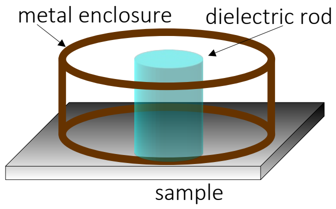
Microwave studies of the surface impedance of superconductors in the mixed state

Nicola Pompeo

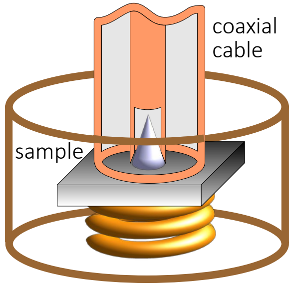
UNIVERSITÀ DEGLI STUDI ROMA TRE

Engineering Department
University Roma Tre

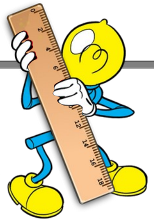
Measurement techniques

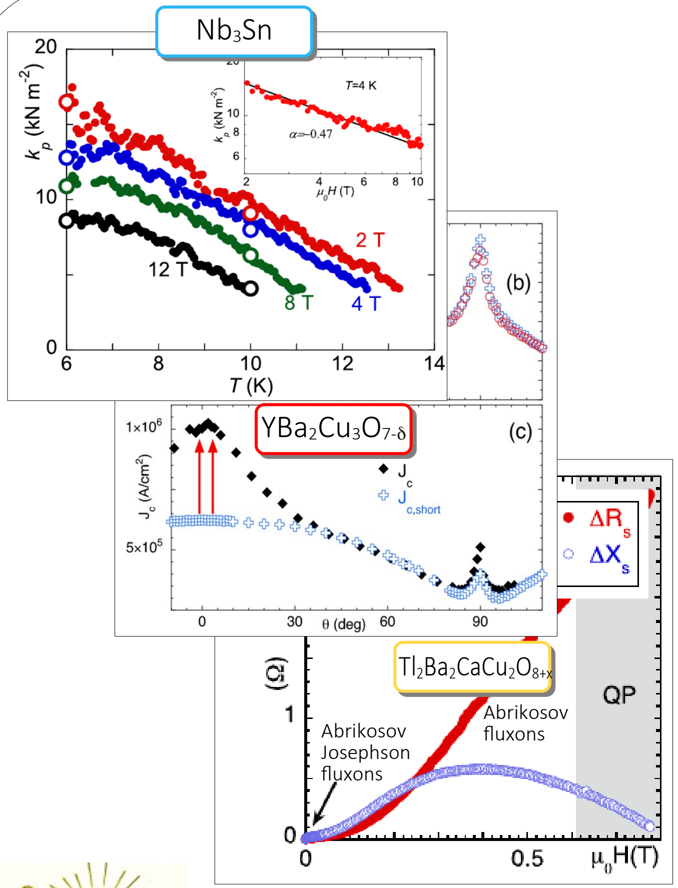


Dielectric-loaded Resonators
mono/dual frequency
8-48 GHz



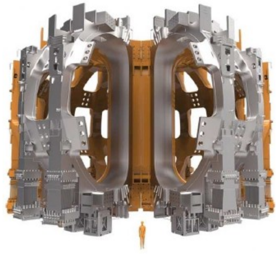
Corbino Disk
wide band
1-20 GHz





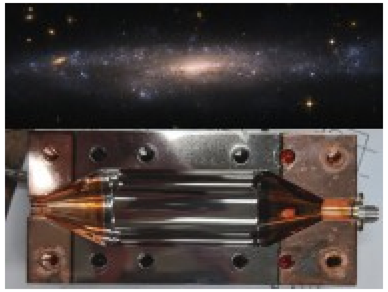
Vortex dynamics at rf

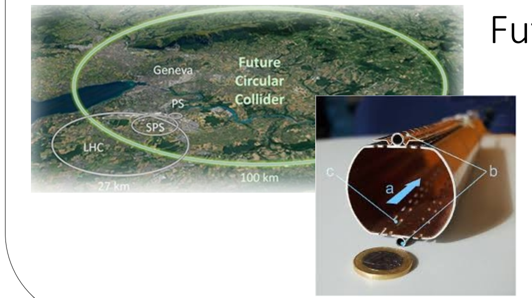
Input for applications



ITER
fusion reactor

Dark matter
search





Future Circular
Collider
Beam
screen

ROMA TRE
UNIVERSITÀ DEGLI STUDI

Electrodynamics of the Matter Lab

Nicola Pompeo*, Kostiantyn Torokhtii, Andrea Alimenti

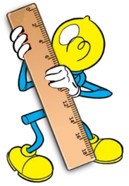
Group Leader
prof. E. Silva

Engineering
Department
University
Roma Tre

*nicola.pompeo@uniroma3.it

Outline

- Measurand at microwaves: surface impedance Z_s
- High frequency vortex dynamics
- The techniques
  - dielectric resonators
  - Corbino disk
- Selected results:
  - Low Tc: Nb_3Sn, Nb
  - MgB_2
  - Cuprates: $YBa_2Cu_3O_{7-\delta}$
  - Iron superconductors: $FeSe_{0.5}Te_{0.5}$
- Conclusions



Surface impedance

Measurand at microwaves:

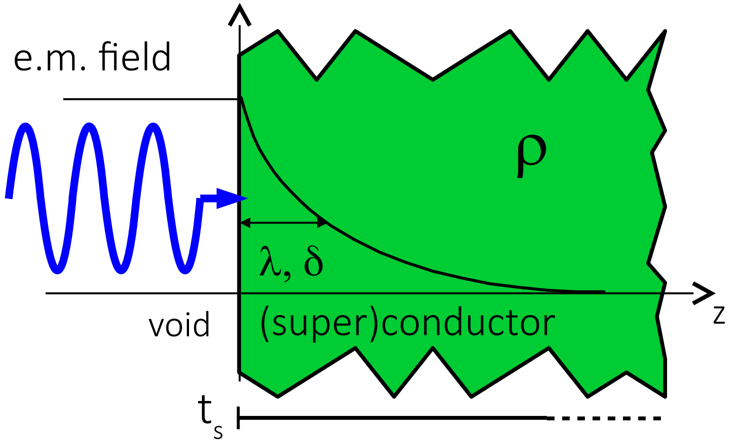
$$Z_s = \frac{E_{\parallel}}{H_{\parallel}} = R_s + \mathrm{i}X_s$$

R_s: dissipation

X_s: reactive energy

Bulk (super)conductor

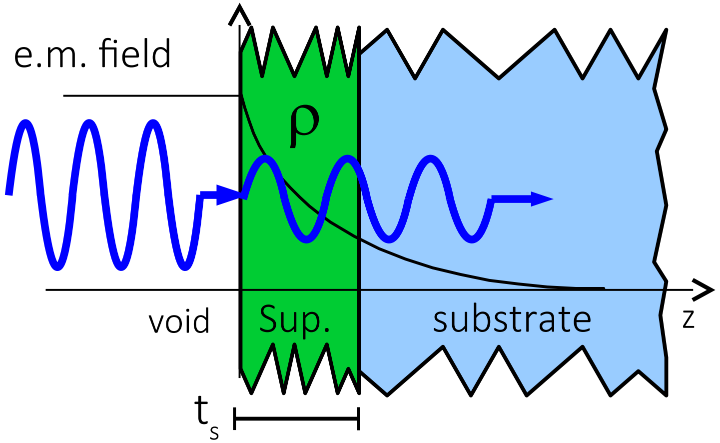
$$t_s \gg \max(\lambda, \delta)$$



$$Z_s = \sqrt{\mathrm{i}2\pi\nu\mu_0\rho}$$

Thin film on insulating substrate

$$t_s \ll \min(\lambda, \delta)$$



$$Z_s \simeq \frac{\rho}{t_s}$$

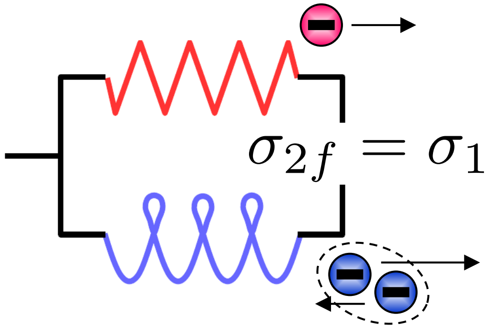
Pompeo et al, Supercond. Sci. Technol. 20, 1002 (2007)
Pompeo, Torokhtii, Silva, IEEE I2MTC, doi 10.1109/I2MTC.2017.7969902 (2017)

Superconductor surface impedance

Zero field (Meissner state)

- Two fluid model

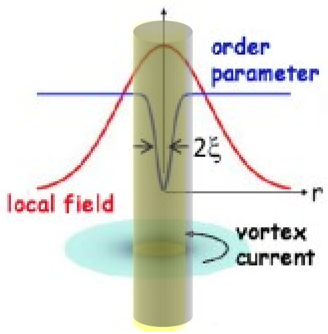
$$\sigma_1 = \frac{n_n e^2 \tau}{m}$$



$$\sigma_{2f} = \sigma_1 - \mathrm{i}\sigma_2$$

$$\sigma_2 = \frac{n_s e^2}{m\omega} = \frac{\omega\mu_0}{\lambda^2}$$

In-field (Mixed state) (Type II SC)



fluxon (vortex)

- rf current ⇒ $\mathbf{F}_L = \mathbf{J}_{rf} \times \mathbf{\Phi}_0$
  ⇒ oscillatory **vortex motion**
  ⇒ **dissipation**
- Material defects:
  fluxon on defect lowers energy
  ⇒ **pinning**
  ⇒ **dissipation reduction**

vortex motion resistivity ρ_{vm}

$$\rho = \frac{\rho_{vm} + \mathrm{i}\frac{1}{\sigma_2}}{1 + \mathrm{i}\frac{\sigma_1}{\sigma_2}}$$

Coffey, Clem PRB 67, 386 (1991)

no pair-breaking ($B \ll B_{c2}$)
$\sigma_1/\sigma_2 \ll 1$ ($T<T_c$)

$$\Delta\rho(H) = \rho(H) - \rho(0) \simeq \rho_{vm}(H)$$

High frequency vortex motion response

- J_{rf} → vortices oscillates around equilibrium positions (pins)
- Force balance (per unit length) (averaged over vortex length and vortices):
  (vortex as massless damped harmonic oscillator)

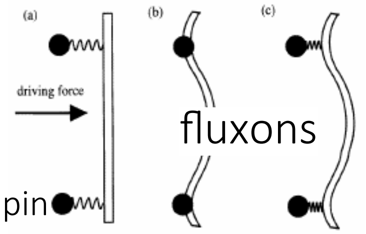
$$\mathbf{J}_{rf} \times \mathbf{\Phi}_0 - \eta\dot{\mathbf{u}} - k_p\mathbf{u} + \mathbf{F}_{thermal} = m\ddot{\mathbf{u}}$$

Driving force — $\mathbf{J}_{rf} \times \mathbf{\Phi}_0$ **Very short oscillations** < 1 nm

Viscous drag → Viscosity η — Flux flow resistivity ρ_{ff} — $\rho_{ff} = \frac{\Phi_0 B}{\eta} = \alpha\rho_n \frac{B}{B_{c2}}$

