Surface Impedance Measurements on Nb₃Sn in High Magnetic Fields

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Abstract—Nb₃Sn is a superconductor of great relevance for perspective RF applications. We present for the first time surface impedance (Zₔ) measurements at 15 GHz and low RF field amplitude on Nb₃Sn in high magnetic fields up to 12 T, with the aim of increasing the knowledge of Nb₃Sn behavior in such conditions. Zₔ is a fundamental material parameter that directly gives useful information about the dissipative and reactive phenomena when the superconductor is subjected to high-frequency excitations. Therefore, we present an analysis of the measured Zₔ with the aim of extracting interesting data about pinning in Nb₃Sn at high frequencies. From Zₔ we extract the vortex motion complex resistivity to obtain the r-parameter and the depinning frequency νᵥ in high magnetic fields. The comparison of the results with the literature shows that the measured νᵥ on bulk Nb₃Sn is several times greater than that of pure Nb. This demonstrates how Nb₃Sn can be a good candidate for RF technological applications, also in high magnetic fields.

Index Terms—High magnetic fields, microwave, Nb₃Sn, depinning frequency, surface impedance.

I. INTRODUCTION

CURRENtly Nb₃Sn is the most interesting technological superconductor both for high performance dc applications like magnets for nuclear fusion or particle accelerators, and for potential radiofrequency applications as resonating cavities [1]–[6].

In applications like superconductive power cables in high magnetic fields, it is well known that vortex motion is the main contribution to the conduction losses. Hence, the experimental study of fluxons behavior, and their pinning, is of great relevance.

At radiofrequency (RF) and microwaves (mw), pinning is still a relevant topic, since vortices are much more free to dissipate. Challenging applications of Nb₃Sn are represented by the RF accelerating cavities for particles accelerators [3], [7]. Nb cavities are currently being used but their technological limits seem to be reached [3], so to overcome their performances it is necessary to consider other superconductors and Nb₃Sn is a potential candidate [8]. Nb₃Sn offers approximately twice the critical temperature T_c and the superheating field H_{sh} with respect to Nb. This yields an improved cryogenic efficiency and perspective higher accelerating fields [3]. However, it must be mentioned that to date, Nb₃Sn cavities show a limit of peak surface magnetic field at ~ 70 mT [3] which is still lower than the highest peak RF magnetic field reached with bulk Nb cavities ~ 209 mT [9].

The improvement of the actual technological limits of this superconductor, in terms of critical current J_c and superheating field H_{sh}, is a mandatory requirement for the development of some of the presented applications. For this reason an in depth study of the RF electrodynamic response of Nb₃Sn when subjected to extreme working conditions is needed.

For RF applications the depinning frequency νᵥ is the most relevant parameter because it marks the boundary between the frequency band where the response of fluxons to harmonic excitation is mainly elastic (ν < νᵥ) and the range where the vortex oscillation becomes purely dissipative (ν > νᵥ) [10]. The higher the νᵥ, the higher the usable working frequencies are with a given SC with reduced dissipation.

Despite the relevance of Nb₃Sn, to our knowledge no high magnetic fields microwave measurements are present in literature on Nb₃Sn. In this work we present the first microwave characterization of Nb₃Sn in high magnetic fields through Zₔ measurements, performed with low RF field amplitude. From the Zₔ analysis, the νᵥ is determined as a function of temperature T. We find that νᵥ attains values much larger than in Nb, thus making Nb₃Sn an attractive material for its RF and mw potential performance in high magnetic fields.

The paper is organized as follows. In Sec.II we briefly recall the main model for Zₔ in a superconductor in the vortex state. In Sec.III we describe the experimental setup and method. In Sec.IV we present the characterization of the sample and the experimental results for Zₔ. Short conclusions are presented in Sec.V.

II. SURFACE IMPEDANCE IN THE MIXED STATE

At high frequencies, the electromagnetic response of a conductor is modelled by the complex surface impedance Zₔ. For bulk good conductors in the local limit and normal incidence electromagnetic waves, the surface impedance [11] is defined as Zₔ = R_s + iX_s = \sqrt{\omega \mu_0 \lambda} = i \omega \mu_0 \lambda, where R_s and X_s are the surface resistance and reactance respectively, ω the angular frequency, μ₀ the vacuum magnetic permeability and \lambda the complex resistivity and \lambda a complex shielding length. The magnetic field H and temperature T dependence of \lambda models the dissipative and reactive phenomena of type–II superconductors: quasiparticle scattering and vortex flow,
as well as the pinning properties. As defined in [12], \( \tilde{\lambda} \) is a function of the complex conductivity \( \sigma_{2f} = \sigma_1 - i\sigma_2 \) and of the vortex motion resistivity \( \rho_{cm} \) [13]. If \( \sigma_1 \ll \sigma_2 \), hence not too close to \( T_c \) and \( H_{c2} \), one finds:

\[
Z_s = i\omega\mu_0 \sqrt{\lambda^2 - i\rho_{cm}/\omega\mu_0},
\]

where \( \lambda \) is the London penetration depth and \( \rho_{cm} \) is the vortex motion complex resistivity. If the applied magnetic field \( H = 0 \) and \( T \to 0 \) K, there are no fluxons in the SC, hence \( \rho_{cm} = 0 \) and \( R_{s,ref} \sim 0 \), \( X_{s,ref} = \omega\mu_0\lambda \).

High–frequency microwave measurements are particularly interesting since at these frequencies the displacements of the fluxons from their equilibrium positions, due to the induced microwave (mw) currents \( (J_{mw}) \), are so small that dynamic mutual interactions of fluxons can be discarded or reduced to an average effect. Thus, \( \rho_{cm} \) can be described by simplified, single–fluxon, local models such as the Gittleman–Rosembloom (GR) model where one writes (having neglected thermal fluctuations) [10], [14]:

\[
\rho_{cm} = \rho_{cm}' + i\rho_{cm}'' = \rho_{ff} \frac{1}{1 - i\nu_P},
\]

with \( \rho_{ff} \) the flux–flow resistivity, and \( \nu_P \) appears explicitly.

Within the GR model the so called \( r \)-parameter, defined as \( r = \rho_{cm}'/\rho_{cm} \), gives immediately \( r = \nu_P/\nu \), and thus \( \nu_P \) is directly obtained.

III. EXPERIMENTAL TECHNIQUE

Dielectric loaded resonators offer high sensitivity for \( Z_s \) measurement [15]. In this technique the dielectric crystal, loaded into the cavity, is used to focus the electromagnetic (e.m.) field near the axis of the resonator, thus limiting the conduction losses. The higher the electrical permittivity of the crystal, the more the physical dimension of the resonator are reduced at the same working frequency, useful to probe small samples.

The sample is loaded into the cavity in order to substitute a base of the resonator (end-wall replacement configuration) [15]. We measure the changes in the quality factor \( Q \) and in the resonating frequency \( \nu_{res} \), with \( T \) or \( H \) due to the change in surface impedance of the superconducting sample. \( Q \) and \( \nu_{res} \) are obtained fitting the complex scattering parameters \( S_{12}(\nu) \) or \( S_{21}(\nu) \). \( S_{11}(\nu) \) and \( S_{22}(\nu) \) are used to evaluate that the coupling factors of the 2–ports \( \beta_1 + \beta_2 = \beta < 0.01 \) [15], firmly in the uncoupled regime, thus the measured quality factor \( Q_L = (1 + \beta)Q \simeq Q \).

\( Q \) and \( \nu_{res} \) yield \( R_s \) and \( X_s \), respectively, by means of the relation:

\[
R_s + i\Delta X_s = \frac{G_s}{Q} - i2G_s \frac{\Delta \nu_{res}}{\nu_{res}} \text{background},
\]

where \( G_s \) is a calculated geometrical factor, \( \Delta \) indicates a variation with respect to a reference value, and \( \text{background} \) indicates the (complex and \( T \)-dependent) contribution given by the resonator itself. A calibration of the resonator with a metallic sample allows to remove the background. Once the background is subtracted, the absolute values of \( Z_s(T, H) \) are obtained making use of the following fixed points: we set \( R_s(H = 0, T \to 0) \sim 0 \) (about this choice, see below for sensitivity comments) and \( R_s = X_s \) above \( T_c \) (real quasiparticle conductivity, Hagen–Rubens limit).

The specific dielectric resonator used here is of Hakkio–Coleman type [16]. The sketch of the resonator is shown in Fig. [1] The entire assembly makes use of several springs in order to avoid issues related to the thermal expansions of the different components. The resonator works in transmission, and it is excited in the TE\(_{011}\) mode at \( \sim 14.9 \) GHz with coaxial cables terminated with magnetic loops. A single–crystal sapphire cylindrical puck, 5.0 mm height and 8.0 mm diameter, loads the OFHC copper. Low dielectric losses \( (\tan \delta < 5 \cdot 10^{-8} \) at 9 GHz below 90 K) and relatively high permittivity \( (\varepsilon_{\parallel} \simeq 11.5, \varepsilon_{\perp} \simeq 9.5) \) [17] allows for negligible field density on the Cu walls. We note that the choice of Cu is dictated by the need to work in magnetic fields: superconducting cavities are ruled out. This constraint is detrimental to the sensitivity at low \( R_s \) values: our setup does not reach the sensitivity needed to assess the residual \( R_s \) at low temperature, but is instead suitable for the high–\( R_s \) regime typical of the vortex motion.

