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

Measurement techniques

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

Corbino Disk
wide band
1-20 GHz

Input for applications

ITER fusion reactor
Dark matter search
Future Circular Collider Beam screen

Vortex dynamics at rf
Electrodynamics of the Matter Lab

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Outline

- Measurand at microwaves: surface impedance $Z_s$
- High frequency vortex dynamics
- The techniques
  - dielectric resonators
  - Corbino disk
- Selected results:
  - Low Tc: Nb$_3$Sn, Nb
  - MgB$_2$
  - Cuprates: YBa$_2$Cu$_3$O$_{7-\delta}$
  - Iron superconductors: FeSe$_{0.5}$Te$_{0.5}$
- Conclusions
Surface impedance

Measurand at microwaves:

\[ Z_s = \frac{E}{H} = R_s + iX_s \]

Bulk (super)conductor

\[ t_s \gg \max(\lambda, \delta) \]

Thin film on insulating substrate

\[ t_s \ll \min(\lambda, \delta) \]

\[ Z_s = \sqrt{i2\pi\nu\mu_0\rho} \]

Pompeo, Torokhtii, Silva, IEEE I2MTC, doi 10.1109/I2MTC.2017.7969902 (2017)
Superconductor surface impedance

Zero field (Meissner state)

- Two fluid model

\[ \sigma_1 = \frac{n_ne^2\tau}{m} \]

\[ \sigma_{2f} = \sigma_1 - i\sigma_2 \]

\[ \sigma_2 = \frac{n_se^2}{m\omega} = \frac{\omega\mu_0}{\lambda^2} \]

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

- 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 \( \rho_{vm} \)

\[ \rho = \frac{\rho_{vm} + i\frac{1}{\sigma_2}}{1 + i\frac{1}{\sigma_1}} \]

Coffey, Clem PRB 67, 386 (1991)

\[ \Delta \rho(H) = \rho(H) - \rho(0) \approx \rho_{vm}(H) \]

no pair-breaking

\( B \ll B_c \)

\( \sigma_1/\sigma_2 \ll 1 \) (\( T < T_c \))
High frequency vortex motion response

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

$$J_{rf} \times \Phi_0 - \eta \ddot{u} - k_p u + F_{thermal} = m \ddot{u}$$

**Driving force** $J_{rf} \times \Phi_0$ **Very short oscillations** $< 1$ nm

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

**Pinning force**  
**Pinning constant** $k_p$  
$$k_p = \frac{d^2 U}{dx^2}$$  
$U(r)$: pinning energy profile

**Stochastic thermal force**  
**$F_{thermal}$** Thermal activated jumps

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

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

Nicola Pompeo – 18-03-2021 – Jefferson Lab
High frequency vortex motion response

\[ J_{rf} \times \Phi_0 - \eta \dot{u} - k_p u + F_{thermal} = m \ddot{u} \]

\[ E = B \times \dot{u} \Rightarrow \rho_{vm} \]

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

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

characteristic freq. \( \nu_c \)

pinning freq. \( \nu_p \)

\( \nu_c \rightarrow 0 \)

related to pinning

barriers heights \( U_0 \)

\( 0 \leq \chi \leq 1 \)

creep factor \( \chi \)

flux flow resistivity \( \rho_{ff} \)

viscosity \( \eta \)

dissipation

pinning constant \( k_p \)

\( k_p = 2\pi \nu_p \eta \)
High frequency vortex motion response

\[ \mathbf{J}_{rf} \times \Phi_0 - \eta \dot{\mathbf{u}} - k_p \mathbf{u} + \mathbf{F}_{thermal} = m \ddot{\mathbf{u}} \]

\[ \mathbf{E} = \mathbf{B} \times \dot{\mathbf{u}} \Rightarrow \rho_{vm} \]

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2 observables 3 parameters

Multifrequency (rarely performed)

\( \nu_c \rightarrow \) different dissipation regimes

\( (1-\chi)\rho_{ff}/2 \)

\( \chi \rho_{ff} \)
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Cavity as a measurement instrument

geometry for measurements of material properties?

\[ Q, \nu_0 \Rightarrow \rho \]

\[ Q, \nu_0 \Rightarrow E_{rf} \]

9-cell TESLA-type accelerating structure
Cavity as a measurement instrument

Cylindrical cavity

\[ Q, \nu_0 \Rightarrow \rho \]