Pinning force → Pinning constant k_p — $k_p = d^2U/dx^2$

U(r) : pinning energy profile



Stochastic thermal force — $\mathbf{F}_{thermal}$ Thermal activated jumps

Inertial term — $m\ddot{\mathbf{u}}$ Relevant at high (THz) frequency, neglected

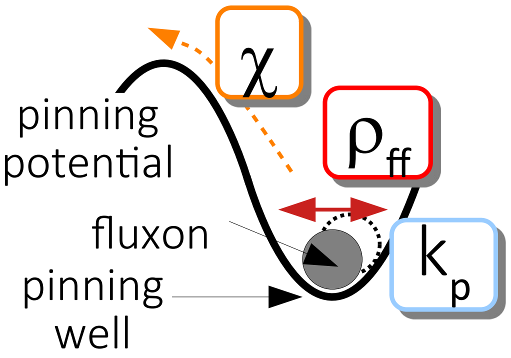
Vortex core physics

Vortex system physics

Gittleman, Rosenblum PRL 16 734 (1966)
Coffey, Clem PRL 67 386 (1991)
Brandt PRL 67 2219 (1991)
Golosovsky et al SUST 9 (1996)

High frequency vortex motion response

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

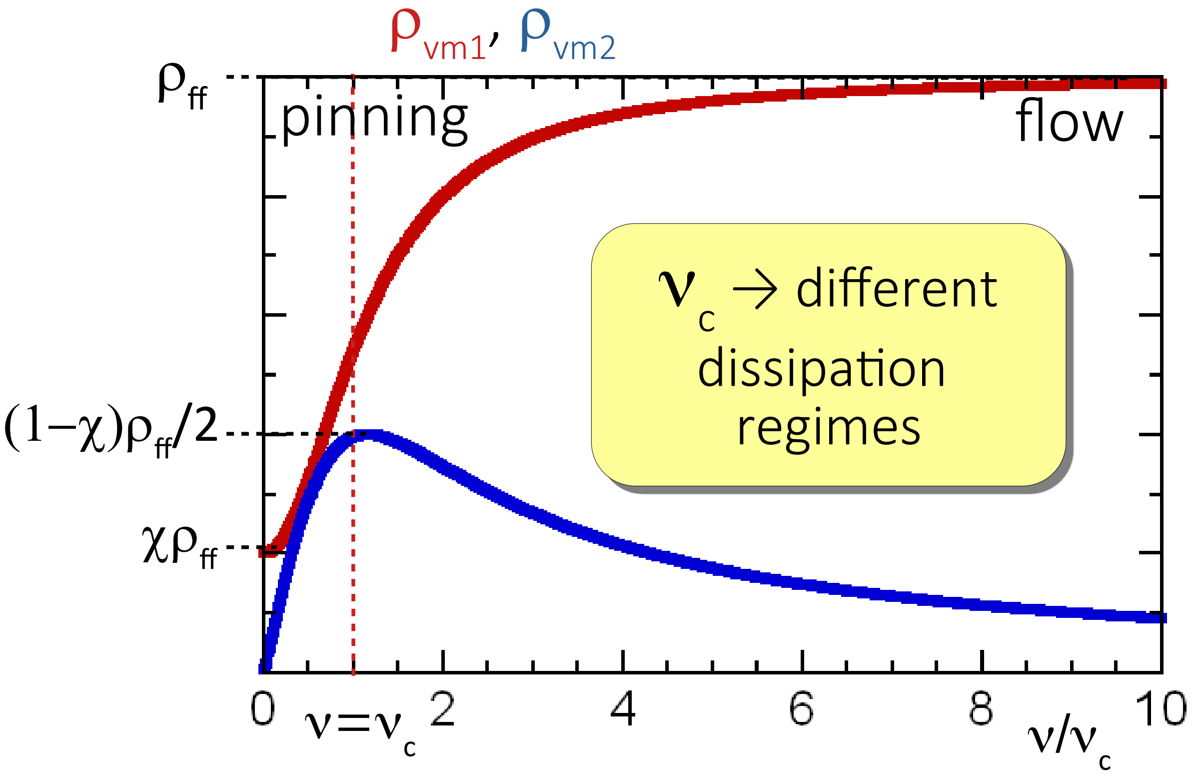


$$\rho_{vm} = \rho_{vm1} + \mathrm{i}\rho_{vm2} = \rho_{ff}\frac{\chi + i\nu/\nu_c}{1 + i\nu/\nu_c}$$

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

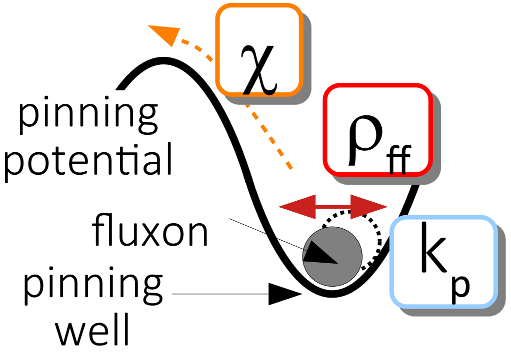


$\nu_c \rightarrow$ different dissipation regimes

characteristic freq. ν_c pinning freq. ν_p	$\nu_c \xrightarrow[\chi \to 0]{} \nu_p$
creep factor χ	related to pinning barriers heights U_0 $0 \le \chi \le 1$
flux flow resistivity ρ_{ff} viscosity η	dissipation
pinning constant k_p	$k_p = 2\pi\nu_p\eta$

High frequency vortex motion response

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



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

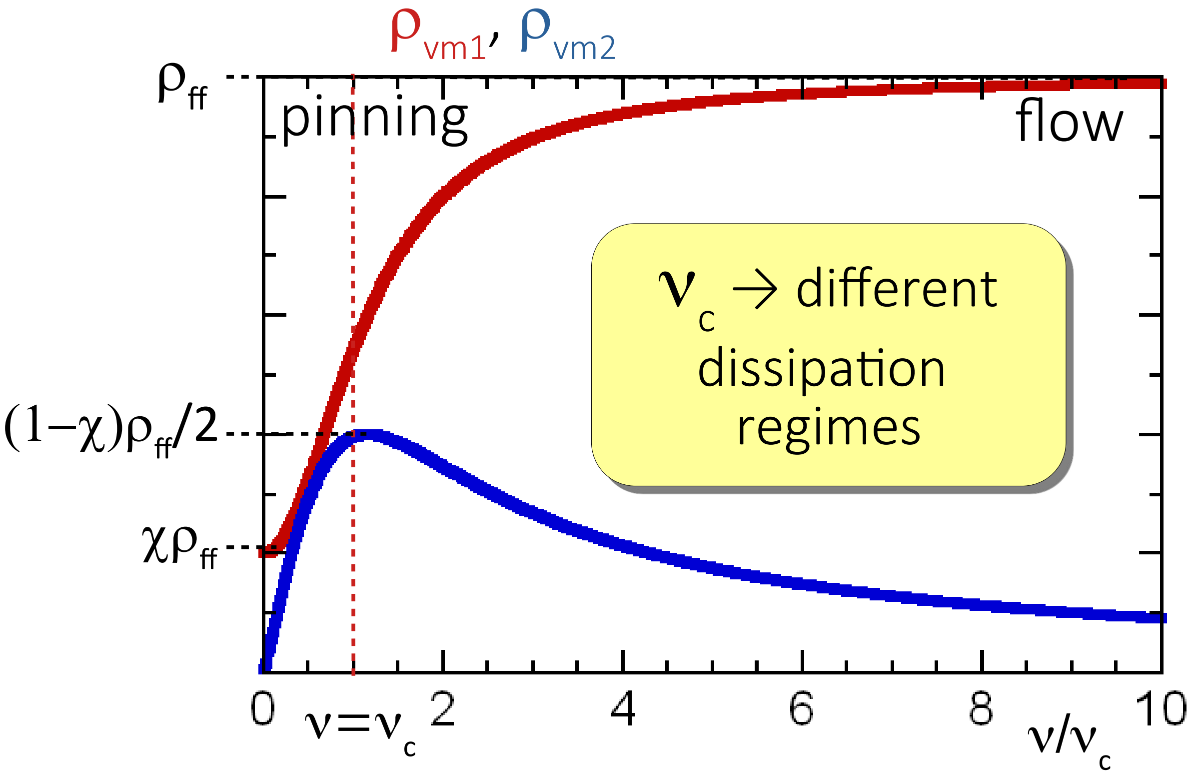
2 observables 3 parameters

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

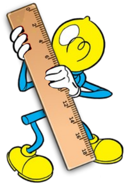
Multifrequency (rarely performed)



Outline

- Measurand at microwaves: surface impedance Z_s

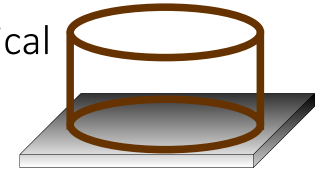
- High frequency vortex dynamics
- The techniques



  - dielectric resonators
  - Corbino disk
- Selected results:

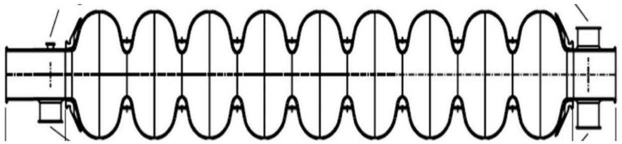
  - Low Tc: Nb_3Sn, Nb
  - MgB_2
  - Cuprates: $YBa_2Cu_3O_{7-\delta}$
  - Iron superconductors: $FeSe_{0.5}Te_{0.5}$
- Conclusions

Cavity as a measurement instrument



$$Q, \nu_0 \Rightarrow \rho$$

VS



9-cell TESLA-type accelerating structure

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

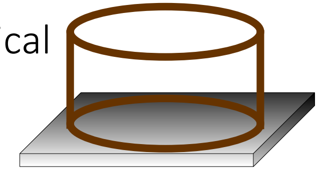
$$Q, \nu_0 \Rightarrow \vec{E}_{rf}$$

geometry for measurements of material properties?

Cavity as a measurement instrument

cylindrical cavity

sample



$$Q, \nu_0 \Rightarrow \rho$$

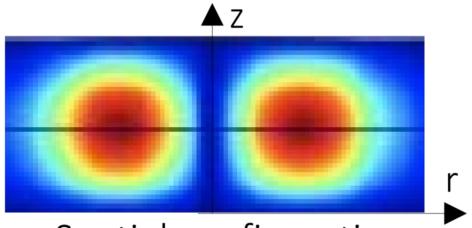
Resonant mode

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

quality factor

$$\nu_0$$

resonant frequency



Spatial configuration (TE, TM, TEM, HEM)

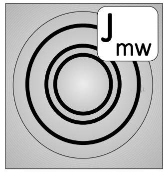
Perturbation theory

$$\frac{1}{Q} = \sum_i \frac{R_i}{G_i}$$ dissipation

$$\frac{\Delta\nu_0}{\nu_0} = \frac{W_H - W_E}{W} = -\sum_i \frac{\Delta X_i}{2G_i}$$ stored energy

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

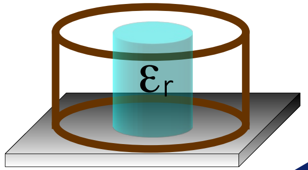
- Cylindrical geometry (optimal Q)
- Mode: TE_{011} (probing currents: planar → in-plane properties)



$\langle Z_s \rangle$ sample surface

- sensitivity (Q^2/G) not optimal:
  - sample surface << whole surface
  - losses from metal enclosure

- High sensitivity: dielectric loaded resonator
  - focus e.m. field –> reduces lateral losses
  - reduces overall size → smaller samples
  - same enclosure for different rods/operating frequencies

