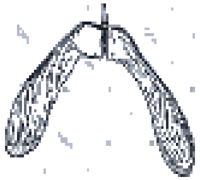
INFN
ROMA TRE

Nicola **Pompeo**
Enrico **Silva**

ROMA TRE
UNIVERSITÀ DEGLI STUDI

Andrea **Alimenti**
Kostiantyn **Torokhtii**

SMARA

Superconducting **A**lternative **M**aterials for **A**ccelerating cavities and haloscope **R**esonators for **A**xions

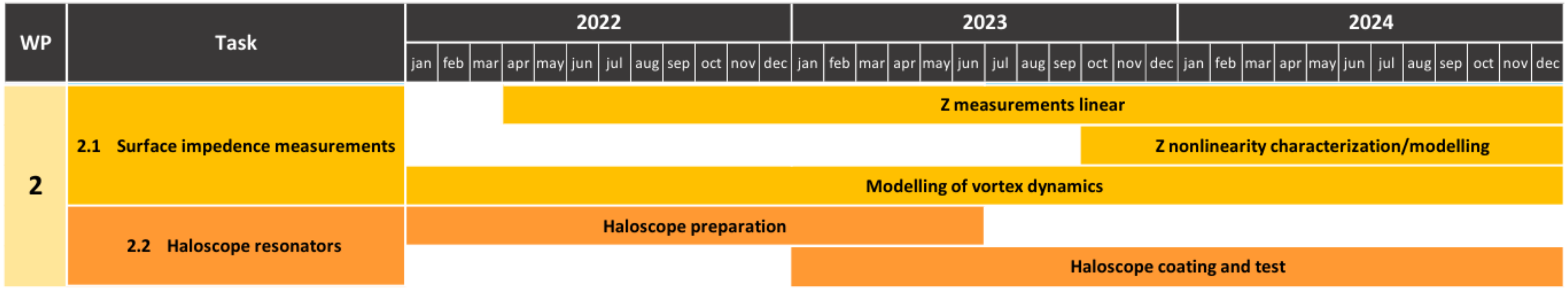
nicola.pompeo@uniroma3.it

Role in the project and Status

WP2 – SRF in extreme conditions

WP2: SRF in extreme conditions		
	Task 2.1 Surface impedance measurements	
	Sample coatings: NbTi and Nb_3Sn	LNL
	Dielectric-loaded resonators measurements	RM3
	Patterned coplanar waveguide resonator measurements	TO
	Multi-harmonic susceptibility	LNF
	Physical Modelling	RM3, TO
	Nonlinearity studies	TO, RM3
	Task 2.2 Haloscope resonators	
	Haloscope design and production	LNF
	Haloscope deposition	LNL
	Haloscope measurement	LNF

GANTT



Proposed Milestones 2022

First surface impedance measurements on
✓ **NbTi** and Nb_3Sn films on insulating substrates

- ΔZ measurements on 2 NbTi samples
- T range 4-15 K
- H range <1.2 T (⊥ and //)

Budget 2022

✓ - 500 l LHe acquired (≃1st year budget)
- acquired additional 1.5 k€

Outline

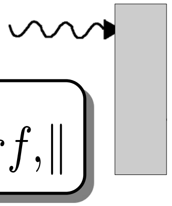
- The measurand: surface impedance in the mixed state
- The experimental technique
- Measurements & preliminary results

Surface impedance

Surface impedance - introduction

- Electrodynamic response at high frequency: surface impedance

At the surface:



$$\boxed{\mathbf{E}_{rf,\parallel} = Z_s \hat{\mathbf{n}} \times \mathbf{H}_{rf,\parallel}}$$

$$Z_s = R_s + \mathrm{i}X_s$$

losses + screening

- Z_s : “performance” of microwave cavities

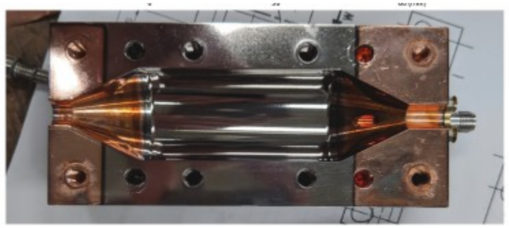
$$\boxed{Q = \frac{2\pi\nu_0 W}{P_{diss}}}$$

quality factor

$$\frac{1}{Q} = \frac{R_s}{G}$$

dissipation

W: stored energy
P_{diss}: dissipated power
G: geometrical factors
(computed | calibrated)

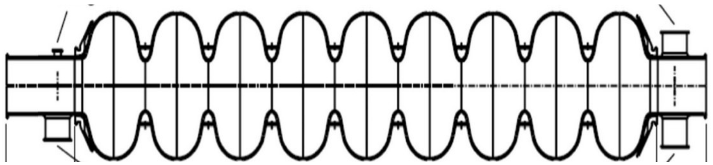


NbTi haloscope

Alesini et al.
Phys. Rev. D 99
101101(R) (2019)

$$R_s(H) \Rightarrow Q \Rightarrow \text{Axion signal}$$

(linear regime)



9-cell TESLA-type
accelerating cavity

H. Padamsee,
Supercond. Sci. Technol. 30,
053003 (2017)

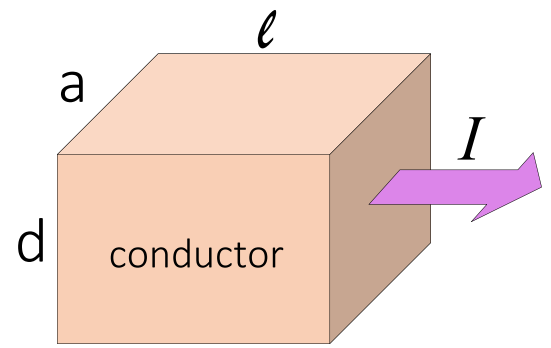
$$R_s(H_{rf}) \Rightarrow Q \Rightarrow E_{acc}$$

(non linear regime)

