New Insights into RF Field Amplitude and Frequency Dependence of Vortex Surface Resistance

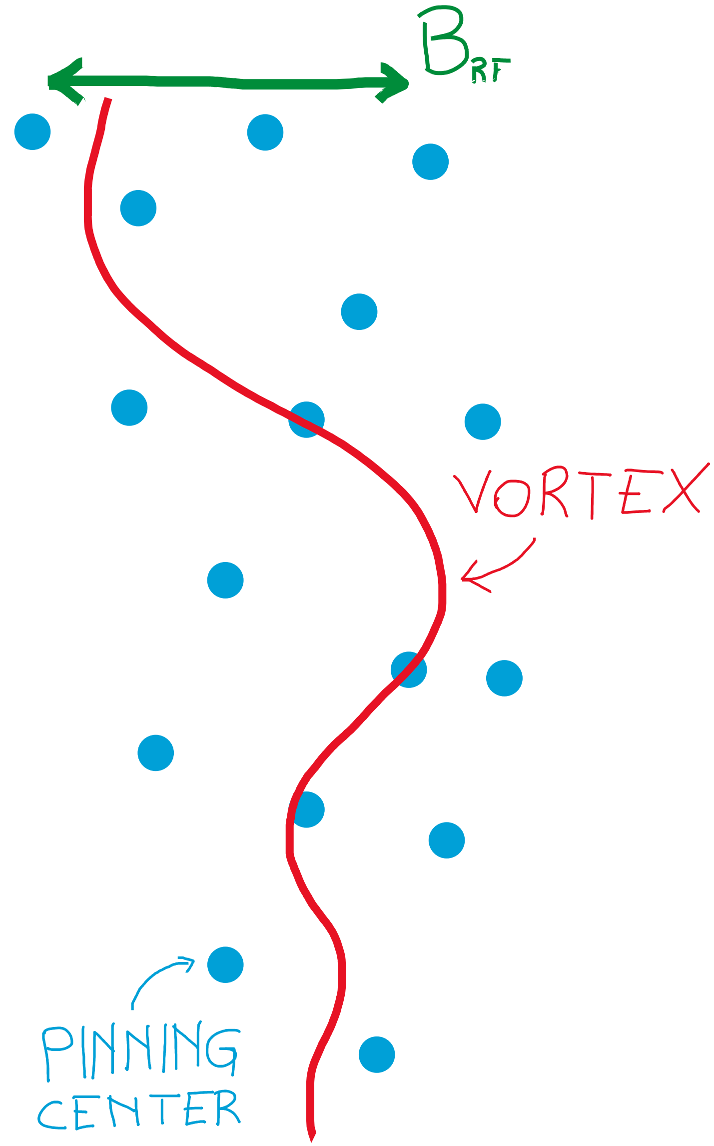
Mattia Checchin

19th International Conference on RF Superconductivity

02 Jul 2019

Why do vortices dissipate under RF driving?

- Vortices oscillate driven by the RF current
- Random pinning centers in the material defines a "pinning landscape" against which the vortex moves
- Part of the EM energy in the resonator is converted into vortex motion
  - Power is dissipated by the vortex
    - ⇝ we can define a vortex surface resistance R_{fl}

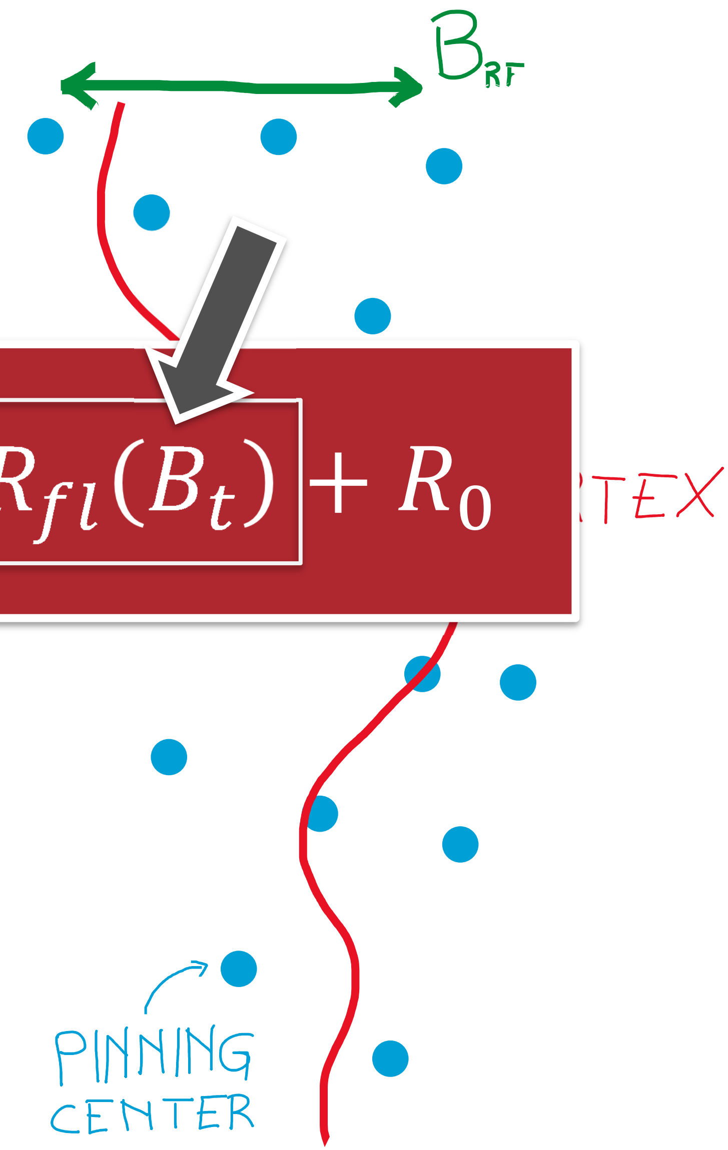


Why do vortices dissipate under RF driving?

- Vortices oscillate driven by the RF current
- Random pinning centers in the
  m
  la
  m

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

- Part of the EM energy in the resonator is converted into vortex motion
  - Power is dissipated by the vortex
    - ⇝ we can define a vortex surface resistance R_{fl}



Low RF field sensitivity

- Trapped flux sensitivity:

$$S = \frac{R_{fl}}{B_t}$$

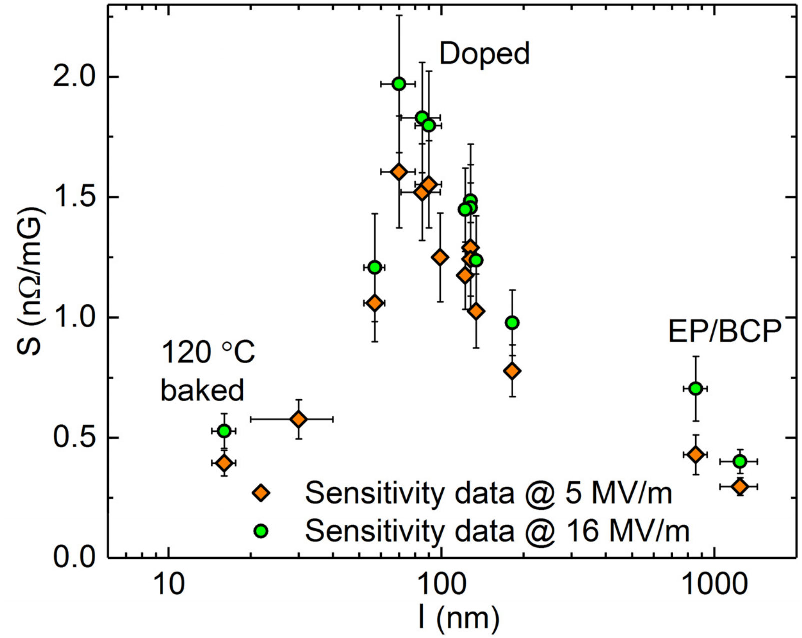
- Non-monotonic trend of S as a function of mean-free-path

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

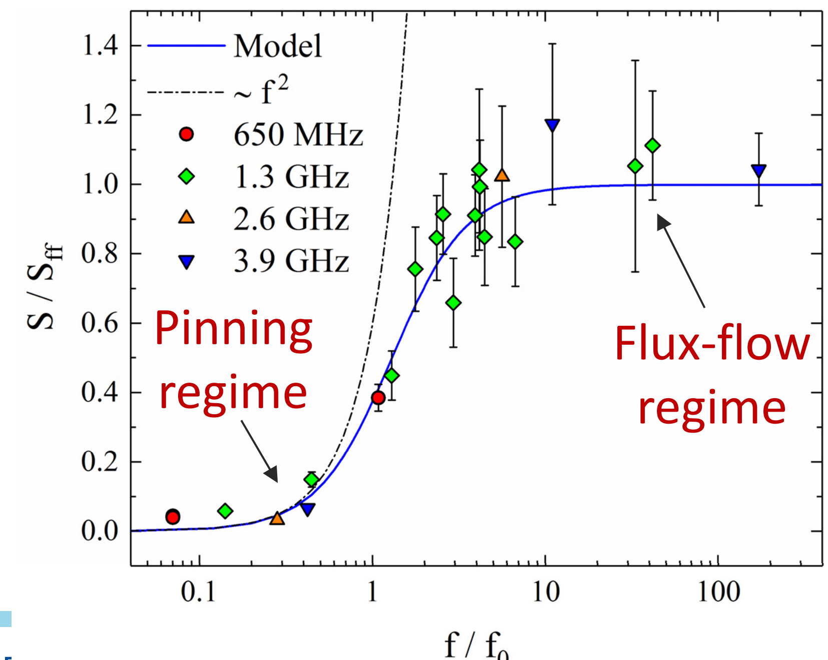
- Vortex surface resistance is well understood at low RF amplitudes

M. Checchin et al., Supercond. Sci. Technol. 30, 034003 (2017)
A. Gurevich and G. Ciovati, Phys. Rev. B 87, 054502 (2013)
And many others….

- Two different regimes:
  - ***Pinning regime***: S increases if $l \uparrow$ and $\omega^2 \uparrow$
  - ***Flux-flow regime***: S decreases if $l \uparrow$, but independent on ω