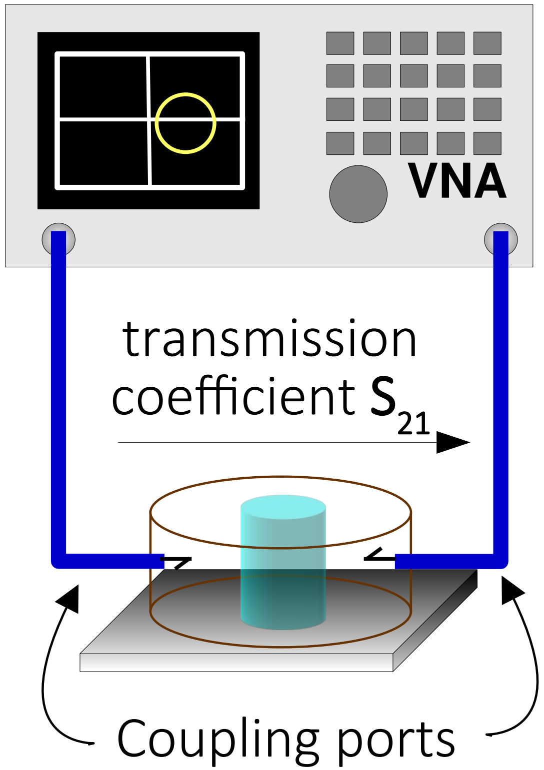


Resonators: measurement of Q, ν_0 (basics)

- Operation in transmission, resonance curve:

$$S_{21}(\nu) = \frac{S_{21}(\nu_0)}{1 + 2\mathrm{i}Q_l \frac{\nu-\nu_0}{\nu_0}}$$

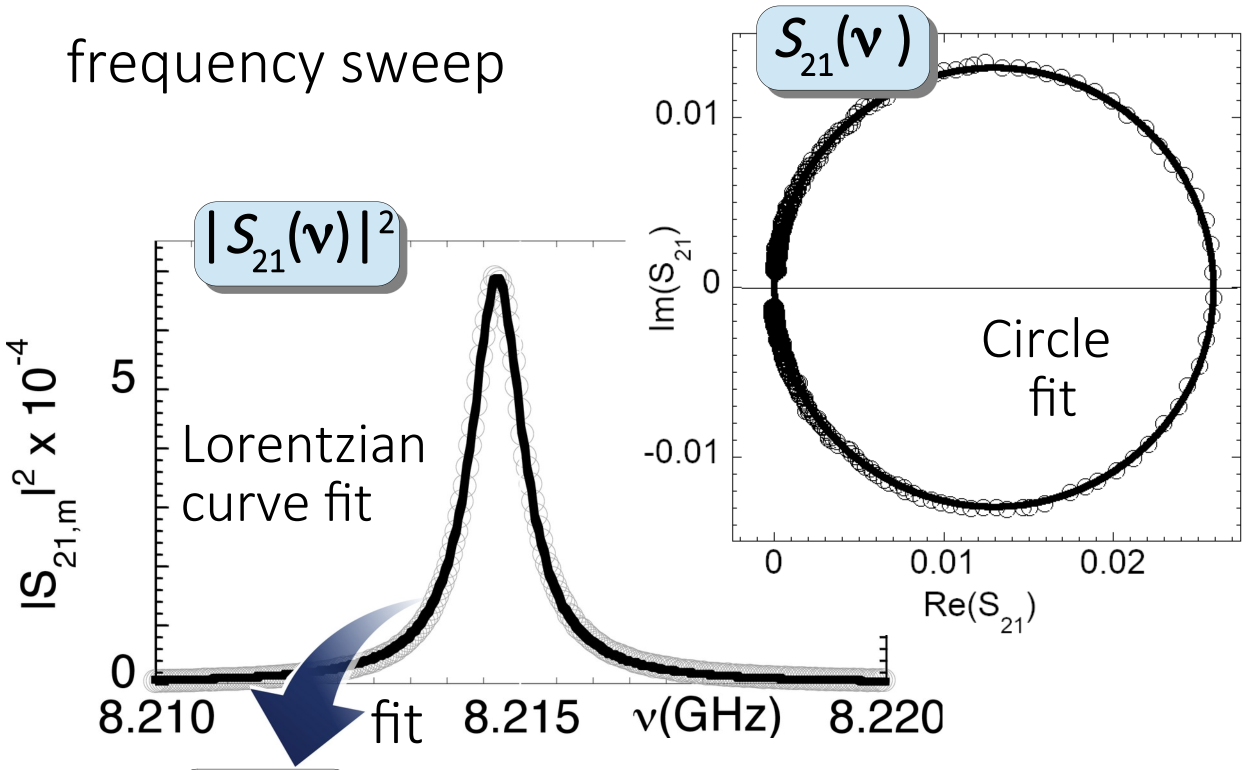
S_{21}: scattering coefficient (complex, ν-dependent)
Q_l: *loaded* quality factor



coupling factors $\beta \ll 1$

$\Rightarrow Q_l \rightarrow Q$

frequency sweep



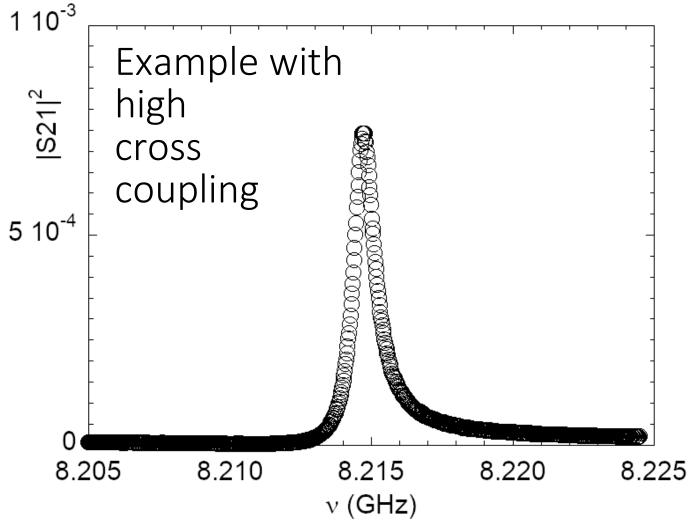
Q_l, ν_0 → geom. factors → $R_s, \Delta X_s$

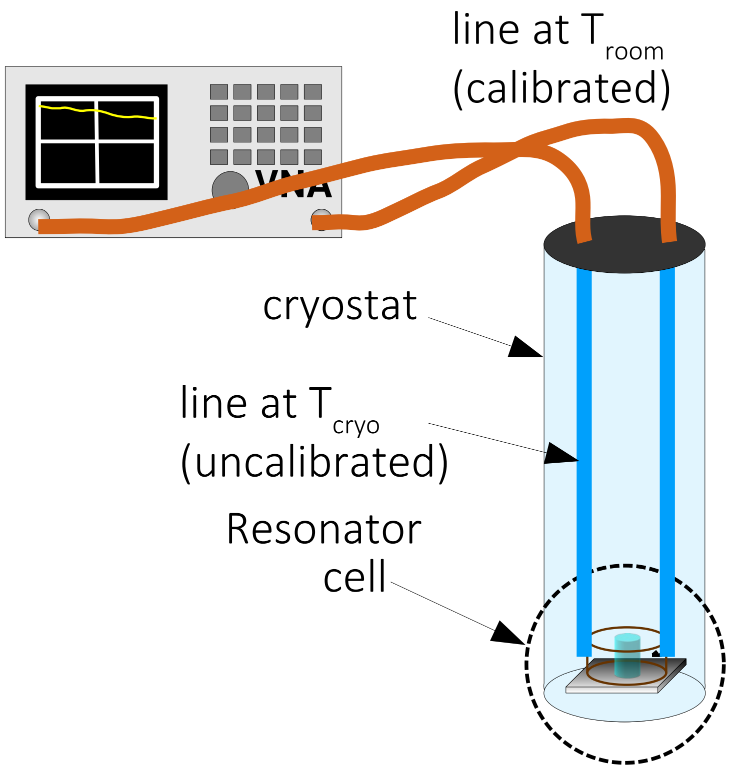
Pompeo et al. Meas. Sci. Rev. 14 164 (2014)

Resonators: measurement of Q, ν_0 (advanced)

- Non idealities on S_{21} → deformation of resonance curve
  - partially uncalibrated line
  - cross coupling between ports
  - interference from nearby modes

Extended models for S_{ij}





- Metrological aspects:
  - assessment of uncertainties in uncalibrated measurements
  - choice of optimal frequency span for minimum uncertainties on Q and ν_0

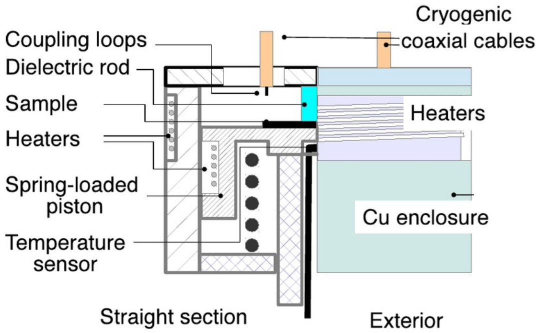
Torokhtii et al. "Frequency span optimization for asymmetric resonance curve fitting", Conf. Proc. I2MTC 2021
Alimenti et al. Meas. Sci. Technol. 30 065601 (2019)
Torokhtii et al. ActaIMEKO 3 47 (2020)

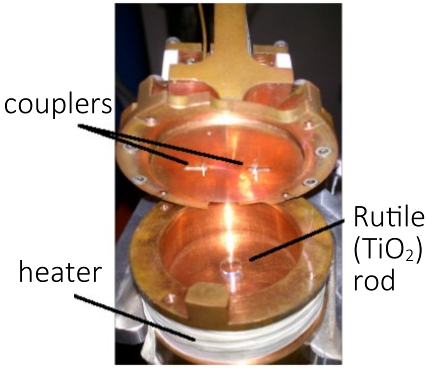
Our dielectric resonators - some figures

General features:
- custom made
- compatible with cryostat space & cyrogenic T
- compatible with fields 1-10 T

- Sample geometry: flat&parallel surfaces
- Probing area: ∅≃3-10 mm

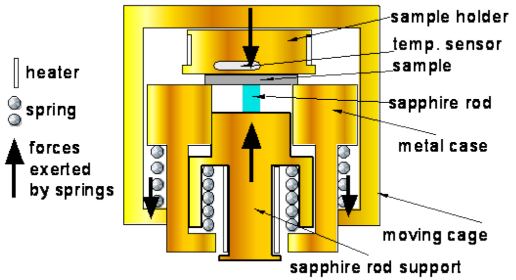
8 GHz — Single mode, High field

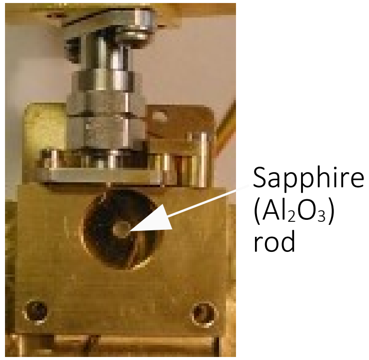




Rutile rod:
Re(ε_r)≃120 @ 20 K
Q range: 1000-15000

47 GHz — Single mode, High frequency





Sapphire rod:
Re(ε_r)≃9 @ 20 K
Q range: 1000-12000

16, 27 GHz — Dual frequency

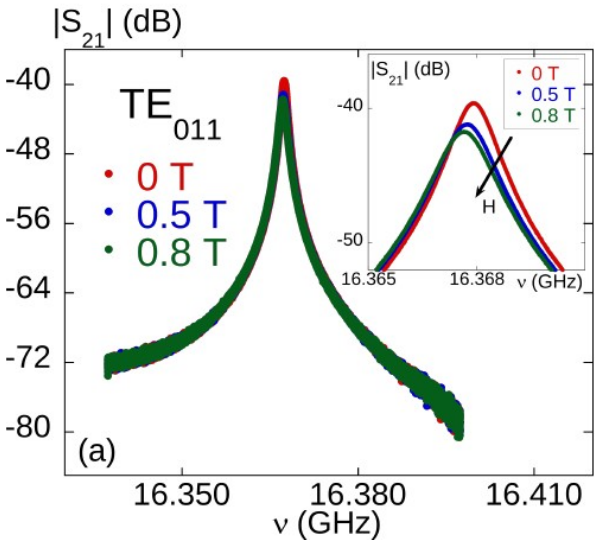
Sapphire rod:
Re(ε_r)≃9 @ 20 K
Q range: 1000-30000

