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HIGH QUALITY FACTORS AND HIGH GRADIENTS IN SUPERCONDUCTING NIOBIUM RESONATORS

Mattia Checchin

JLab Accelerator Seminar
08-Dec-2016

Outline

- High Q-factors
  - N-doping
  - Trapped Flux Surface Resistance
  - Vortex Surface Resistance Description
  - Best Treatment
- High Q-factors & High Gradients
  - N-infusion
  - Layered Superconducting Surface
    - Energetics of the Vortex Penetration
    - Enhancement of the Accelerating Gradient
- Conclusions

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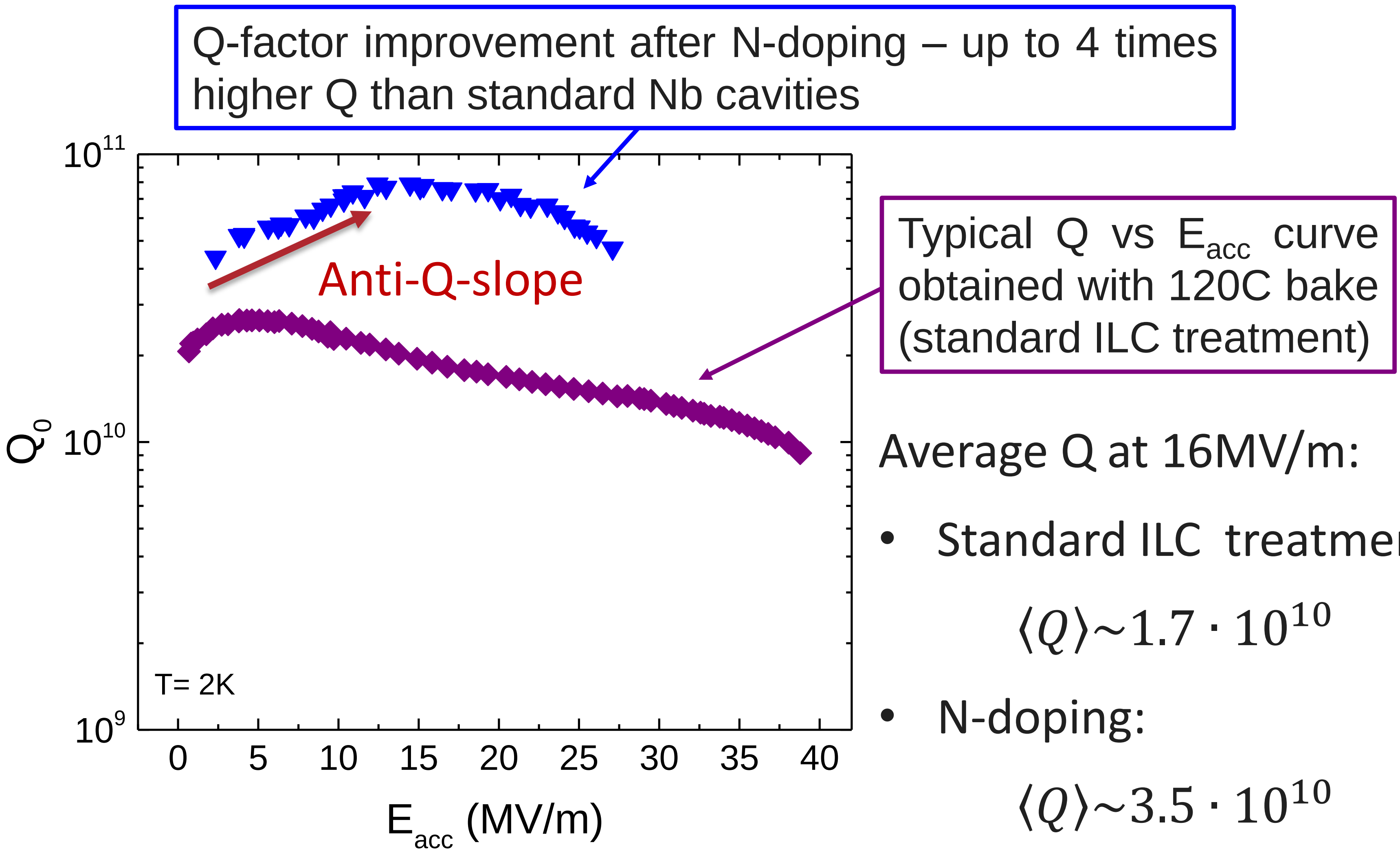
The Discovery of N-doping



Average Q at 16MV/m:

- Standard ILC treatment:

$$\langle Q \rangle \sim 1.7 \cdot 10^{10}$$

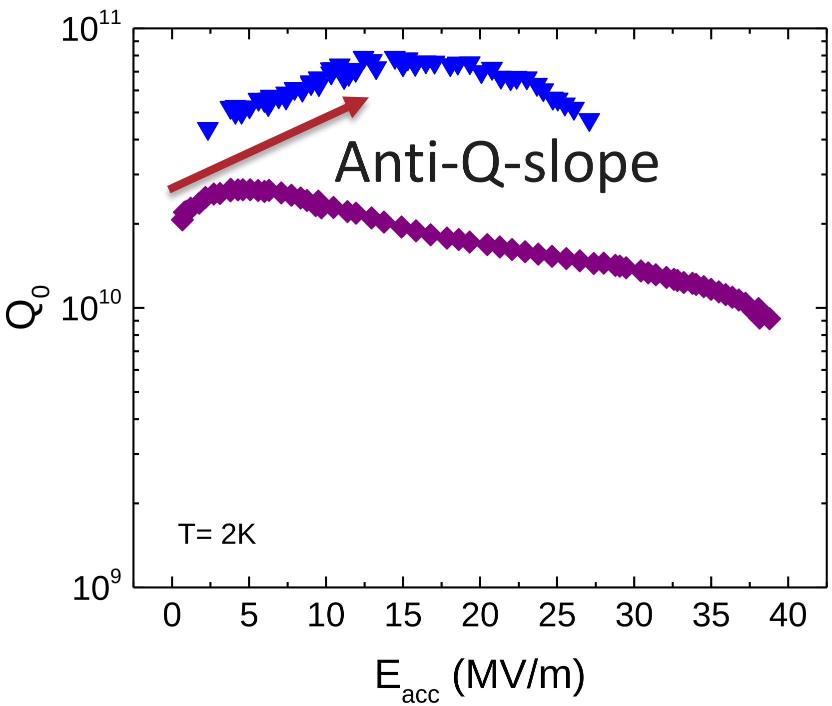
- N-doping:

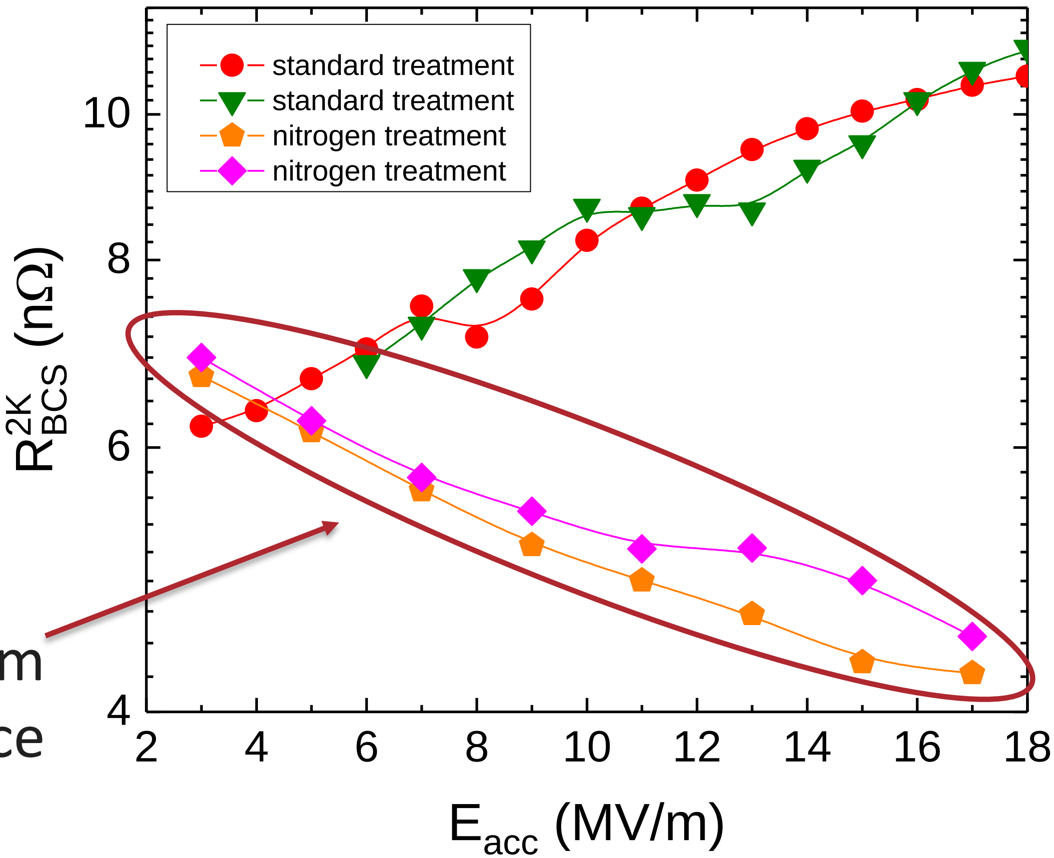
$$\langle Q \rangle \sim 3.5 \cdot 10^{10}$$

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

Origin of the Anti-Q-Slope

$$R_s(T,\omega,B,l) = \boxed{R_{BCS}(T,\omega,l)} + R_{res}(B,\omega,l)$$



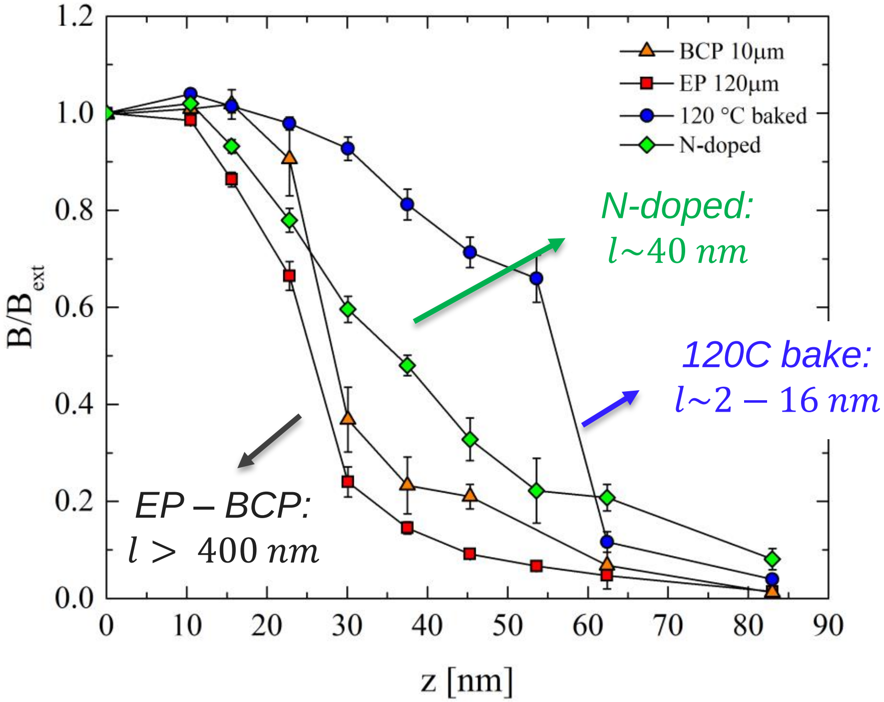


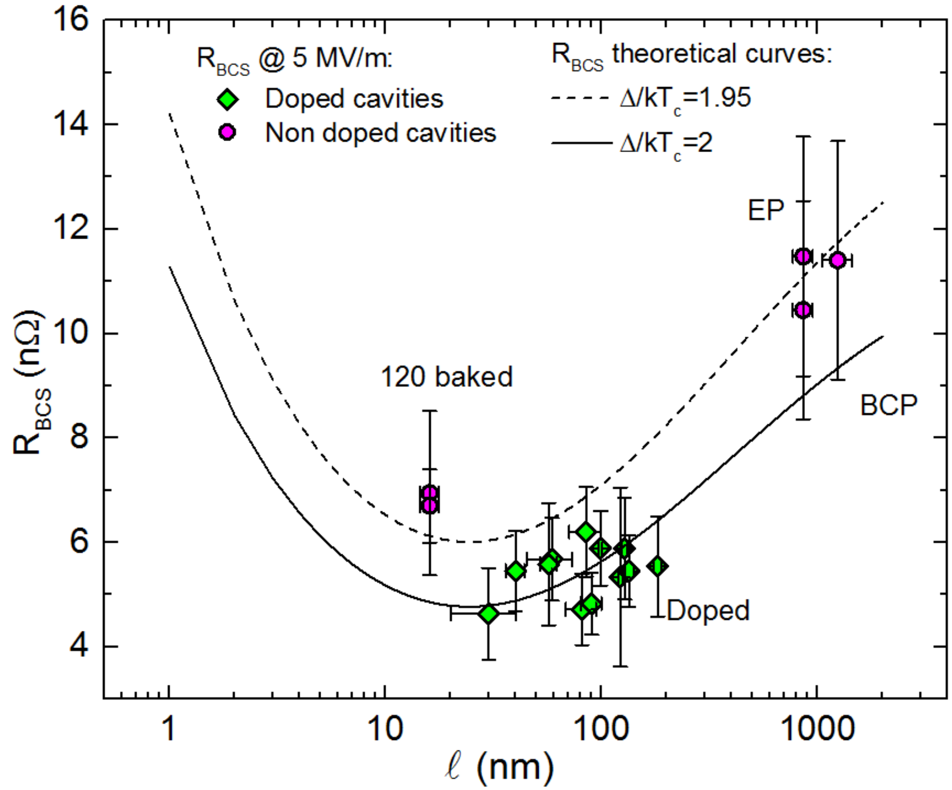
Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

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

Surface Resistance Minimum

LE-μSR measurements ($B_{ext} = 25\ mT$)





A. Romanenko *et al.*, Appl. Phys. Lett. **104**, 072601 (2014)
A. Grassellino *et al.*, Proc. of SRF2015

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

- ✓ N-doping modify the mean free path
  - → Mean free path close to theoretical minimum of R_{BCS}
- ✓ N-doping seems to increase the reduced energy gap $\Delta/\kappa_B T_c$

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Trapped Flux Surface Resistance

$$R_s(T,\omega,B,l) = R_{BCS}(T,\omega,l) + \underline{R_{res}(B,\omega,l)}$$

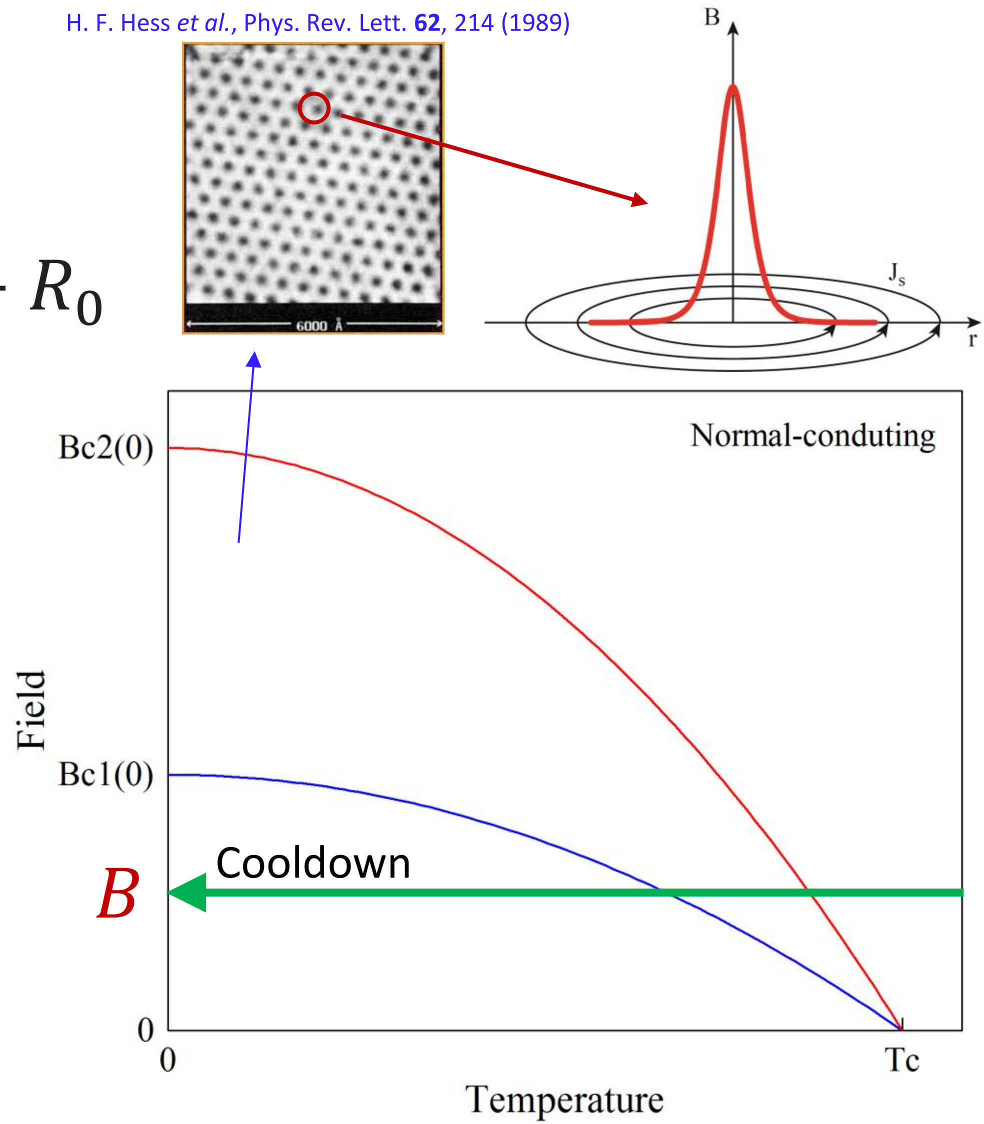
$$R_{res}(B,\omega,l) = \boxed{R_{fl}(B,\omega,l)} + R_0$$