- Z_s : probe for basic properties → input to theory and material engineering

Surface impedance

d.c. regime, normal conductor



Ohm laws

$$P_{diss} = RI^2 = \rho\frac{l}{ad}I^2$$

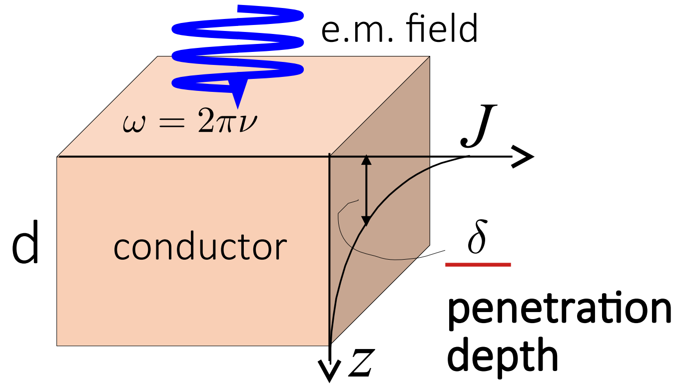
$$\frac{P_{diss}}{\square} = \rho\frac{l}{ad}I^2\frac{1}{al}$$

$$\frac{P_{diss}}{\square} = R_s J_s^2$$

$\boxed{R_s = \frac{\rho}{d}}$ sheet resistance

$J_s = \frac{I}{a}$ surface current density

high frequency ν, normal conductor



- J(z) attenuated along skin depth:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0}} \quad , \ \rho \ \text{ real}$$

- surface resistance:

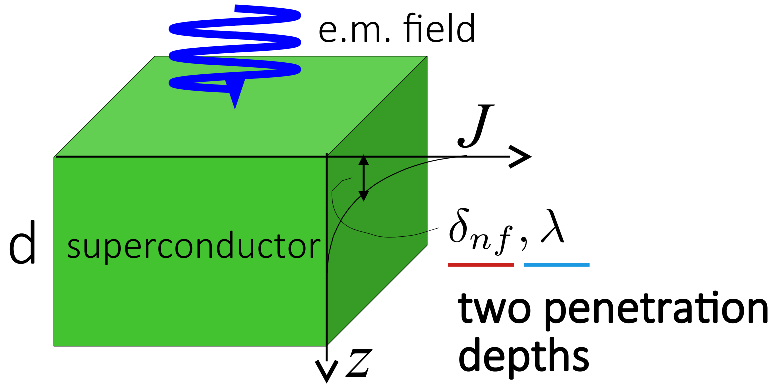
$\boxed{R_s = \frac{\rho}{\delta}}$ dissipation

- surface impedance:

$$\boxed{Z_s = \sqrt{\mathrm{i}\omega\mu_0\rho} = R_s + \mathrm{i}X_s}$$

(bulk limit: $\delta \ll d$)

high frequency, superconductor, H=0



- complex ρ , two fluid model:

$$\tilde{\rho}^{-1} = \sigma_{2f} = \sigma_{nf} - \mathrm{i}\frac{1}{\omega\mu_0\lambda^2} \quad , \ \delta_{nf} = \sqrt{\frac{2\rho_{nf}}{\omega\mu_0}}$$

normal fluid skin depth

- (bulk) surface impedance:

$$\boxed{Z_s = \sqrt{\mathrm{i}\omega\mu_0\tilde{\rho}}}$$

λ

London penetration depth

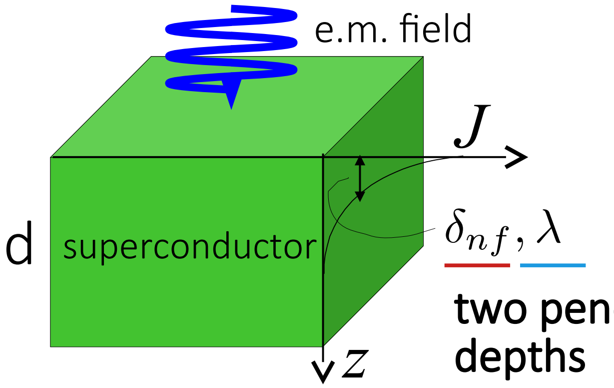
(bulk limit: $(\delta_{nf}, \lambda) \ll d$)

- actual surface resistance for SRF:

$$R_s = \mathrm{Re}(Z_s)_{(BCS)} + R_{res} + R_{fl}$$

Surface impedance in superconductors

high frequency, superconductor, H=0



two penetration depths

$$\delta_{nf} = \sqrt{\frac{2\rho_{nf}}{\omega\mu_0}}$$

normal fluid skin depth

$$\lambda$$

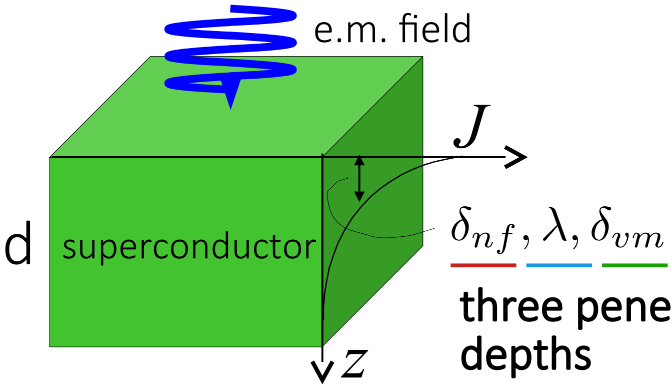
London penetration depth

- (bulk) surface impedance:

$$\boxed{Z_s = \sqrt{\mathrm{i}\omega\mu_0\tilde{\rho}}}$$

(bulk limit: $(\delta_{nf}, \lambda) \ll d$)

high frequency, superconductor, mixed state



three penetration depths

- complex ρ : two fluid σ_{2f} +vortex motion ρ_{vm}

$$\tilde{\rho} = \frac{\rho_{vm} + \mathrm{i}\omega\mu_0\lambda^2}{1 + \mathrm{i}\sigma_n\omega\mu_0\lambda^2}$$

