Microwave vortex-dynamics characterization in Nb_3Sn under high magnetic fields

P. Vidal García[1,2], A. Alimenti[1,2], G.V. Eremeev[3], D. Fonnesu[4], D. Ford[4], A. Magalotti[1,2], G. Mota[1], C. Pira[4], S. Posen[3], A. Salmaso[4], E. Silva[1,2], B.M. Tennis[3], K. Torokhtii[1], and N. Pompeo[1,2]

[1] Roma Tre University [2] INFN-Roma Tre [3] Fermilab [4] INFN-LNL

11th International Workshop on Thin Films
and New Ideas for Pushing the Limits of RF Superconductivity

September 17, 2024

Outline

- Motivation
- Theoretical background
- Methods
    - Measurement technique
    - Data elaboration
- Samples
- Results
- Wrap-up

Motivation

- Axion-like particles: *dark matter* candidates
  - Axion field (a) to explain *CP*-violating interactions in $\mathcal{L}_{\mathrm{EM}}$ leads to [1,2]:

$$\varepsilon \nabla \mathbf{E} = \rho - g_{a\gamma\gamma}\, \mu_0^{-1} \mathbf{B}\cdot\nabla a \;;$$

$$\mu_0^{-1}\nabla\times\mathbf{B} = \mathbf{J} + \varepsilon\dot{\mathbf{E}} + g_{a\gamma\gamma}\,\mu_0^{-1}\dot{a}\mathbf{B} - g_{a\gamma\gamma}\nabla a\times\mathbf{E}\;;$$

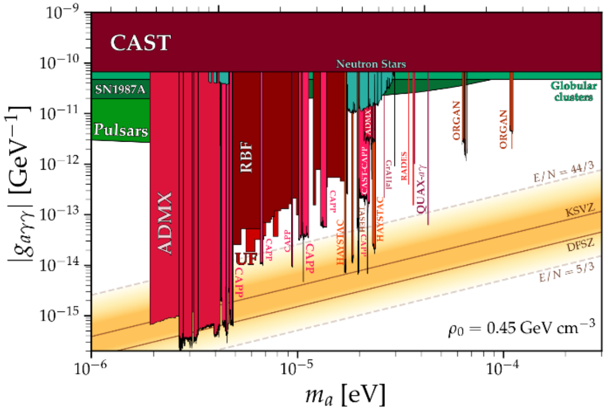
$a \sim a_0 e^{\mathrm{i}\omega_a t}$ is source of e.m. radiation in (high static) $\boldsymbol{B}_0$:

$$[\mathcal{O}(g_{a\gamma\gamma})]\;\nabla\times\boldsymbol{B}_{rf} \sim \mathrm{i}g_{a\gamma\gamma}\omega_a a_0 \boldsymbol{B}_0 e^{\mathrm{i}\omega_a t}\;,$$

where $\hbar\omega_a \approx m_a c^2 + \mathcal{O}(10^{-6})$.

  - In *haloscopes* $\boldsymbol{J}_{rf} /\!/ \boldsymbol{B}_0$ at $\omega_0 \equiv \omega_a$

$\Rightarrow$ probe a (so m_a and $g_{a\gamma\gamma}$) !

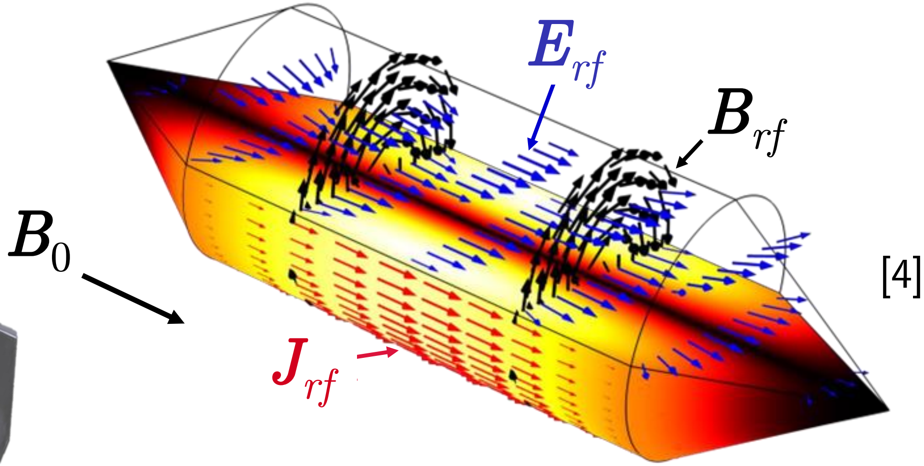


[3]

[1] P. Sikivie, *Phys. Rev. Lett.* **51**, 1415 (1983)
[2] P. Sikivie, *Rev. Mod. Phys.* **93**, 015004 (2021)
[3] https://cajohare.github.io/AxionLimits/

Motivation

- *Haloscopes*: Design and e.m. field



- a «maps onto» E_{rf} of TM-like mode:
  - $V_{\mathrm{eff}} \approx 1/2\left(\int|\boldsymbol{E}|dV\right)^2 U^{-1}$

[4] A. Alimenti *et al.*, *Instruments*, *6*(1), 1 (2022)

Motivation

- *Haloscopes*: Figures of merit and milestones
  - $S_{a\gamma\gamma} = c_\beta \, g^2_{a\gamma\gamma} \omega_0 a_0^2 V_{\rm eff} B_0^2 Q_{\rm eff}$, with $Q_{\rm eff}^{-1} \equiv Q_a^{-1} + Q_L^{-1}$;
  - $\mathbf{SNR} \equiv S_{a\gamma\gamma} \Delta t^{1/2} (k_{\rm B} T)^{-1} \, {\rm b}^{-1/2}$, with ${\rm b} \equiv \omega_0 \min(Q_a^{-1}, \; Q_L^{-1})$;
  - $\boldsymbol{\Delta f / \Delta t} \equiv \omega_0 Q_{\rm a}^{-1} \, {\rm b}^{-1} S^2_{a\gamma\gamma} (\mathrm{SNR} \, k_{\rm B} T)^{-2}$.

