High-Q R&D at FNAL

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Performance frontier group, SRF sector, TD

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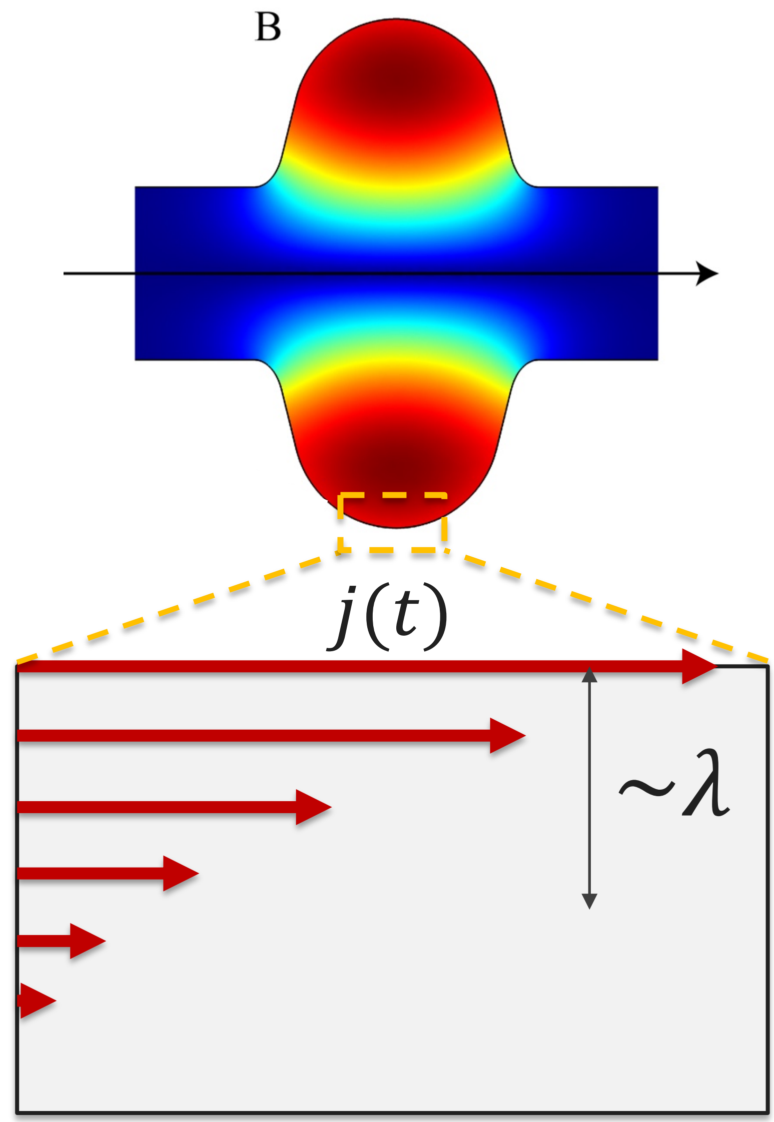
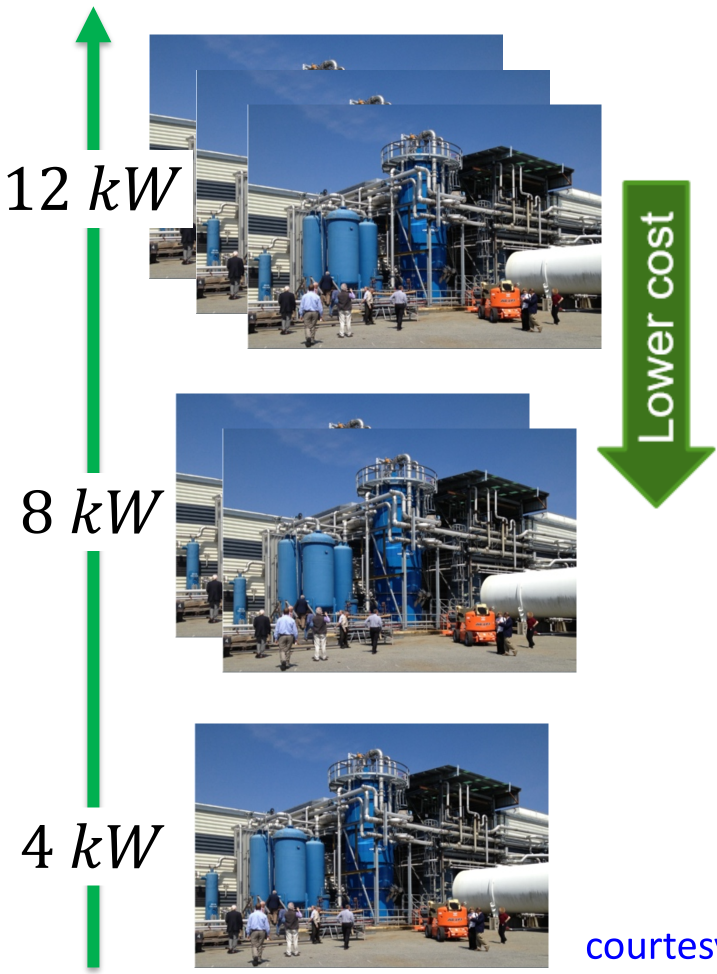
Superconducting RF resonators

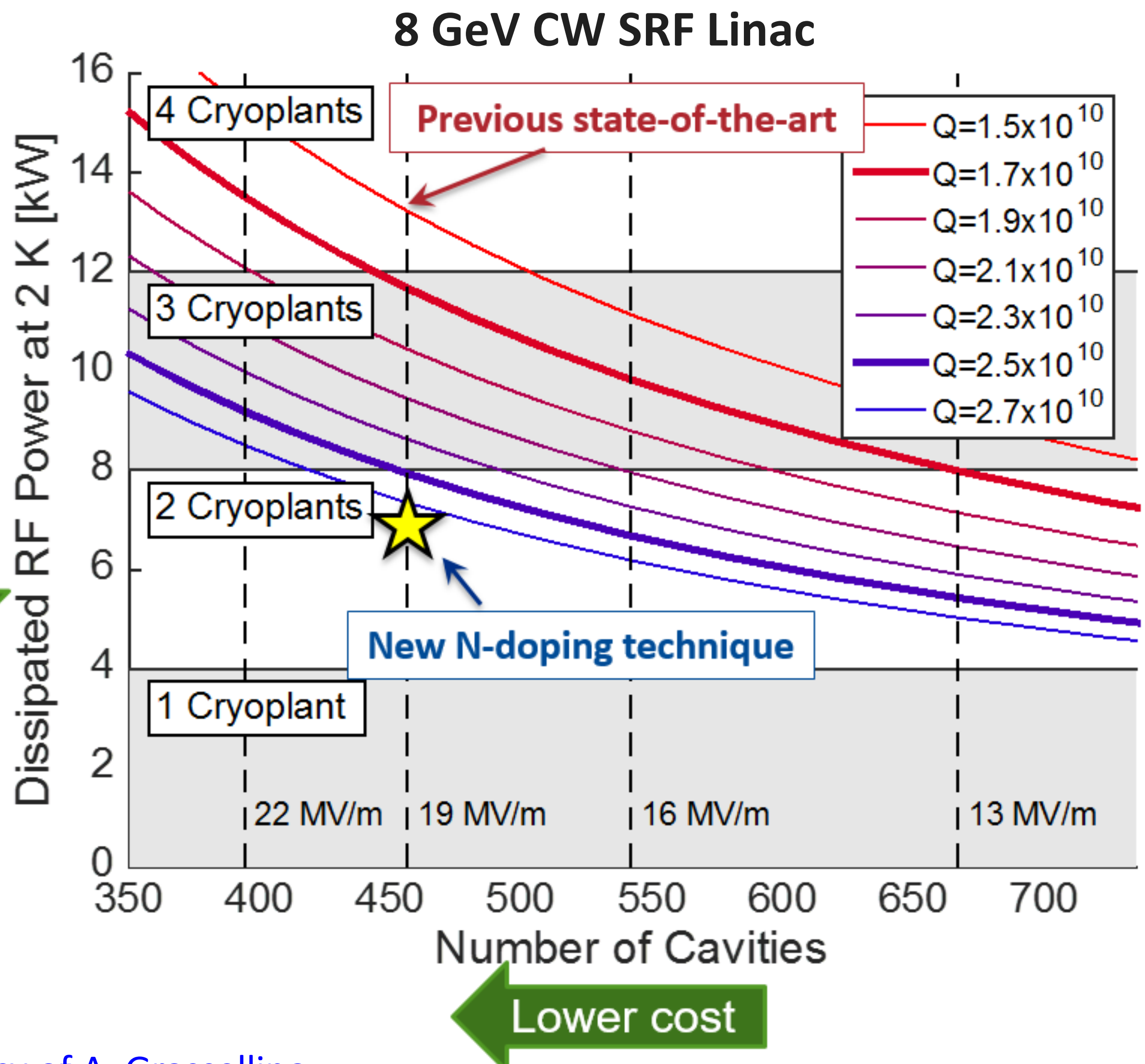
- EM field resonates efficiently with very low dissipation
- Performance defined by the first hundreds of nanometers form the RF surface (λ), where the current flows
- $R_s(T) = R_{BCS}(T) + R_{res}$
- High $Q_0 \Rightarrow$ minimization of $R_{BCS}(T)$ and R_{res}



Why high-Q?

$$P_{diss} \sim E_{acc}/Q_0$$





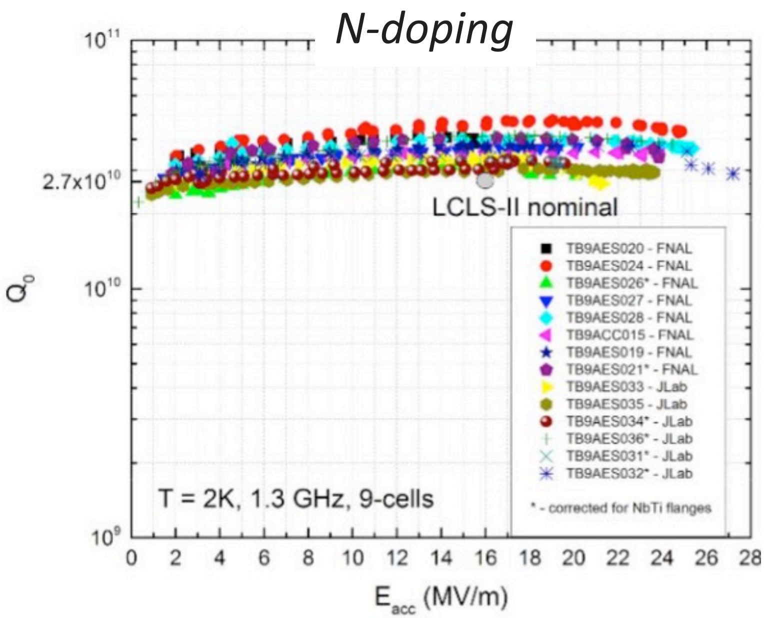
courtesy of A. Grassellino

High Q_0 studies at FNAL

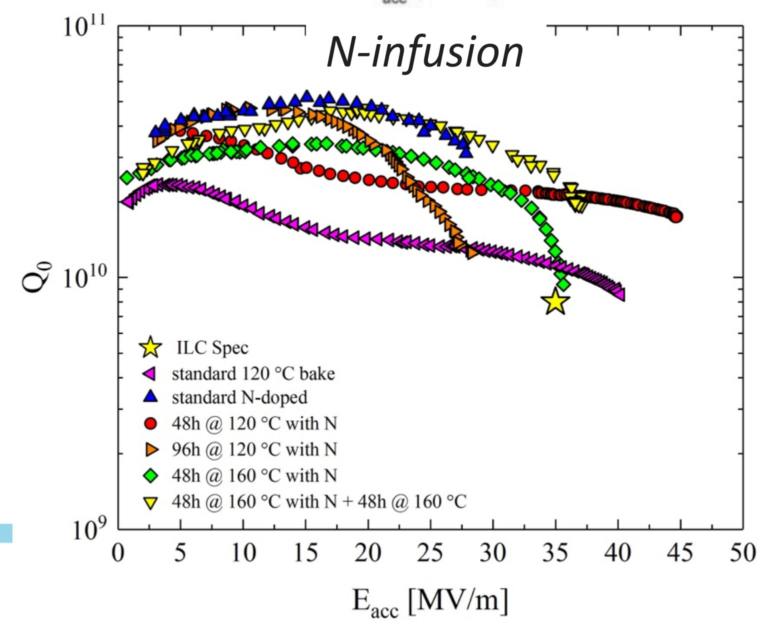
N-doping & N-infusion

High Q_0 treatments studied at FNAL

- *N-doping*
  - *High T treatment* in HV with N_2
  - N_2 injection done at *T = 800 – 1000 C for 2 – 20 min*
  - Successfully implemented on large scale production (LCLS-II)



- *N-infusion*
  - *Low T treatment* in HV with N_2
  - N_2 injection done at *T = 120 – 160 C for 48 – 96 h*
  - Being deeply investigated



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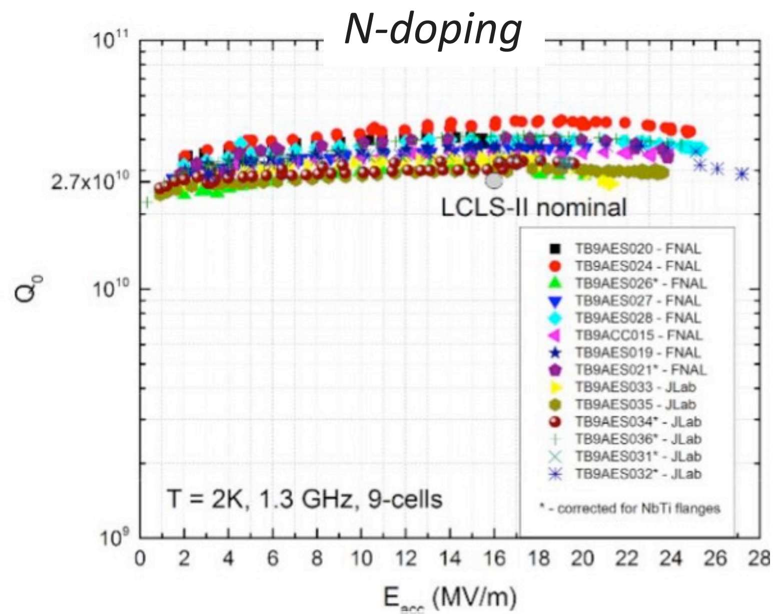