- additional penetration depth:

$$\delta_{vm} = \sqrt{\frac{2\rho_{vm}}{\omega\mu_0}}$$

Vortex motion penetration depth

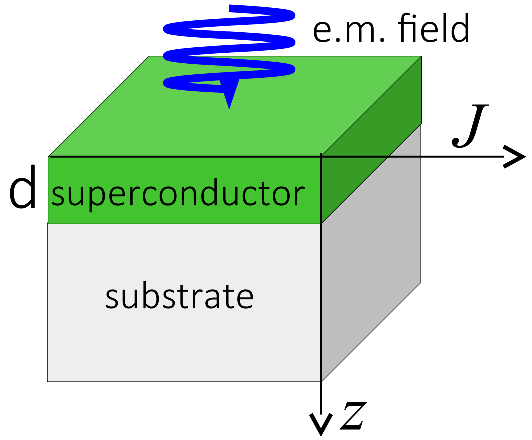
- overall complex penetration depth:

$$\tilde{\lambda}^2 = \frac{\lambda^2 - \frac{\mathrm{i}}{2}\delta_{vm}^2}{1 + 2\mathrm{i}\frac{\lambda^2}{\delta_{nf}^2}}$$

complex interplay
$|\tilde{\lambda}| > \lambda$

Coffey and Clem, Phys. Rev. Lett. 67 386 (1991)

finite thickness effects



- $d \sim (\delta_{nf}, \lambda, |\delta_{vm}|)$

→ rf fields reach the substrate
→ **effective** Z_s depends on both SC and substrate

Pompeo et al, IEEE Trans. App. Supercond. 5 8003405 (2019)
Pompeo et al, I2MTC 2017 Conf. Proceedings

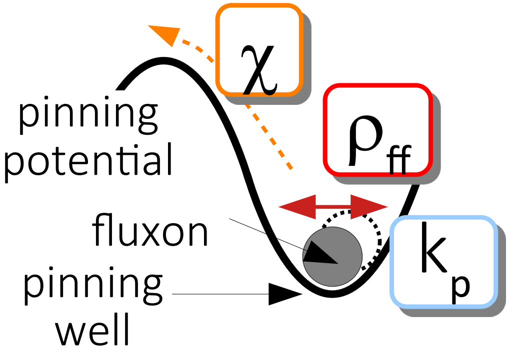
- thin film approx:

$$d \ll (\delta_{nf}, \lambda, |\delta_{vm}|)$$

insulating substrate

$$\boxed{Z_s = \frac{\tilde{\rho}}{d}}$$

High frequency vortex motion response



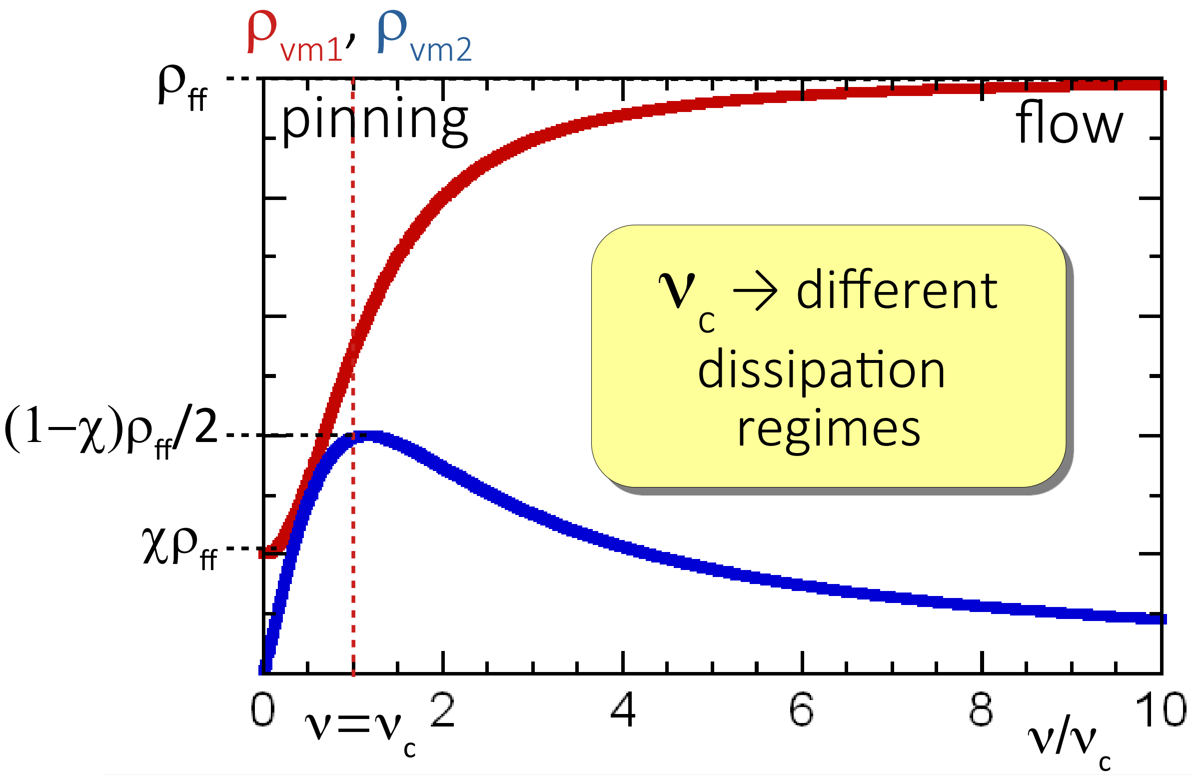
$$\mathbf{J}\times\mathbf{\Phi}_0 - \eta\dot{\mathbf{u}} - k_p\mathbf{u} + \mathbf{F}_{thermal} = m\ddot{\mathbf{u}} \quad \Rightarrow \quad \mathbf{E}_{rf} = \mathbf{B}\times\dot{\mathbf{u}} \Rightarrow \rho_{vm}$$

$$\boxed{\rho_{vm} = \rho_{vm1} + \mathrm{i}\rho_{vm2} = \rho_{ff}\frac{\chi + \mathrm{i}\nu/\nu_c}{1 + \mathrm{i}\nu/\nu_c}}$$

