High-Frequency Electrodynamics of Trapped Vortices in Superconductors

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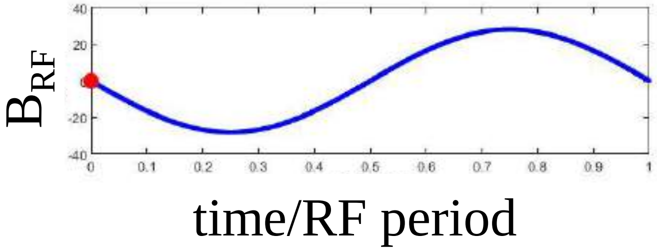

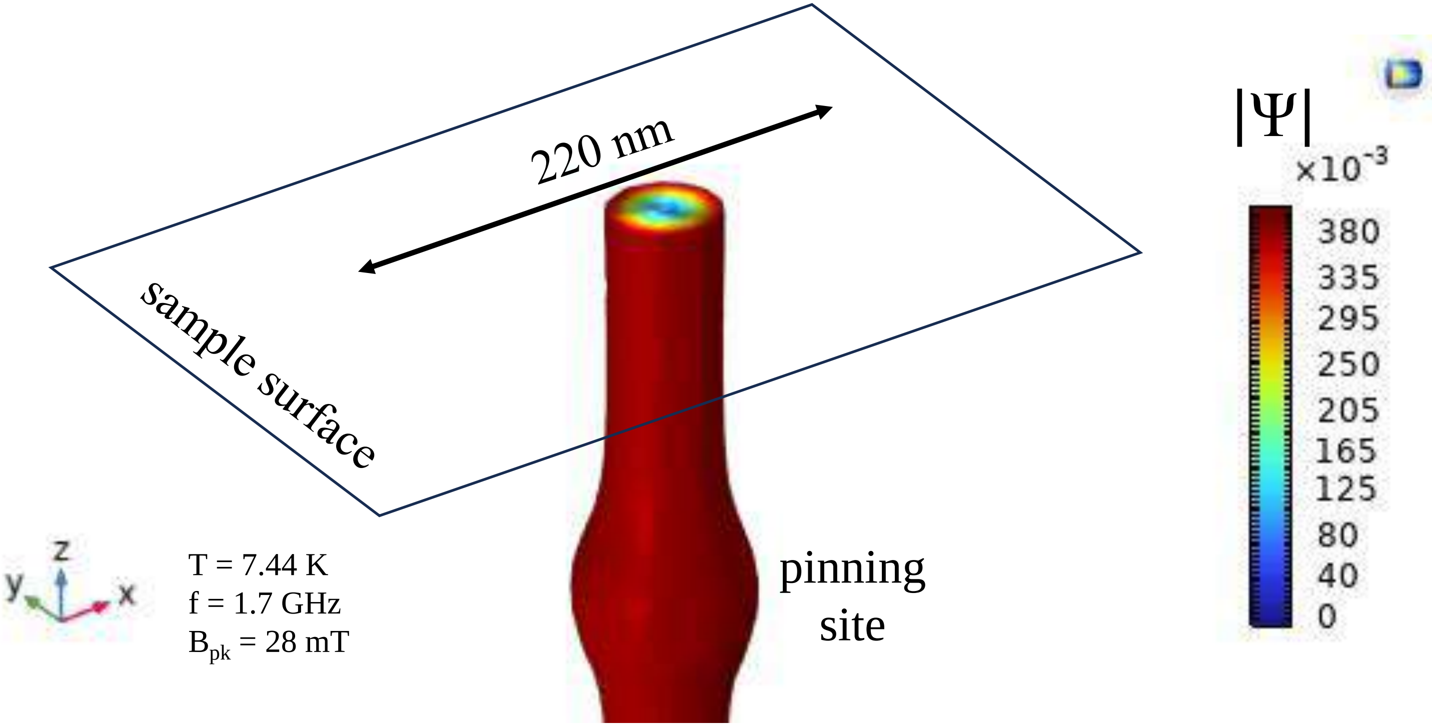

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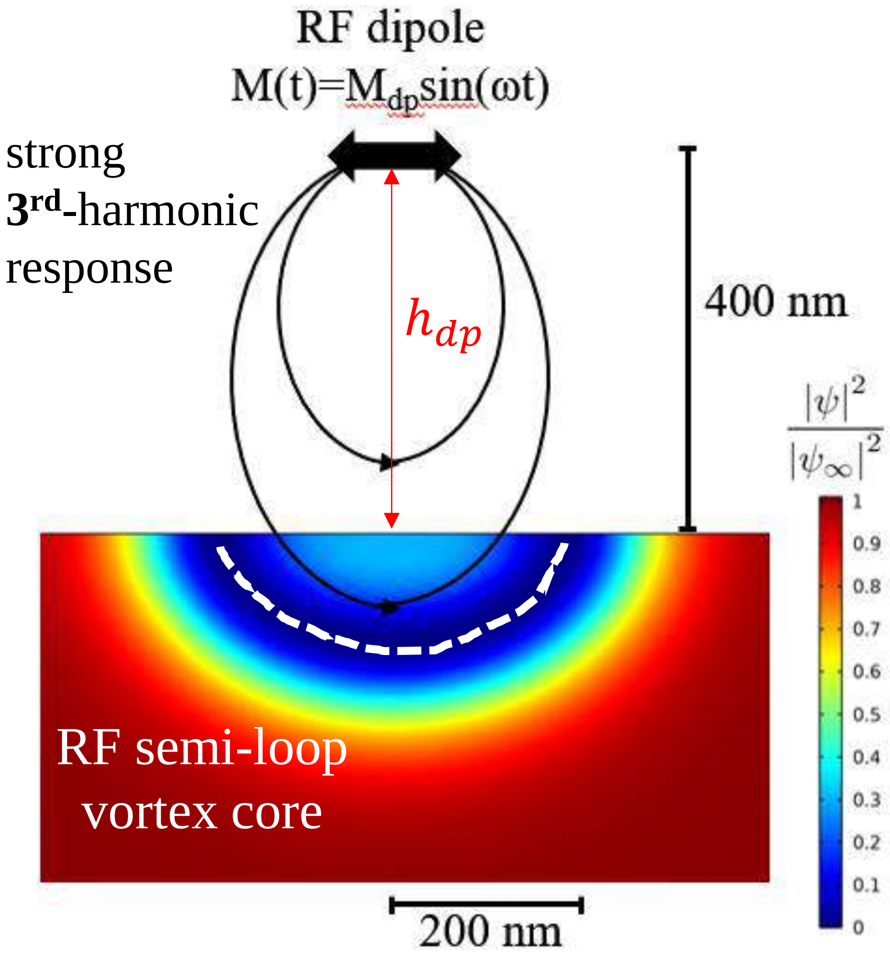
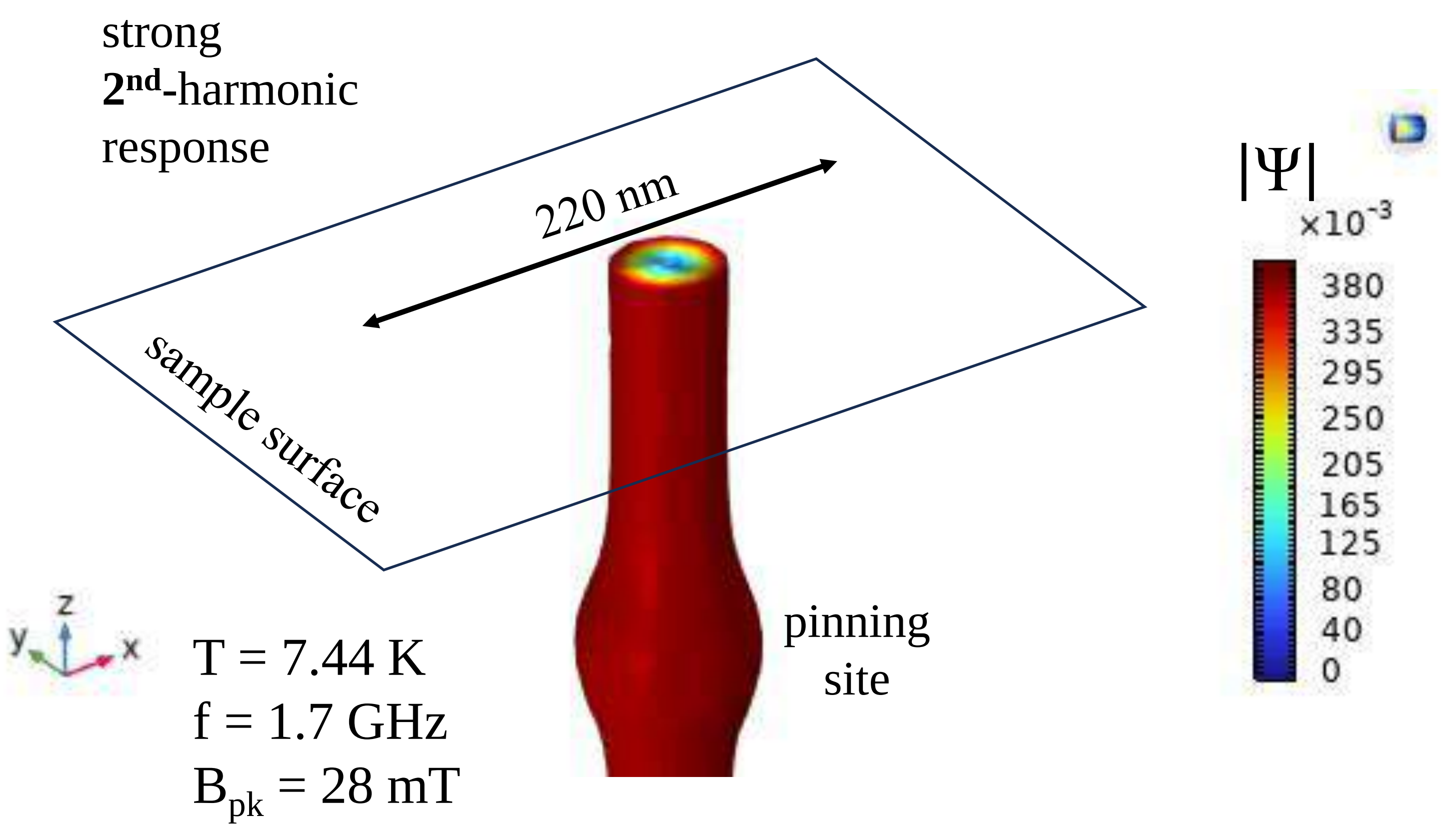
Nanoscale Ion Beam Materials Modification for Next-generation Superconducting Digital Logic