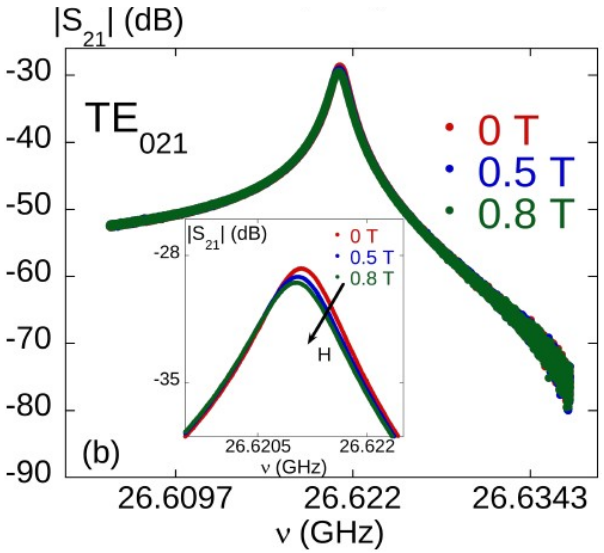
Pompeo et al., J. Supercond. and Novel Magn. 20 71 (2007)
Torokhtii et al. Meas. Sci. Technol. 25 025601 (2014)
Pompeo et al., Meas. Sci. Rev. 14 164 (2014)
Pompeo et al, 24th IMEKO TC4 Int. Symp. Proc. 2020

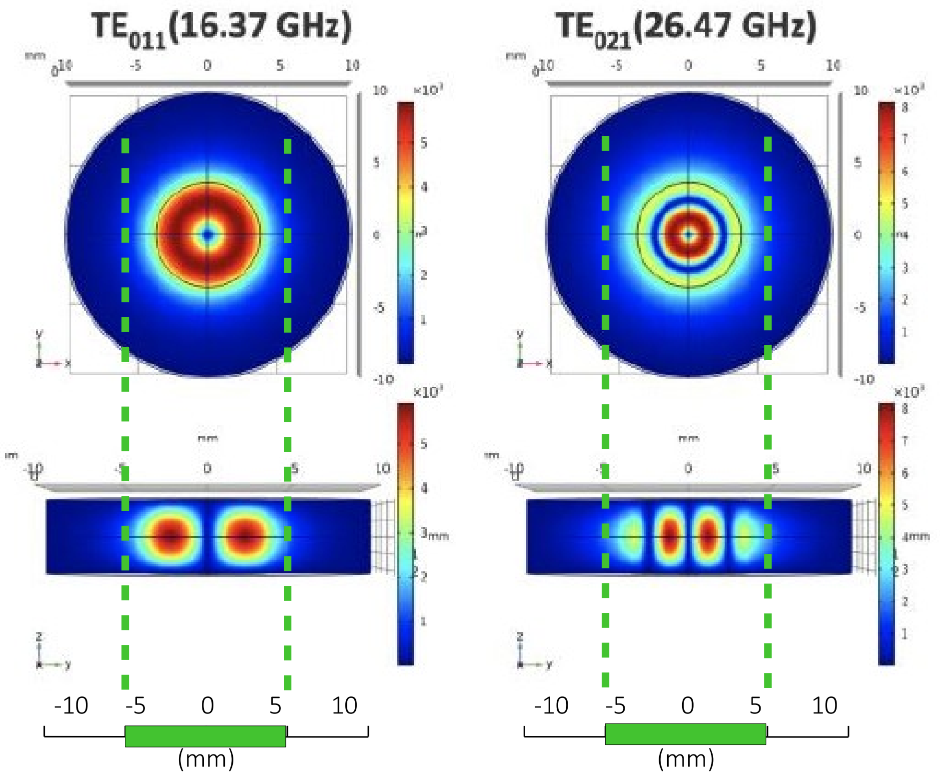
Multifrequency measurements

- Design criteria
  - well separated ν_0
  - well isolated modes
  - similar J(r)
- Modes: TE_{011} and TE_{021}

dual frequency operation
ν_1=16.4 GHz, ν_2=26.6 GHz







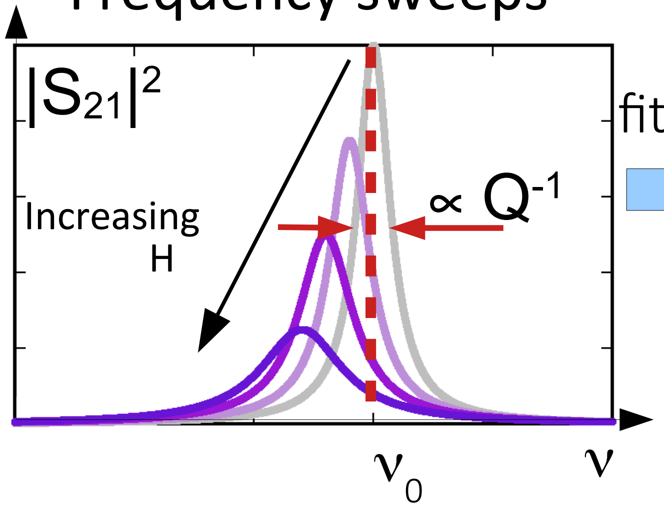
e.m. field profiles

Pompeo et al, 24th IMEKO TC4 Int. Symp. Proc. 2020
Pompeo et al, Measurement, submitted 2021

Resonator technique - the measurement process

Z_s vs H, fixed T

Frequency sweeps



fit → Q, ν_0 resonator parameters → std. em theory →

H-induced variations:

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

$$\Delta X(H) = -2G\frac{\nu_0(H) - \nu_0(0)}{\nu_0(0)}$$

→ $\Delta Z_s(H)$ → ρ_{vm}

Various limits:

- film/insulator $Z_s \propto \rho$
- bulk $Z_s \propto \sqrt{\rho}$
- film/metal (CC) $Z_s(\rho)$

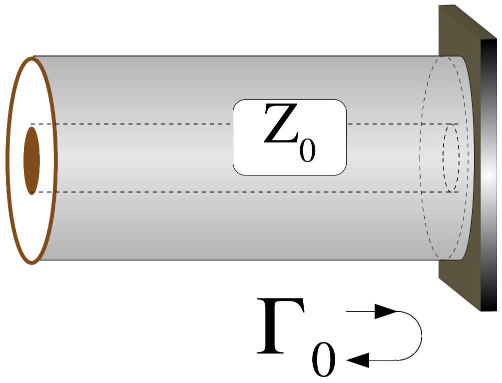
Z_s vs T, fixed H

- Z vs T: separate evaluation of resonator background

$$R_s(T,H) = \frac{G_s}{Q(T,H)} + \mathrm{background_R(T)}$$

$$\Delta X_s(T,H) = -2G_s\frac{\Delta\nu_0(T,H)}{\nu_{0,ref}} + \mathrm{background_X(T)}$$

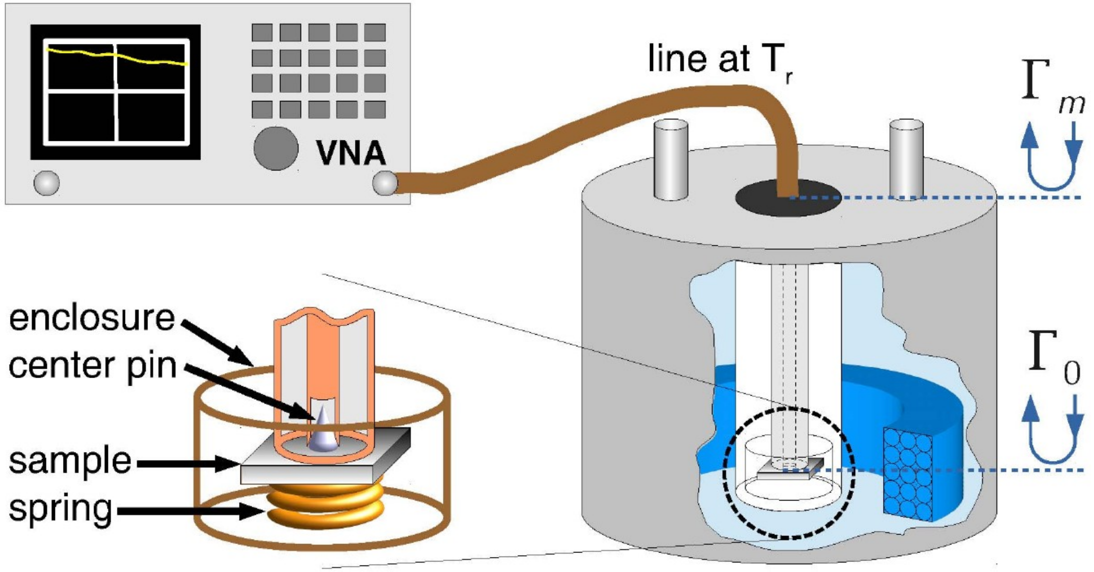
Corbino disk – microwave spectroscopy



$$Z_s(\nu) = Z_0 \frac{1+\Gamma_0(\nu)}{1-\Gamma_0(\nu)}$$

Γ_0: (complex) reflection coefficient
ν : frequency
Z_0: line characteristic impedance
Z_s: sample impedance

- Main features
- ✔ wide band (TEM mode): 1-25 GHz
- ✔ mw currents J_{mw} :
  planar → in-plane properties
  subcritical → linear regime
- ✘ **Approximate line calibration**
  various strategies

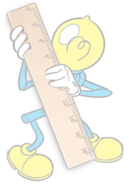


E. Silva et al, IEEE Trans. Instrum. Meas. 65, 1120 (2016)

Outline

- Measurand at microwaves: surface impedance Z_s

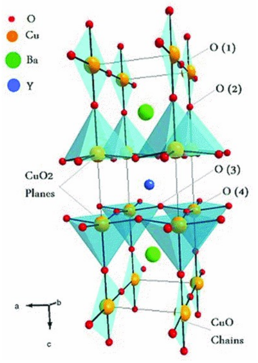
- High frequency vortex dynamics
- The techniques
  - dielectric resonators
  - Corbino disk

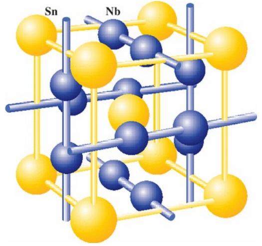


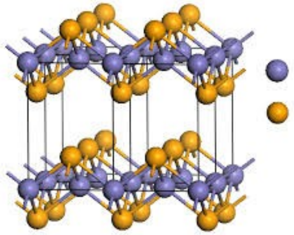
- Selected results:
  - Low Tc: Nb_3Sn, Nb
  - MgB_2
  - Cuprates: $YBa_2Cu_3O_{7-\delta}$
  - Iron superconductors: $FeSe_{0.5}Te_{0.5}$