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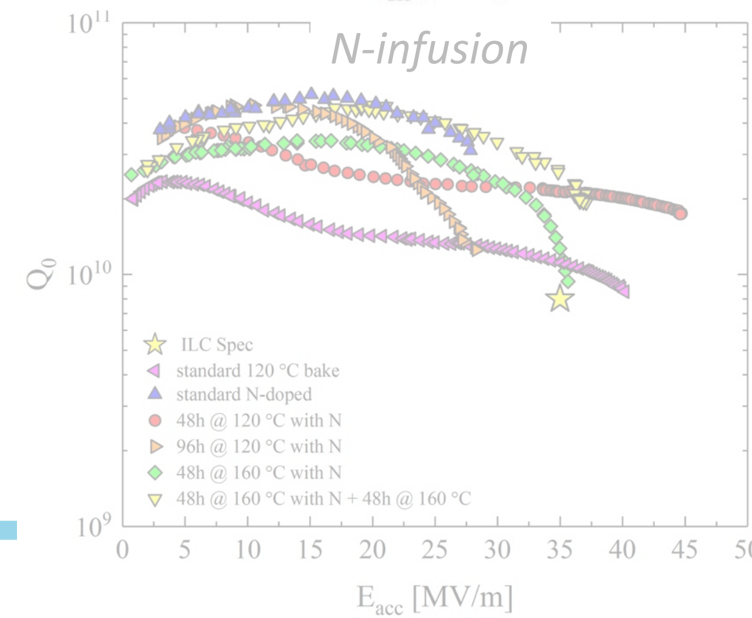
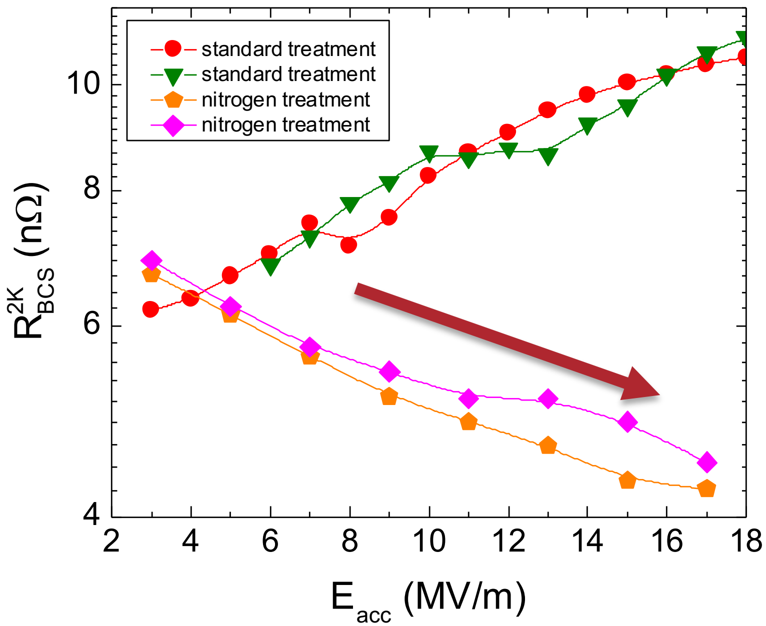
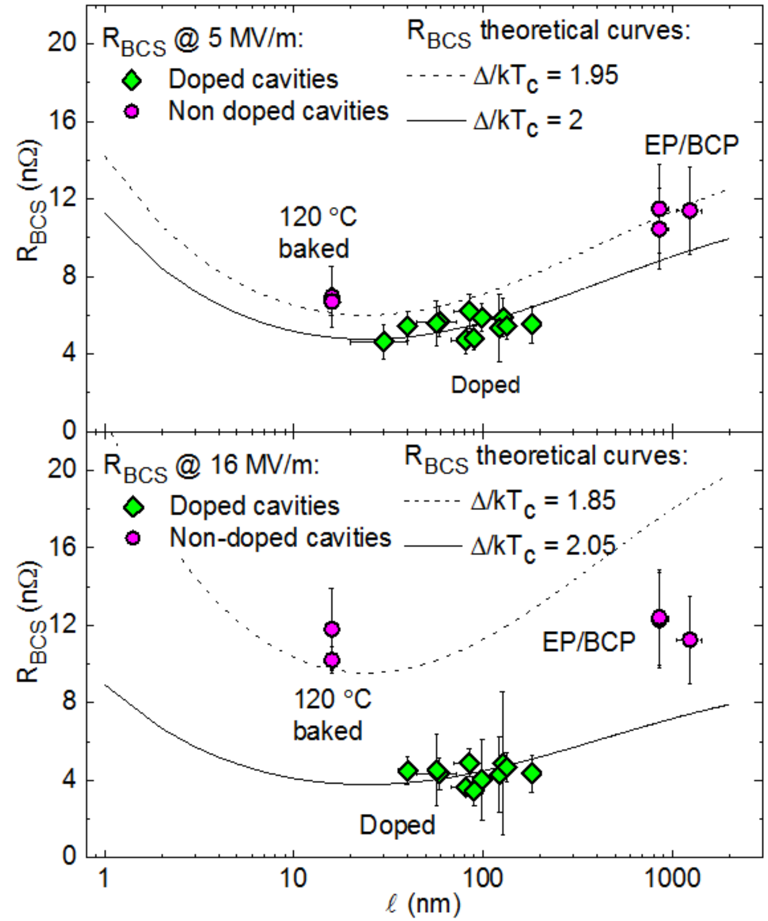


N-doping: reversal of BCS surface resistance

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

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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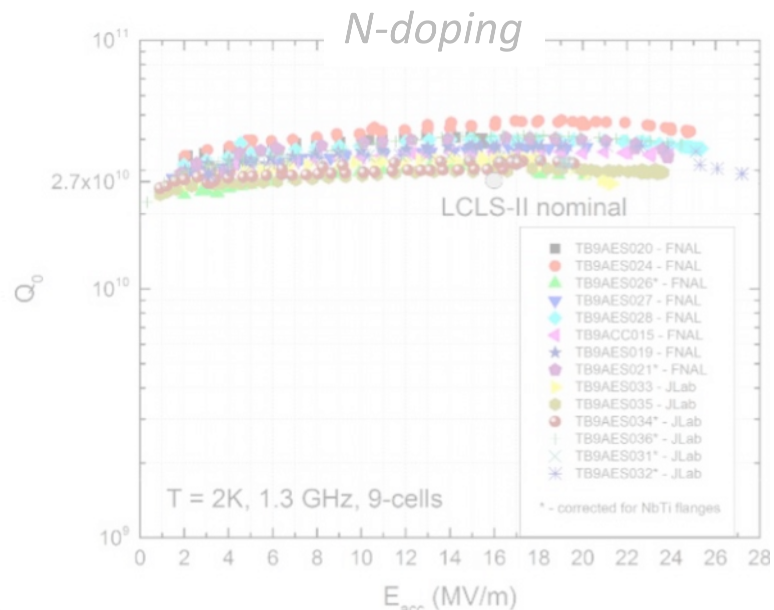

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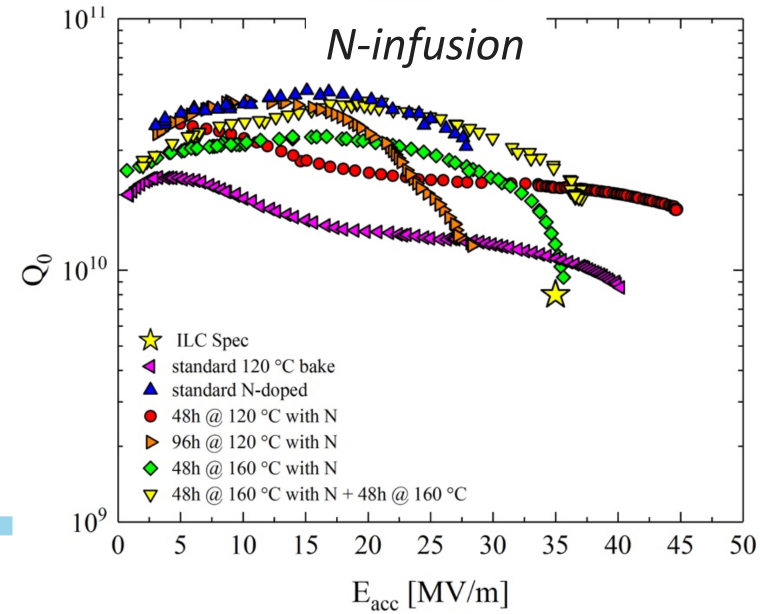
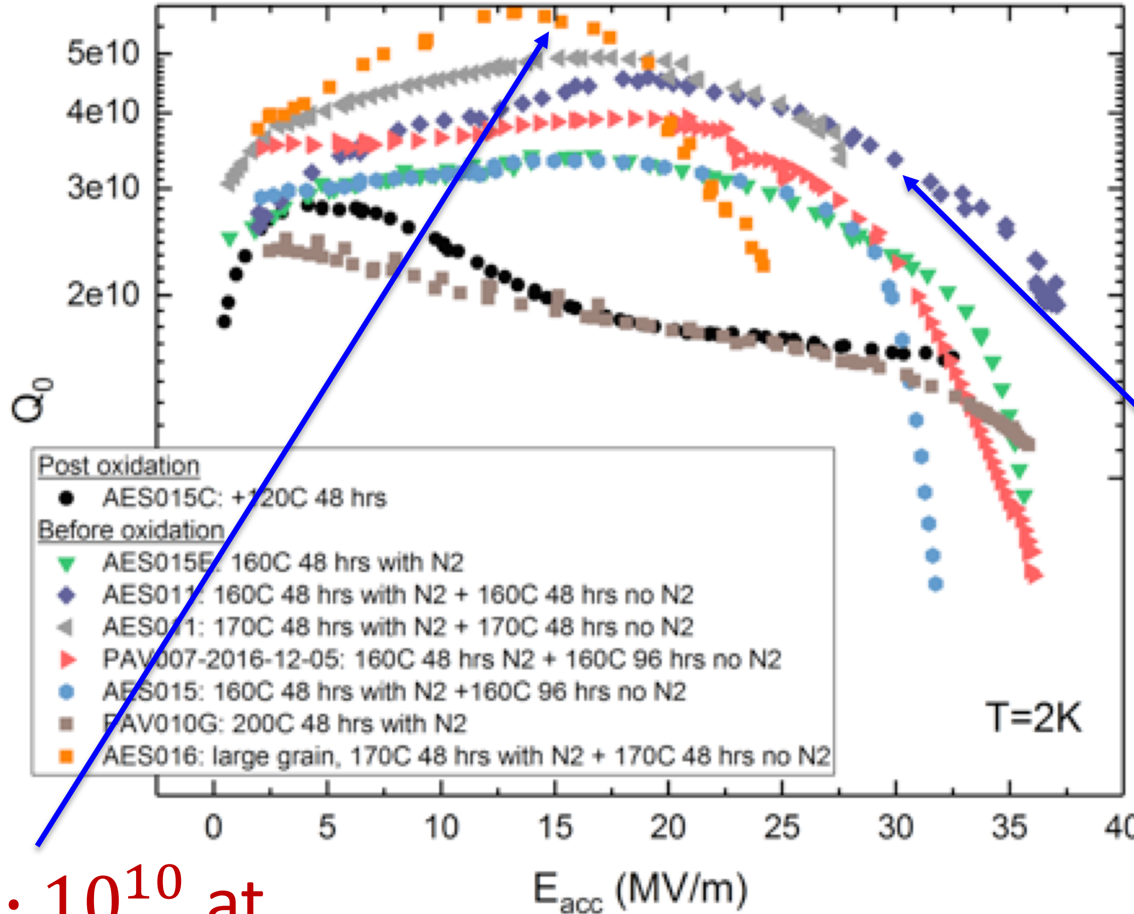


N-infusion: a larger parameter space to be explored

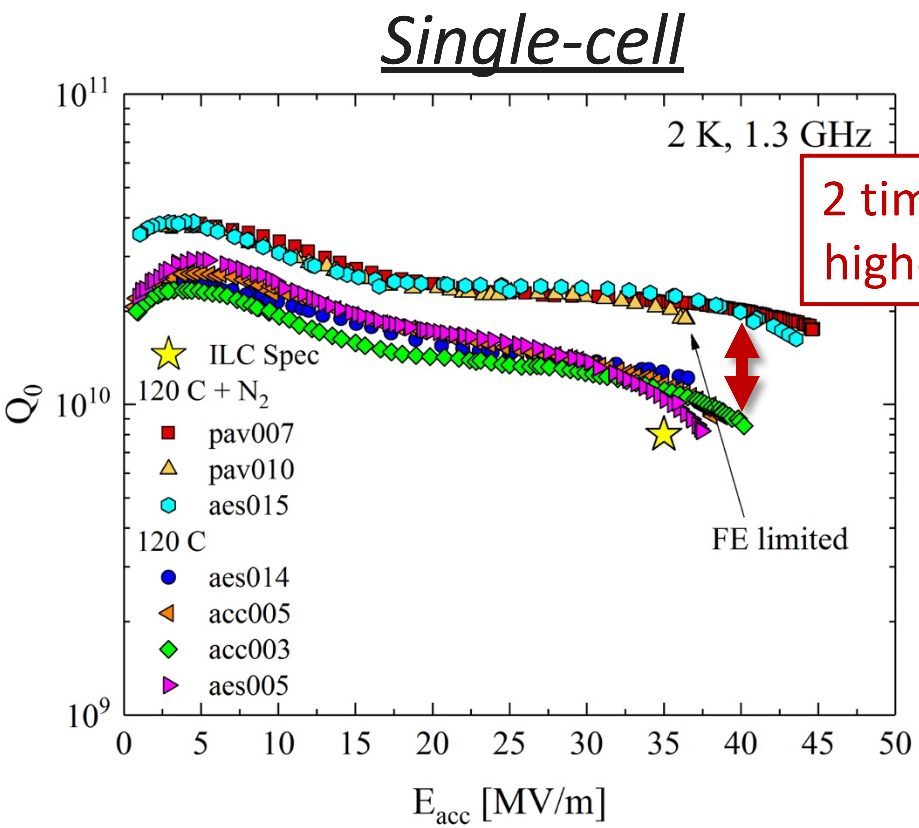


$Q_0 > 3 \cdot 10^{10}$ at $31.5\ MV/m$!

