Millimeter-imaging spectrometer using magnetic field tunable kinetic inductance detectors (H-KID)

Florence Levy-Bertrand, solid state physicist (Institut Néel, Grenoble)

Work within the Scientific Interest Group on KIDs with

M. Calvo, J. Goupy, U. Chowdhury, A. Monfardini
B. Sacépé, G. Donnier-Valentin, T. Gandit

A. Gomez

Financial support

Millimeter-imaging spectrometer using magnetic field tunable kinetic inductance detectors (H-KID)

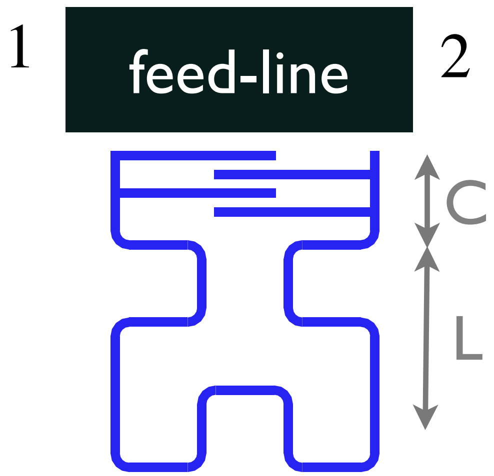
- Working principle of KID
- Magnetic field effect on KID: H-KID
- Toward a real mm-spectrometer with H-KID ?

Working principle of KID

Day et al, Nature 425, 817 (2003)

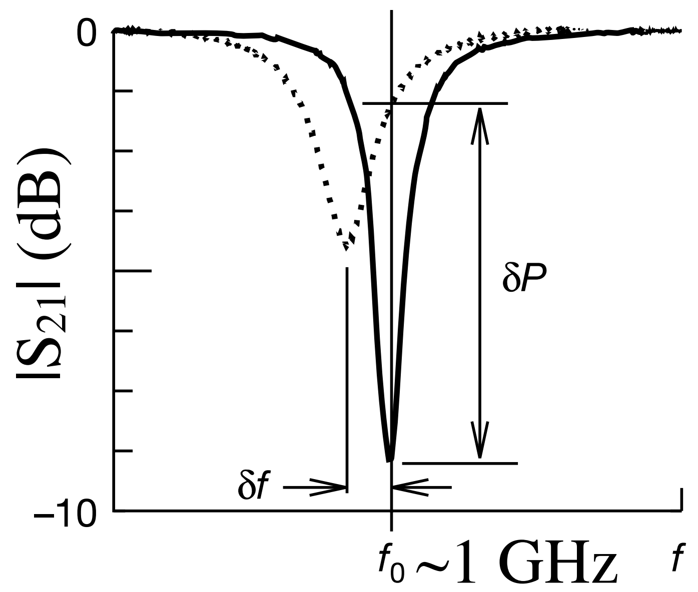
Planar superconducting LC resonator on an insulating substrate

design



superconducting resonator

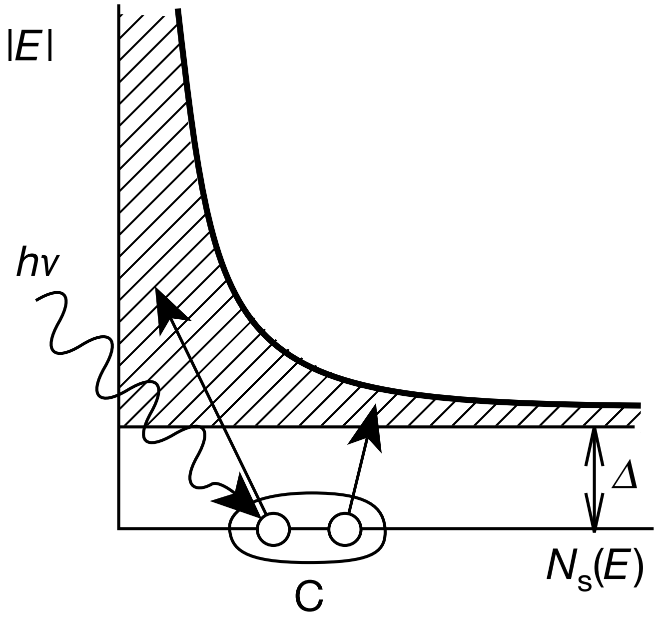
RF-electrical measurement



$f_0 \sim (LC)^{-1/2}$

photon detection principle :

$h\nu > 2\Delta$



L ~ kinetic inductance of the superfluid

$L \sim 1/n_s$

Working principle of KID

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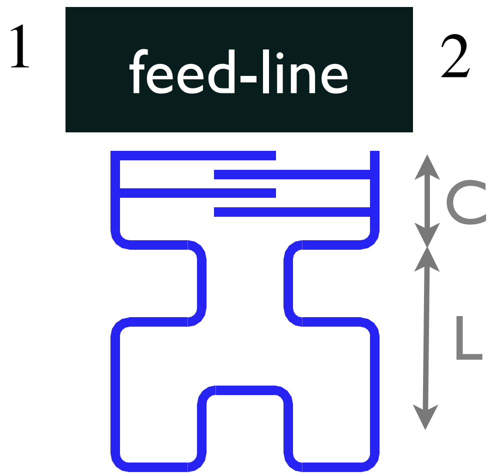

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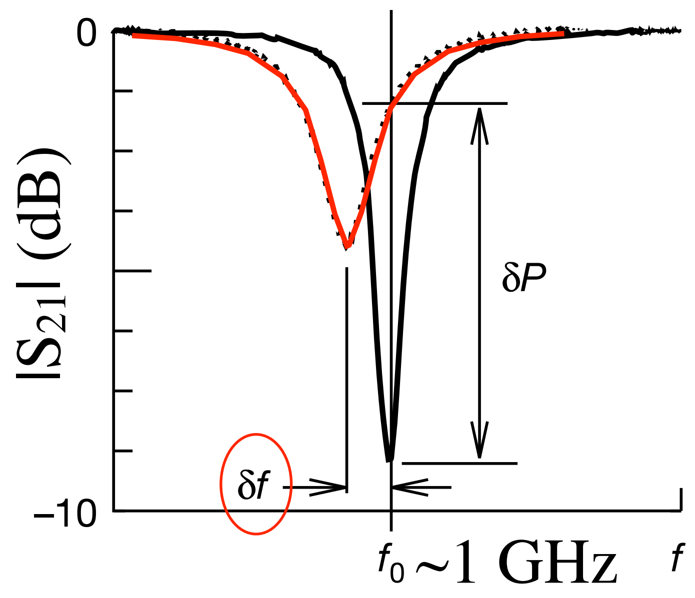

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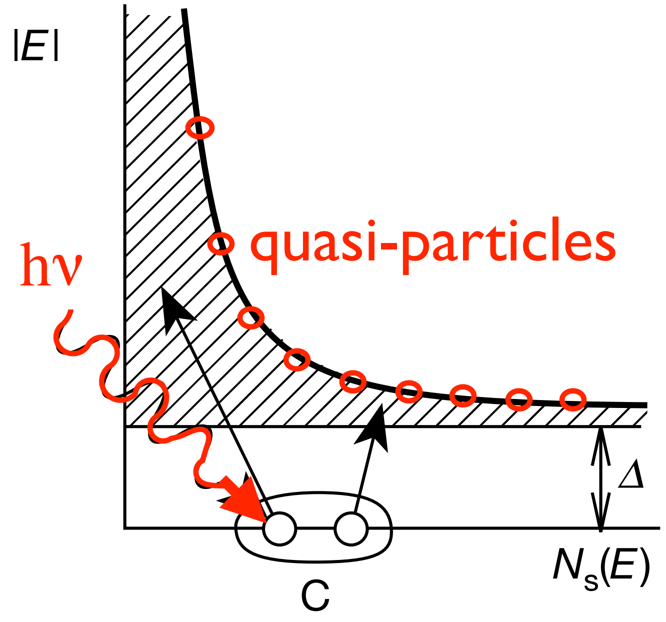

frequency shift: δf due to $n_s\downarrow$

Q-factor↓ due to dissipation↑

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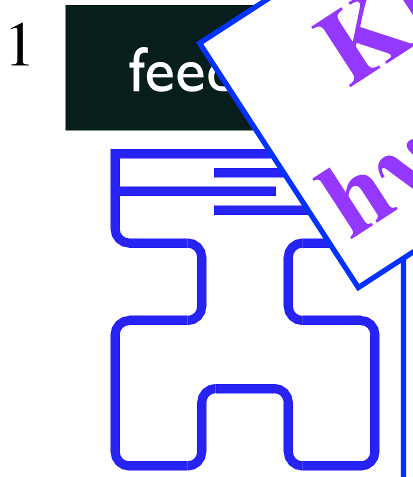