Objective

Investigate high-frequency response of stray (few in number) magnetic vortices

- How do they disrupt SC digital electronics? We examine *one* aspect of this problem…
  - First step: Understand their response to *high-frequency* fields (as opposed to dc-current offsets)
    - Harmonic generation: Vortex semi-loops generate 3rd-harmonic response, vs. 2nd-harmonic from trapped vortex

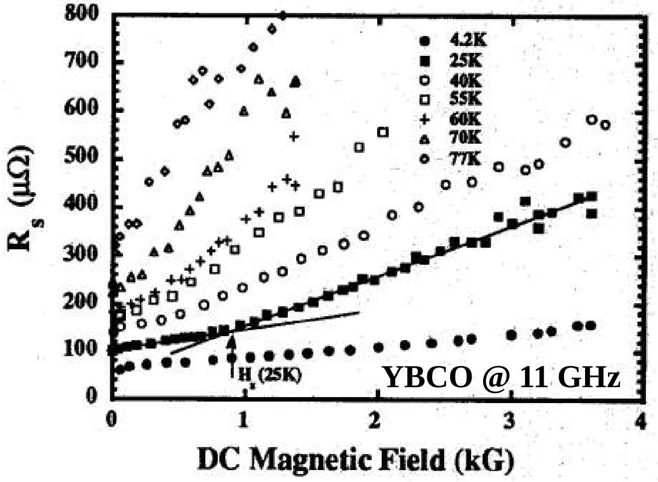




C.-Y. Wang, *et al*., Phys. Rev. Applied 22, 054010 (2024)

Objective

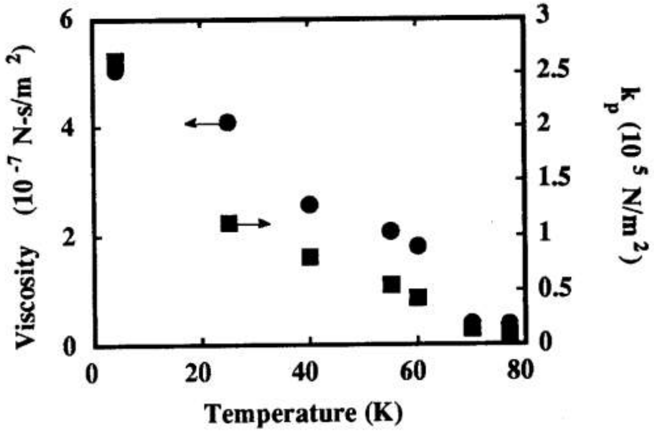
Settings:
Near-field microwave microscopy
CPW Transmission-line with trapped vortices incorporated at engineered sites



Traditional high-frequency measurements of vortices in superconductors
Macroscopic response from many vortices (10^6 – 10^{10})
Single-particle model to extract vortex viscosity (η) and pinning force constant (κ_{pin})

$$m\,\ddot{u} = J \times \Phi_0 + f_{Thermal} - \eta\,\dot{u} - \kappa_{pin}\,u \qquad \omega_{pin} = \kappa_{pin}/\eta$$

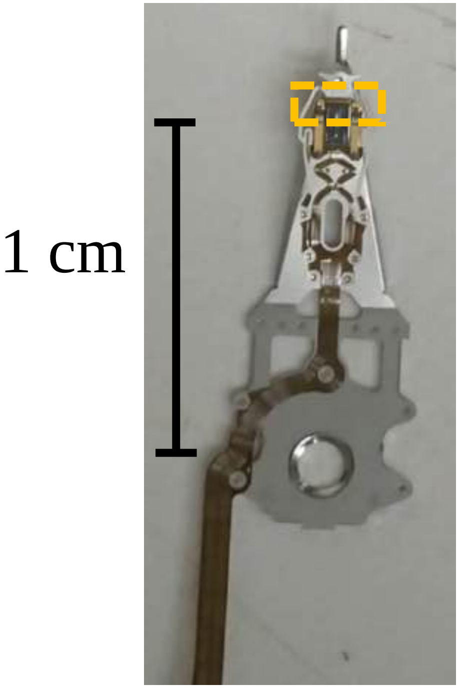
Traditional TDGL studies: Maximize DC I_c in the presence of strong B_{DC}

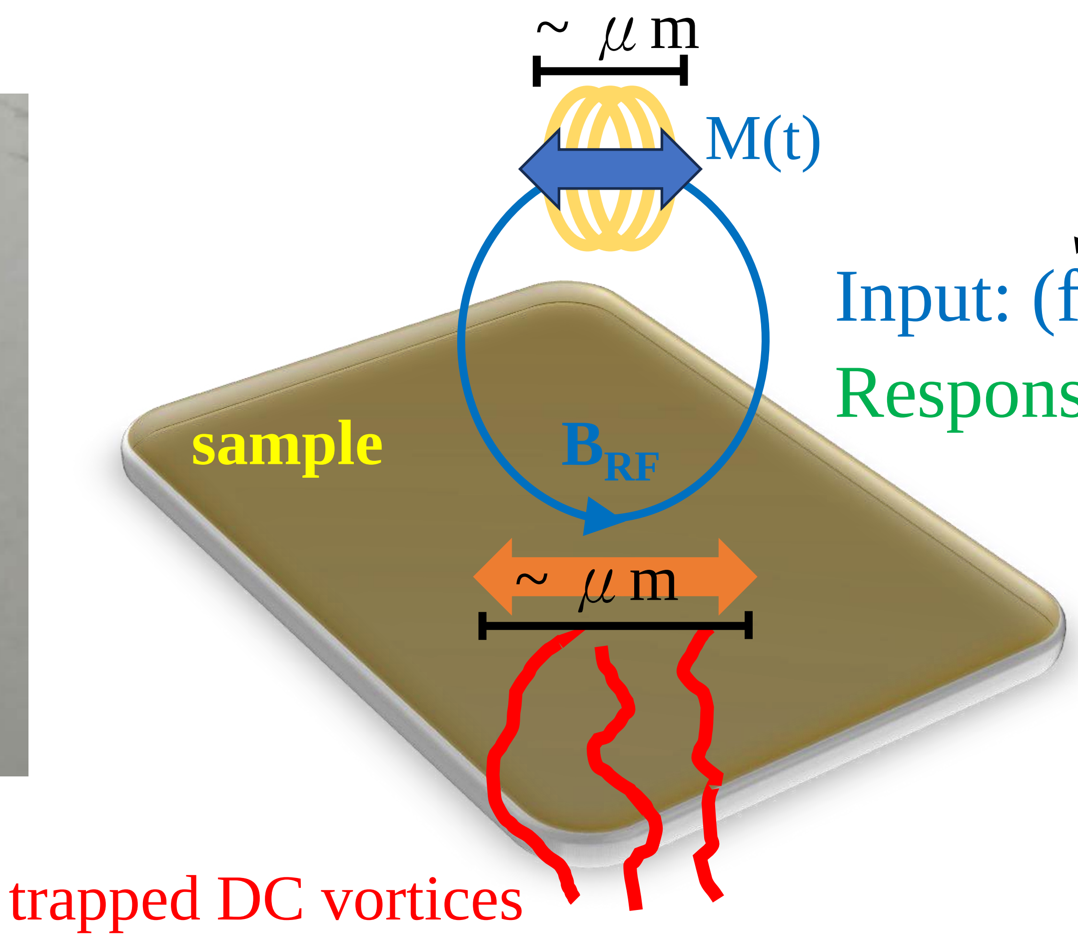


M. Pambianchi, *et al.*, IEEE TAS <u>3</u>, 2774 (1993)

Our approach:
<u>Measure</u> nonlinear microwave response in the context of
a small numbers of vortices
engineered pinning profiles
<u>Simulate</u> the response of the vortices to controlled microwave signals

Near-field magnetic microwave microscope





Driving force: $B_{RF}\sin(\omega t)$

Response: J_{SC}, B_{SC}

GHz

Input: (f, P_{input})