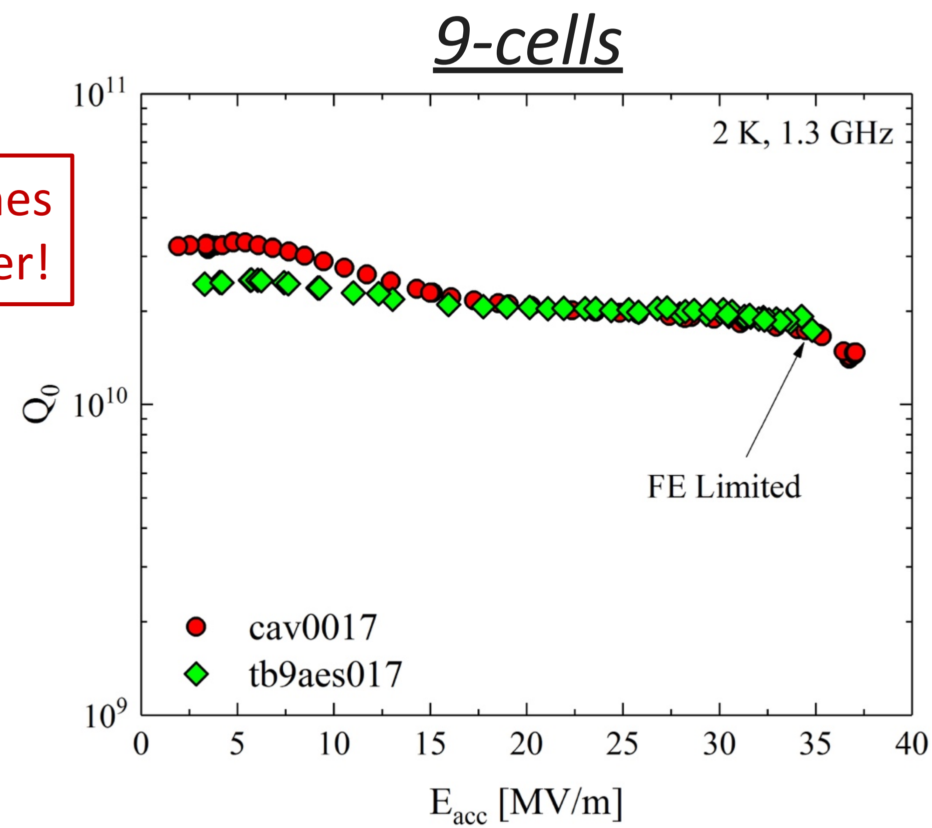
$Q_0 \sim 6 \cdot 10^{10}$ at $15\ MV/m$

A. Grassellino *et al.*, **arXiv:1701.06077** (submitted to SUST)

120 C N-infusion: high Q_0 at high gradients



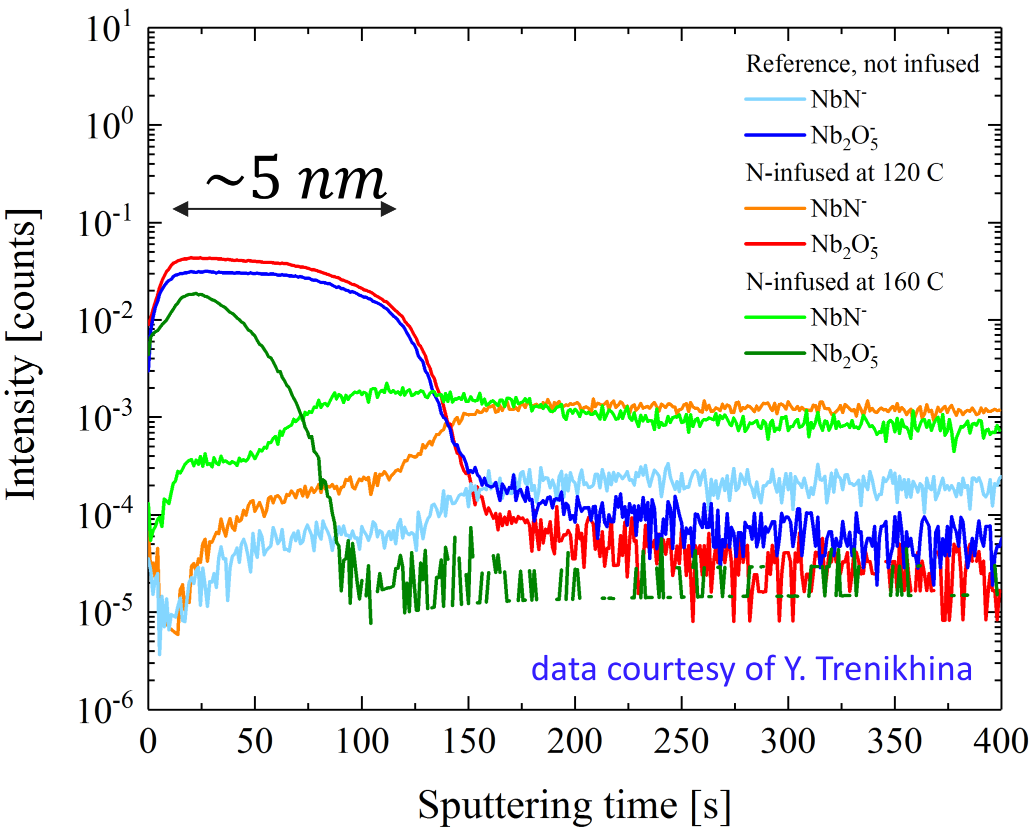
2 times higher!



Higher Q-factor at higher field may allow for higher duty-cycles and therefore higher luminosity!

A. Grassellino *et al.*, **arXiv:1701.06077** (submitted to SUST)

Nitrogen role in N-infusion



No nitrides formation at the RF surface

- Higher N_2 background than not infused samples
- Small ($\sim 1 - 2\,nm$) N_2 enriched layer below native oxide
- SIMS data suggest that performances are related to the first nm from the RF surface
- Being investigated with subsequent HF rinsing experiment

A. Grassellino *et al.*, **arXiv:1701.06077** (submitted to SUST)

Fermilab

Q_0 preservation

Understanding the trapped flux surface resistance

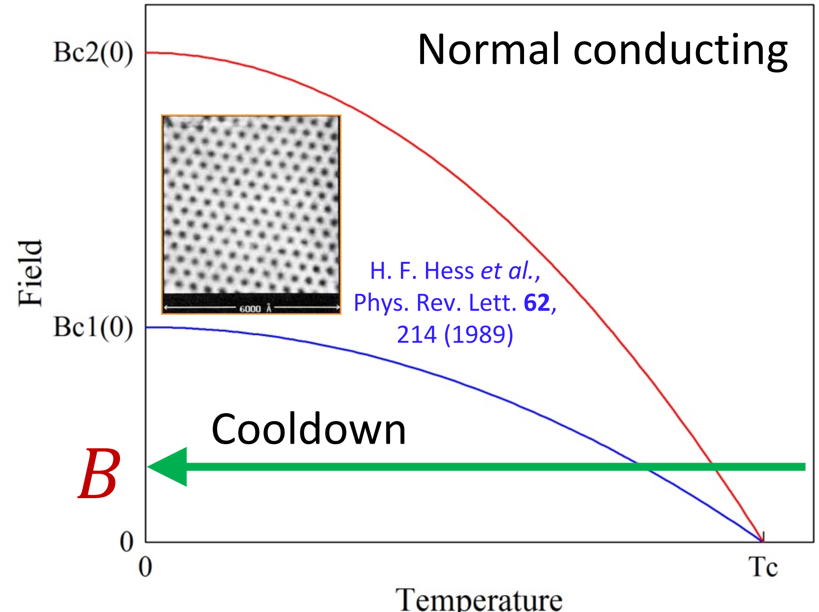
Trapped flux surface resistance

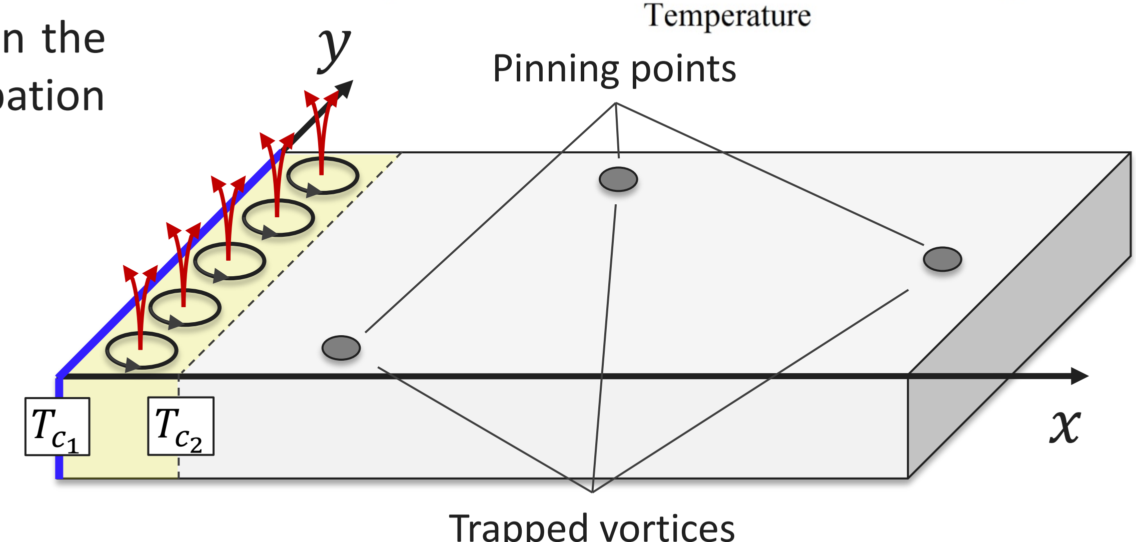
$$R_s(T,B) = R_{BCS}(T) + \overbrace{\boxed{R_{fl}(B)} + R_0}^{R_{res}}$$

$R_0 \Rightarrow$ intrinsic residual resistance

$R_{fl} = \eta_t S B \Rightarrow$ trapped magnetic flux surface resistance:

- If pinned, vortices may survive in the Meissner state introducing dissipation
- η_t—flux trapping efficiency
- S—trapped flux sensitivity
- B—external magnetic field





Trapped flux surface resistance contributions

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

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

External Magnetic Field — B
- Magnetic shielding and hygiene

Flux Trapping Efficiency — η_t
- Fast cooling / pinning

Trapped Flux Sensitivity — S
- Optimizing mean free path

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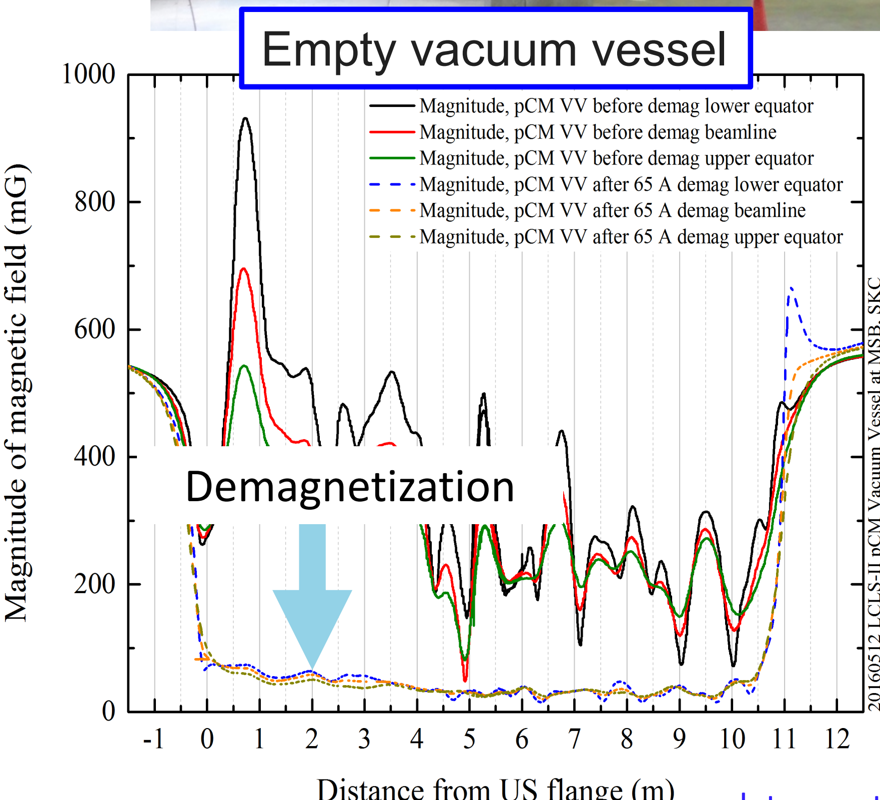
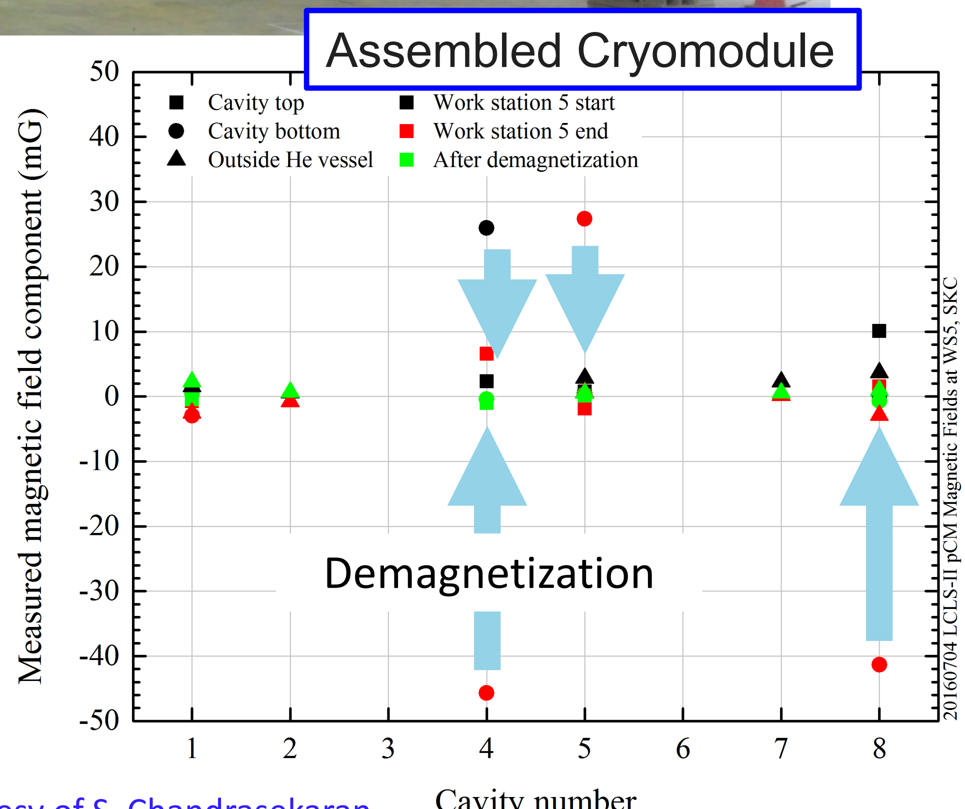
$$R_{fl} = \eta_t \, S \, B$$