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

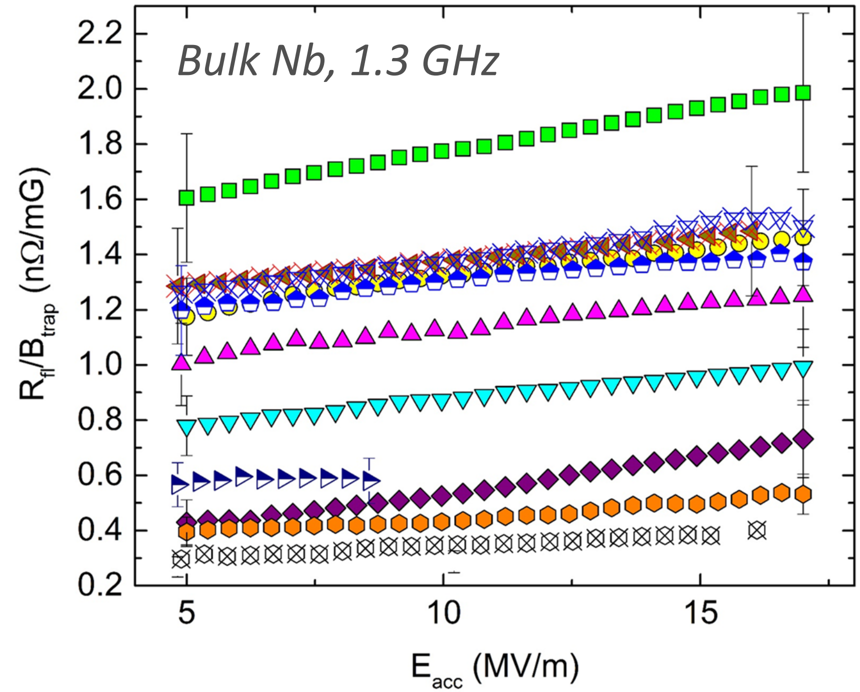


M. Checchin et al., Appl. Phys. Lett. 112, 072601 (2018)

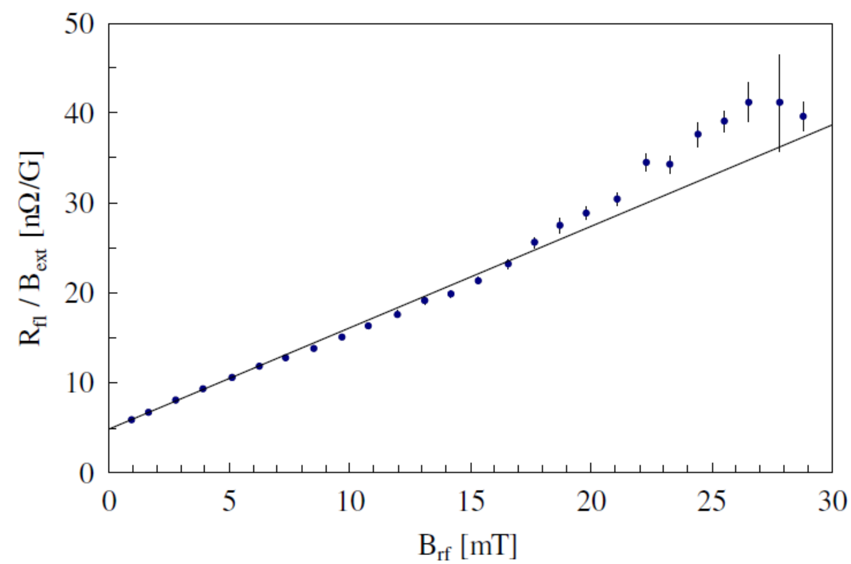
Medium RF field sensitivity

- S has almost linear RF field dependence up to $\sim 70\ mT$
  M. Martinello et al., Appl. Phys. Lett. 109, 062601 (2016)
  C. Benvenuti et al., Physica C 316, 153 (1999)
  D. Hall et al., IPAC 2017 (Nb_3Sn)

- Linear behavior of S vs B_p can be explained as the occurrence of a non-linear pinning force (S. Calatroni and R. Vaglio, Phys. Rev. Accel. Beams 22, 022001 (2019)), or as generated by hysteretic losses in the framework of a mean field description of pinning (D. Liarte et al., Phys. Rev. Applied 10, 054057 (2018))



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

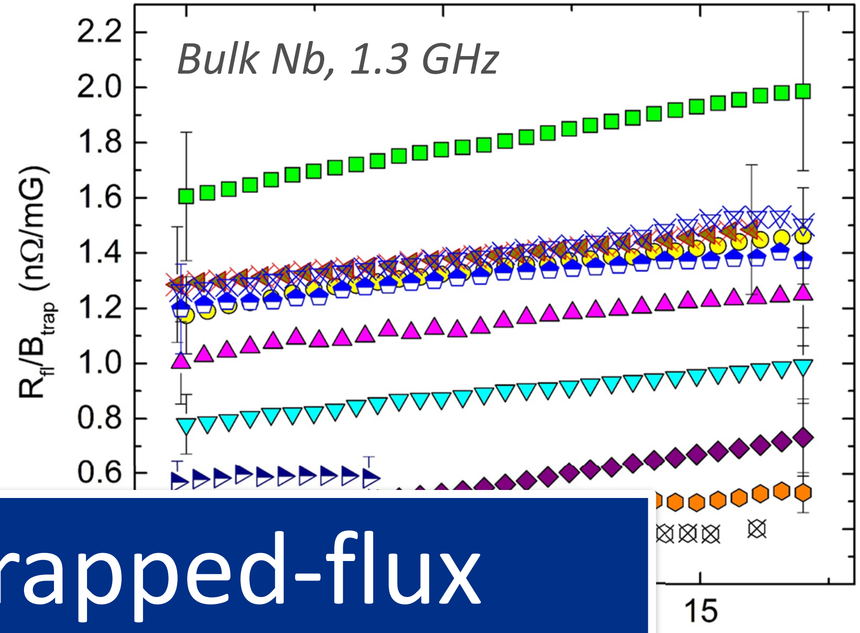


C. Benvenuti et al., Physica C 316, 153 (1999)

Medium RF field sensitivity

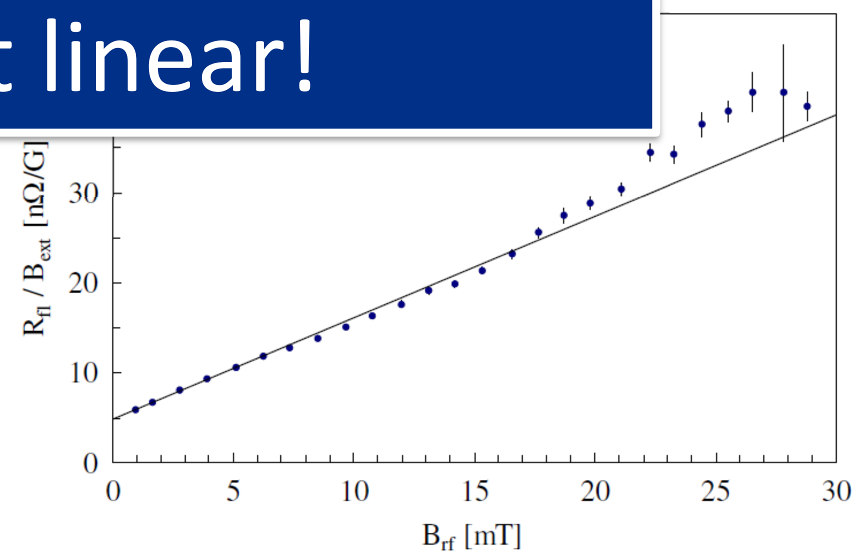
- S has almost linear RF field dependence up to $\sim 70\ mT$
  M. Martinello et al., Appl. Phys. Lett. 109, 062601 (2016)
  C. Benvenuti et al., Physica C 316, 153 (1999)
  D. Hall et al., IPAC 2017 (Nb_3Sn)

- Line
  be e
  of a
  Calatr
  02200
  hys
  framework of a mean field description of pinning (D. Liarte et al., Phys. Rev. Applied 10, 054057 (2018))



2601 (2016)

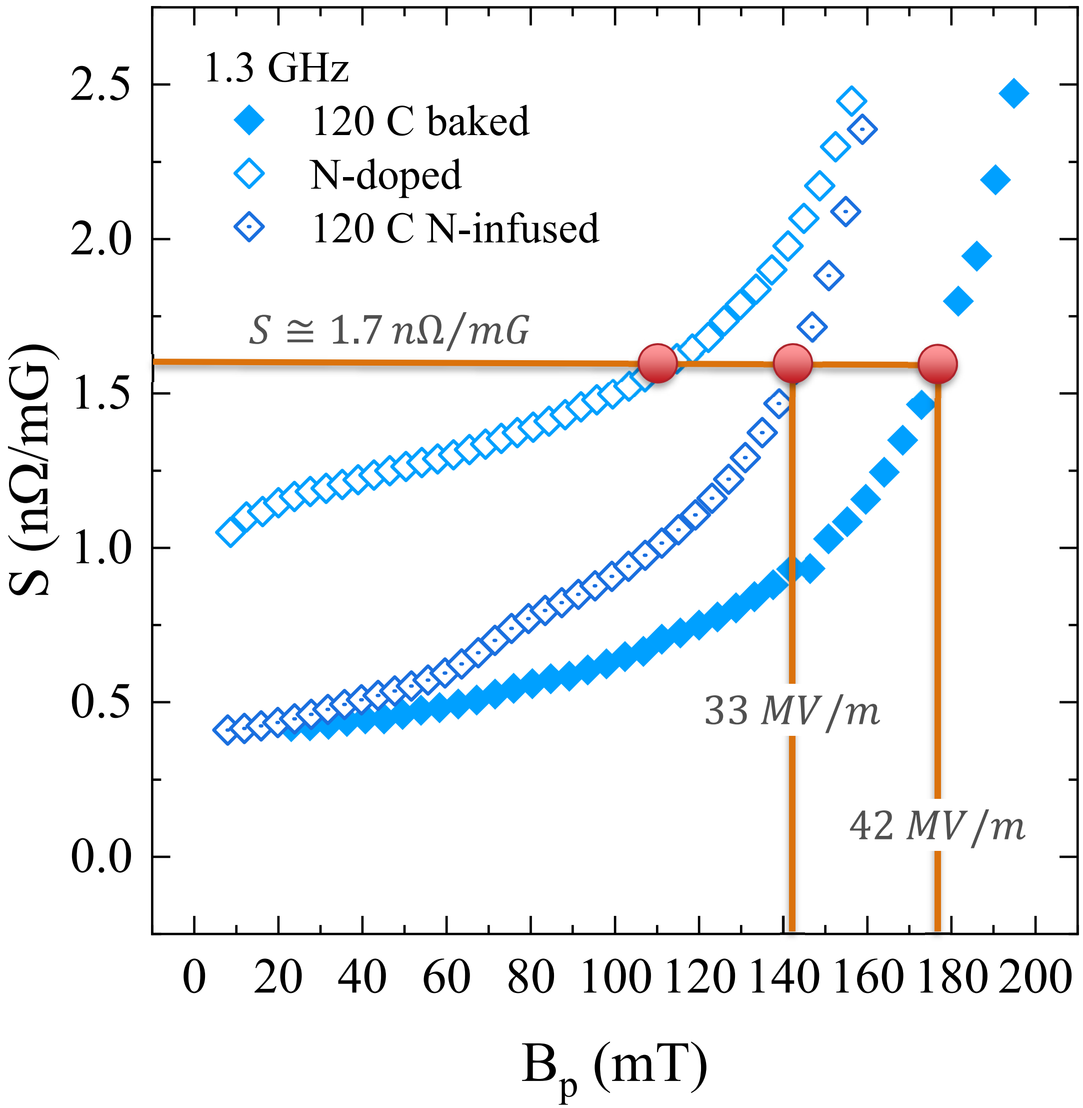
However, the trapped-flux surface resistance at high RF fields is not linear!