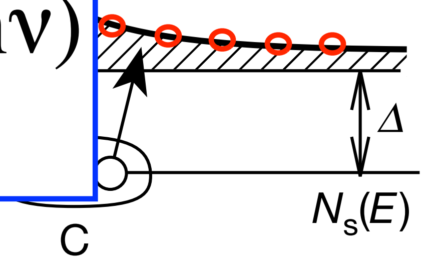
superconducti
resonator

KID
$h\nu > 2\Delta$

=

Kinetic Inductance Detector : KID

detection <u>$h\nu > 2\Delta$</u> through $\delta f \propto \delta n_{qp} \propto P(h\nu)$



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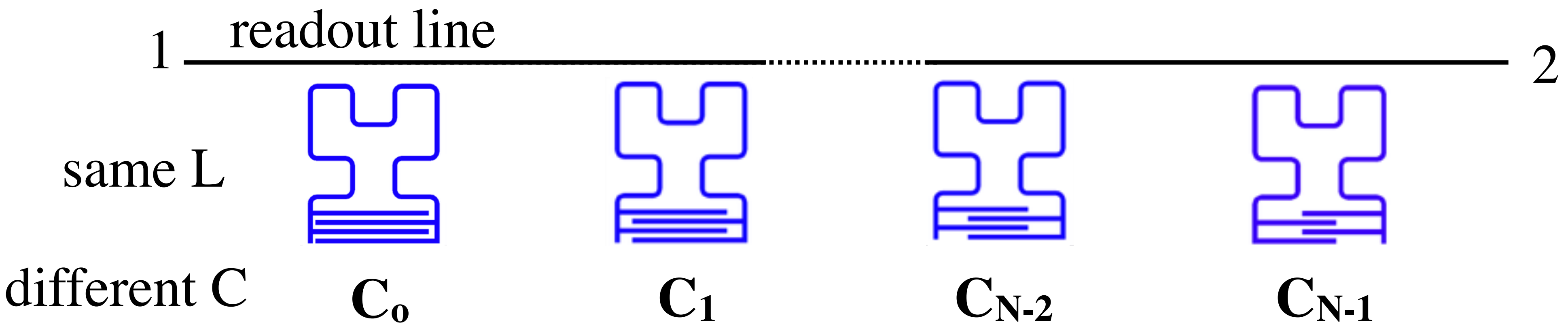
$L \sim 1/n_s$

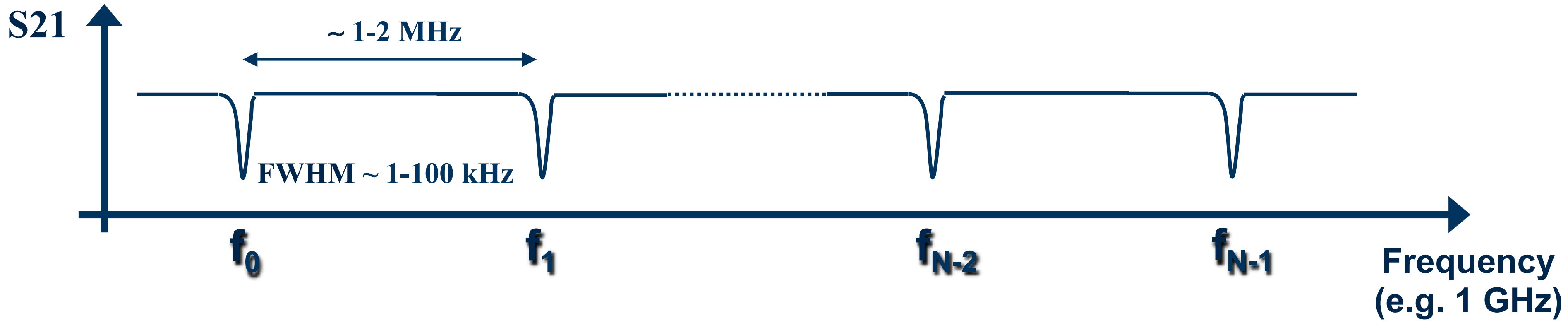
frequency shift: δf due to $n_s\downarrow$

Q-factor$\downarrow$ due to dissipation$\uparrow$

Working principle of KID

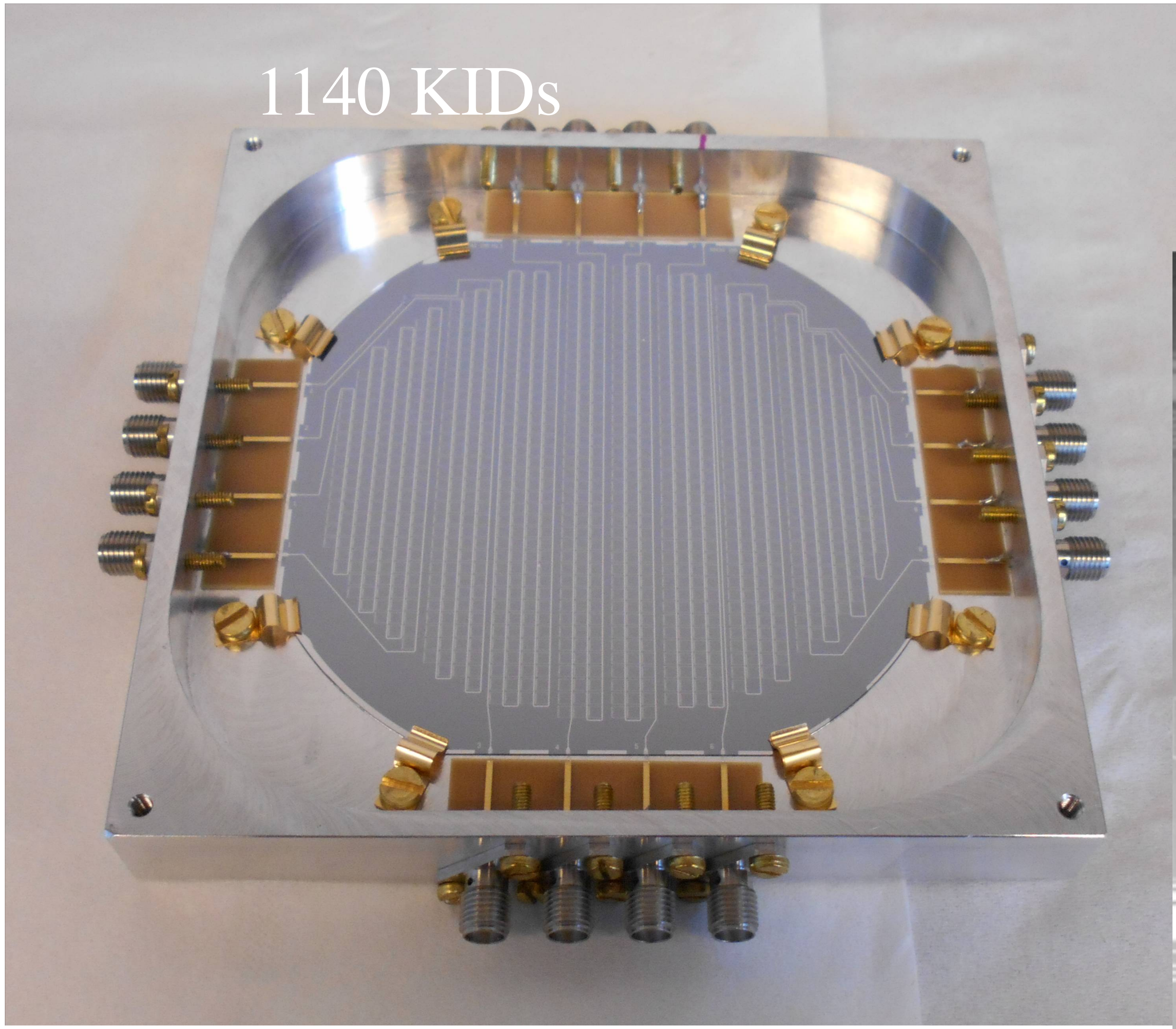
Frequency multiplexing: $\boxed{f \sim (LC)^{-1/2}}$

