# R.f. field response of metallic superconductors by microstrip resonators

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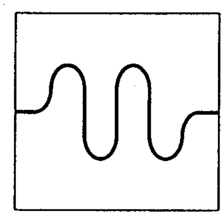
**Abstract.** Annular and meander-line microstrip resonators have been fabricated on sapphire using superconducting films of potential interest for inner coating of accelerating cavities. The r.f. field response of Nb, (Nb-Ti)N, $V_3Si$, and $Nb_3Sn$, produced by magnetron sputtering, has been measured and interpreted in terms of available theoretical models.

## Introduction.

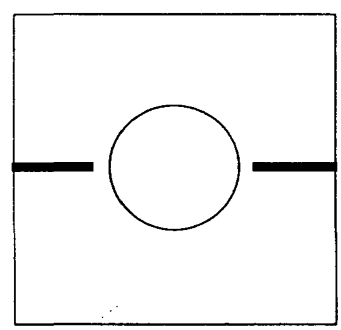
The study of the surface impedance in the superconducting state $Z_S = R_S + jX_S$ ($R_S$ is the surface resistance and $X_S = \mu_0\omega\lambda$ is the surface reactance) can provide important information of superconducting materials in applications such as r.f. and microwave devices.

In high-Q cavities for particle accelerators the study of the r.f. field amplitude dependence of the surface resistance is important to infer how and why their performances deteriorate at high power.

In this context in our laboratory we perform simultaneous measurements of the surface resistance and surface reactance using microstrip resonators of different geometries (meander-line and annular) with a sapphire dielectric layer. Our testing apparatus allows us to study on a small scale (10 x 10 mm$^2$ or 1" x 1" sized samples) the r.f. behavior of innovative materials for accelerating cavities, in order to define the strategies to improve the coating quality [1,2]. A schematical picture of the resonators is shown in Figure 1.



a)



b)

*Figure 1. Geometries used for the superconducting microstrip resonators: a) meander-line; b) annular.*

The signal launchers are capacitively coupled to the device and adjusted in order to measure the resonators in the unloaded regime. The temperature of the system can be varied in a controlled way in the range 1.5-300 K and a uniform d.c. field ($\leq$ 100 Oe) can be applied by means of a pair of Helmoltz coils. The input power can be increased up to 10 dBm, usually corresponding to $H_{r.f.} \approx 100$ Oe. This value would correspond to a peak electric field of about 3 MV/m in a closed resonant cavity .

We measure the variations of the quality factor Q of the resonance curve related to the variation of microwave losses ($\Delta Q^{-1} = \Delta R_S/\Gamma$, where $\Gamma$ is the resonator geometrical factor, ranging between 0.1 and 2 $\Omega$ in our configurations) and the shift of resonance frequency $\Delta\nu_0$ related to the changes of penetration depth $\lambda$ ( $-2\Gamma\Delta\nu/\nu_0 = \mu_0\omega\Delta\lambda = \Delta X_S$) as a function of temperature, frequency, input power, and d.c. magnetic field. $\Delta R_S$ and $\Delta X_S$ and their ratio $r = \Delta R_S/\Delta X_S$, being independent of the particular resonator geometry, can be used to compare results obtained in different experimental contexts and to test theoretical models [3, 4].

## Experimental results and discussion.

Different superconducting metallic such as Nb, (Nb-Ti)N, $V_3Si$, $Nb_3Sn$ films, all produced by magnetron sputtering techniques, have been investigated in our laboratory by the method described above: In all cases the temperature dependence of both $R_S$ and $X_S$ was highly consistent with the BCS theory including the appropriate strong-coupling corrections [1, 2].

In high quality Nb films we did not observe any power dependence of the surface impedance, as predicted for an ideal superconductor in the Meissner state, up to the maximum input power available. On the contrary, in low quality Nb films a relation between $Z_S$ and the values of the applied r.f. magnetic field was observed. Both the surface resistance and the penetration depth change according with a linear law (Figures 2a and 2b):

$$\Delta R_S = \alpha H \qquad \text{and} \qquad \Delta\lambda = \beta H$$

where $\alpha = 0.72$ $\mu\Omega$/Oe and $\beta = 0.04$ nm/Oe at $T = 5$ K and $\nu_0 = 3.5$ GHz.

These field dependences are consistent with a model where the loss mechanisms are related to flux penetration in grain boundaries [4]. This explanation of the observed nonlinearity is supported by the high r value measured ($r \approx 0.65$, see Figure 2c), appearing also field and temperature independent.

