Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

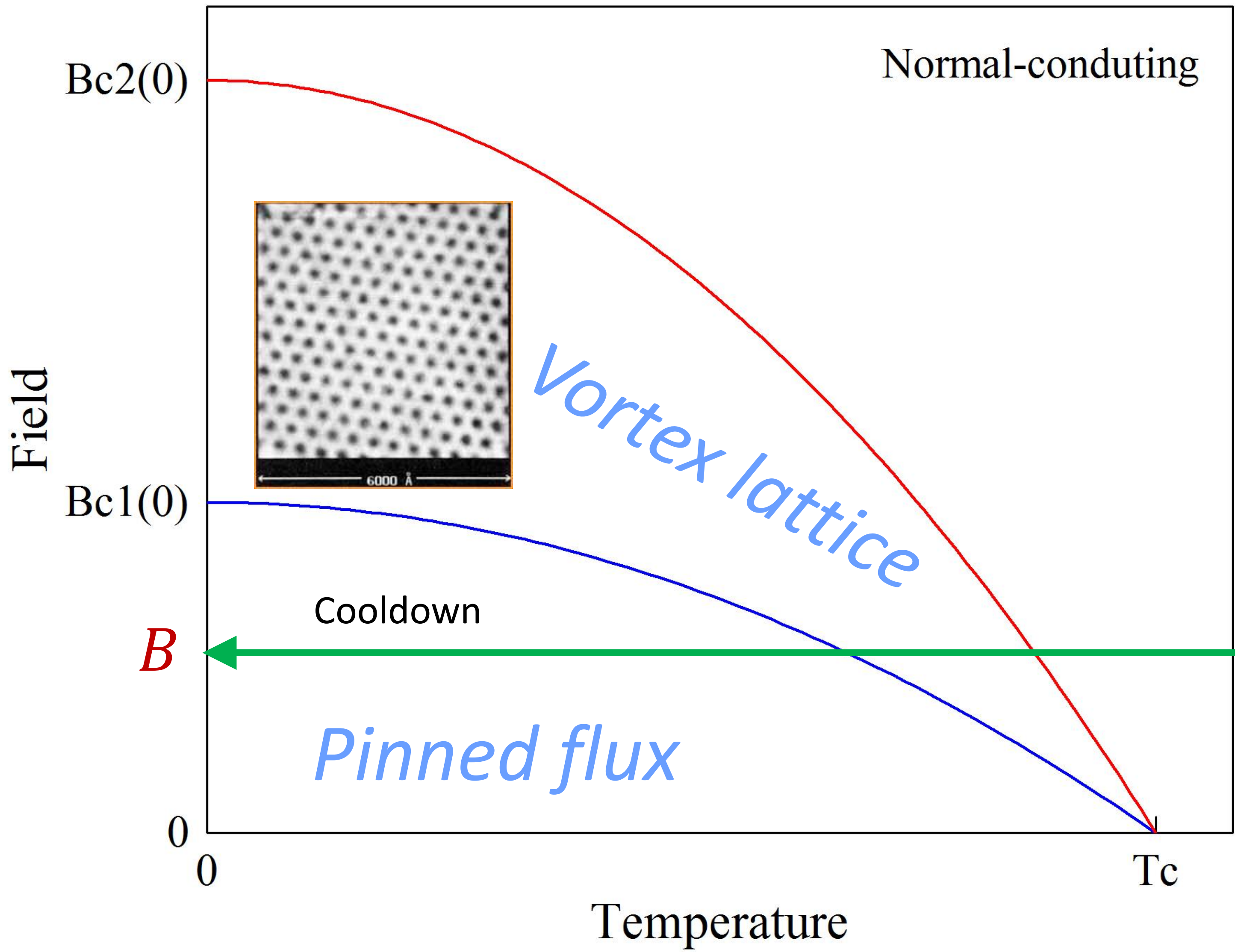
Trapped-flux Surface Resistance at High Gradients

Mattia Checchin

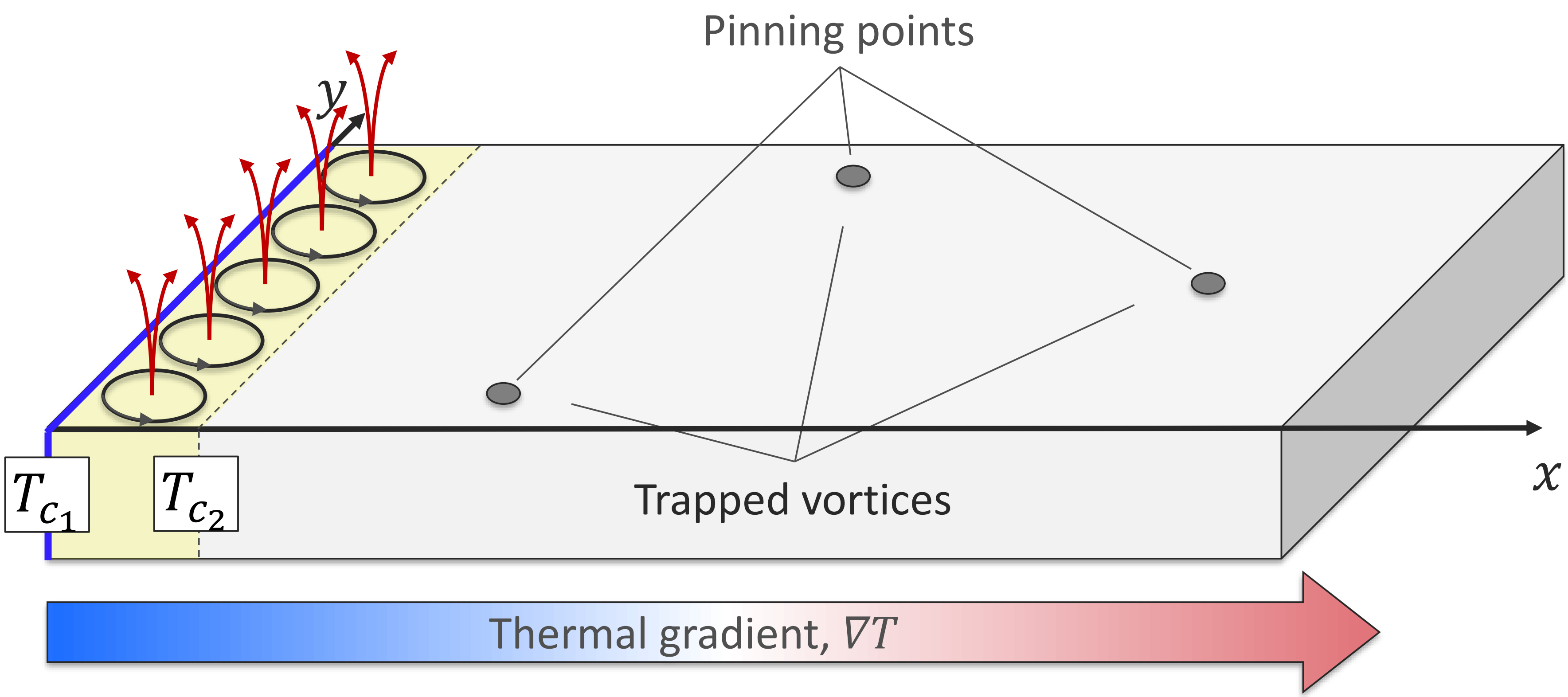
LCWS 2019, Sendai, Japan

29 November 2019

How do vortexes form?



Vortex motion during cooldown



Why do vortices dissipate under RF driving?

- Vortices oscillate driven by the RF current
- Random pinning centers in the m
  la
  m
- Part of the EM energy in the resonator is converted into vortex motion
  - Power
    - we
      sur

$$R_s(T, B_t) = R_{BCS}(T) + R_{fl}(B_t) + R_0$$

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

- η_t flux trapping efficiency
- S sensitivity to trapped flux

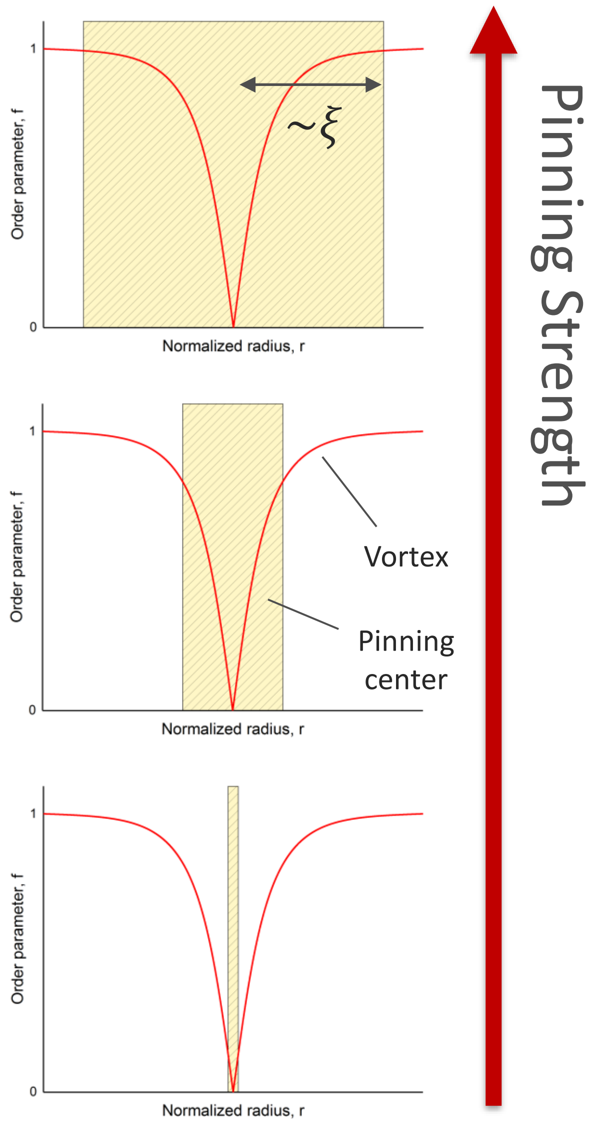
TEX

What is a pinning site?

- Pinning sites are *material imperfections or defects*:
  - Normal-conducting and dielectric inclusions
  - Grain boundaries
  - Dislocations
  - Local disorder

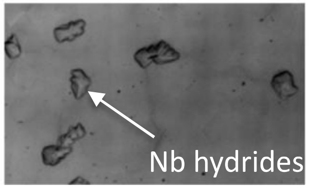
- Pinning ⇒ *minimization of the system energy*
  - Vortex = loss in condensation energy
  - Defect = weak or not superconducting site

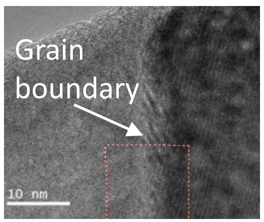
- An efficient pinning center has *dimension* at least *comparable to the coherence length* ξ
  - **At 2 K for niobium $\xi \cong 10 - 38\ nm$**
  - **Near Tc for niobium $\xi \cong 150 - 300\ nm$**
  - ξ is the characteristic variation length of the order parameter in the superconductor