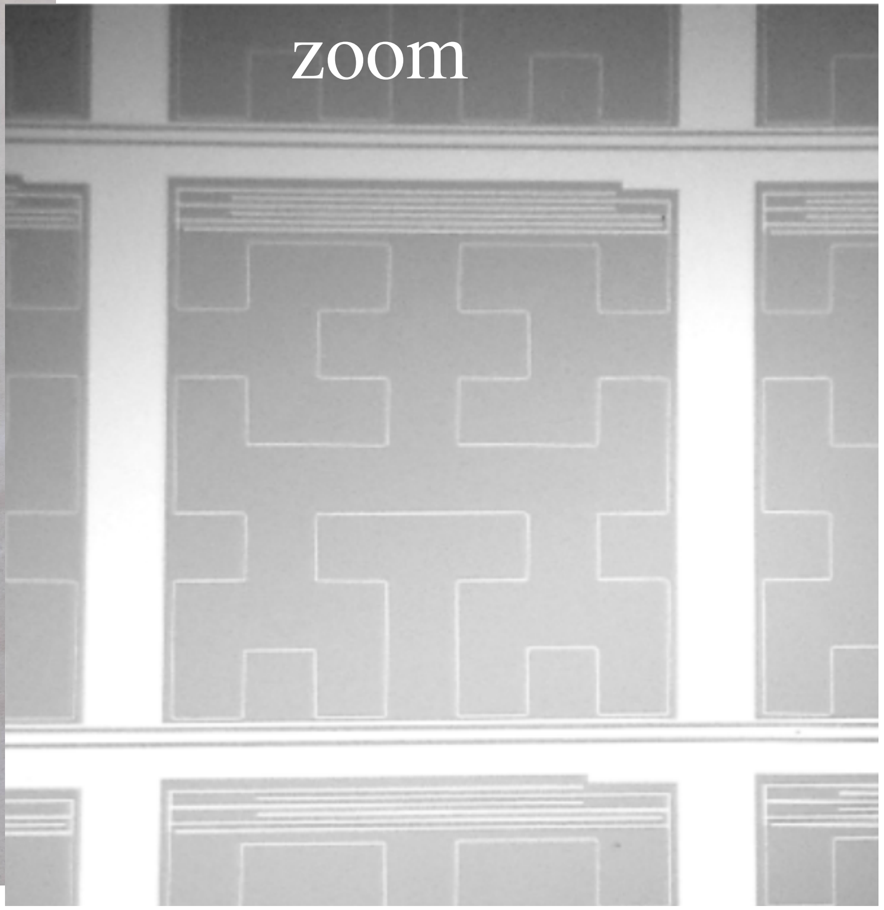




-> <u>one line to address hundreds of detectors</u>

Working principle of KID





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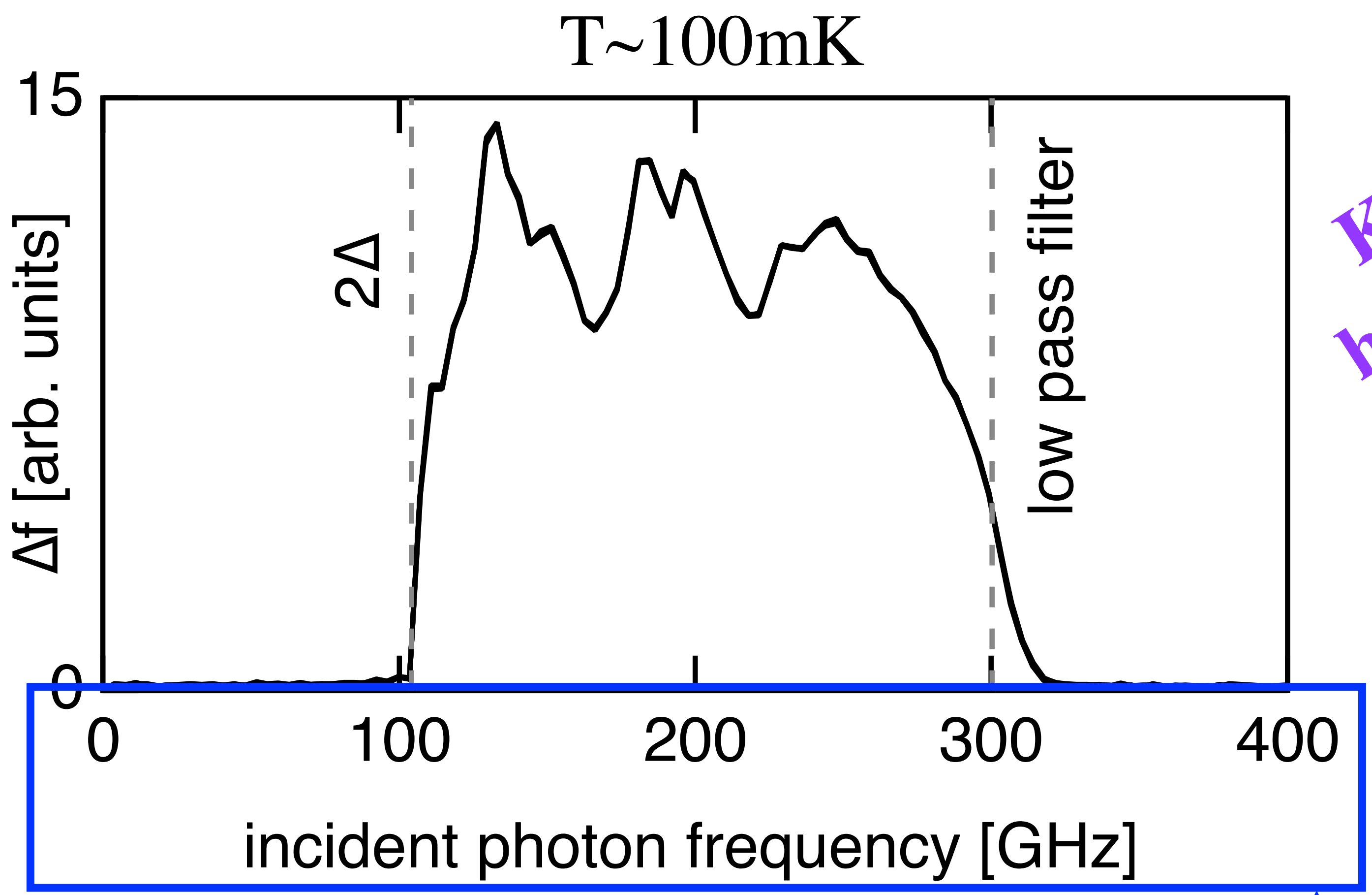
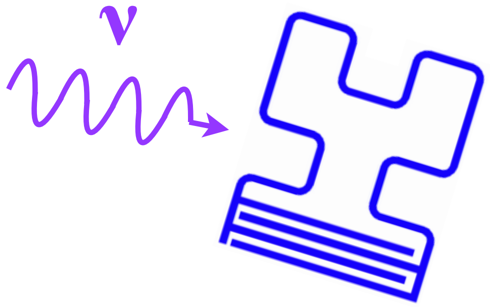
Working principle of KID

Optical response of KID made of **20nm-thick Al**



KID

$h\nu > 2\Delta$



No sub-gap response.

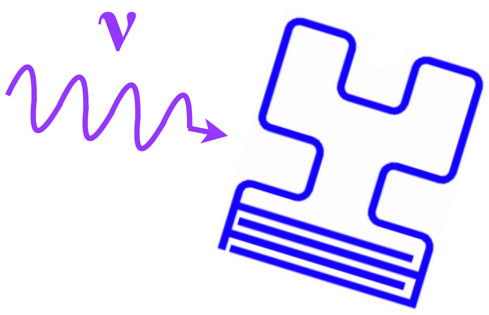
Incoming photons
break Cooper pairs.