C. Benvenuti et al., Physica C 316, 153 (1999)

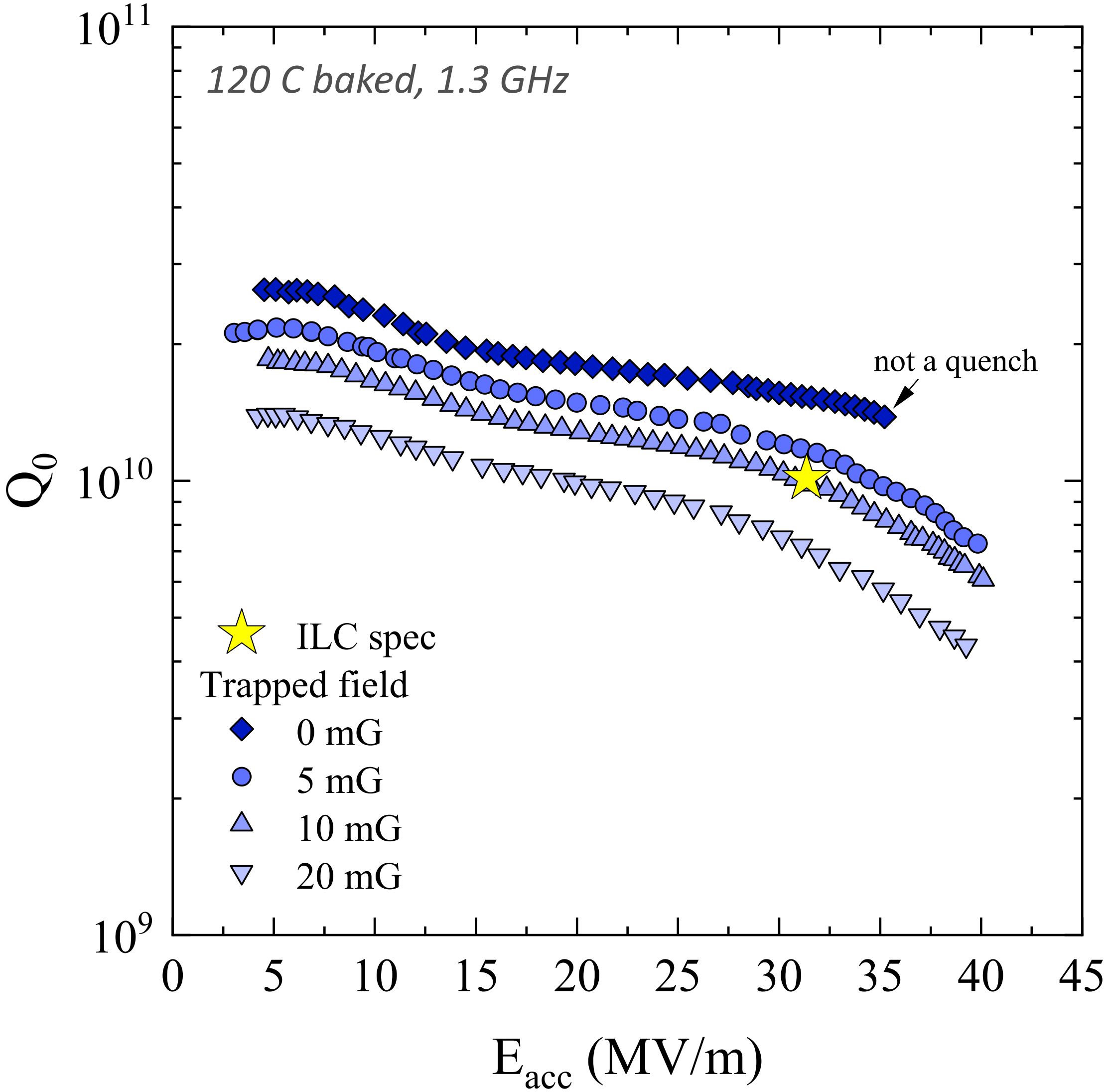
Sensitivity at high RF field

- ***S*** **strongly deviates from linearity at high RF field!**
- Trapped flux sensitivity of 120 C baking and N-infusion as high as N-doped cavities at high fields!



Sensitivity at high RF field

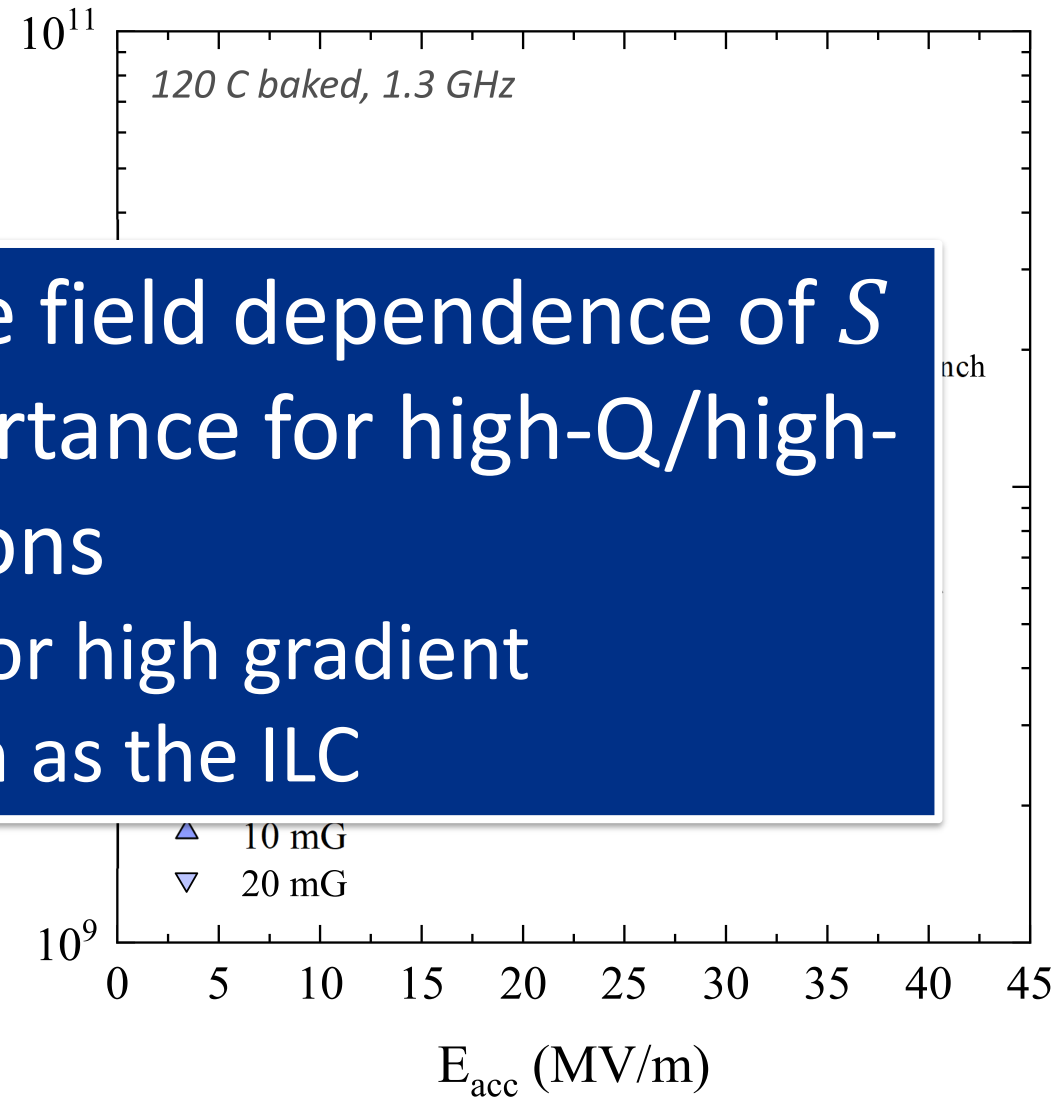
- ***S* strongly deviates from linearity at high RF field!**
- Trapped flux sensitivity of 120 C baking and N-infusion as high as N-doped cavities at high fields!
- **Q_0 is highly affected at high field** when field is trapped during the cooldown



Fermilab

Sensitivity at high RF field

- *S* **strongly deviates from linearity at high RF field!**
-
- **at high field** when field is trapped during the cooldown



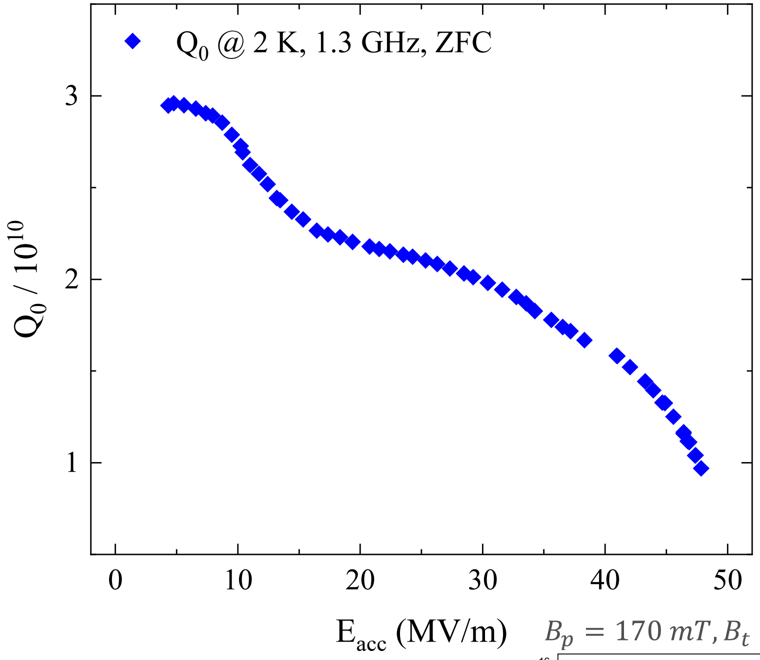
Understanding the field dependence of *S* is of upmost importance for high-Q/high-gradient applications

⇨ Very important for high gradient accelerators such as the ILC

Detailed study of high gradient sensitivity for 120 C baking

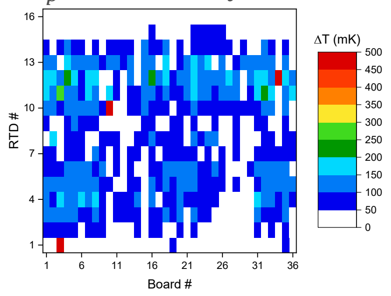
Detailed study of sensitivity at high RF amplitude

- 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)

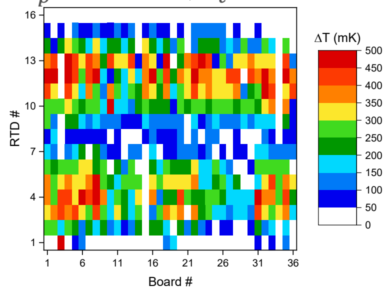


- Objective:
  - Gather new insights on trapped flux sensitivity at high RF field level
  - Study the dissipation pattern due to trapped vortices with Tmap