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

External Magnetic Field	B	• Magnetic shielding and hygiene
Flux Trapping Efficiency	η_t	• Fast cooling / pinning
Trapped Flux Sensitivity	S	• Optimizing mean free path

Minimization of remnant field in the cryomodule





data courtesy of S. Chandrasekaran

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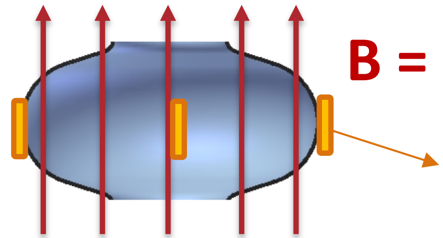
- Optimizing mean free path

Magnetic field redistribution after SC transition

$$\boxed{\eta_t = B_t/B = f(B_{sc}/B_{nc})}$$

B_t: trapped magnetic field
B_{sc}/B_{nc}: expulsion ratio

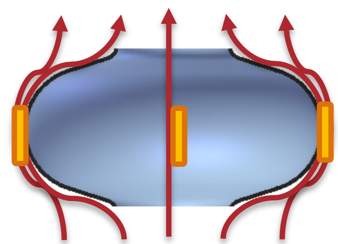
Before the SC transition:



fluxgate magnetometers
to measure external field

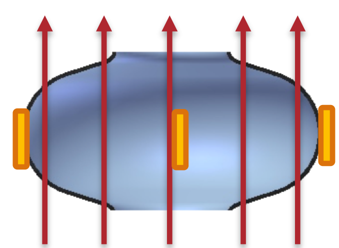
After the SC transition:

- Field completely expelled



$B_{sc}/B_{nc} = 1.74$ after complete Meissner effect (COMSOL simulation)

- Field completely trapped

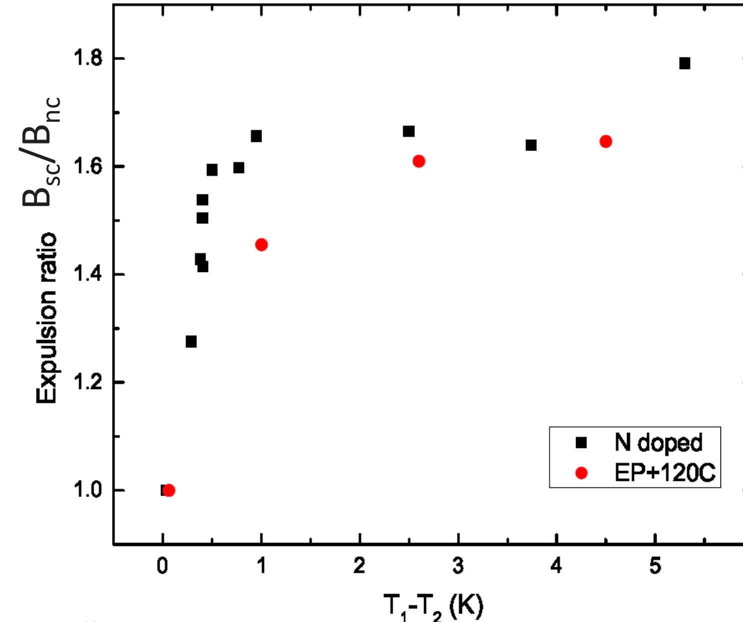


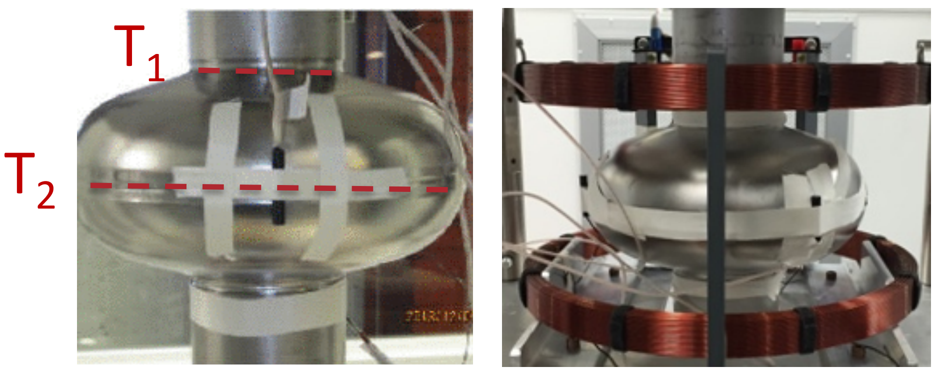
$B_{sc}/B_{nc} = 1$ after full flux trapped

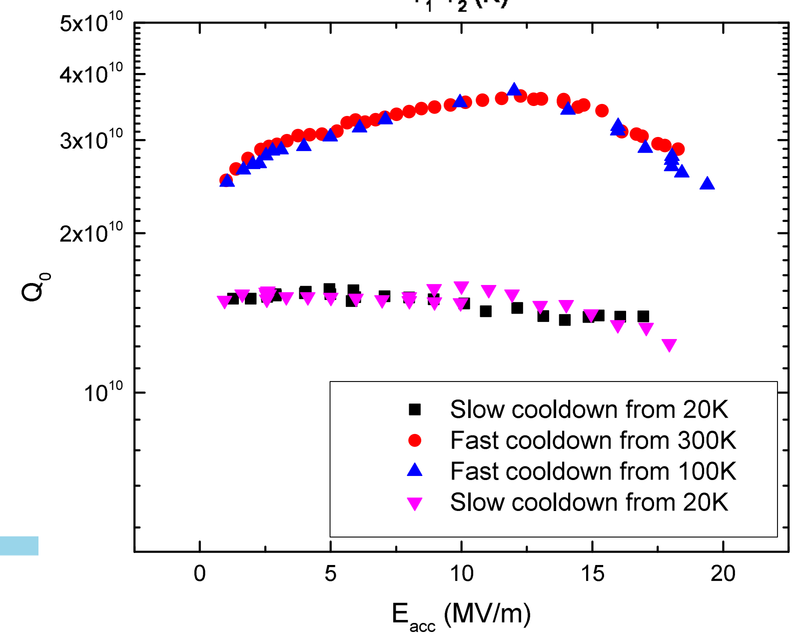
Fermilab

Fast cooldown helps flux expulsion

- *Fast cool-down*: large thermal gradients
  ⟶ efficient flux expulsion
- *Slow cool-down*: small thermal gradients
  ⟶ poor flux expulsion





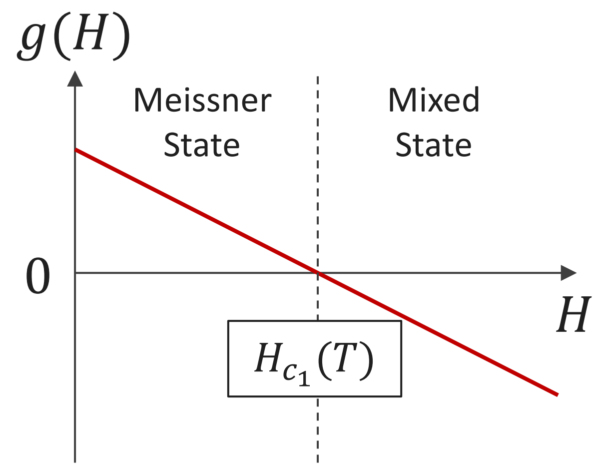


A. Romanenko *et al.*, Appl. Phys. Lett. **105**, 234103 (2014)
A. Romanenko *et al.*, J. Appl. Phys. **115**, 184903 (2014)
D. Gonnella *et al.*, J. Appl. Phys. **117**, 023908 (2015)
M. Martinello *et al.*, J. Appl. Phys. **118**, 044505 (2015)
S. Posen *et al.*, J. Appl. Phys. **119**, 213903 (2016)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

Thermodynamic force during cooldown

The Gibbs free energy density defines the stability of vortices in the SC:

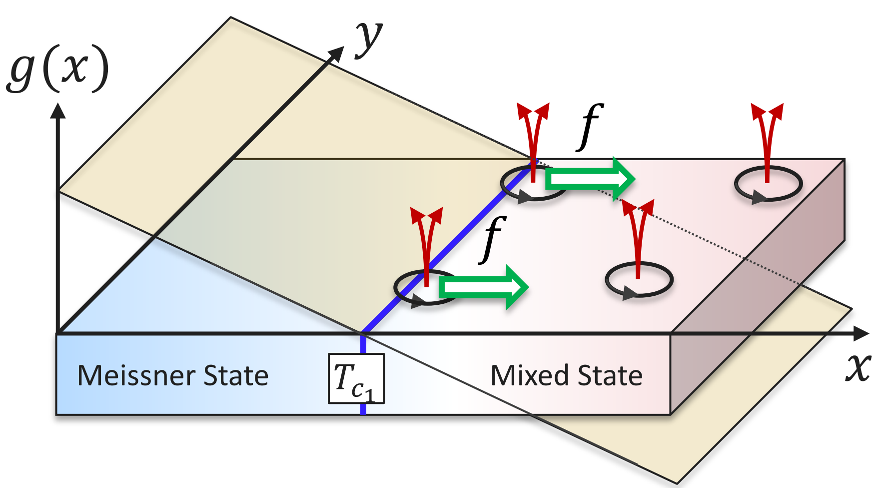
$$g = B(H_{c_1}(T) - H)$$



We can define the *thermodynamic force* acting on the vortex as:

$$f = -\frac{\partial g}{\partial x} = -\frac{\partial g}{\partial T}\frac{\partial T}{\partial x}$$

$$\boxed{f = \frac{2BH_{c_1}(0)T}{T_c^2}\nabla T}$$



M. Martinello, M. Checchin *et al.*, to be published

Critical thermal gradient

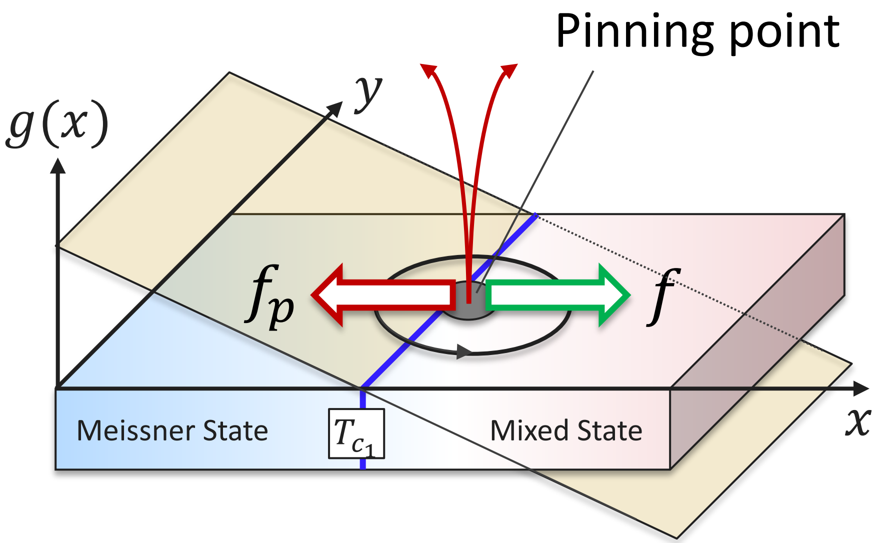
The *pinning force acting against the expulsion* is defined in terms of critical current density J_c:

$$f_p = |\bar{J}_c \times n\bar{\Phi}_0| = J_c B$$

The *minimum thermal gradient needed to expel vortices* is the critical thermal gradient ∇T_c :

$$\boxed{\nabla T_c = \frac{J_c T_c^2}{2H_{c_1}(0)T}}$$

$$\nabla T_c \propto J_c \propto f_p$$

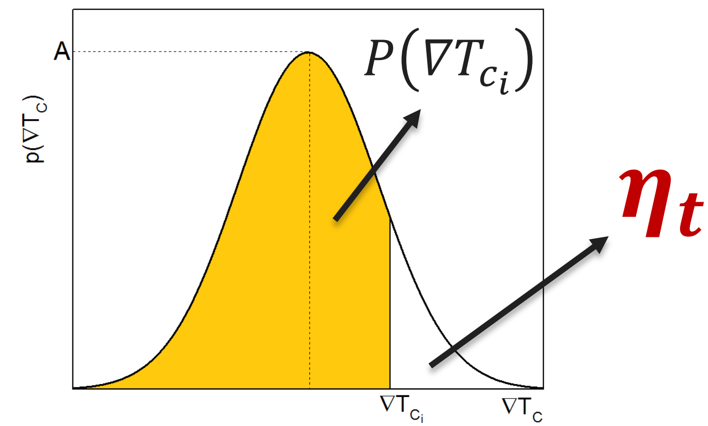


M. Martinello, M. Checchin *et al.*, to be published

Statistical model for the expulsion ratio

Let's define a probability density function for flux expulsion:

→ the *probability of expelling vortices with the thermal gradient* ∇T_{c_i} *is* $P(\nabla T_{c_i})$, hence the expulsion ratio is:

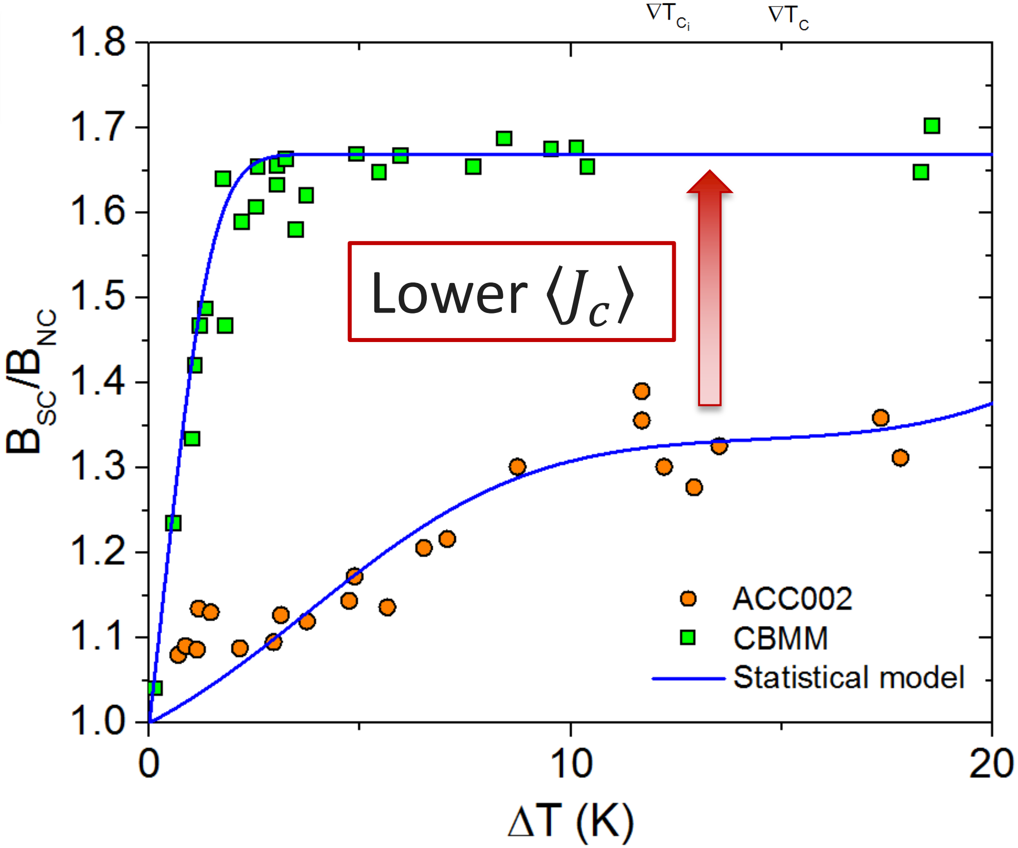


For TESLA shape

$$\boxed{B_{sc}/B_{nc} = 1 + 0.74 \cdot P(\nabla T_{c_i})}$$

The model predicts $\langle J_c \rangle$ *in agreement with literature*[1,2]:

Cavity name	$\langle J_c \rangle$ (A/mm^2)
CBMM	0.3
ACC002	1.6



M. Martinello, M. Checchin *et al.*, to be published

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

[1] G. Park *et al.*, Phys. Rev. Lett. **68**, 12 (1992)

[2] L. H. Allen and J. H. Claassen, Phys. Rev. B **39**, 4 (1989)

Trapped flux surface resistance contributions

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

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

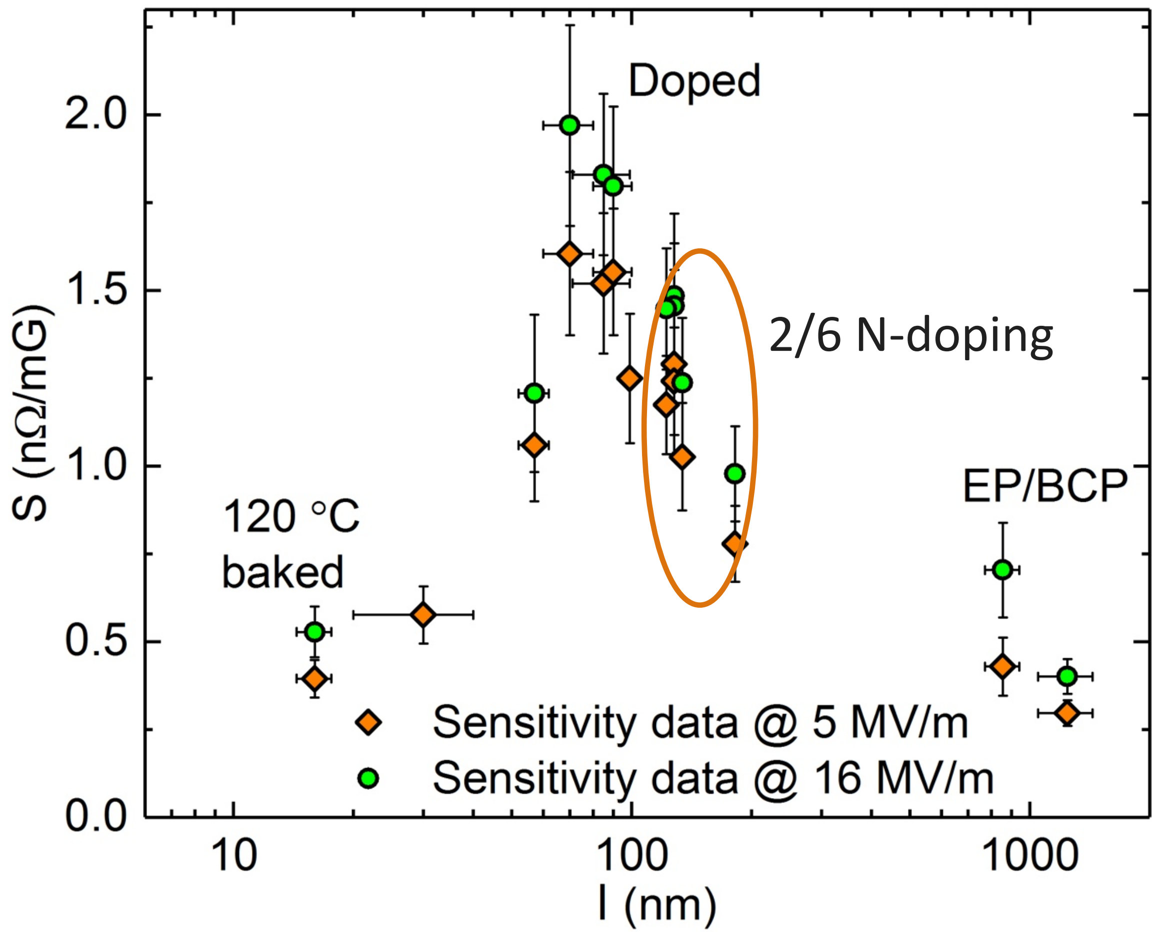
External Magnetic Field	B	• Magnetic shielding and hygiene
Flux Trapping Efficiency	η_t	• Fast cooling / pinning
Trapped Flux Sensitivity	S	• Optimizing mean free path

Light doping to minimize trapped flux sensitivity

Trapped flux sensitivity:

$$S = \frac{R_{fl}}{\eta_t\, B}$$

- Bell-shaped trend of S as a function of mean free path
- N-doping cavities present higher sensitivity than standard treated cavities
- *Light doping* is needed to *minimize* trapped flux *sensitivity*

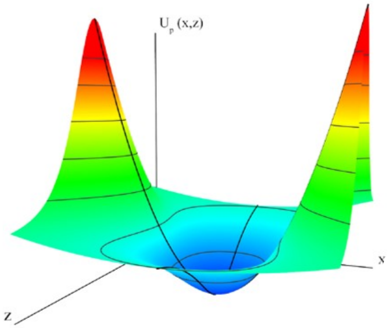


M. Martinello et al., App. Phys. Lett. **109**, 062601 (2016)
D. Gonnella et al., J. Appl. Phys. **119**, 073904 (2016)

Single vortex equation of motion

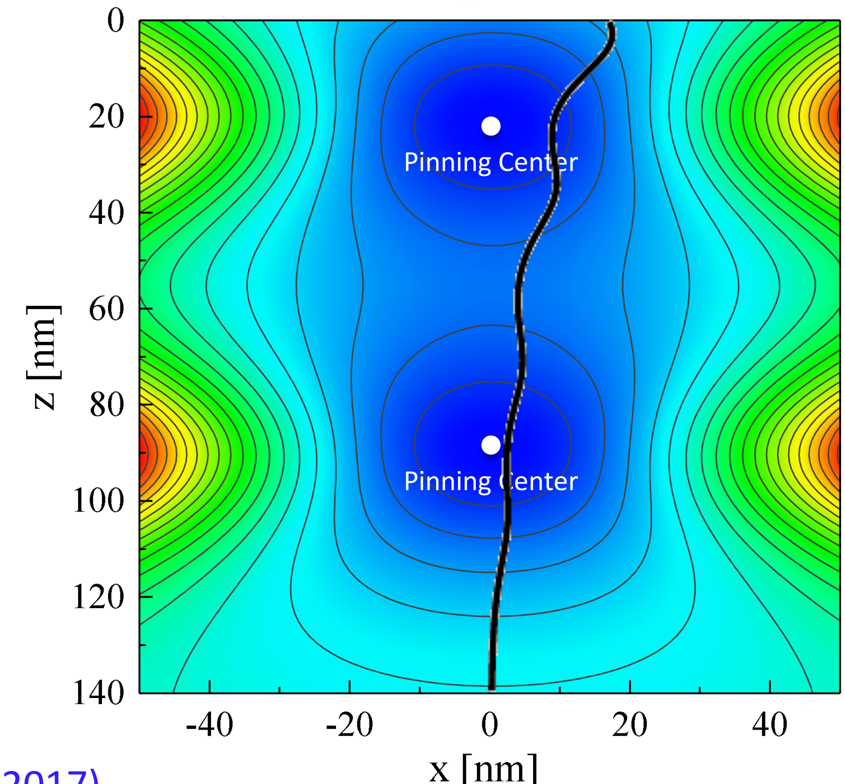
The motion equation has form:

$$M(l)\ddot{x} + \eta(l)\dot{x} + p(z,l)x = j_0\phi_0\sin(\theta)e^{i\omega t - z/\lambda(l)}$$



The solution is valid from $z = 0$ to $z \to \infty$

- The pinning potential assumed is a 2D Lorentzian function
  $\Rightarrow$ *parabolic approximation along x*
- The pinning constant $p(z,l)$ is depth-dependent
  $\Rightarrow$ *flexible vortex line*
- Multiple pinning centers can be considered



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

Sensitivity vs mean-free-path

- Small l – <u>*pinning regime*</u> $\eta \ll p$:

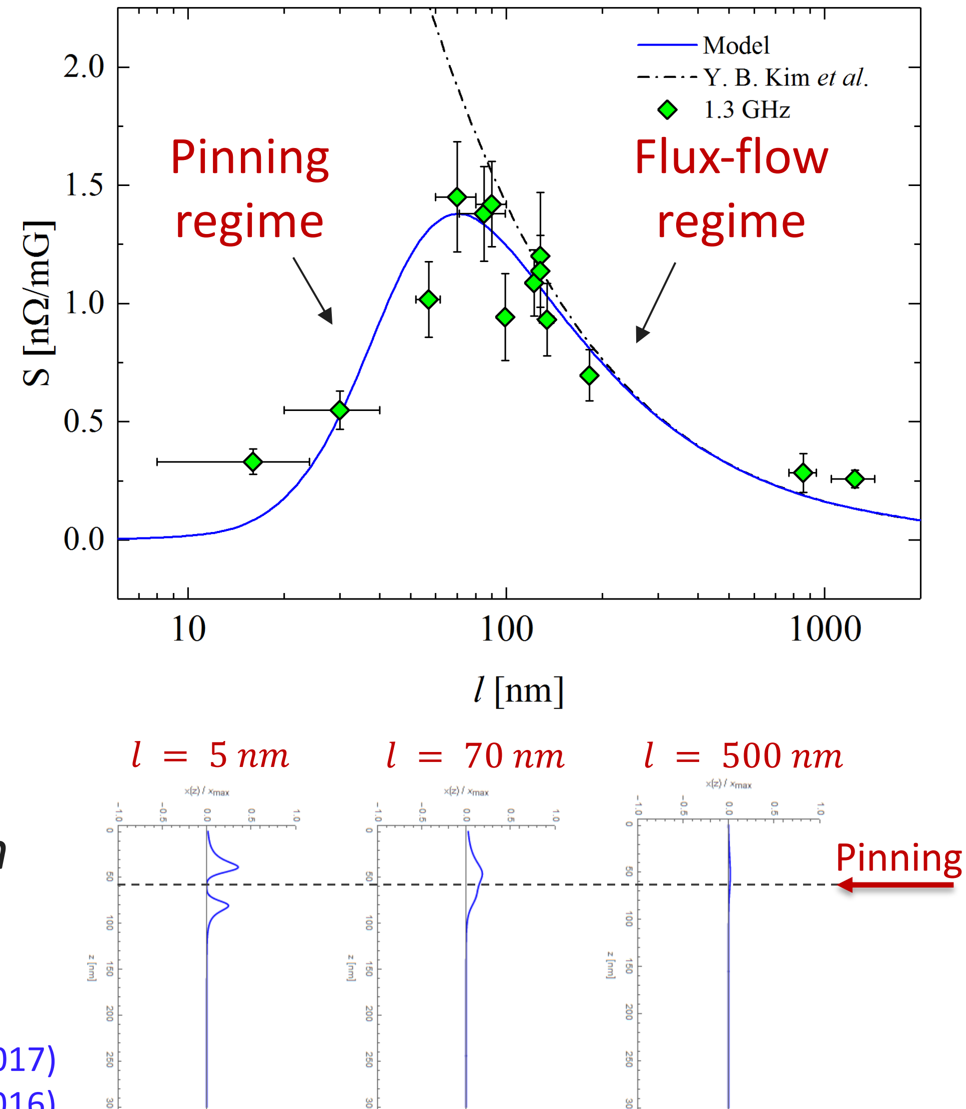
$$\rho_1(l, U_0) \approx \frac{\eta(l)}{p(l, U_0)^2}$$

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

- Large l – <u>*flux-flow regime*</u> $\eta \gg p$:

$$\rho_1(l) \approx \frac{1}{\eta(l)}$$

ρ_1 decreases with l, independent on ω and U_0



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

Sensitivity vs frequency

- Small l – <u>*pinning regime*</u> $\eta \ll p$:

$$\rho_1(\omega) \approx \omega^2$$

ρ_1 *increases with* ω^2

- Large l – <u>*flux-flow regime*</u> $\eta \gg p$:

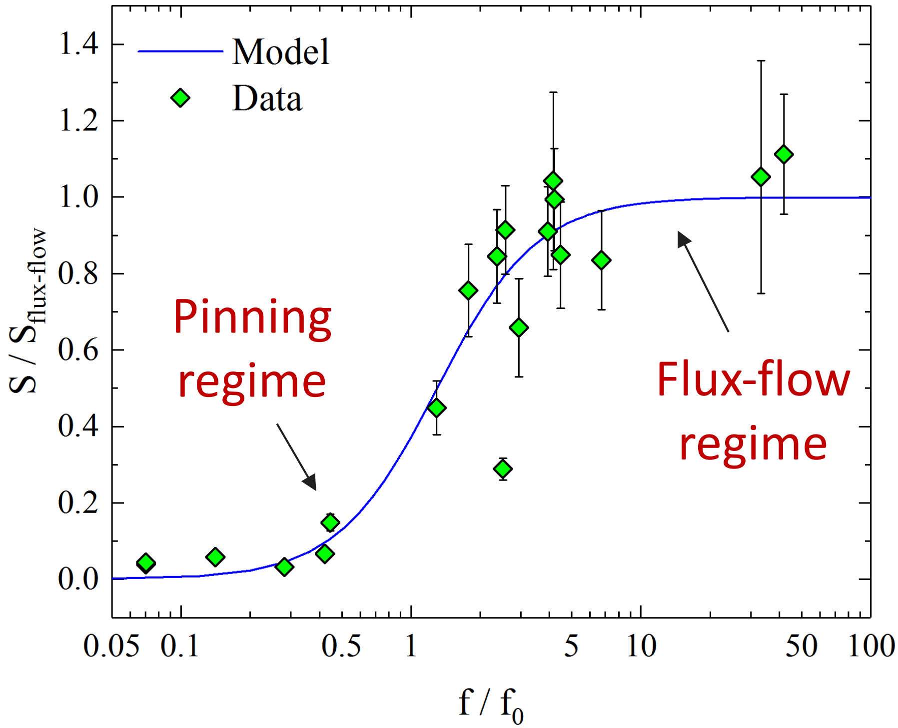
$$\rho_1 = constant$$

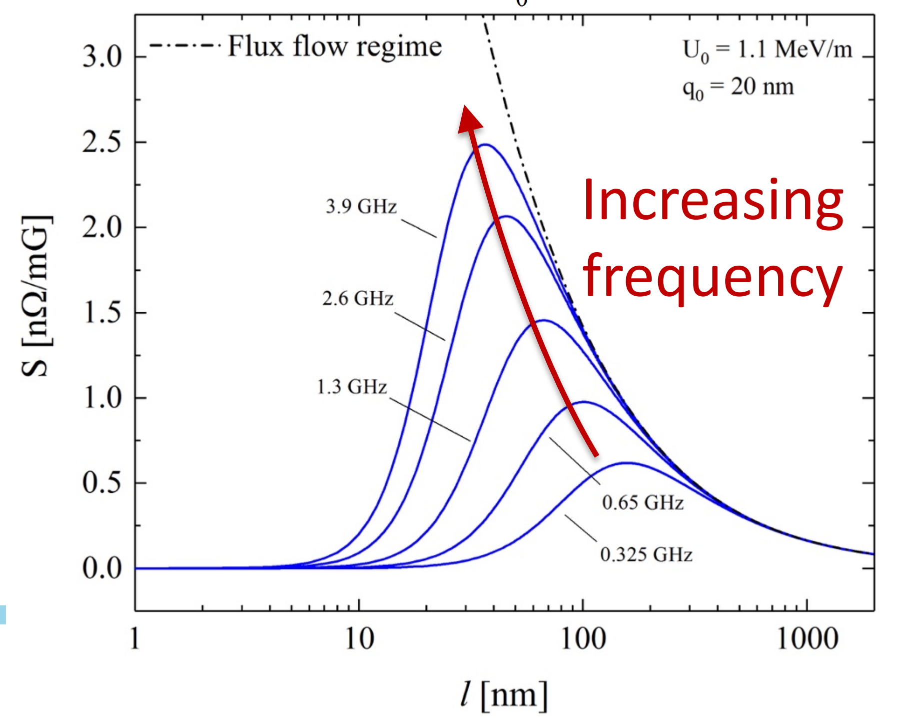
ρ_1 *independent on* ω

- The higher f the higher the sensitivity peak

- *Lower frequencies* are favorable to *minimize the sensitivity*

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

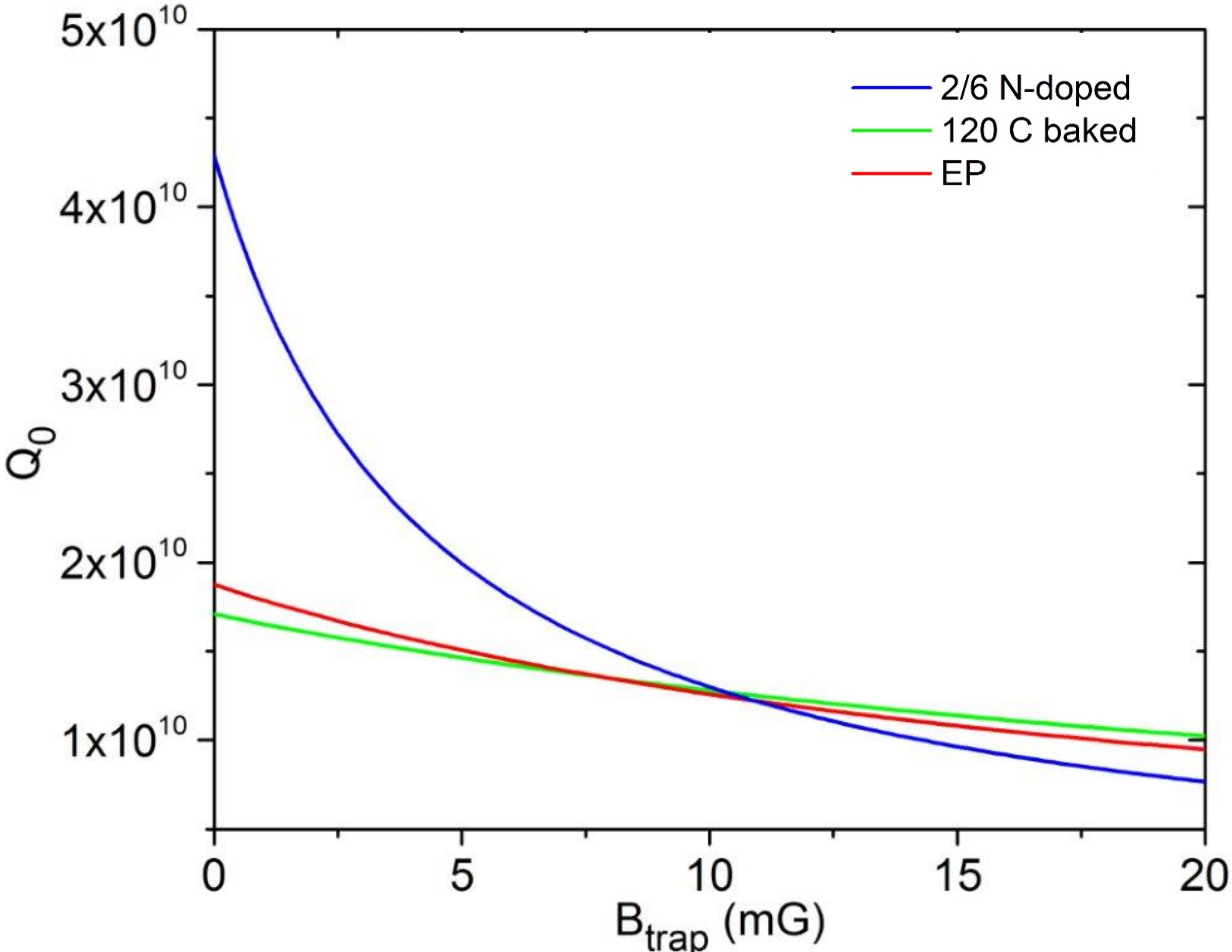




Summary

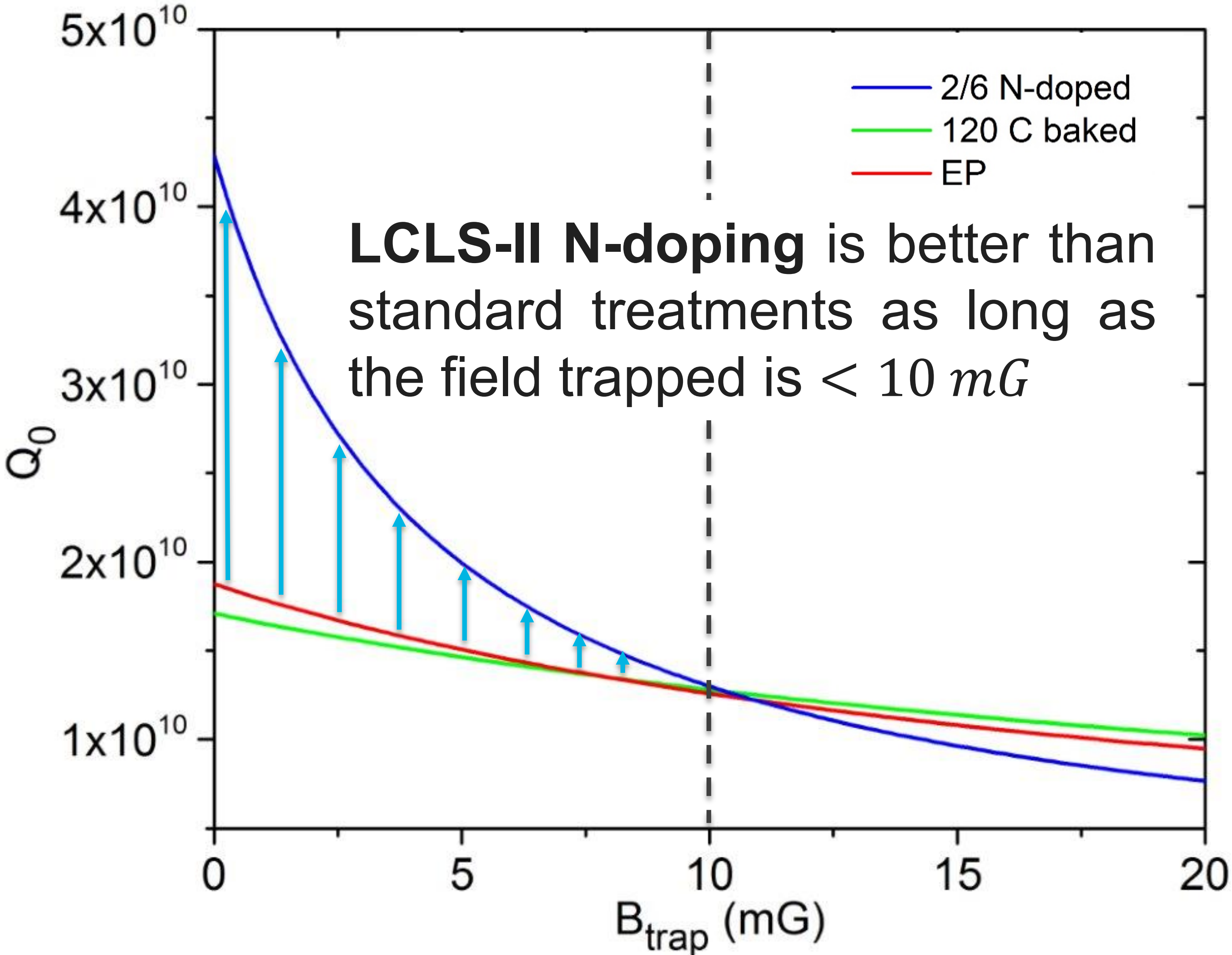
State-of-the-art surface treatment for high Q_0 at 1.3 GHz

Q_0 in condition of full flux-trapping @ 1.3 GHz



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

Q_0 in condition of full flux-trapping @ 1.3 GHz



LCLS-II N-doping is better than standard treatments as long as the field trapped is $< 10\, mG$

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

LCLS-II prototype cryomodule test at FNAL

LCLS-II spec: 2.7×10^{10} at 16 MV/m

Cavity	Usable Gradient* [MV/m]	Cryomodule Q_0 @16MV/m** Fast Cool Down
TB9AES021	18.2	2.6e10
TB9AES019	18.8	3.1e10
TB9AES026	19.8	3.6e10
TB9AES024	20.5	3.1e10
TB9AES028	14.2	2.6e10
TB9AES016	16.9	3.3e10
TB9AES022	19.4	3.3e10
TB9AES027	17.5	2.3e10
Average	**18.2**	**3.0e10**
Total Voltage	**148.1 MV**	

Acceptance = 128 MV

* Radiation <50 mR/h
** TB9AES028 Q_0 was at 14 MV/m

courtesy of G. Wu

Fermilab

Frequency dependence study

We are now extending the same study to *different frequencies* and *many surface treatments* (EP, 120 C bake, N-doping and N-infusion)….