$$\boxed{\textbf{Objective}: \uparrow Q_L \gg Q_a \approx 10^6 \;\; @ \max(B_0)}$$

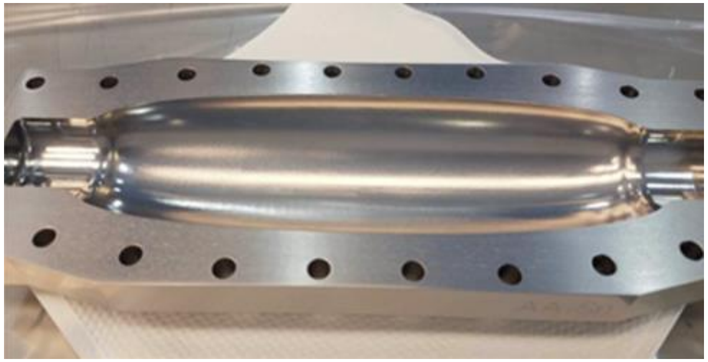
- **Proposal**: use type-II superconducting coatings .

[5] P.W. Graham *et al.*, *Annu. Rev. Nucl. Part. Sci.* **65**, 485–514 (2015)
[6] R. Cervantes *et al.*, *Phys. Rev. D* **110**, 043022 (2024)

Motivation

- *Haloscopes*: Film coatings

SQMS



QUAX-$a\gamma$

- ➢ NbTi-on-Nb $9\,\mathrm{GHz}$ [7]:
  - $Q_0 \approx 3 \cdot 10^5 @ 4\mathrm{K}, 5\mathrm{T}$
- ➢ Nb3Sn-on-Nb $3.9\,\mathrm{GHz}$ [8]:
  - $Q_0 \approx 5.7 \cdot 10^5 @ 4\mathrm{K}, 5\mathrm{T}$
- ➢ **Observation**: Vortex-motion resistivity ultimately limits Q_0.

- **Proposal**: characterize vortex-motion in Nb- samples.

SAMARA

[7] D. Alesini *et al.*, *Phys. Rev. D* **99**, 101101(R) (2019)
[8] S. Posen et al., *Phys. Rev. Applied* **20**, 034004 (2023)

Theoretical background

- Microwave surface impedance Z_s in type-II scs. at high fields :
  - $Z_s \equiv \dfrac{E_{//}}{H_{//}} \simeq \sqrt{\mathrm{i}\omega\mu_0\tilde{\rho}}$ $\qquad \tilde{\rho} \equiv \dfrac{1-\mathrm{i}\sigma_2\tilde{\rho}_{vm}}{\sigma_1-\mathrm{i}\sigma_2} \approx \tilde{\rho}_{vm} + \mathrm{i}\lambda^2\omega\mu_0$

    GLAG : $B \gg B_{c1} \Rightarrow$ local limit ($\kappa_{\mathrm{GL}} \gg 1$)

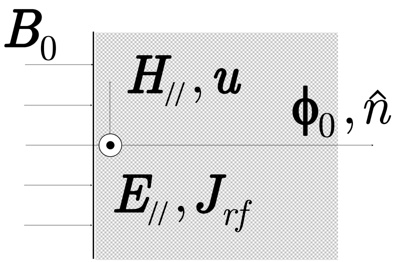
    Vortex-motion in London two-fluid

    $\nu \lesssim 100\,\mathrm{GHz},\ T \ll T_c$: $\sigma_1/\sigma_2 \equiv \sigma_1\lambda^2\omega\mu_0 \ll 1$
  - Coffey-Clem model (CC) of vortex-motion resistivity [9,10] :

$$\boxed{\tilde{\rho}_{vm}(\omega) \equiv \rho_{\mathrm{ff}} \frac{\overset{\text{LTS: } \simeq 0}{\cancel{\chi}} + \mathrm{i}\omega/\omega_c}{1+\mathrm{i}\omega/\omega_c}} \text{ ; s.t. } \tilde{\rho}_{vm} J_{rf} \simeq \dot{u}B_0 \text{ , and}$$

Linearized force balance (p.u.l)

$$\boxed{k_p u + \eta\dot{u} = \underset{\text{LTS: } J_{rf}\,\phi_0 \gg F_{\mathrm{th}}}{\cancel{F_{\mathrm{th}}}} + J_{rf}\,\phi_0} \text{ ; } u \equiv u_0 e^{\mathrm{i}\omega t} \text{ ; } F_{\mathrm{th}} \sim N(0, k_{\mathrm{B}}T)$$



[9] M.W. Coffey and J.R. Clem, *Phys. Rev. Lett.* **67**, 386 (1991)

Theoretical background

- Microwave surface impedance Z_s in type-II scs. at high fields :
  - Z_s in granular superconductors [10,11] :

$$Z_s \equiv \simeq \sqrt{\mathrm{i}\omega\mu_0\tilde{\rho}} \quad ; \quad \tilde{\rho} \equiv \frac{1-\mathrm{i}\sigma_2\tilde{\rho}_{vm}}{\sigma_{\mathrm{GS}}} \; ; \qquad \frac{1}{\sigma_{\mathrm{GS}}} = \frac{1}{\sigma_1-\mathrm{i}\sigma_2} + \frac{\mathrm{i}}{\omega\mu_0\lambda_{\mathrm{J}}^2}\left[\left(1-\frac{\omega^2}{\omega_{\mathrm{pJ}}^2}\right)-\mathrm{i}\omega\tau_{\mathrm{J}})\right]$$

  - Vortex-motion resistivity : CC model as in-series building block :

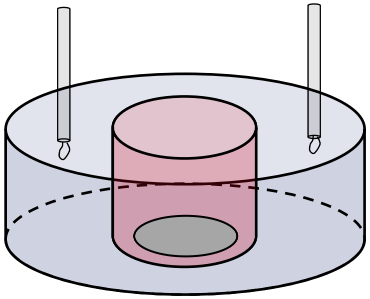
$$\boxed{\tilde{\rho}_{vm} \equiv \tilde{\rho}_{vm,\,\mathrm{A}} + \tilde{\rho}_{vm,\,\mathrm{J}} \cong \rho_{\mathrm{ff,\,A}} \frac{\mathrm{i}\omega/\omega_{c,\mathrm{A}}}{1+\mathrm{i}\omega/\omega_{c,\mathrm{A}}} + \rho_{\mathrm{ff,\,J}} \frac{\mathrm{i}\omega/\omega_{c,\mathrm{J}}}{1+\mathrm{i}\omega/\omega_{c,\mathrm{J}}}}$$