Many models,
one equation

Pompeo, Silva, PRB 78 , 094503 (2008)

Gittleman, Rosenblum PRL 16 734 (1966)	No creep
Coffey, Clem PRL 67 386 (1991)	Sinusoidal potential
Brandt PRL 67 2219 (1991)	Thermally relaxing pinning
Placais et al PRB 54 13083 (1996)	Two-modes



ν_c → different dissipation regimes

flux flow resistivity ρ_{ff} (viscosity η)

$$\rho_{ff} = \alpha\rho_n\frac{B}{B_{c2}}$$

dissipation

characteristic freq. ν_c
pinning freq. ν_p

$$\nu_c \xrightarrow[\chi\to 0]{} \nu_p$$

pinning constant k_p

$$k_p = 2\pi\nu_p\eta$$

creep factor χ

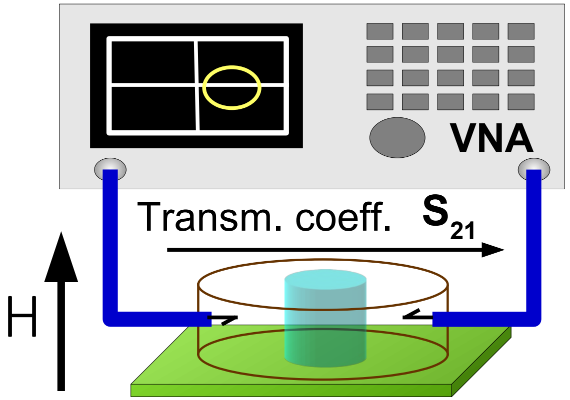
related to pinning barriers heights U_0

$$0 \le \chi \le 1$$

Experimental technique

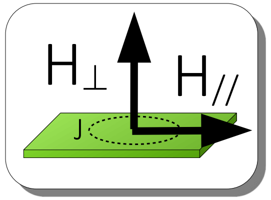
Measurement technique

Dielectric-loaded resonator (surface perturbation method).



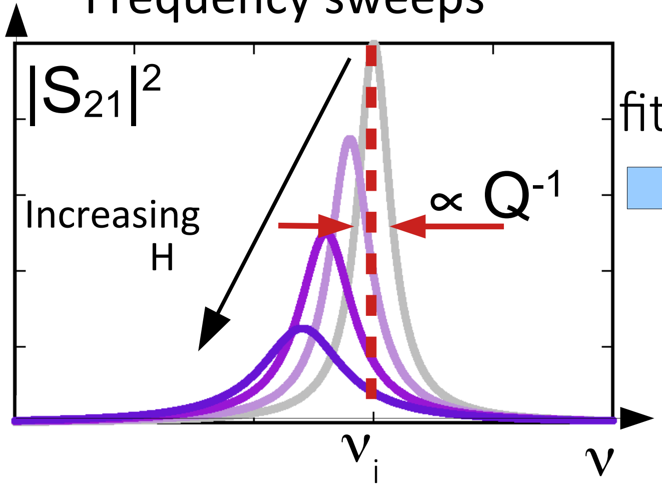
- dual frequency operation:
  ν_1=16.5 GHz,
  ν_2=26.7 GHz

- Probing area
  ∅≤20 mm



- Rotatable H
- 0 < μ_0H < 1.2 T

Frequency sweeps



fit → Q, ν resonator parameters → std. em theory →

H-induced variations:

$$\Delta R_s(H) = G\left(\frac{1}{Q(H)} - \frac{1}{Q(0)}\right)$$

$$\Delta X_s(H) = -2G\frac{\nu(H)-\nu(0)}{\nu(0)}$$

→ $\Delta Z_s(H)$ → ρ_{vm}

Various limits:

- thin film on insulator	$Z_s \propto \rho$
- bulk	$Z_s \propto \sqrt{\rho}$
- film on metal & thick film	$Z_s(\rho)$

2 observables vs many parameters

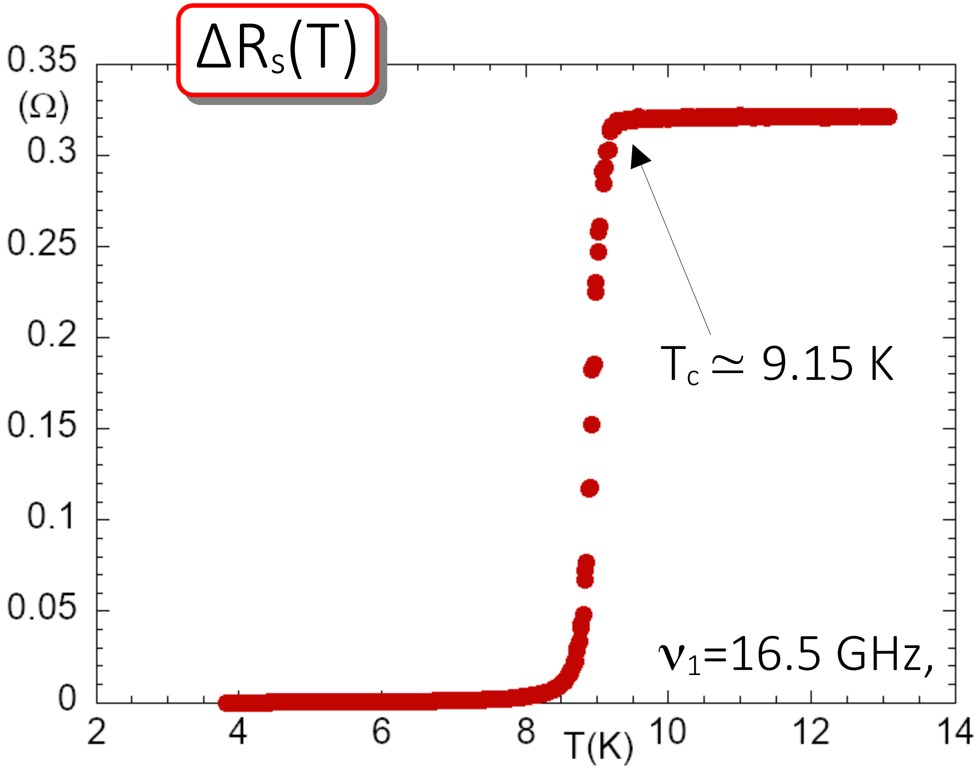
↳ Multifrequency (rarely performed)