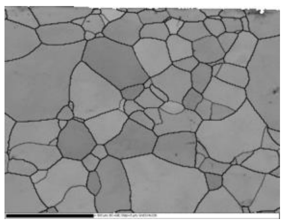


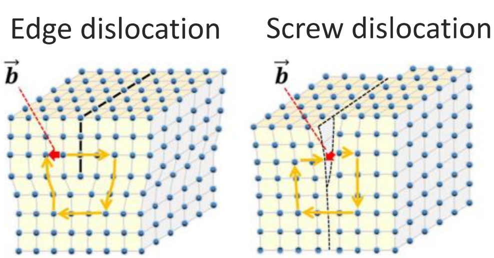
Curtesy of M. Martinello

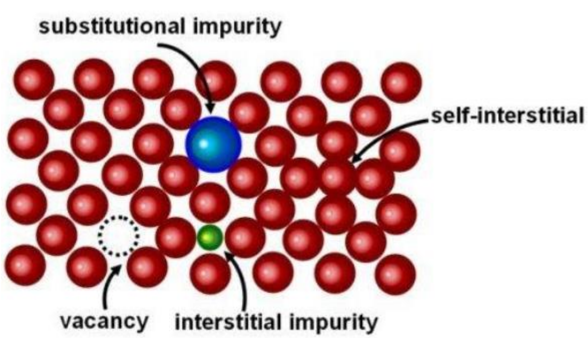
Possible pinning sites in Nb







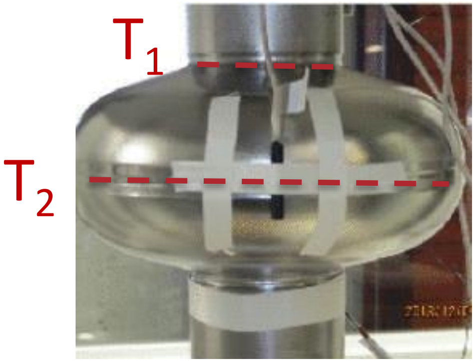




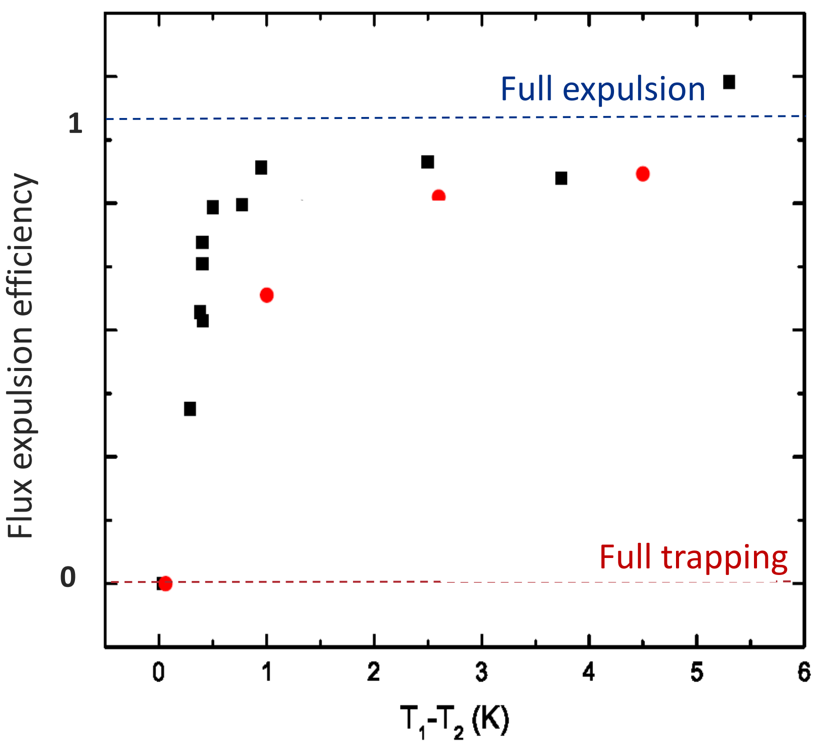
- Normal-conducting and dielectric inclusions: 3-D defects that introduce large κ variation (ex: nano-hydrides in the near-surface area)
- Grain boundaries: 2-D defects in the crystal structure, they define the interface between 2 grains.
  - Low-angle GBs: the misorientation between the two grains is <15 degrees
- Dislocations: areas were the atoms are out of position in the crystal structure.
  - Tangles: after plastic deformation very small grain forms (cells) that are surrounded by tangles of dislocations
- Local disorder: 1-D defects (ex: impurities, vacancies)

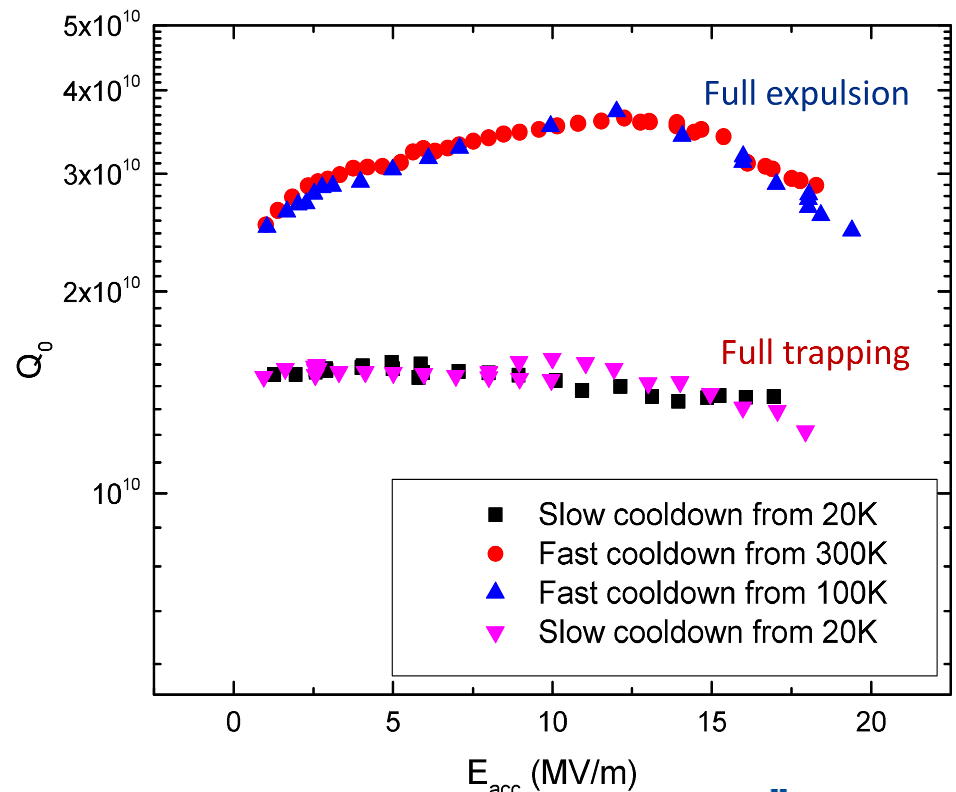
Flux expulsion

Fast cool-down helps flux expulsion



- Fast cool-down leads to large thermal gradients → efficient flux expulsion
- Slow cool-down leads to small thermal gradients → poor flux expulsion

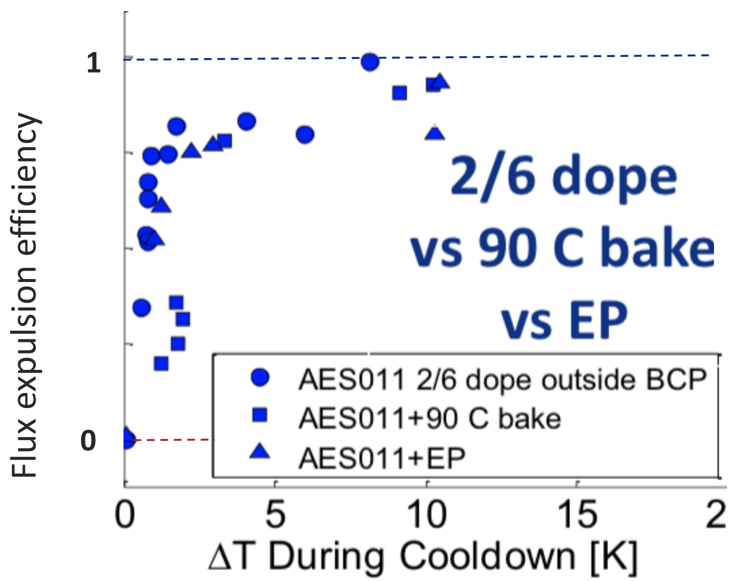


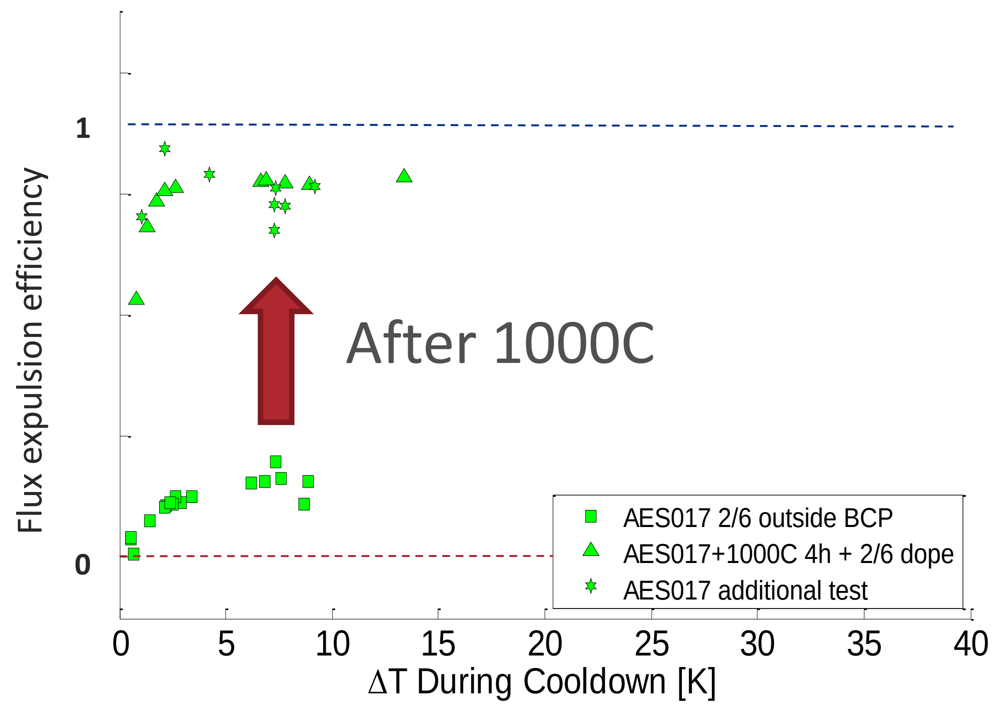


A. Romanenko et al., Appl. Phys. Lett. **105**, 234103 (2014)
A. Romanenko et al., J. Appl. Phys. **115**, 184903 (2014)

Flux expulsion depends on bulk properties

- Flux expulsion is a **bulk property** → does not depend on surface treatment
- Not all materials show good flux expulsion, even with large thermal gradient during the SC transition → high T treatments allow to improve materials flux expulsion properties





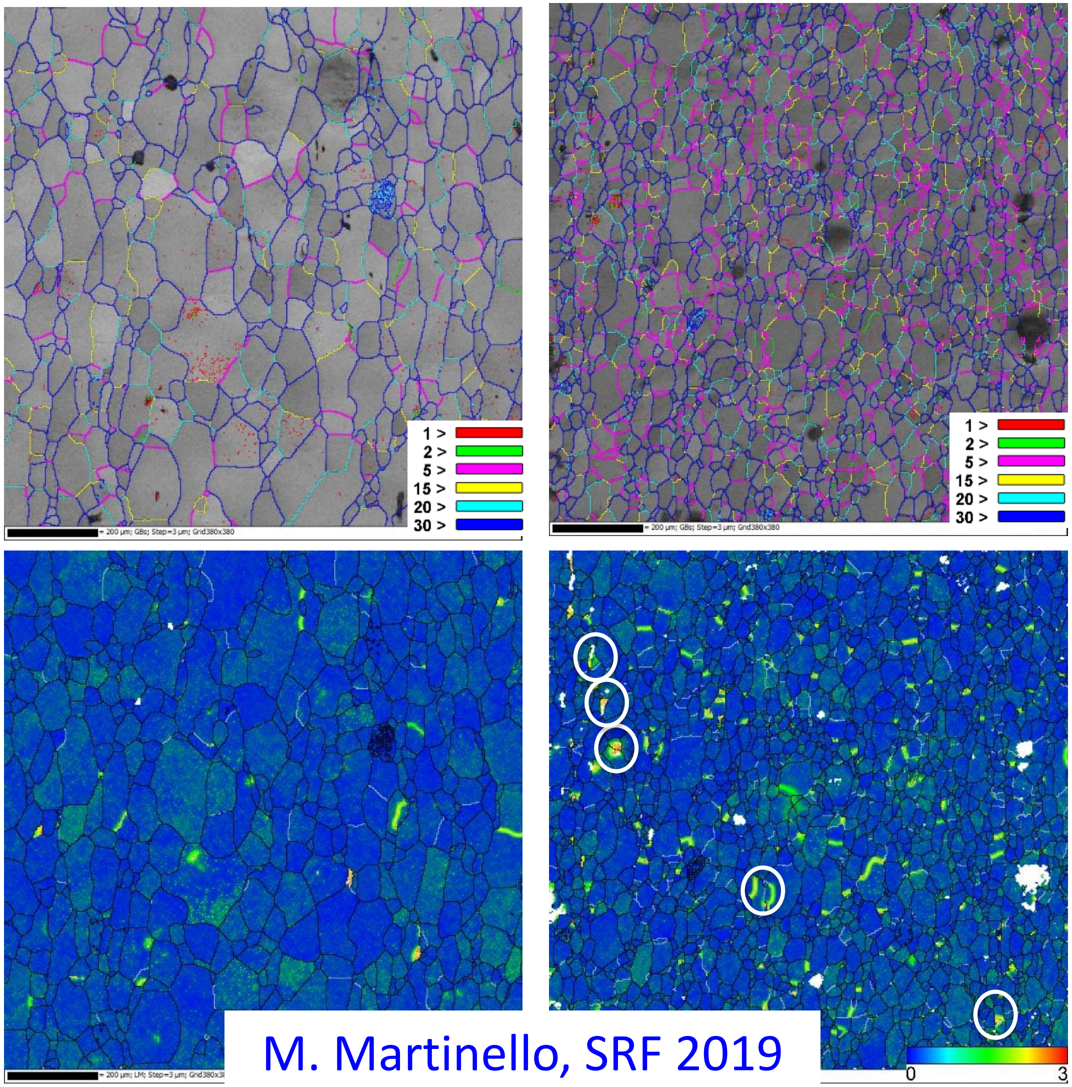
S. Posen et al., J. Appl. Phys. **119**, 213903 (2016)