$R_0 \Rightarrow$ intrinsic residual resistance

$R_{fl}(B,\omega,l) \Rightarrow$ trapped flux surface resistance:

- In the mixed state vortices are stable in the SC
- If pinned, vortices may survive in the Meissner state introducing dissipation

H. F. Hess *et al.*, Phys. Rev. Lett. **62**, 214 (1989)



Trapped Flux Surface Resistance Contributions

$$R_{fl} = B_{ext} \cdot \eta \cdot S$$

R_{fl} can be reduced by minimizing these contributions:

External Magnetic Field	B_{ext}	• Magnetic shielding and hygiene
Flux Trapping Efficiency	η	• Fast cooling / pinning
Trapped Flux Sensitivity	S	• Optimizing mean free path

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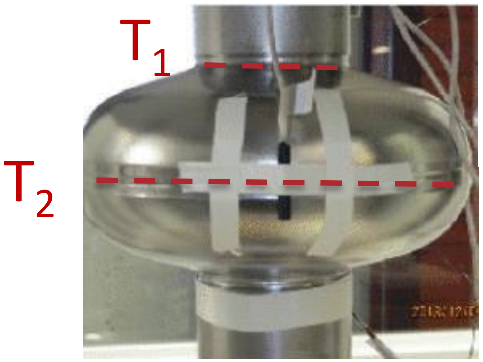
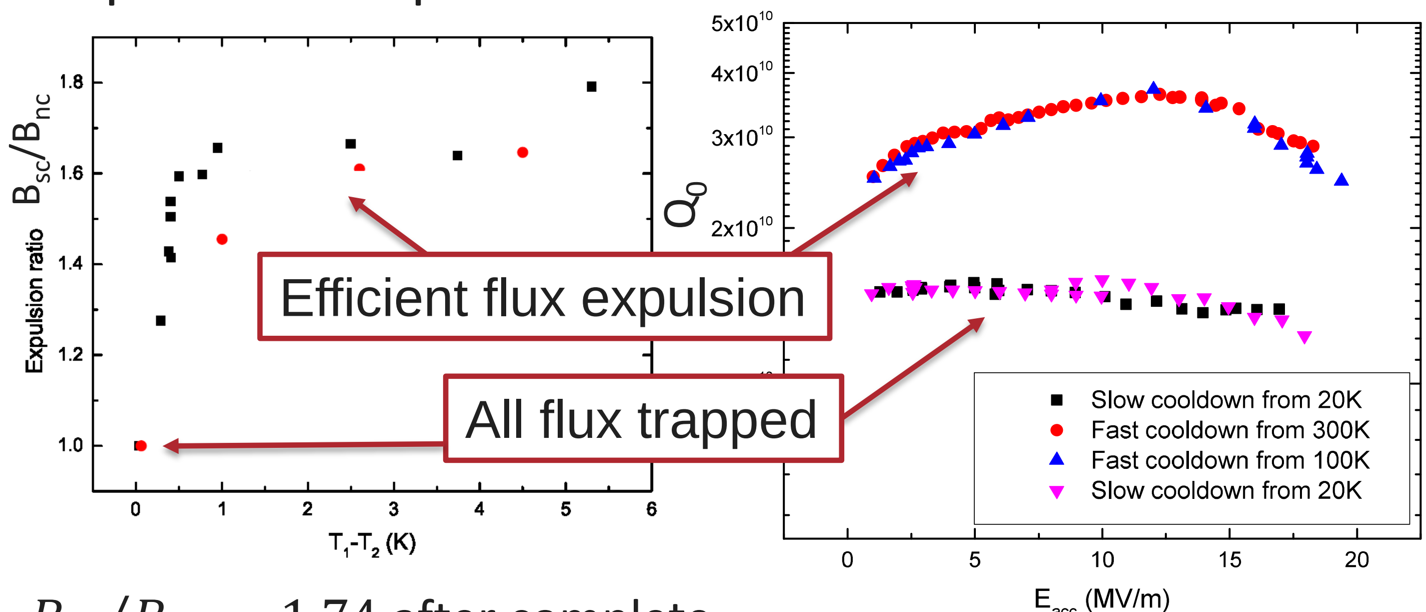
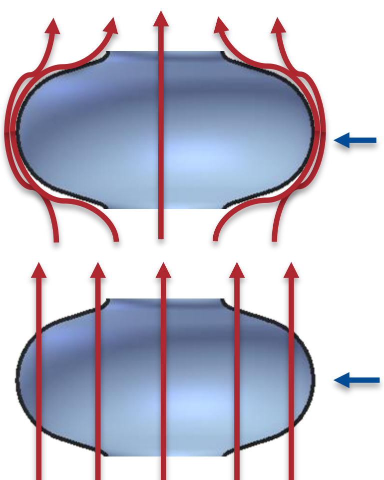
Fast Cooldown

- **Fast cool-down** lead to **<u>large thermal gradients</u>** which promote efficient flux expulsion

- Slow cool-down → poor flux expulsion







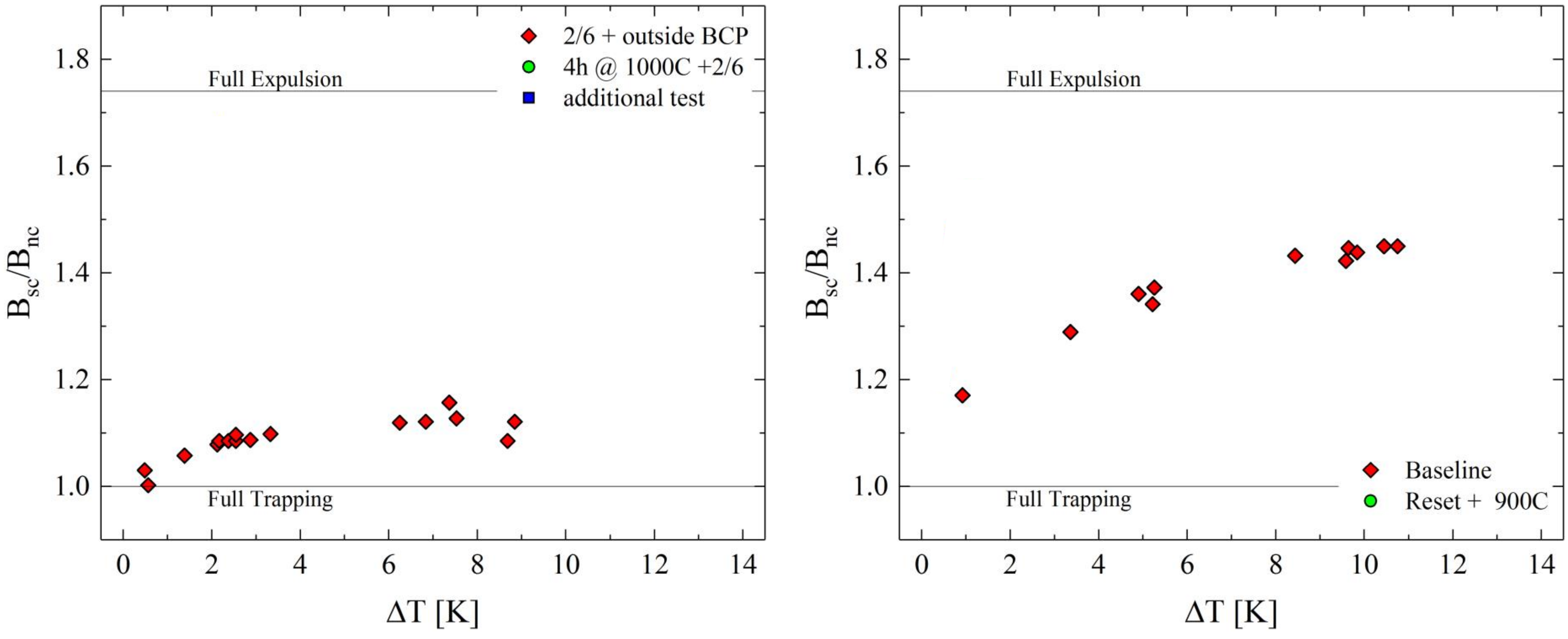
$B_{sc}/B_{nc} = 1.74$ after complete Meissner effect

$B_{sc}/B_{nc} = 1$ after full flux trapping

A. Romanenko *et al.*, Appl. Phys. Lett. **105**, 234103 (2014)
A. Romanenko *et al.*, J. Appl. Phys. **115**, 184903 (2014)
D. Gonnella *et al.*, J. Appl. Phys. **117**, 023908 (2015)
M. Martinello *et al.*, J. Appl. Phys. **118**, 044505 (2015)
S. Posen *et al.*, J. Appl. Phys. **119**, 213903 (2016)
S. Huang *et al.*, Phys. Rev. Accel. Beams **19**, 082001 (2016)

Flux Expulsion Improvement

- Not all materials show good flux expulsion even with large thermal gradient
- High T treatments are capable to improve materials flux expulsion properties



S. Posen *et al.*, J. Appl. Phys. **119**, 213903 (2016)
A. D. Palczewski *et al.*, LINAC 2016

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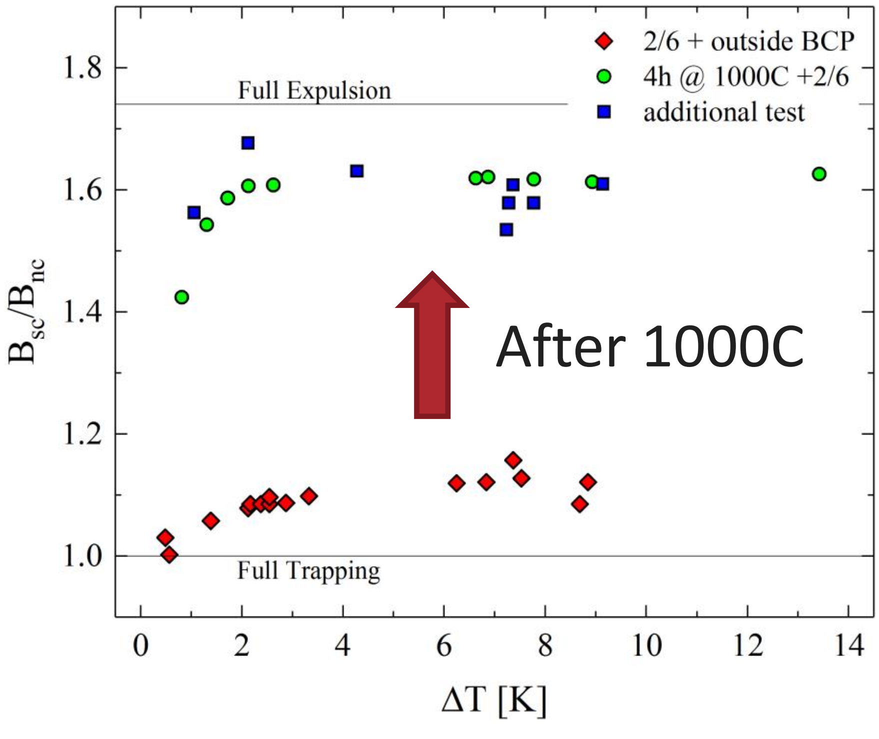

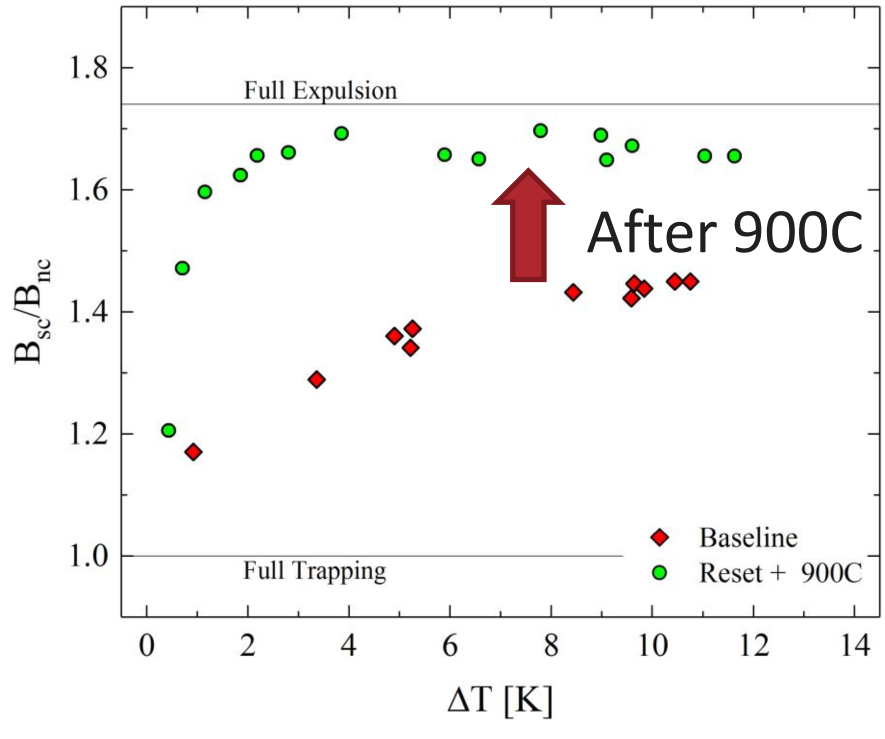

S. Posen *et al.*, J. Appl. Phys. **119**, 213903 (2016)
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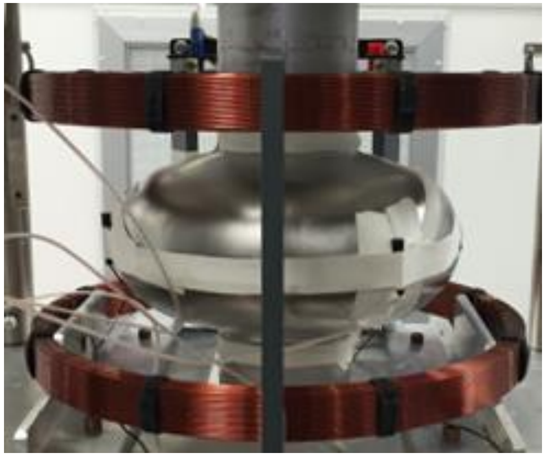
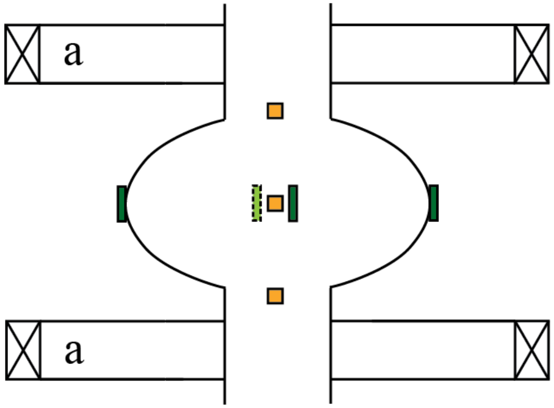
Trapped Flux Surface Resistance Calculation