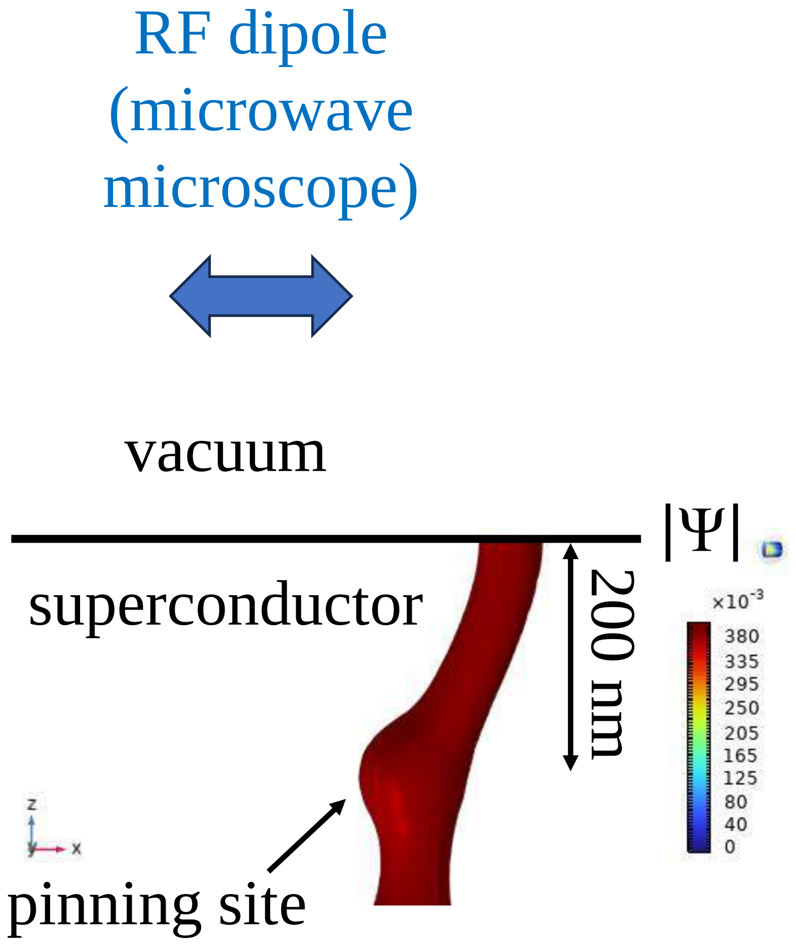
Response: (f, P_f), (2f, P_{2f}), (3f, P_{3f}), etc.

focus of this work
(filters out the background)

1. Apply a localized oscillating magnetic field
2. Trapped DC vortices wiggle
3. Measure the response

Trapped DC vortex driven by local RF field

Time-dependent Ginzburg-Landau simulation

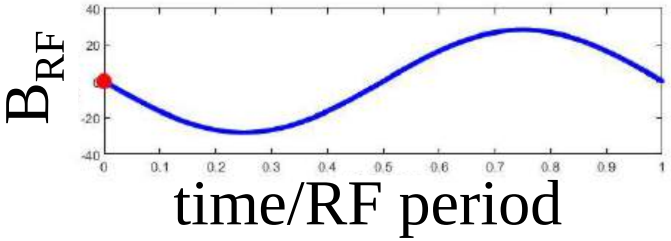


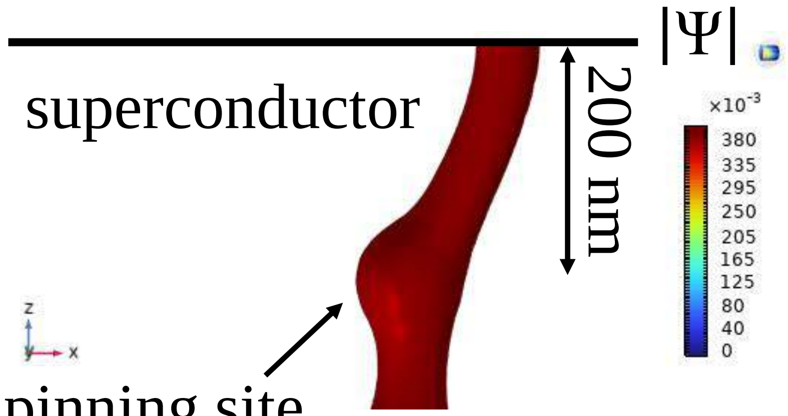
Time-dependent Ginzburg-Landau Treatment of RF Magnetic Vortices in Superconductors: Vortex Semiloops in a Spatially Nonuniform Magnetic Field, Phys. Rev. E **101**, 033306 (2020)

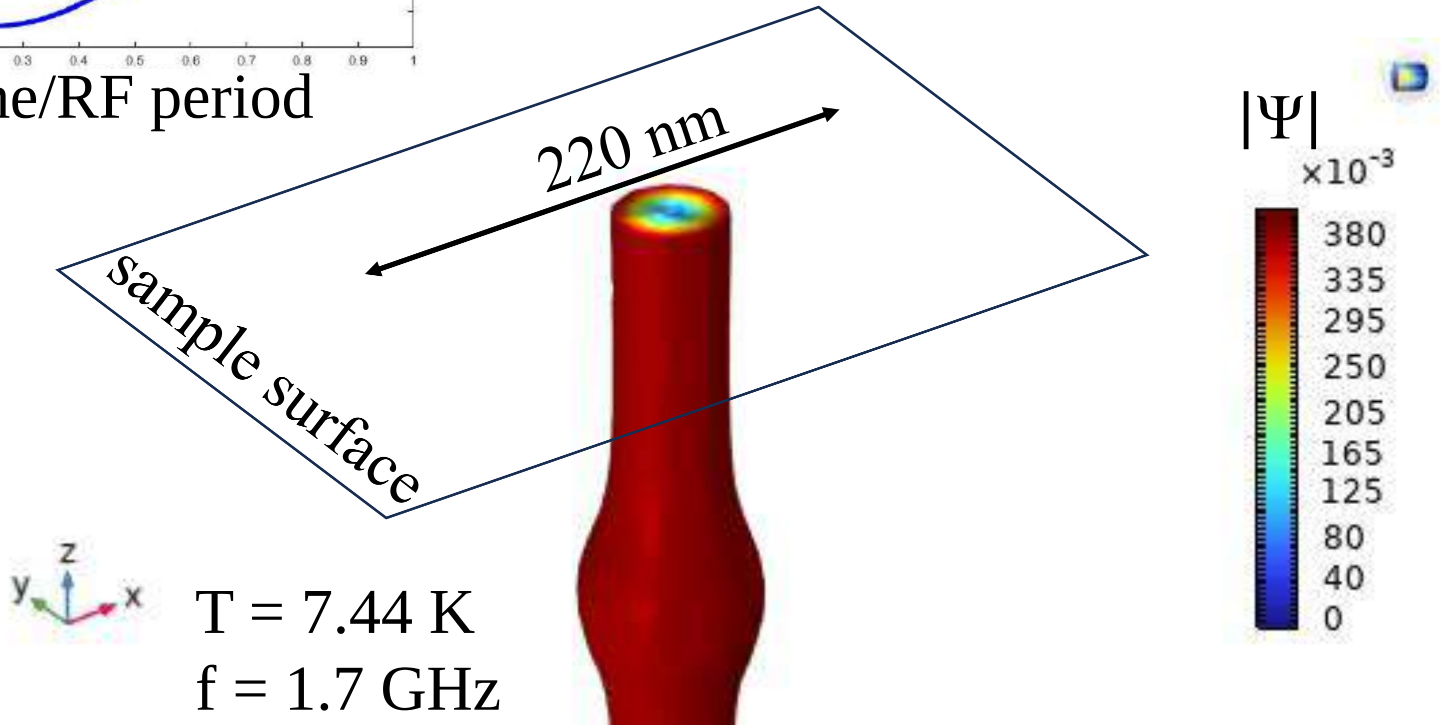
Trapped DC vortex driven by local RF field

Time-dependent Ginzburg-Landau simulation

RF dipole (microwave microscope)







T = 7.44 K

f = 1.7 GHz

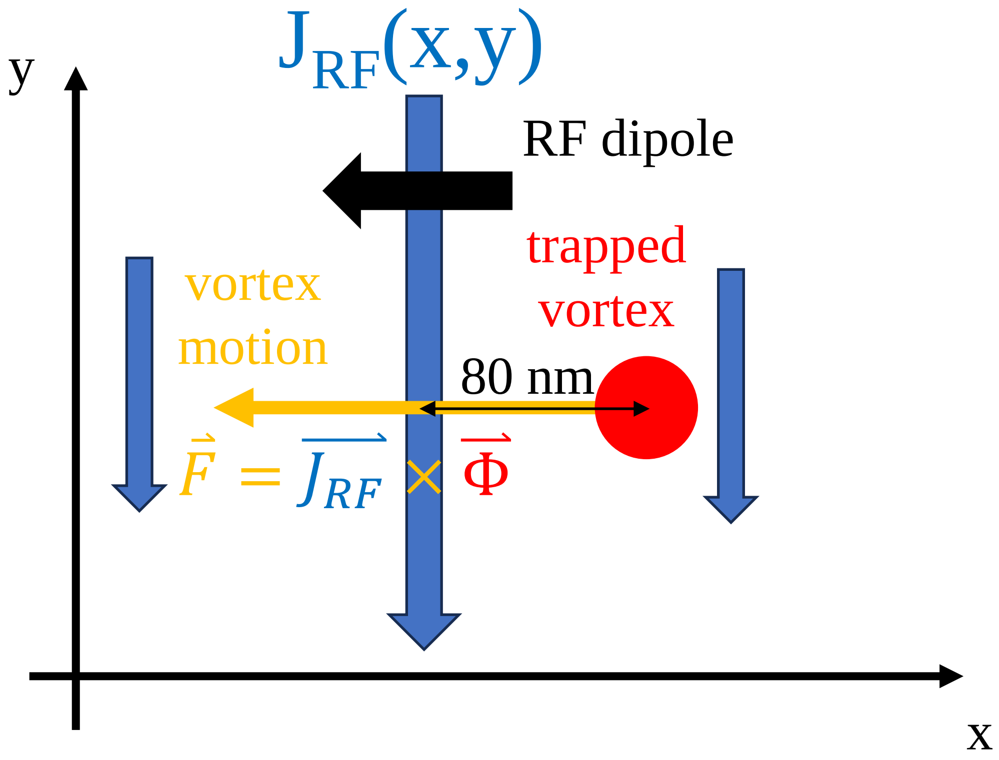
B_{pk} = 28 mT

Time-dependent Ginzburg-Landau Treatment of RF Magnetic Vortices in Superconductors: Vortex Semiloops in a Spatially Nonuniform Magnetic Field, Phys. Rev. E **101**, 033306 (2020)