Resonant mode

\[ Q = \frac{2\pi \nu_0 W}{P_{\text{diss}}} \]

quality factor

\[ \nu_0 \]

resonant frequency

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

- Cylindrical geometry (optimal Q)
- Mode: \( \text{TE}_{011} \)
  - (probing currents: planar \( \rightarrow \) in-plane properties)

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

High sensitivity: dielectric loaded resonator
- focus e.m. field \( \rightarrow \) reduces lateral losses
- reduces overall size \( \rightarrow \) smaller samples
- same enclosure for different rods/operating frequencies

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

Sample

MW sample surface

Spatial configuration (TE, TM, TEM, HEM)

High sensitivity dielectric loaded resonator

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Resonators: measurement of $Q$, $\nu_0$ (basics)

Operation in transmission, resonance curve:

\[
S_{21}(\nu) = \frac{S_{21}(\nu_0)}{1 + 2iQ_l\frac{\nu - \nu_0}{\nu_0}}
\]

$S_{21}$: scattering coefficient (complex, $\nu$-dependent)
$Q_l$: loaded quality factor

Frequency sweep

Coupling ports

Coupling factors $\beta \ll 1$

$\Rightarrow Q_l \rightarrow Q$

Resonators: measurement of $Q$, $\nu_0$ (advanced)

- Non idealities on $S_{21} \rightarrow$ 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 $\nu_0$

Our dielectric resonators - some figures

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

- Sample geometry: flat&parallel surfaces
- Probing area: Ø ≈ 3-10 mm

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

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

8 GHz Single mode
High field

47 GHz Single mode
High frequency

16, 27 GHz Dual frequency

Rutile (TiO_2) rod

Sapphire (Al_2O_3) rod

Pompeo et al., J. Supercond. and Novel Magn. 20 71 (2007)
Multifrequency measurements

- Design criteria
  - well separated $\nu_0$
  - well isolated modes
  - similar $J(r)$
- Modes: $\text{TE}_{011}$ and $\text{TE}_{021}$

**dual frequency operation**

$v_1=16.4$ GHz, $v_2=26.6$ GHz

Pompeo et al, Measurement, submitted 2021
Resonator technique - the measurement process

**Z_s vs H, fixed T**

- Frequency sweeps
- Fit to resonator parameters

\[
|S_{21}|^2 \propto Q^{-1}
\]

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

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

**Z_s vs T, fixed H**

- Z vs T: separate evaluation of resonator background

\[
R_s(T, H) = \frac{G_s}{Q(T, H)} + \text{background}_R(T)
\]

\[
\Delta X_s(T, H) = -2G_s \frac{\Delta \nu_0(T, H)}{\nu_{0,ref}} + \text{background}_X(T)
\]

Various limits:
- film/insulator: \( Z_s \propto \rho \)
- bulk: \( Z_s \propto \sqrt{\rho} \)
- film/metal (CC): \( Z_s(\rho) \)
Corbino disk – microwave spectroscopy

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

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

- $\Gamma_0$: (complex) reflection coefficient
- $\nu$: frequency
- $Z_0$: line characteristic impedance
- $Z_s$: sample impedance

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# Studied materials

<table>
<thead>
<tr>
<th>superconductor</th>
<th>$T_c$ (K)</th>
<th>geometry</th>
<th>applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb$_3$Sn</td>
<td>$\sim 18$</td>
<td>bulk</td>
<td>haloscopes, RF cavities, cables</td>
</tr>
<tr>
<td>YBa$_2$Cu$<em>3$O$</em>{7-\delta}$</td>
<td>$\sim 92$</td>
<td>thin film coated conductor</td>
<td>beam screen coating (FCC), cables for fusion reactors, haloscopes</td>
</tr>
<tr>
<td>FeSe$<em>{0.5}$Te$</em>{0.5}$</td>
<td>$\sim 18$</td>
<td>thin film</td>
<td>development of new coated conductor tapes</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>$\sim 39$</td>
<td>thin film bulk</td>
<td>PIT cables (CERN/fusion reactors), RF cavities</td>
</tr>
<tr>
<td>Tl$_2$Ba$_2$CaCu$<em>2$O$</em>{8+x}$</td>
<td>$\sim 110$</td>
<td>thin film</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>$\sim 9$</td>
<td>thin film</td>
<td>RF cavities</td>
</tr>
</tbody>
</table>
Corbino disk – example measurements (1)

MgB$_2$ thin film

Sarti et al, PRB 72 024542 (2005)
Corbino disk – example measurements (2)

$\rho_{vm1}/\rho_n$

$\rho_{vm2}/\rho_n$

$\chi$

$\nu_p$

$\rho_{ff}$

$\rho_n$ = 22 m$\Omega$ cm

t = 20 nm

$\nu_{ph}$

Creep significantly $\neq$ 0

Field dependent

deviation from simple Bardeen-Stephen B-dep.