Trapped flux sensitivity S: surface resistance per amount of trapped field B:

$$S = \frac{R_{fl}}{B} \qquad B = \eta \cdot B_{ext}$$

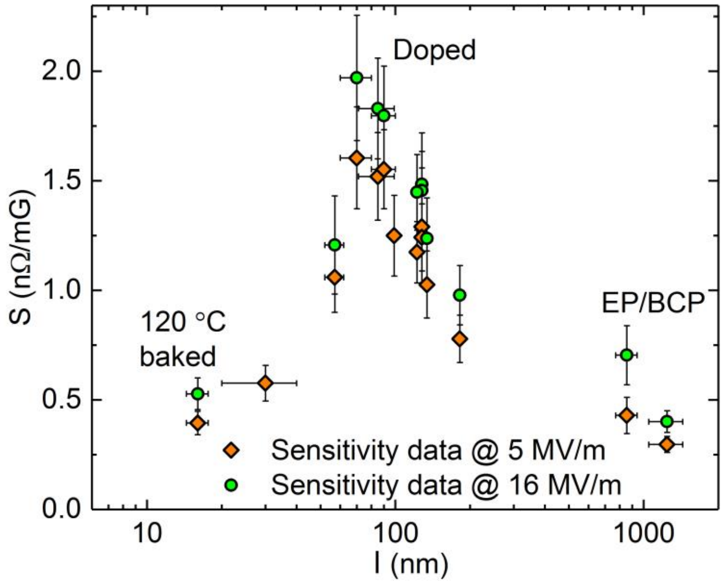
The trapped flux sensitivity is calculated as:

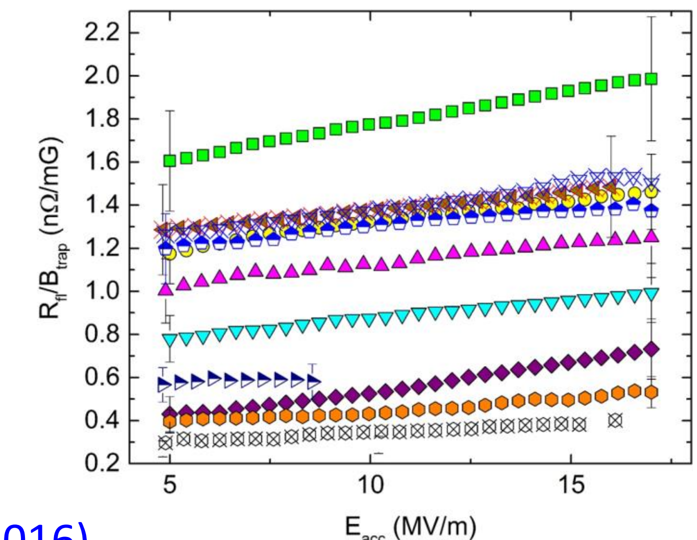
$$\boxed{R_{fl} = R_s(1.5\,K, B) - R_0}$$

- $R_s(1.5\,K, B)$ measured after **slow cooldown** in a known amount of external magnetic field: $\boxed{B = B_{ext}}$
- R_0 measured after **fast cooldown in compensated magnetic field**: $B_{ext} = 0$, $R_{fl} = 0$

Sensitivity

- Bell-shaped trend of S as a function of the mean-free-path
- N-doping cavities present higher sensitivity than standard treated cavities
- Very heavy/light doping needed to minimize trapped flux sensitivity
- Dependence of S as a function of the field
- A model can describe the data at low fields (zero-field approximation)
  - $\longrightarrow$ The zero-field sensitivity is extrapolated with a linear fit





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

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Model Assumptions

1. Non-interacting vortices
2. Single flux quantum per vortex
3. $T \ll T_c$ (no T dependent)
4. Low field approximation (small oscillations)
   $\longrightarrow$ Intercept of S vs E_{acc}
5. Magnetic field 100% trapped
6. Ideal 2D Lorentzian pinning potential
   $\longrightarrow$ Pinning potential dependent on mean-free-path l
   $\longrightarrow$ Multiple pinning centers per vortex (q_i and U_{0_i})
   $\longrightarrow$ Gaussian distribution of pinning centers position and strength ($\Gamma(q_i)$ and $\Lambda\left(U_{0_i}\right)$)

M. Checchin *et al.*, Supercond. Sci. Technol. – to be published

Forces Acting on a Vortex

A vortex interacts with the RF currents via Lorentz force:

$$f_L = |\boldsymbol{j} \times \phi_0 \hat{n}| = j_0 \phi_0 \sin(\theta) e^{i\omega t - z/\lambda}$$

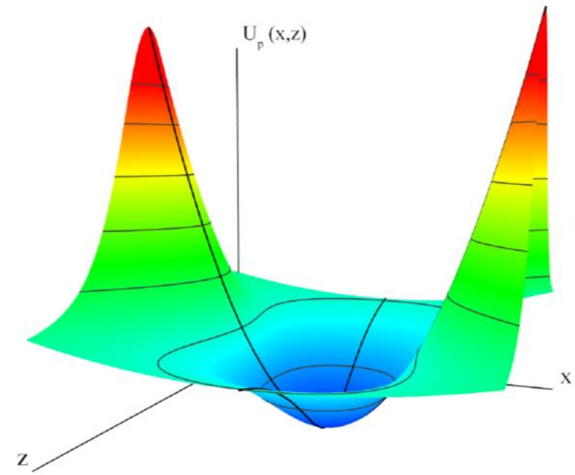
While moving the vortex experiences the counteraction of viscous force (f_v):

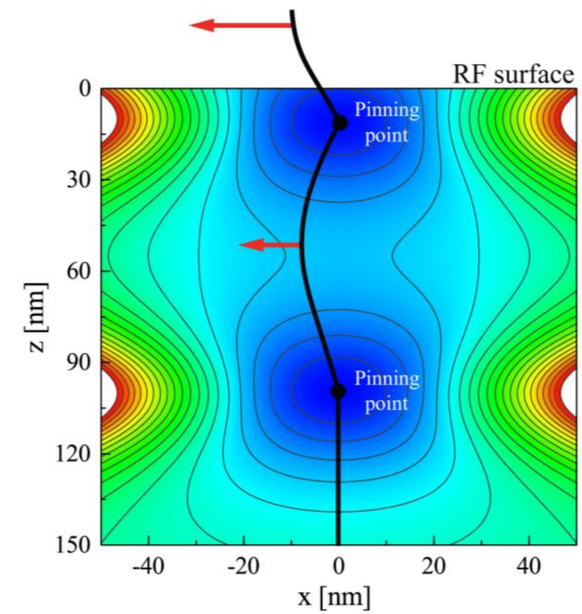
$$f_v = -\eta \dot{x} \qquad ; \qquad \eta = \frac{\phi_0 B_{c2}(T)}{\rho_n}\ ^{1}$$

[1] J. Bardeen, M. J. Stephen, Phys. Rev. **140**, A1197 (1965)

and pinning force (f_p):

$$f_p(x,z,l) = -\frac{\partial}{\partial x} U_p = -\sum_{i=0}^{n} \frac{2 U_{0_i} \xi^2}{(\xi^2 + (z - q_i)^2)^2} x$$
$$= -p(z,l)x$$



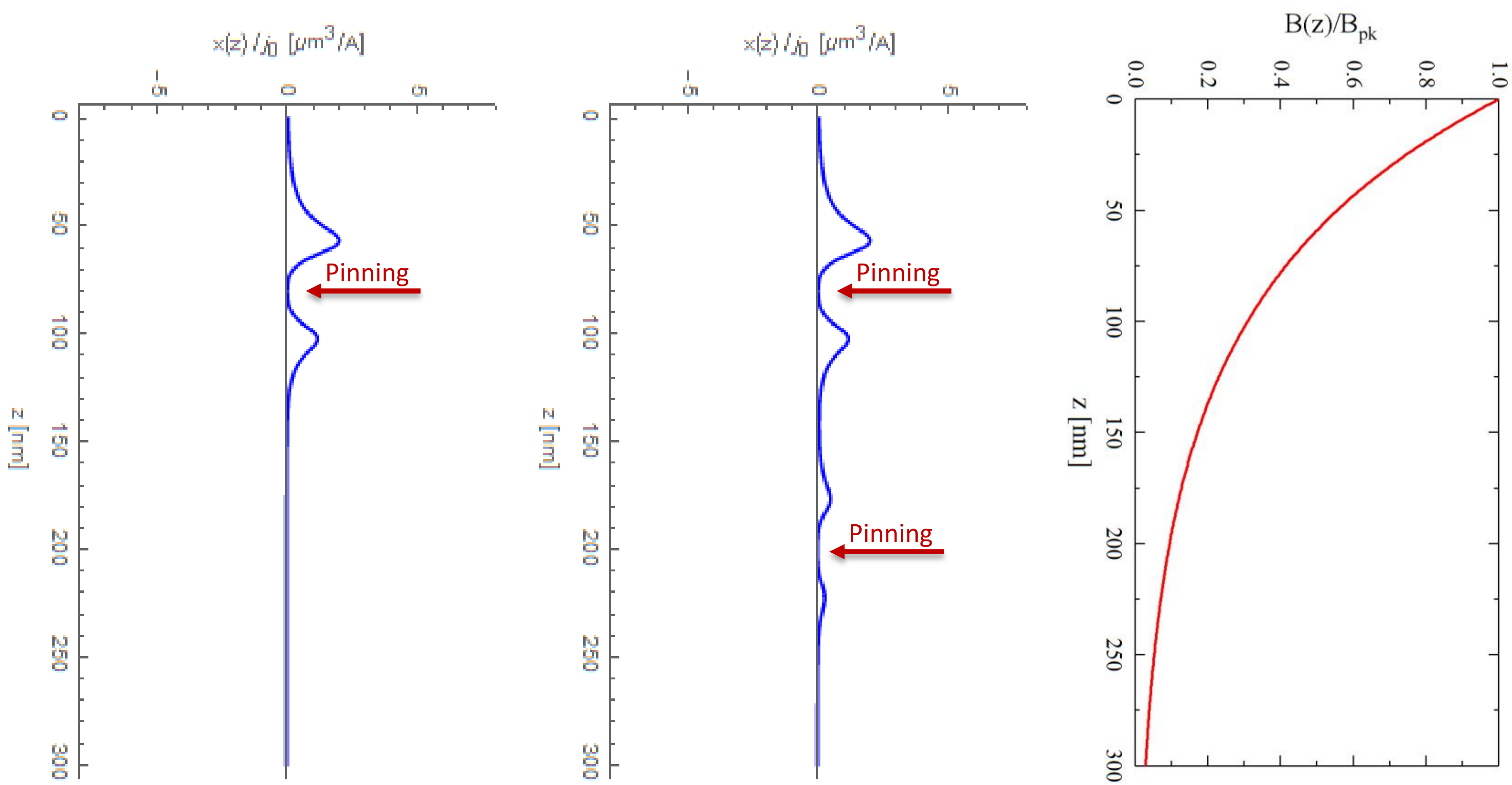


M. Checchin *et al.*, Supercond. Sci. Technol. – to be published

Vortex Displacement: One Pinning Center

The vortex has a complex response to the RF currents:

$$x(z,l,t) = \frac{j\phi_0 \sin\theta}{(p - M\omega^2)^2 + (\eta\omega)^2}\left[(p - M\omega^2) - i(\eta\omega)\right]e^{i\omega t}$$



M. Checchin *et al*., Supercond. Sci. Technol. – to be published

Vortex Impedance

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Solving vortex motion equation:

$$M\ddot{x}(t,z,l) = f_L + f_v + f_p$$; with M [1] the vortex inertial mass

[1] J. Bardeen, M. J. Stephen, Phys. Rev. **140**, A1197 (1965)

we can calculate the apparent power (active plus reactive power) and therefore the complex resistivity of the vortex line:

$$\rho(z,l,U_0) = \rho_1 + i\rho_2 = \frac{\phi_0^2 \sin^2(\theta)}{\pi\xi_0^2[(p - M\omega^2)^2 + (\eta\omega)^2]}[\eta\omega + i(p - M\omega^2)]$$

The vortex surface impedance (using the classic definition of Z) is then:

$$Z(l) = \frac{\pi\xi_0^2 B}{\phi_0} \int_0^{q_0^\vee} \int_{U_{0_0}^\wedge}^{U_{0_0}^\vee} \cdots \int_0^{q_n^\vee} \int_{U_{0_n}^\wedge}^{U_{0_n}^\vee} \frac{\prod_{i=0}^{n} \Gamma(q_i)\Lambda\left(U_{0_i}\right)}{\int_0^L \frac{e^{-z/\lambda}}{\rho(z,l)} dz} dU_{0_0} dq_0 \cdots dU_{0_n} dq_n$$

Number of vortices B/B_v

Single vortex impedance weighted over normal distributions of pinning positions and strengths

Pinning and Flux-Flow Regimes

- Small l – pinning regime $\eta \ll p$:

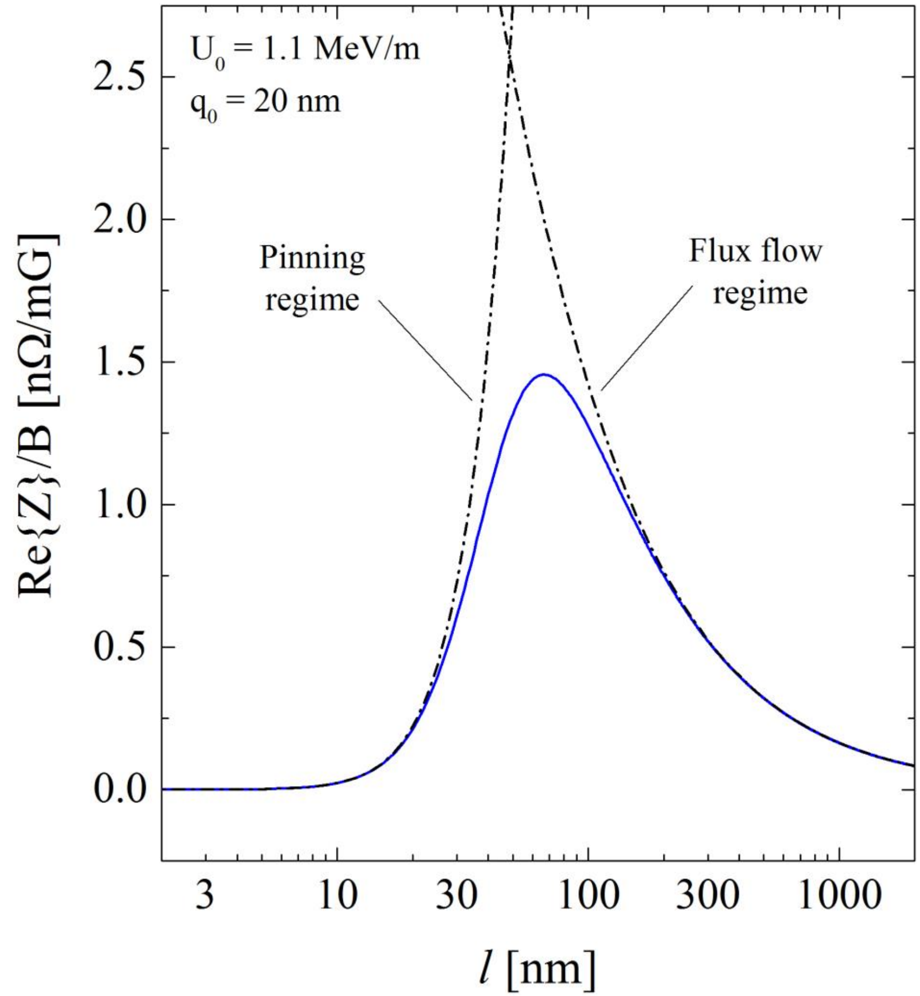
$$\rho_1(z, l, U_0) \approx \frac{\phi_0^2 \sin^2(\theta)\eta(l)\omega^2}{\pi\xi_0^2 p(l, U_0)^2}$$