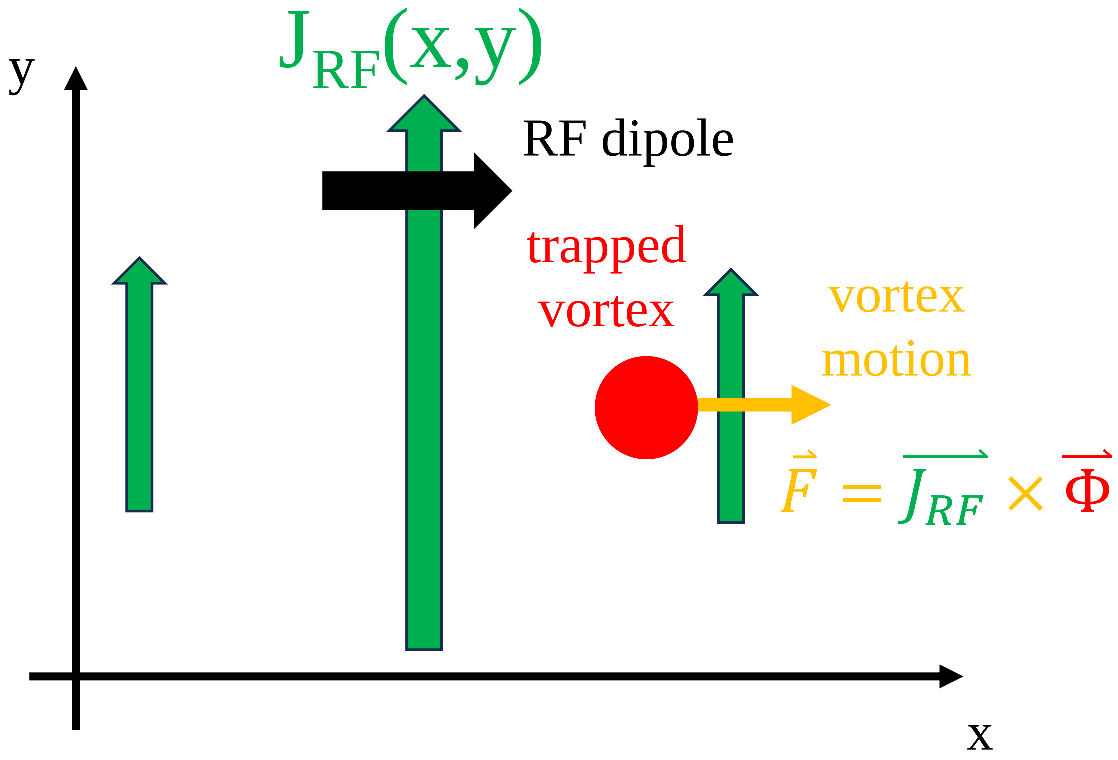
P_{2f} mechanism: gradient of the induced RF current

microscopic measurement → RF field is localized → induced RF current has a strong gradient → asymmetric vortex dynamics → P_{2f} signal from a very localized region of the sample

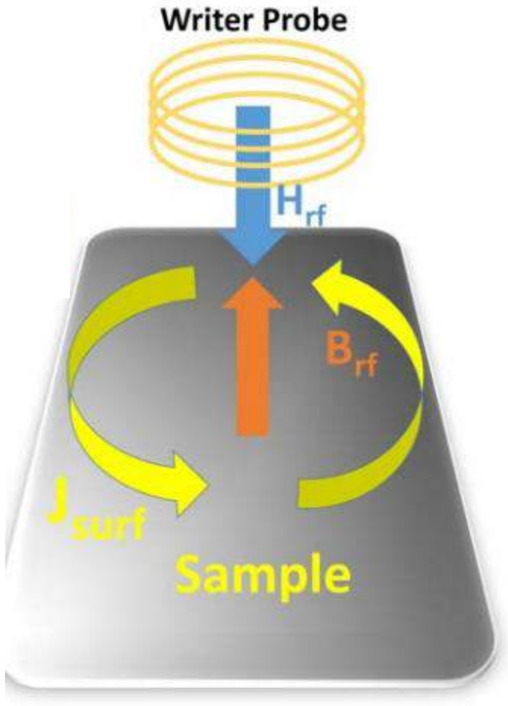
first half-RF cycle (top view)



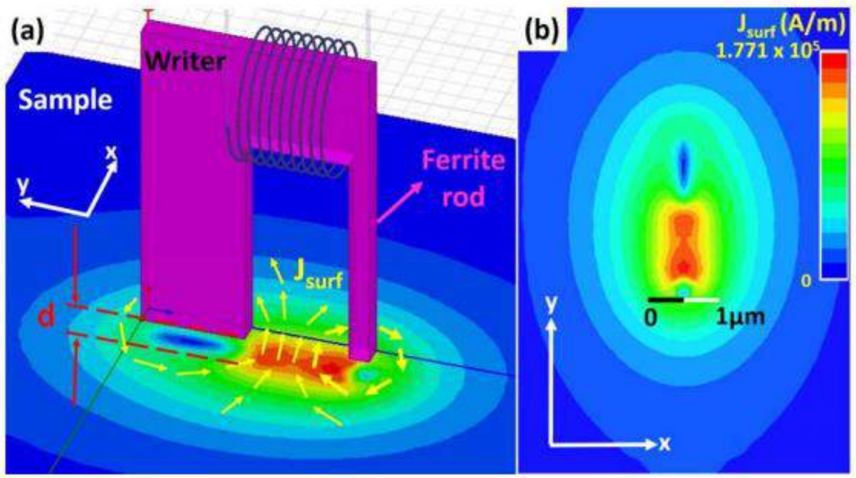
second half-RF cycle (top view)



Field of View of the Microwave Microscope

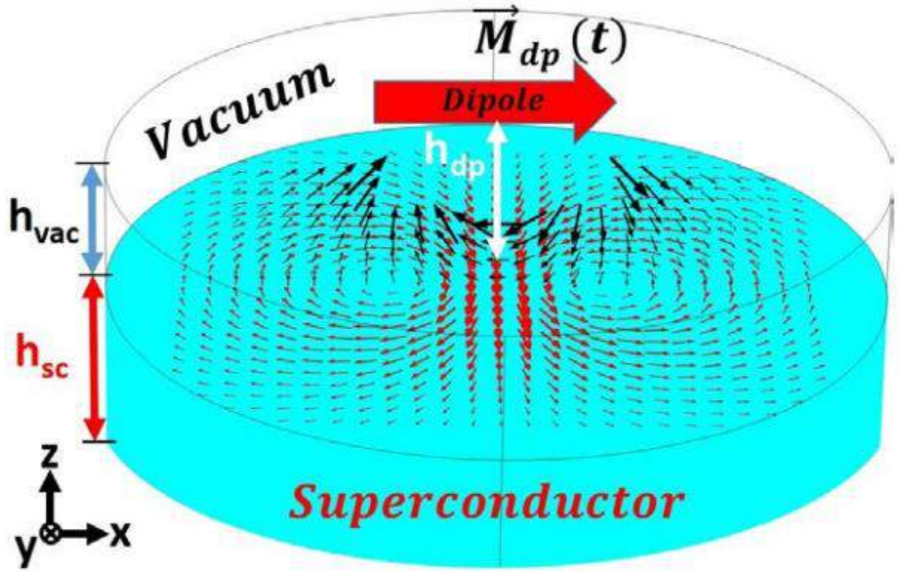


HFSS simulation

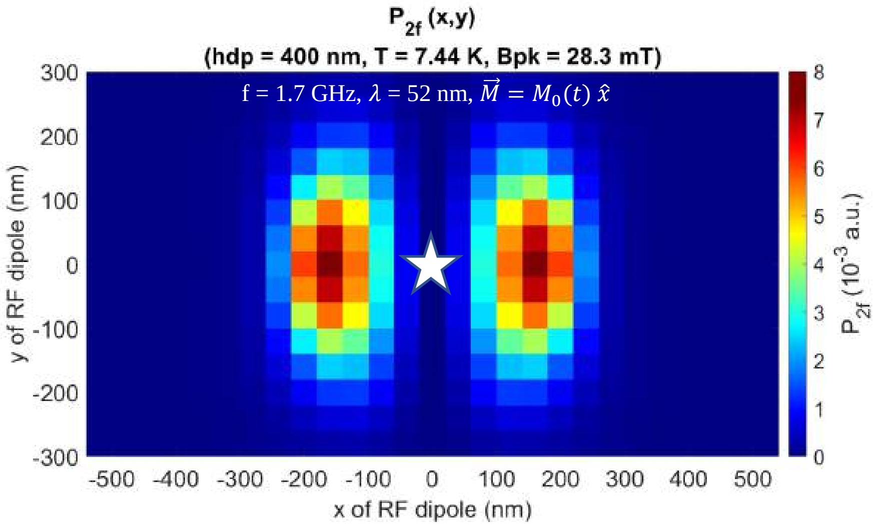


B. Oripov, Ph.D. thesis, UMD, 2020: https://doi.org/10.13016/gdll-9g1a

TDGL/COMSOL simulation



Red arrows – surface current
Black arrows – magnetic field



TDGL/COMSOL calculated $P_{2f}(x, y)$ due to a single pinned vortex at the location of the star