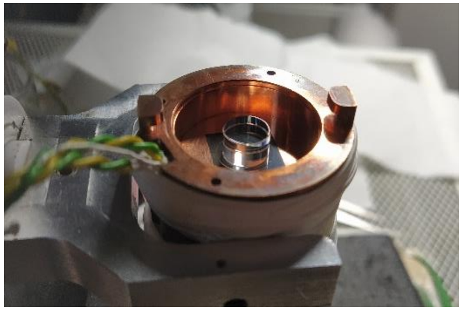
; s.t. $\tilde{\rho}_{vm} J_{rf} \simeq \dot{u}_{\mathrm{A}} n_{\mathrm{A}} \phi_0 + \dot{u}_{\mathrm{J}} n_{\mathrm{J}} \phi_0 \equiv \dot{u} B_0$,

[10] J. Halbritter, *J. Supercond.* **8**, 691–703 (1995)
[11] M. Hein, "High-Temperature-Superconductor Thin Films at Microwave Frequencies", *Springer-Verlag*, Berlin (1999)

Methods: Measurement technique

- Microwave two-port resonator S_{ij}–parameter measurements:
  - Dual-frequency dielectric-loaded resonator:
    - TE modes.
    - Low-loss tangent dielectric.
    - Masked sample.
  - Cryo-magnet ($<12\mathrm{T}$), or rotating electromagnet ($<1.2\mathrm{T}$)
    - $(B_0,\, T)$–sweeps
    - $B_0 \perp$ circ. J_{rf}





Methods: Data elaboration

- S_{ij}

Each mode :

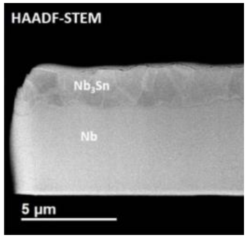
- $Q_0\,,\nu_0$:
  - ➢ $Q_L\,,\nu_0$ from S_{21} «modified Lorentzian» curve fit :
    - Discrepancy cal-uncal [12,13] : $\bar{\varepsilon}_Q \lesssim 2\%$ $\bar{\varepsilon}_\nu \lesssim 6\,\text{ppm}$
  - ➢ $\beta_1\,,\beta_2$ from $S_{11}\,,S_{22}$ Q–circles in the Smith Chart [14] .
- $\Delta Z\,(B_0;T)$:
  - ➢ $\Delta Z(B_0;T) = G_s\,[(\Delta Q_0^{-1})(B_0;T) - \mathrm{i}\,2\nu_{0,\text{ref}}^{-1}\,(\Delta\nu_0)(B_0;T)]$:
    - G_s simulated .
- $\tilde{\rho}_{vm}\,(B_0;T)$:
  - ➢ Thin-film : $\tilde{\rho}_{vm}\,/\,d$
  - ➢ Bulk : $Z_{s,m} \equiv \Delta Z + \mathrm{i}\omega\mu_0\lambda(B_0;T)$

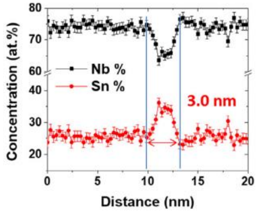
[12] K. Torokhtii *et al.*, *Measurement: Sensors*, **18**, 100314 (2021)
[13] A. Alimenti *et al.*, *Meas. Sci. Technol.* **30** 065601 (2019)
[14] K. Leong et al., *IEEE Trans. Microw. Theory Tech.*, **50**(9) (2002)

Samples

VTD

- Nb_3Sn - on - Nb grown by *Vapor Tin Diffusion* at Fermilab
  - ➢ Substrate : large–RRR Nb rolled sheets ($\simeq 3\,\mathrm{mm}$)
    - $R_\mathrm{a} \approx 40\,\mathrm{nm}$
  - ➢ Coating [15-17] : polycrystalline Nb_3Sn at.%Sn
    - $R_\mathrm{a} \approx 130\,\mathrm{nm},\ d = 2.0 \pm 0.6\,\mu\mathrm{m},\ d_g = 1.4 \pm 0.6\,\mu\mathrm{m}$.
    - Sn - segregation at GBs of $d_\mathrm{gb} \approx 3\,\mathrm{nm}$.