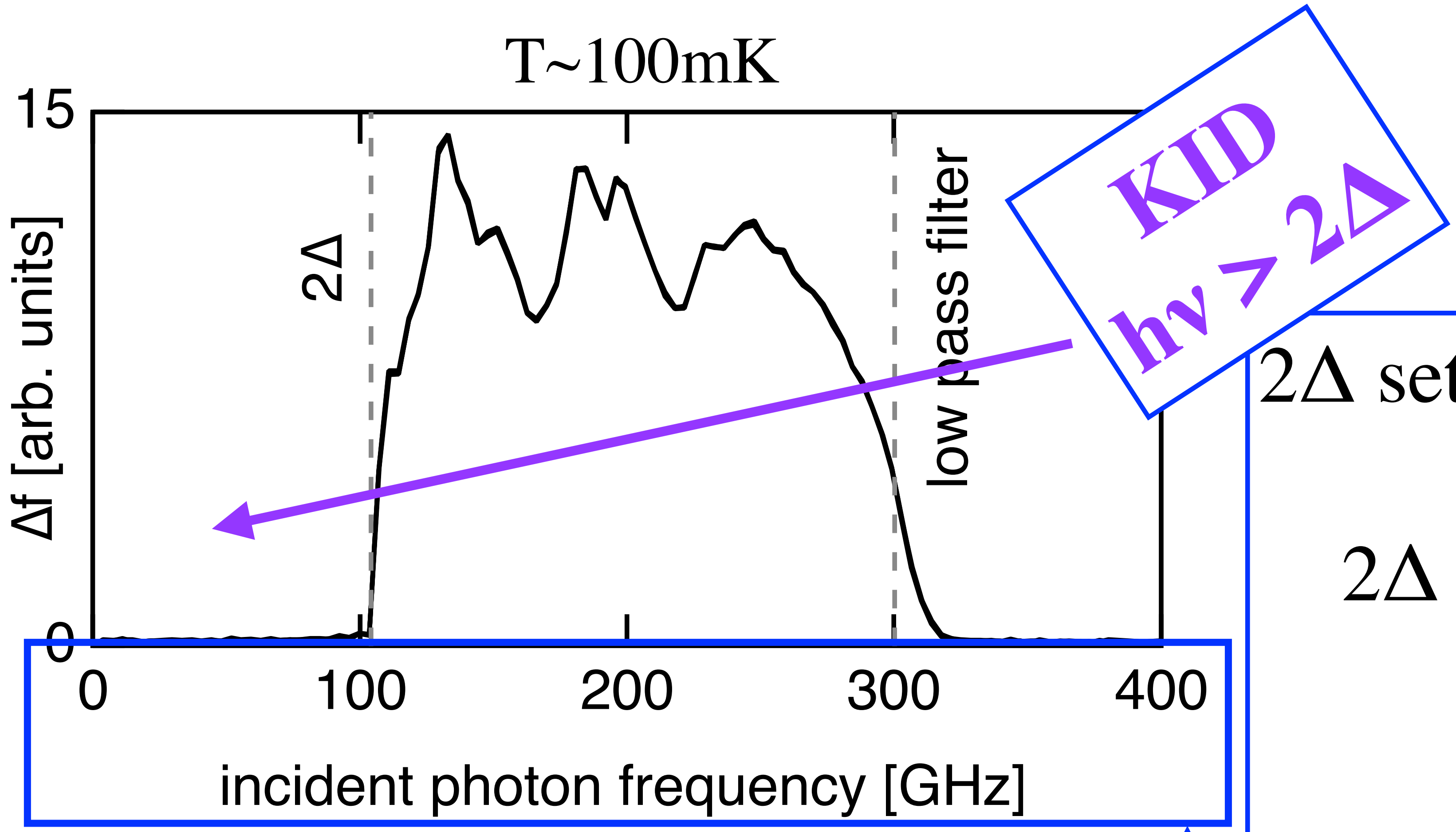
$$\nu_{min} = 2\Delta/h$$

Al-KID is a sensitive
detector in the mm-range

Working principle of KID

Optical response of KID made of **20nm-thick Al**





KID
$h\nu > 2\Delta$

2Δ sets a spectroscopy cut-off

2Δ is material dependent

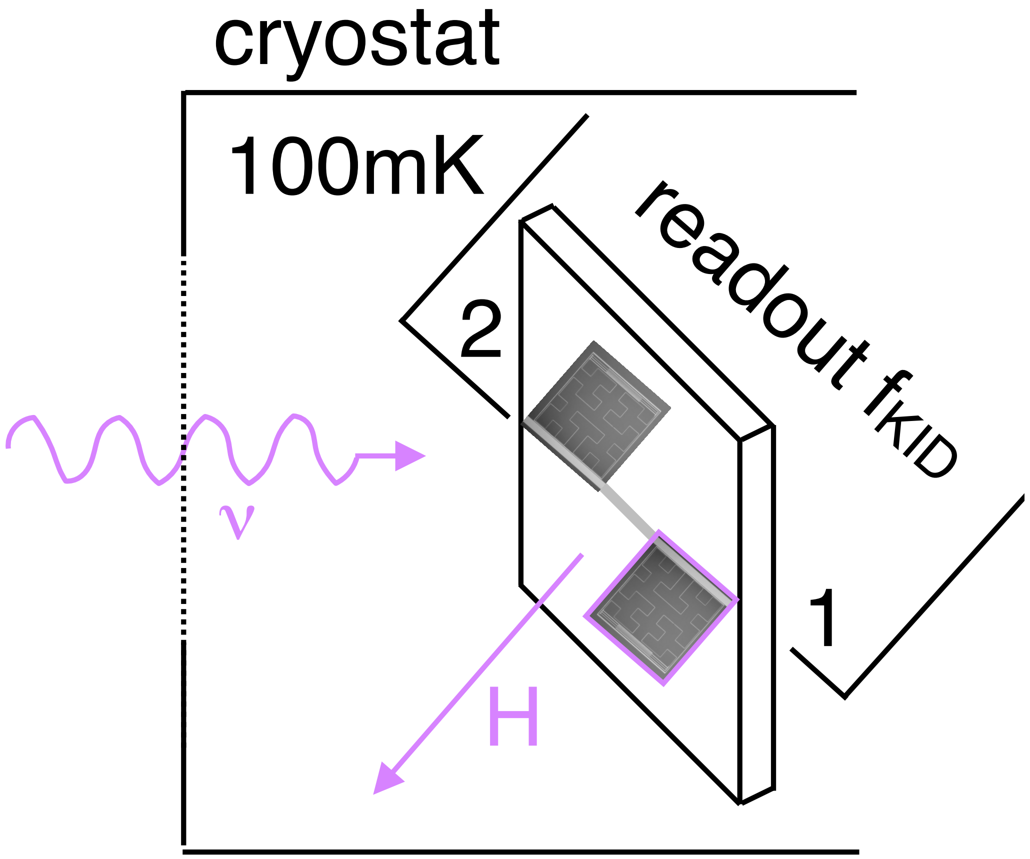
$$2\Delta = 3.52 k_b T_c$$

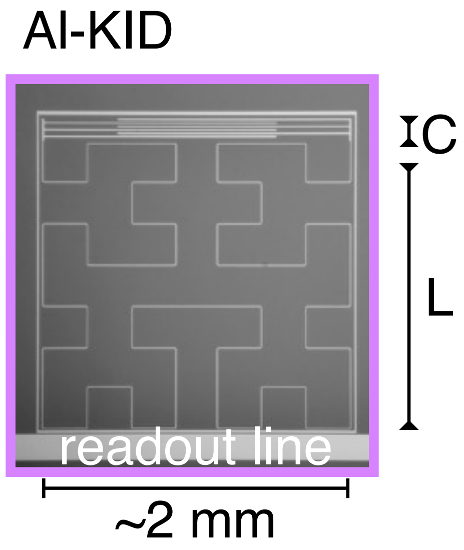
2Δ can be H-tuned

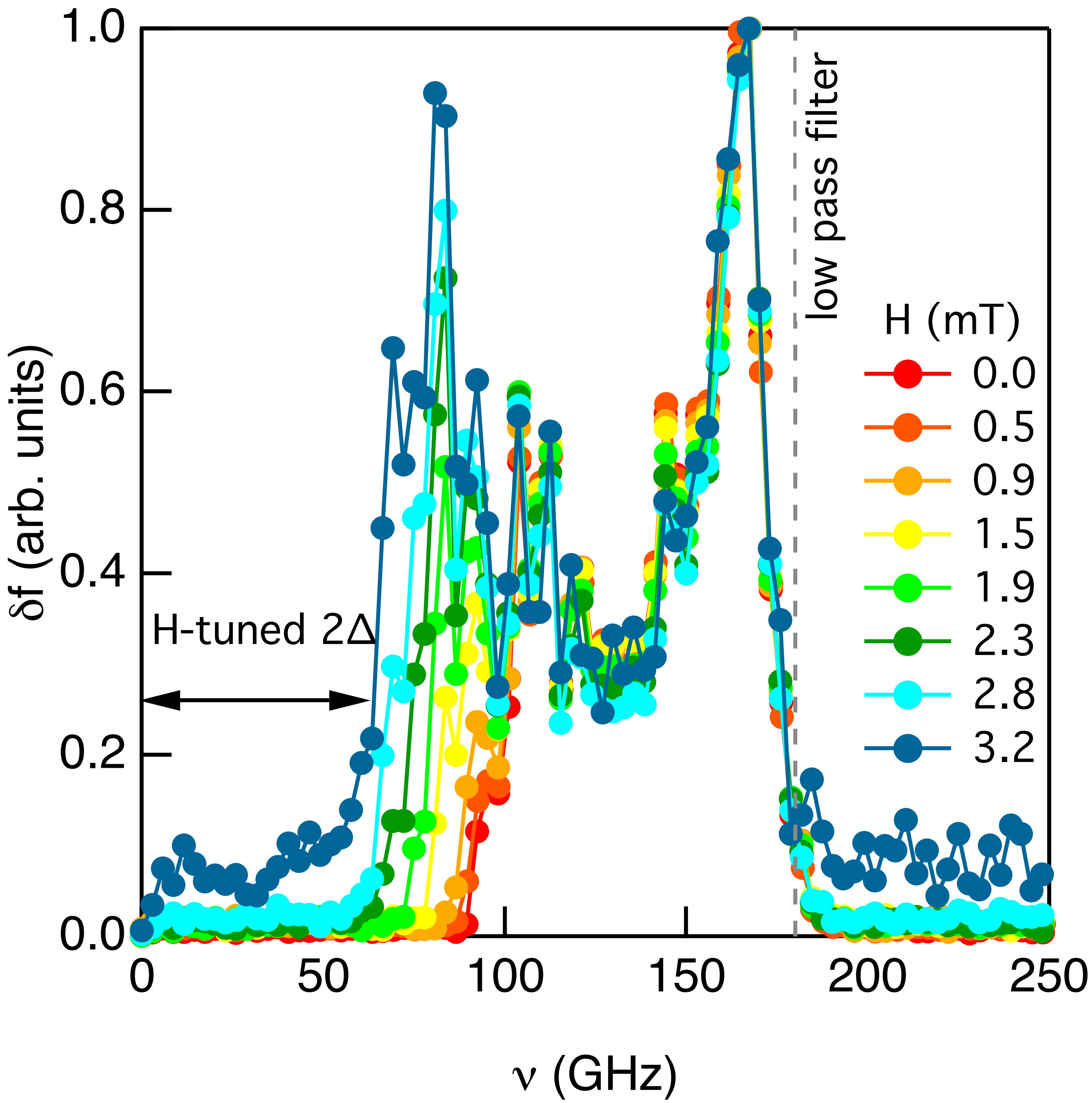
Al-KID is a sensitive detector in the mm-range