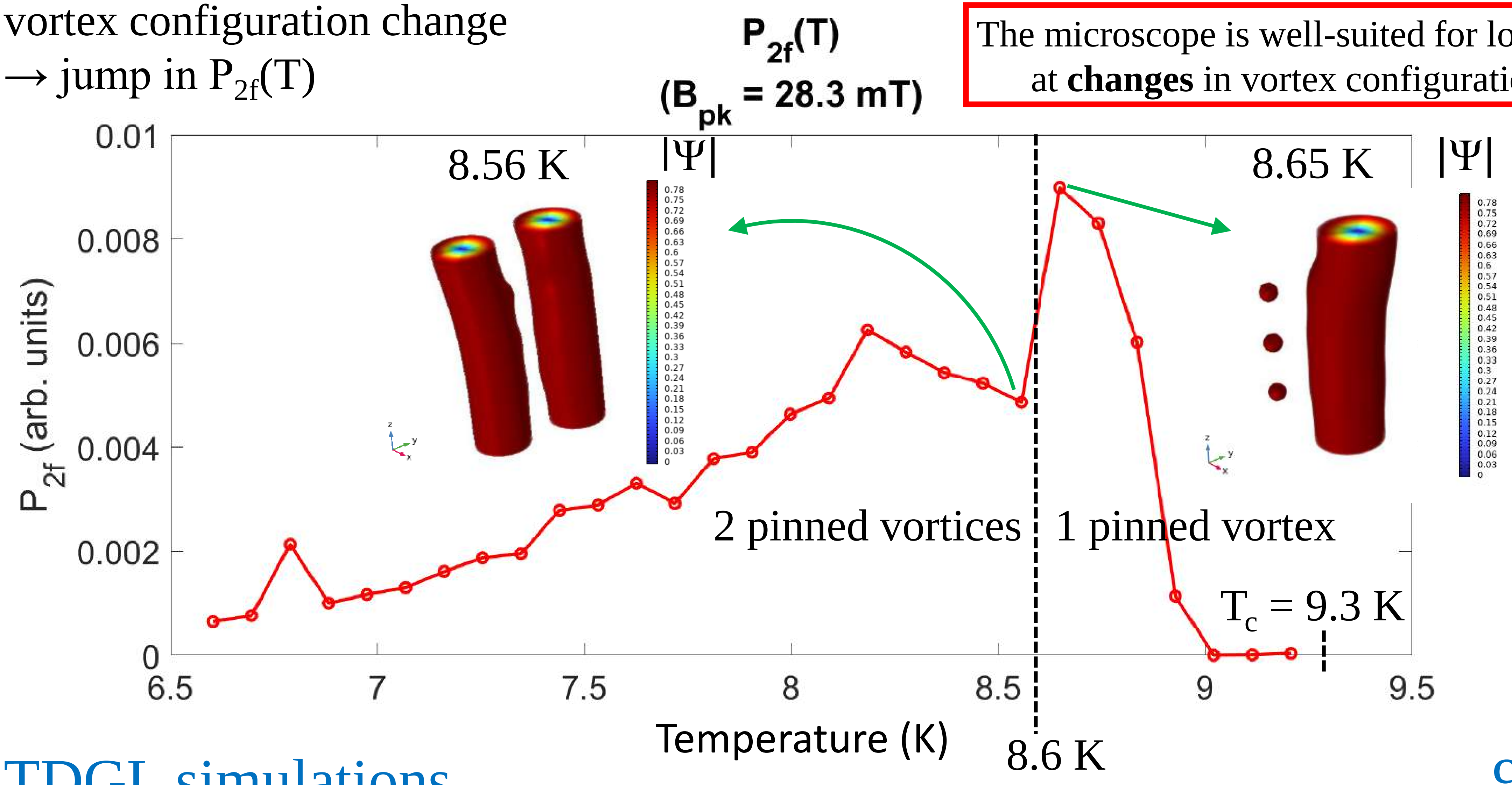
Empirical results from P_{2f} measurements indicate probe/vortex interaction range of ~ 1 µm

P_{2f} Point-Spread Function of a single vortex

Simulation: vortex de-pinning and $P_{2f}(T)$ jump

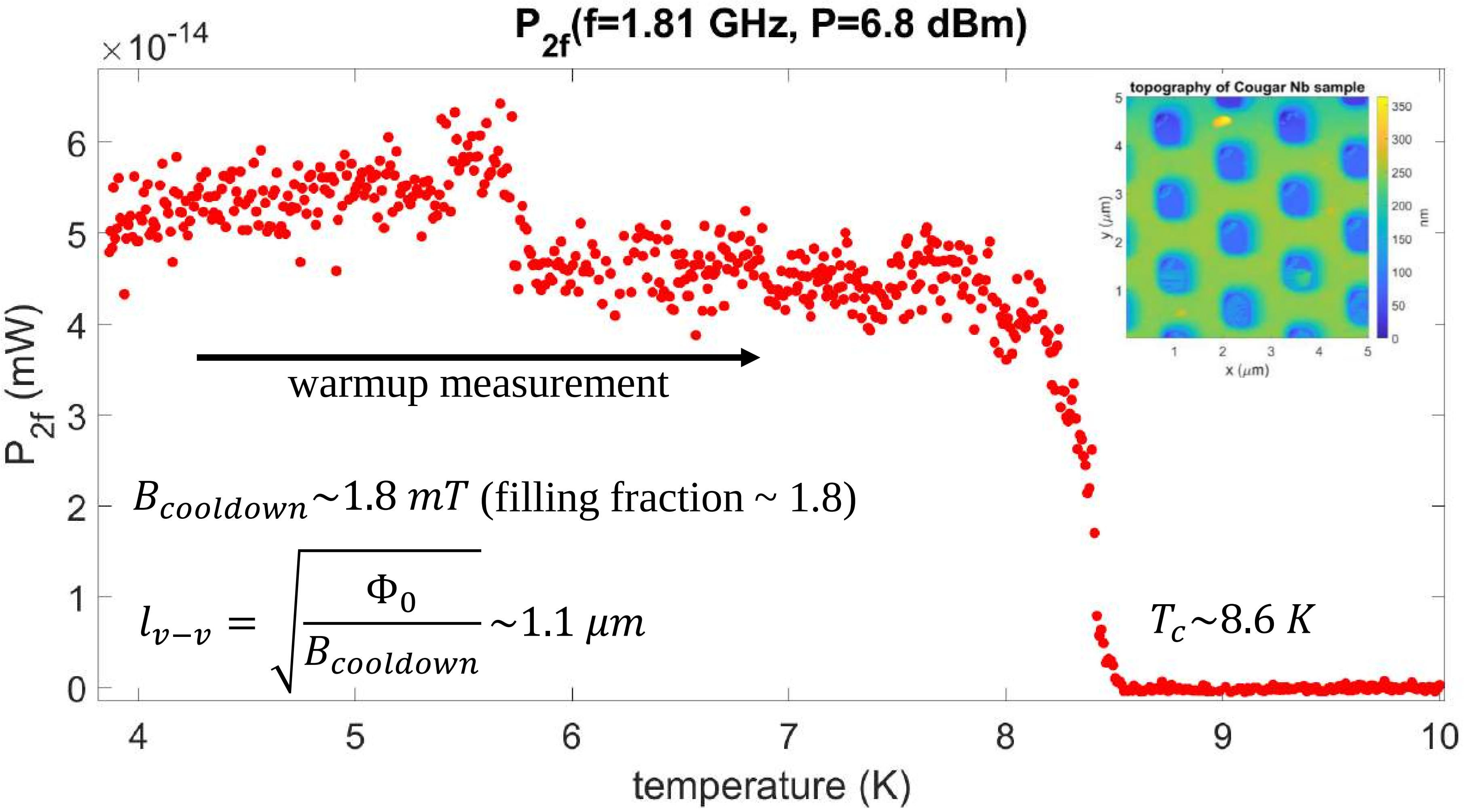
vortex configuration change
→ jump in $P_{2f}(T)$

The microscope is well-suited for looking at **changes** in vortex configuration



TDGL simulations

Fixed-point measurement $P_{2f}(T)$ with trapped DC vortices



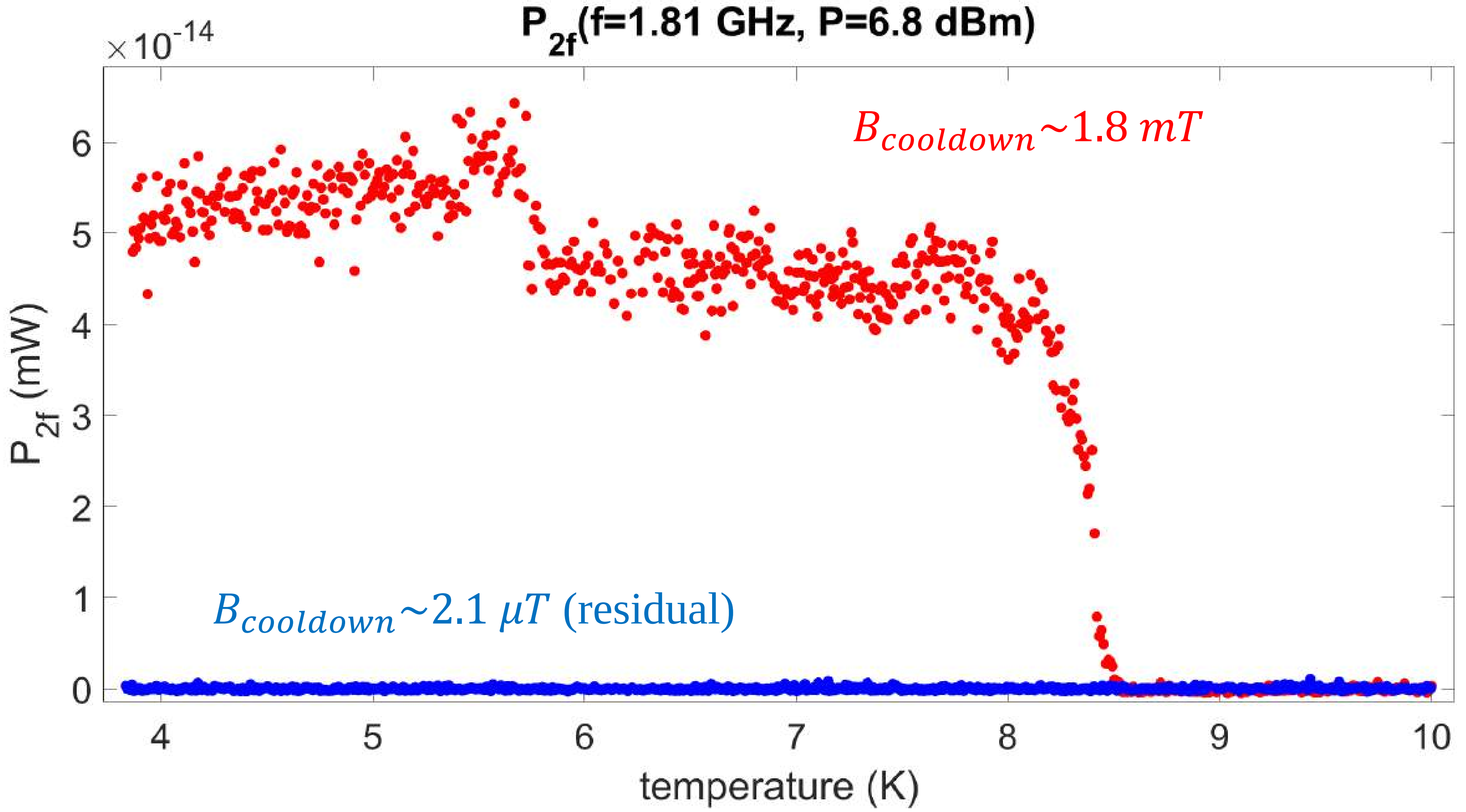
Measurement protocol

1. Warm up to 10 K
2. Turn on DC field
3. Cool down to 4 K (cooling rate ~ 0.033 K/min)
4. Turn off DC field
5. Turn on RF field
6. Warmup measurement