ρ_1 increases with l and ω^2, decreases with the increasing of U_0

- Large l – flux-flow regime $\eta \gg p$:

$$\rho_1(l) \approx \frac{\phi_0^2 \sin^2(\theta)}{\pi\xi_0^2 \eta(l)}$$

ρ_1 decreases with l, independent on ω and U_0



M. Checchin *et al.*, Supercond. Sci. Technol. – to be published

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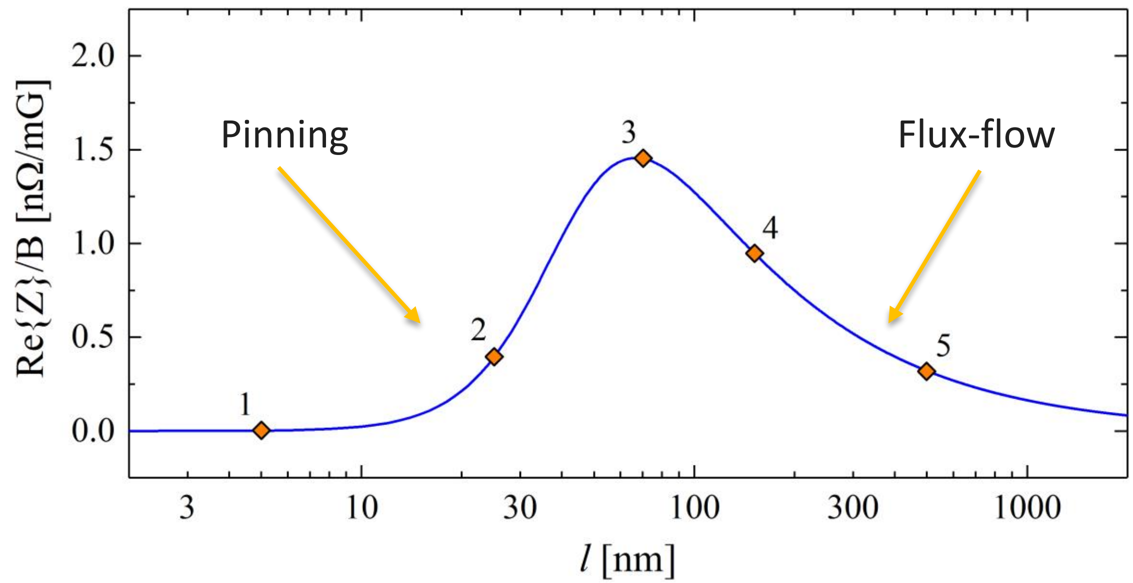
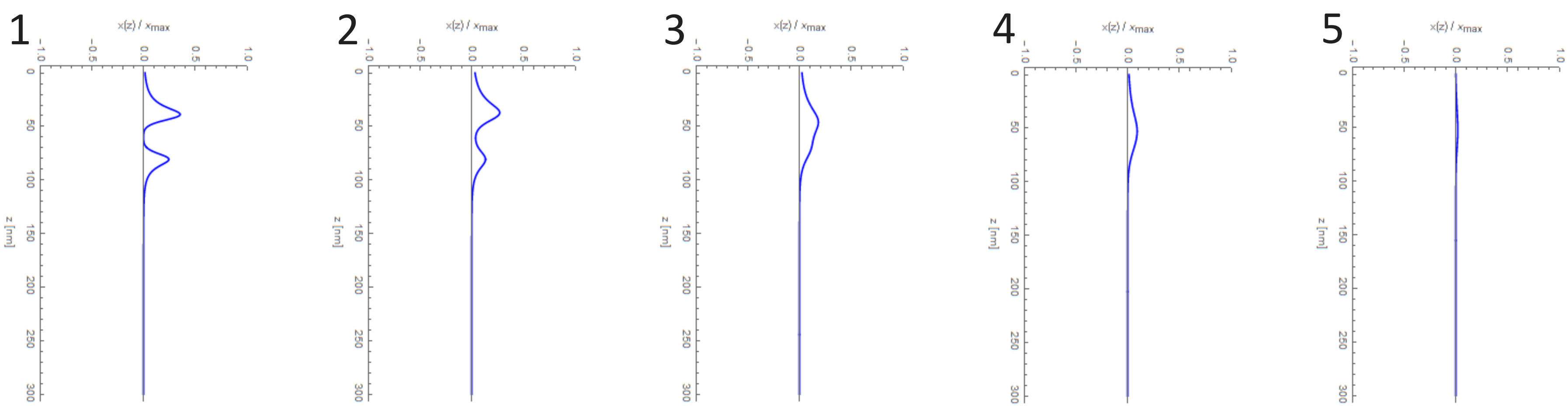
From Pinning to Flux-flow Regime

- In the pinning regime vortices are constrained by the pinning centers
- In the flux-flow regime the vortex oscillation is counteracted by the material viscosity

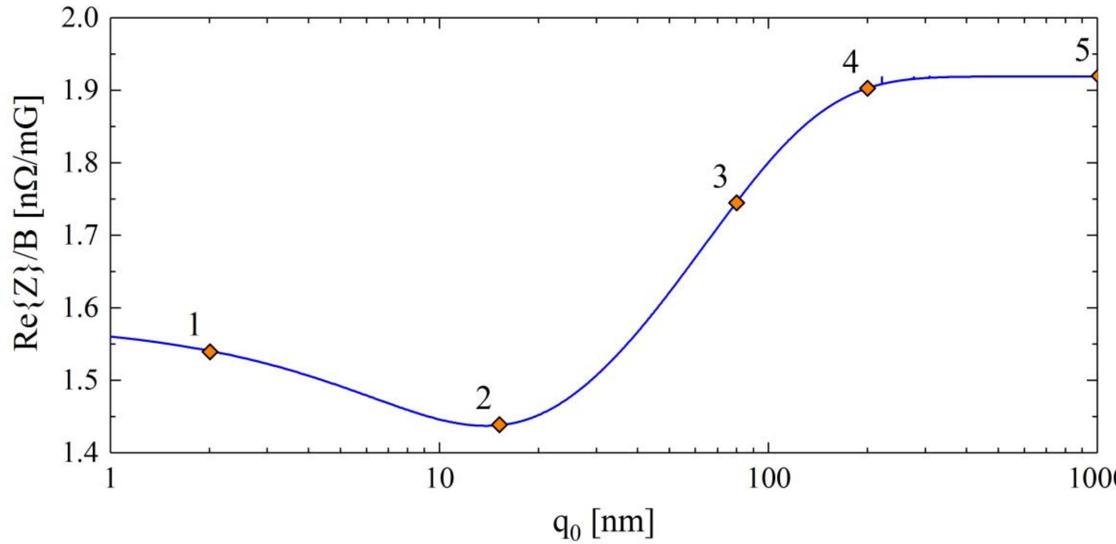


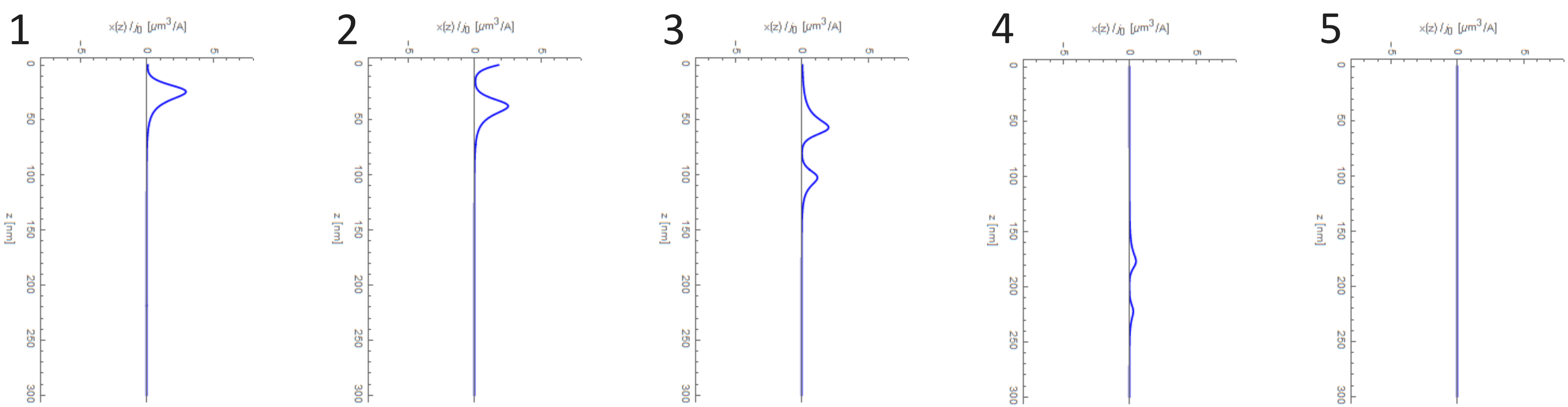


M. Checchin *et al.*, Supercond. Sci. Technol. – to be published

Dependence on the Position of the Pinning Center

- The wider the oscillation the higher the resistance
- At $q_0 \cong 15\ nm$ the vortex is very constrained, the resistance is the lowest
- For $q_0 > 400\ nm$ the resistance is constant, the pinning center does not perturbate the oscillation





M. Checchin *et al.*, Supercond. Sci. Technol. – to be published

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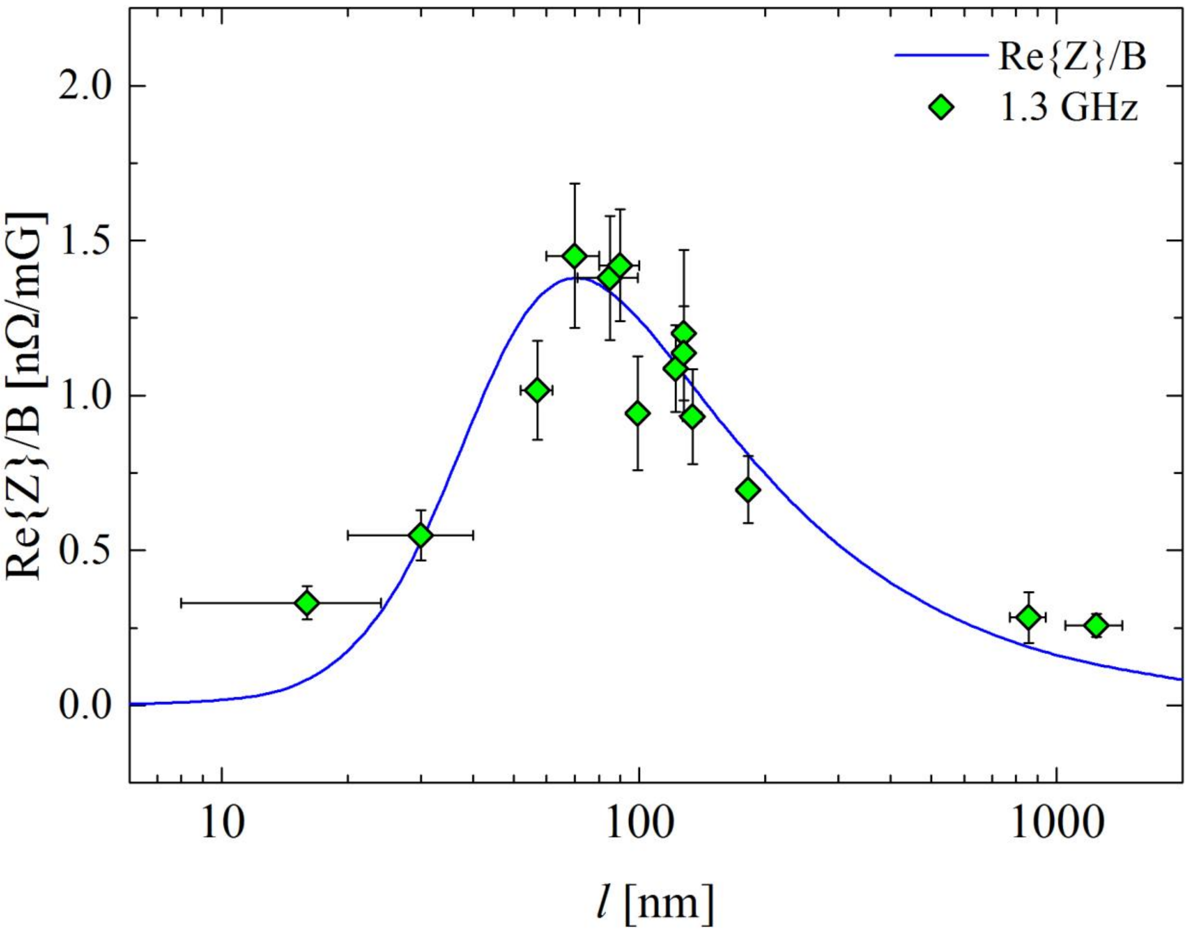
Theory vs Experimental Data



Parameters used:

$$\begin{cases} q_0 = 20\ nm \\ \sigma_{q_0} = 30\ nm \end{cases}$$

$$\begin{cases} U_0 = 1.4\ MeV/m \\ \sigma_{U_0} = 0.08\ MeV/m \end{cases}$$

$f_p = 3.97 \cdot 10^{-6}\ N/m$ in perfect agreement with niobium data: L. H. Allen and J. H. Claassen, Phys. Rev. B **39**, 2054 (1989)

M. Checchin *et al.*, Supercond. Sci. Technol. – to be published
exp. data: M. Martinello *et al.*, App. Phys. Lett. **109**, 062601 (2016)

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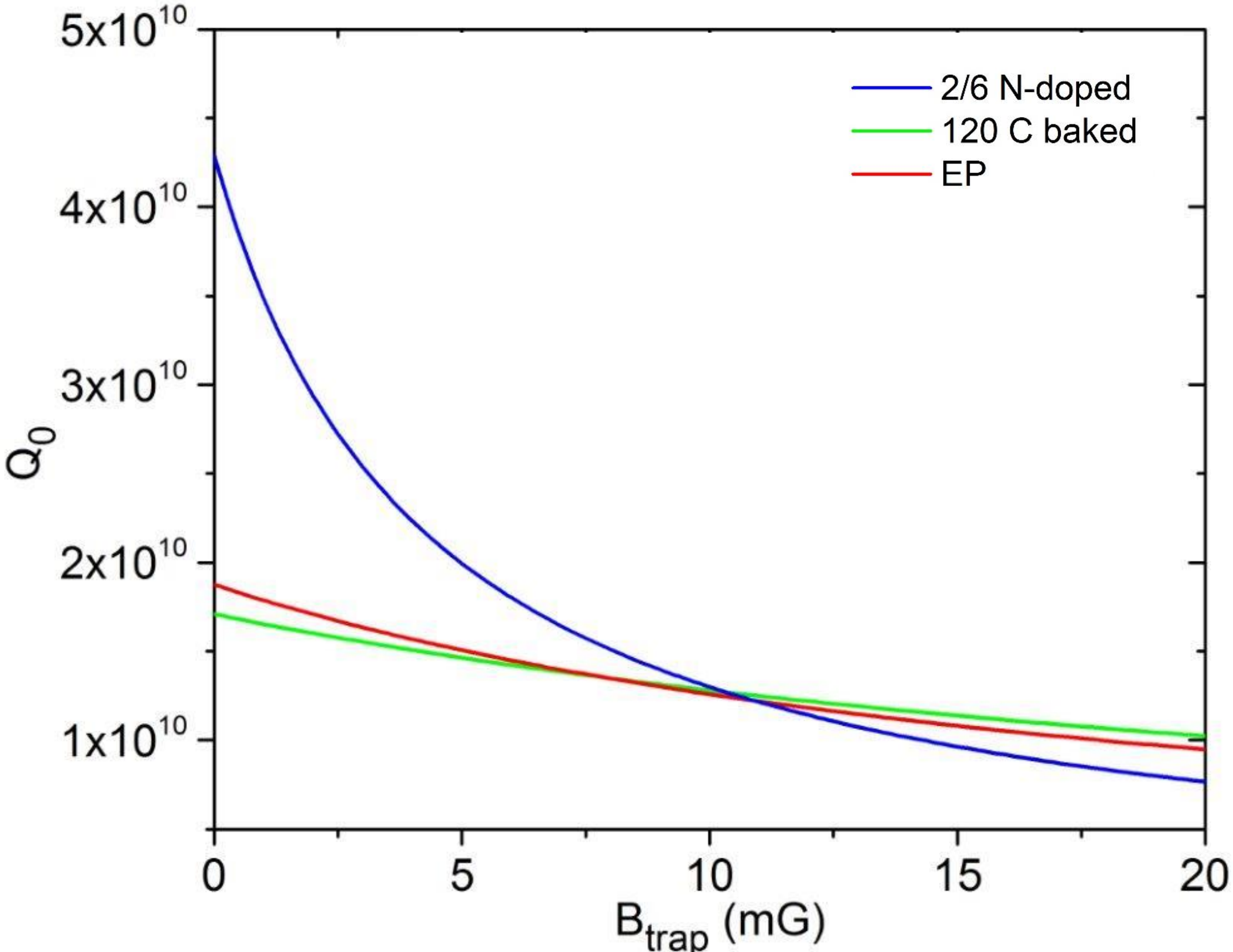
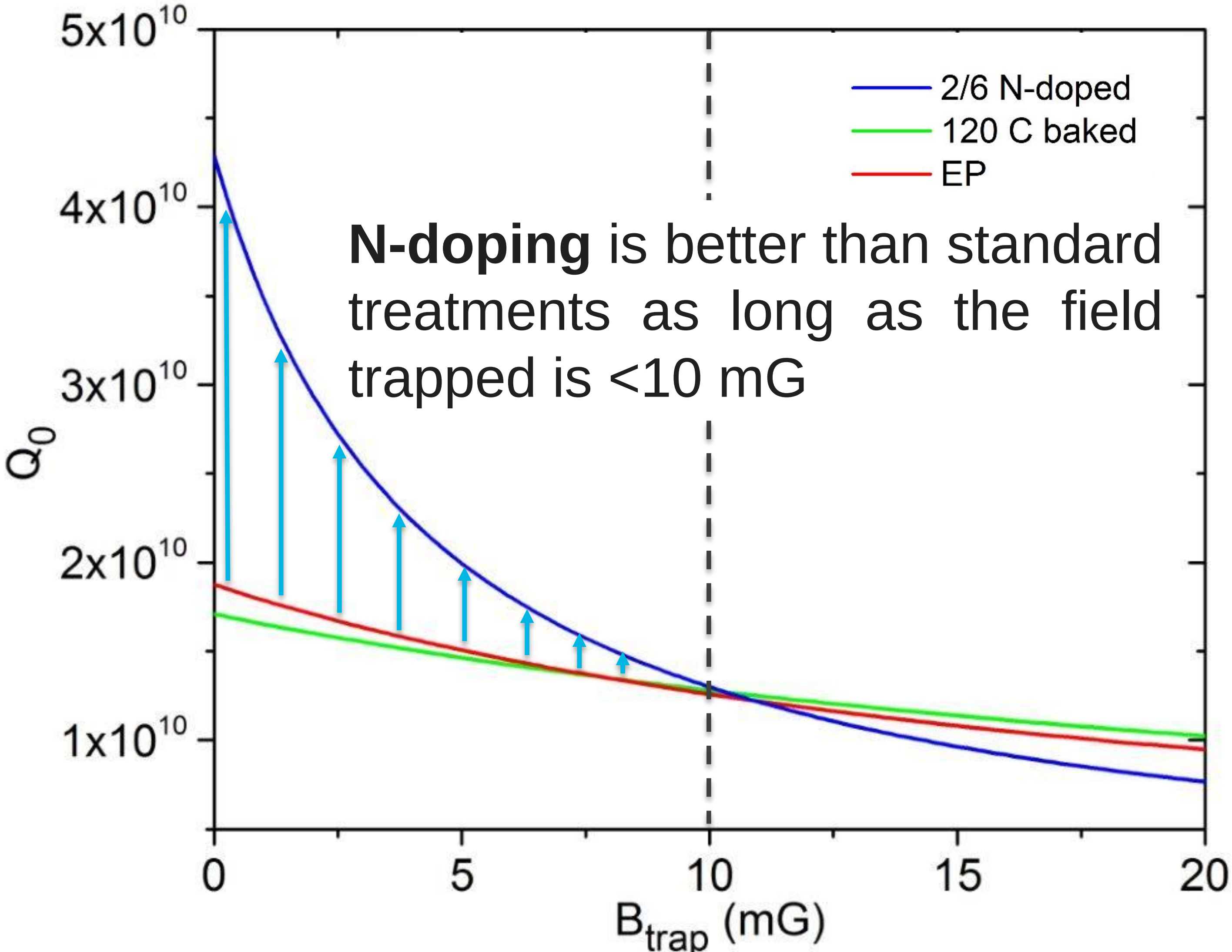
N-doping in Condition of Full Flux-Trapping