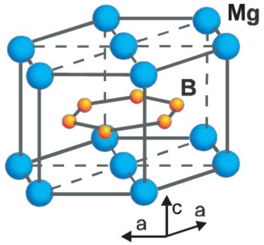
- Conclusions

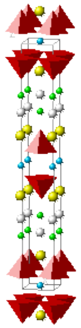
Studied materials

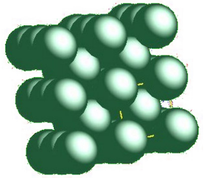








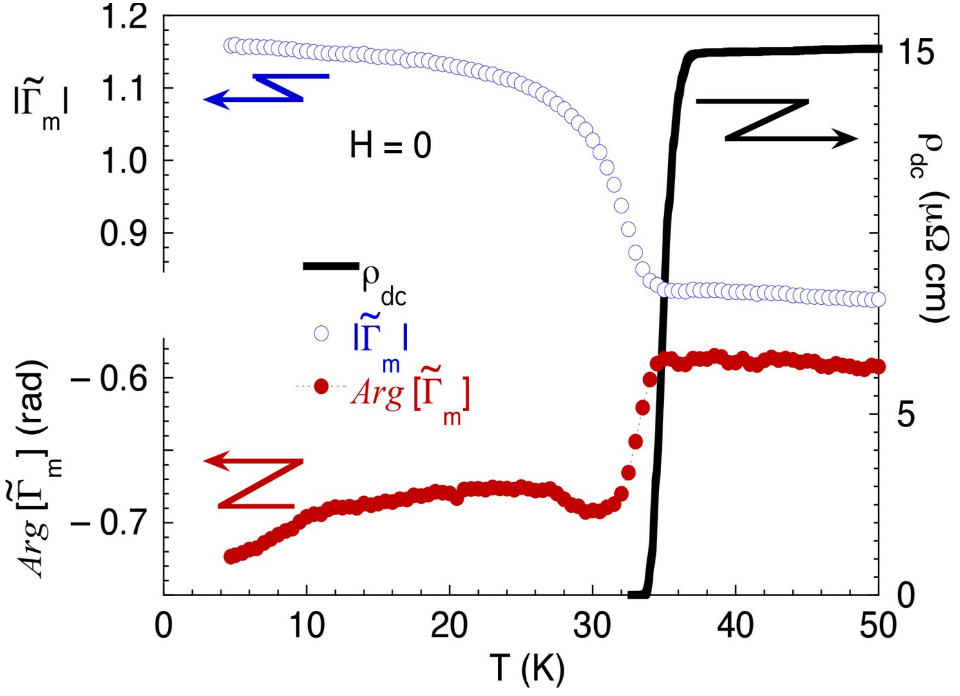


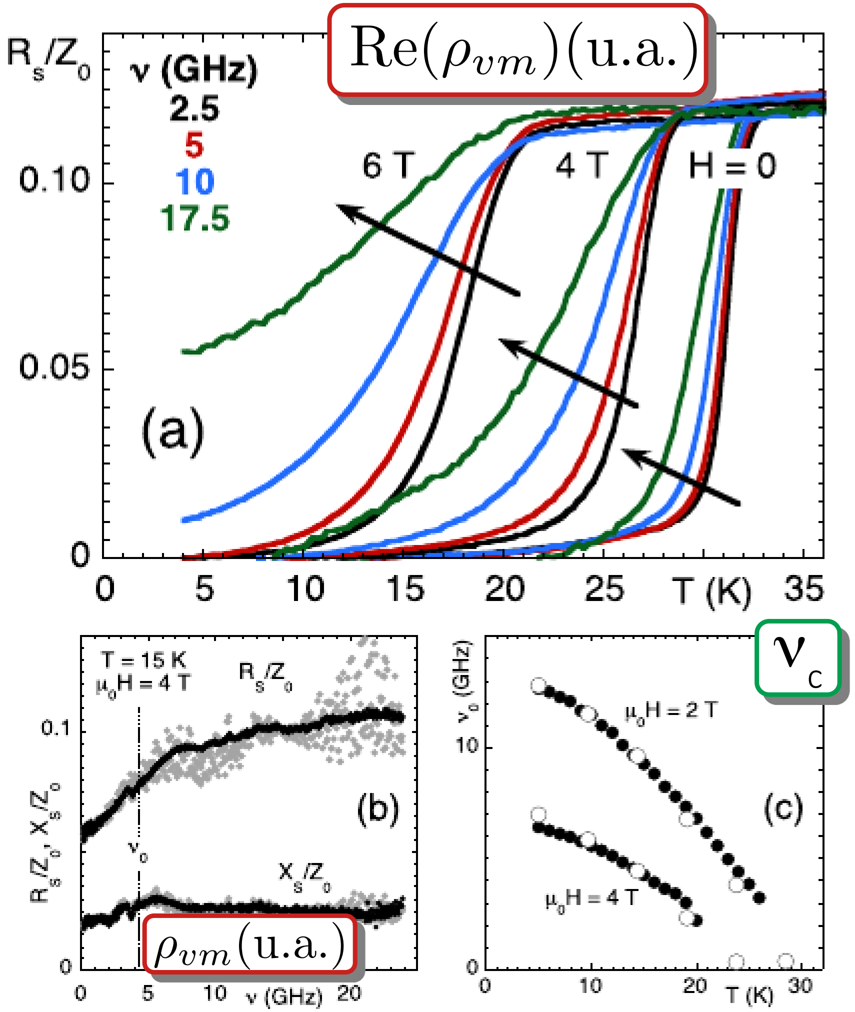


superconductor	T_c(K)	geometry	applications
Nb_3Sn	~18	bulk	haloscopes, RF cavities, cables
$YBa_2Cu_3O_{7-\delta}$	~92	thin film coated conductor	beam screen coating (FCC), cables for fusion reactors, haloscopes
$FeSe_{0.5}Te_{0.5}$	~18	thin film	development of new coated conductor tapes
MgB_2	~39	thin film bulk	PIT cables (CERN/fusion reactors), RF cavities
$Tl_2Ba_2CaCu_2O_{8+x}$	~110	thin film	
Nb	~9	thin film	RF cavities

Corbino disk – example measurements (1)

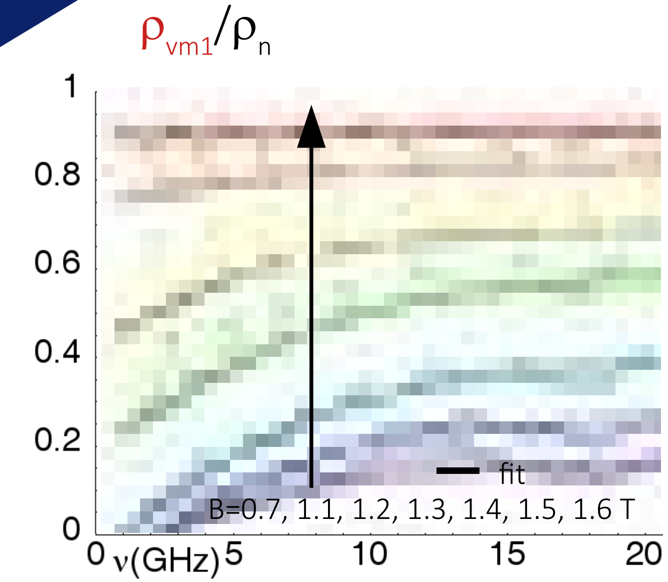
MgB$_2$ thin film



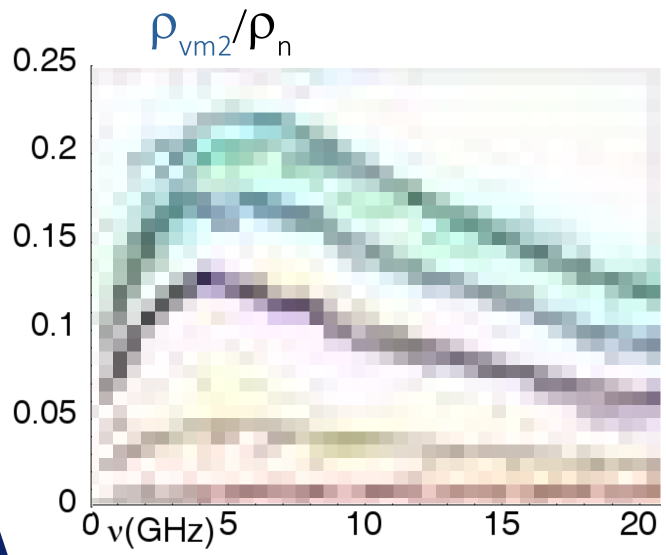


Sarti et al, PRB 72 024542 (2005)
Silva et al, IEEE Trans. Instrum. Meas. 65 1120 (2016)

Corbino disk – example measurements (2)



unpublished data

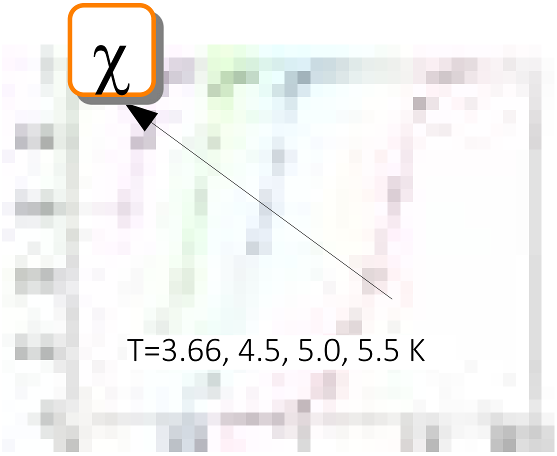


t_s=20 nm

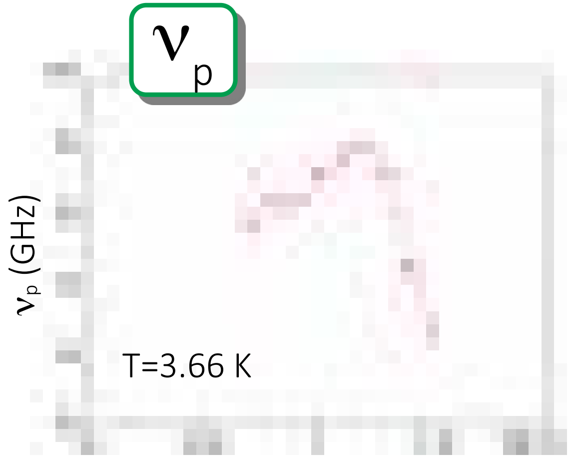
ρ_n=22 mΩ cm

Pompeo et al, Phys. C Supercond. 470 901 (2010)
Silva et al, SuST 24 024018 (2011)
Torokhtii et al, J. Supercond. 26 571 (2012)

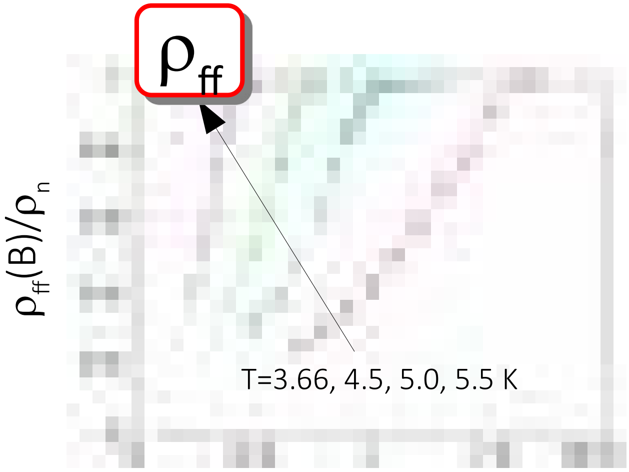
Nb thin film



Creep significantly $\neq 0$



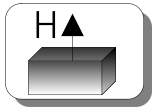
Field dependent



deviation from simple
Bardeen-Stephen B-dep.