NO applied DC field during measurement

Experiment results of a Nb film

With vs. without trapped DC vortices



$$l_{v-v} = \sqrt{\frac{\Phi_0}{2.1\ \mu T}} \sim 31\ \mu m$$

dilute DC vortices

↓

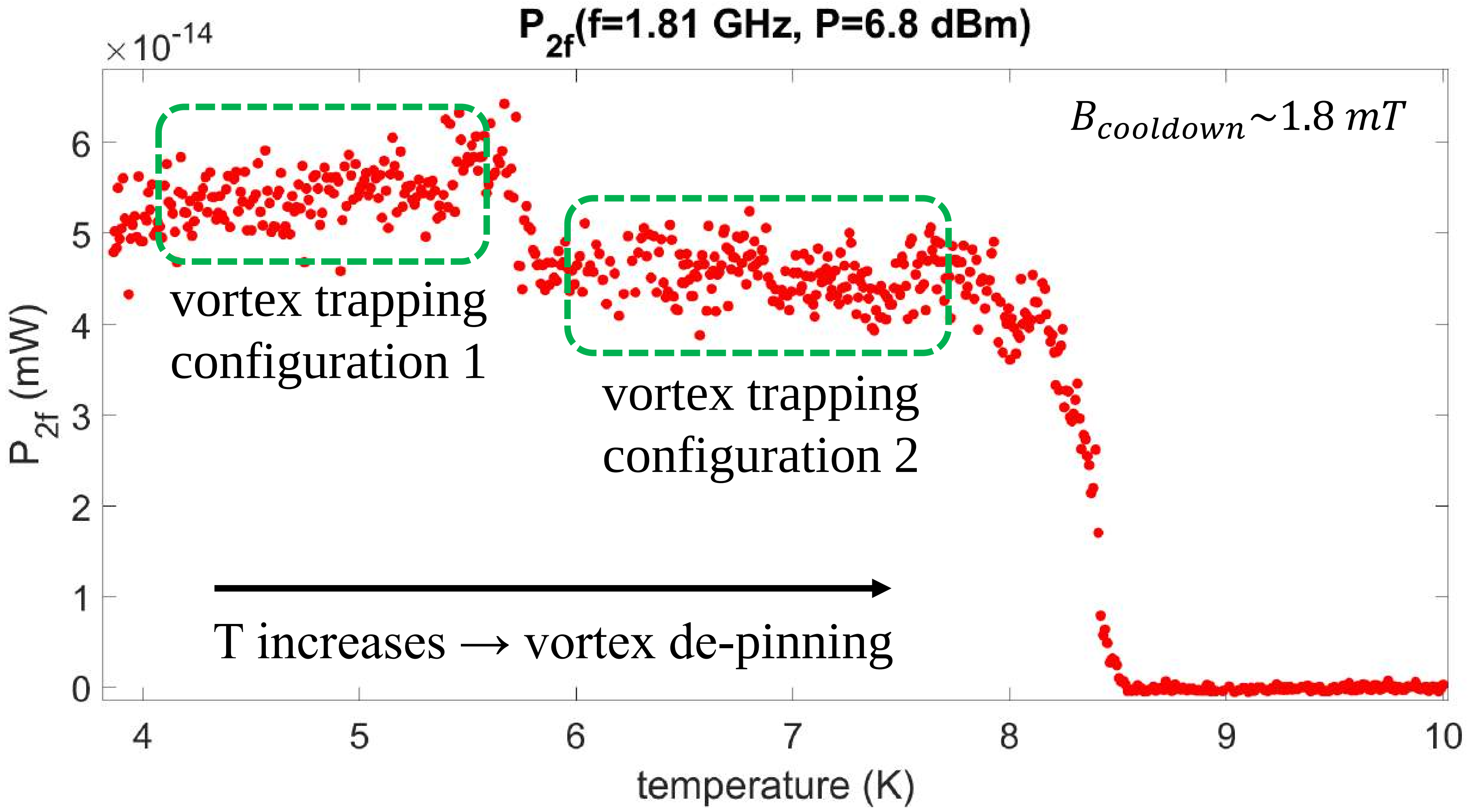
no DC vortices near the probe

↓

$P_{2f} = 0$

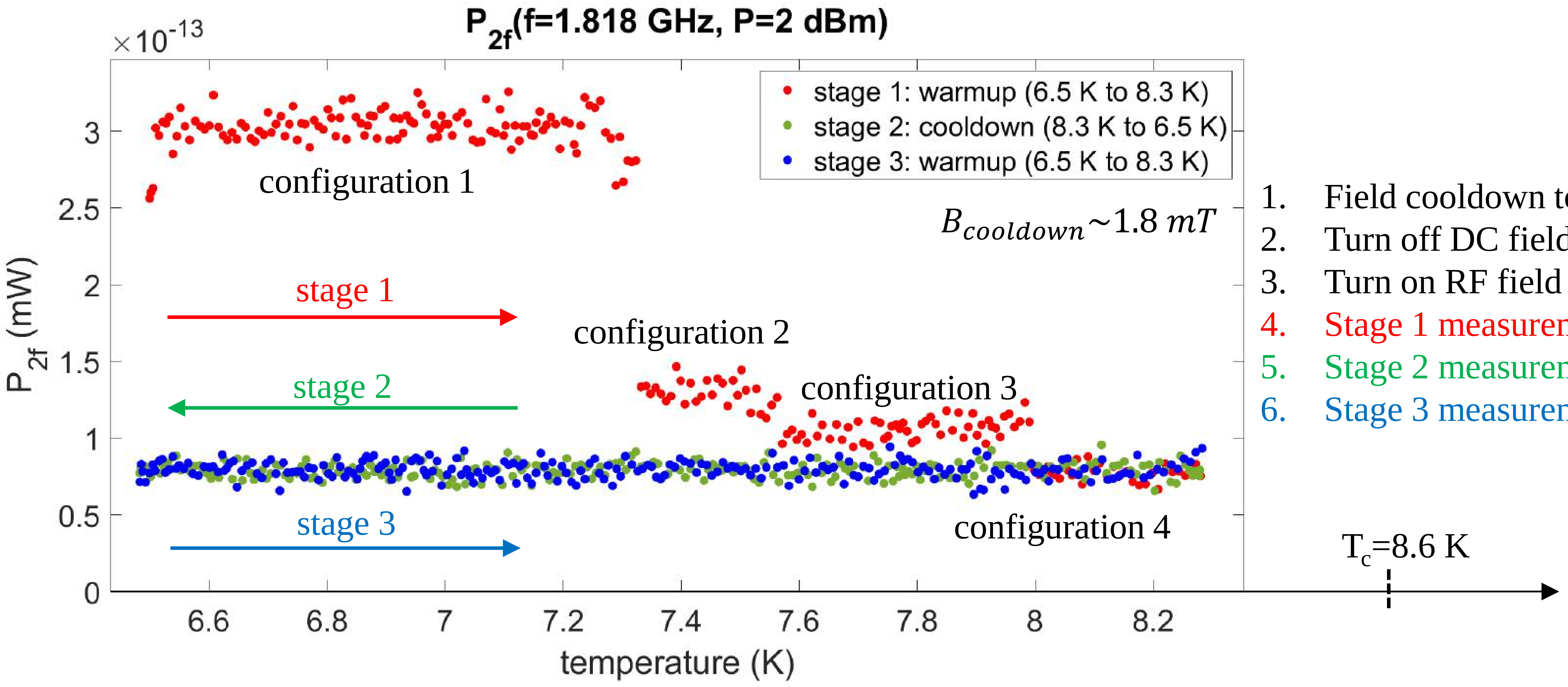
Experiment results of a Nb film

A candidate for discrete jumps: vortex de-pinning

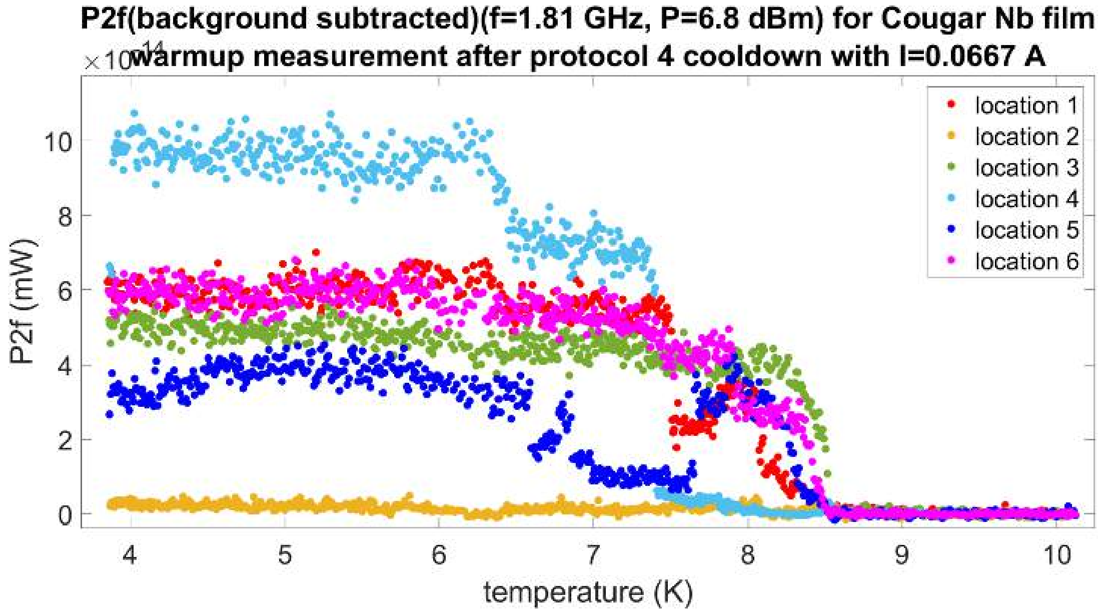


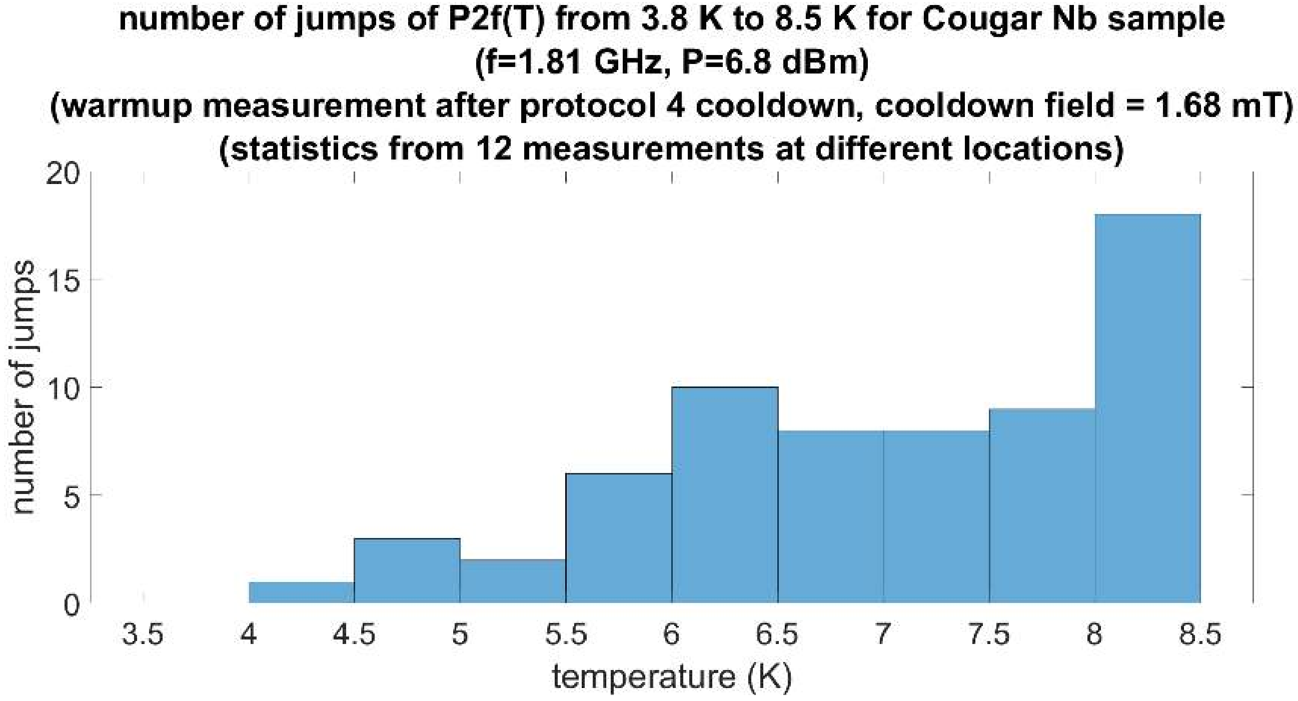
configuration change:
- vortex-vortex interaction
- RF field-vortex interaction

Hysteresis in $P_{2f}(T)$



1. Field cooldown to 6.5 K
2. Turn off DC field
3. Turn on RF field
4. Stage 1 measurement
5. Stage 2 measurement
6. Stage 3 measurement





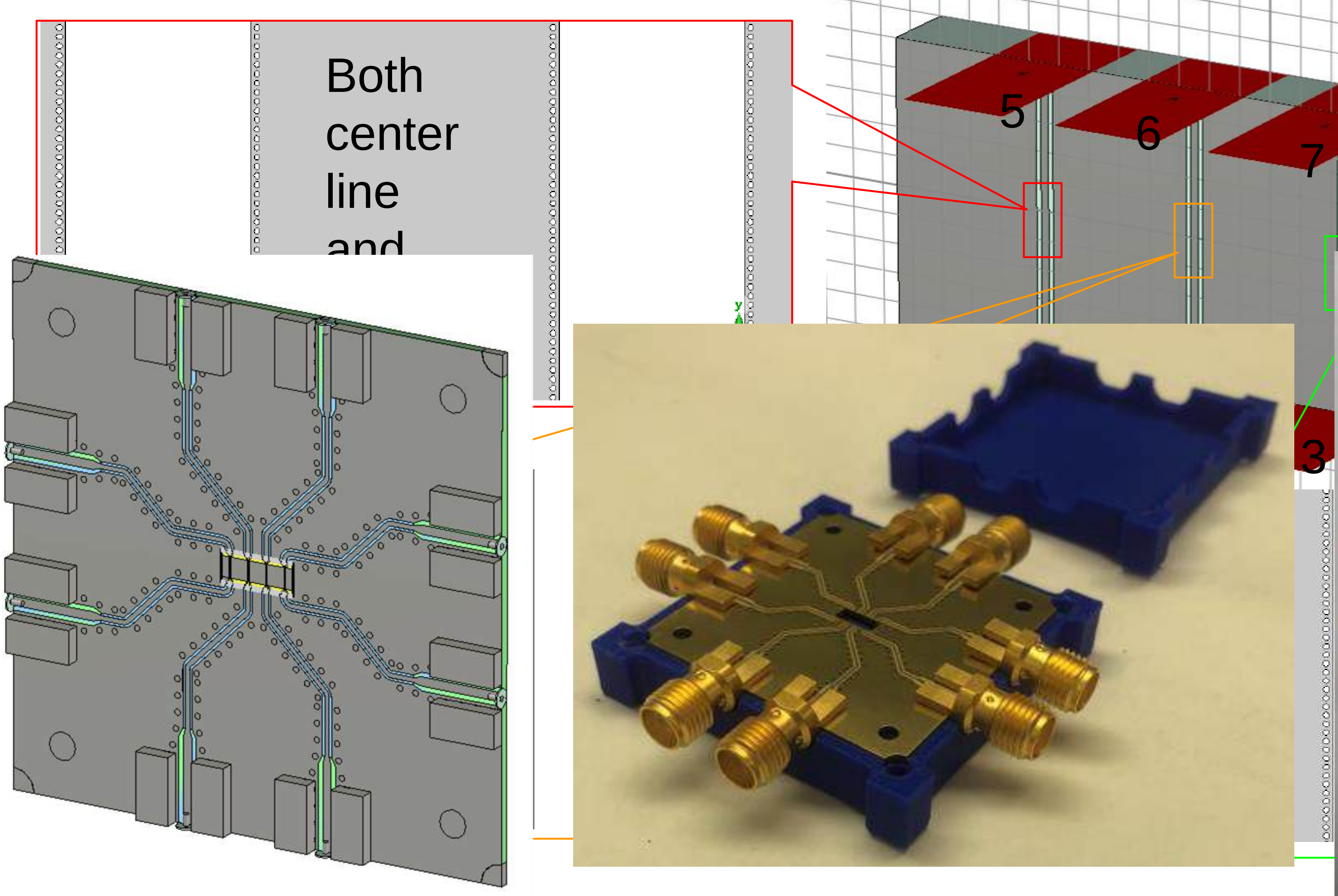
The microwave microscope is sensitive to re-arrangement of small numbers of vortices

Vortex pinning strength directly influences the rate of re-arrangement

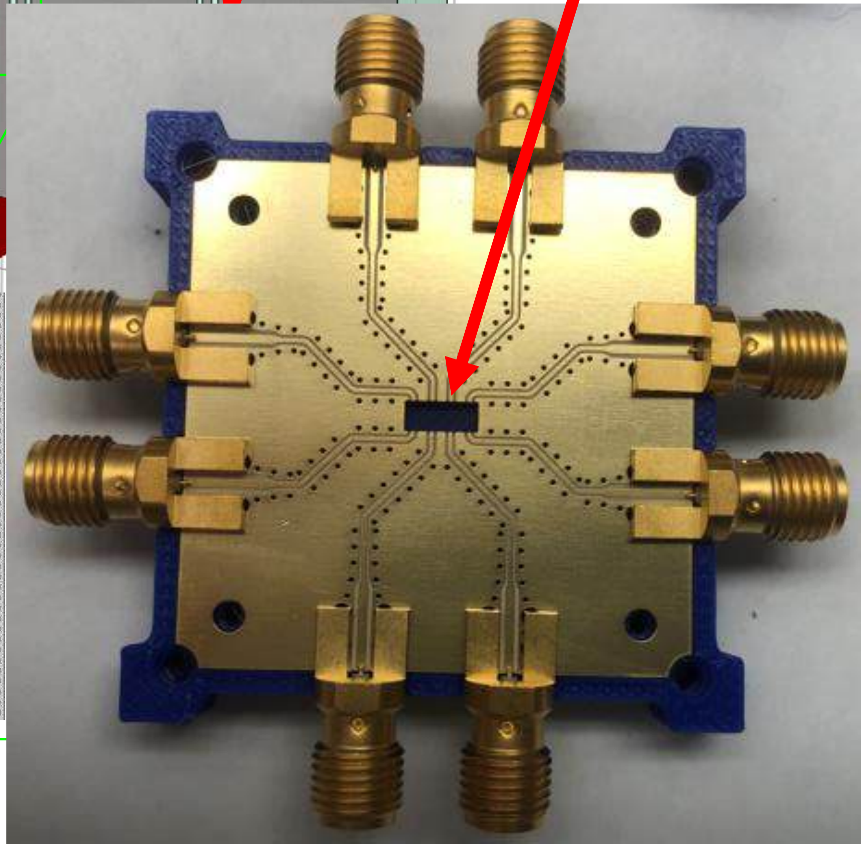
The "field of view" of the microscope is approximately 1 μm^2