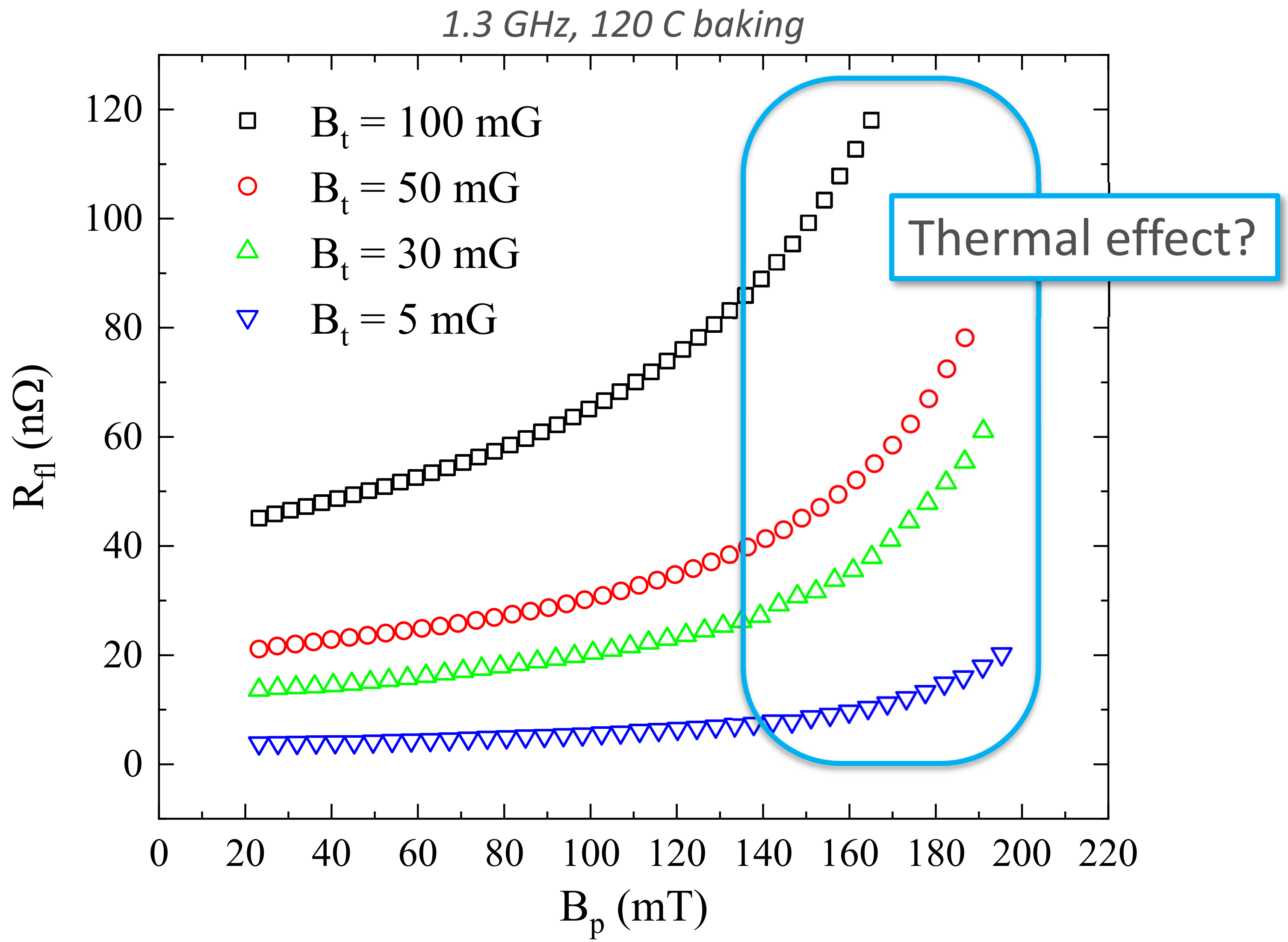
$B_p = 170\ mT, B_t = 30\ mG$



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

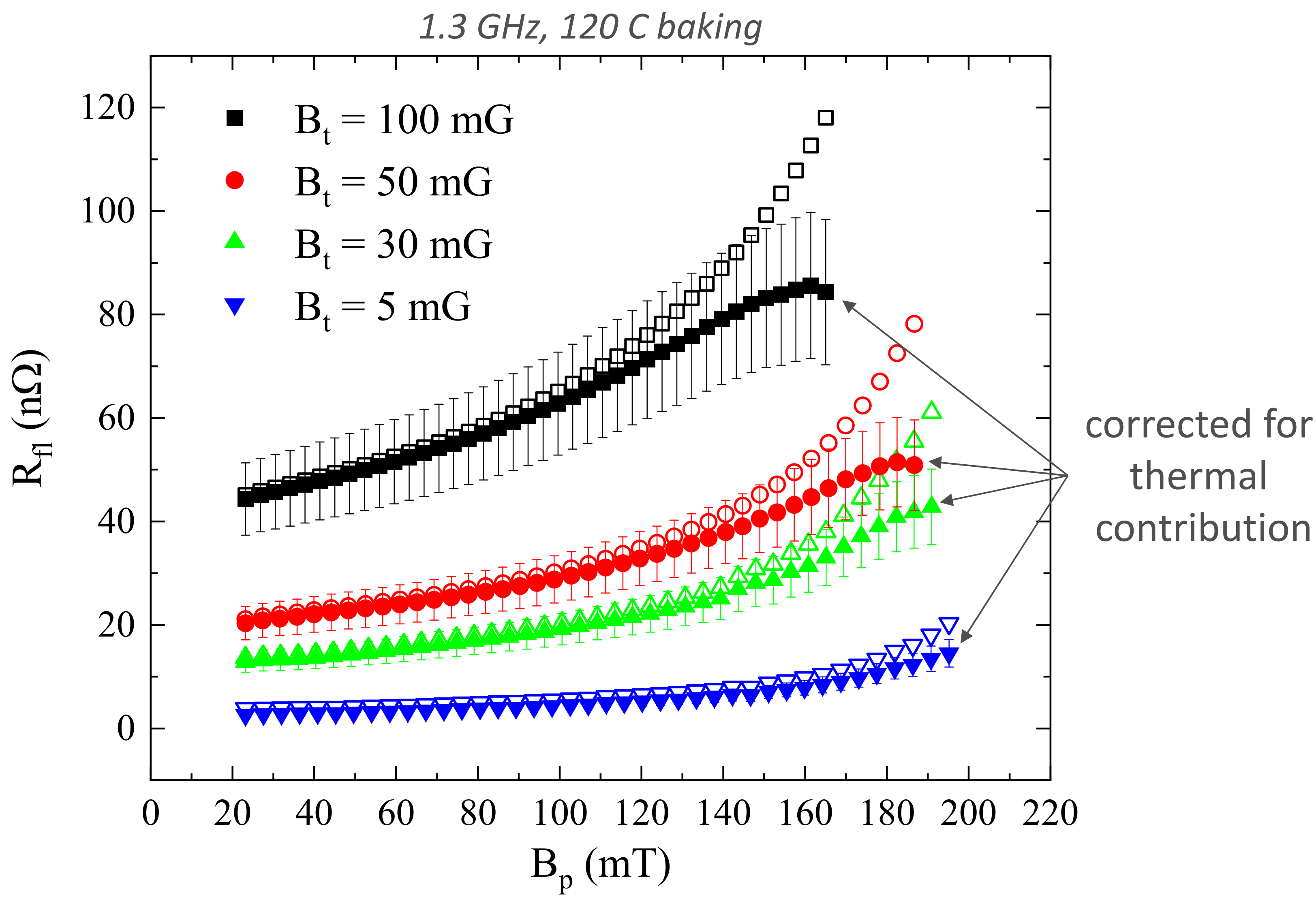


Vortex surface resistance at high RF amplitudes



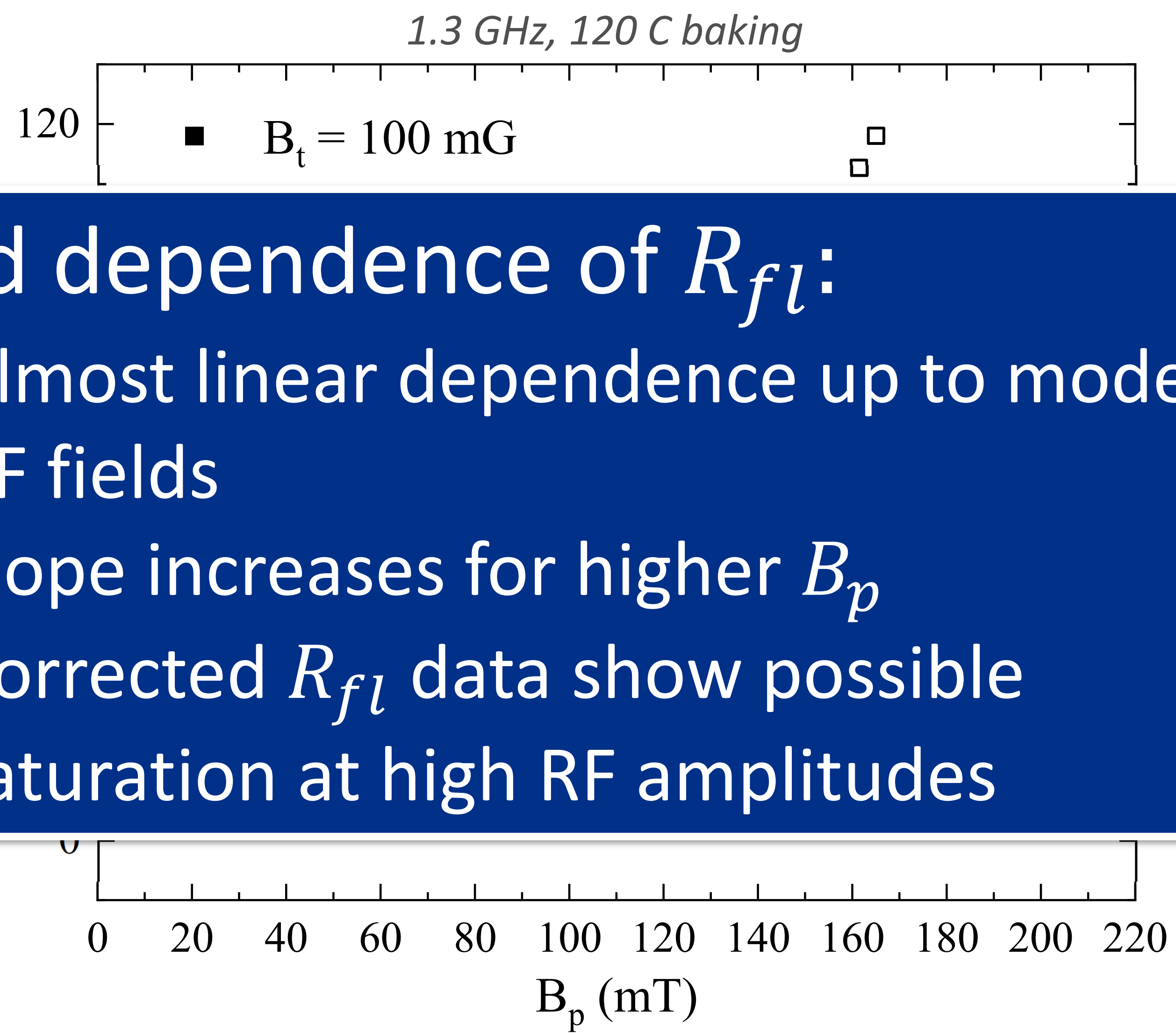
Fermilab

Vortex surface resistance at high RF amplitudes



Fermilab

Vortex surface resistance at high RF amplitudes



Field dependence of R_{fl}:

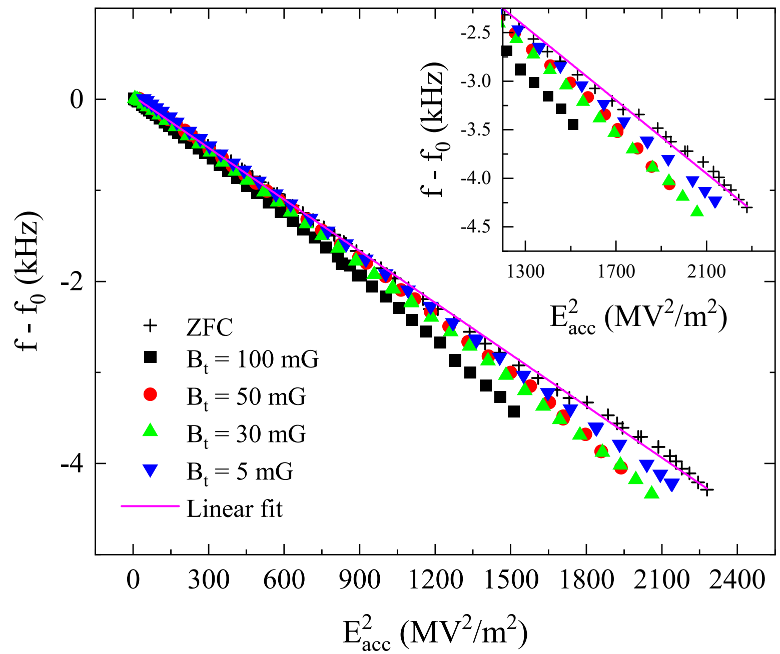
- Almost linear dependence up to moderate RF fields
- Slope increases for higher B_p
- Corrected R_{fl} data show possible saturation at high RF amplitudes