Magnetic field effect on KID: H-KID

KID made of 200nm-Al, **perpendicular H**







Magnetic field effect on KID: H-KID

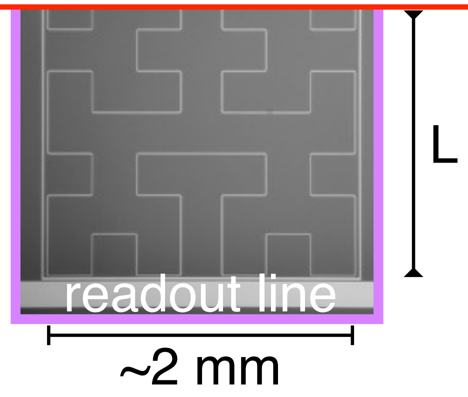
KID made of 200nm-Al, **perpendicular H**

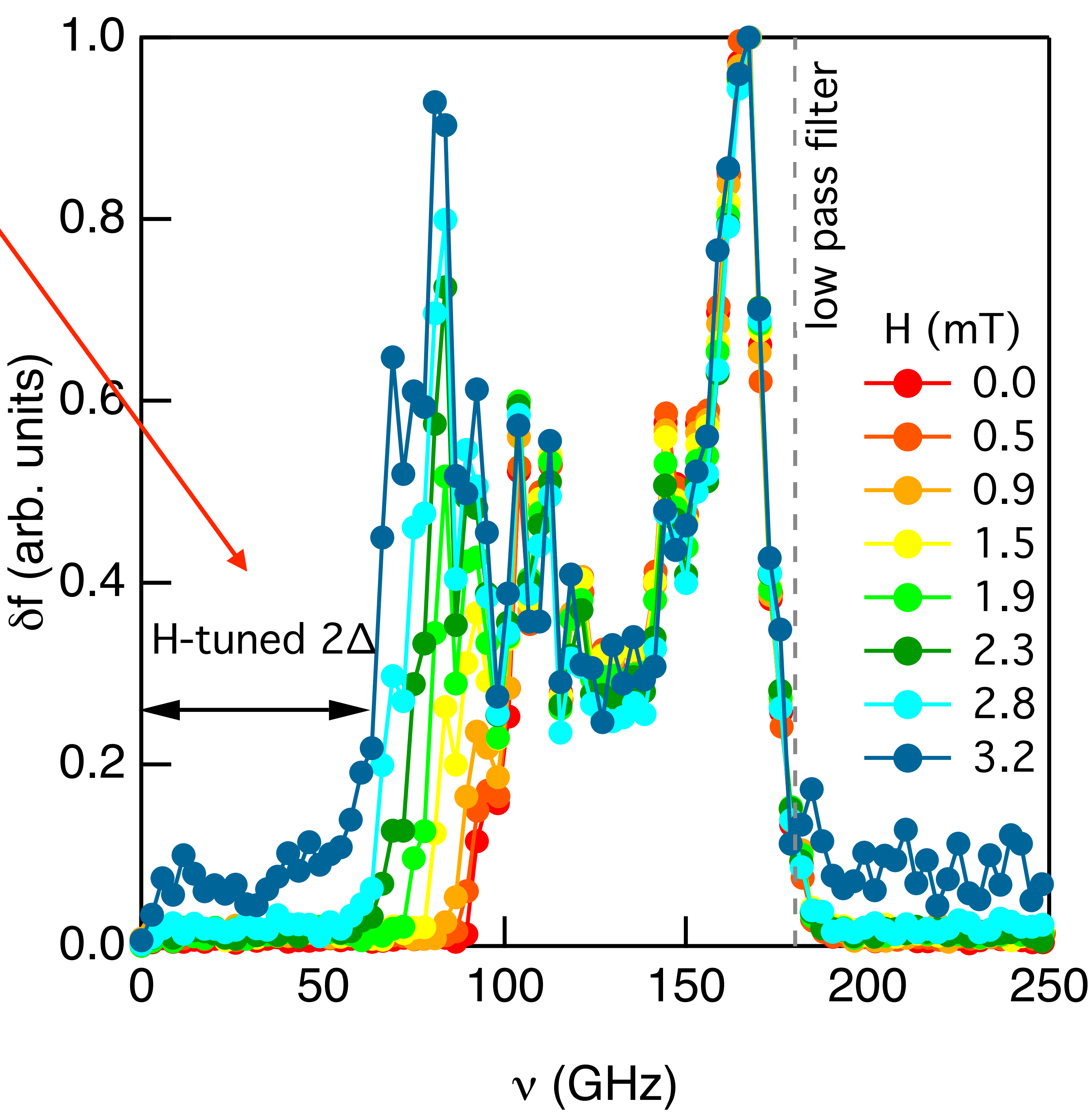
H-tuned 2Δ

possible spectroscopy
with different ν-bands ?

BUT

some contraints to overcome
related to H





Magnetic field effect on KID: H-KID

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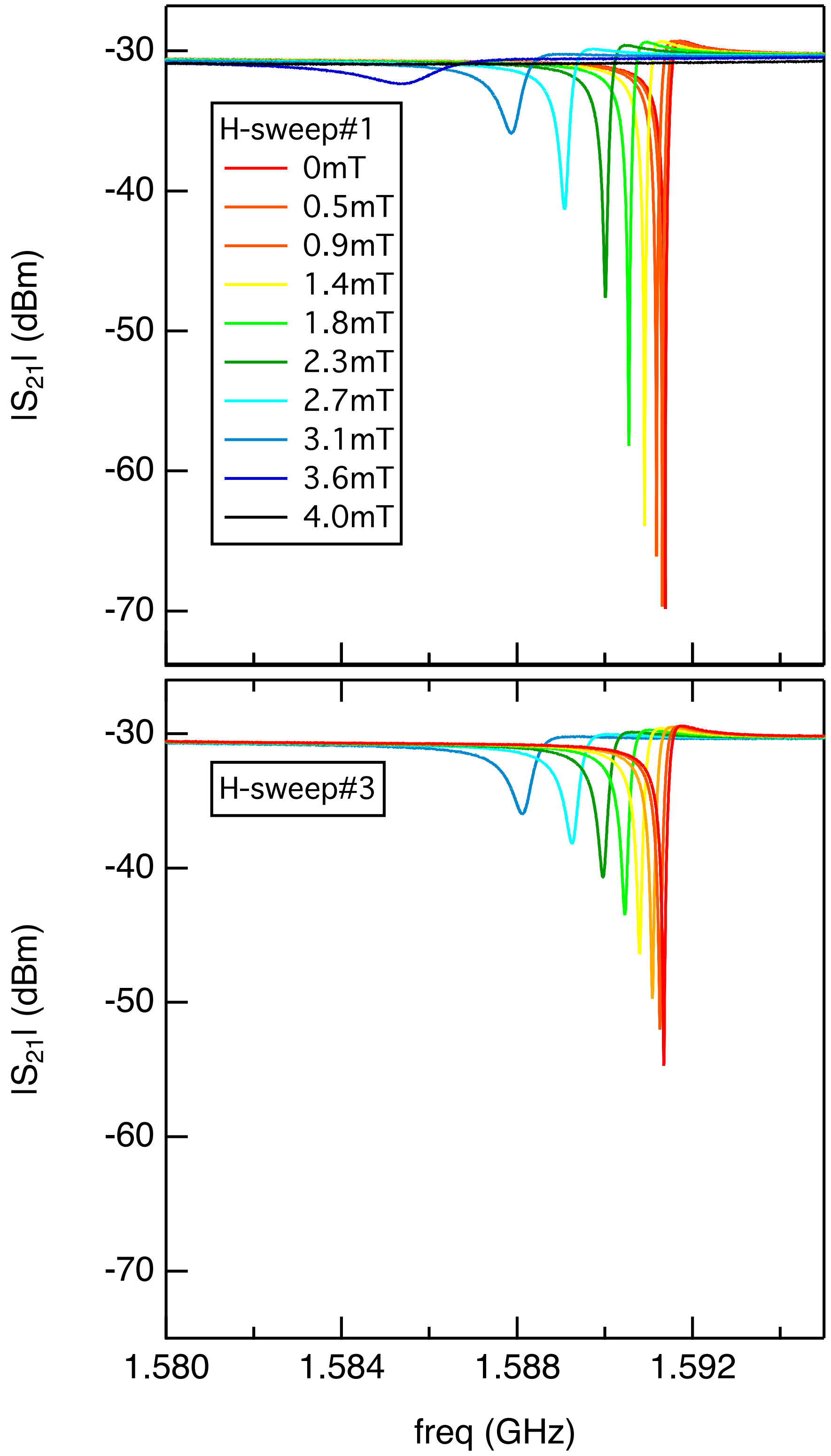