The measurements are performed in helium flow by slowly raising the temperature \( (0.1 \text{ K/min}) \) after Field Cooling (FC) to the lowest temperature (typically 6 K). The field \( H \) is applied perpendicular to the flat face of the sample.

Finally, in our experimental setup, the peak RF magnetic field amplitude parallel to the surface of the sample is assessed to be \( < 20 \) \( \mu \)T. The low RF field amplitude allows a characterization of the surface impedance in the linear regime where the \( Z_s \) does not depend on the power of the applied RF field [18]. It should be noted that the surface impedance in superconductors increases with the RF field amplitude [19] and in Nb\(_3\)Sn this trend is particularly accentuated (e.g. in Nb\(_3\)Sn the vortex dissipation due to the trapped field increases faster than what is observed in clean Nb) [19], [20].

IV. RESULTS AND DISCUSSION

The flat polycrystalline bulk Nb\(_3\)Sn sample, of approximate dimensions 7 mm \( \times \) 5 mm, and 1 mm thick, was obtained by sintering Nb and Sn powder \( (25 \text{ at.}\% \text{Sn}) \) mixture under an Argon pressure of 2 kbar at 1250 \( ^\circ \)C in Hot Isostatic Pressure (HIP) conditions. Through X-ray diffraction methods (Rietveld refinement), the long–range order parameter \( S \) was measured,
showing a state of atomic ordering close to perfect ordering
\((S = 0.98 \pm 0.02)\). [21]

In order to check the consistency of the data on our samples
with the literature, we derived the normal state resistivity from
the Nb–Sn surface resistance \(R_{s,n}\) measured above \(T_c\) (see
Fig. 2): \(\rho_n = 2R_{s,n}^2/\omega_0\mu_0 = 14.8 \mu\Omega\)cm. The measured \(\rho_n\) is
typical of Nb–Sn samples with \(S = 0.97\) and 25 at.%Sn [22],
[23], entirely consistent with our results [21]. The penetration
depth \(\lambda(0) = X_s(H = 0, T \to 0)/\mu_0\omega \sim 100\) nm is evaluated
by extrapolating \(X_s(\mu_0H = 0\) T) at low temperature. The
obtained value is in fair agreement with reported data [24].

The Nb–Sn surface impedance, measured in FC at \(\mu_0H = \{0, 4, 12\}\) T, is shown in Fig. 2. The beginning of
the resistive transitions as a function of \(T\) and \(H\) are highlighted
by the vertical arrows. We found that the behavior of the so-obtained \(H_{c2}(T)\) is perfectly linear, and we estimate the derivative of the upper critical field \(H_{c2}\) near
\(T_c\), \(\mu_0dH_{c2}/dT = 2.03\) T/K. The obtained value is fully
consistent with literature [25].

Fig. 2 reports the set of measurements of \(Z_s(T, H)\). The data
do not present anomalous features. It can be deduced already from the raw data that the depinning frequency is of the same order of magnitude of the measuring frequency. In fact, the increases of \(R_s\) and \(X_s\) with the field are different, although not much. Recalling (1), (2), one see that for both \(\nu < \nu_p\) and \(\nu > \nu_p\), the increase of \(R_s\) and \(Z_s\) should be the same. We then focus on the variations \(\Delta Z_s = Z_s - Z_s(\mu_0H = 0)\) in the temperature range \(T/T_c \lesssim 0.8\), in order to avoid the high-\(T\) region, where thermal effects introduce additional phenomena and then model parameters. We note in passing that working with the differences allows to alleviate the potential issues concerning the sensitivity of the resonant frequency to thermal expansion. We set, consistent with our results, \(\lambda(T) = \lambda_0\sqrt{1 - (T/T_c)^4}\), and then from \(\Delta Z_s\) we isolate \(\Im(\rho_{vm}) = \rho_{vm}^p\) and \(\Re(\rho_{vm}) = \rho_{vm}^r\). The vortex motion complex resistivity is reported in Fig. 3. It is clearly seen that \(\rho_{vm}^p > \rho_{vm}^r\), although the latter is non negligible. It can be also observed that \(\rho_{vm}^r\) shows a tendency to decrease at high \(T\): this is completely reasonable, since at \(T_c\) one has no imaginary part in the resistivity. Accordingly, \(\rho_{vm}^p\) steadily increases with \(T\). We recall that, should it be pure flux-flow (no imaginary part), the well-known Bardeen–Stephen model [26] predicts \(\rho_{vm}^p \propto (T_c - T)^{-1}\), consistent with our data.