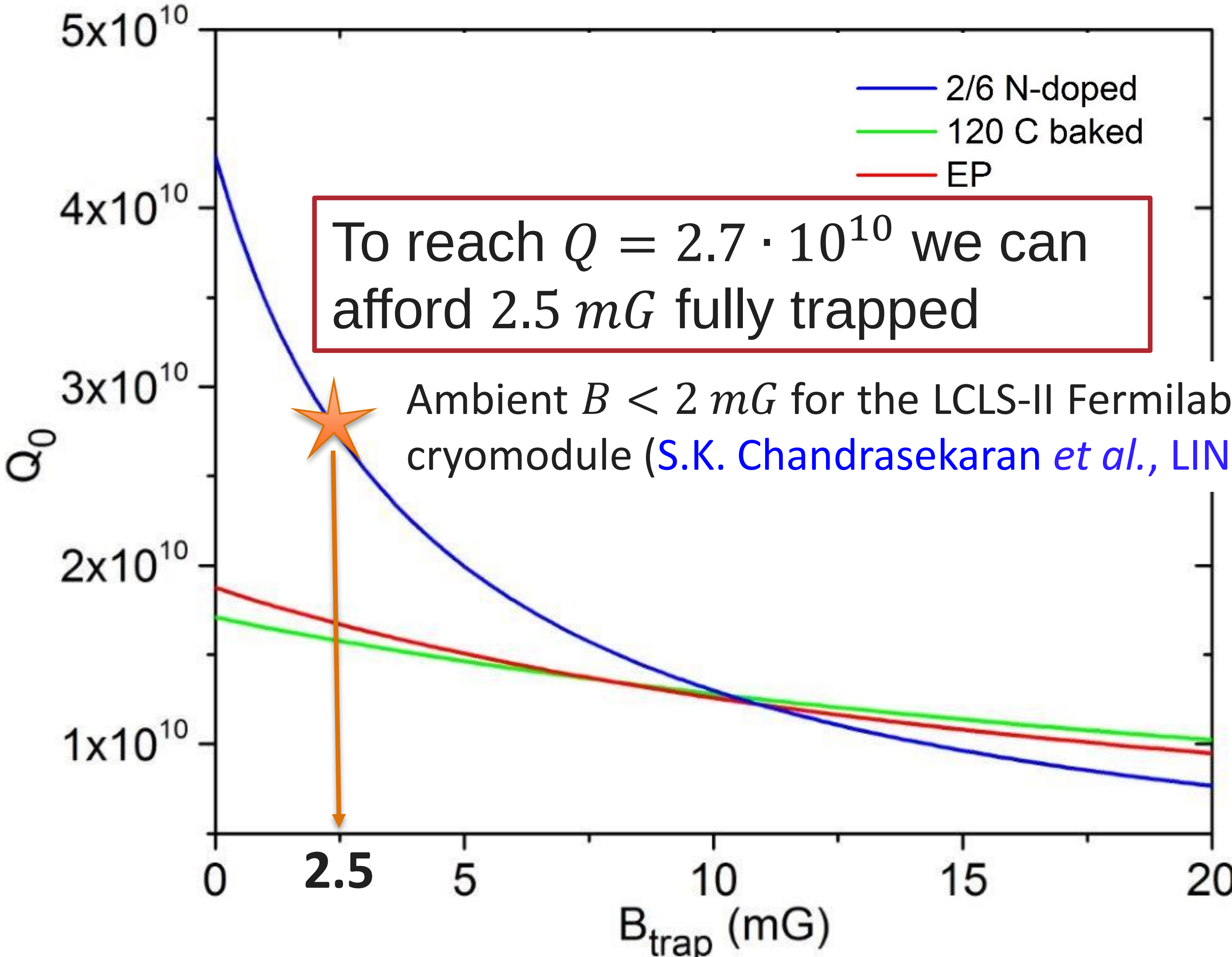
M. Martinello *et al.*, App. Phys. Lett. **109**, 062601 (2016)

N-doping in Condition of Full Flux-Trapping, cont’d



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

Example with LCLS-II Specifications



To reach $Q = 2.7 \cdot 10^{10}$ we can afford $2.5\ mG$ fully trapped

Ambient $B < 2\ mG$ for the LCLS-II Fermilab prototype cryomodule (S.K. Chandrasekaran *et al.*, LINAC 2016)

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

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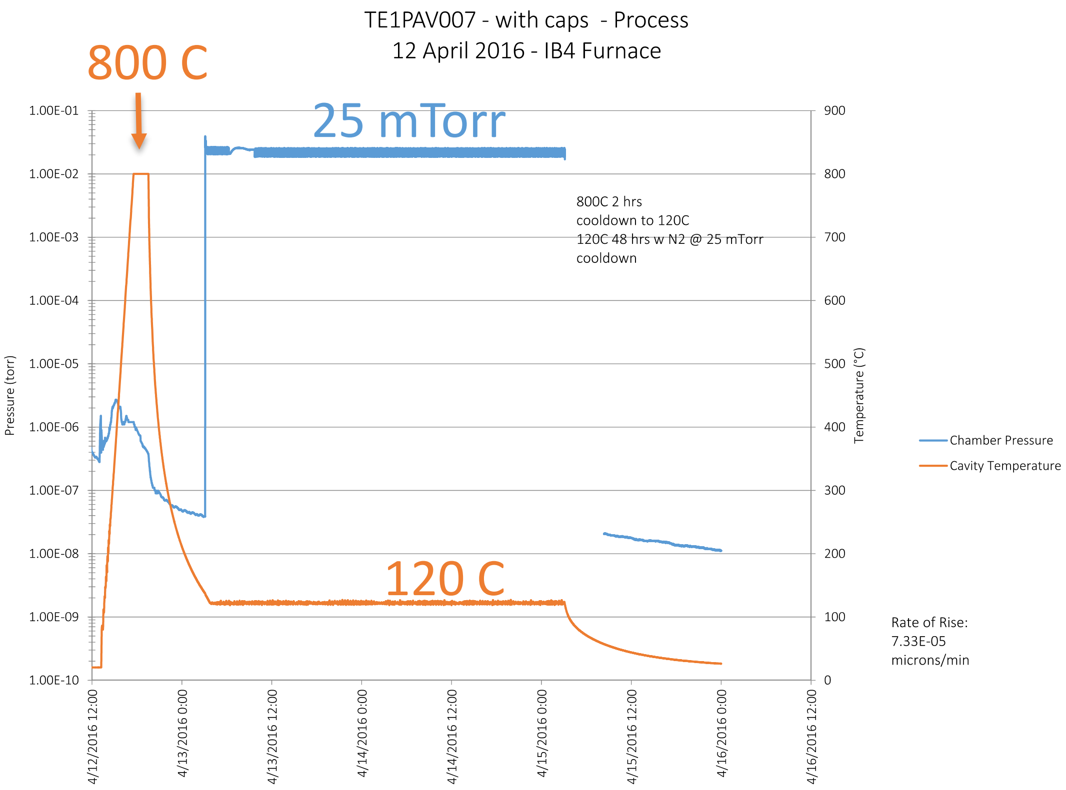
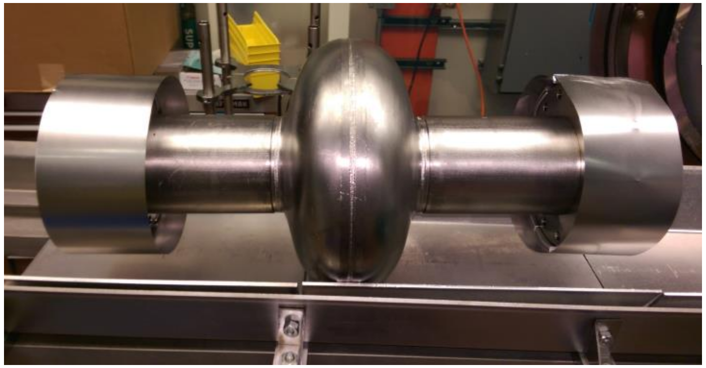
N-infusion Thermal Process

- Bulk electro-polishing
- High T furnace with caps to avoid furnace contamination:
  - 3h @ 800C in HV
  - 48h @ 120-160 C with N_2 (25 mTorr)
  - Optional annealing 48h @ 120-160 C
- NO chemistry post furnace
- HPR, VT assembly

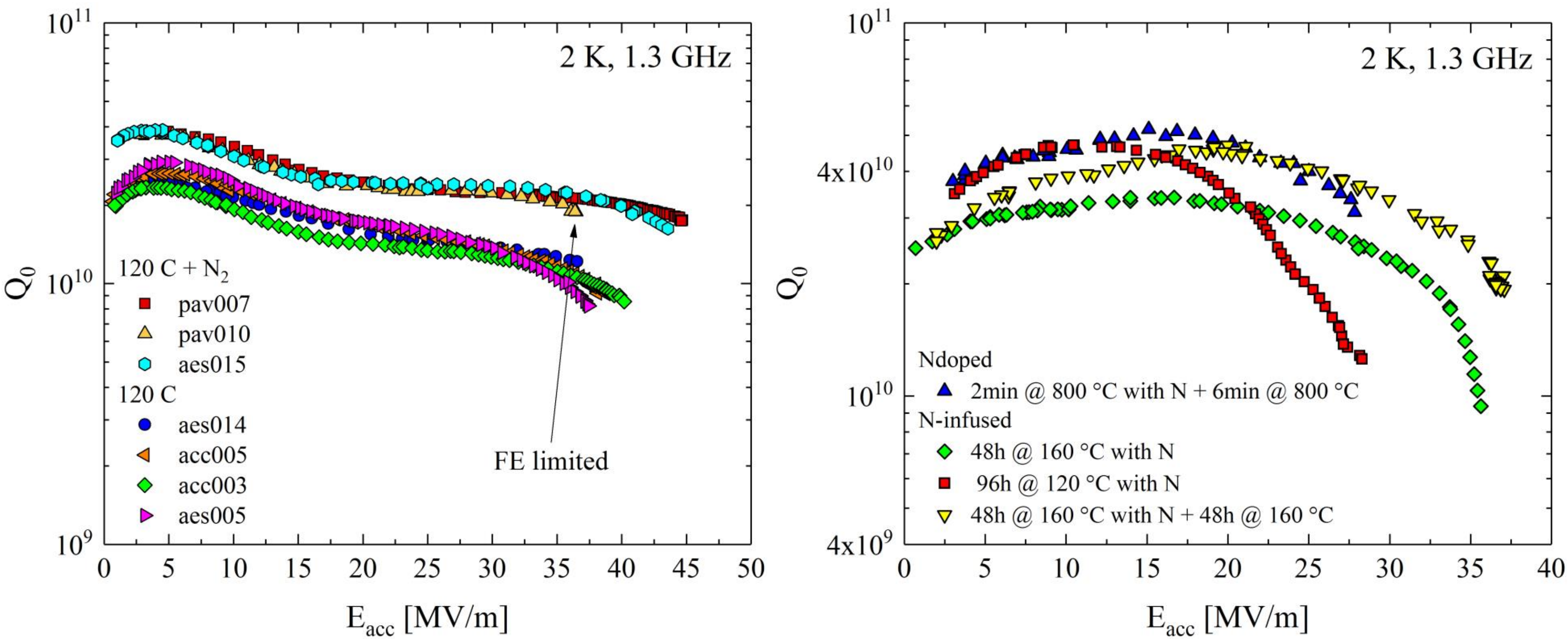




Protective caps and foils are BCP'd prior to every furnace cycle and assembled in clean room, prior to transporting the cavity to furnace area

A. Grassellino *et al.*, **arXiv:1305.2182**

N-infusion Performance



The N-infusion performance can be tuned by acting on time and temperature:

- Shorter treatment and lower T → 120 C baking like behavior
- Longer treatment and/or higher T → N-doping like behavior

Experimental Data vs Theory

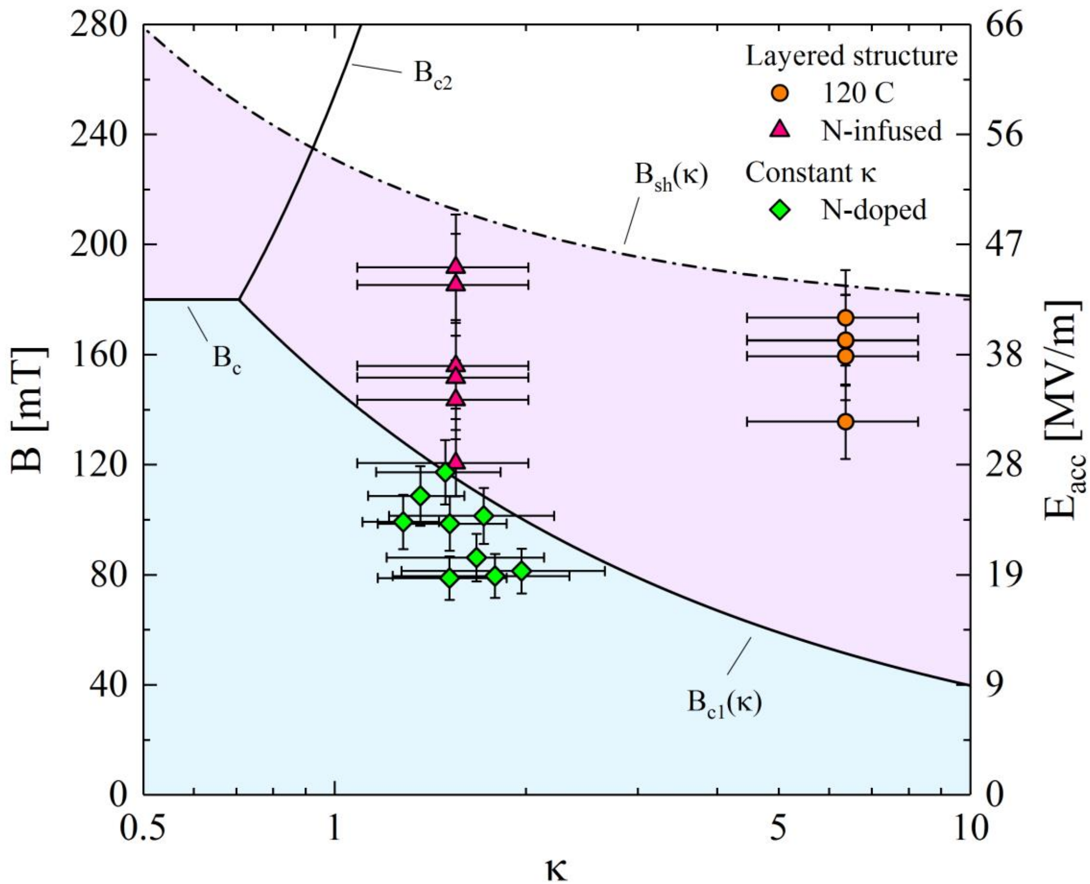
M. Checchin *et al.*, IPAC 2016 and LINAC 2016