The initial results are extremely interesting….**STAY TUNED!**

Conclusions

Conclusions

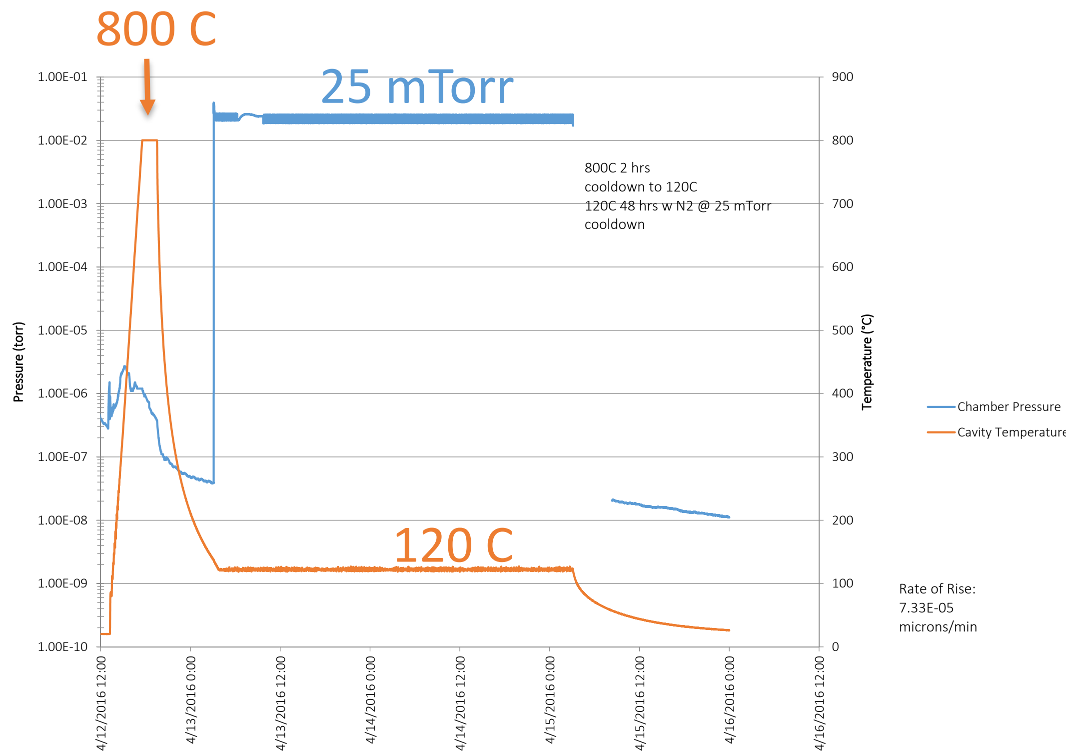
- N-doping and N-infusion both increases Q_0
- $R_{fl} = \eta_t\, S\, B$ can be minimized by:
  - → Efficient magnetic field shielding (low B)
  - → Fast cooling, minimize pinning (low η_t)
  - → Decreasing as much as possible the sensitivity (low S)
- Two different regimes of vortex dissipation
  - → Small l , *pinning regime*: ρ_1 increases if $l\uparrow$, $\omega^2\uparrow$ and $U_0\downarrow$
  - → Large l , *flux-flow regime*: ρ_1 decreases if $l\uparrow$, but independent on ω and U_0
- Only by understanding R_{fl} N-doping could be successfully implemented to mass production
  - → LCLS-II cryomodule specification exceeded

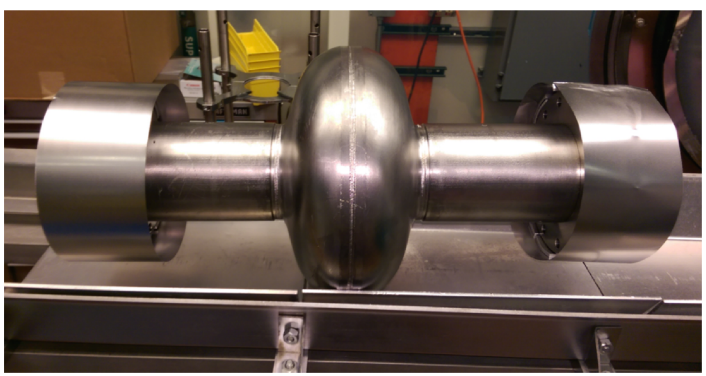
Thank you for the attention

Back-up slides

N-infusion thermal process

- Bulk electro-polishing
- High T furnace <u>with caps to avoid furnace contamination</u>:
  - 3h @ 800C in HV
  - 48h @ 120-160 C <u>with N_2 (25 mTorr)</u>
  - Optional annealing 48h @ 120-160 C
- 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 the cavity to furnace area

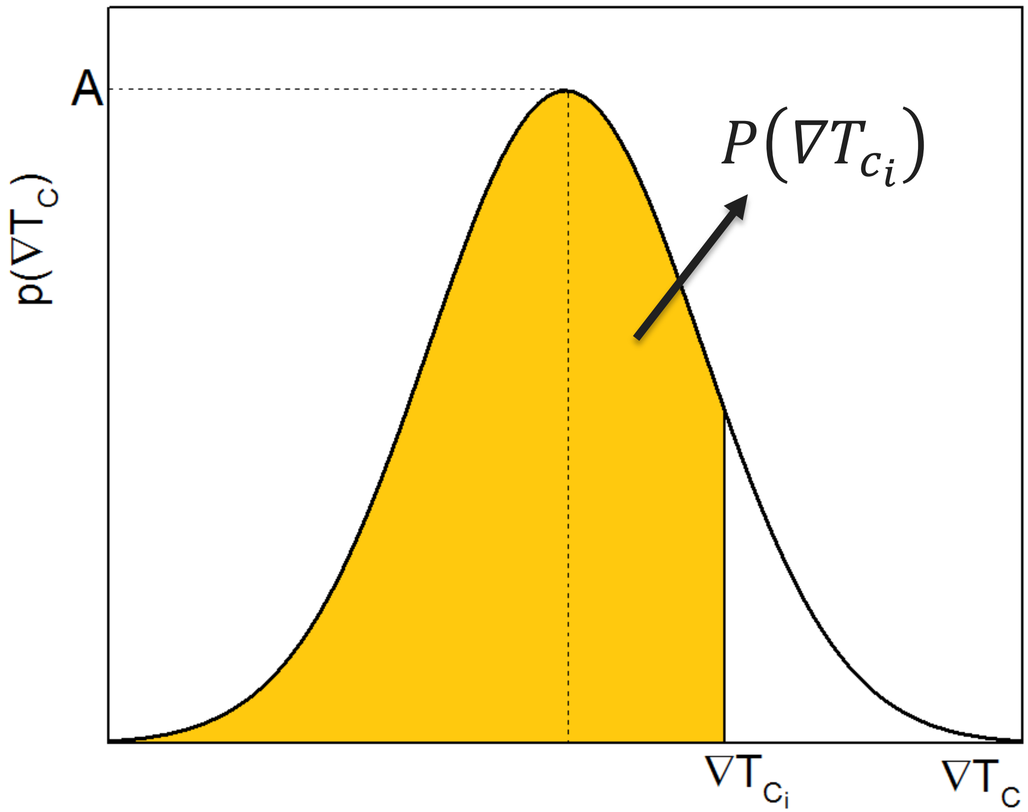
A. Grassellino *et al.*, **arXiv:1701.06077** (submitted to SUST)

Statistical definition of trapping efficiency

- The probability of expelling vortices with the thermal gradient ∇T_{c_i} is $P(\nabla T_{c_i})$
- The trapping efficiency η_t is function of ∇T_{c_i}:

$$\boxed{\eta_t = [1 - P(\nabla T_{c_i})]}$$

$$P(\nabla T_{c_i}) = \int_0^{\nabla T_{c_i}} p(\nabla T_c)\, d\nabla T_c$$



- The trapped field is then:

$$B_t = \eta_t B = B[1 - P(\nabla T_{c_i})]$$

For TESLA shape

$$\boxed{\frac{B_{sc}}{B_{nc}} = 1 + 0.74 \cdot P(\nabla T_{c_i})}$$

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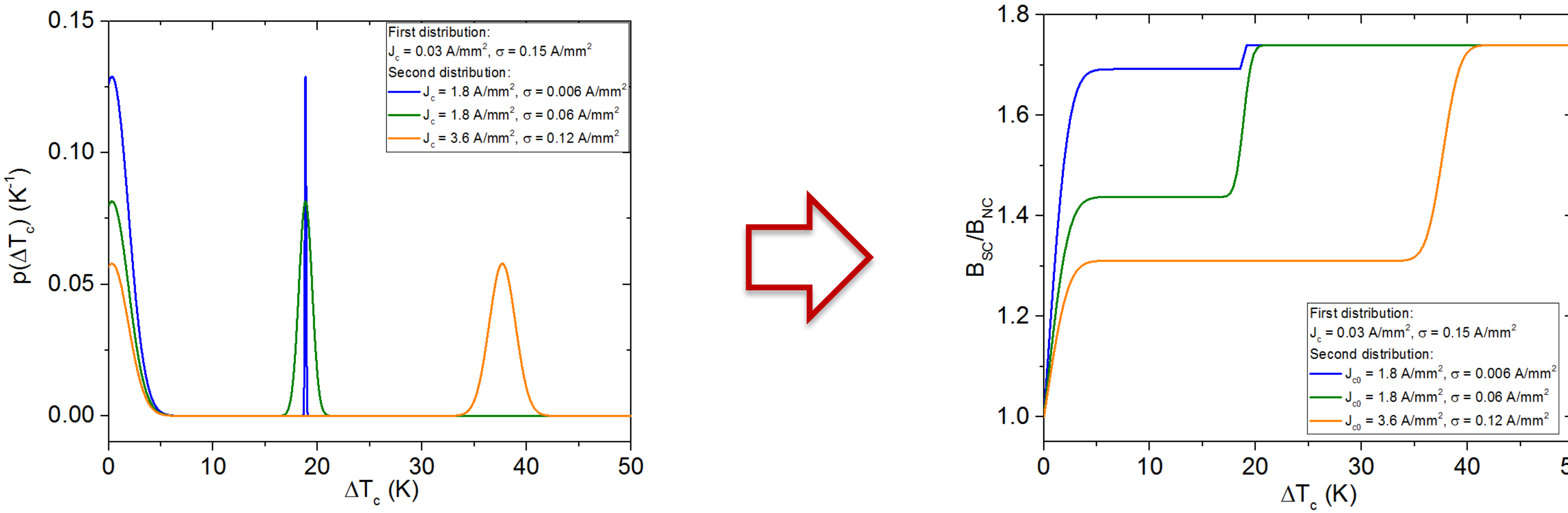
Double-peaked probability density function



- Double distribution of pinning centers (e.g. dislocations + grain boundaries)
- $p(\Delta T_c \rightarrow 0) \neq 0 \;\Rightarrow\;$ finite probability that vortices are not pinned
- First plateau defined by the ratio of the two peaks' area
- Complete flux expulsion reached when ΔT_c is larger enough so that $P(\Delta T_c) = 1$

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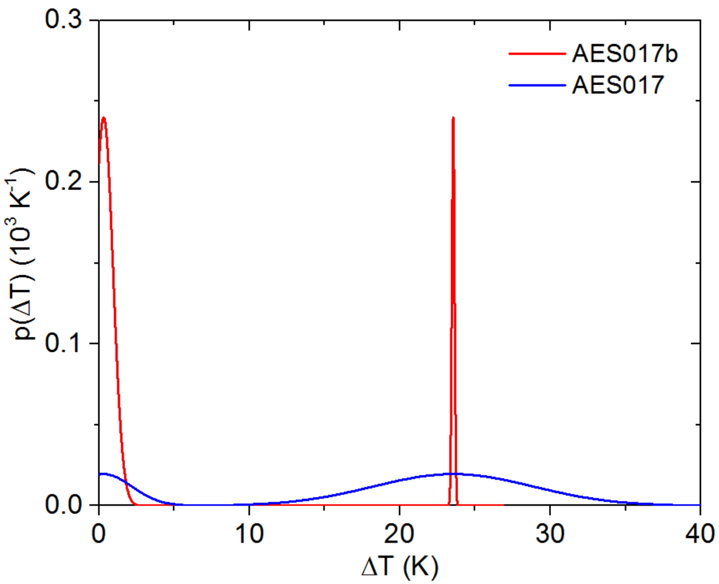
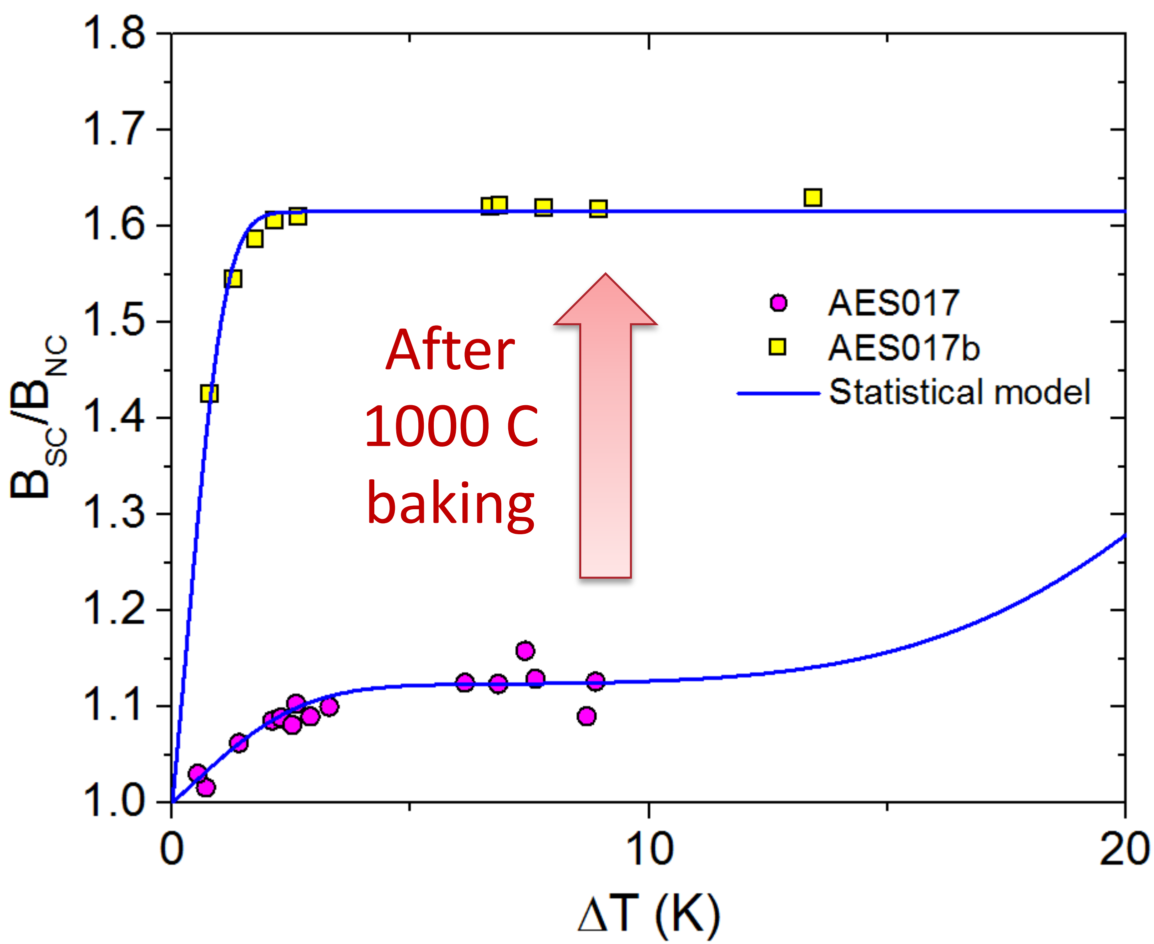
High T baking effects

High T baking effects:

- Decreases the number of pinning points
  $\longrightarrow$ pdf narrowing
- Smaller J_c