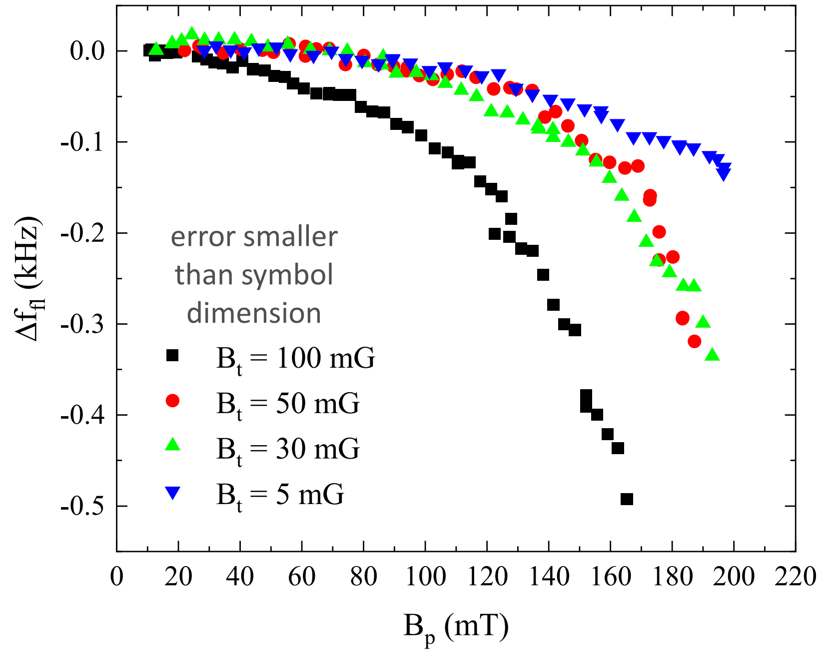
Trapped-flux frequency shift

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

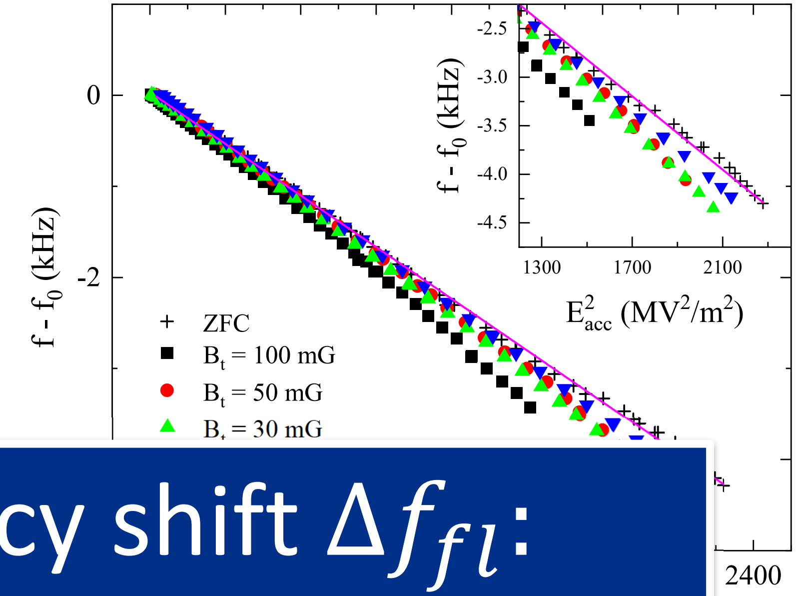
$$\Delta f_{fl} = \Delta f_{FC} - \Delta f_{ZFC}$$

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





Trapped-flux frequency shift

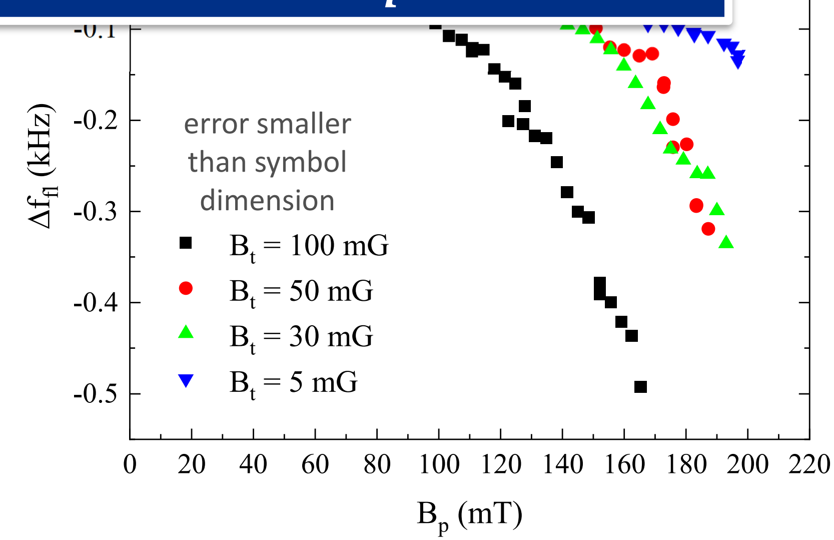


- Deviations from Lorentz force detuning observed when the cavity is field-cooled (FC)

Trapped-flux frequency shift Δf_{fl}:

- ➪ Signature of flux trapped in the resonator
- ➪ $|\Delta f_{fl}|$ increases as a function of B_p

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



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 → $\eta_0 \dot{u}(t,z)$

LINE TENSION → $\epsilon u''(t,z)$

PINNING FORCE → $f_p\big(u(t,z)\big)$

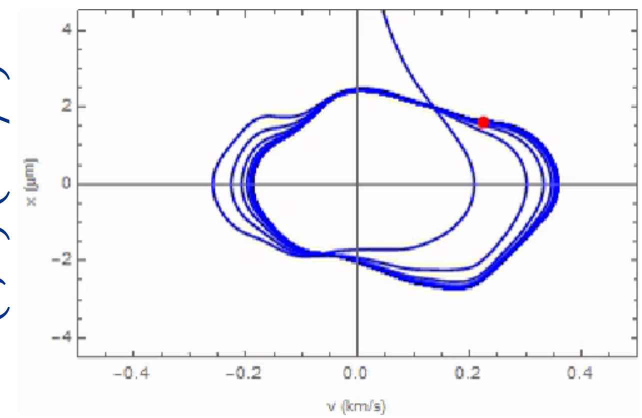
LORENTZ FORCE → $f_L(t,z)$

Single-vortex dynamics simulation

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

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

Example of convergence to steady-state solution



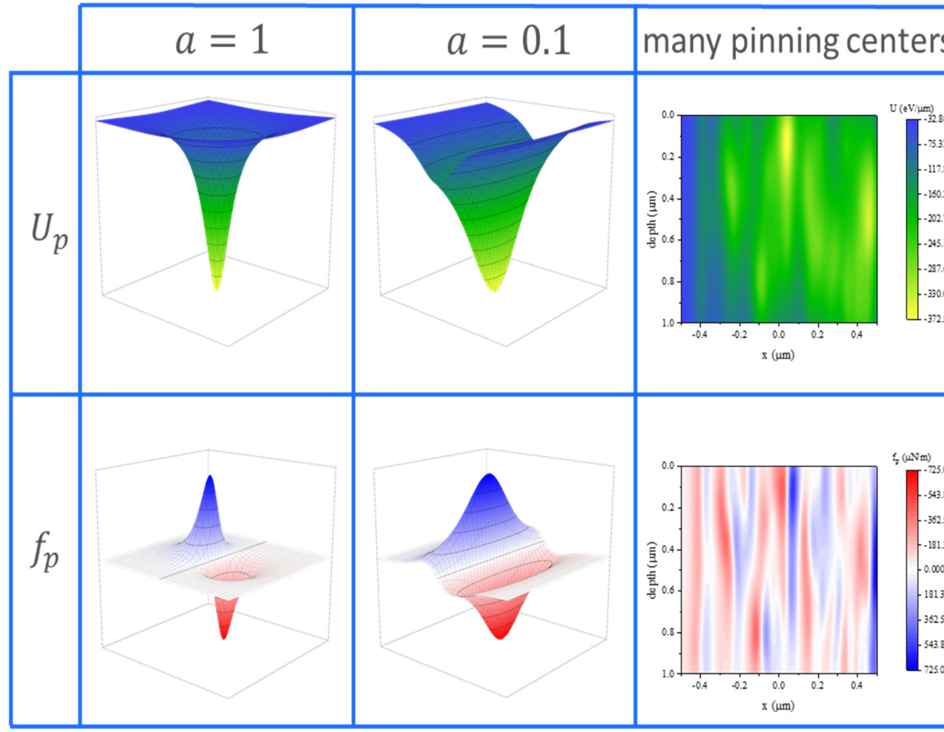
Equation solved with method of lines until steady-state, then the surface resistance is calculated as:

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

Fermilab

Pinning landscape from building block potential

- 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



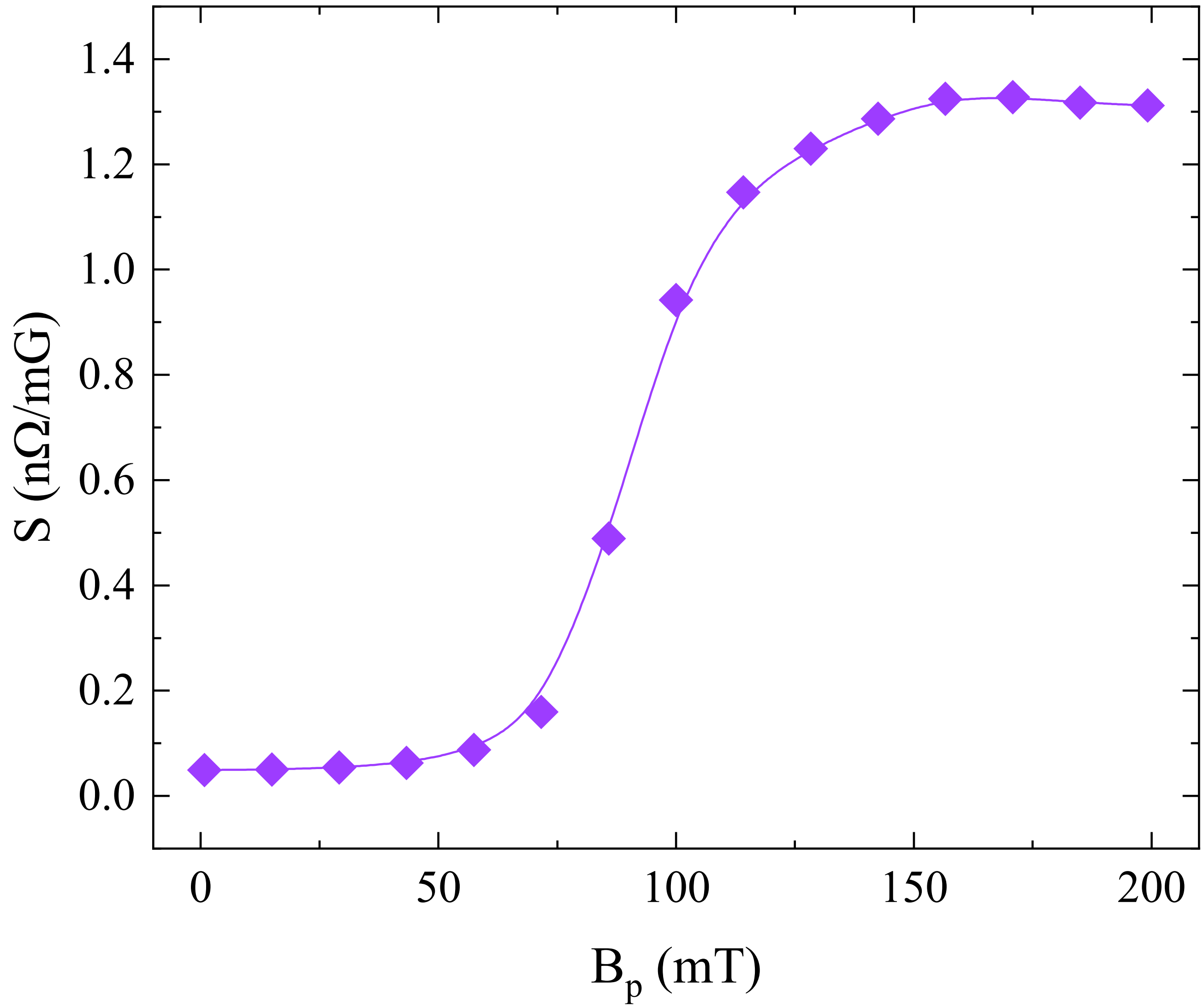
GAUSSIAN DISTRIBUTION

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

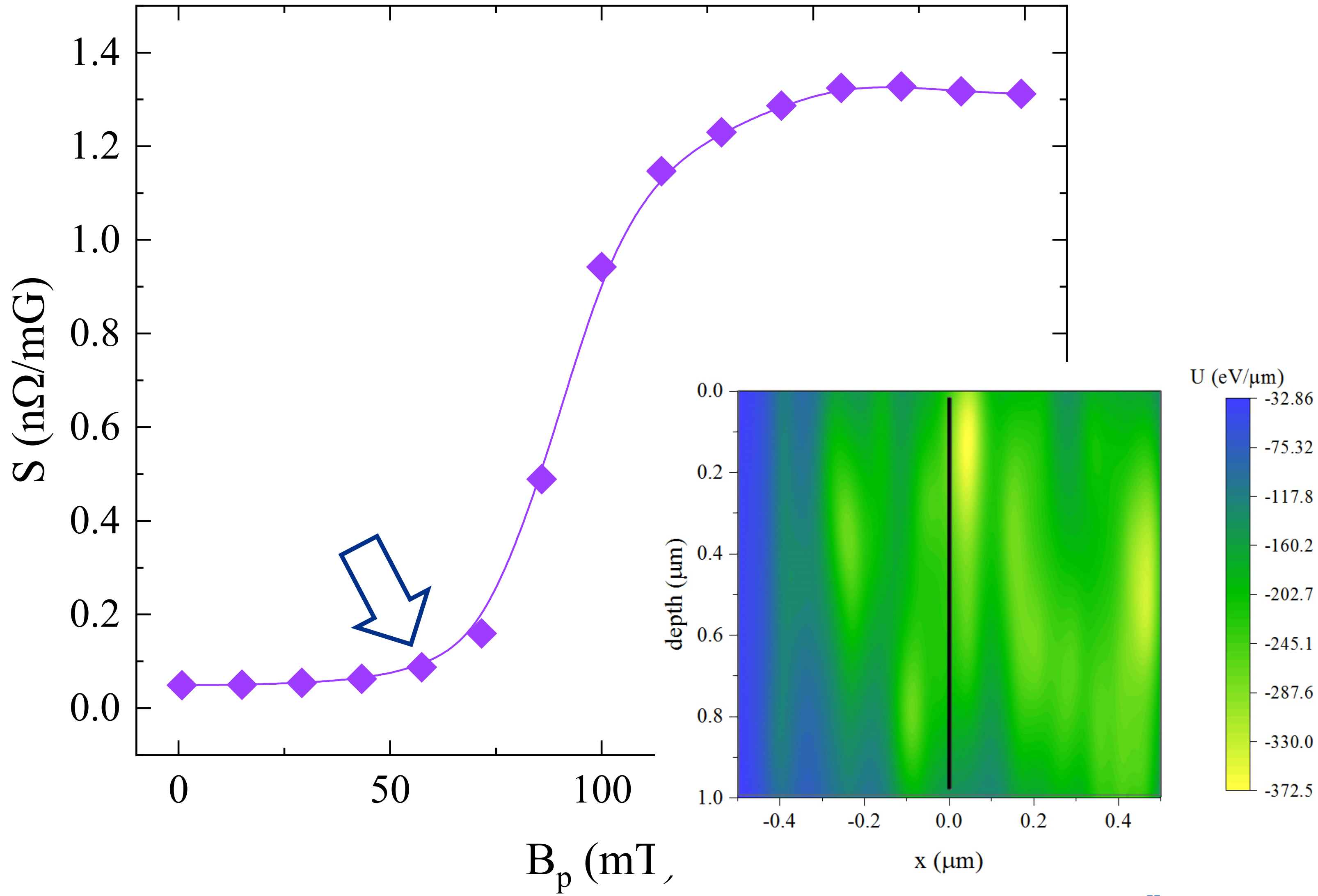
RANDOM DISTRIBUTION

Fermilab

Example of simulated sensitivity

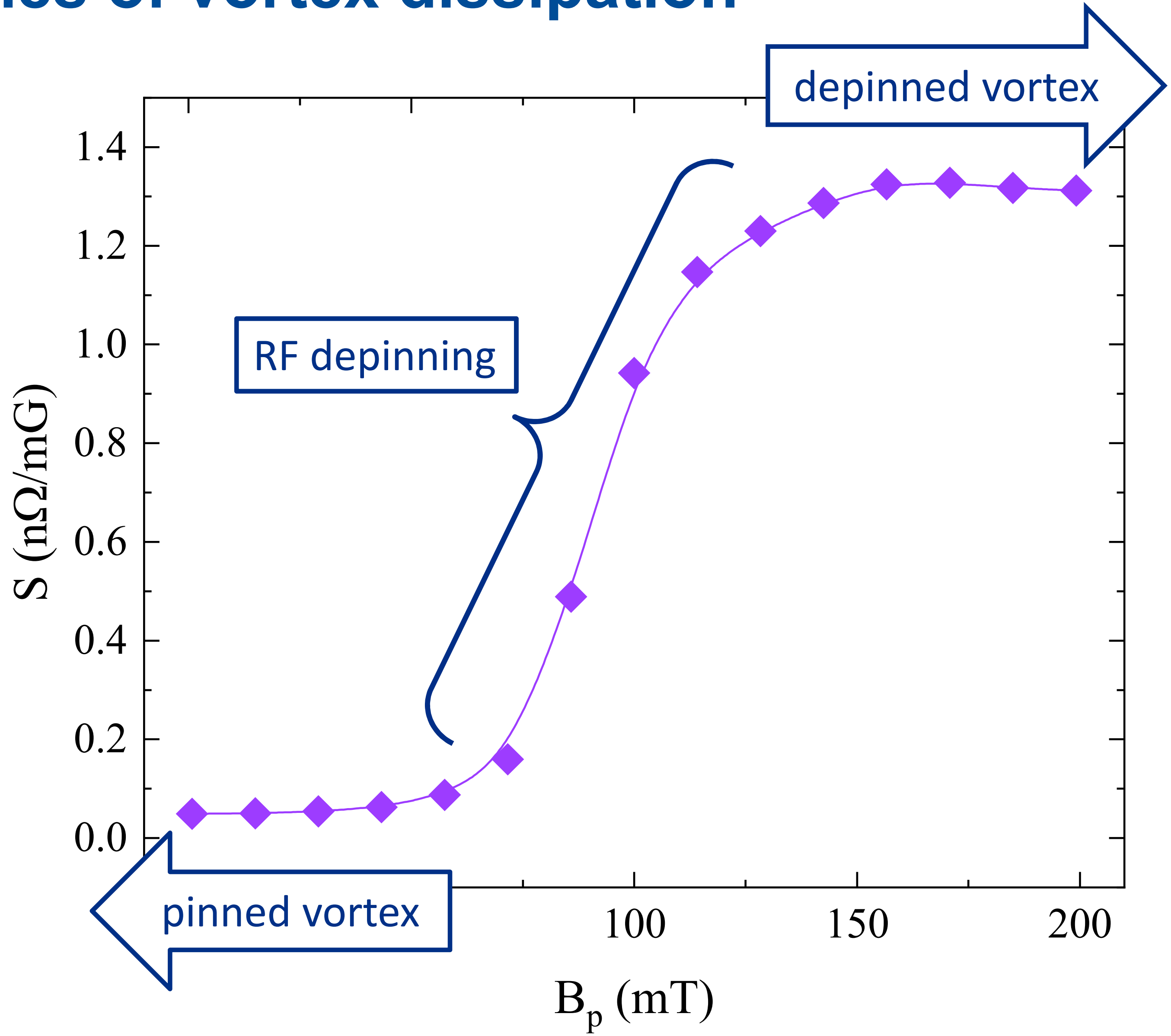


RF depinning



Fermilab

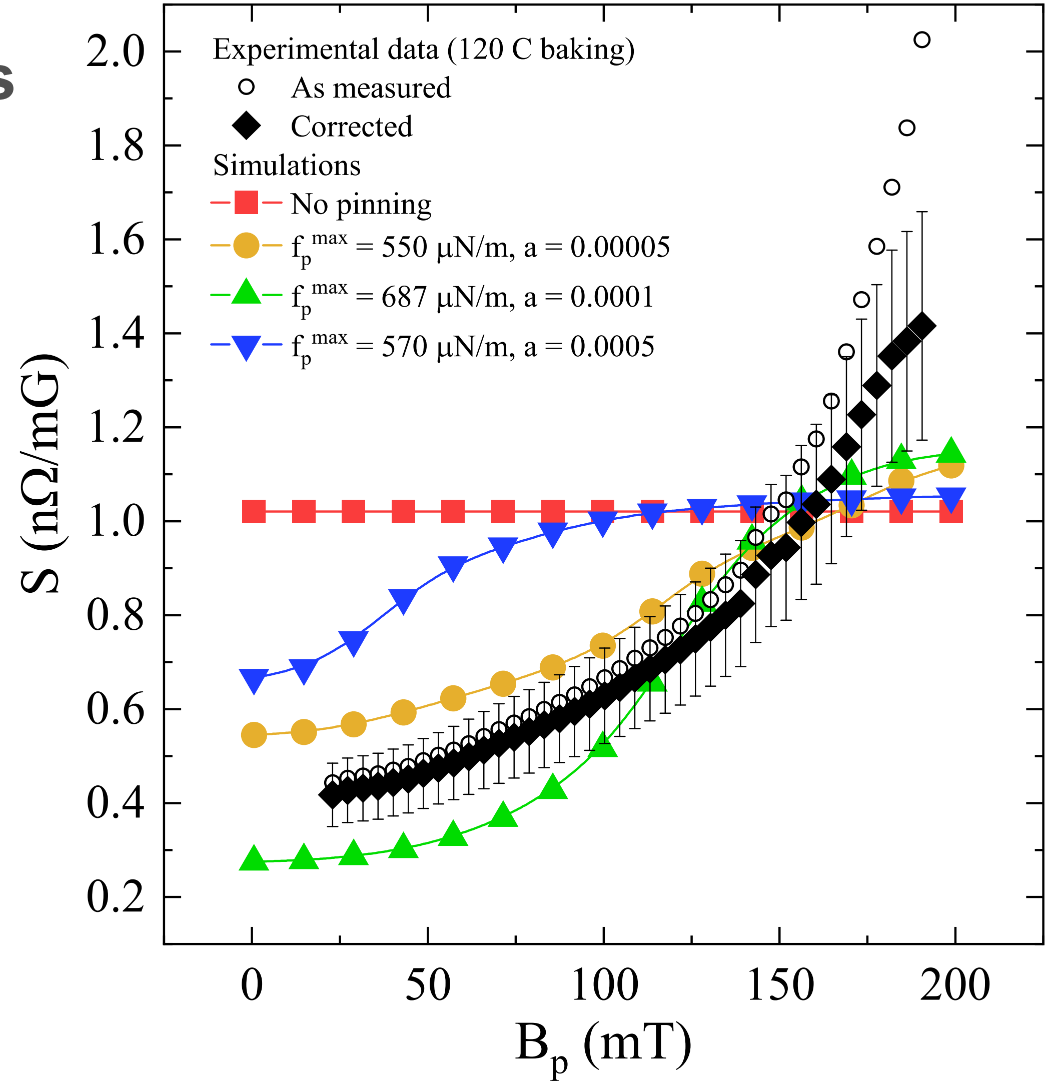
Regimes of vortex dissipation



Interpretation of experimental data at 1.3 GHz

Comparison with experimental data at 1.3 GHz

- At **low field, oscillations within a non linear pinning potential**
- **Slope change** due to **RF depinning**
- Corrected experimental data show **possible saturation at high RF fields**
  - The vortex is totally depinned