Analysis of "as received" materials

- Material that shows **good flux expulsion** properties after annealing at 800C has <u>bigger grain size</u> in the "as received" condition
- Material with **bad flux expulsion** properties shows <u>larger density of low-angle GBs</u> (misorientation < 15°)
- Material with bad flux expulsion properties shows <u>larger density of regions with very high local misorientation</u>

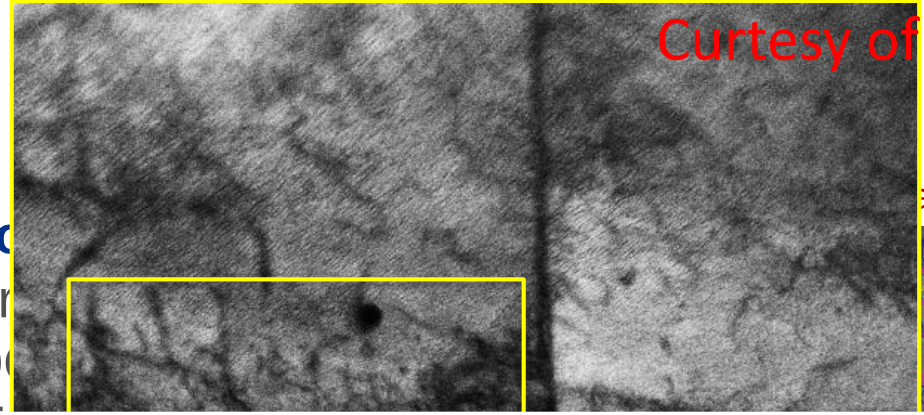
ATI -good flux expulsion-

Ningxia -bad flux expulsion-



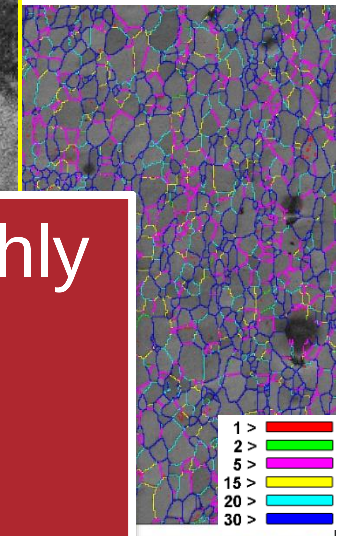
M. Martinello, SRF 2019

Analysis of “as



- Material that shows go
  flux expulsion proper
  after annealing at 800
  has bigg
  the “as r

ad flux expulsion-

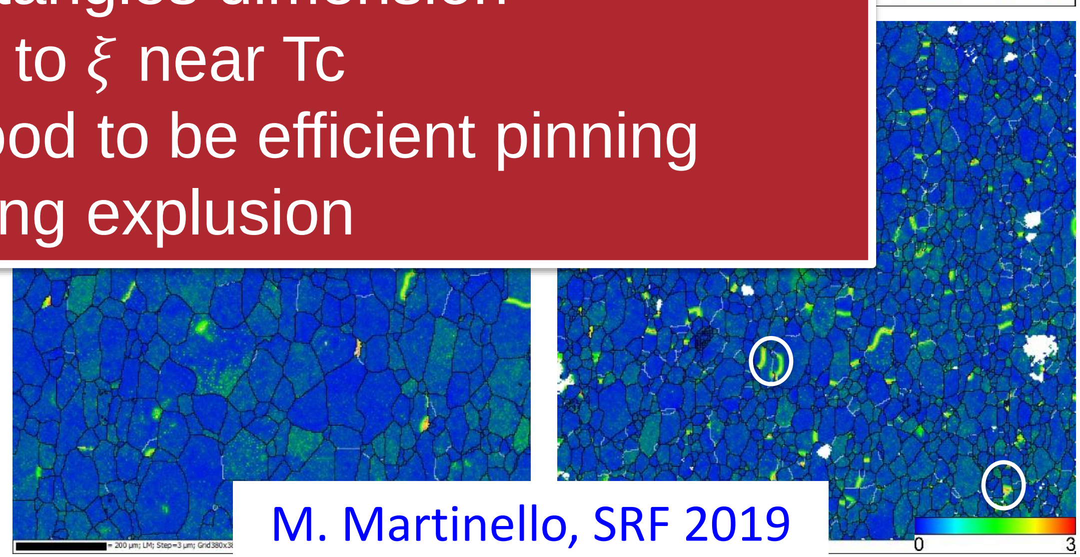


- Material
  expulsi
  shows la
  low-ang
  (misorie

- Material
  expulsion properties
  shows larger density of
  regions with very high
  local misorientation

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

- ➪ Dislocation tangles dimension comparable to ξ near Tc
- ➪ High likelihood to be efficient pinning centers during explusion



M. Martinello, SRF 2019

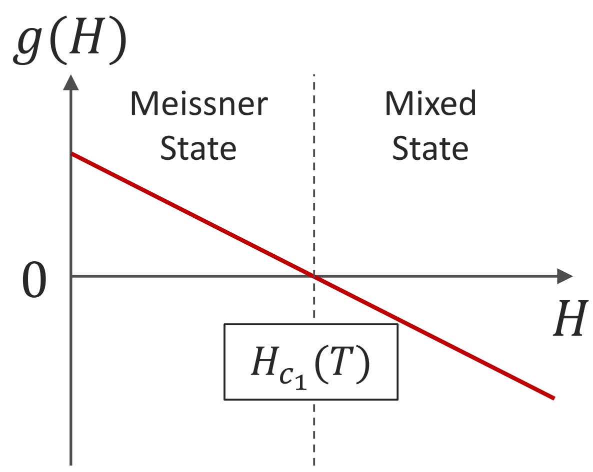
Fermilab

Thermodynamic considerations on flux expulsion

Thermodynamic force during cooldown

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

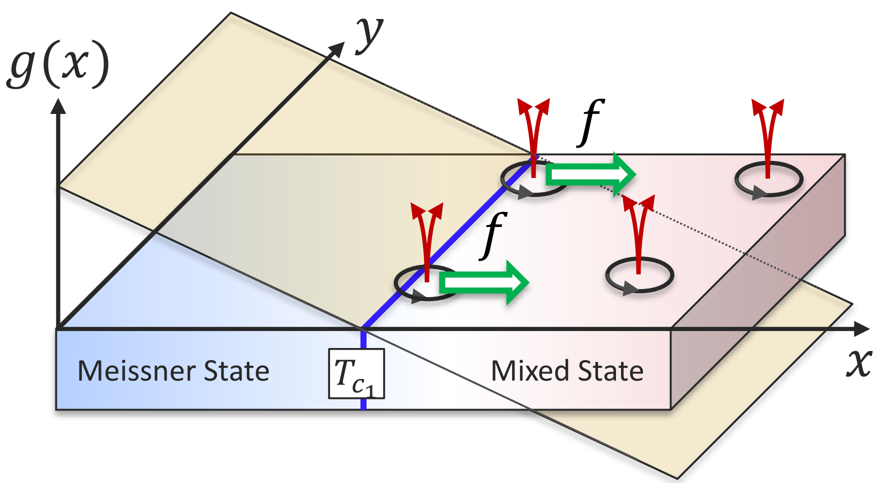
$$g = B(H_{c_1}(T) - H)$$



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

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

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



M. Checchin, TTC, MSU 2017

Critical thermal gradient

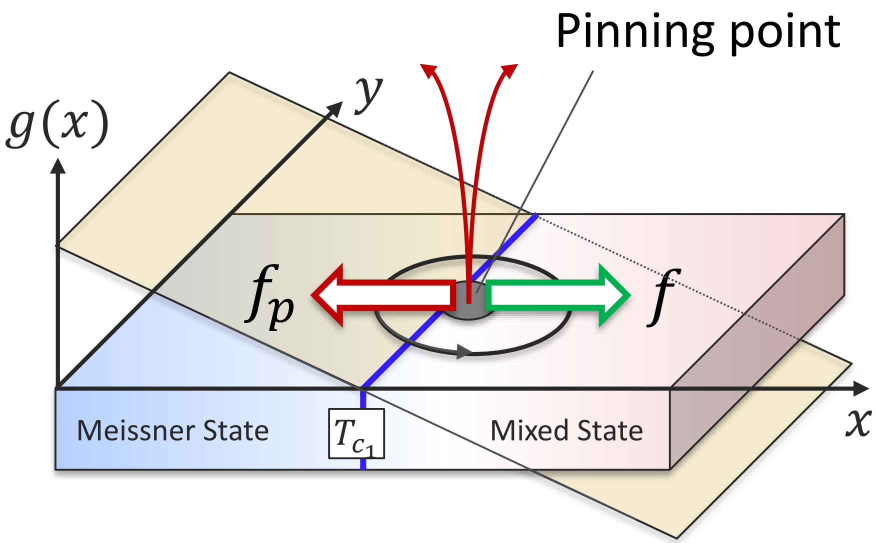
The *pinning force acting against the expulsion* is defined in terms of critical current density J_c:

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

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

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

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



M. Checchin, TTC, MSU 2017

Statistical definition of trapping efficiency

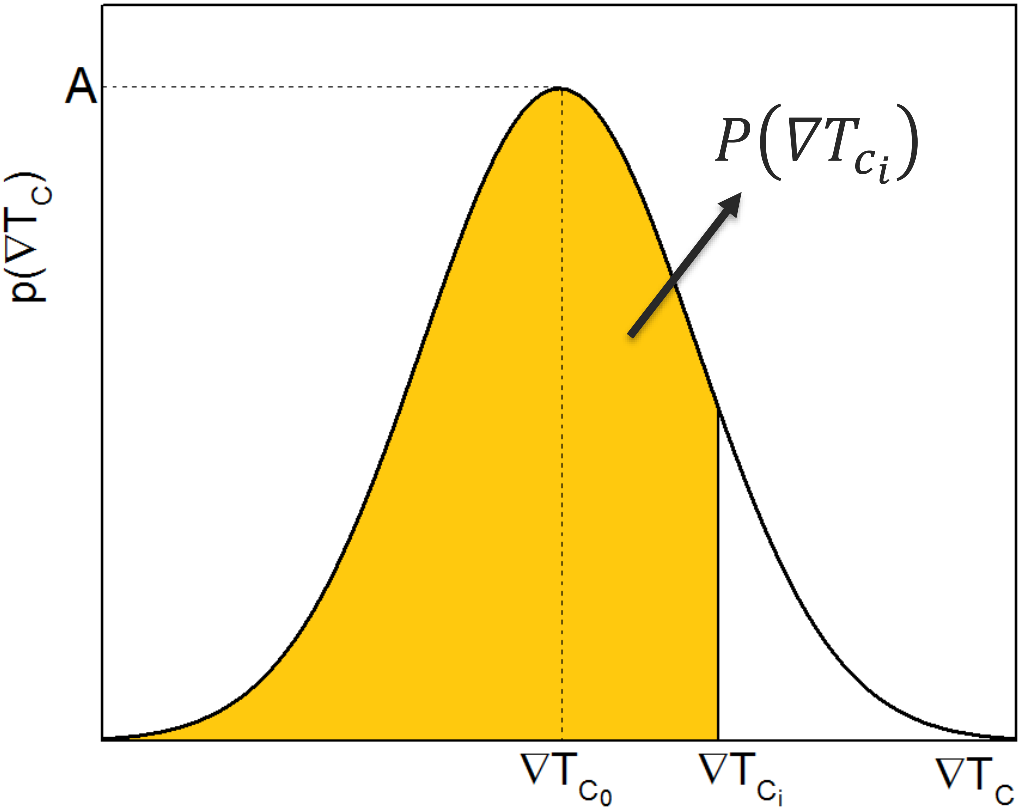
- The probability of expelling vortices with the thermal gradient ∇T_{c_i} is $P(\nabla T_{c_i})$
- The trapping efficiency η_t is function of ∇T_{c_i}:

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

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

- The trapped field is then:

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



M. Checchin, TTC, MSU 2017

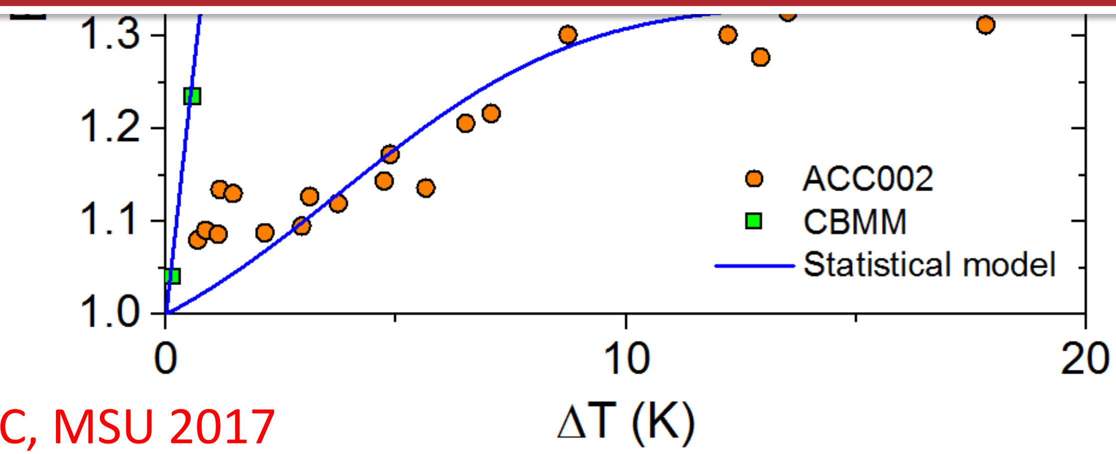
Comparison with experimental data

Good agreement with experimental data

Estimated J_c in agreement with literature values for Nb $(1-10\ \mathrm{A/mm^2})$

J_c measurement near T_c can provide us lot of info on the expulsion properties of the cavity material

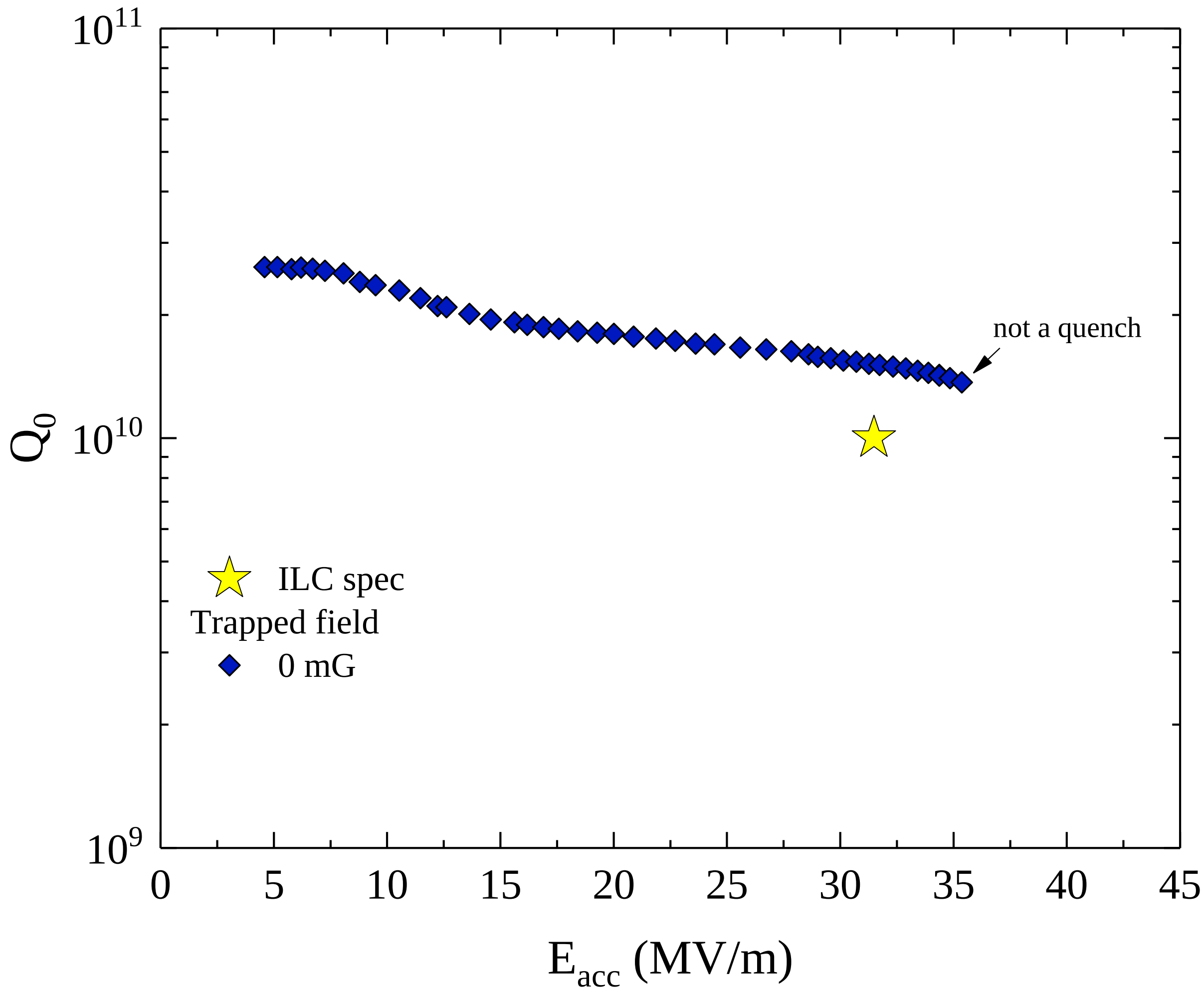
- J_c measurements are being conducted at Fermilab



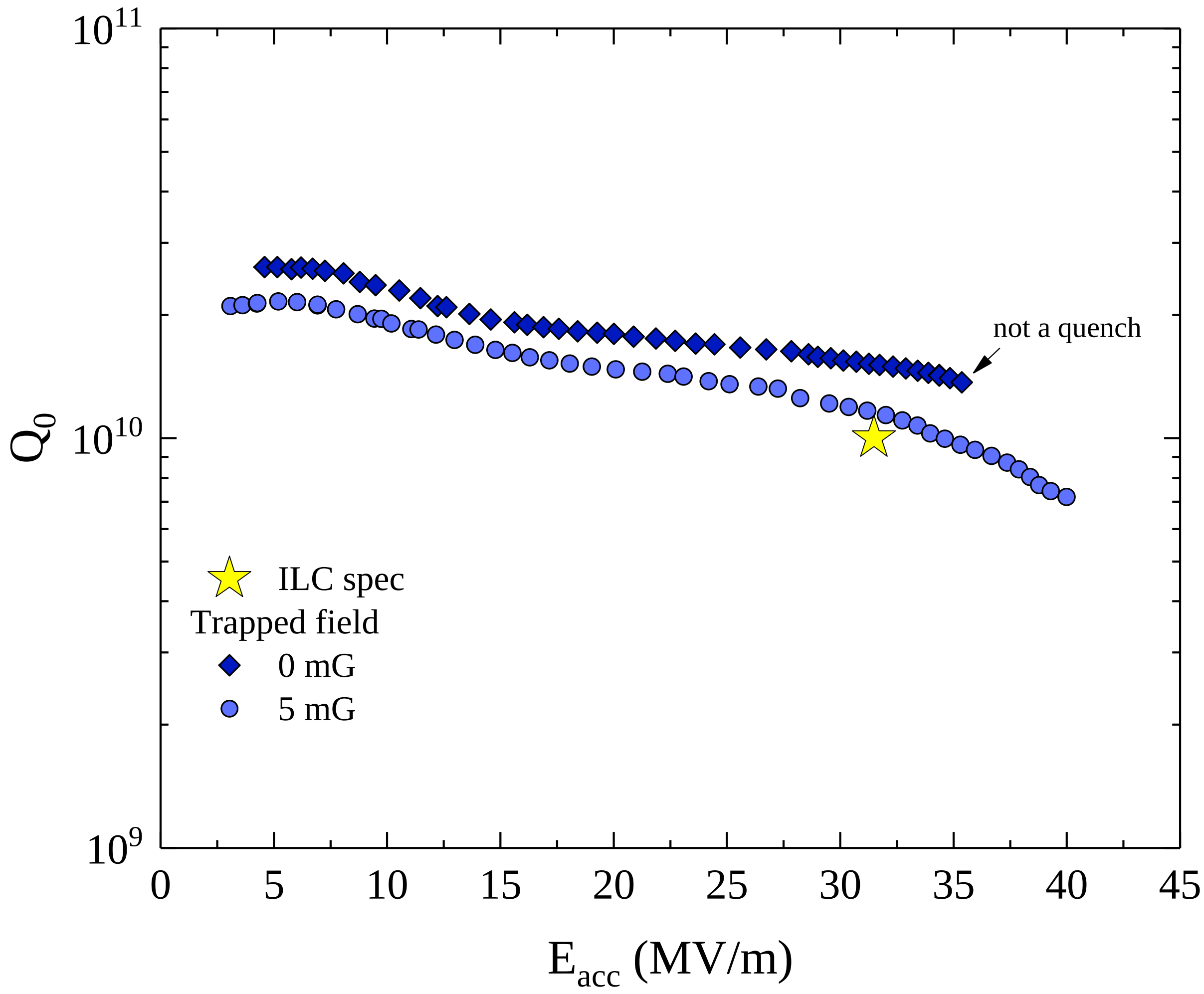
M. Checchin, TTC, MSU 2017

Trapped flux sensitivity at high accelerating gradients

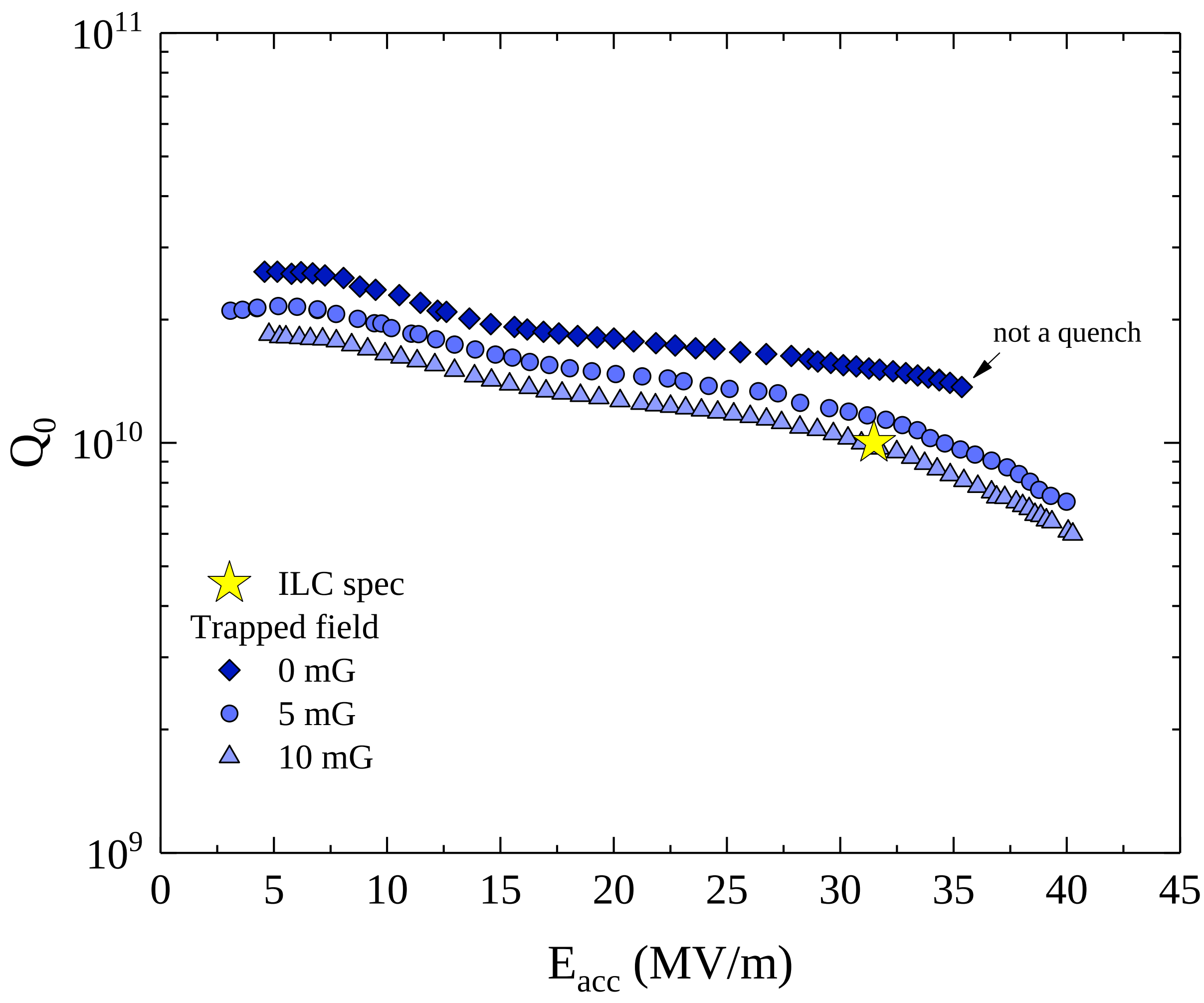
Standard ILC cavity performance (no trapped field)