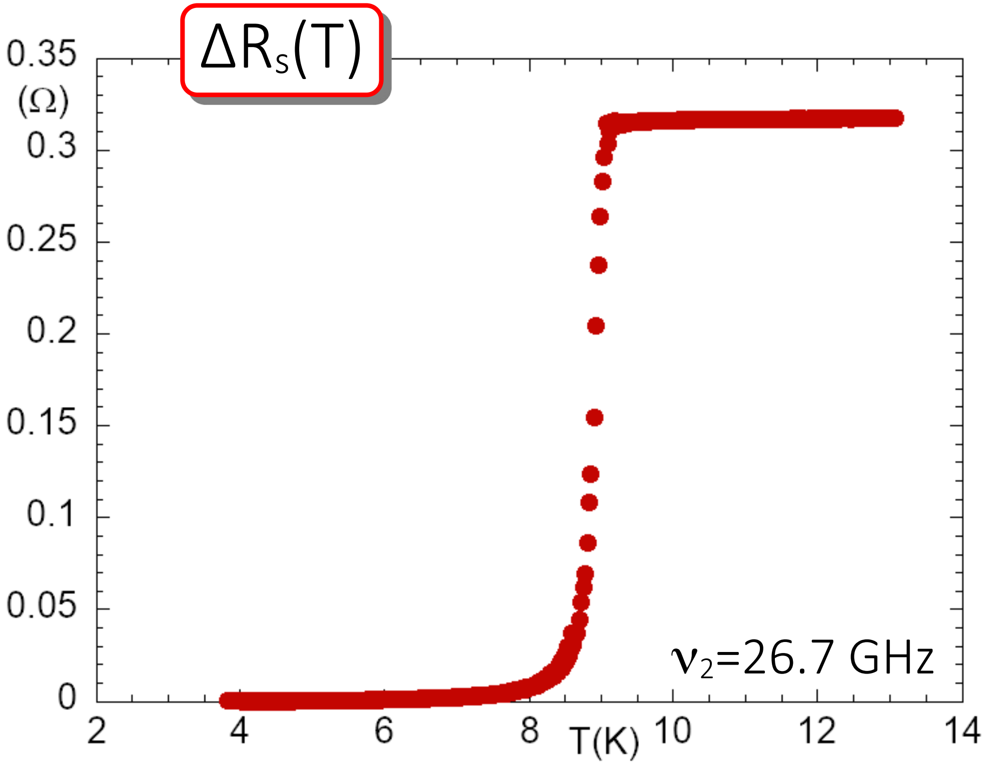
Alimenti et al. Meas. Sci. Technol. 30 065601 (2019)
Pompeo et al, Measurement 184 109937 (2021)

Measurements and preliminary analysis

Superconducting transition

- $Nb_{60}Ti_{40}$ films on dielectric ($d \simeq 1.7 \pm 0.2$ μm thick) - sample 1





$\Delta R_s = R_s(T) - R_s(T_{min})$

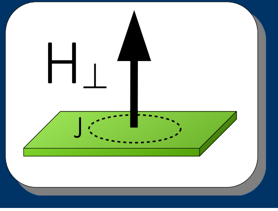
- Normal state resistivity:

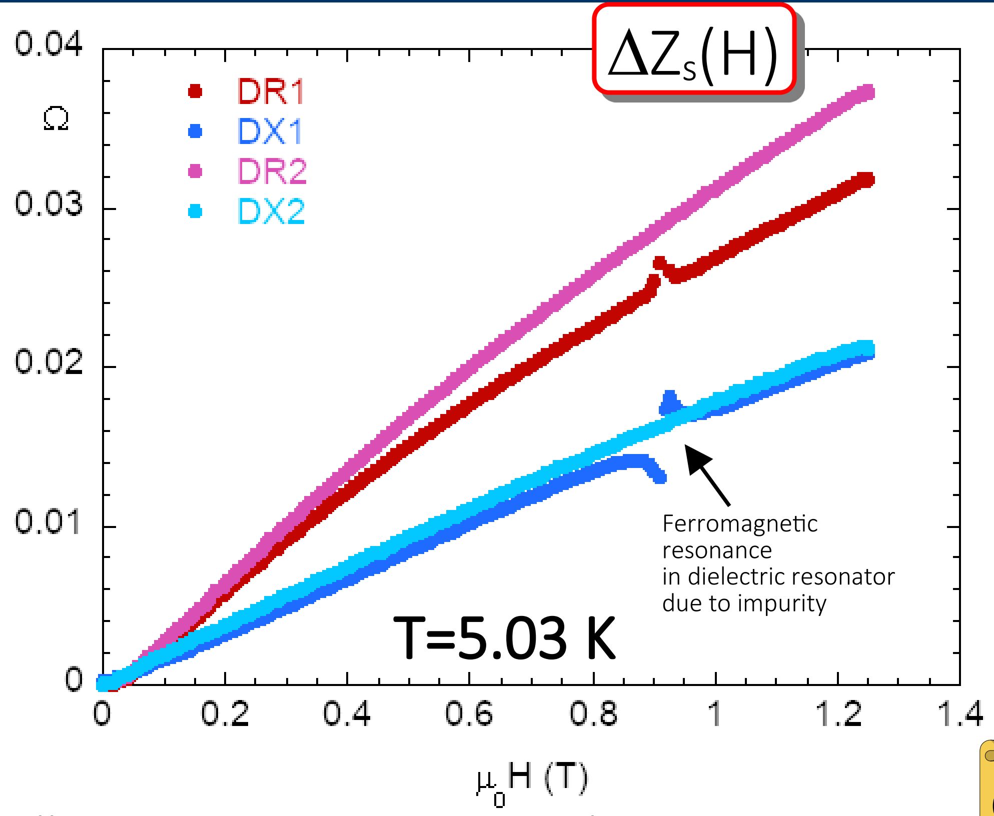
$$\rho_n = R_s(T > T_c) \cdot d \simeq 5.4 \cdot 10^{-6} \Omega \cdot m$$