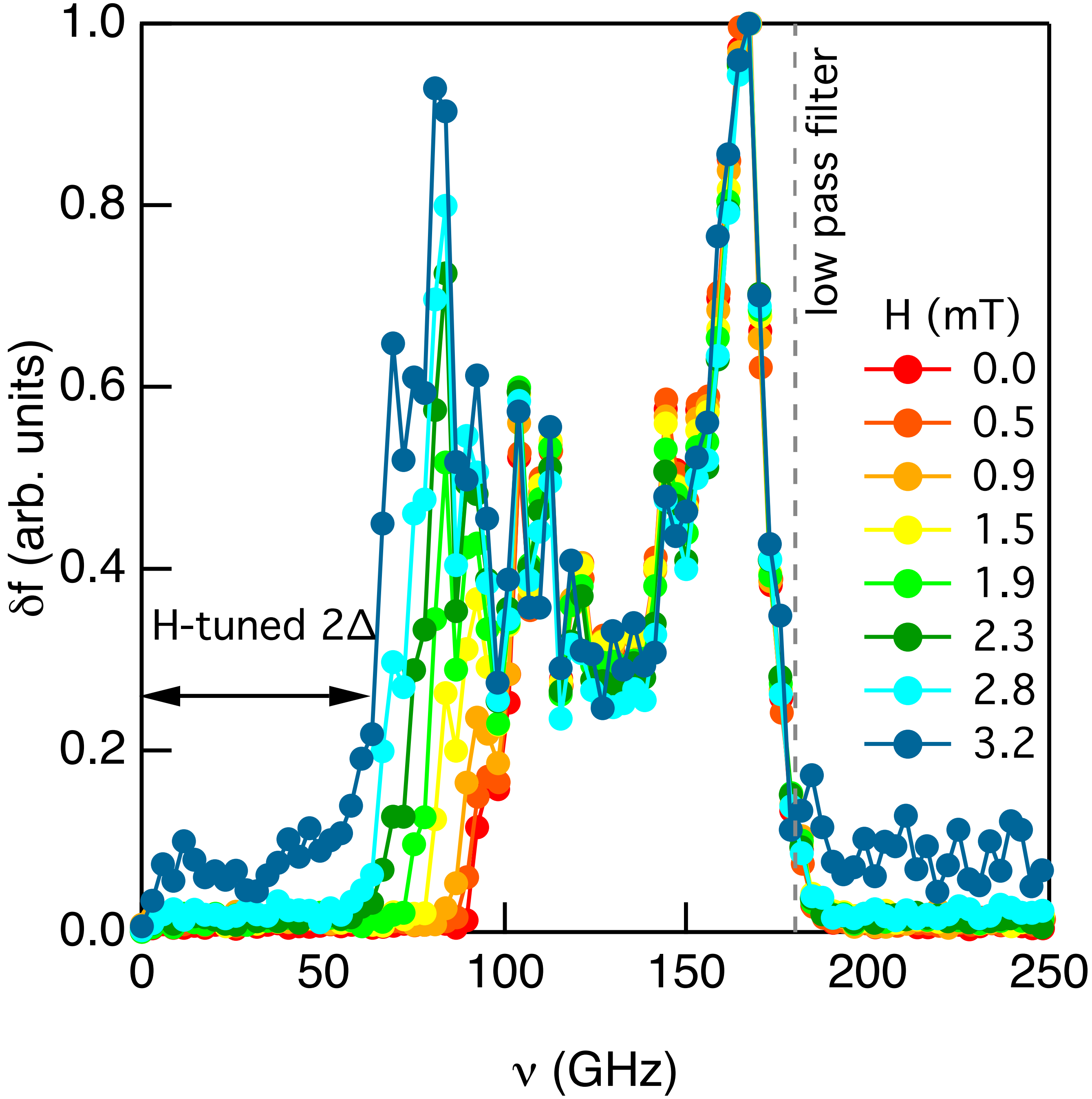

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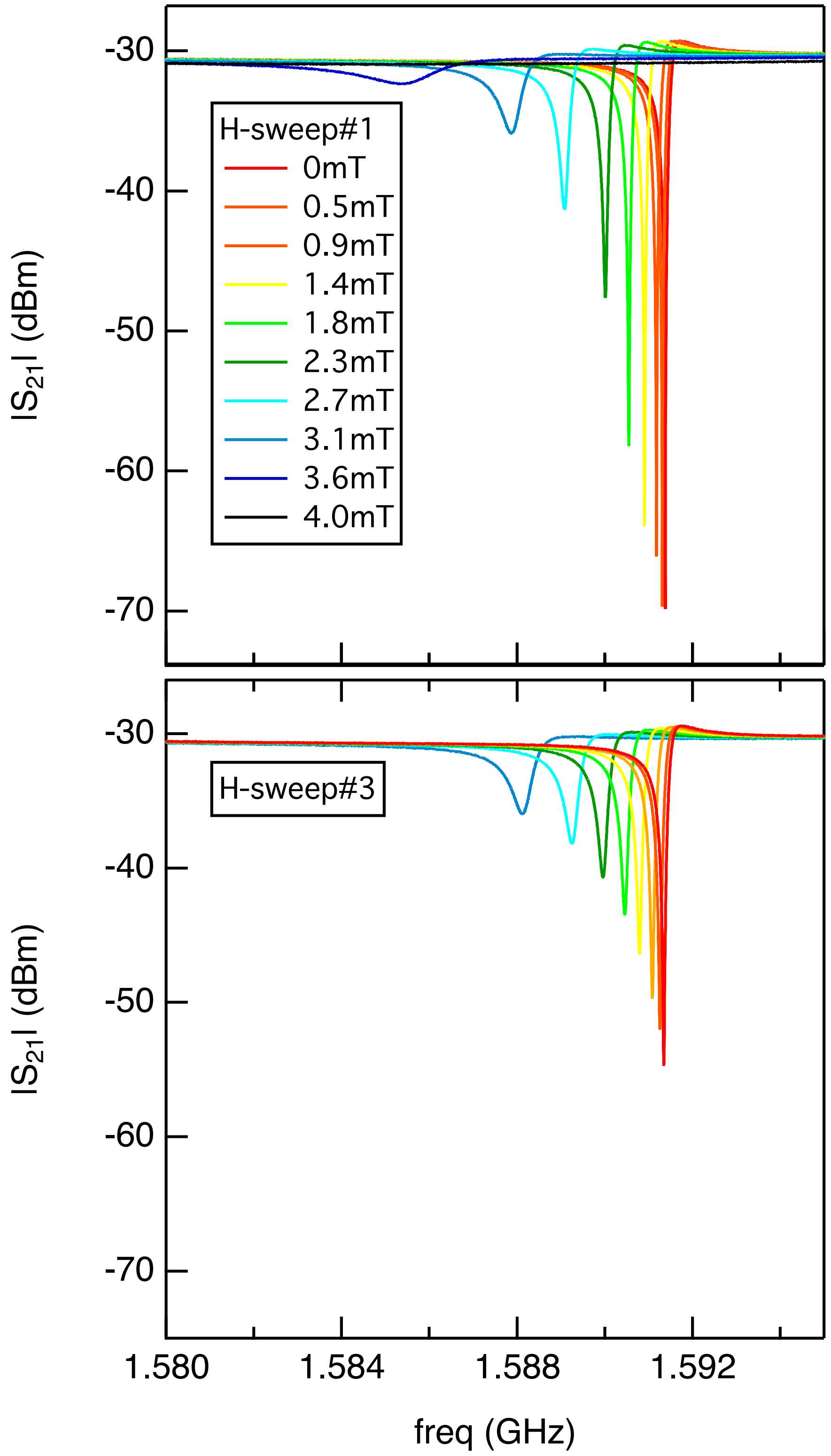
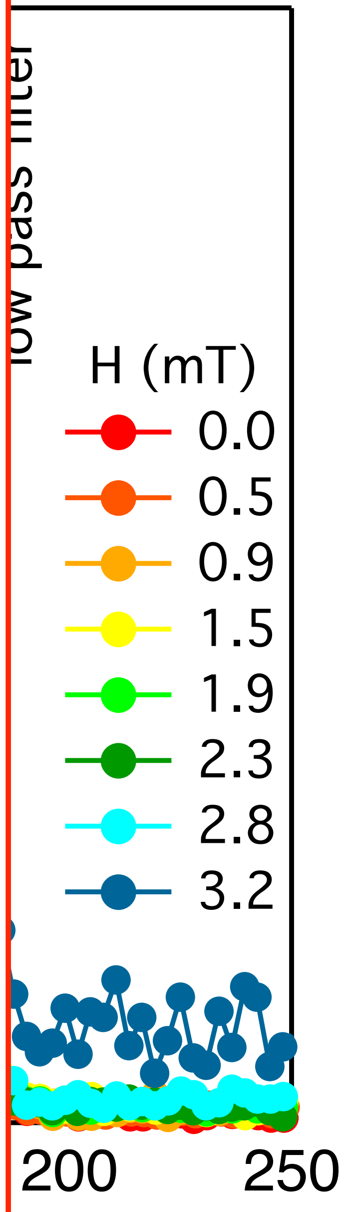