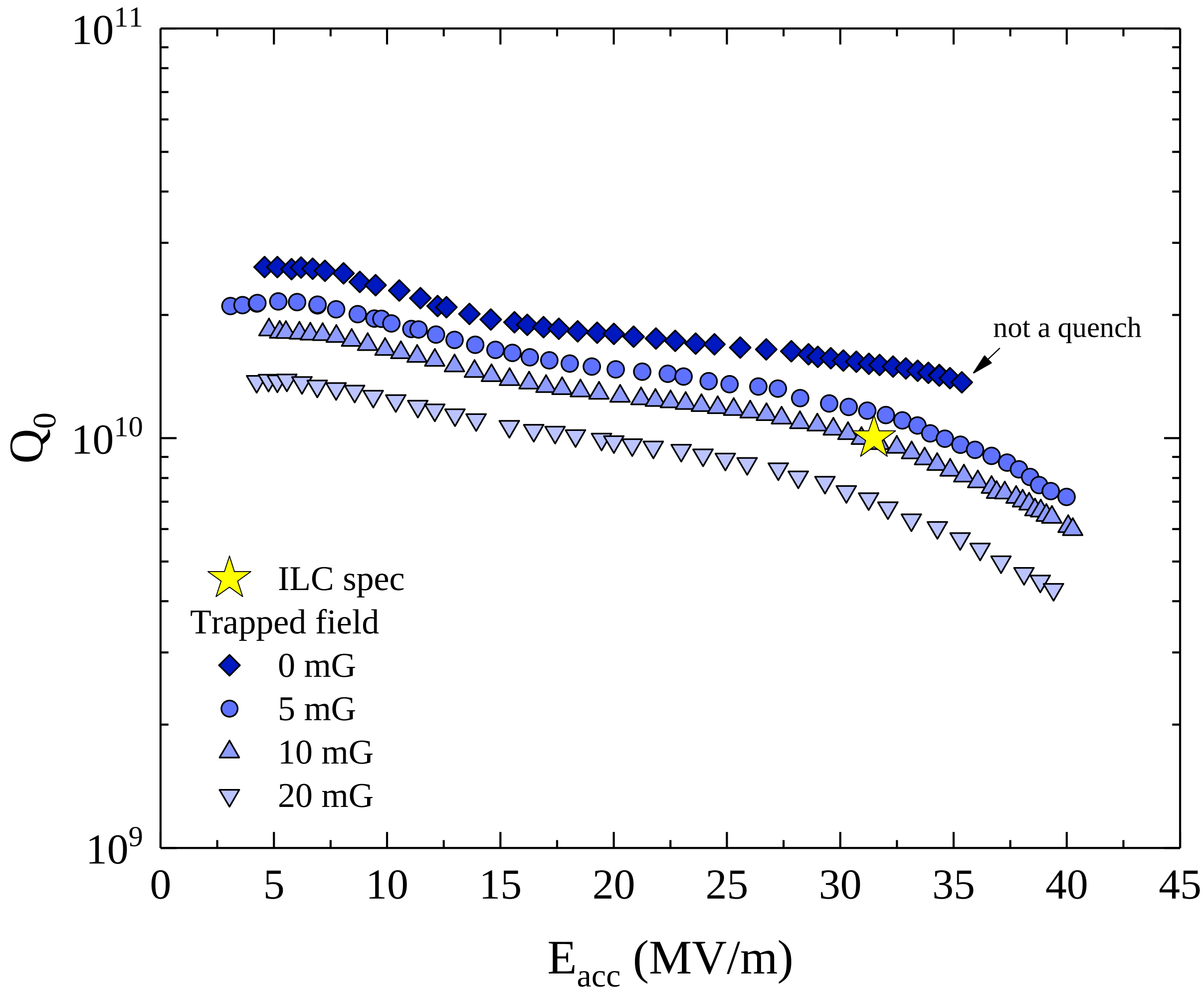
Standard ILC cavity performance (5 mG trapped)



Standard ILC cavity performance (10 mG trapped)

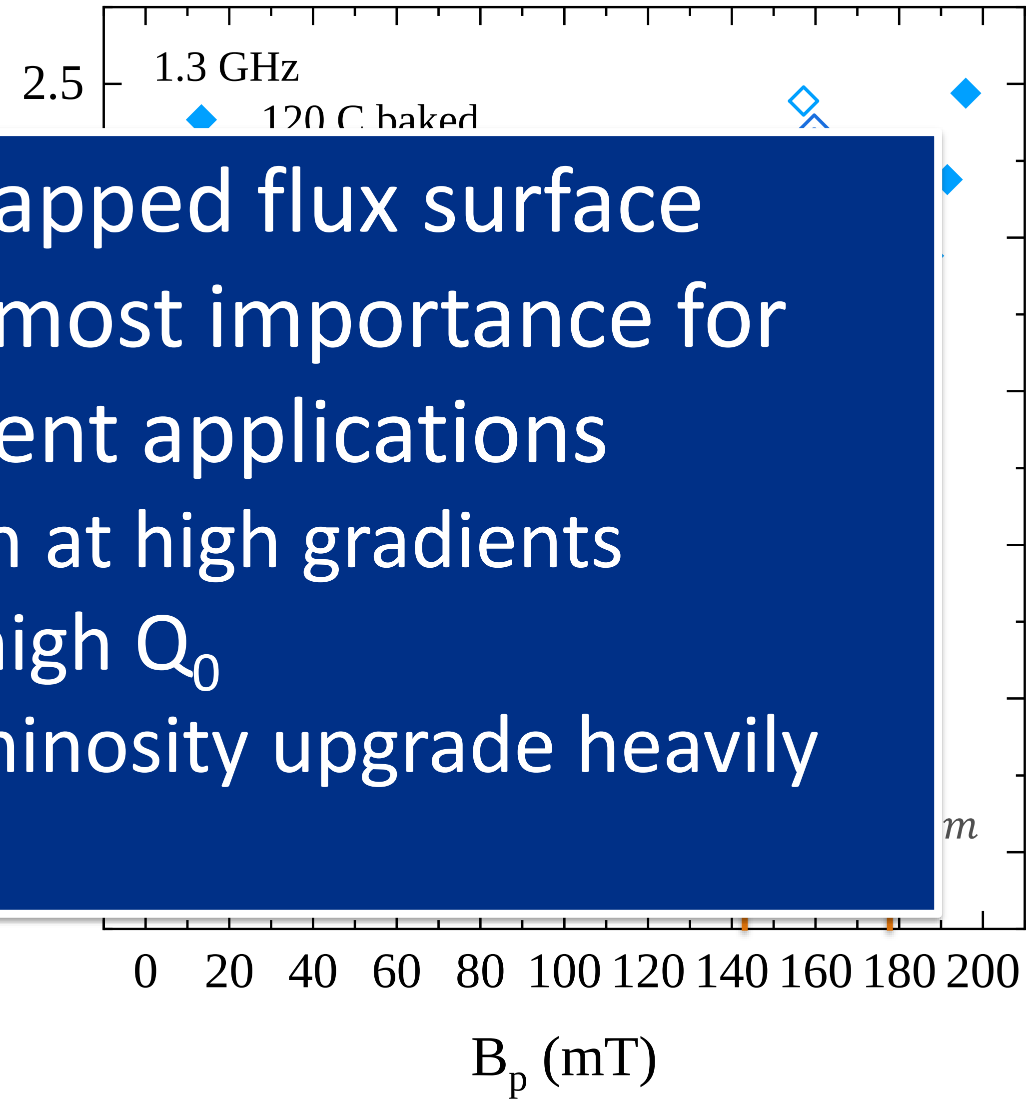


Standard ILC cavity performance (20 mG trapped)



Sensitivity at high RF field

- ***S*** assumes values **as high as** **2 nΩ/mG at**



gradients

Minimization of trapped flux surface resistance is of upmost importance for high-Q/high-gradient applications

- ⇨ Power dissipation at high gradients minimized with high Q_0
- ⇨ Possible high-luminosity upgrade heavily depends on Q_0

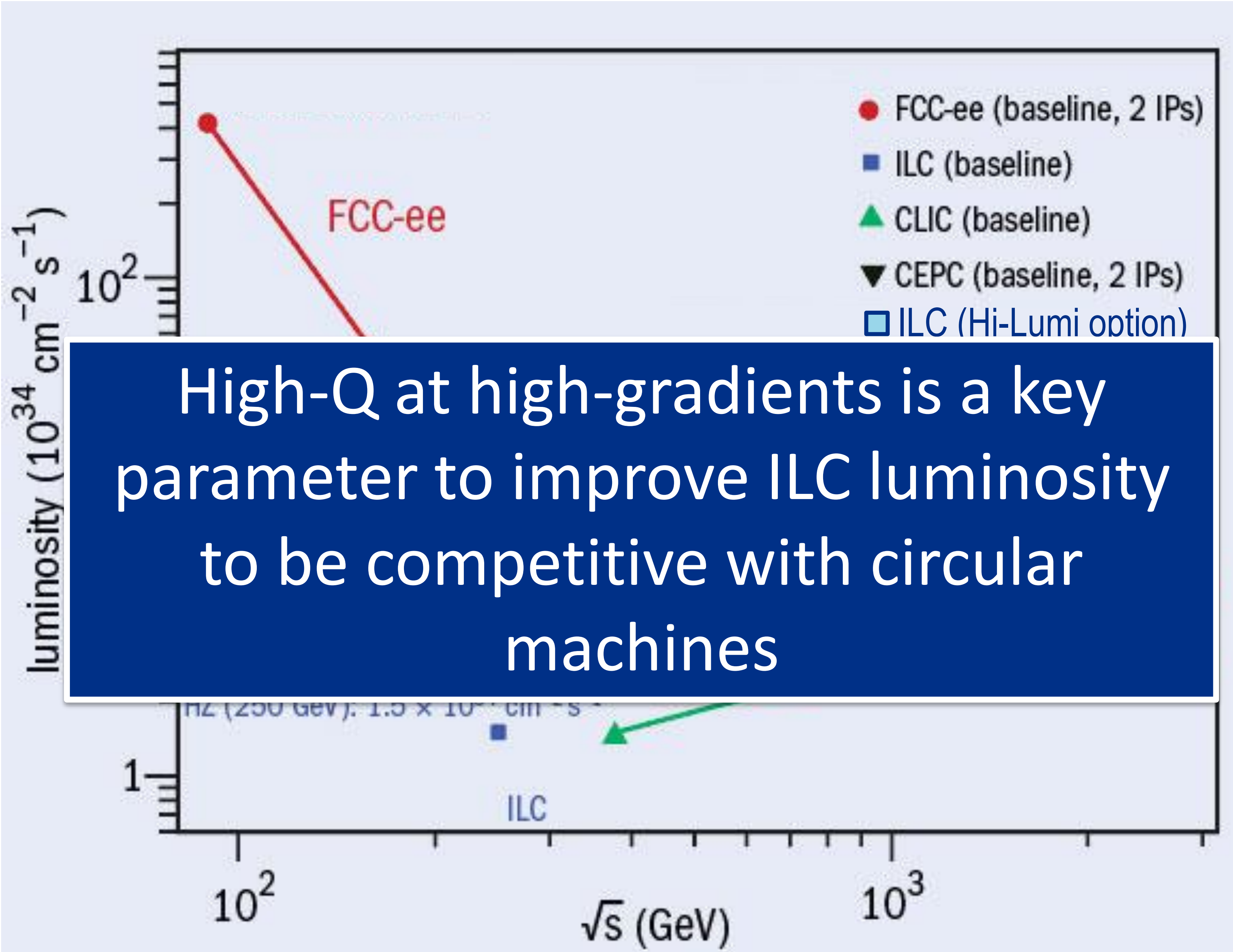
Fermilab High Luminosity ILC Workshop (May 2019)