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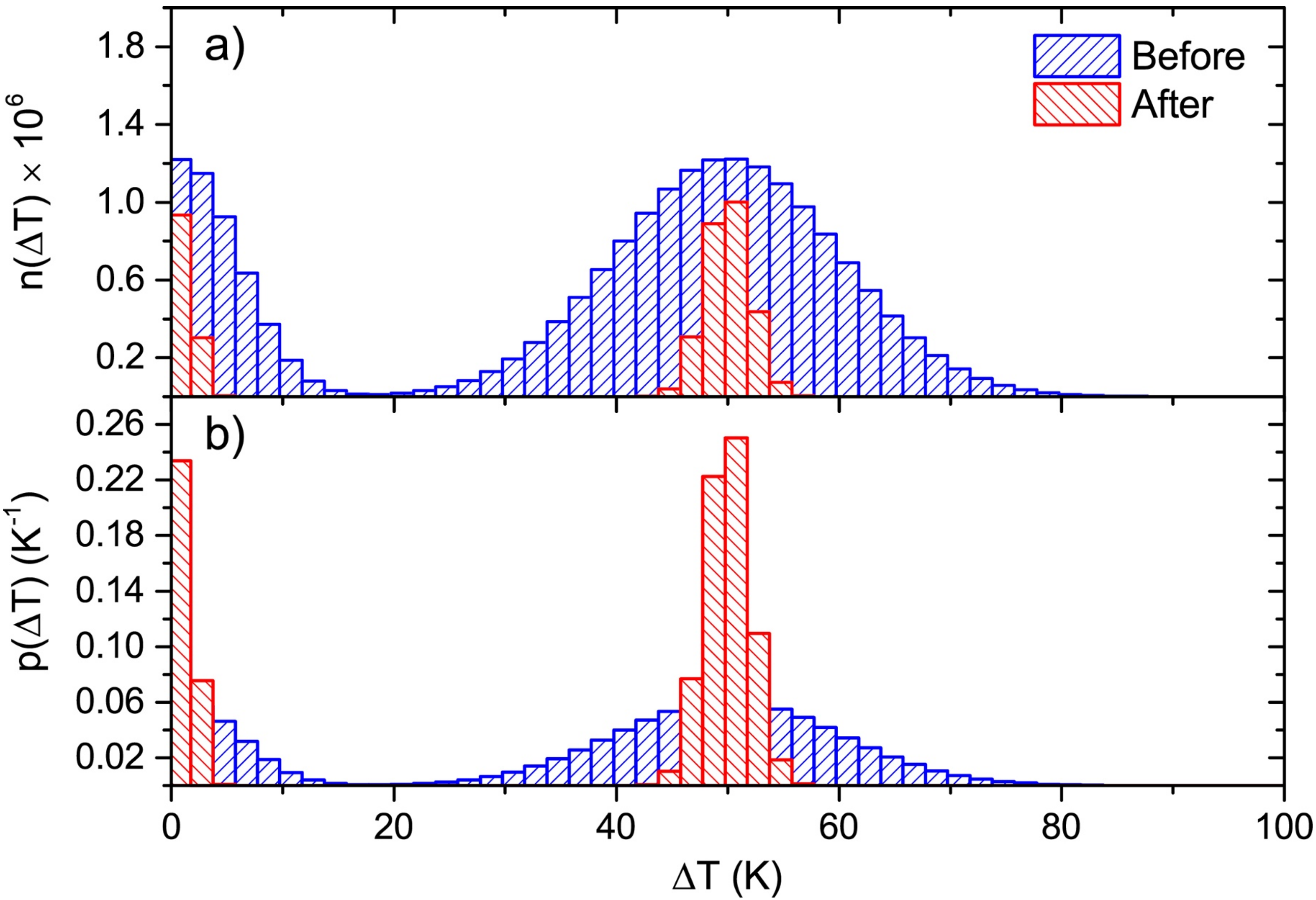
Data: S. Posen *et al.*, J. Appl. Phys. **119**, 213903 (2016)

Pdf before/after 1000 C annealing example



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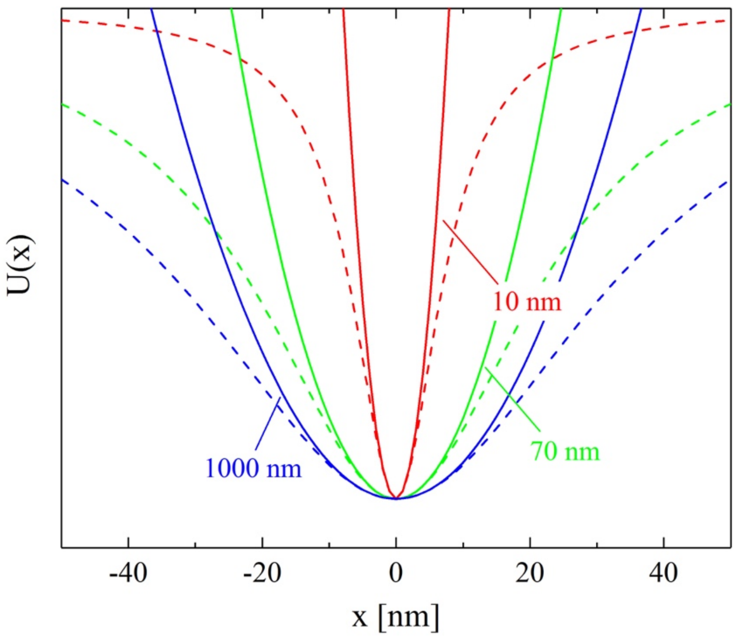
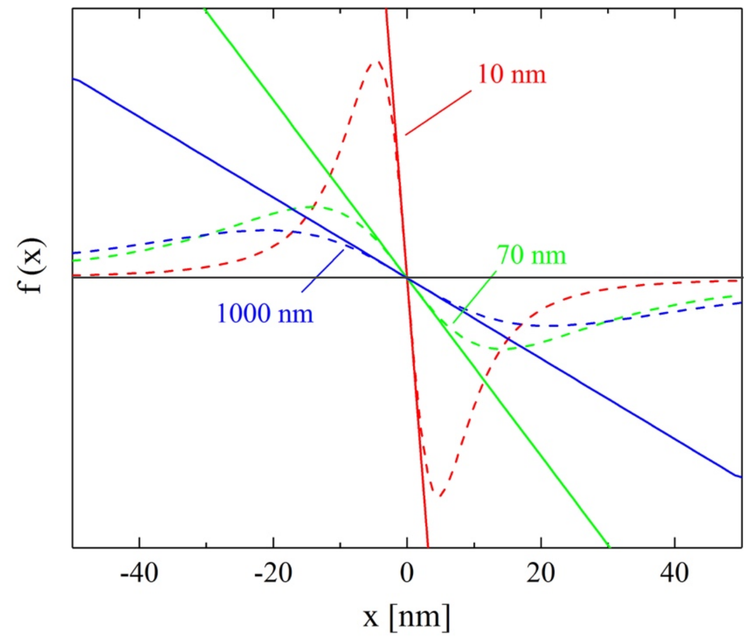
Pinning potential

The smaller l, the steeper the potential:

$$U_p(z) = -\sum_{i=0}^{n} \frac{U_{0_i}\xi^2}{\xi^2 + x^2 + (z - q_i)^2}$$
$$\approx -\sum_{i=0}^{n} \frac{U_{0_i}\xi^2}{\xi^2 + (z - q_i)^2} + \sum_{i=0}^{n} \frac{U_{0_i}\xi^2}{[\xi^2 + (z - q_i)^2]^2} x^2$$





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Vortex surface impedance

The *complex resistivity* of the vortex line follows from the calculation of the apparent power (active plus reactive power) :

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

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

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

Number of vortices B/B_{vortex}

Vortex impedance weighted over normal distributions of pinning positions and strengths

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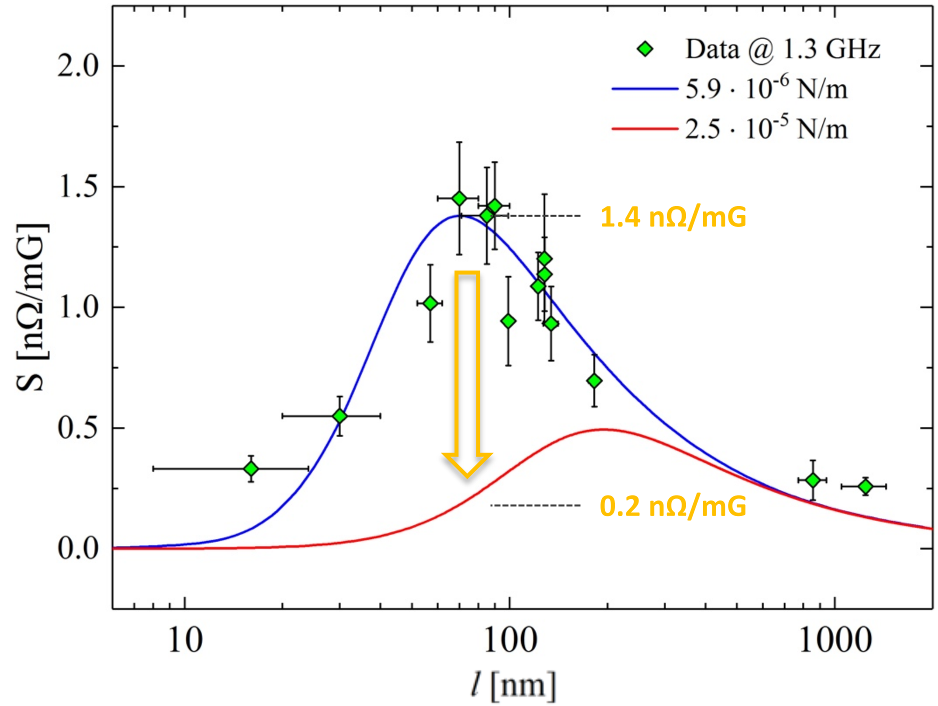
Pinning strength dependence

The higher the pinning force, the more constrained the oscillation

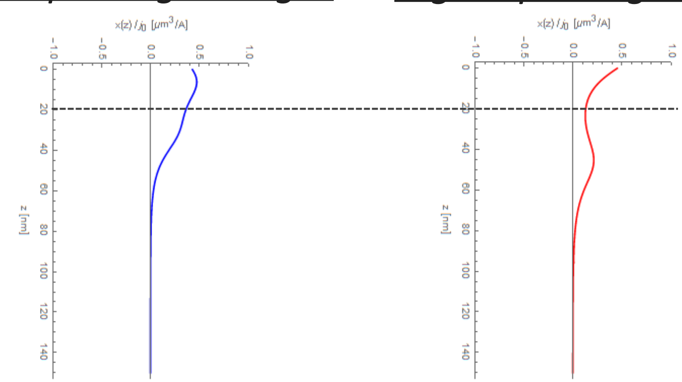
Dirtier or more defective materials (e.g. *thin films*) have larger pining strength

Lower sensitivity!

By increasing the pinning force of one order of magnitude the *sensitivity is 7 times smaller*!



Lower pinning strength *Higher pinning strength*



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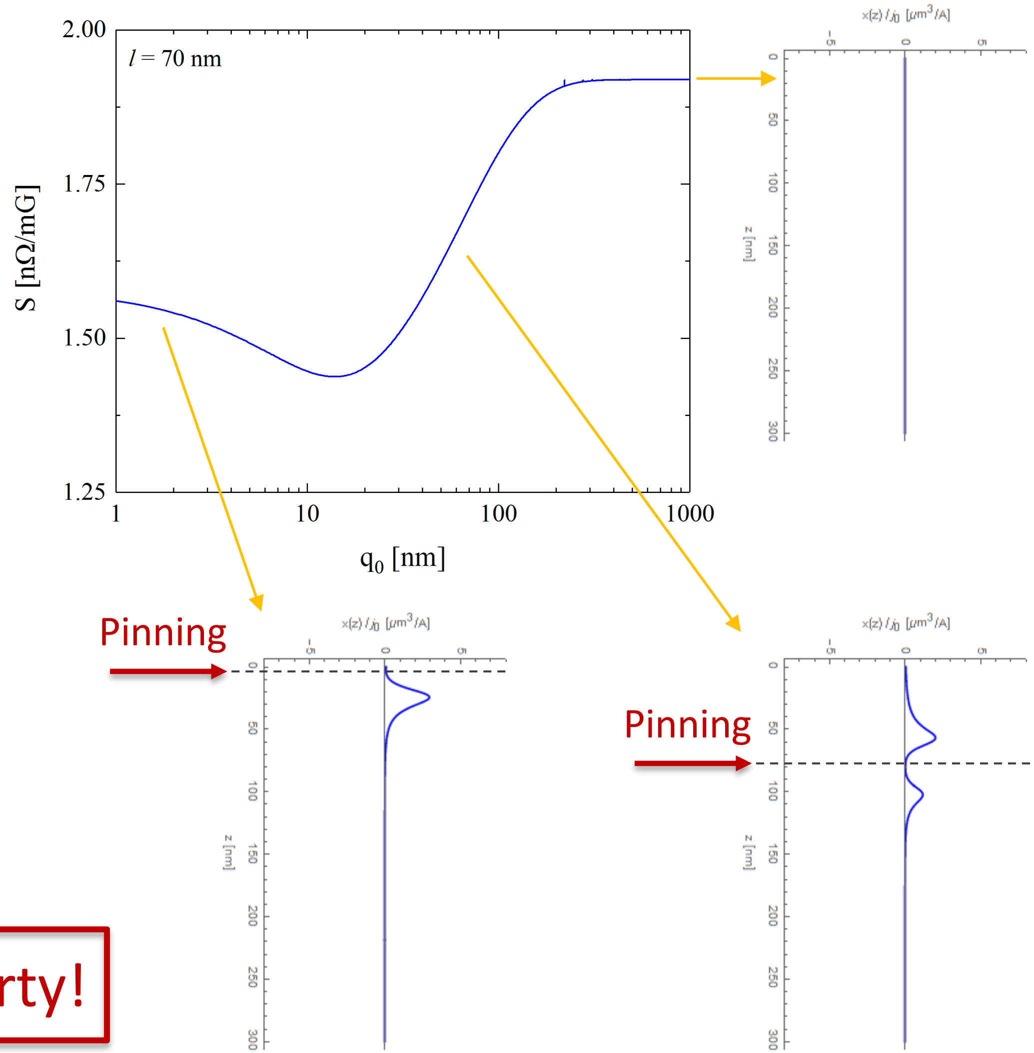
Fermilab

Sensitivity vs pinning site depth

- Vortex dissipation is a *near-surface property*
- The pinning site distance from the surface q_0 determines the resistance
- For instance, if $l = 70\ nm$:
  - $q_0 \cong 15\ nm \Rightarrow$ *sensitivity is the lowest*
  - $q_0 > 400\ nm \Rightarrow$ *constant sensitivity*
  - *bulk pinning does not affect the vortex oscillation*!



$\Rightarrow$ S is a near surface property!

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