High-T treated cavities quench below B_{c1}

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

Low-T treated cavities quench above B_{c1}

→ 120 C baked and N-infused cavities reach the meta-stable Meissner state above the lower critical field



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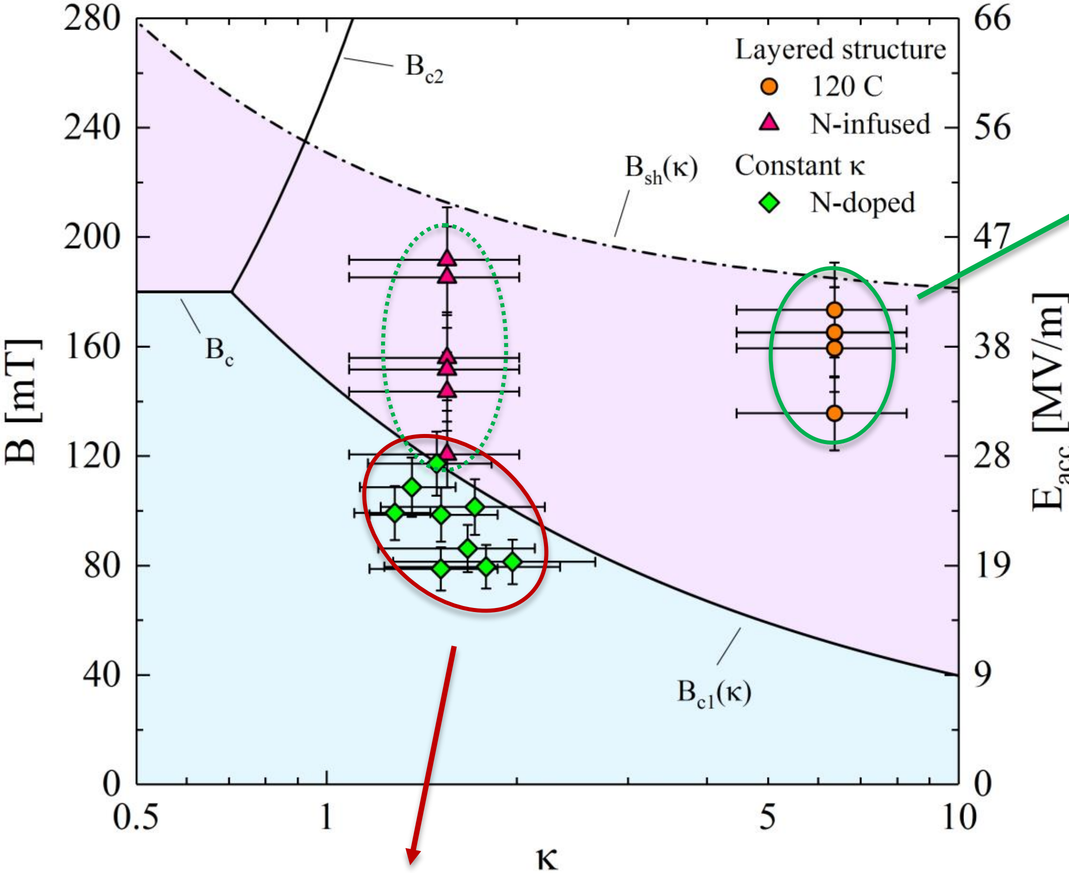


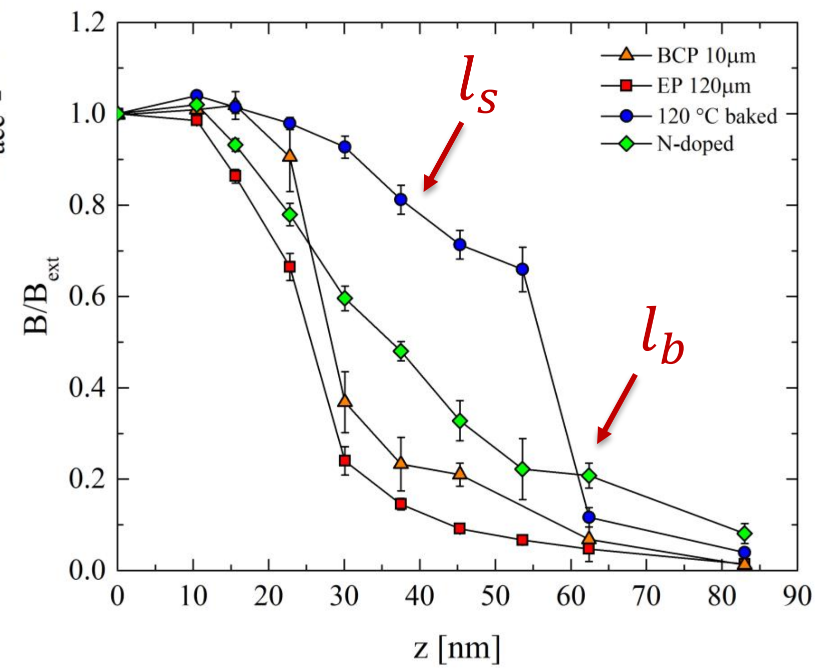
Constant κ

inside the penetration depth

Non-constant κ

inside the penetration depth

$l_s < l_b$



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

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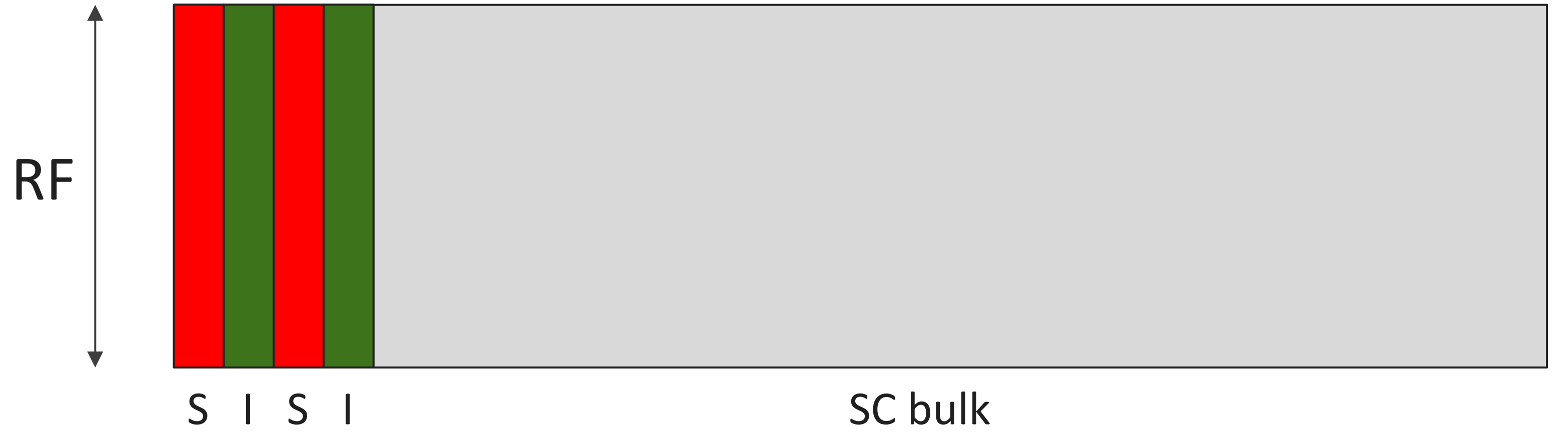
Superconductor-Isolator-Superconductor structure

The possibility of enhancing the accelerating gradient in SRF cavities by means of layered superconducting structures (SIS) was introduced by A. Gurevich:

A. Gurevich, AIP Advances **5**, 017112 (2015)
T. Kubo *et al.*, Appl. Phys. Lett. **104**, 032603 (2014)
S. Posen *et al.*, Phys. Rev. Applied **4**, 044019 (2015)

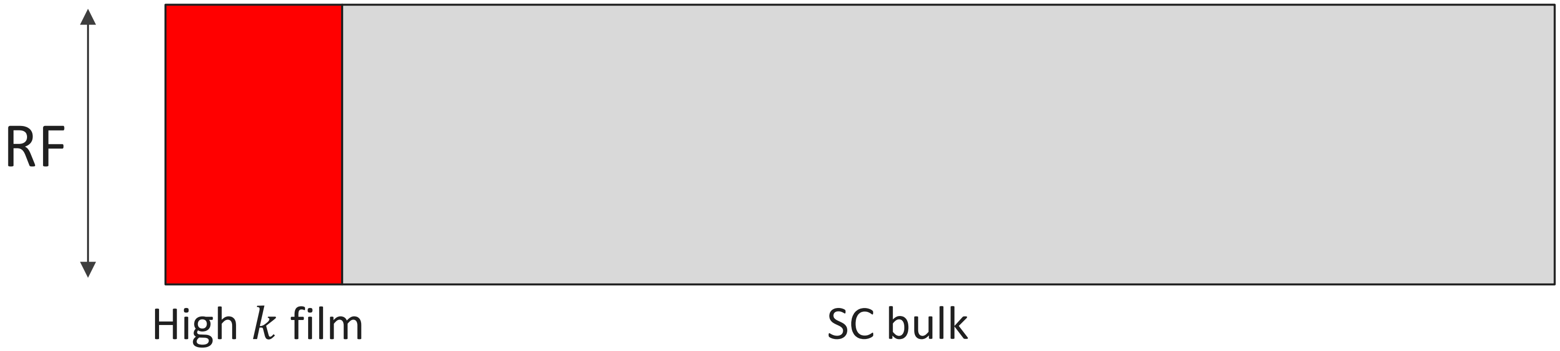


Drawback: SIS structures are challenging to produce in SRF cavities
very good control on the deposition system is needed

Superconductor-Superconductor structure

- <u>High κ film</u>: analytical from London eqs., valid for $k \gg 1$

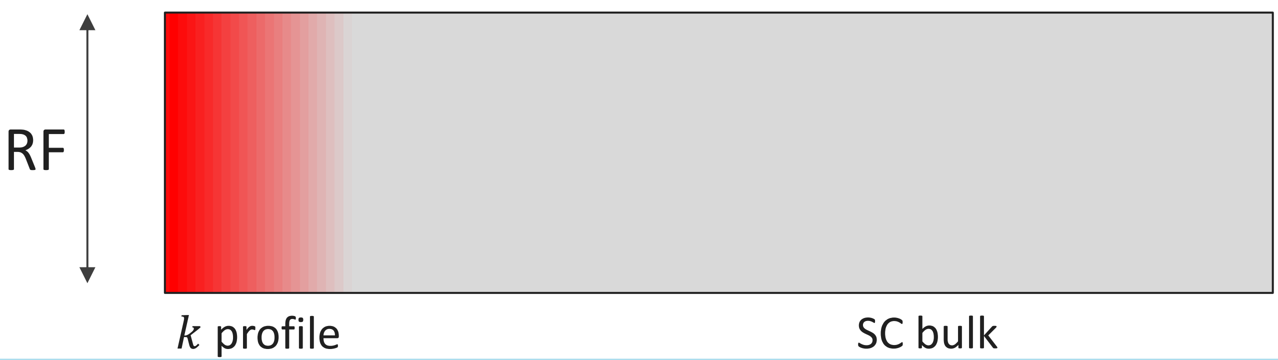
  T. Kubo, LINAC 2014



- <u>Diffused κ profile</u>: numerical from Ginzburg-Landau eqs., valid for arbitrary k

  M. Checchin *et al.*, IPAC 2016

  M. Checchin *et al.*, LINAC 2016



Can be produced by thermal diffusion!

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Outline

- High Q-factors
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  - Vortex Surface Resistance Description
  - Best Treatment
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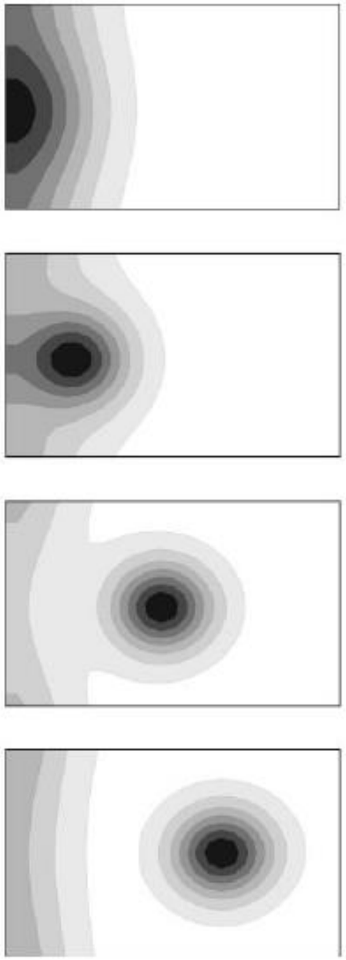
Bean-Livingston Barrier

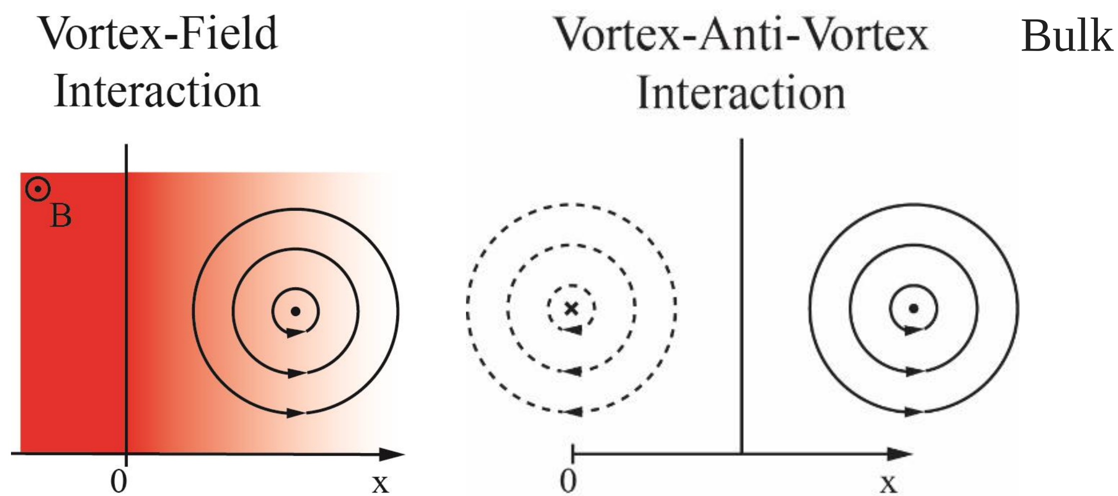
$t = t_0$
Vortex nucleation at the surface

$t = t_1$
Vortex penetration

$t = t_2$
Vortex stale in the bulk



$$g(x) = g_f(x) + g_v(x) + g_\infty = \frac{4\pi}{\kappa}\left(h_f(x) - h_v(2x) + h_{c1}(\kappa) - h\right)$$



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

C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964)