wrt $(4 \div 7) \cdot 10^{-6} \Omega \cdot m$

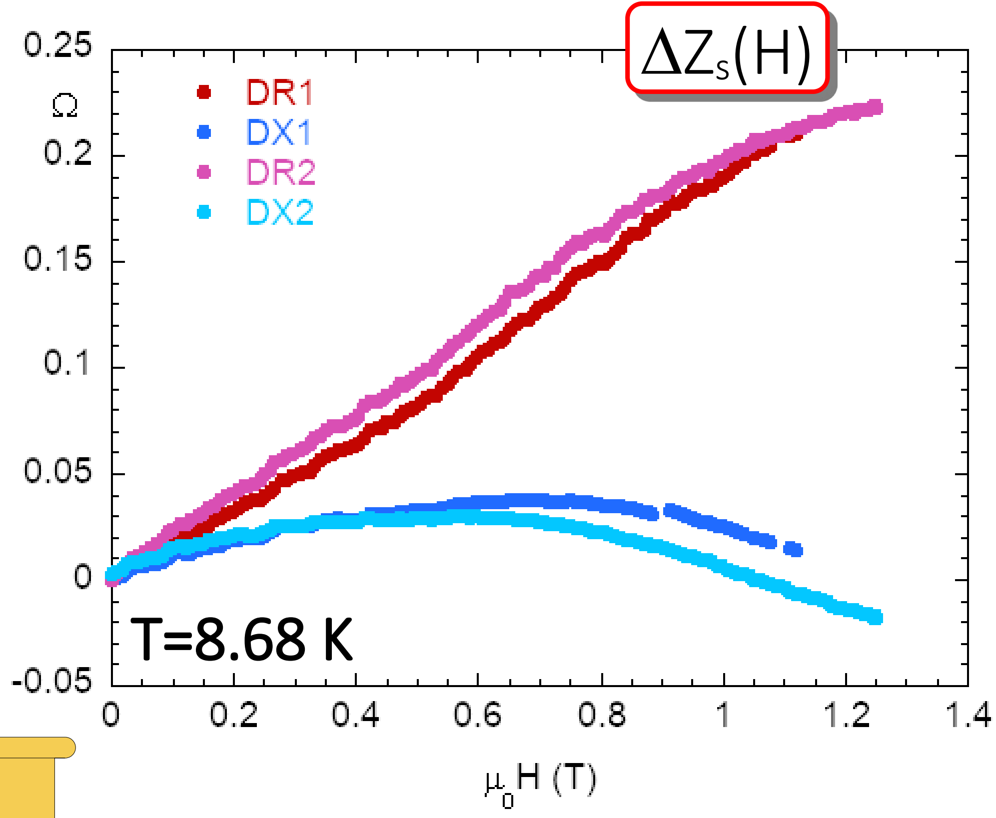
Benvenuti et al, Fifth Workshop RF Supercond. 1991

ΔZ(H) at selected T





Ferromagnetic resonance in dielectric resonator due to impurity



All T : ΔR & ΔX increase with H
→ vortex motion

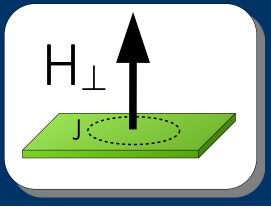
Low T : downward curvature
→ possible **bulk regime**