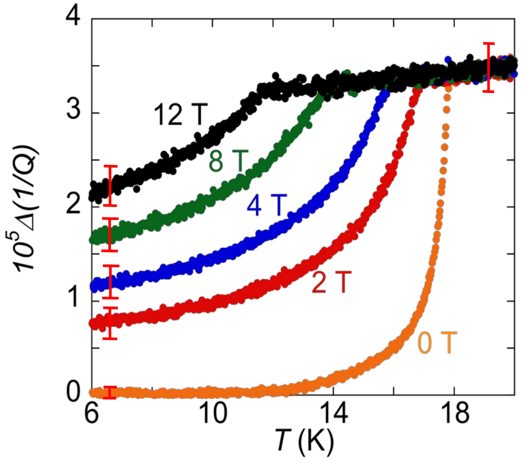
Nb_3Sn – High fields

In collaboration with: UNIVERSITÉ DE GENÈVE R. Flükiger Fermilab T. Spina

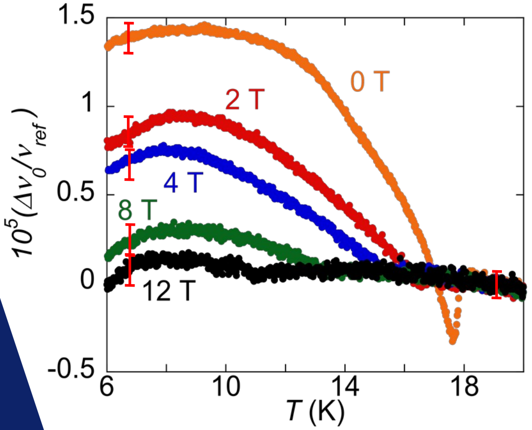


$Z_s \propto \sqrt{\rho}$ Bulk limit

15 GHz

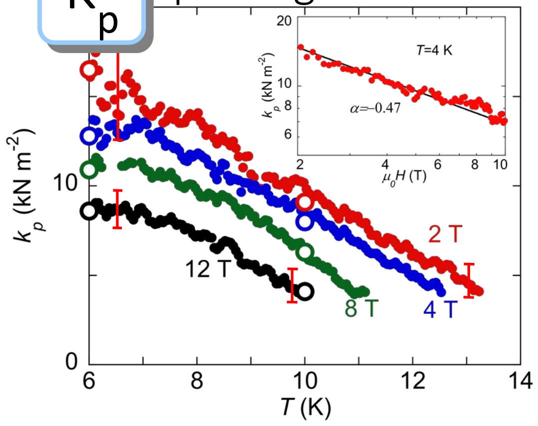


$\Delta R(T;H)$

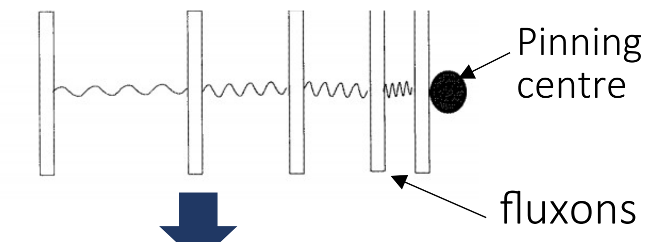


$\Delta X(T;H)$

k_p pinning constant

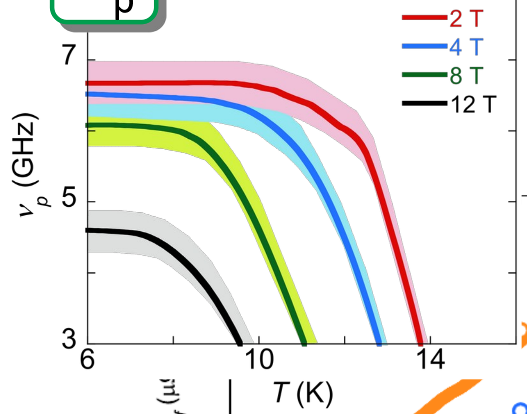


Field dependent → Collective pinning regime

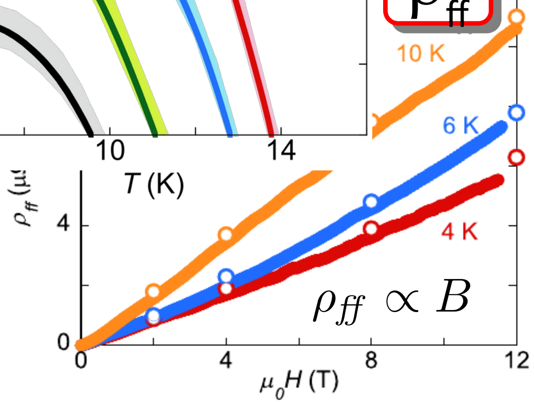


Room for advanced material ingegnerization for rf improved pinning

ν_p pinning frequency



ρ_{ff}



~ operating frequencies of haloscopes but

Q @ (1 T, 9 GHz) of axion cavity
- Cu-based: 9×10^4 @ 4.2 K
- NbTi-based: 55×10^4 @ 4.2 K

Alesini et al PRD 99 101101 (2019)

- Nb_3Sn-based: $<7.5\times10^4$ @ 4.2 K (computed)

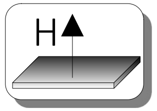
consistent with Bardeen-Stephen model
material "intrinsic" property

Alimenti et al, Supercond. Sci. Technol. 34 014003 (2021)
Alimenti et al, IEEE Trans. Appl. Supercond. 29 3500104 (2019)

$YBa_2Cu_3O_{7-\delta}$ – High fields

Supported by: EUROfusion

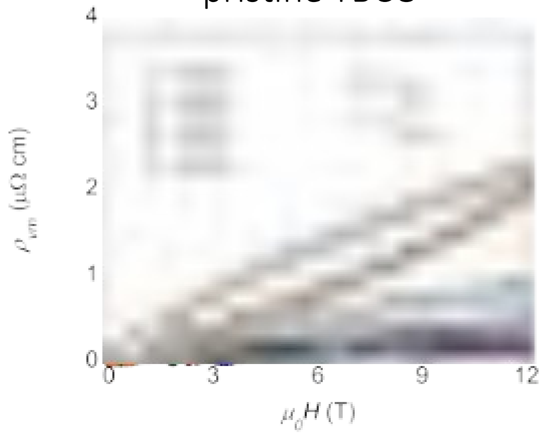
In collaboration with: ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile — G. Celentano; ICMAB Institut de Ciència de Materials de Barcelona — A. Palau



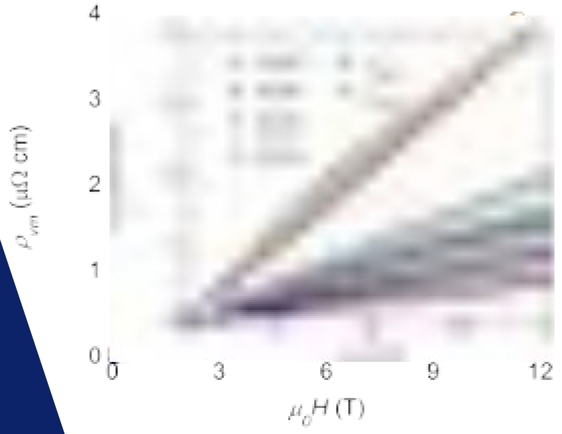
$$Z_s = \rho / t_s$$ thin film

15 GHz

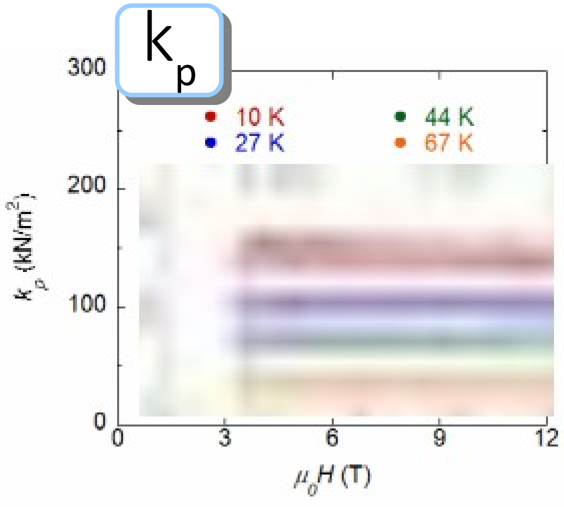
Pulsed Laser Deposition (PLD) pristine YBCO



Chemical Solution Deposition (CSD) – YBCO + 5% $BaZrO_3$

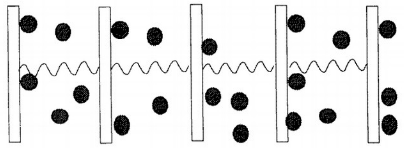


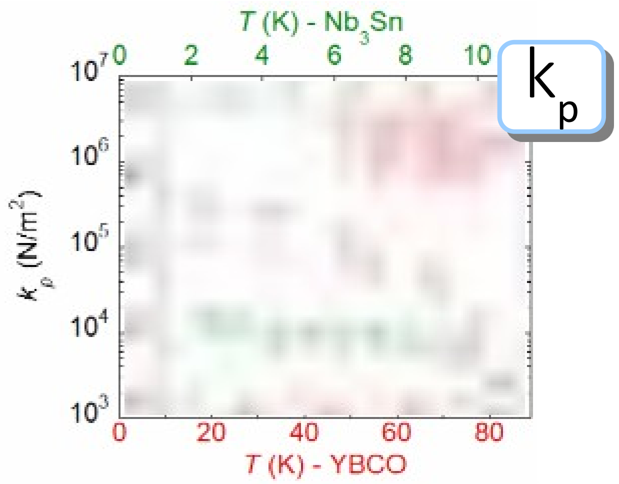
Alimenti et al - paper in preparation

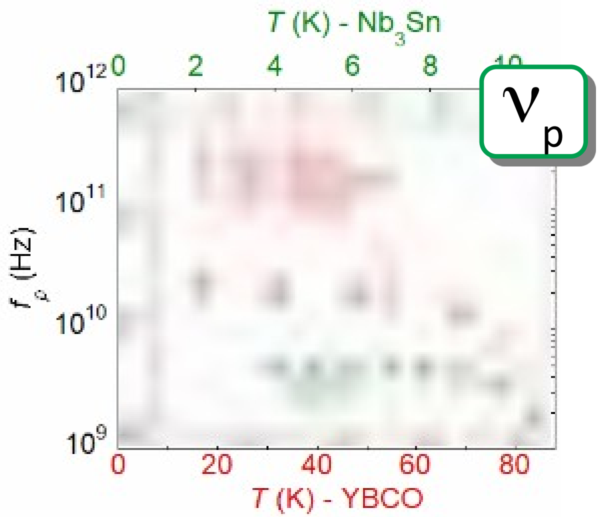


Field independent

Fluxons individually pinned



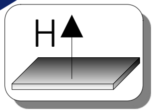




- **Best rf performances for the PLD-YBCO**
- Higher than Nb_3Sn
- Particularly suitable for rf applications – **FCC**

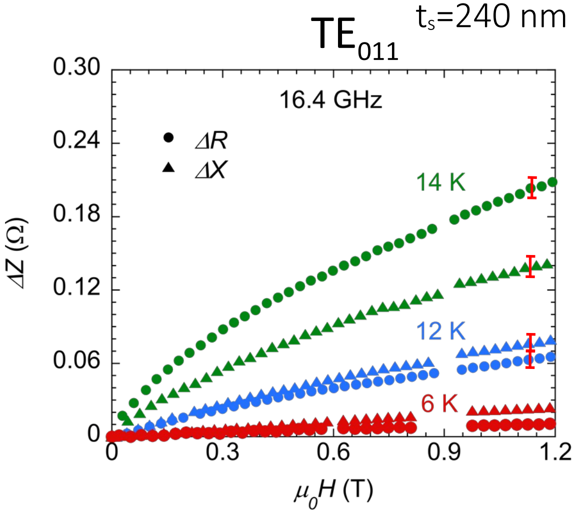
$FeSe_{0.5}Te_{0.5}$ – multifreq.