The deposition parameters and the results for the r.f. power dependence in (Nb-Ti)N and $V_3Si$ films are reported in refs. 1 and 2. In the first case we observed a very strong r.f. field dependence of both $R_S$ and $X_S$, following a quadratic law possibly related to the highly granular nature of this material. The r value (at $T = 4.2$ K) is about 0.01, consistent with models assuming Josephson coupling between grains [5, 6, 7]. The data on $V_3Si$ show a weaker field dependence of $Z_S$ in respect to (Nb-Ti)N, with $r \approx 0.06$. The data show a quadratic field dependence but, due to some scattering, a linear dependence would also fit the data fairly well.

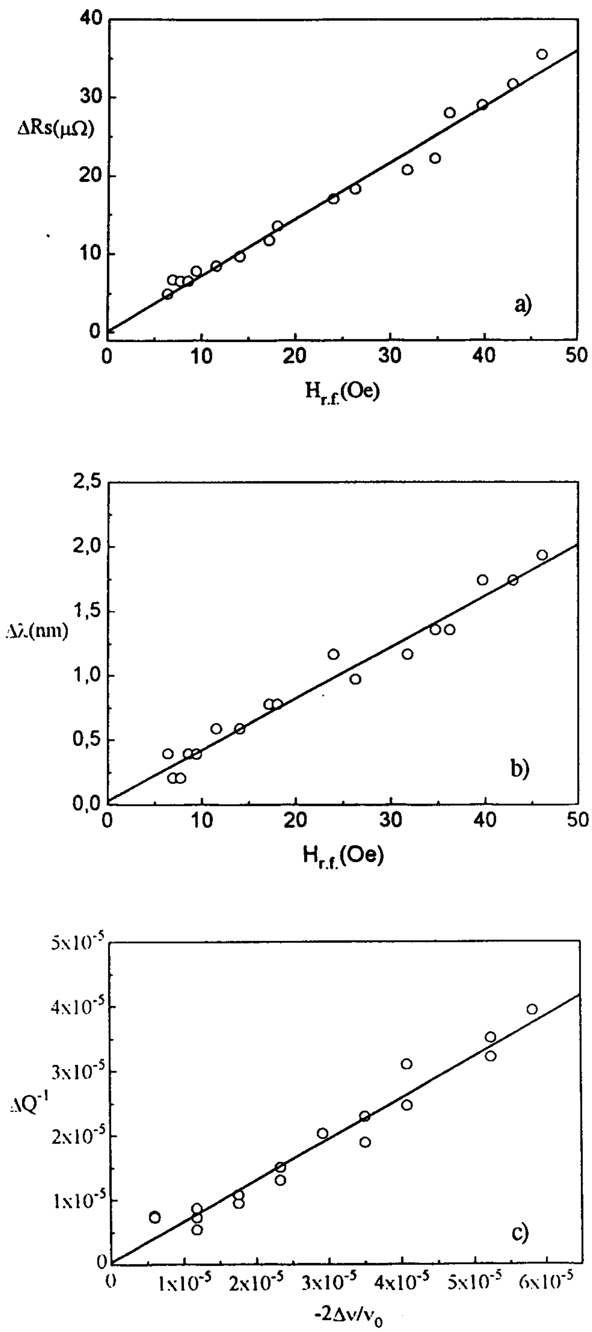



*Figure 2. Non linearity in a Nb film, at T = 5 K and $v_0$ = 3.5 GHz. a) Surface resistance variations ($\Delta R_s = R_s(H) - R_s(H_{min})$) as a function of the applied r.f. magnetic field. b) Penetration depth variations ($\Delta\lambda = \lambda(H) - \lambda(H_{min})$) as a function of the applied r.f. magnetic field. c) $\Delta Q^{-1} = \Delta R_s/\Gamma$ vs $-2\Delta v/v_0 = \Delta X_s/\Gamma$ plot, showing the field independent value of their ratio r (r ≈ 0.55).*

Preliminary data are reported for $Nb_3Sn$ films deposited by a dc magnetron sputtering technique [8] from a stoichiometric target at the nominal substrate temperature T = 720°C and $P_{Ar}$ = 2 Pa. The film thickness ranges between 3000 and 5000 Å.

The samples have been characterized by XPS and X-ray diffraction technique and by transport measurements. XPS analyses give a stoichiometric composition of the samples within a few percent. X-ray data show a well defined A15 structure. The lattice parameter ranges between 5.28 Å and 5.30 Å. The best film has a residual resistivity $\rho_0$ = 56 μ Ω cm and Tc = 17.4 K with a width transition (10% - 90%) ΔTc = 0.5 K.

In Figure 3a and 3b the quality factor Q normalized at $Q_0$ (= $Q(H_{min})$ ) as a function of the r.f. magnetic field for a $Nb_3Sn$ meander-line resonator at T = 4.2 K, $v_0$ = 1.5 GHz and the corresponding $\Delta R_s$ vs $H_{r.f.}$ curve are shown. In the low field region (< 50 Oe) a linear dependence is clearly observed. This result suggests that, similarly to niobium, the physical mechanism responsible for field degradation is flux penetration at the grain boundaries.