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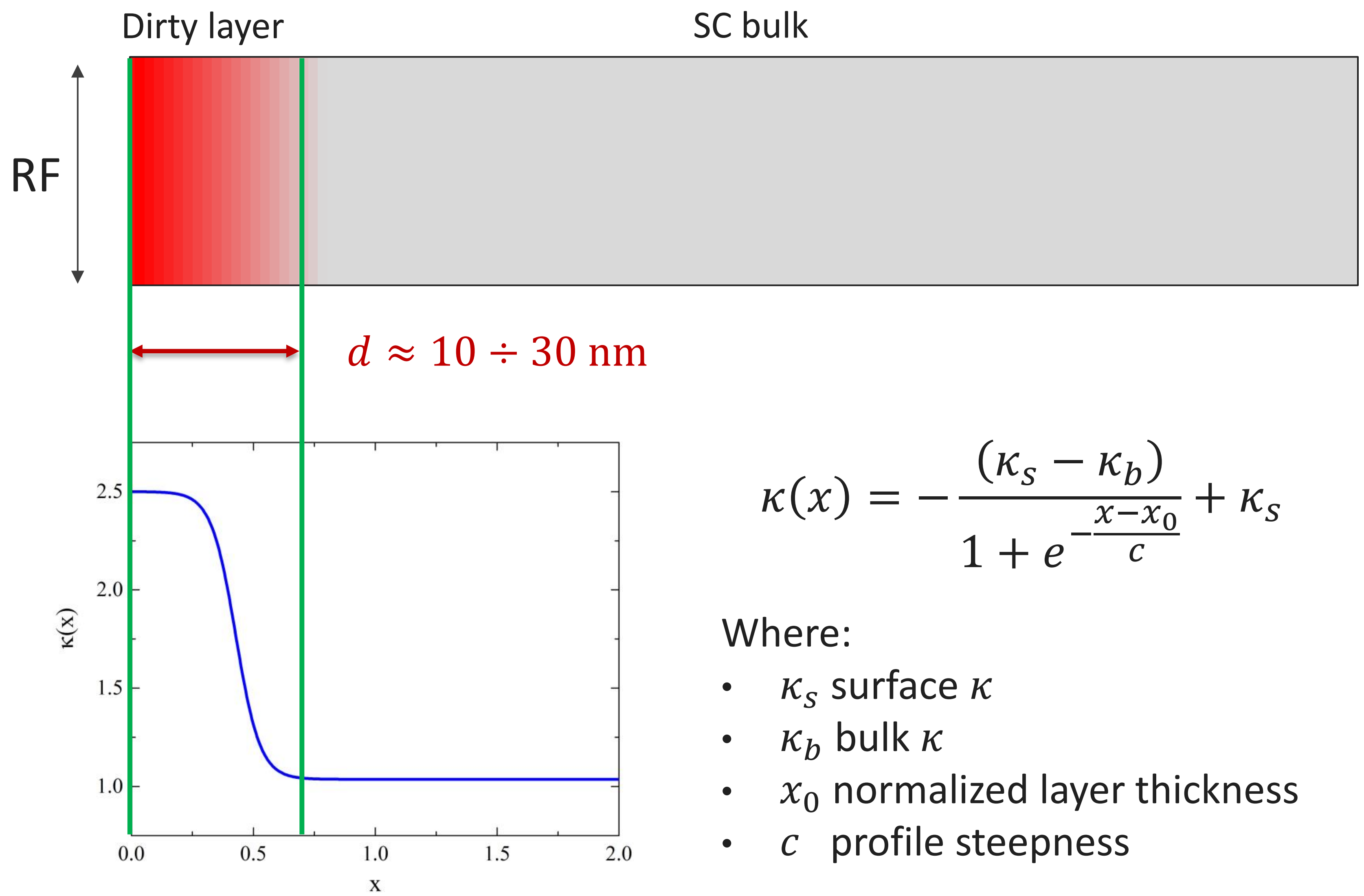
Dirty Layer on top of a Clean Superconductor



$$\kappa(x) = -\frac{(\kappa_s - \kappa_b)}{1 + e^{-\frac{x - x_0}{c}}} + \kappa_s$$

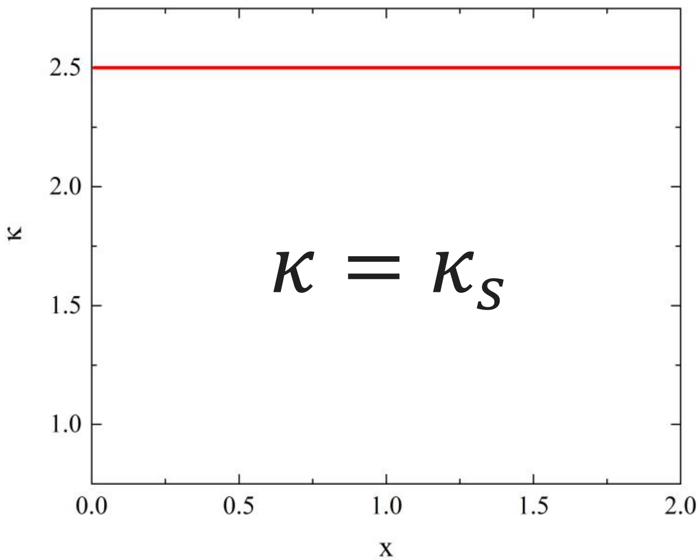
Where:

- κ_s surface κ
- κ_b bulk κ
- x_0 normalized layer thickness
- c profile steepness

Assumptions for the Calculation

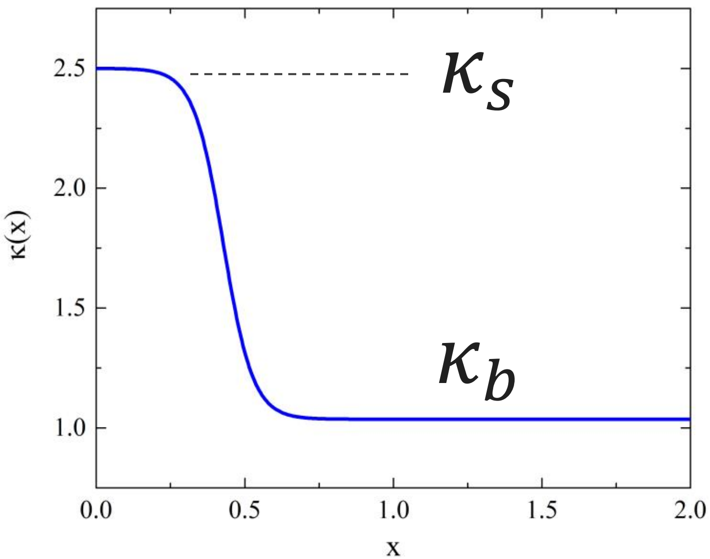
- Comparison between constant κ and dirty layer conditions

Constant κ



VS

Dirty layer



- κ profile thickness d smaller than penetration depth of the field at the surface: $d < \lambda_s$

$\rightarrow$ Bulk properties not modified by the presence of the layer

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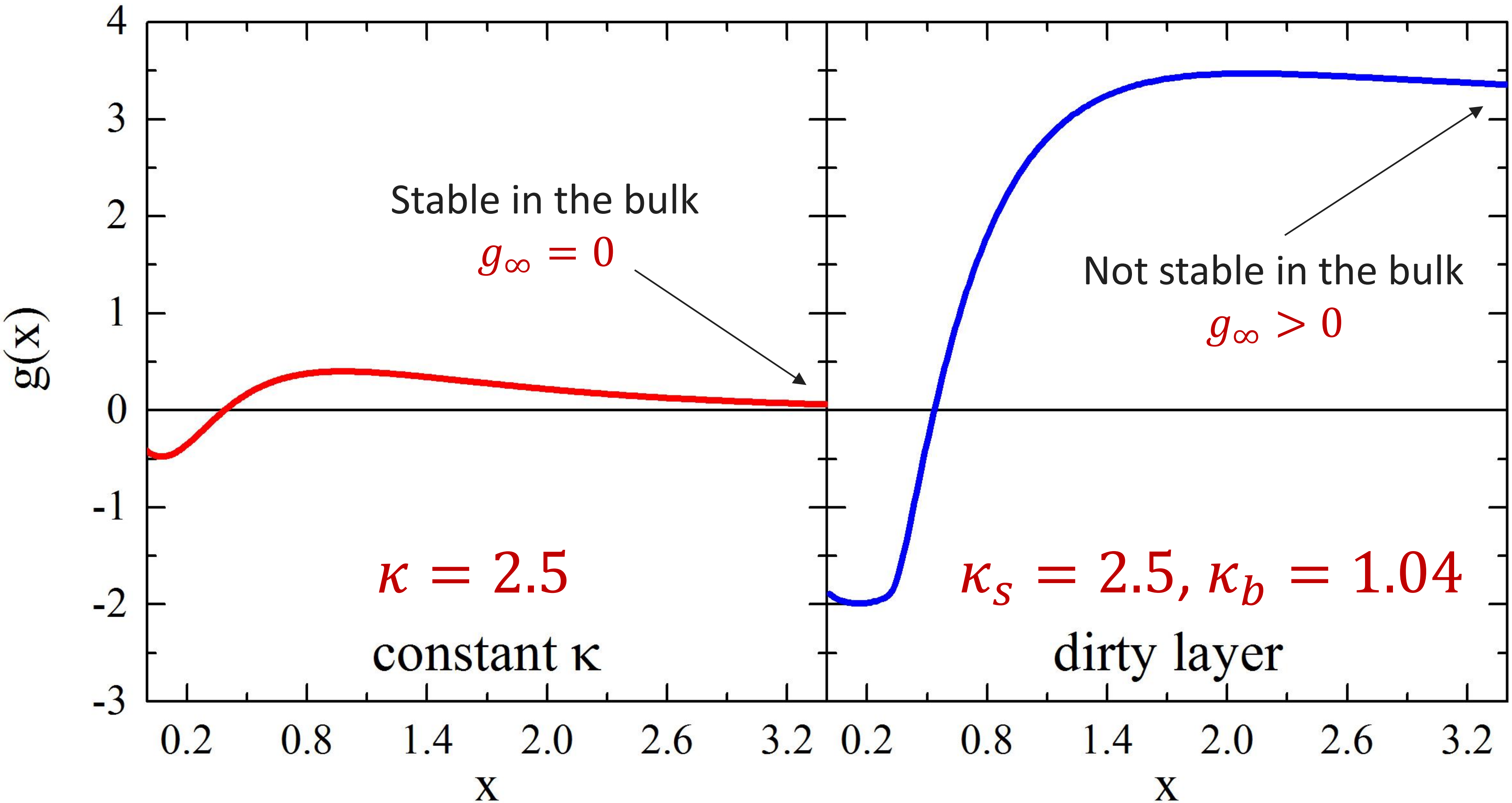
Gibbs Free Energy with $B = B_{c1}(\kappa_s)$



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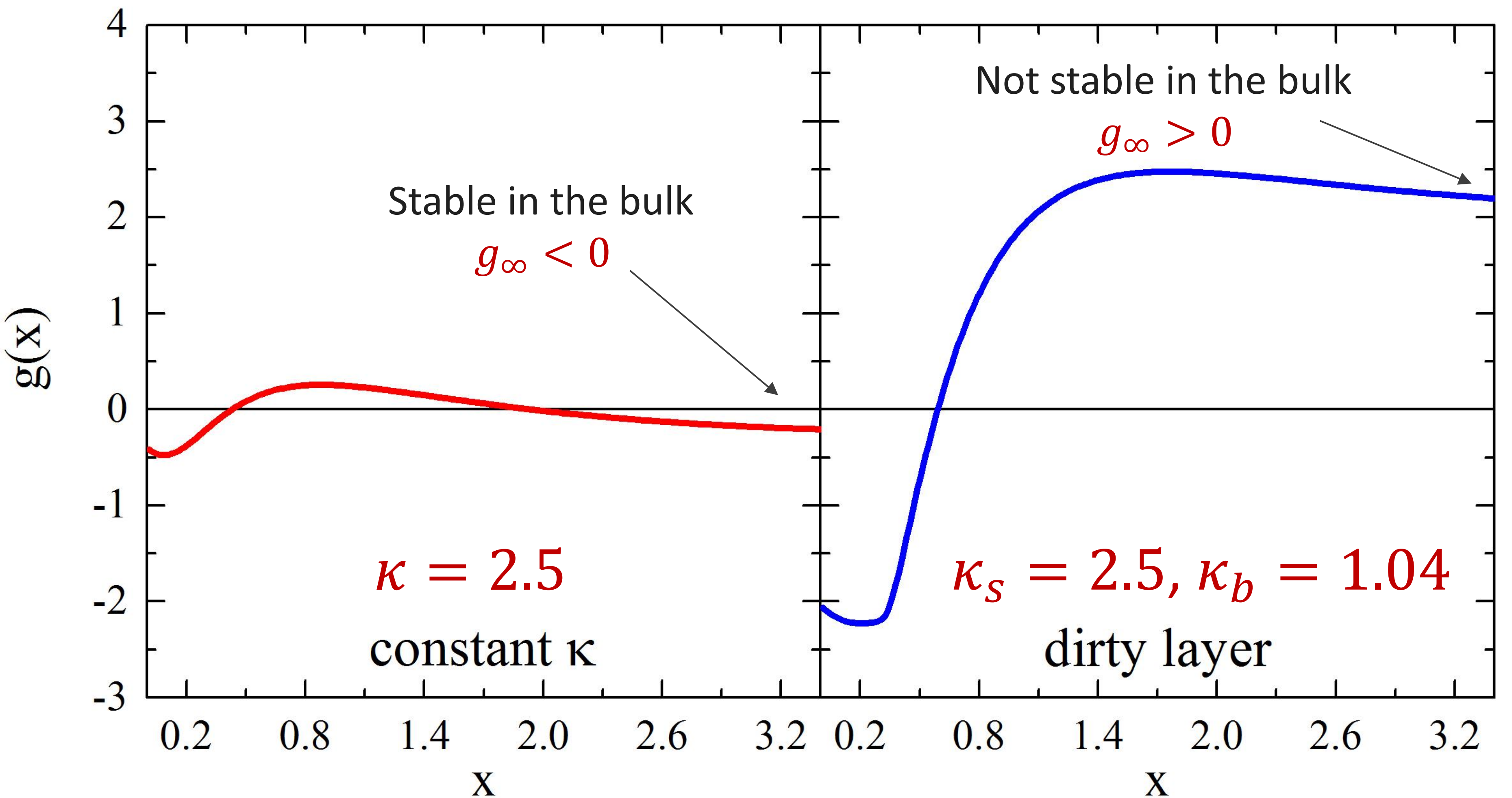
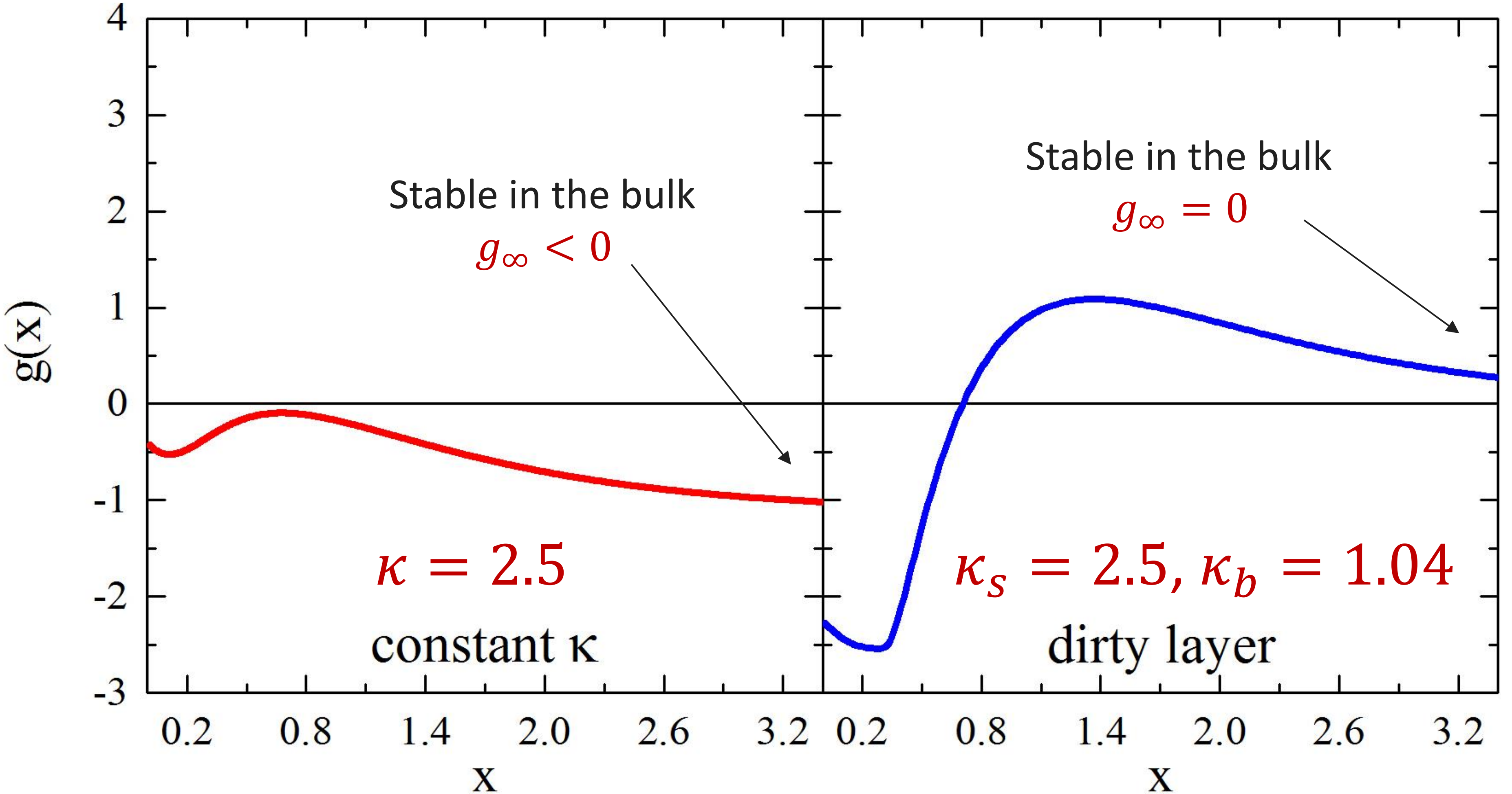
Gibbs Free Energy with $B_{c1}(\kappa_s) < B < B_{c1}(\kappa_b)$



Gibbs Free Energy with $B = B_{c1}(\kappa_b)$



Vortex Penetration Field in the Worst Case Scenario

In the worst case scenario the energy barrier is totally suppressed by the presence of defects. Therefore, we should expect vortex penetration at:

Field Level	Constant κ	Dirty Layer $\kappa_s = \kappa$
$B = B_{c1}(\kappa_s)$	**YES**	NO
$B_{c1}(\kappa_s) < B < B_{c1}(\kappa_b)$	**YES**	NO
$B = B_{c1}(\kappa_b)$	**YES**	**YES**

$\rightarrow$ For the same κ at the surface, in the worst case scenario, cavities with dirty layer have larger quench field!!