Contraints to overcome:

- f-variation with H
  -> reproducible
  -> calibration: possible

- Q-variation with H
  -> vary with H-history
  -> calibration: impossible
  -> Q too low for H/Hc>0.6

… due to vortex effect



Magnetic field effect on KID: H-KID

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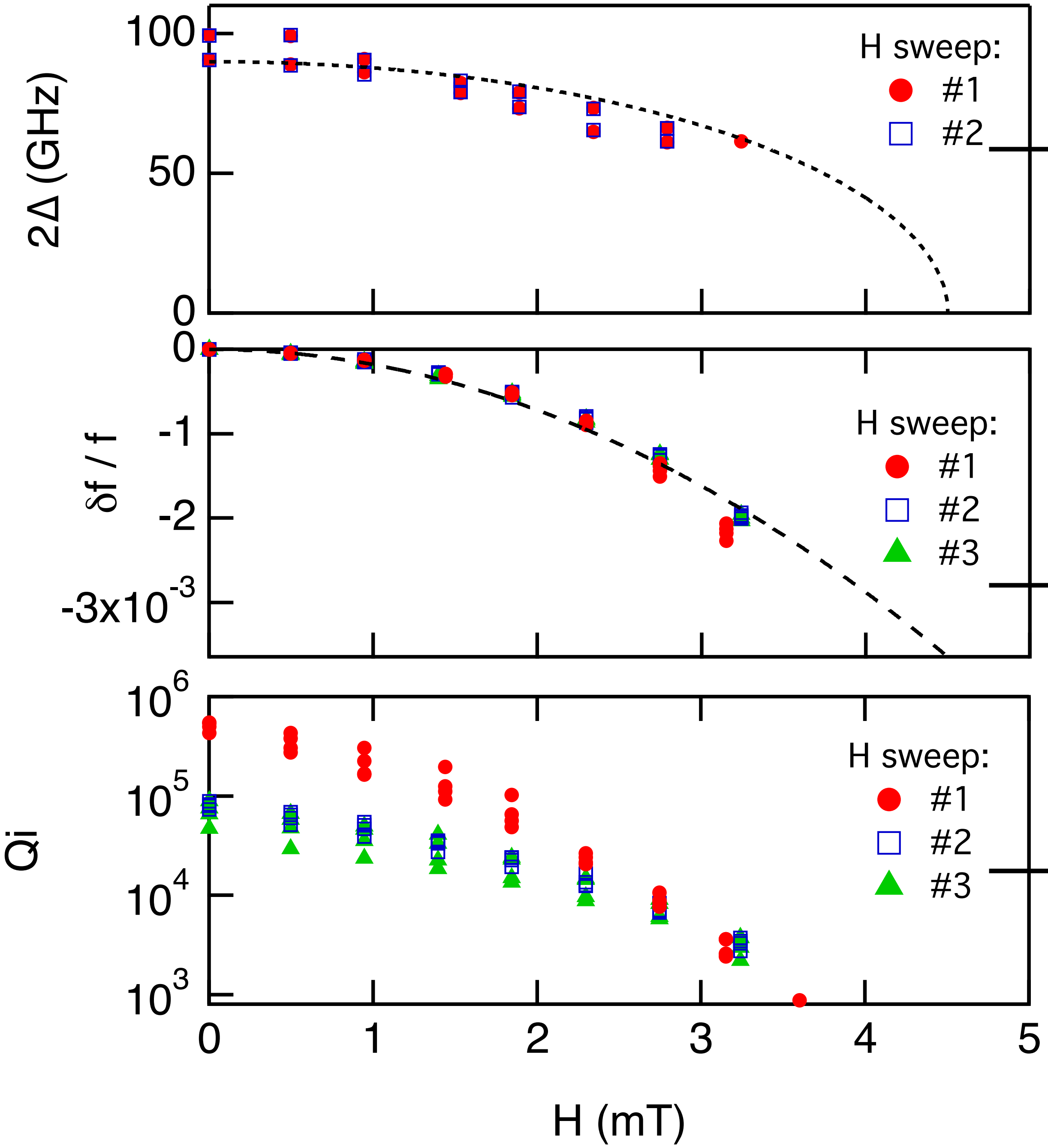


$$\Delta(H) = \Delta_0\sqrt{1-(\frac{H}{H_c})^2}$$

$$\frac{\delta f}{f} = -KH^2$$

vortex effect

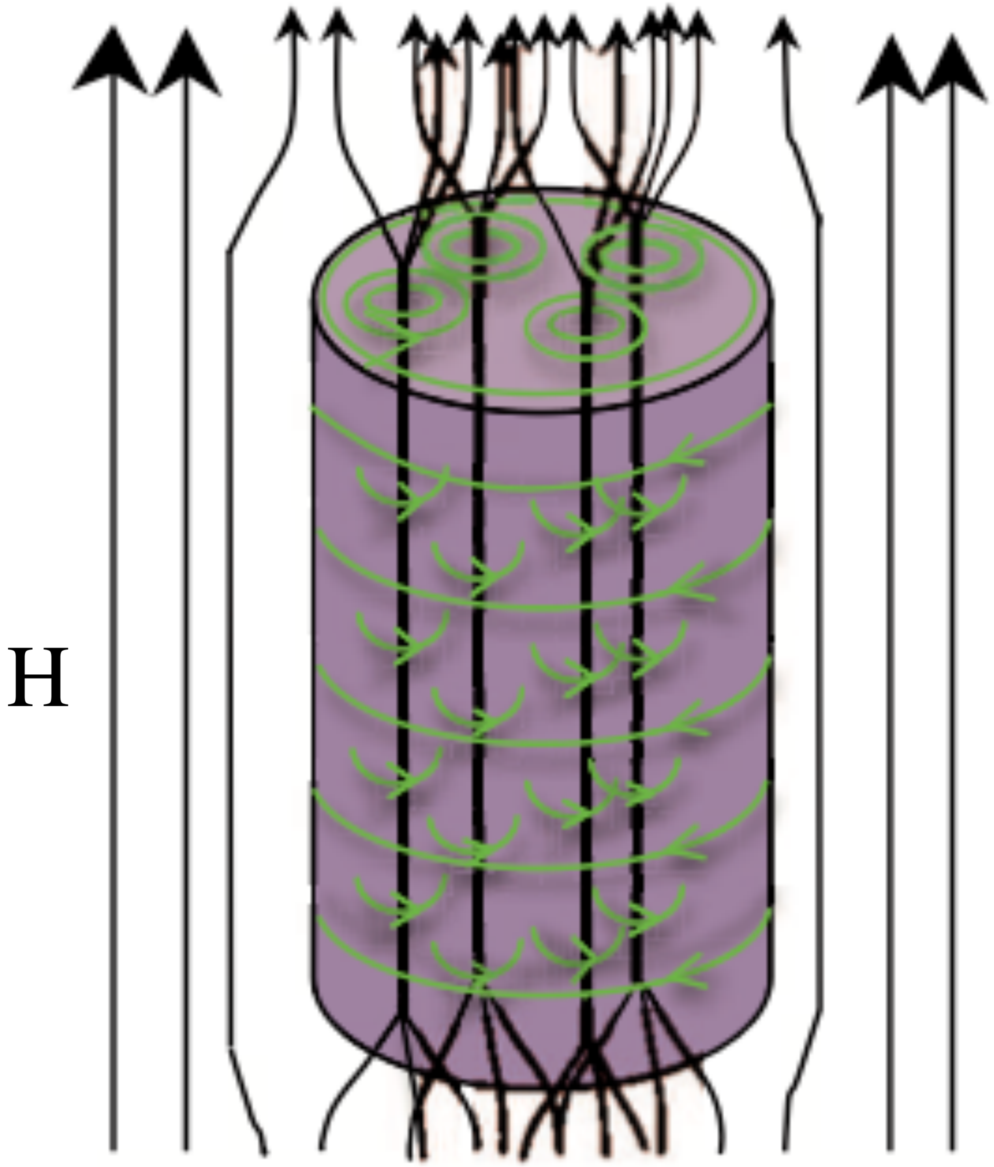
Magnetic field effect on KID: H-KID

What is a **vortex?**

Supercurrent circulating around a **normal core**.