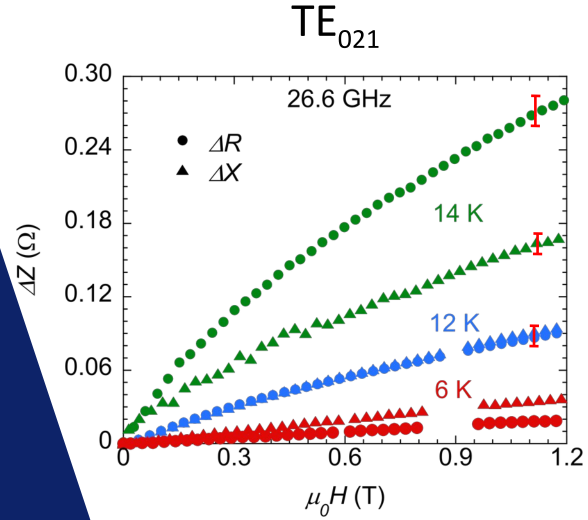
Supported by: PRIN HIBiSCUS
In collaboration with: Università degli Studi di Genova, M. Putti; SPIN, V. Braccini

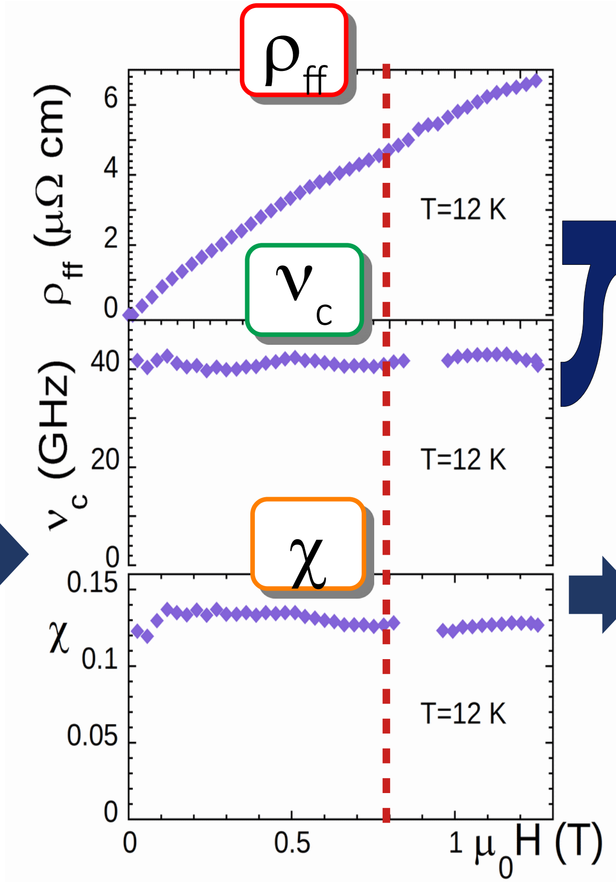


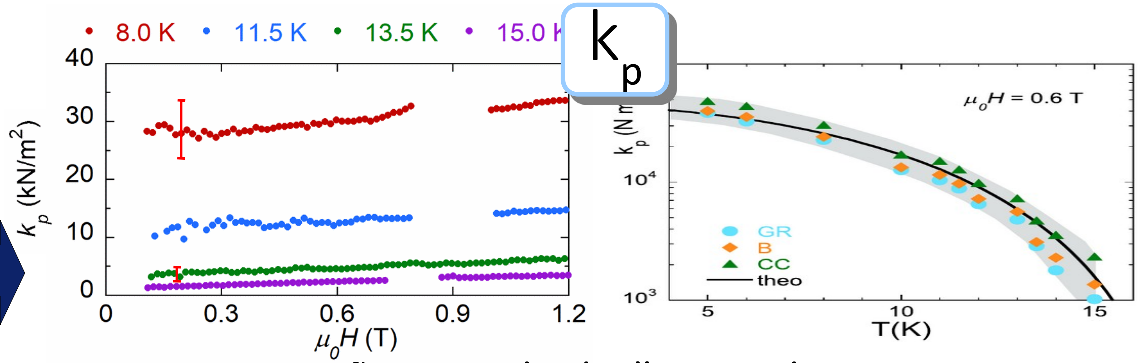
$Z_s = \rho / t_s$ thin film

t_s=240 nm

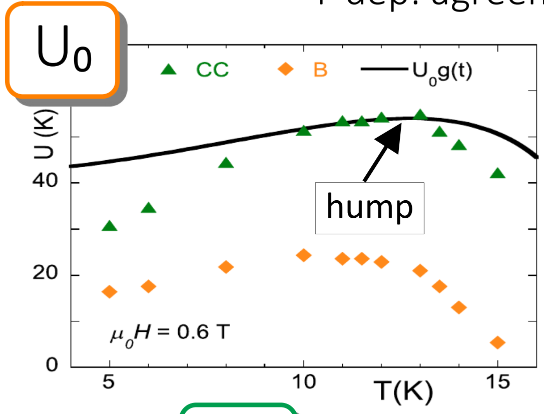




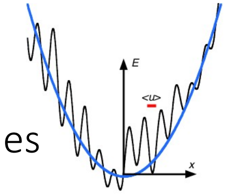


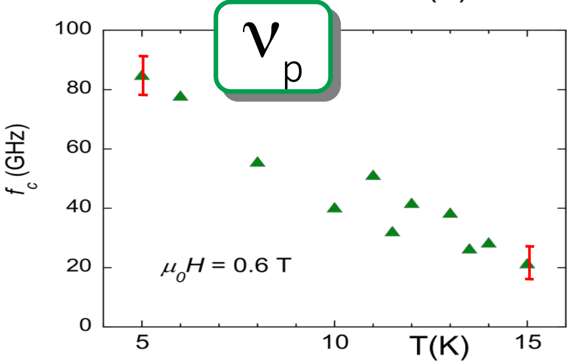


- fluxons **individually pinned**
- T-dep: agreement with theory



- ξ^3 volumes jumping by thermal activation **"point" pins**
- U_0 much smaller wrt other techniques

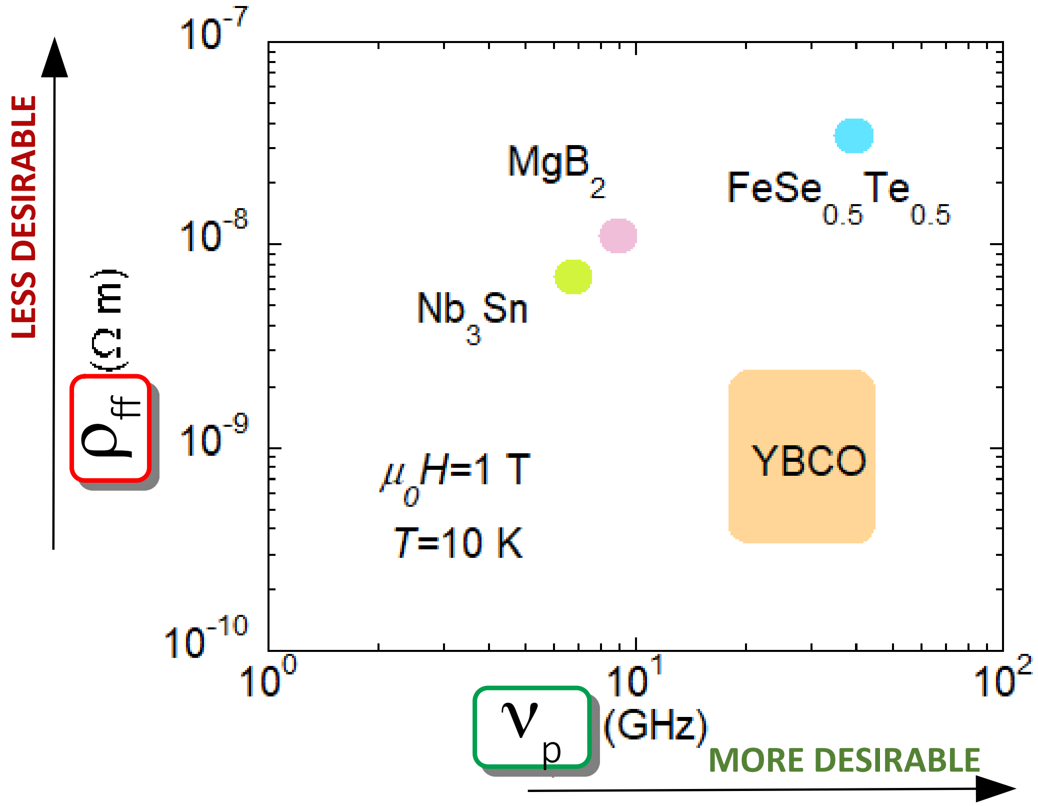


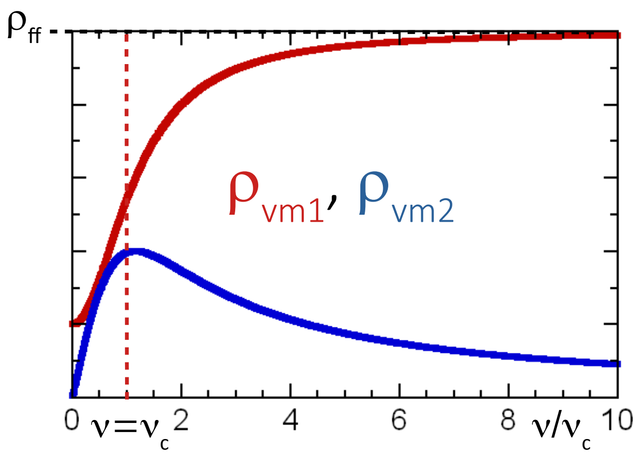


- ν_p(FeSeTe) > ν_p(YBCO) ⇒ **lower losses**?