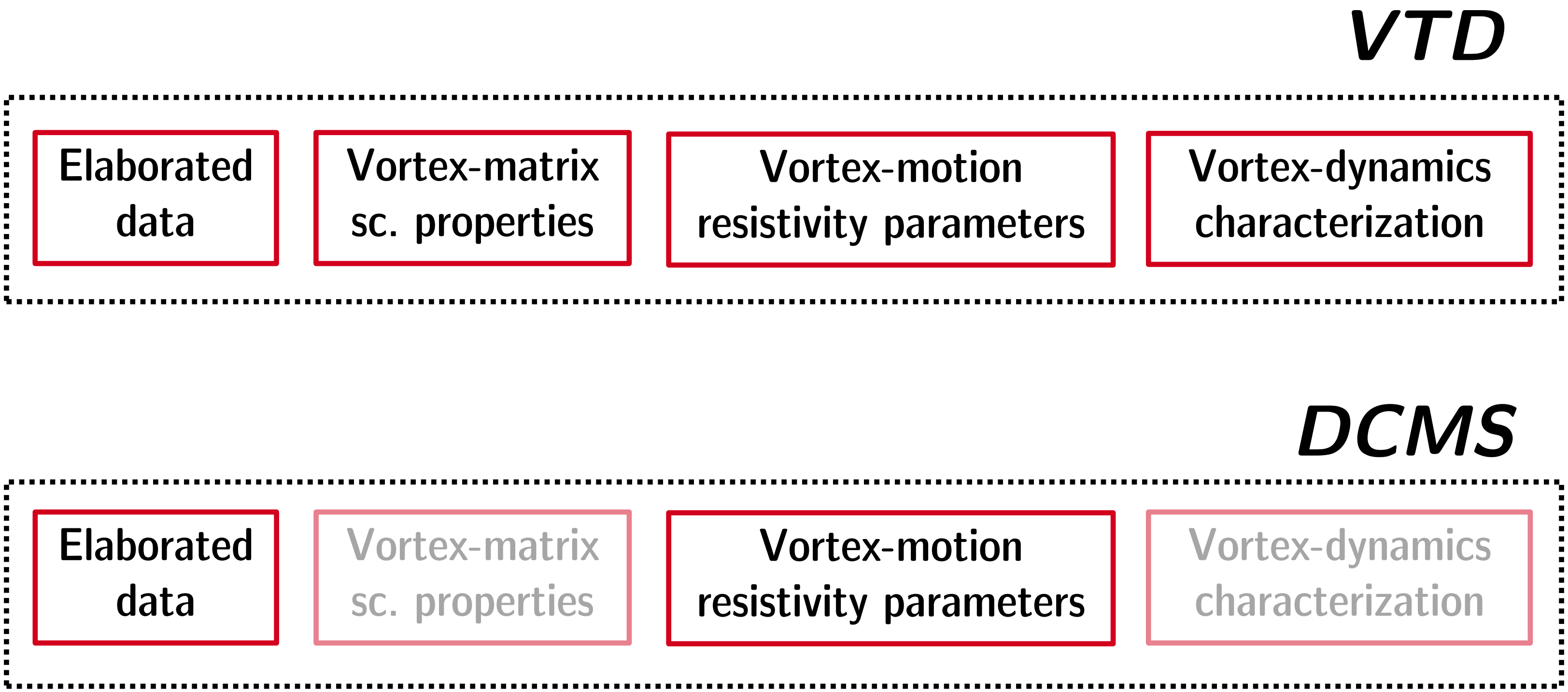
DCMS

- Nb_3Sn - on - $Al_2 0_3$ grown by *DCMS* at INFN-LNL
  - ➢ Substrate : $\simeq 2\,\mathrm{mm}$ sapphire .
  - ➢ Coating [18] : polycrystalline
    - $2 \times$ thin film ($\simeq 250\,\mathrm{nm}$)
    - $1 \times$ bulk ($\simeq 6\,\mu\mathrm{m}$).

[15] S. Posen *et al.*, *Supercond. Sci. Technol.* **34** 025007 (2021)
[16] J. Lee *et al.*, Acta Materialia, **188**, 155–165 (2020)
[17] J. Lee *et al.*, *Supercond. Sci. Technol.* **32**, 024001 (2019)
[18] C. Pira *et al.*, "Progress in European Thin Film Activities", *SRF23'*

Results

- **Samples current results scheme :**



VTD

Elaborated data
Vortex-matrix sc. properties
Vortex-motion resistivity parameters
Vortex-dynamics characterization

DCMS

Elaborated data
Vortex-matrix sc. properties
Vortex-motion resistivity parameters
Vortex-dynamics characterization

Warning

- Keep in mind that :
  - ! $R_s \simeq [1\text{-}100]\ \mathrm{m\Omega}$ (not $\sim \mathrm{n\Omega}$)
  - ! $\boldsymbol{B}_0 \,//\, \hat{n}$ (static; not $\boldsymbol{B}_{pk} \perp \hat{n}$)
  - ! $B_0 \sim \mathrm{T}$ (not $\sim 10\,\mathrm{mT}$)
  - ! $E_{acc} \simeq [10^{-4} - 10^{-2}]\ \mathrm{MVm^{-1}}$ (not $\sim 10\,\mathrm{MVm^{-1}}$)

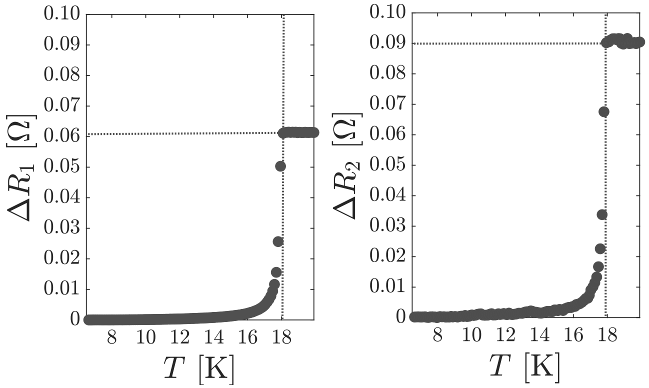
MIND THE GAP

Results

VTD

- **Elaborated data :**
  - ➢ $\nu_{01} \approx 8.504\,\mathrm{GHz}\,,\ \nu_{02} \approx 14.391\,\mathrm{GHz}$
  - ➢ $\Delta R(T) \simeq R(T)$
    - $T_c = 18.02 \pm 0.05$
  - ➢ $\Delta Z(B_0;T)$:
    - $B_{c2}(T^*)$:

$\{T^*\} \equiv$

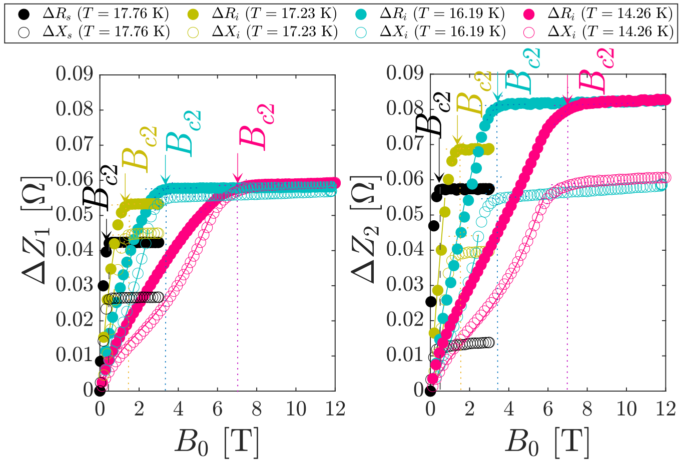


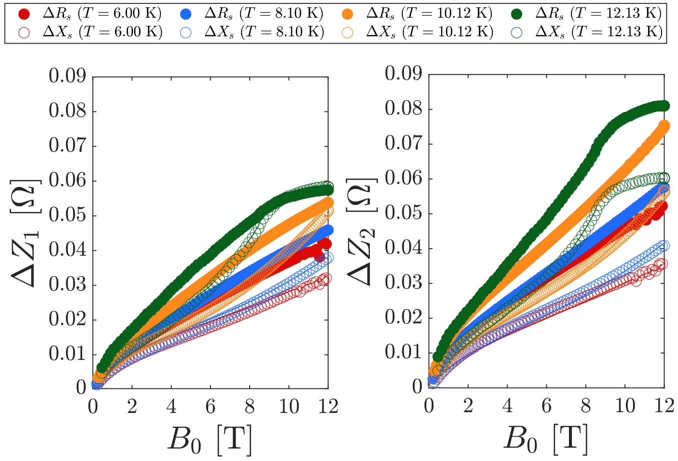
Coated conductor

$\{T^*\}$:
ρ_n , λ, ρ_{qp}
$(d,\ \rho_{n,\mathrm{subs}})$

➢

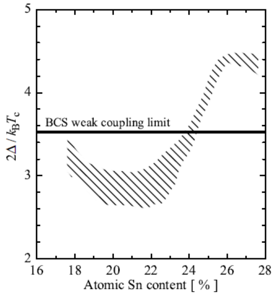
λ(0) [nm]	ρ_n [μΩ cm]	$\rho_{n,\mathrm{subs}}$ [μΩ cm]	d[μm]
246±16	13.2±0.1	0.65±0.08	2.05±0.01



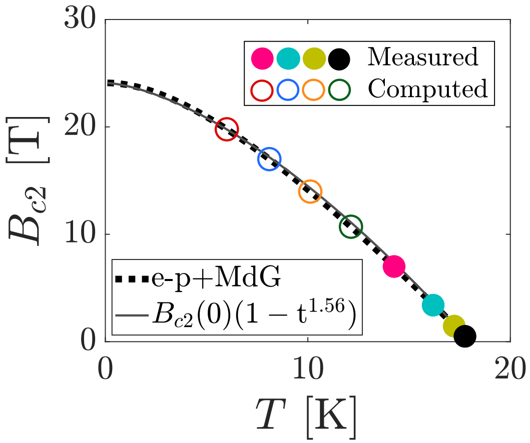


Results *VTD*

- **Vortex-matrix superconducting properties :**



  - T_c , ρ_n of 3:1 stoichiometry ⇔ *strong coupling* sc. Nb_3Sn [19]
  - "Scaled BCS" [20,21]: $X \equiv \eta_X(\widetilde{\Omega}, T_c)\, X^{BCS}(x_n{}^*)$:
    - (Meas. [22]) $\Delta(k_B T_c)^{-1} \approx 2.45 \Rightarrow \widetilde{\Omega} \approx 9.4\,\mathrm{meV} \Rightarrow \lambda_{e\text{-}p} \approx 1.68$;
    - $\eta_{B_{c2}} \approx 1.22$.
  - $\eta_{B_{c2}}^{-1}(dB_{c2}/dT|_{T_c}) \Rightarrow \xi_{GL} \approx 4\ (\sim \xi_0) \gtrsim d_{gb}$ (weak pinning at GBs)
  - Expected $\ell \gtrsim \xi_0$ (relatively "clean").
  - Phase diagram [23-25] :



[19] A. Godeke, *Supercond. Sci. Technol.* **19**, R68 (2006)
[20] T.P. Orlando *et al.*, *Phys. Rev. B* **19**, 4545 (1979)
[21] B.T. Geilikman *et al.*, *J. Low Temp. Phys.* **18**, 241–271 (1975)
[22] S. Posen and M. Liepe, *Phys. Rev. ST Accel. Beams* **17**, 112001 (2014)
[23] K. Maki, Phys. Physique Fizika **1**, 127 (1964)
[24] P.G. de Gennes, *Phys. kondens Materie* **3**, 79–90 (1964)
[25] Y. Li and Y. Gao, *Scientific Reports* **7**, 1133 (2017)

Results

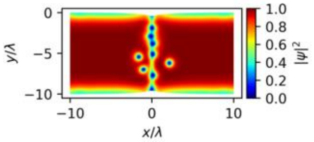
VTD

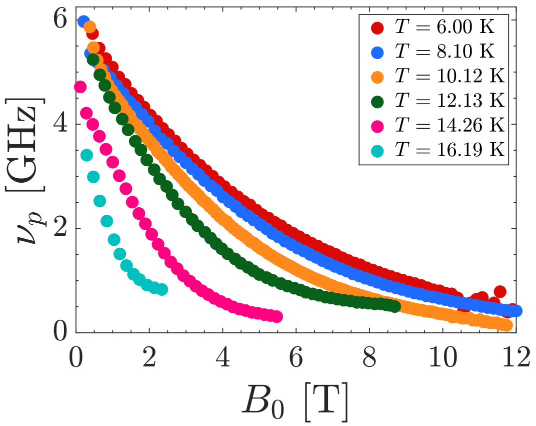
- **Vortex-motion resistivity parameters :**
  - Vortex nucleation and type :
    - Nucleation of vortices at Sn–GBs ;
    - Transf. to grains as *Abrikosov−type* .
    - Then : $\tilde{\rho}_{vm} \cong \tilde{\rho}_{vm,\mathrm{A}}$ (at $B_0 \gg B_{c1}$).
  - *Pinning frequency* :
    - $\nu_2 > \nu_1 \gg \nu_{\mathrm{c}} \cong \nu_p \rightarrow 0 \ (\uparrow B_0/\uparrow T)$