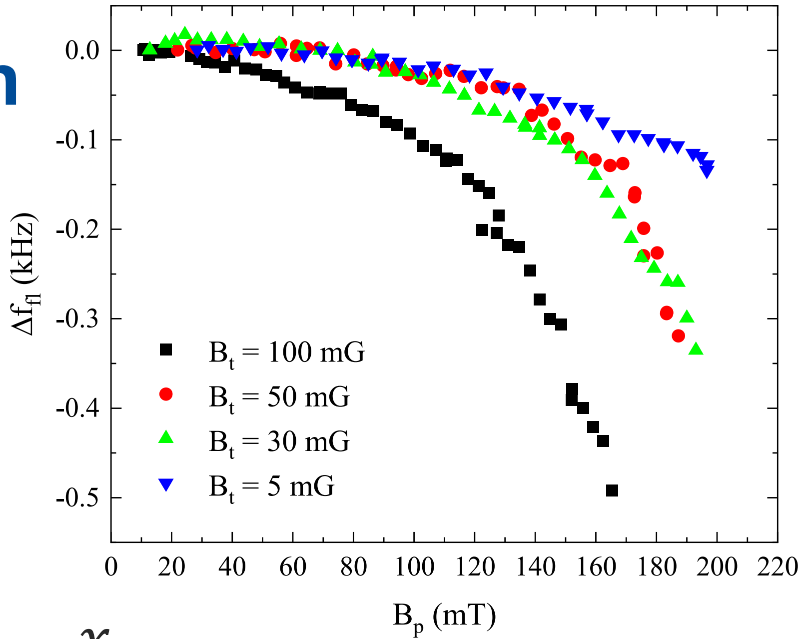


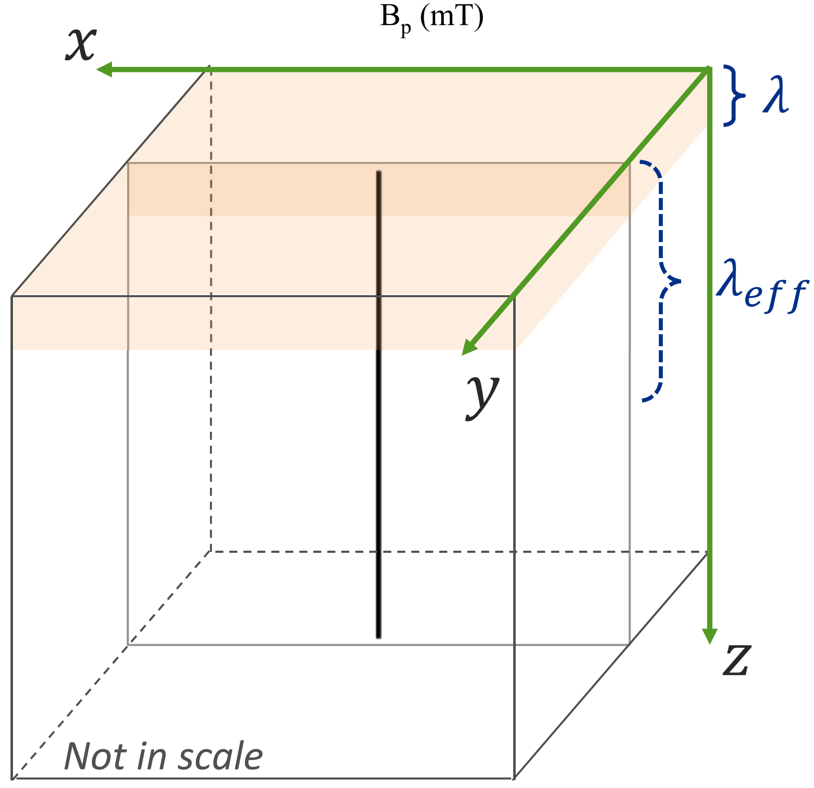
Fermilab

Frequency shift interpretation

- **Vortex oscillation generates induced currents in the SC**[1]
  - Effective penetration depth of the RF current increases
    → lower cavity frequency
  - λ_{fl} **defines the vortex contribution** to the current profile reach in the material
- We observe Δf_{fl} dependent on B_p!
  - The freq. shift is not constant
- $\Delta\lambda_{fl}$, penetration depth variation due to vortex oscillation

$$\Delta\lambda_{fl} = -\frac{g\Delta f_{fl}}{\mu_0 \pi {f_0}^2}$$

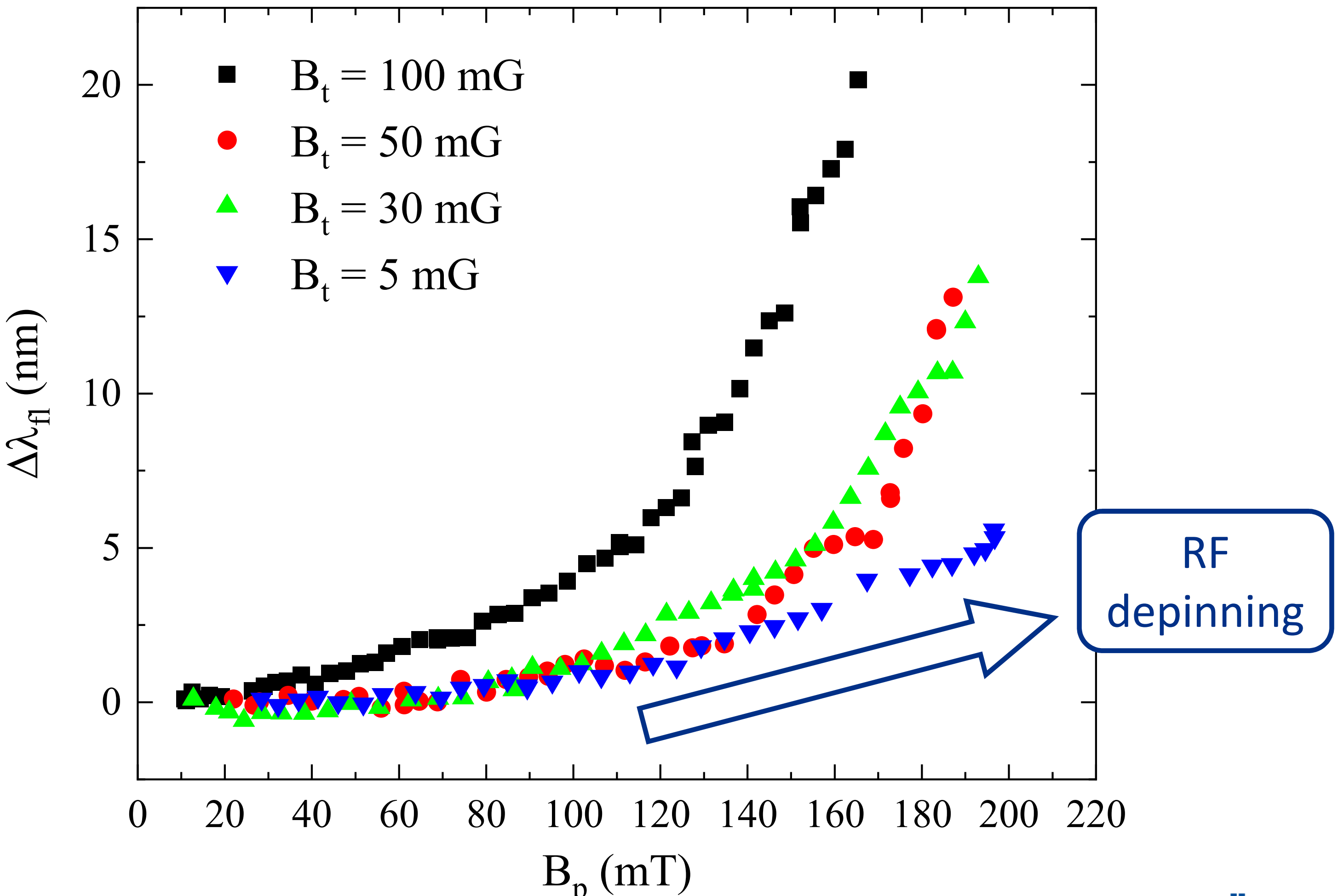




[1] M. W. Coffey and J. R. Clem, Phys. Rev. Lett. 67, 386 (1991)

Penetration depth variation due to RF depinning

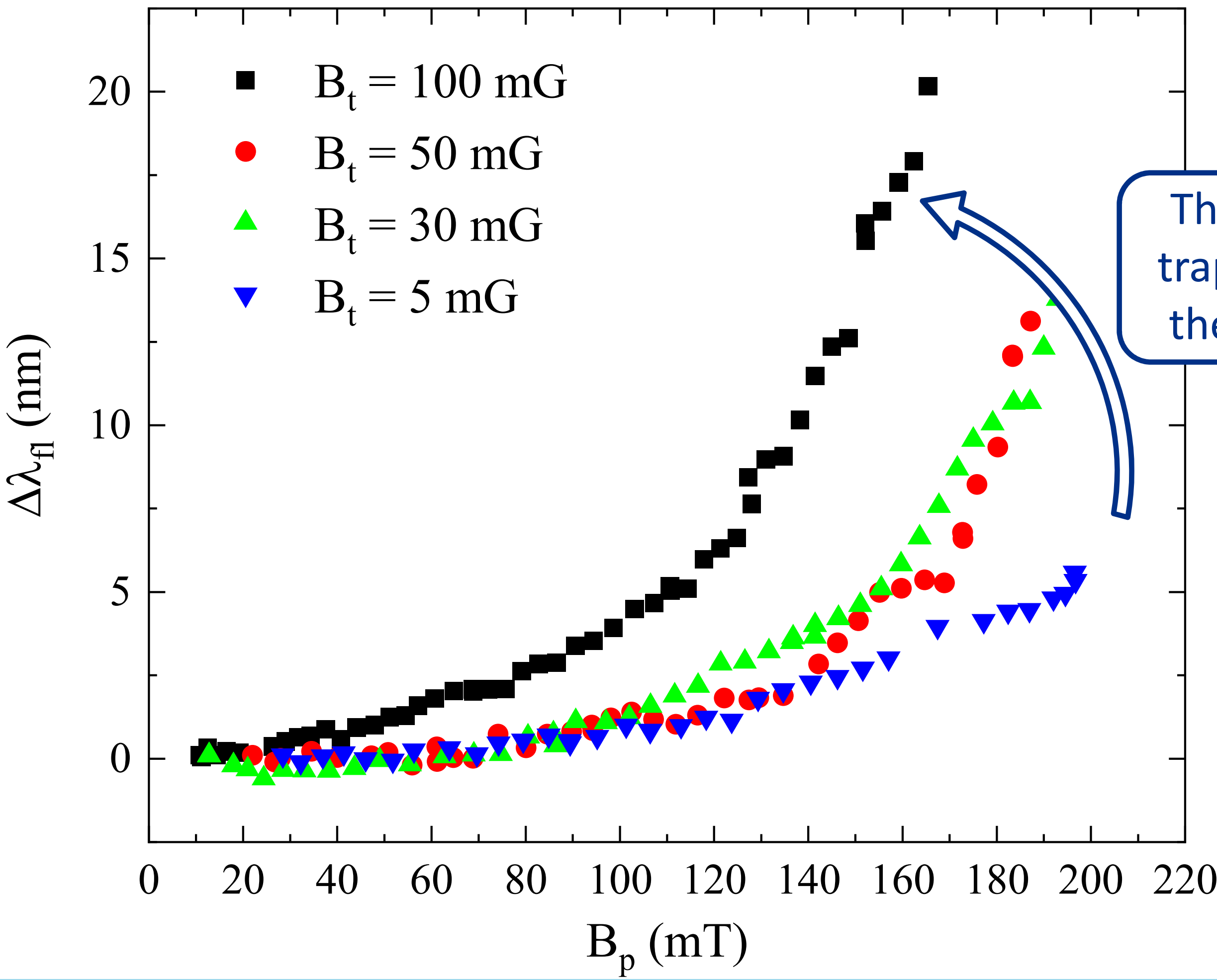
Higher B_p → RF depinning → deeper induced currents → larger $\Delta\lambda_{fl}$