- Significant luminosity improvements are made possible by SRF R&D advances since TDR
- Main result is given in table below – by implementing technically feasible changes, ILC baseline luminosity of 1.35 x 10^{34} can be increased
  - Increased number of bunches x 2
  - Increased rep rate x 3
  - Increased Q_0 x 2
  - Beam and IP parameters same as ILC baseline

× 14.8

- Effective luminosity with polarization advantage (x 2.5) is 20 x 10^{34} $cm^{-2}s^{-1}$ (ILC) vs. 17 x 10^{34} $cm^{-2}s^{-1}$ (FCC-ee, including multiplier of 2 for multiple interaction points)
- AC power 267 MW (ILC) vs. 282 MW (FCC-ee)
- Capital cost ~7.7B (ILC) vs. 10.5B (FCC-ee)
  - Not including labor or detectors

Details in https://arxiv.org/abs/1910.01276



High-Q at high-gradients is a key parameter to improve ILC luminosity to be competitive with circular machines

Based on CERN Courier, 24 January 2019

Details in https://arxiv.org/abs/1910.01276

Numerical simulations of vortex dynamics and surface resistance

Single-vortex dynamics simulation

Neglecting the inertial term ($m_v \approx 0$):

$$\eta_0 \dot{u}(t,z) = \epsilon u''(t,z) + f_p\big(u(t,z)\big) + f_L(t,z)$$

VISCOUS DRAG

LINE TENSION

PINNING FORCE

LORENTZ FORCE

Single-vortex dynamics simulation

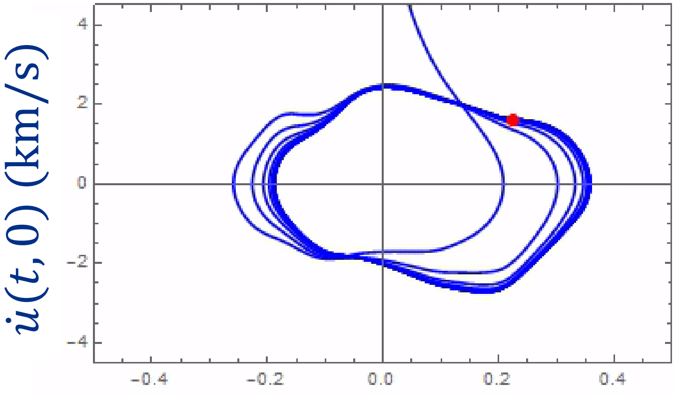
Neglecting the inertial term ($m_v \approx 0$):

$$\begin{cases} \eta_0 \dot{u}(t,z) = \epsilon u''(t,z) + f_p\big(u(t,z)\big) + f_L(t,z) \\ u(0,z) = 0 \\ u'(t,0) = 0 \\ u'(t,Z_{max}) = 0 \end{cases}$$

Equation solved with method of lines until steady-state, then the surface resistance is calculated as:

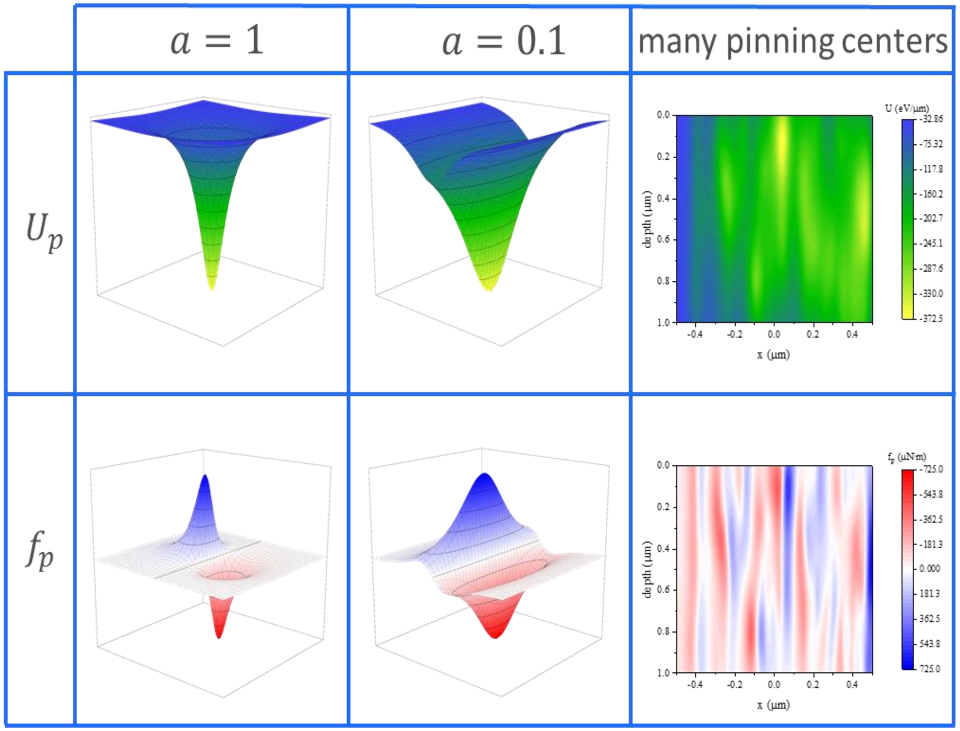
$$R_{fl} = \frac{2B_t\mu_0 f}{\lambda B_p} \int_0^{1/f} \cos\omega t \int_0^{\infty} \dot{u}\, e^{-z/\lambda}\, dz\, dt$$

Example of convergence to steady-state solution



Pinning landscape from building block potential

- Real pinning potential is unknown
- Pinning landscape defined as the sum of many pinning potentials
- Every pinning potential is a modified Lorentzian function
  - a is the anisotropy parameter
  - U_i potential depth
  - X_i and Z_i pinning center coordinates



GAUSSIAN DISTRIBUTION

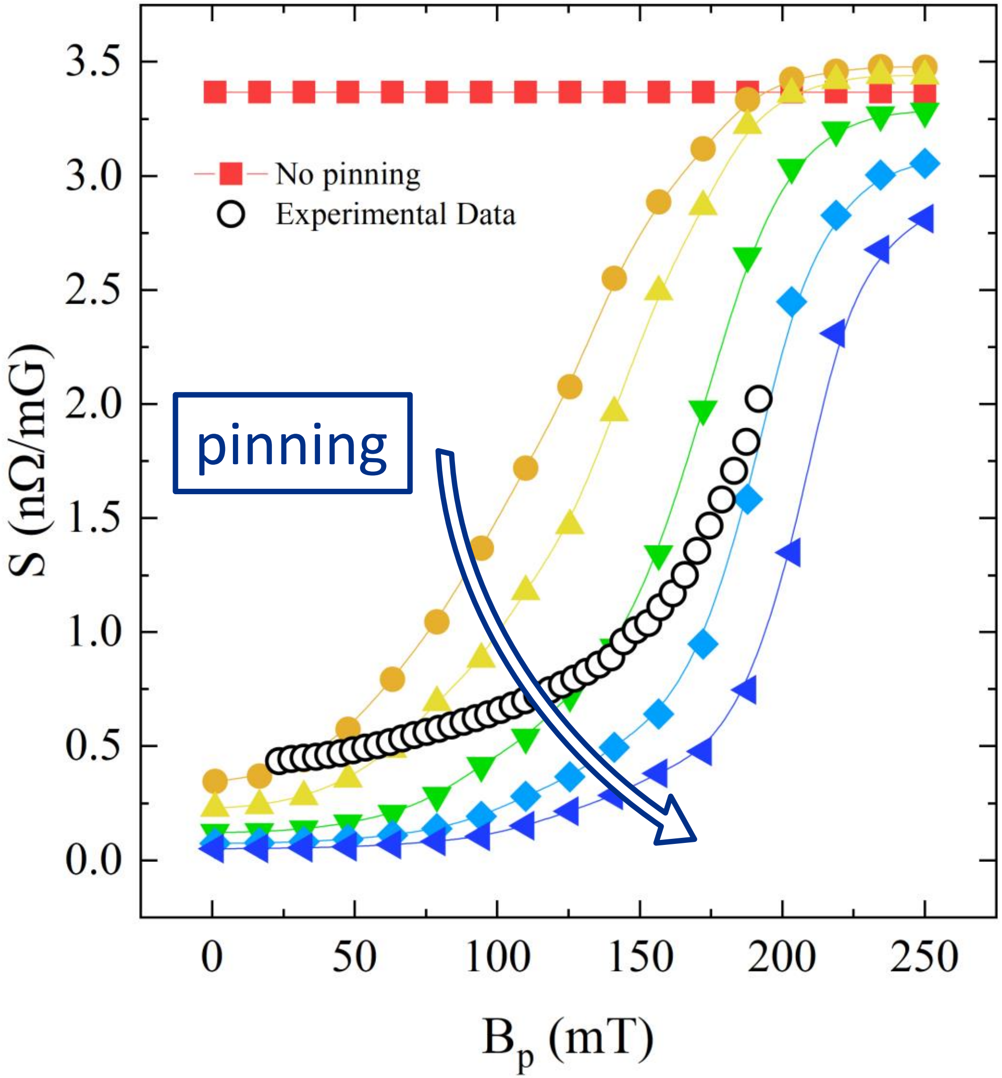
$$U_p(u,z) = -\sum_i \frac{(2\xi)^2 U_i}{(2\xi)^2 + (u - X_i)^2 + a(z - Z_i)^2} \qquad f_p(u,z) = -\frac{\partial U_p(u,z)}{\partial x}$$

RANDOM DISTRIBUTION

Fermilab

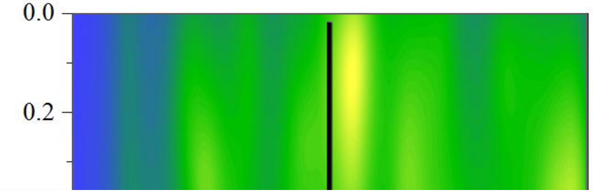
Comparison with experimental data at 1.3 GHz