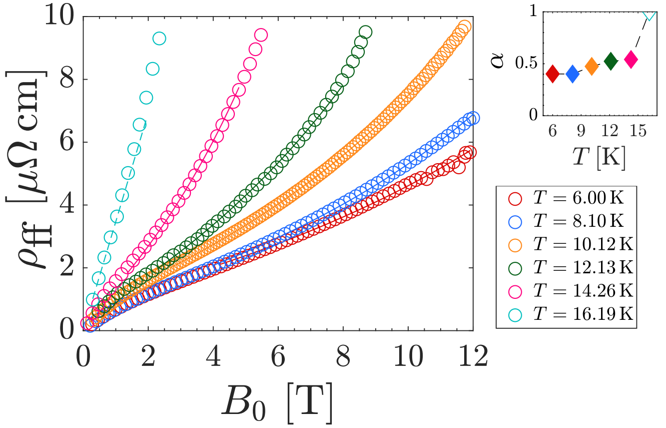
      $\Rightarrow$ flown motion!
  - *Flux-flow resistivity* :
    - $$\rho_{\mathrm{ff}} \simeq \rho_n \frac{\alpha B_0/B_{c2}}{1+(\alpha-1)B_0/B_{c2}},$$

      $\alpha \propto \gamma^{-1}$ in $\boldsymbol{J}_{\mathrm{bflow}} \Rightarrow$ FLL $\dot{u}$ boost [25] .

[26]





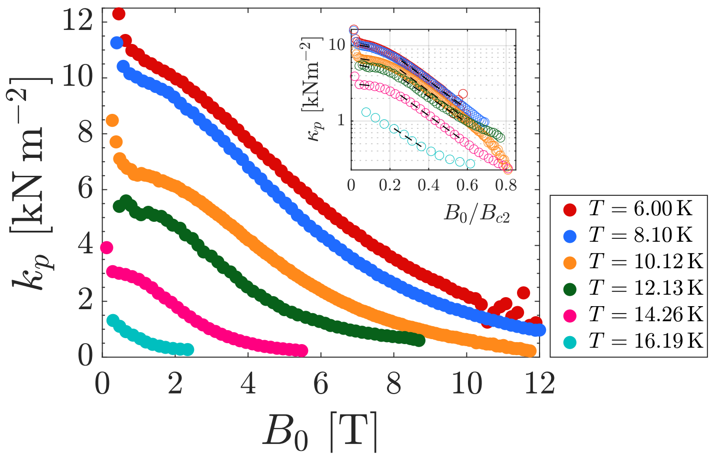


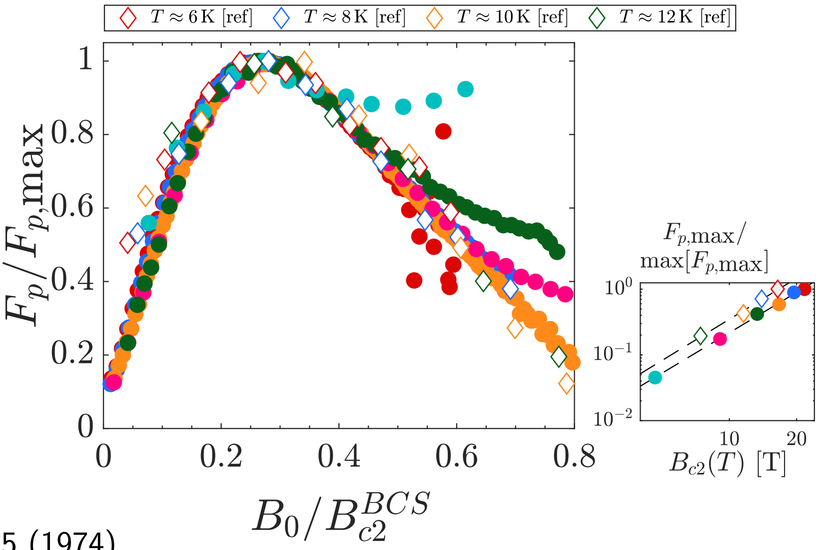
[26] J. Carlson *et al.*, Phys. Rev. B **103**, 024516 (2021)
[27] R.J. Troy and A.T. Dorsey, Phys. Rev. B **47**, 2715 (1993)

Results

VTD

- **Vortex-dynamics characterization :**
  - *Pinning constant* :
    - $F_p \equiv J_c B_0 \simeq k_p \xi_{\mathrm{GL}} B_0 \propto B_{c2}^m \, (B_0/B_{c2})^p \, (1\text{-}B_0/B_{c2})^q$ [28,29]
    - Fit : $m=2, p=1, q=2$: 0D pinpoints (“invisible” GBs: $\xi_{\mathrm{GL}} > d_{\mathrm{gb}}$) .
    - $B_0/B_{c2} \gtrsim 0.1$ FLL moving ~frictionless over those small potential wells .





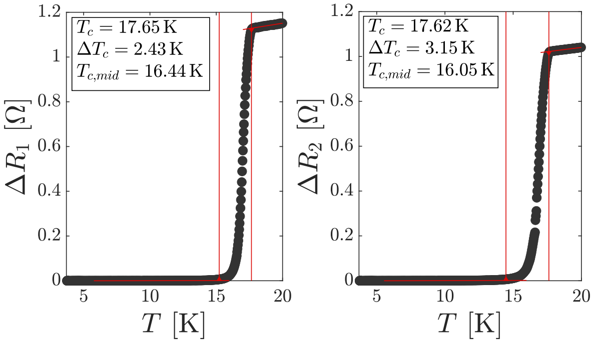
[28] E.J. Kramer, *J. Appl. Phys.* **44**, 1360–1370 (1973)
[29] D. Dew-Hughes, *J, Theor. Experim. and Appl. Phys*, **30**(2), 293–305 (1974)
[30] T.R. Haller and B.C. Belanger, *IEEE Trans. Nucl. Sci.* **18**, 3, 671-673 (1971)

