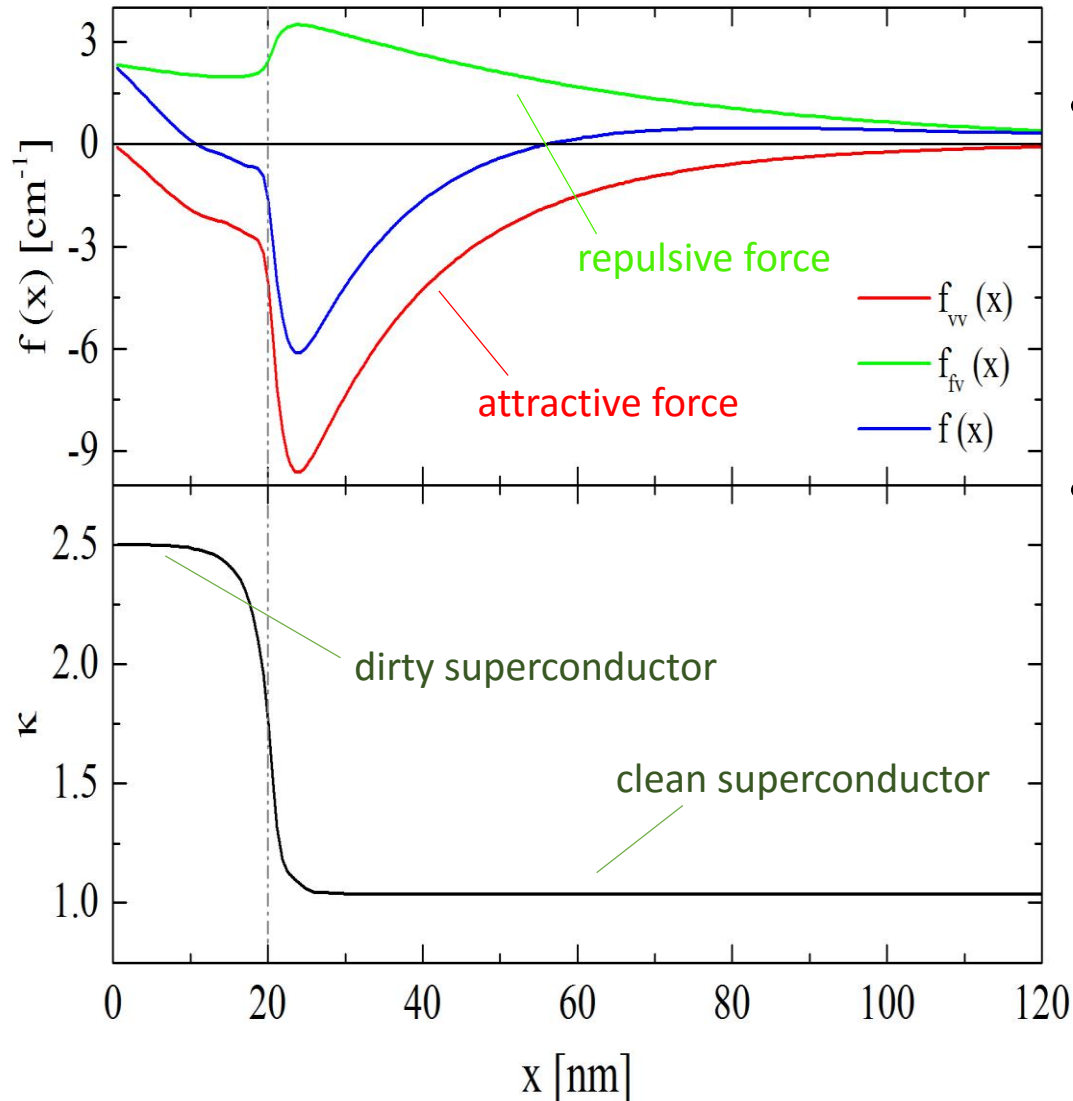
# Effect of the dirty layer on clean bulk superconductor