$\nu(B)$

Silva et al, SuST 24 024018 (2011)
**Z_s \propto \sqrt{\rho} \quad \text{Bulk limit}**

- **Pinning Constant** \( k_p \) vs. field at different temperatures.
- **Pinning Frequency** \( \nu_p \) vs. temperature at different fields.

**Operating Frequencies**

- Cu-based: \( 9 \times 10^4 \) @ 4.2 K
- NbTi-based: \( 55 \times 10^4 \) @ 4.2 K
- Nb\(_3\)Sn-based: <\( 7.5 \times 10^4 \) @ 4.2 K (computed)

**Pinning Centre**

- Room for advanced material ingegnerization for rf improved pinning

**Consistent with Bardeen-Stephen Model**

- Material "intrinsic" property

**High fields**

- Q @ (1 T, 9 GHz) of axion cavity

**Collective Pinning Regime**
YBa$_2$Cu$_3$O$_{7-\delta}$ – High fields

\[ Z_s = \frac{\rho}{t_s} \text{ thin film} \]

15 GHz

Pulsed Laser Deposition (PLD) pristine YBCO

Chemical Solution Deposition (CSD) – YBCO + 5% BaZrO$_3$

- Best rf performances for the PLD-YBCO
- Higher than Nb$_3$Sn
- Particularly suitable for rf applications – FCC

Supported by: EUfusio

In collaboration with:

G. Celentano
A. Palau

Alimenti et al - paper in preparation
FeSe$_{0.5}$Te$_{0.5}$ – multifreq.

\[ Z_s = \rho / t_s \]

thin film

\[ \rho_{ff} \]

\[ \nu_c \]

\[ \chi \]

\[ U_0 \]

\[ k_p \]

\[ 8.0 \, K \quad 11.5 \, K \quad 13.5 \, K \quad 15.0 \, K \]

\[ \mu_0 H (T) \]

\[ k_p \, (K/m^3) \]

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

\[ \xi^3 \] volumes jumping by thermal activation
- "point" pins
- \( U_0 \) much smaller wrt other techniques

\[ \nu_p(\text{FeSeTe}) > \nu_p(\text{YBCO}) \]

\[ \Rightarrow \text{lower losses?} \]

Supported by:

In collaboration with:

M. Putti
V. Braccini

\[ \mu_0 H = 0.6 \, T \]

\[ \text{Supported by:} \]

PRIN

HIBISCUS

\[ \text{In collaboration with:} \]

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Referências:

Pompeo et al. SuST 33 114006 (2020)
rf vortex motion - physical comparison

- **YBCO**: high $v_p$, lowest $\rho_{ff}$
- high $v_p \neq$ lowest losses
Angle dependent measurements – mass anisotropy

BGL scaling
Blatter, Geshkenbein and Larkin PRL 68 875 (1992)

\[ Q(H, \theta) = s Q(\theta) Q(H \epsilon(\theta)) \]
\[ \epsilon(\theta) = (\gamma^{-2} \sin^2 \theta + \cos^2 \theta)^{-1/2} \]

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

angle dependent Lorentz term

\( \gamma\) mass anisotropy (intrinsic)

CSD YBCO thin film

FeSe\(_{0.5}\)Te\(_{0.5}\)

YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\)
Angle dependent measurements – pinning anisotropy

$k_p(\theta)$ curves superimpose → isotropic (point) pinning

$k_p(\theta)$ curves do not superimpose → anisotropic (correlated) pinning

1) $k_p(H, \theta)$ curves do not superimpose
2) $J_c(\theta)$ vs $J_{c,\text{short}}(H, \theta) = c \frac{k_p(H, \theta) \xi_{ab} \epsilon(\theta)}{\Phi_0}$

(d.c. vs rf regimes): different time-scales → different dynamical effects

FeSe$_{0.5}$Te$_{0.5}$

YBa$_2$Cu$_3$O$_{7-\delta}$
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 ($\rho_{\#}, \nu_c, \text{creep}$)
  - accurate extrapolation of $Z_s$ at different (lower) frequencies

- The materials
  - Low Tc: Nb$_3$Sn – improvements on pinning needed
  - Cuprates: YBa$_2$Cu$_3$O$_{7-\delta}$ – 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