Fermilab

Penetration depth variation due to RF depinning

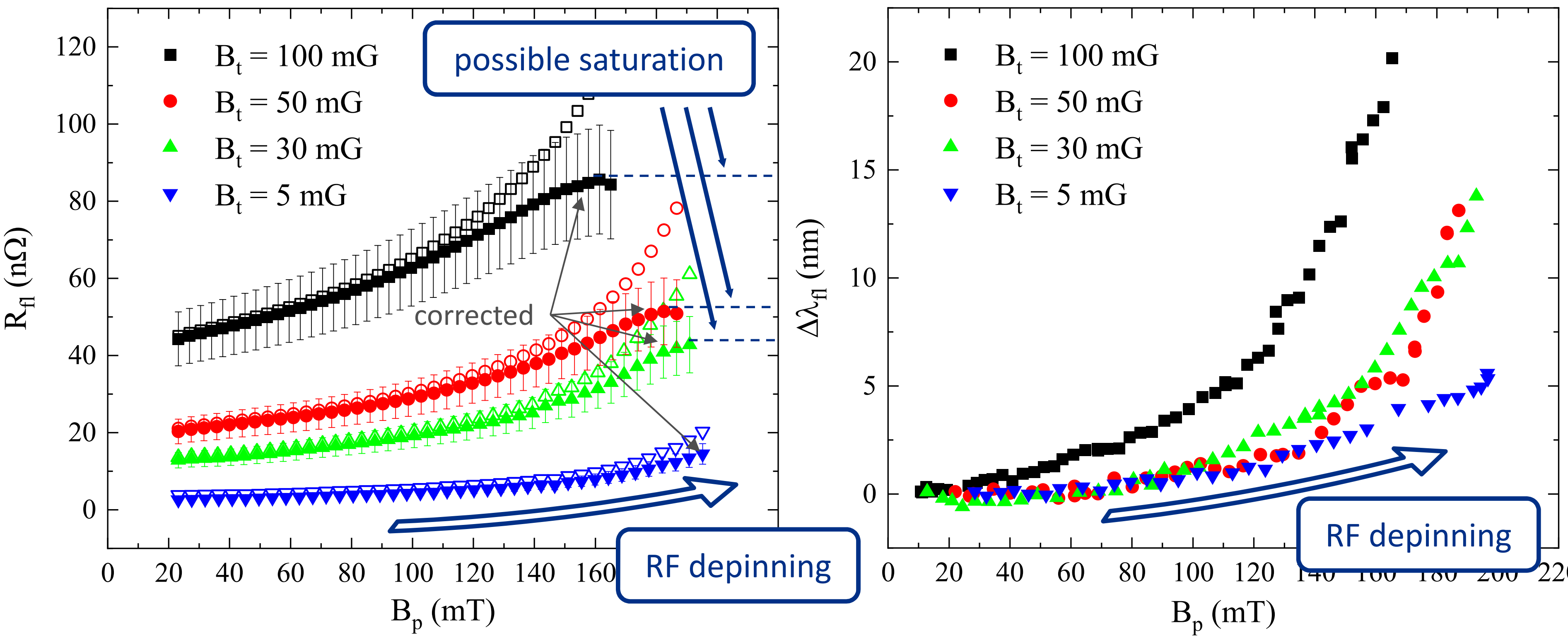
Higher B_t → larger vortex contribution to λ_{eff} → larger $\Delta\lambda_{fl}$



The higher the trapped field B_t the larger $\Delta\lambda_{fl}$

Summary

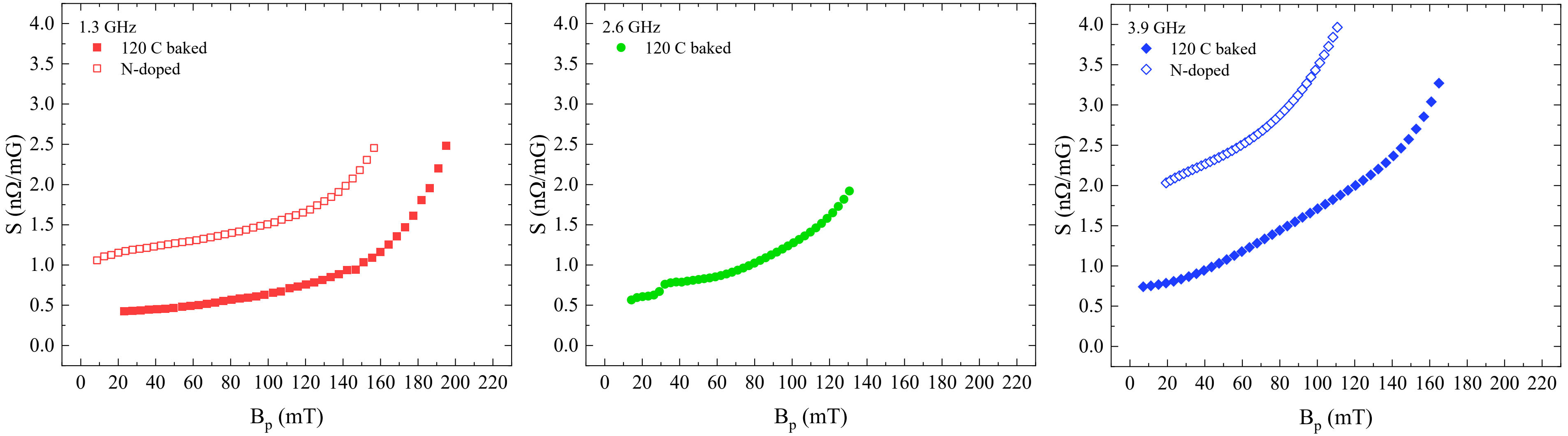
- Vortex dynamics in SRF cavities at high RF fields seems to be dictated by the pinning condition
  - **RF depinning can explain both R_{fl} and $\Delta\lambda_{fl}$ field dependence**
  - At high field, **possible saturation of R_{fl}**
    - ⇝ consistent with numerical simulations



Dependence on thermal treatment and frequency

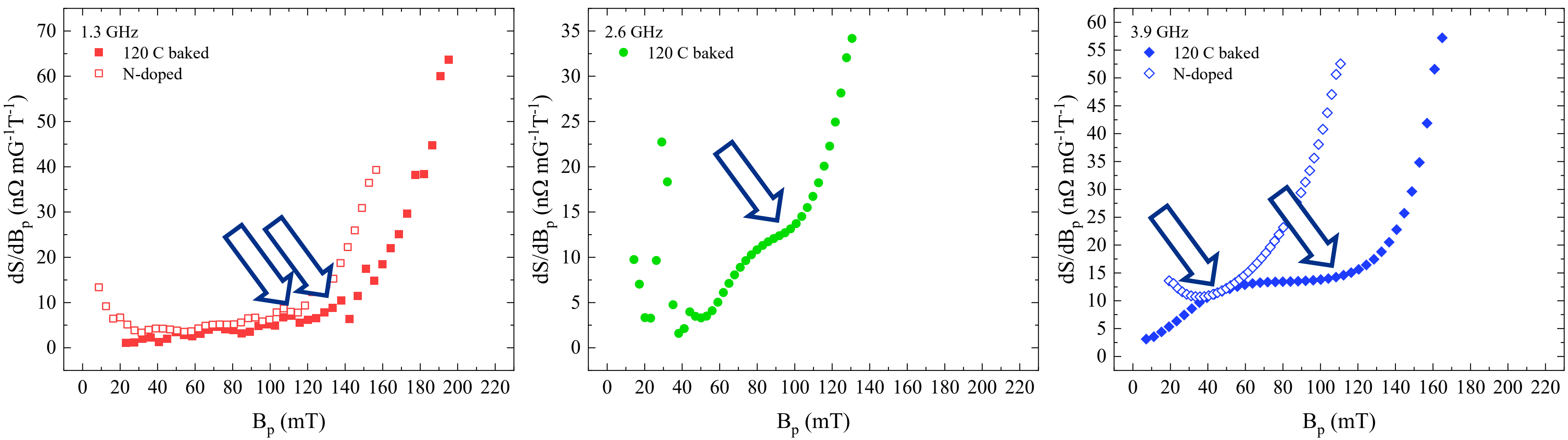
Dependence on treatment and frequency

- Measurements were done for 120 C baked and N-doped cavities operating at 1.3 GHz, 2.6 GHz and 3.9 GHz
- Qualitatively **the trend is similar in all cases**
  - ⇝ Almost linear trend till moderate fields
  - ⇝ Steeper dependence at higher fields



Dependence on treatment and frequency

- Measurements were done for 120 C baked and N-doped cavities operating at 1.3 GHz, 2.6 GHz and 3.9 GHz
- Qualitatively **the trend is similar in all cases**
  - ⇝ Almost linear trend till moderate fields
  - ⇝ Steeper dependence at higher fields

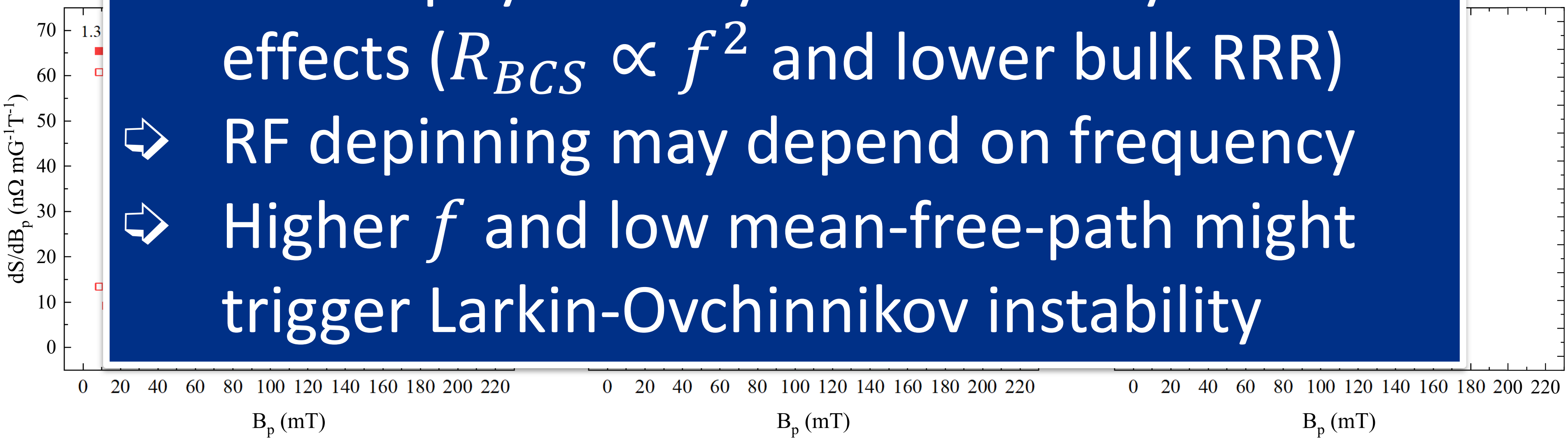


Dependence on treatment and frequency

- Measurements were done for 120 C baked and N-doped

For higher frequencies and N-doping the onset appears at lower fields:

- ⇨ Vortex physics may be masked by thermal effects ($R_{BCS} \propto f^2$ and lower bulk RRR)
- ⇨ RF depinning may depend on frequency
- ⇨ Higher f and low mean-free-path might trigger Larkin-Ovchinnikov instability



Concluding...

Conclusions

- **High-gradient sensitivity can be very large** also for treatments showing low S at low RF fields
- Numerical simulations suggest that the field dependence of S is determined by the pinning condition
  - ~ linear dependence due to oscillations within pinning potential
  - **Non-linear field dependence due to RF depinning**
    - Agreement with frequency shift variation with RF field
  - Saturation to constant value at high fields
    - Possibly observed after subtraction of thermal contributions
- High frequency and N-doped cavities show lower onset of non-linear field dependence
  - Larger thermal contribution? RF depinning dependent on frequency? LO instability?

Many thanks to the whole Fermilab’s SRF team for the support and stimulating discussions

Many thanks to the whole Fermilab's SRF team
for the support and stimulating discussions

and…

Thank you for your attention!