From (2) we directly derive \(\nu_p\) from the data in Fig. 3.
The data for \(\nu_p\) are reported in Fig. 4. We immediately note that the values for \(\nu_p\) are quite large, ranging at low \(T\) from \(\sim 6\) GHz at 4 T to 4 GHz at 12 T. These values compare very favourably to Nb. In pure Nb films \(\nu_p\) rises with the decrease of film thickness, up to \(\nu_p \sim 20\) GHz in 10 nm film in 0.2 T perpendicular field, but it sharply falls down to 1 GHz in 160 nm films at 5 K [27]. It can be deduced that \(\nu_p\) in thick Nb films or bulks lays at best at 1 GHz, and more likely, well below. A second relevant aspect is the field resilience exhibited by Nb–Sn: \(\nu_p\) is in the
several GHz range in fields as high as 12 T, so that $\nu_p$ at 12 T in bulk Nb$_3$Sn is almost 5 times that of Nb thin film (thickness 160 nm) below 1 T, demonstrating enhanced Nb$_3$Sn RF behavior with respect to elementary Nb thin films [27]–[29]. Further improvements on Nb$_3$Sn $\nu_p$ are realistically reachable with Nb$_3$Sn thin films, where $\nu_p$ is expected to rise in analogy to Nb, opening interesting possibilities of Nb$_3$Sn applications at microwave frequencies. In order to complete the comparison with other superconductors, we note that a comparable depinning frequency (5 GHz) is exhibited by 13 μm thickness foils of Pb$_{0.83}$In$_{0.17}$ at 1.7 K and 0.5 $H_c2$ [10]. Cuprates are known to have large depinning frequency [30], [31], with high values in YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) single crystal, about $\nu_p \sim 20$ GHz at 45 K [30], [31]. YBCO thin films with BaZrO$_3$ columnar and elongated defects exhibits still enhanced pinning frequencies: $\nu_p \sim 50$ GHz at 70 K [32]. However, it must be mentioned that, at least in Tl$_2$Ba$_2$Ca$_2$CuO$_8+x$, such high $\nu_p$ are anomalously accompanied by a very large dissipation [33].

We make a final note on the possible effects of thermal activation (flux–creep). Should it be present, the effect is to reduce $\rho''_{cm}$ and to increase $\rho'_{cm}$: the more the thermal creep is prominent the more the pinning effect vanishes and $\rho''_{cm} \rightarrow \rho''_{ff}$ [12], [14]. From [2] and measurement frequency $\nu > \nu_p$, it can be shown that this phenomenon is modeled as a first approximation with a lowering of $\nu_p$ in [2] in order to obtain the same creep-induced increase in $\rho'_{cm}$ and reduction of $\rho''_{cm}$. Thus within this model, the obtained $\nu_p$ is at worst an underestimate. For this reason, we can state that our measurements set a lower limit to the Nb$_3$Sn depinning frequency (Fig. 3) without the need for entering any other parameter (i.e. the creep factor). Therefore, this result is robust against the possible presence of flux–creep: the depinning frequency remains rather high in Nb$_3$Sn, much higher than in Nb.

V. Conclusion

We presented the first microwave (≈ 15 GHz) characterization of Nb$_3$Sn in high magnetic fields (up to 12 T). The Nb$_3$Sn surface impedance $Z_s$ was evaluated in the mixed state to obtain information about the dissipative and reactive phenomena of vortex motion. From $Z_s$, elaborations we obtained and showed the vortex motion complex resistivity, a quantity that directly allowed us to obtain the depinning frequency $\nu_p$ of Nb$_3$Sn. The depinning frequency is a parameter of great relevance because it establishes the frequency above which the elastic RF vortex motion becomes purely resistive. Hence, $\nu_p$ is the highest theoretical working frequency for low loss RF applications in high magnetic fields.

The measured $\nu_p$ is almost constant in temperature (up to 0.65 $T_c$) and decreases from 6.0 GHz at 4 T, to 4.5 GHz at 12 T. This result shows that the Nb$_3$Sn exhibits much better RF characteristics than Nb and encourages the use of Nb$_3$Sn in technological RF and mmw applications up to few GHz also in presence of dc magnetic fields.

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