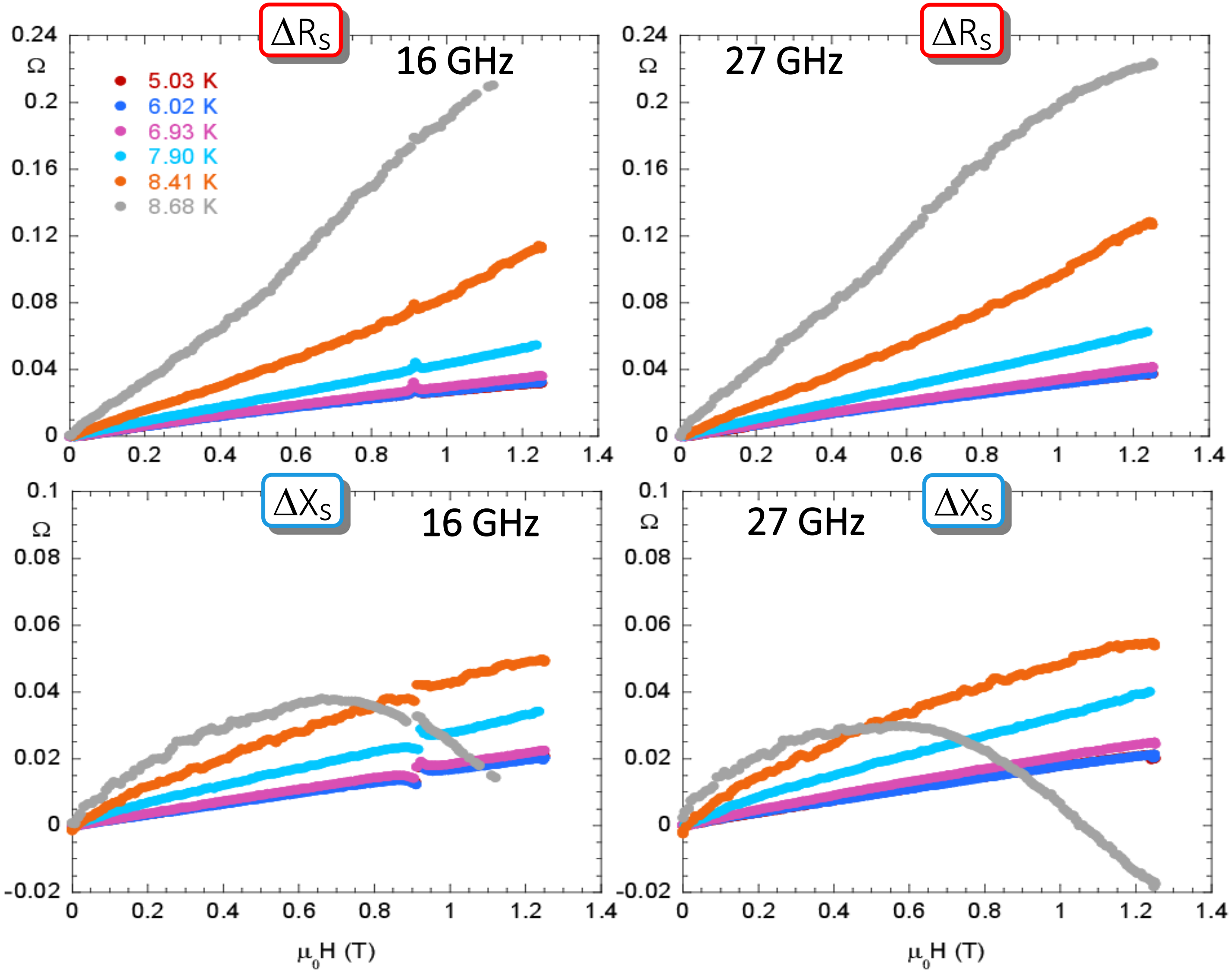
Change in effective regime

Near T_c : ΔX<0
→ e.m. **thin film** & 2-fluids contribution

by nearing $H_{c2}(T)$ → thin film regime
→ choice of coating thickness in function of (H,T, ν)

ΔZ(H) – temperature evolution

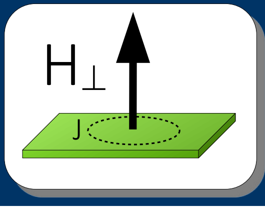




- ΔR(H) curvature changes with T → complex electrodynamics (thermal creep, two fluid, B-dep. vortex parameters)

Focus on low T

Extraction of vortex parameters



Fit model

- complex resistivity:

$$\tilde{\rho} = \rho_{ff}\frac{1+\mathrm{i}\frac{\nu_p}{\nu}}{1+\left(\frac{\nu_p}{\nu}\right)^2} + \mathrm{i}\omega\mu_0\lambda^2(T)$$

$$\rho_{ff} = \alpha\rho_n\frac{B}{B_{c2}(T)} \qquad \lambda(T) = \lambda_0/(1-(T/T_c)^4)$$

→ **two field independent fit parameters**: $\boxed{\alpha, \nu_p}$

Parameters set from other measurements: ρ_n, T_c

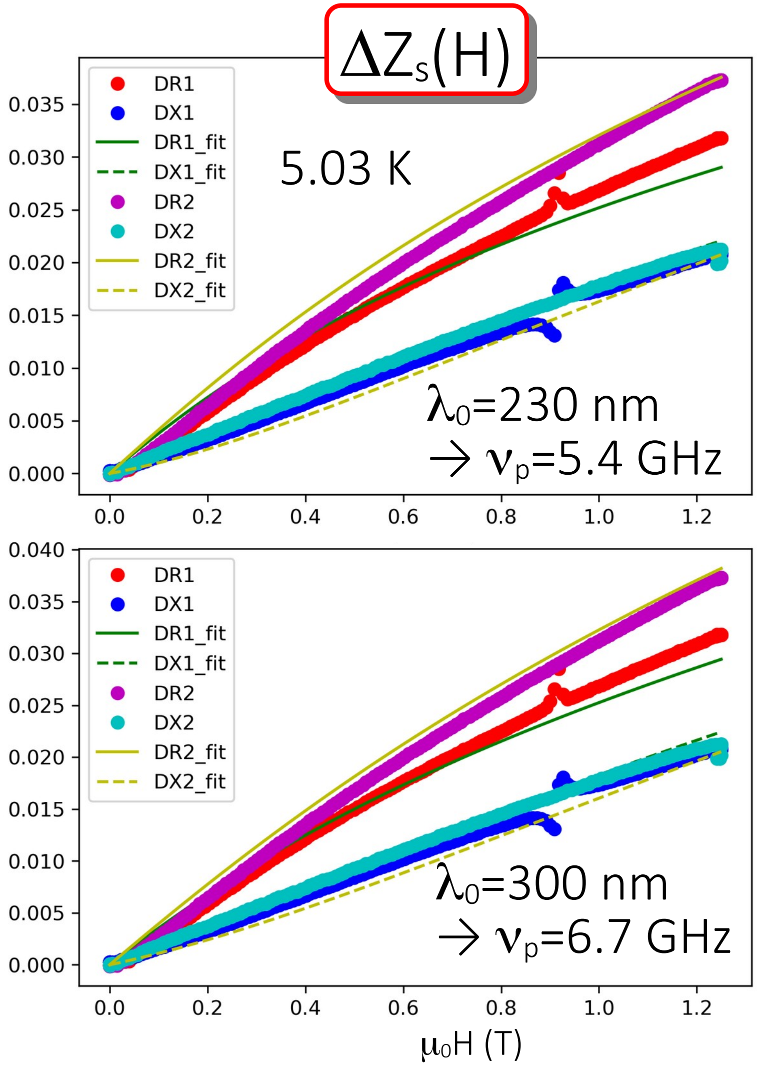
Parameters taken from literature: $B_{c2}(0\ \mathrm{K})$

$$\lambda_0 \in [230, 300]\mathrm{nm}$$

Giordano et al, IEEE Trans. Magn. v. MAG-11 437 (1976)
Benvenuti et al, Fifth Workshop RF Supercond. 1991