- Good qualitative agreement with experimental data

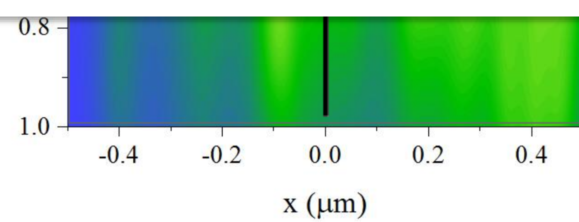


Fermilab

RF depinning



ILC should follow LCLS-II example to mitigate trapped flux surface resistance

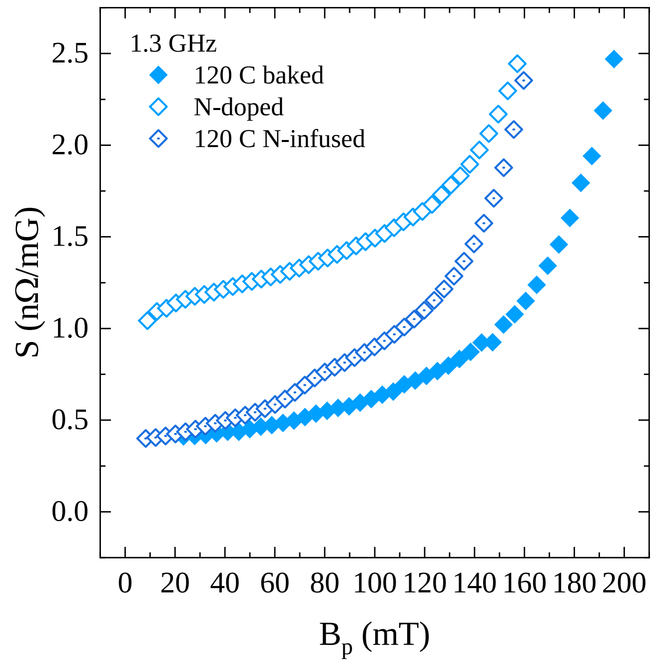


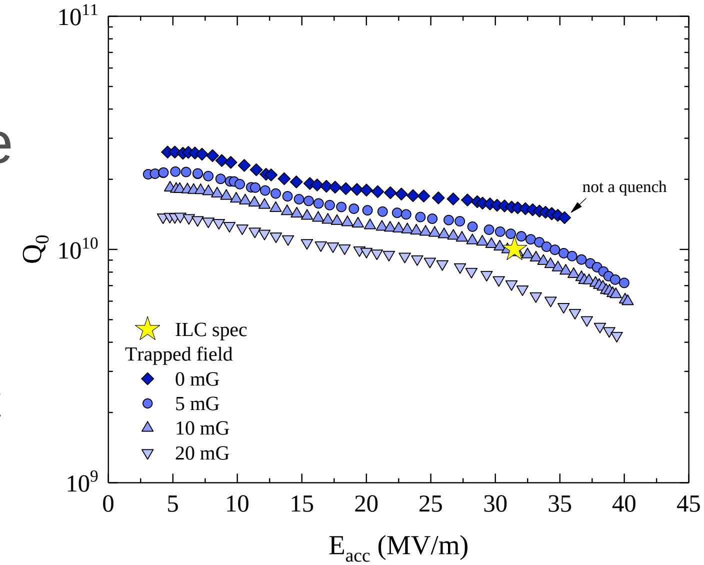
Fermilab

Concluding…

Conclusions

- **High-gradient sensitivity is very large** and jeopardizes the performance of high-Q/high-E_{acc} SRF cavities
- To mitigate this issue, it is of primary importance to:
  - utilize materials with low occurrence of high local misorientation (good expulsion)
  - allow for fast cool-down in CMs
  - implement strict magnetic field hygiene
  - improve magnetic shielding (compensation coils?)
- **LCLS-II** is a **successful example ILC should follow** to mitigate this issue



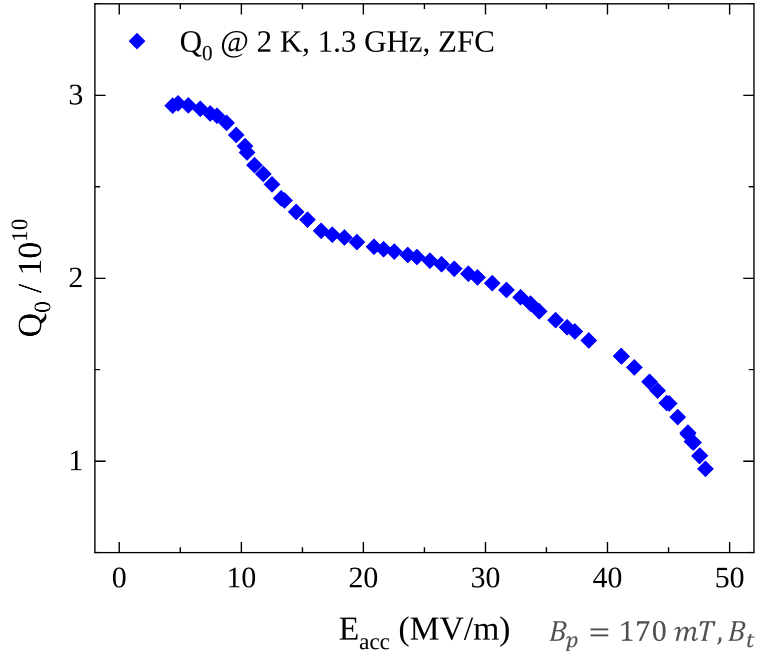


Thank you for your attention!

Backup slides

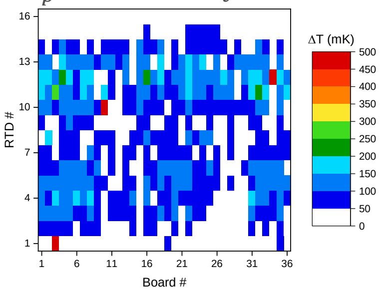
Detailed study of sensitivity at high RF amplitude

- Set-up for sensitivity study:
  - High gradient cavity with ILC recipe ($E_{max} = 48\ MV/m$)
  - Helmholtz coils
  - 3 FGs at equator
  - RTDs at irises and equator
  - Temperature mapping (Tmap)

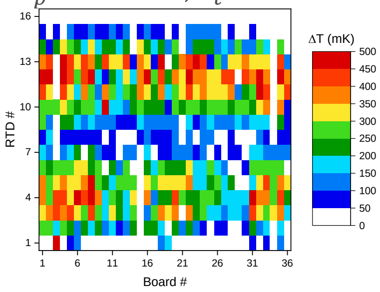


- Objective:
  - Gather new insights on trapped flux sensitivity at high RF field level
  - Study the dissipation pattern due to trapped vortices with Tmap

$B_p = 170\ mT, B_t = 30\ mG$



$B_p = 170\ mT, B_t = 100\ mG$

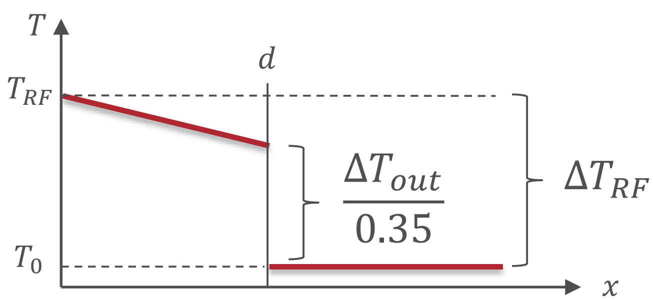


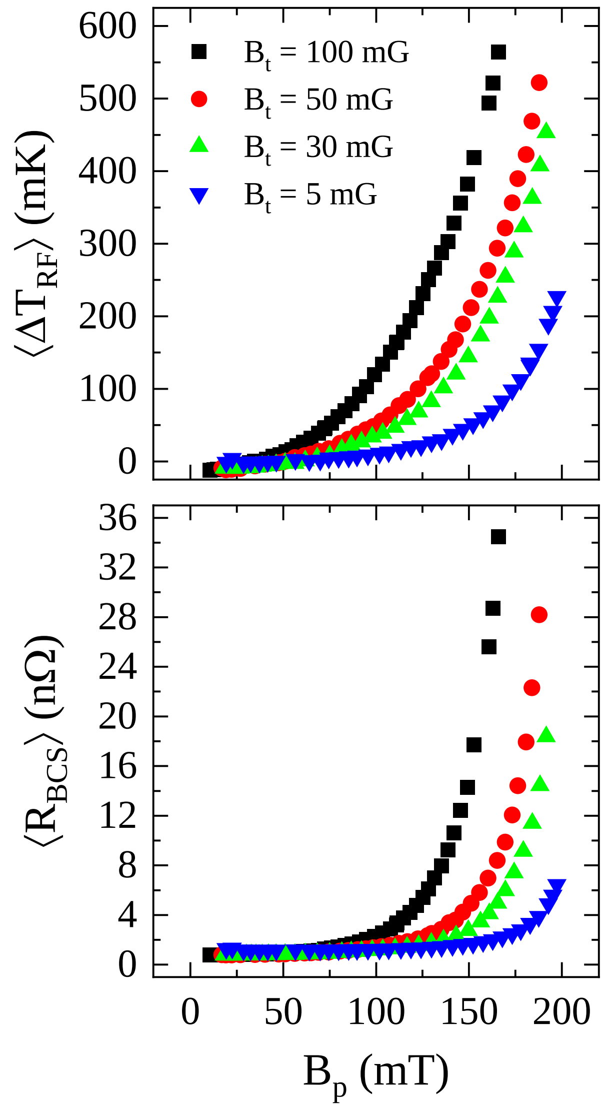
Thermal contribution estimation

- 1D thermal diffusion model
- From Tmap data: $\langle \Delta T_{out} \rangle$
  - RTD efficiency ~35%
- From RF data: $P_c = \frac{g}{2} \frac{H_p^2}{Q_0}$

$$\langle \Delta T_{RF} \rangle = \frac{d}{\kappa(T)} P_c + \frac{1}{0.35} \langle \Delta T_{out} \rangle$$

- $\langle R_{BCS} \rangle$ estimated with Halbritter code

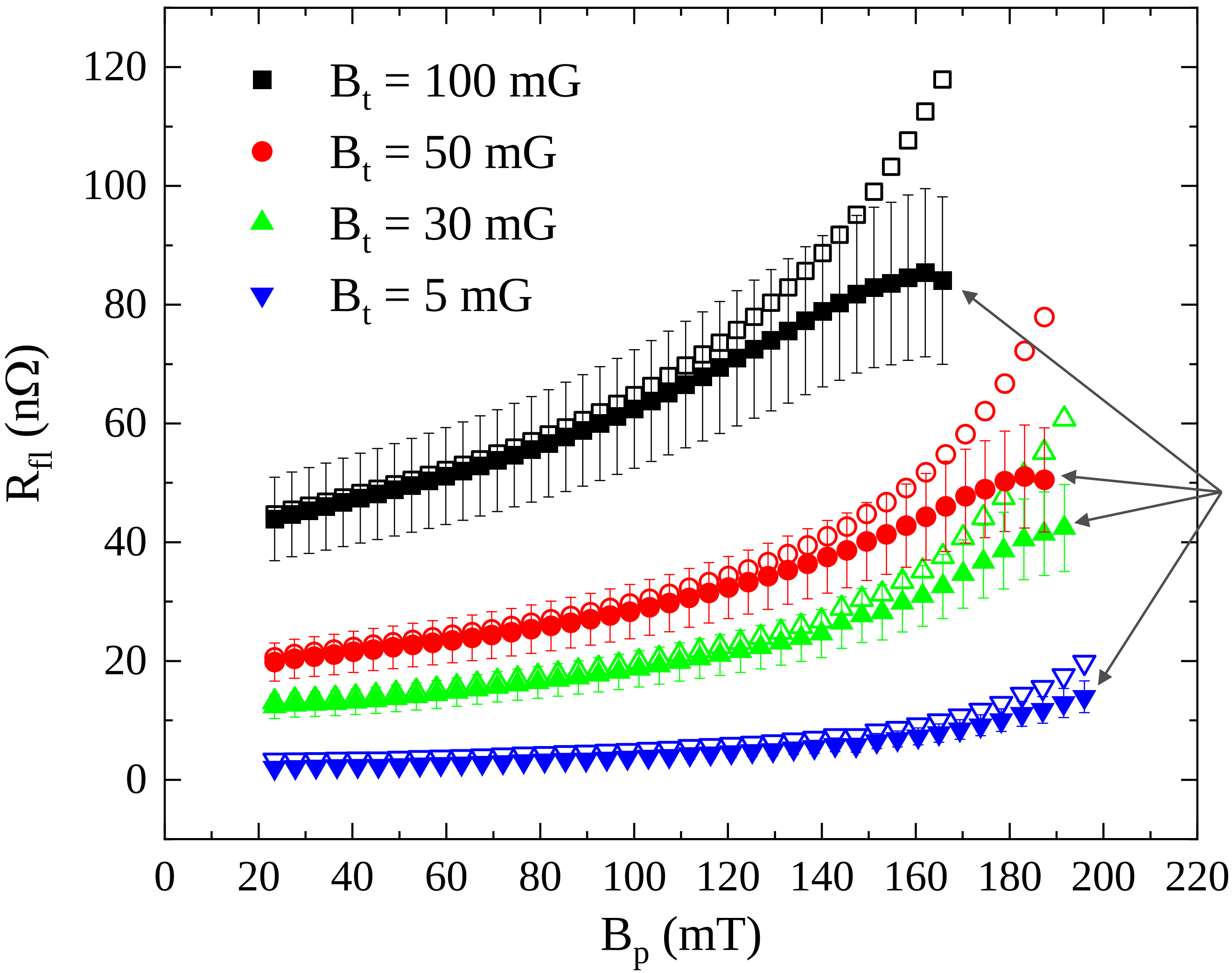




$\kappa(T) = 0.7 e^{1.65T - 0.1T^2}$ – P. Bauer et al. Physica C 441, 51 (2006)