Pompeo et al SuST 33 114006 (2020)
Pompeo et al IEEE Trans. Appl. Supercond. doi:10.1109/TASC.2021.3063665 (2021)

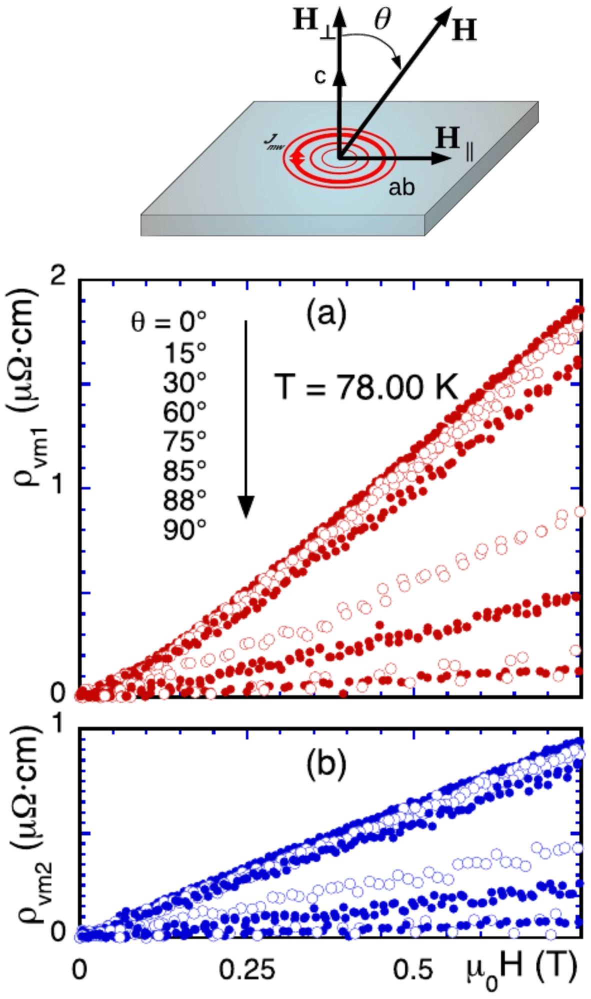
rf vortex motion - physical comparison





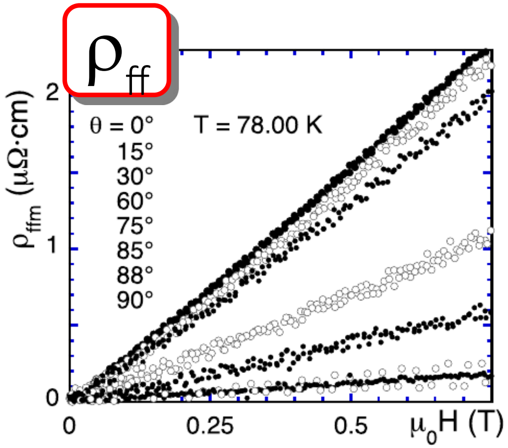
- YBCO: high ν_p, lowest ρ_{ff}
- high ν_p $\not\Rightarrow$ lowest losses

Angle dependent measurements – mass anisotropy

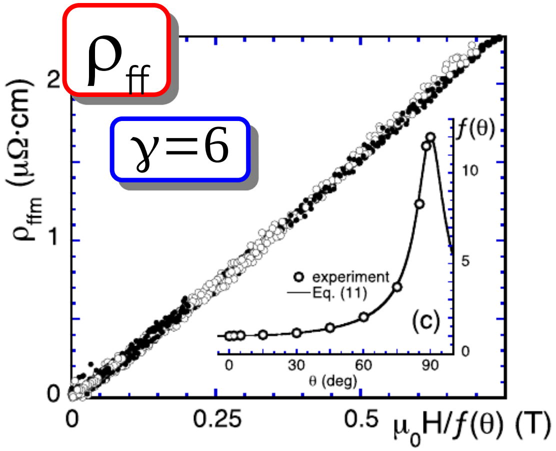


CSD YBCO thin film

Pompeo et al SuST 33 044017 (2020)
Bartolomé et al SuST 33 74006 (2020)
Bartolomé et al PRB 100 054502 (2019)



scaling



$YBa_2Cu_3O_{7-\delta}$

BGL scaling

Blatter, Geshkenbein and Larkin PRL 68 875 (1992)

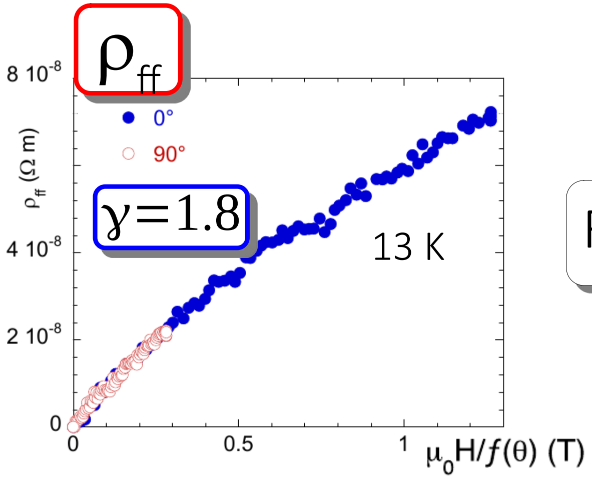
$$\mathcal{Q}(H,\theta) = s_{\mathcal{Q}}(\theta)\mathcal{Q}(H\epsilon(\theta))$$
$$\epsilon(\theta) = (\gamma^{-2}\sin^2\theta + \cos^2\theta)^{1/2}$$

Scaling of measured ρ_{ff}

$$\rho_{ff}(H,\theta) \text{ vs } H/f(\theta)$$
$$f(\theta) = \epsilon(\theta)^{-1} f_L(\theta)^{1/\beta}$$
$$f_L(\theta) = \frac{\gamma^{-2}\sin(\theta)^2 + \cos(\theta)^2}{\frac{\gamma^{-2}}{2}\sin(\theta)^2 + \cos(\theta)^2}$$

angle dependent Lorentz term

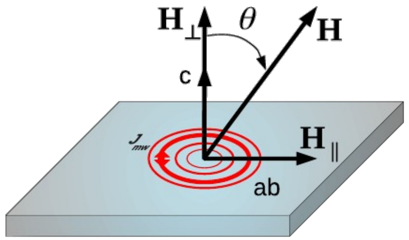
→ γ mass anisotropy (intrinsic)

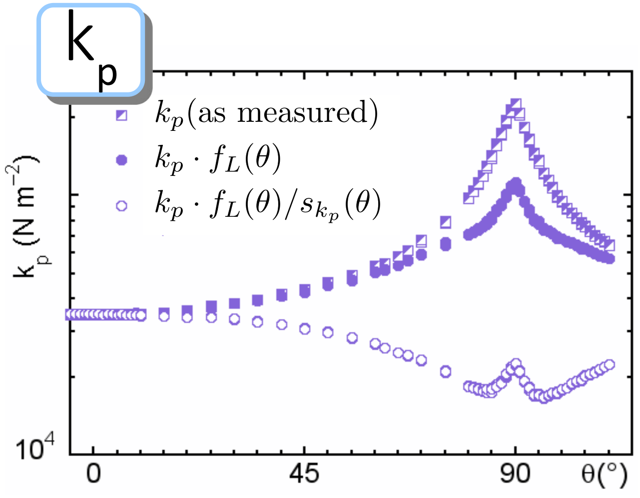


$FeSe_{0.5}Te_{0.5}$

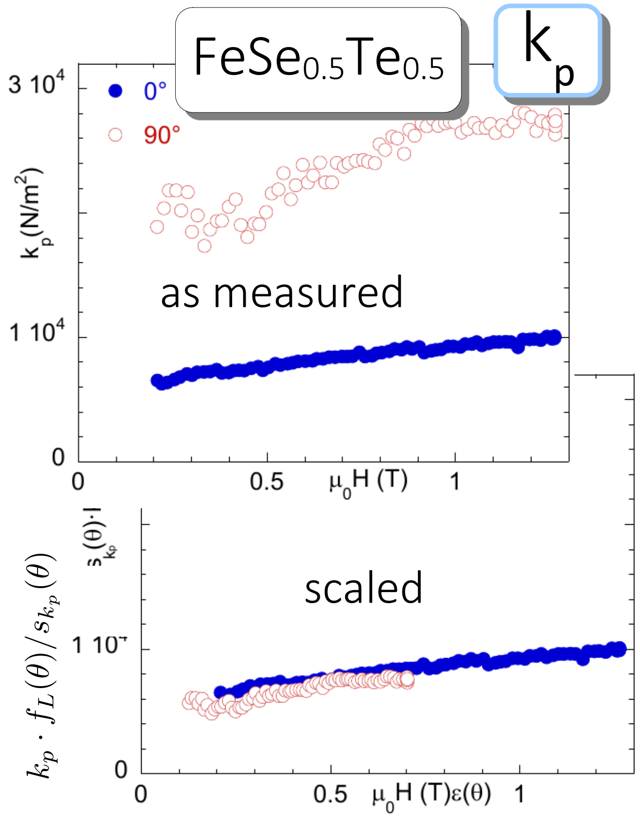
Pompeo et al IEEE Trans. Appl. Supercond. doi:10.1109/TASC.2021.3063665 (2021)

Angle dependent measurements – pinning anisotropy

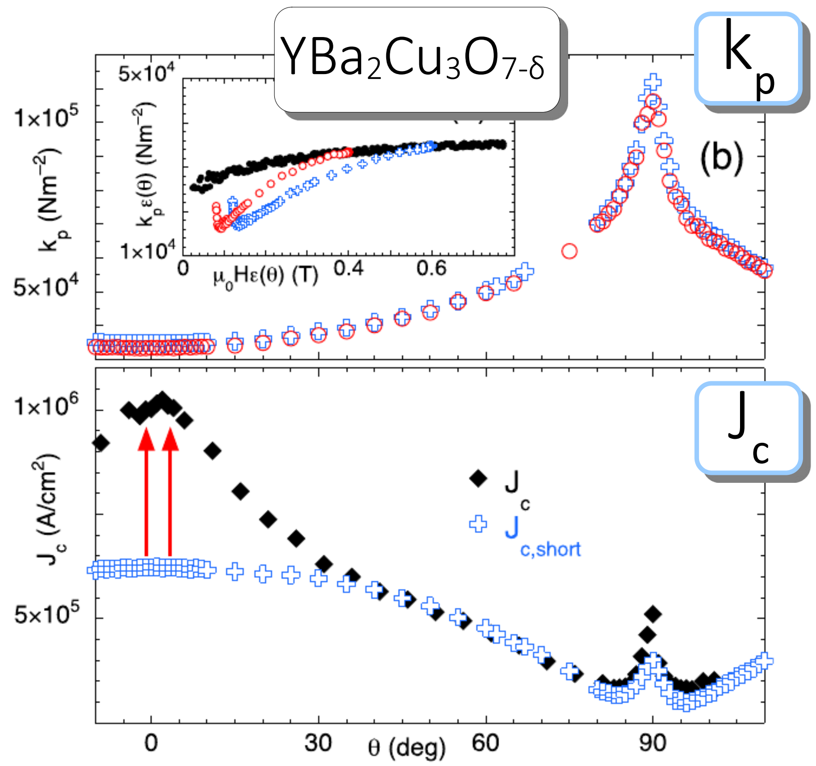




scaled k_p (H,θ) curves superimpose only for isotropic pinning



k_p(H,θ) curves superimpose
→ **isotropic (point) pinning**



1) k_p(H,θ) curves do not superimpose
→ **anisotropic (correlated) pinning**

2) $J_c(\theta)$ vs $J_{c,short}(H,\theta) = c\,\frac{k_p(H,\theta)\xi_{ab}\epsilon(\theta)}{\Phi_0}$
(**d.c. vs rf regimes**):
different time-scales
→ different **dynamical effects**

Pompeo et al IEEE Trans. Appl. Supercond. doi:10.1109/TASC.2021.3063665 (2021)
Pompeo et al APL 103 022603 (2013)

Conclusions

- Surface impedance measurement techniques
  - Multifrequency dielectric resonator: sensitive, measurements vs frequency
  - Corbino disk: wide band, for niche studies
- High frequency vortex dynamics
  - many physical aspects (vortex core/system physics, pinning, anisotropy)
  - relevance of multifrequency measurements for
    - correct determination of all the relevant vortex parameters (ρ_{ff}, ν_c, creep)
    - accurate extrapolation of Z_s at different (lower) frequencies
- The materials
  - Low Tc: Nb_3Sn – improvements on pinning needed
  - Cuprates: $YBa_2Cu_3O_{7-\delta}$ – best performances, candidate for FCC beam screen
  - Iron sc: $FeSe_{0.5}Te_{0.5}$ – high pinning frequency but significant dissipation

Thanks for the attention