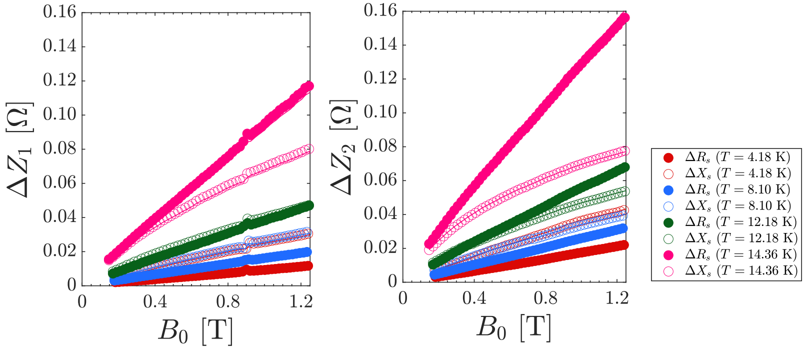
Results

DCMS

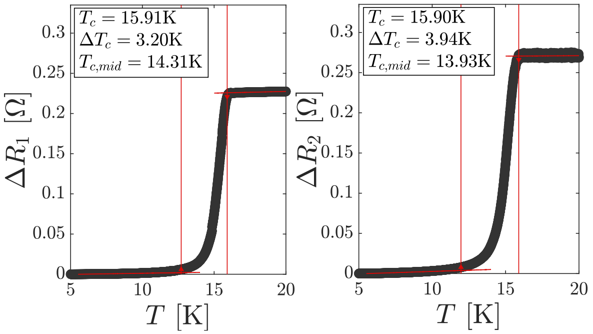
- **Elaborated data :**
  - $\nu_{01} \approx 16.49\,\mathrm{GHz}\ ,\ \nu_{02} \approx 26.69\,\mathrm{GHz}$
    - $\Delta R\,(T)$:
    - $\Delta Z\,(B_0;T)$:

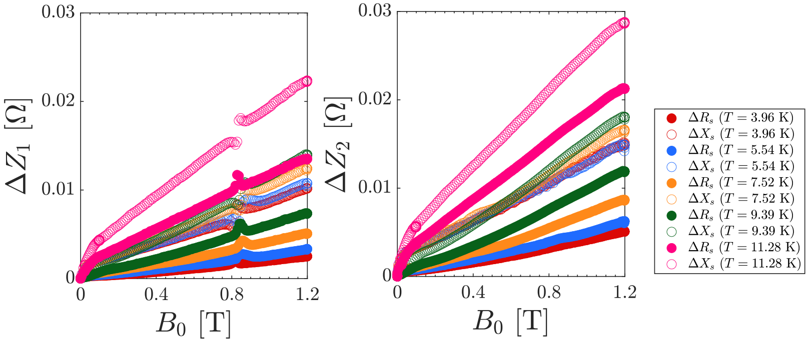
Film





Bulk

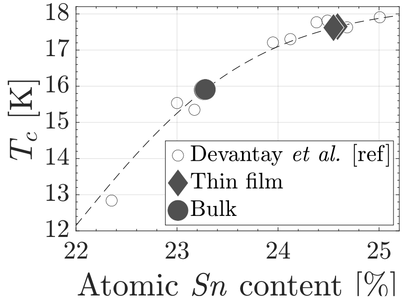


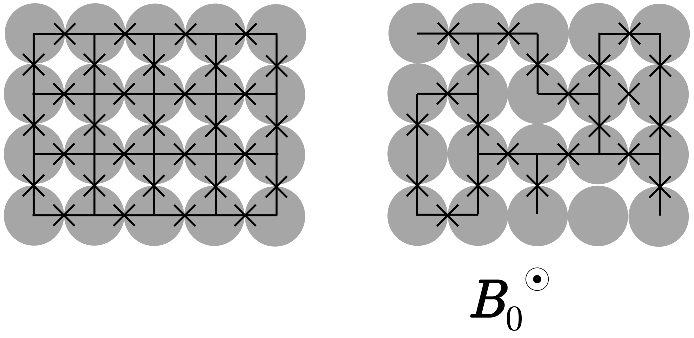


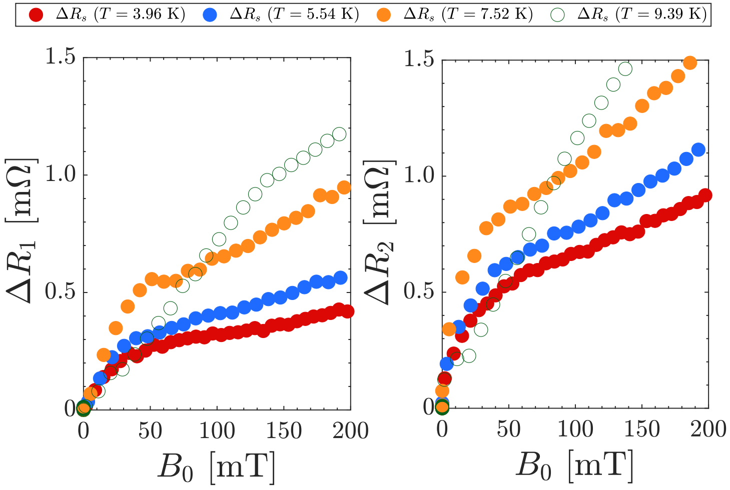
Results

DCMS

- **Vortex-matrix superconducting properties:**
  - T_c out-of-stoichiometry [19]
  - Granular superconductor:
    - Matrix of grains connected through JJs.
    - WLs decoupling $\Rightarrow \Delta R = \Delta R_0 \left[1 - e^{-(B_0 - B_{c1,\mathrm{J}})/B_{0,\mathrm{d}}}\right]$ [31]
    - Long JJs ($d_{\mathrm{gb}} > \lambda_{\mathrm{J}}$) trap *Josephson-type* vortices [10,11]







[31] M. Giura *et al.*, *Phys. Rev. B* **40**, 4437 (1989)