The coefficient in the linear behavior ($\Delta R_s = \alpha H$) is 0.07 μΩ/Oe, about one order of magnitude lower than the value observed for low quality Nb. The quality factor degradation is comparable to the value observed for the optimized $V_3Si$ films [2], confirming the appealing potentiality of $Nb_3Sn$ for cavity applications [9].

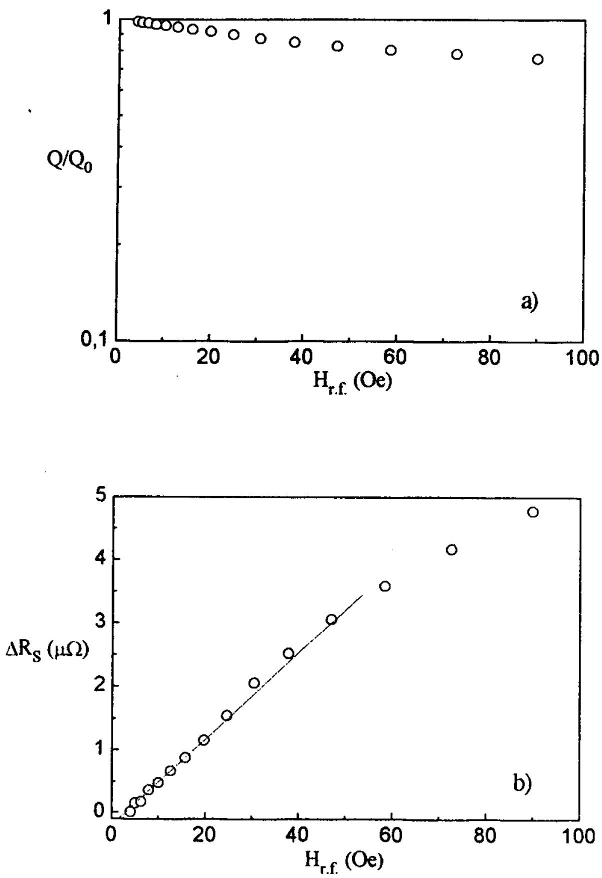



*Figure 3. Preliminary results on a $Nb_3Sn$ resonator, at $T = 4.2$ K and $\nu_0 = 1.5$ GHz. a) $Q/Q_0$ as a function of the applied r.f. magnetic field. b) $\Delta R_s = R_s(H) - R_s(H_{min})$ as a function of the applied r.f. magnetic field.*

In Table I the experimental results for Nb, (Nb-Ti)N, $V_3Si$ and $Nb_3Sn$ films are summarized.

Data for epitaxial $YBa_2Cu_3O_{7-x}$ (YBCO) films, also produced in our laboratory by an inverted cylindrical magnetron sputtering technique and measured by the same method [10], are included for comparison.

*Table I. Comparison of the nonlinear field response for different superconductors. $\alpha$ and $\beta$ are the coefficients respectively in the relations $\Delta R_s = \alpha H^n$ and $\Delta\lambda = \beta H^n$, where n is the power exponent. $r = \alpha/\mu_0\omega\beta$, where $\omega$ is the operating frequency of the resonator.*

| Material | T(K) | α | β | r | n |
|---|---|---|---|---|---|
| Nb | 5 | 0.72 (mW/Oe) | 0.04 (nm/Oe) | 0.65 | 1 |
| $V_3Si$ | 4.2 | 0.0005 (mW/Oe$^2$) | 0.0003 (nm/Oe$^2$) | 0.06 | 2 |
| (Nb-Ti)N | 4.2 | 0.0023 (mW/Oe$^2$) | 0.09 (nm/Oe$^2$) | 0.01 | 2 |
| YBC0 | 7 | 0.15 (mW/Oe$^2$) | 0.52 (nm/Oe$^2$) | 1.14 | 2 |
| $Nb_3Sn$ | 4.2 | 0.07 (mW/Oe) | - | - | 1 |

## Conclusions.

Using microstrip resonators of small dimensions it is possible to extract useful information on the electrodynamics of metallic superconductors in the frequency range of interest for accelerating cavities. In particular, the r.f. field response of both surface resistance and surface reactance can be used as a probe to test the material quality and to identify the dissipation mechanisms responsible for the Q factor degradation.

The results on different low Tc samples show that, for granular superconductors like (Nb-Ti)N and $V_3Si$, the dominant losses are likely due to the field dependence of the Josephson inductance modeling the coupling between grains. In $Nb_3Sn$ and in low quality Nb films, flux penetration at the grain boundaries seems to be responsible for the field dependence observed. High quality

Nb films do not show nonlinearities up to the maximum input power available.

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