Harmonic Generation Created by Pinned Vortices on CPW

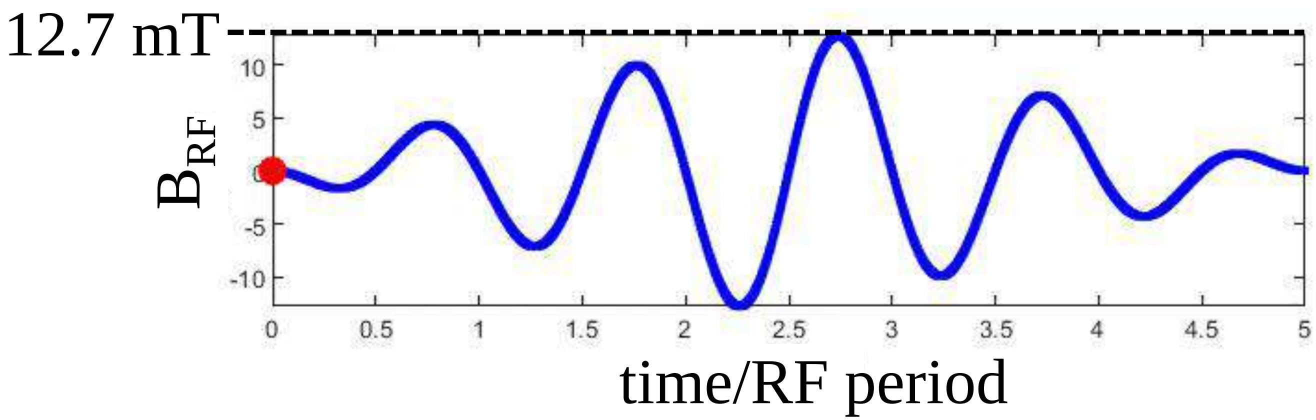
This transmission line will be left un-modified (no anti-dots)



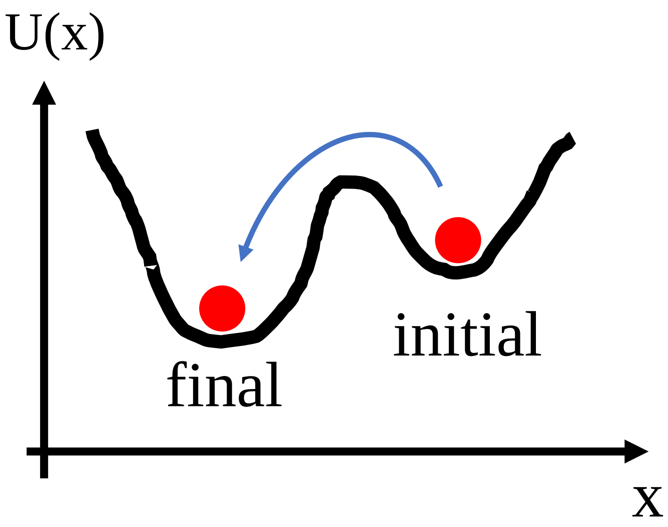
Chip being fabricated by AIST

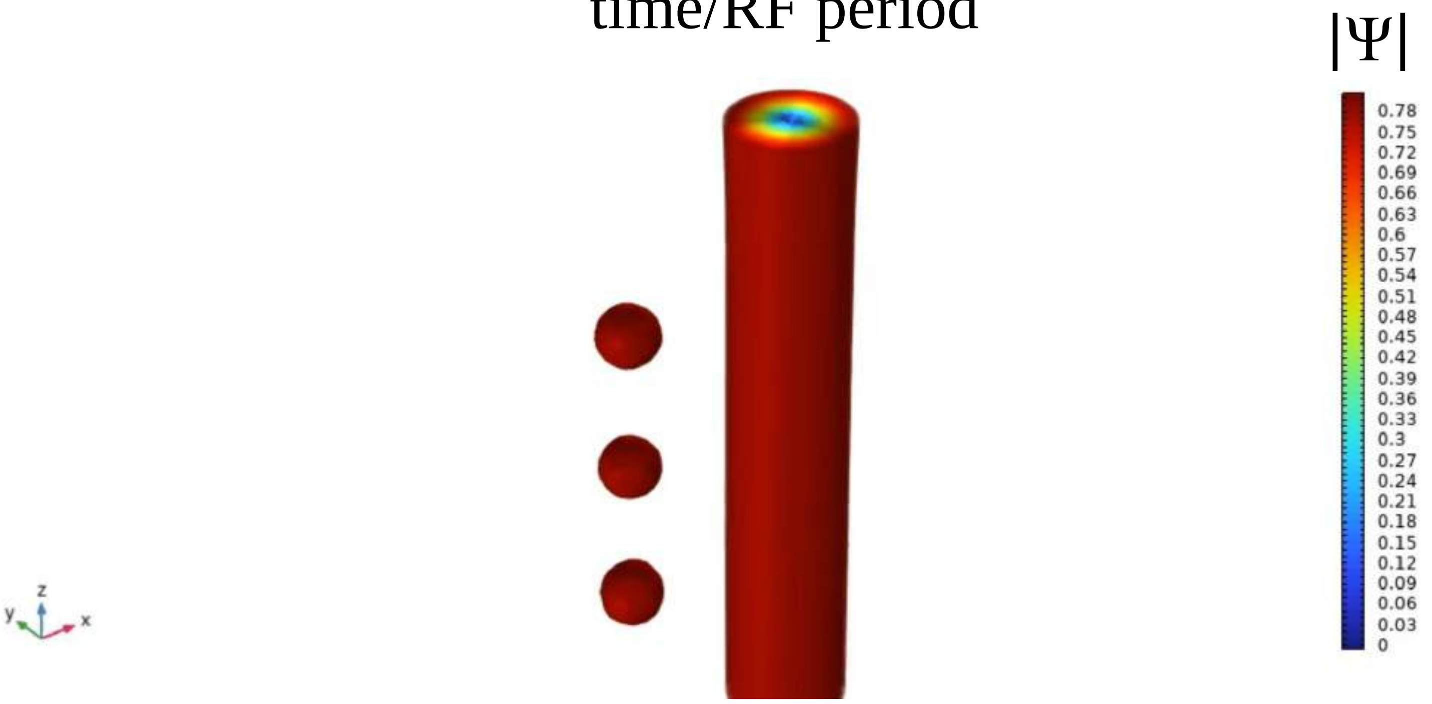


Simulation: RF annealing caused by passing pulse



- Nb
- T = 7.44 K
- f_c = 1.7 GHz





UMD 6-Month Plan

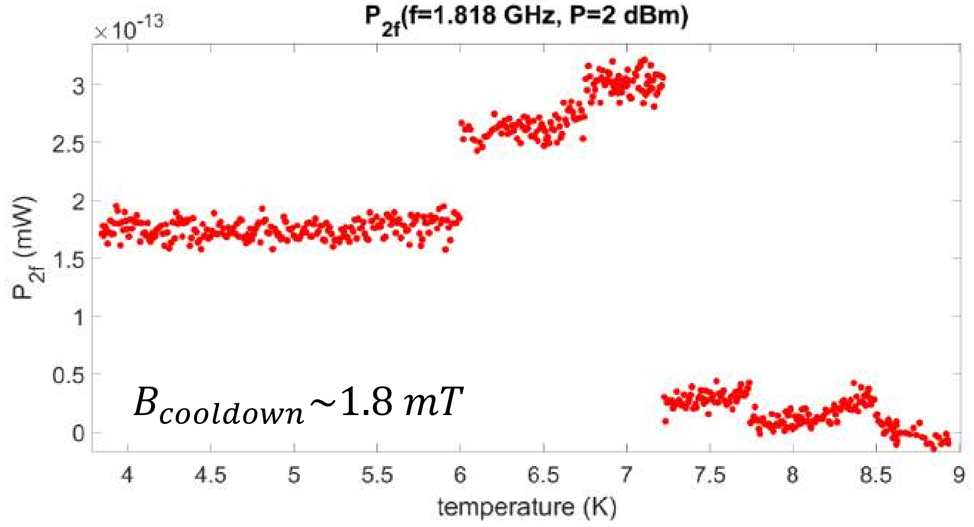
Measurement of vortex re-configuration statistics in Nb anti-dot lattice

TDGL simulations of few-vortex dynamical trapping and re-arrangements

Harmonic generation measurements of trapped flux in/near CPW transmission line

Summary: microwave microscope and trapped vortices

- The wiggling of a trapped DC vortex when stimulated by a local RF field generates the second harmonic response.
- Microscope has a limited “field of view” for vortices
- Immediate application: explore de-pinning of trapped DC vortices.
- Further application: Understand response of vortex to SFQ pulses
- TDGL digital twin of experiment gives insights into microscopics



Acknowledgement:

- Special thanks to Seagate Corp. for providing magnetic probes

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