Results

DCMS

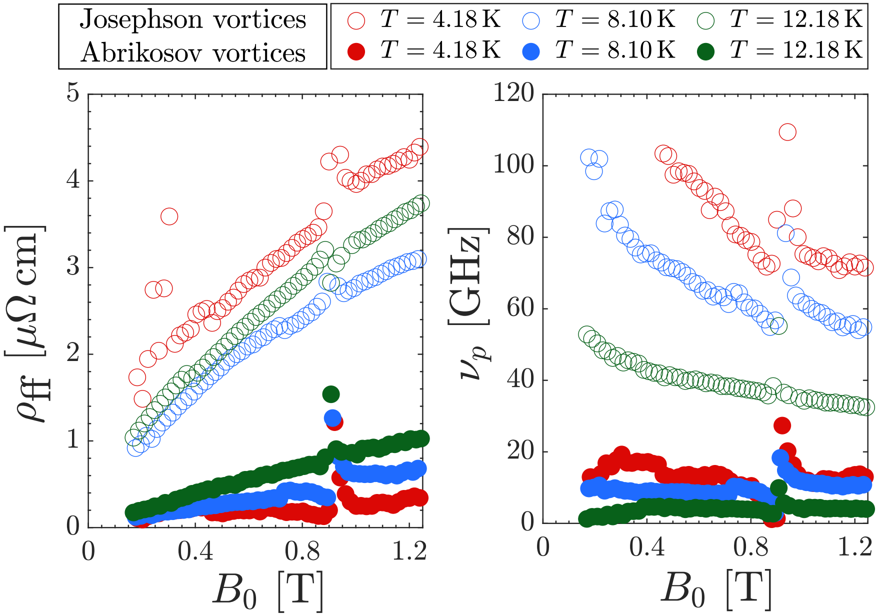
- **Vortex-motion resistivity parameters :**
  - Vortex nucleation-annihilation and types :
    - Complex competing process between different type of vortices !
    - *Abrikosov-type* vortices in the grains ;
    - *Josephson-type* vortices at GBs ;
    - Then (at $B_0 \gg B_{c1} > B_{c1,\mathrm{J}}$) :

$$\tilde{\rho}_{vm} \cong \tilde{\rho}_{vm,\mathrm{A}} + \tilde{\rho}_{vm,\mathrm{J}}$$

  - *Pinning frequency* :
    - $\nu_{p,\mathrm{J}} \gg \nu_{p,\mathrm{A}}$

    Josephson v.: less viscous core.

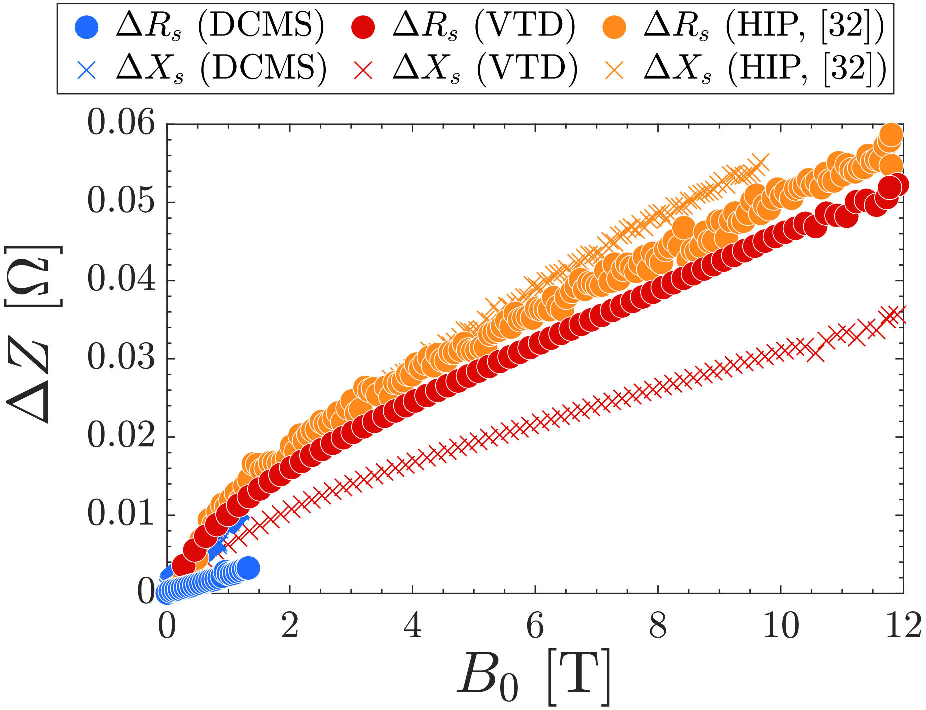
  - *Flux-flow resistivity* :
    - $n_\mathrm{A}/n_\mathrm{J}$?



Results

VTD & DCMS

- **Elaborated data :**
  - All : bulks, $\nu \approx 15\,\mathrm{GHz}$, $T \approx 6\,\mathrm{K}$:



[32] A. Alimenti *et al.*, *Supercond. Sci. Technol.* **34**, 014003 (2021)

Wrap-up

- Beyond acc. cavities, type-II sc. **thin films** meet application in *haloscopes*:
  - Milestone: $Q_L > 10^6$
  - Merit factor: $B_0^2 Q_0$
- Vortex-motion ultimately defines Z_s in sc. **thin films**:
  - Microwave measurements useful in determining vortex-motion resistivity, but
  - renew models, methods, and setups closer to the final appl. are required.
- Nb_3Sn **thin films** are strong candidates to coat *haloscopes*,
  - for which an "optimal coating" could be "not so good" for acc. cavities.
- Strongly-linked JJs hosting less viscous vortices in sc. **thin films**:
  - could be a technological improvement to be implemented but
  - many others (*e.g.*, multilayers, trapping vortices) could also work.

Microwave vortex-dynamics characterization in Nb_3Sn under high magnetic fields

P. Vidal García[1,2], A. Alimenti[1,2], G.V. Eremeev[3], D. Fonnesu[4], D. Ford[4], A. Magalotti[1,2], G. Mota[1], C. Pira[4], S. Posen[3], A. Salmaso[4], E. Silva[1,2], B.M. Tennis[3], K. Torokhtii[1], and N. Pompeo[1,2]

[1] Roma Tre University [2] INFN-Roma Tre [3] Fermilab [4] INFN-LNL

11th International Workshop on Thin Films
and New Ideas for Pushing the Limits of RF Superconductivity

September 17, 2024