The vortex carries a quantum of magnetic flux $\phi_0 = h/(2e)$.

The vortex size is ξ.



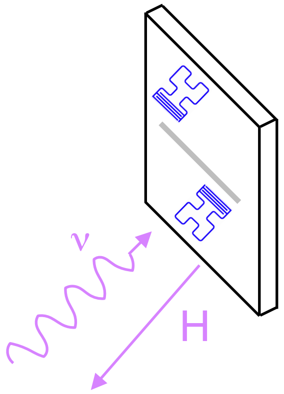
Why a **vortex** generates **dissipation ?**

Because of the **movement** of the **normal electrons** of the vortex core.

For a resonator, the vortex motion is due to the alternative current at ~1 GHz (Lorentz force).

Toward a real mm-spectrometer with H-KID

Vortex issue for perpendicular field



Vortex for : $H > \dfrac{\pi\phi_0}{4w^2}$

$\phi_0 = h/(2e)$ is the magnetic flux quantum

w is **the width** of the resonator

Magnetic earth field : 0.05 mT, vortex for w>5-6 μm.

For Al 15nm, $2\Delta_0$=110 GHz, Hc=40mT,

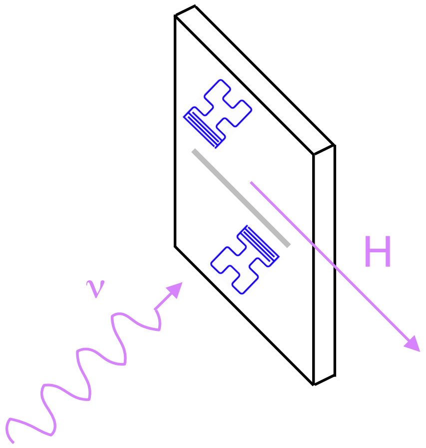
$2\Delta_{min}$=55 GHz corresponds to H=35mT

No vortex for w =200 nm

-> Challenge: **w= 200 nm**, possible with electronic lithography

Toward a real mm-spectrometer with H-KID

Vortex issue for parallel field



Vortex for : $H > \frac{\pi\phi_0}{4w^2}$

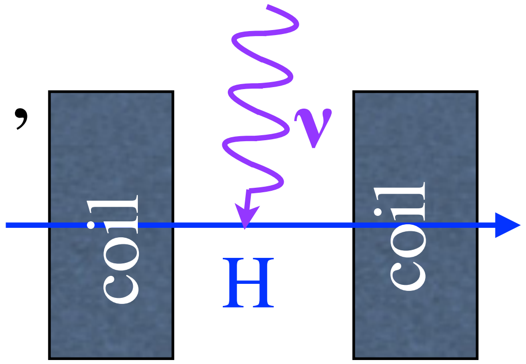
w is **the thickness** of the resonator

For Al 15nm, $H_{\|} \sim 20 - 100 H_{\perp} \sim 0.8 - 4$ T (???)

$2\Delta_{min}$=55 GHz corresponds to H=0.7-3.5T

No vortex for « w » =15 nm up to H=7 T

-> Challenge: **Helmotz coil generating up to 1-4 T** , compatible with cryogenic environnement …



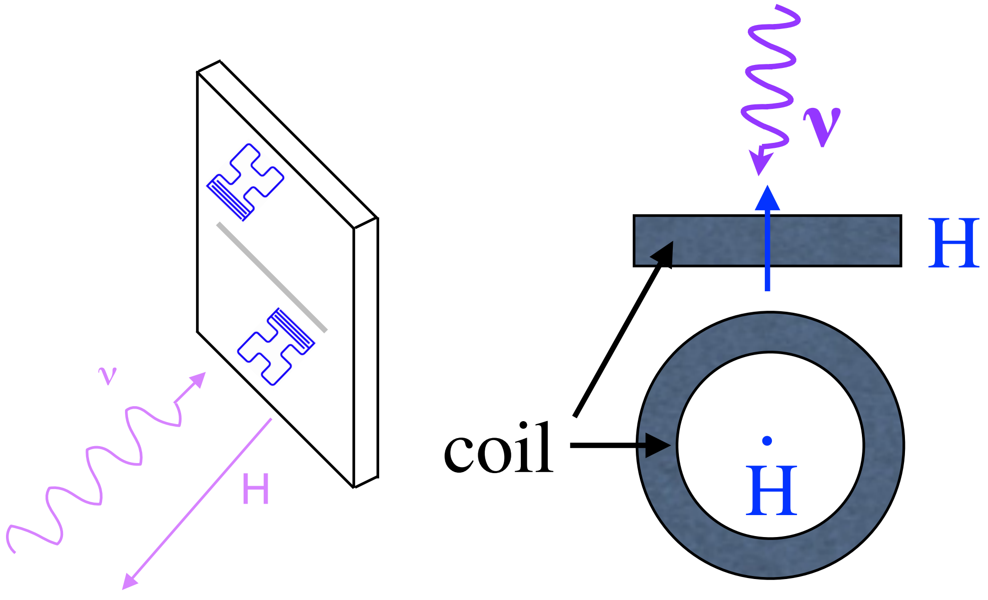
Toward a real mm-spectrometer with H-KID

Magnetic field issue for <u>perpendicular field</u>

Standard coil : $H = \frac{\mu_0 I}{2r} N$

μ_0: vacuum permittivity, I: current,

r: coil diameter, N: number of turns



Ex: r=20cm, I=1A, N=100, H= 0.3mT.

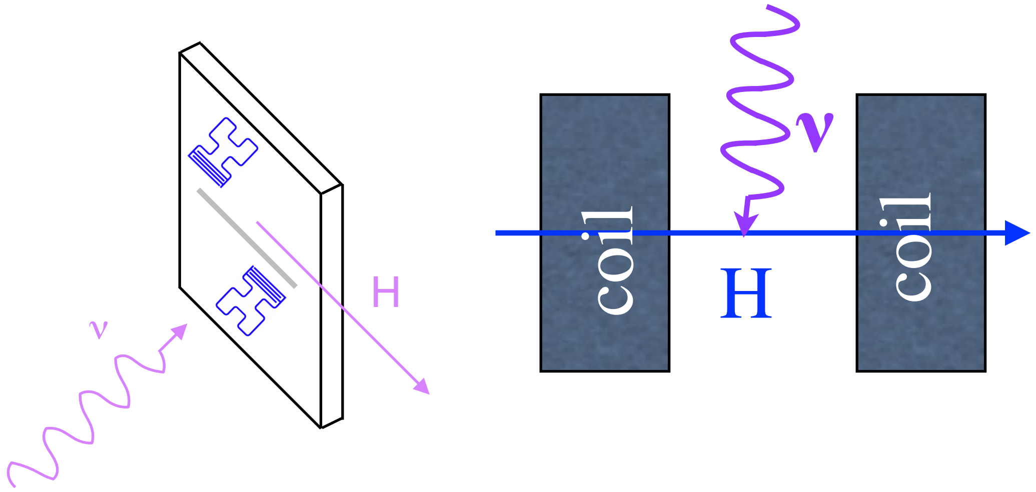
Challenge: make a coil at room temperature,

r=30cm, I=1A, **N=2x10^4**, H= 40mT … possible**.**

Toward a real mm-spectrometer with H-KID

Magnetic field issue for <u>parallel field</u>

Helmotz coil $: H = \dfrac{\mu_0 I r}{2(z^2 + r^2)^{3/2}} N$



I: current, r: coil diameter,
z: distance between coils,
N: number of turns per coil

<u>For a coil at room temperature</u>:

r=30cm, z=30cm I=1A, N=2x10^4, **H= 50mT** **… far from 1 T**

Actual Helmotz coil at 100mK-stage:

r~60mm, z~12mm I_{max}=350mA, N~7x10^3, **H_{max}= 63mT**

(with formula H=400mT)

Toward a real mm-spectrometer with H-KID

Actual Helmotz coil at 100mK-stage:

Internal diameter ~60mm and **H_{max}= 63mT**

For Al 15nm: $2\Delta_0$=110 GHz, Hc=40mT

For H=35mT<63mT, $2\Delta_{min}$=55 GHz.

Perspectives:

- e-beam lithography a (small) array of KID with width w=200nm
- Test the H-KID spectroscopic response
- Test oscillating H at Hz-frequency

Conclusion
Toward a real mm-spectrometer with H-KID ?

YES …most probably

- Challenge1: e-beam lithography (large) array of KIDs

- Challenge2: produce magnetic coil with H=35mT,

for room temperature or for cryogenic environnement

Publications on sub-gap KID:

O. Dupré et al, Superconductor Science and Technology, 30, 045007 (2017). [SUST, ArXiv]
F. Levy-Bertrand et al, Physical Review Applied 15, 044002 (2021). [PRApplied, ArXiv]

Tuning 2Δ with current: the iKID concept… arXiv:2302.12732, section 3.3

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THANK YOU

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