1. The quench field is increased up to a maximum value defined by the dirtiness and thickness of the layer
2. The surface resistance is a “weighted” average of the surface resistance of the layer and of the bulk
3. Quench field and surface resistance can be tuned as needed by engineering the dirty layer at the surface



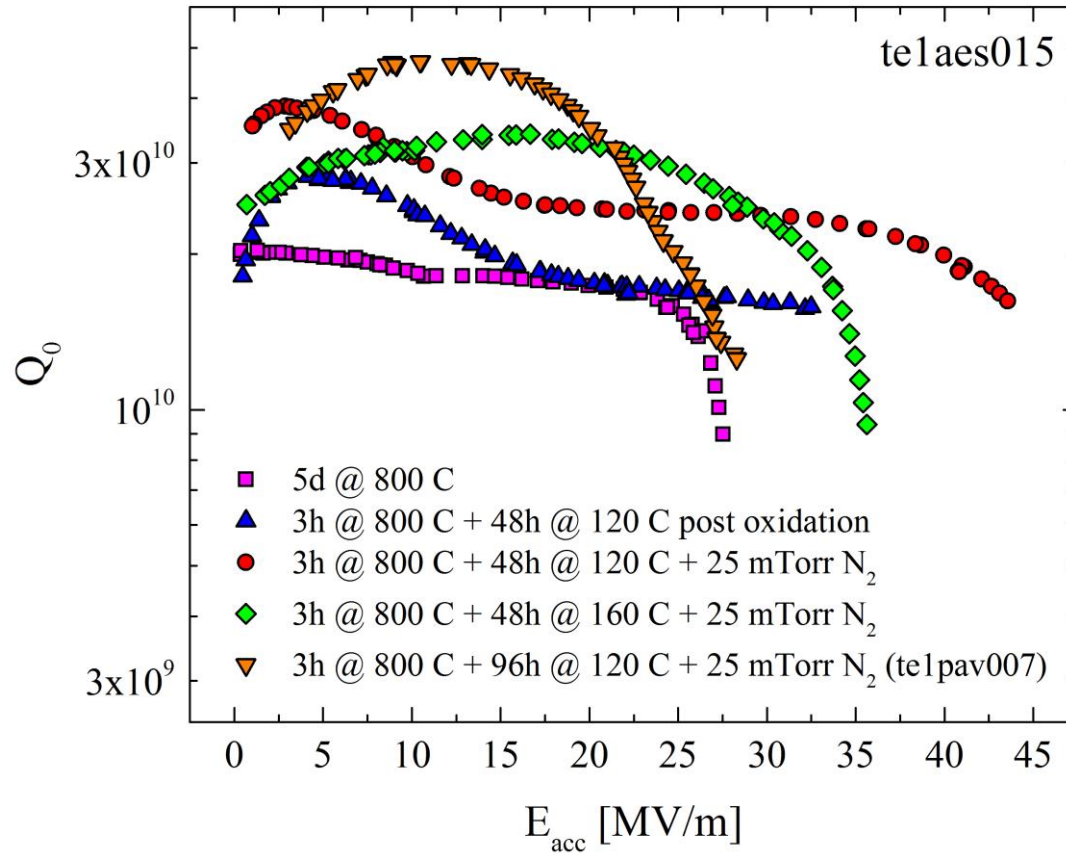
# Why the dirty layer increases the quench field?



- The attractive force (to the surface) acting on the vortex is enhanced at the interface dirty/clean superconductor
- Such force pushes more efficiently the vortex outside the superconductor

**The penetration of the magnetic field is delayed!**

Moving to even higher Q – and maybe gradients too –  
R&D continues to better engineer ideal nanometric N layer



## Conclusion

[High gradient and High-Q]

- At present operation of cryomodule with 35MV/m could be possible. No experience on 40 MV/m operation.
- Field emission is on-going target to improve cavity performance.
- Understanding of materials and thin/multi layers are proceeded by both experimental and theoretical approach.
- Low T nitrogen treatment was proposed and opened the way to control both of cavity gradient and Q.