Vortex surface resistance at high RF amplitudes

1.3 GHz, 120 C baking



corrected for thermal contribution

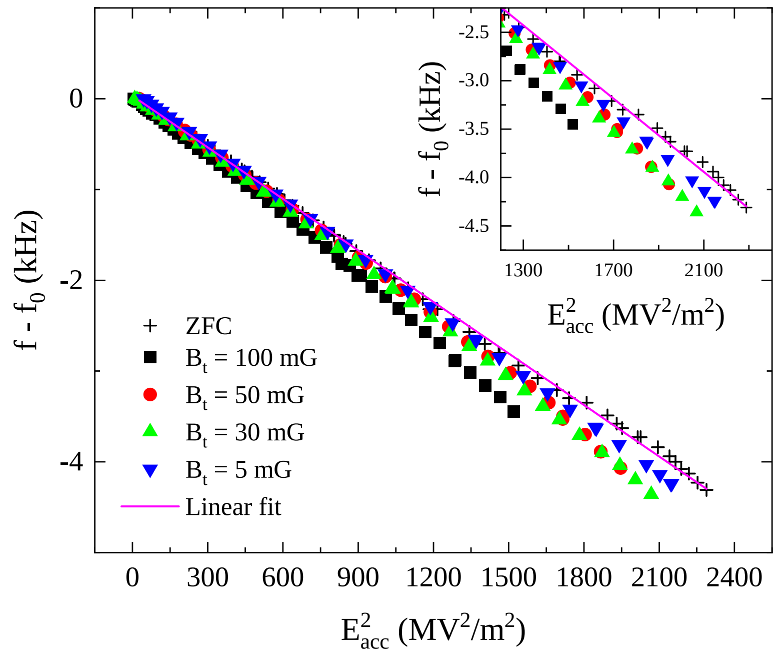
Fermilab

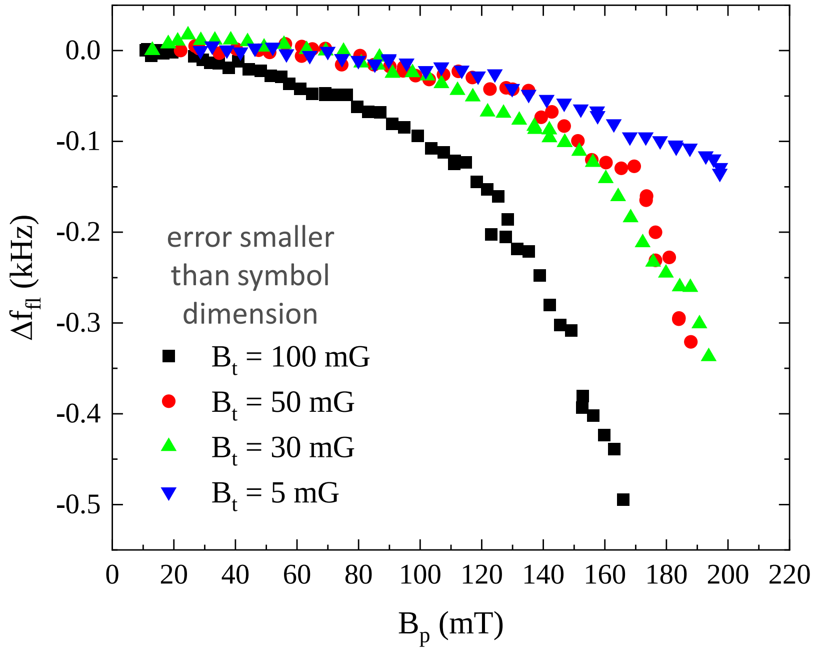
Trapped-flux frequency shift

- Deviations from Lorentz force detuning observed when the cavity is field-cooled (FC)
- Δf_{fl} frequency shift due to trapped vortices

$$\Delta f_{fl} = \Delta f_{FC} - \Delta f_{ZFC}$$

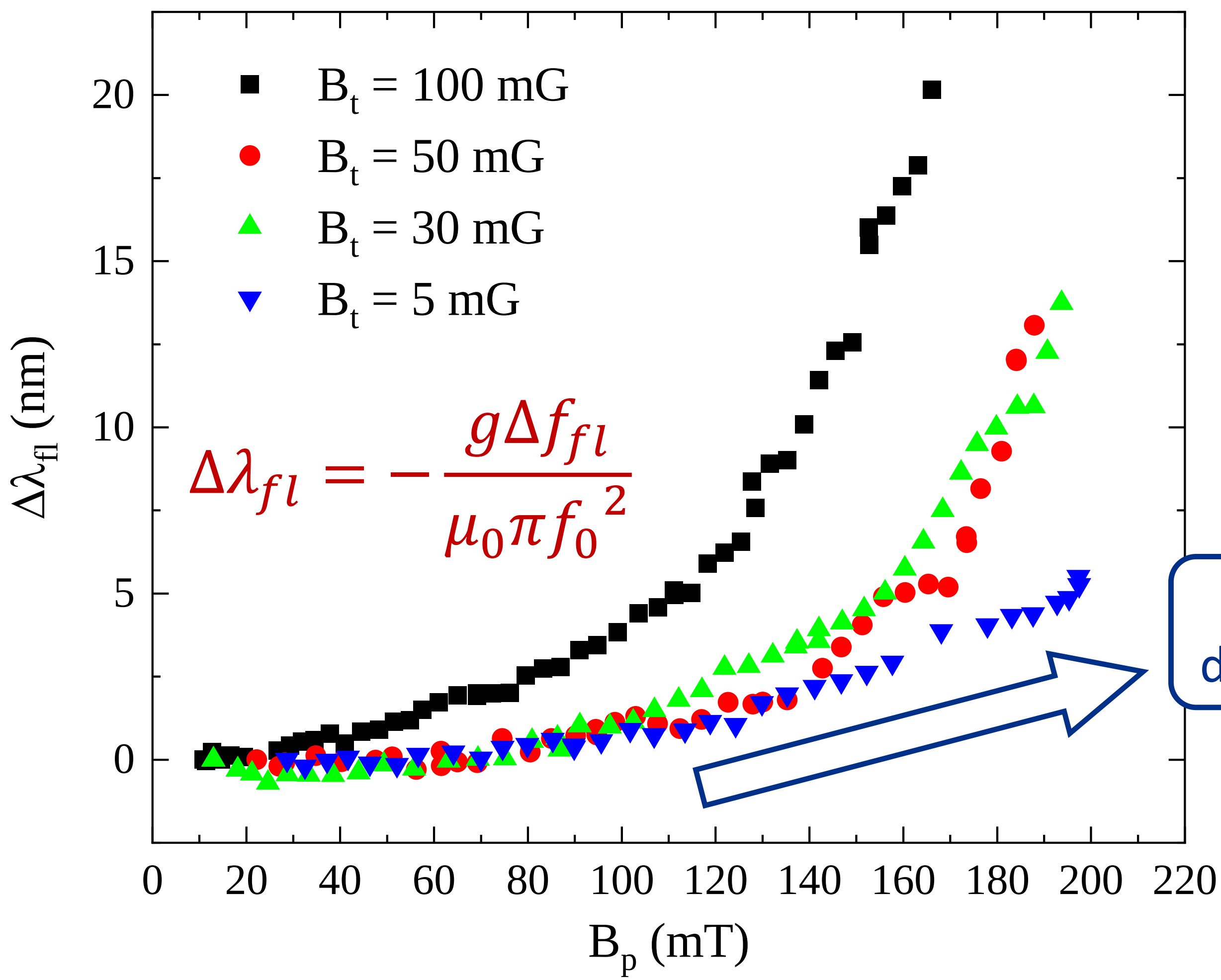
  - Depends on surface peak magnetic field B_p
  - Depends on trapped field B_t



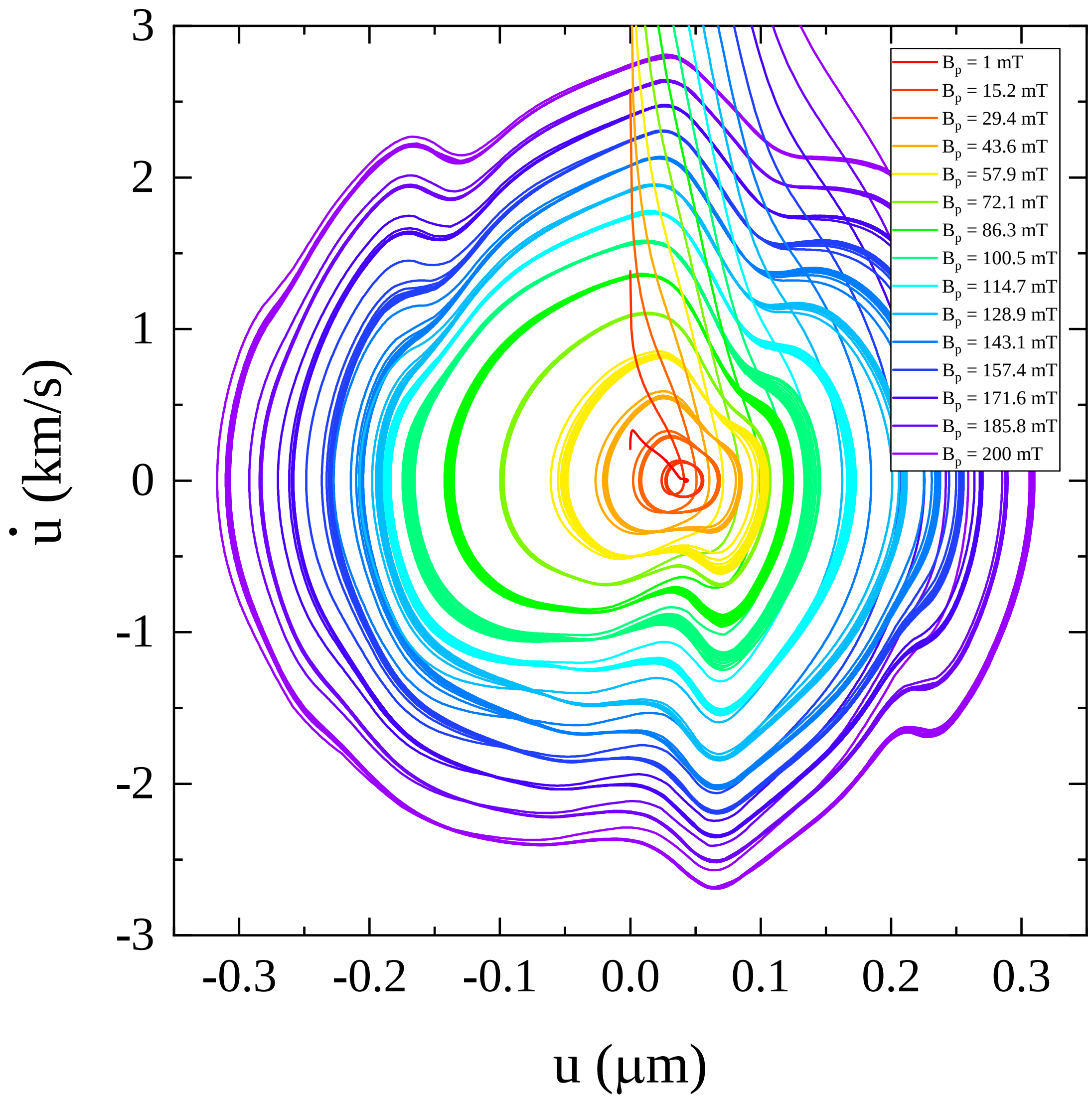


Penetration depth variation due to RF depinning

Higher B_p → RF depinning → deeper induced currents → larger $\Delta\lambda_{fl}$



Vortex phase space for increasing B_p



Effect of pinning on vortex dynamics

- Without pinning
  - $\dot{u}$ is directly proportional to B_p
    - Linear response
- With pinning
  - Slope change at $\boldsymbol{B_p^d}$ (depinning field)
    - **Depinning**, $\dot{u}$ increases rapidly
  - Slope change at $\boldsymbol{B_p^s}$ (saturation field)
    - **Saturation**, $\dot{u}$ approaches the linear response
  - Below B_p^s, R_{fl} is lower:

$$R_{fl} \propto f \int_0^{1/f} \dot{u}\, dt$$