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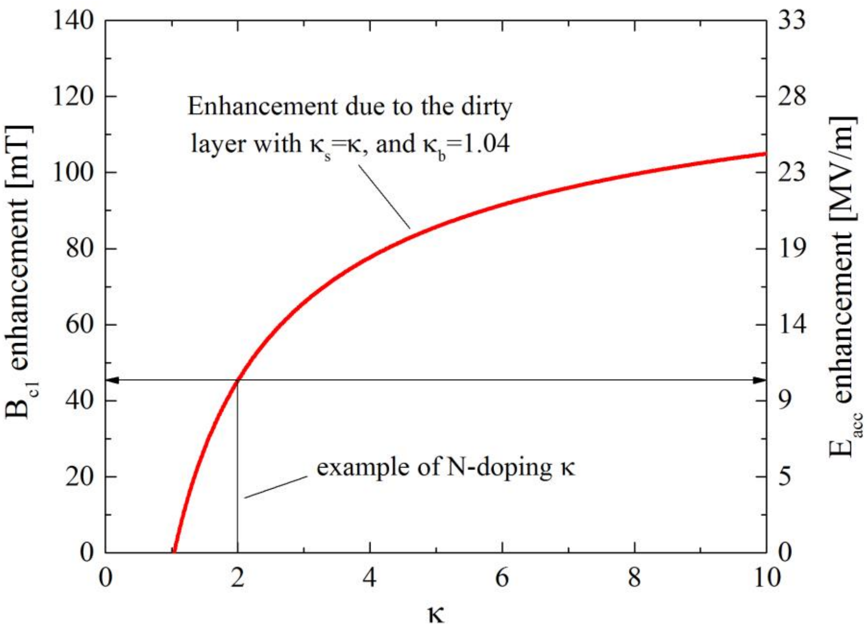
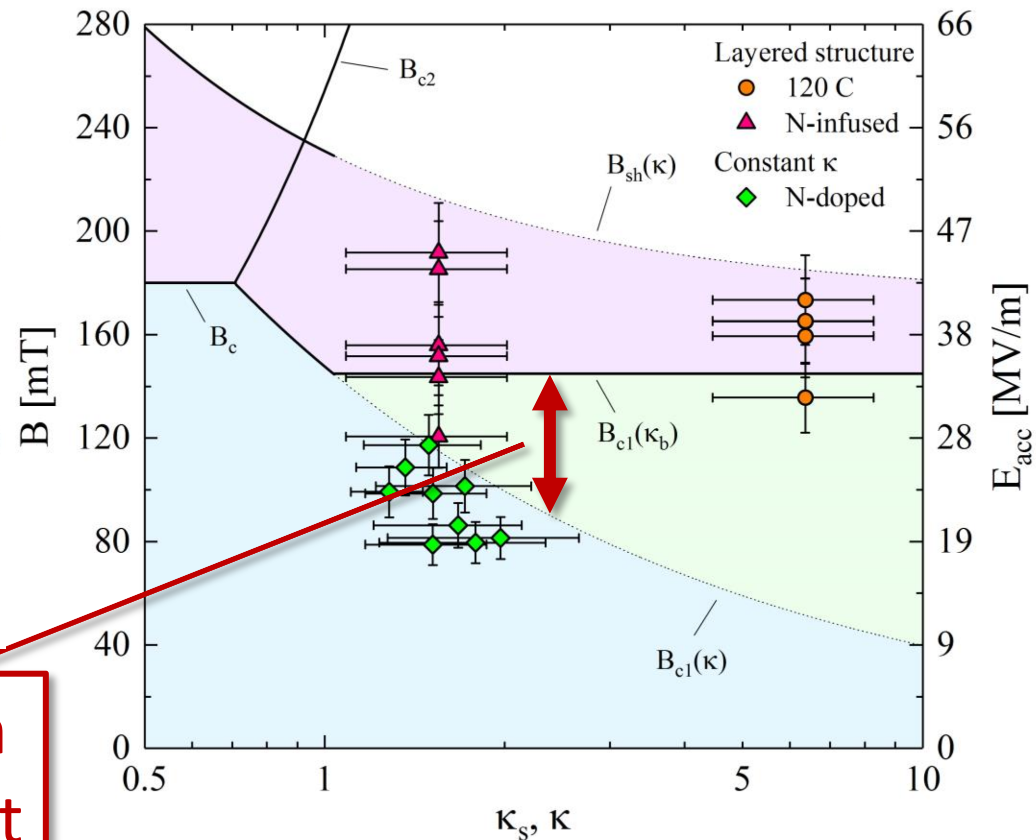
Quench Field Enhancement

⇒ For the same superficial κ the minimum quench field is increased to $B_{c1}(\kappa_b)$

for N-doped cavities the gradient enhancement is at least $\sim 10\ MV/m$





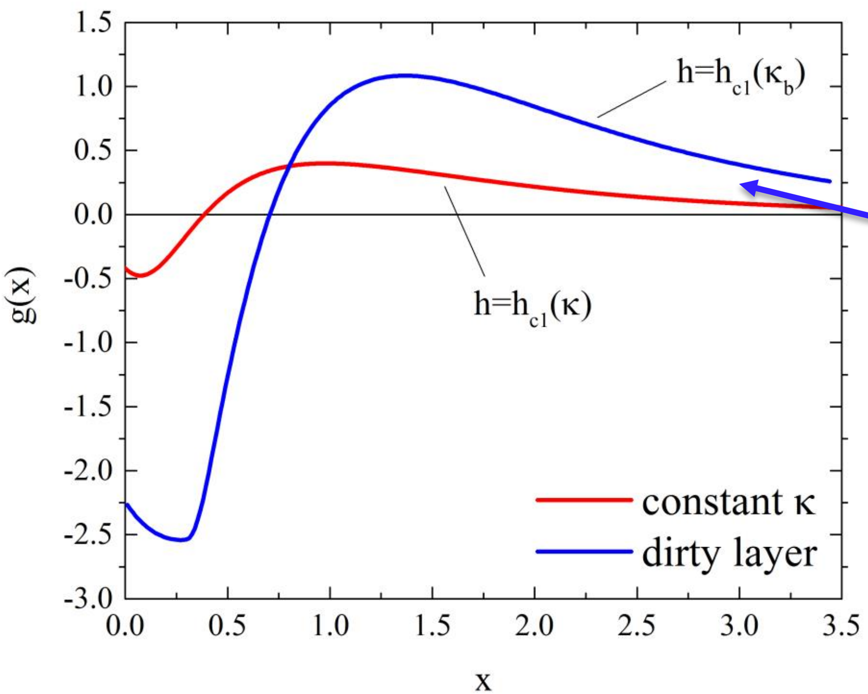
Minimum quench field enhancement

M. Checchin *et al.*, LINAC 2016

Quench Field Enhancement, cont'd

⇒ The meta-stable Meissner state is stabilized

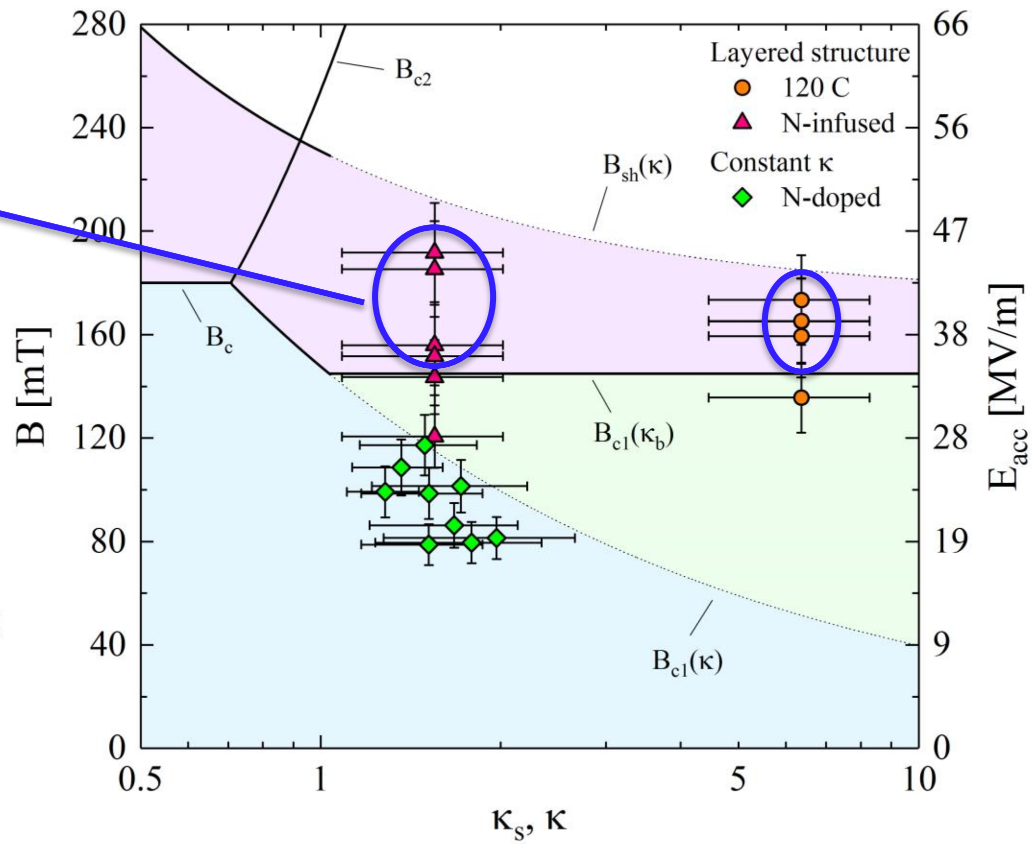
The energy barrier is higher



$d = 15\ nm$

$\kappa = \kappa_s = 2.5$

$\kappa_b = 1.04$



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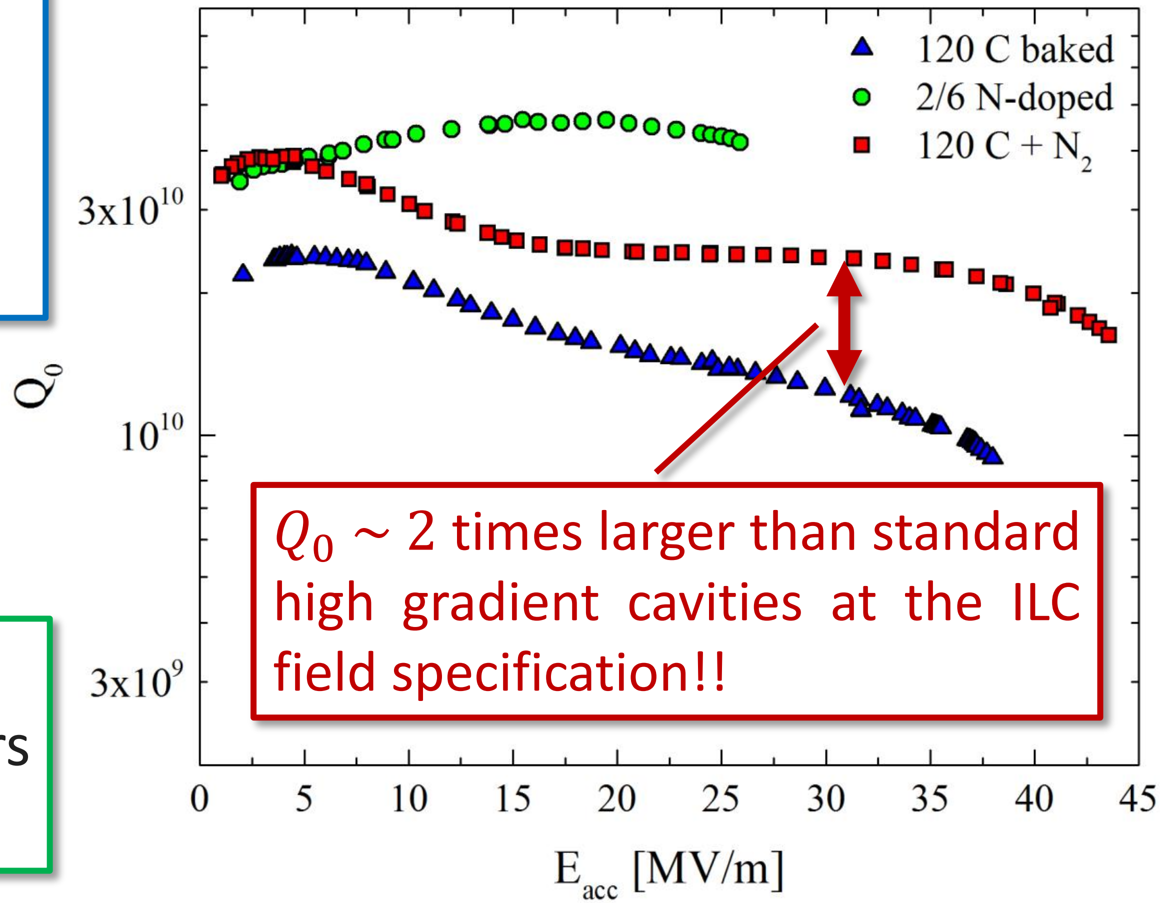
The Path to High Q_0 at Large Gradients

Dirty layer at the RF surface:
→ Enables high gradients

+

Nitrogen-doping:
→ Enables high Q-factors

Nitrogen-infusion:
→ Enables high Q-factors at high gradients!



$Q_0 \sim 2$ times larger than standard high gradient cavities at the ILC field specification!!

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High Q-factor

R_{BCS} is minimized for N-doped cavities

$R_{fl} = B_{ext} \cdot \eta \cdot S$ can be minimized by:

$\longrightarrow$ Efficient magnetic field shielding (low B_{ext})

$\longrightarrow$ Fast cooling, minimize pinning (low η)

$\longrightarrow$ Decreasing as much as possible the sensitivity (low S)

The sensitivity is well described by the model developed:

a. Two different regimes of vortex dissipation

$\longrightarrow$ Small l , pinning regime: ρ_1 increases if $l \uparrow$, $\omega^2 \uparrow$ and $U_0 \downarrow$

$\longrightarrow$ Large l , flux-flow regime: ρ_1 decreases if $l \uparrow$, but independent on ω and U_0

b. In order to minimize the sensitivity

$\longrightarrow$ Low ω, large U_0 and l far from the peak

High Accelerating Gradient

Constant κ profile cavities statistically quench below B_{c1}

$\longrightarrow$ N-doped cavities cannot reach the meta-stable Meissner state

The dirty layer at the surface is beneficial in order to delay the vortex penetration from the RF surface

$\longrightarrow$ Explains N-infused and 120 C baked higher quench fields

$\longrightarrow$ The minimum vortex penetration field enhanced to $B_{c1}(\kappa_b)$

$\longrightarrow$ The meta-stable Meissner state is stabilized

The smart tuning of the very surface might increase both Q_0 and the maximum gradient

$\longrightarrow$ Doped layer tens of nanometers thick (N-infusion)

High Q_0 at high field are possible

$\longrightarrow$ Low cryogenic cost at high fields

$\longrightarrow$ Operational cost reduction of high gradient machines (e.g. ILC)

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