- expression for the **effective** surface impedance Z_s

model sensivity on λ_0



5.03 K

λ_0=230 nm
→ ν_p=5.4 GHz

λ_0=300 nm
→ ν_p=6.7 GHz

- **Robust result** ν_p ~6 GHz

- NbTi coated: ✗
  ν_p ~ 44 GHz
  @ 4.2 K, 0-5 T

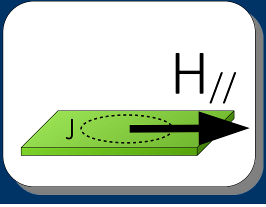
Di Gioacchino et al.
IEEE Trans. Appl. Supercond.
29 3500605 (2019)

(different H orientation)

- Nb_3Sn bulk: ✓
  ν_p ~ 7 GHz,
  @ 6 K, 2 T

Alimenti et al.
Supercond. Sci. Technol.
34 014003 (2021)

ΔZ(H) – temperature evolution - H//ab

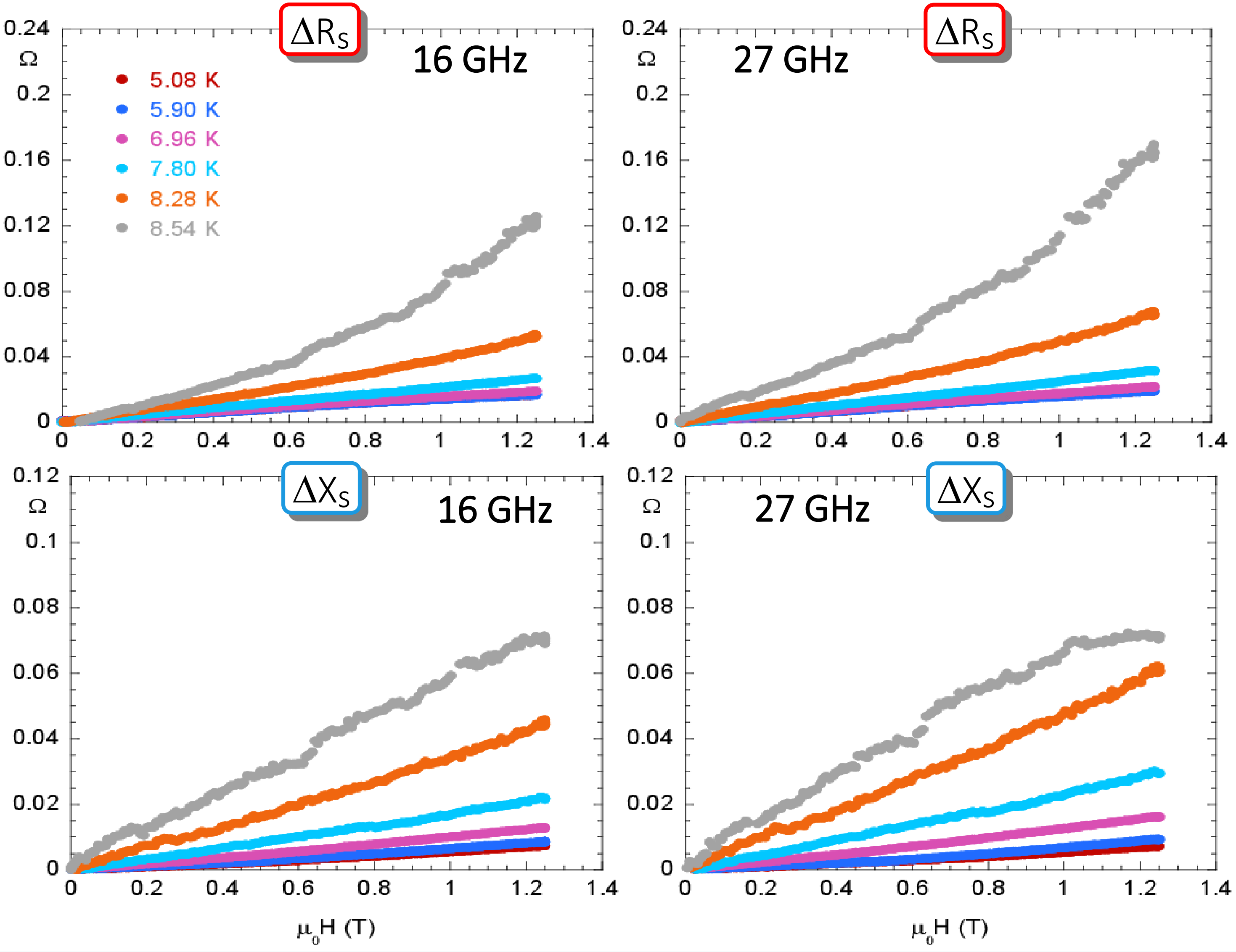


Need for measurements at
different H orientations:
- haloscopes: H // J

Di Gioacchino et al. IEEE Trans. Supercond. 29 3500605 (2019)
Alesini et al. Phys. Rev. D 99 101101(R) (2019)
Alimenti et al Instruments 6 1 (2022)

- typical dielectric resonator setup:
$H \perp J$

→ **use of rotatable magnet**



Preliminary result:
$\nu_p \simeq$5-10 GHz

Summary

Preliminary results on NbTi films on insulator at fields < 1.2 T

- Identification of regimes/models for Z_s
- Determination of
  - pinning frequency: $\nu_p \sim 6$ GHz at 5 K
  - change in regimes (bulk vs thin film) → coating thickness

Thanks!