Intermodulation Measurements in Electroplated Pb-Sn Superconducting Split-loop Resonators

N. R. Lobanov and D. C. Weisser

Nuclear Physics Department, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200 Australia.

Measurement of the non-linear surface impedance and intermodulation distortion (IMD) was conducted on the Linac split-loop resonators (SLR). IMD measurements allow more sensitive detection of non-linearity as compared to surface impedance measurements. All cavities were electroplated with 96%Pb4%Sn film to the final thickness of 1.5 micron followed by mechanically polishing and then re-plating with a cosmetic layer of 0.3 micron. The cavities plated with this technique display a low level of intrinsic non-linearity at operating temperature of 4.3 K and nominal absorbed RF power up to 6 W. The source of the non-linearity in the resonator structure, such as magnetic flux penetration and Josephson vortex dissipation, can be located by their contribution to the non-linear IMD response above a critical RF power level.

1. Introduction

The current technologies to deposit Nb film onto copper substrate are readily applied to simple RF structures but are not feasible for complex geometries like Split Loop Resonators (SLRs) and are challenging for multistub cavities, 2- and 3-QWR and 2-, 3-HWR [1]. In contrast, Pb-Sn plating provides fast and adequate results with modest equipment and at relatively low cost. ANU used Methyl Sulfonic Acid chemistry to re-plate twelve SLRs, which were electroplated earlier with fluoboric chemistry at Oxford. This change in plating chemistry increased the energy gain by almost 100%. A detailed account of the SLR plating technology at ANU is given in ref [2].

There is renewed interest in elecroplated lead for use in a superconducting electron gun for the injector in free electron lasers [3]. This is because lead is a better electron emitter than niobium, the usually used material in superconducting RF devices.

2. Measurement surface resistance of PbSn coated SLR

The re-plating, using the hand polishing surface treatment and reverse pulse plating technique, has produced resonators with accelerating field of greater than 3.5 MV/m at 6 W during on-line test at 4.3 K. The quality factor, Q, at 6 watts is at or above 10^8 with the best resonator achieving E_{acc} about 3.9 MV/m on-line at 6 Watts.

The change in the surface resistance is given by equation $R_s+jX_s = \Gamma(Q_0^{-1} - 2j(\Delta f_0/f_0))$, where $\Gamma = 25\ \Omega$ is the SLR's geometry factor and Δf_0 is the detuning of the cavity due to variation of surface reactance. In determination of Δf_0, the Lorentz force de-tuning of the SLR should be taken into account. In figure 1 the R_s at 4.3 K as a function of B_p is shown.

R_s was calculated from Q_0-measurement data using the equation $R_s = \Gamma Q_0^{-1}$. R_s rises up to B_p = 4 mT probably due to RF losses in the gasket. It remains constant from B_p = 4 mT up to 35 mT followed by sharp rise due to field emission (FE).

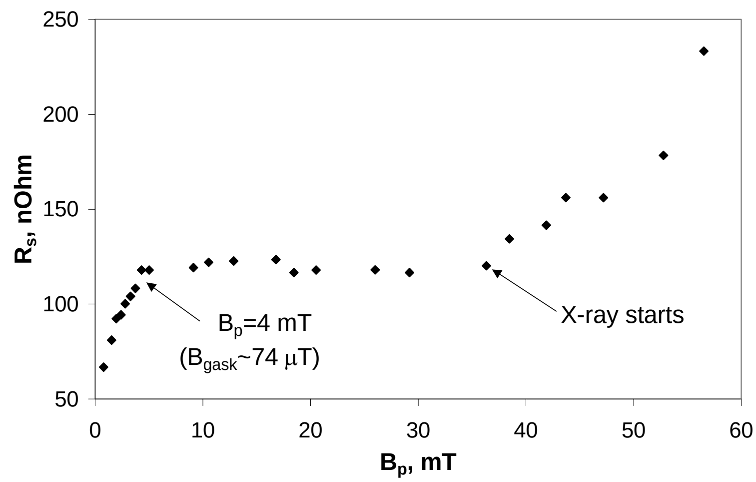

Figure 1. The surface resistance as a function of the applied microwave field at 4.3 K and 150 MHz.

3. Intermodulation distortion (IMD)

To investigate the power dependence of the non-linear microwave properties of the Pb-Sn plated SLR, the measurement of the two-tone intermodulation product as a function of the input power was performed in the same system configuration used for the single-tone experiment. Usually the IMD measurements are performed in a specialized resonator with a small sample inserted. In this work the IMD measurement is done on full-scale superconducting cavity with resonance frequency of 150 MHz.

In figure 2, the surface resistance R_s and the output power of the IMD third-order products as a function of the dissipated P_{diss} in the resonator power are presented at the reduced temperature $t= T/T_c = 0.6$. P_{diss} was calculated from the measured incident power P_{in} and the S-parameters S_{11} and S_{21}, $P_{diss}=P_{in}(1-S_{11}^2-S_{21}^2)$. P_{diss} and P_{in} are expressed in dBm. Dissipated power P_{diss} is proportional to the square of the peak amplitude of the RF field B_p, which is the relevant intrinsic property of superconducting coating. At very small input power the IMP signals are below the spectrum analyzer noise floor and become observable when $P_{IMD3} \geq -66$ dBm. In figure 2, the dashed line illustrates slope 3 and solid line slope 2. The arrows indicate the threshold field $B_{ptr} \sim P^{0.5}_{diss}$ separating domains with different effects causing non-linear response in the Pb-Sn film. The B_{ptr1} and B_{ptr3} have been identified earlier from the surface resistance measurement also shown in figure 1. An operation above B_{ptr3} = 35 mT gives rise of R_s due to FE. B_{ptr1} = 4 mT probably indicates the threshold field where the RF losses in the gasket achieve their maximum value and then saturate. The RF gasket is in a region of low current density where the ratio B_{joint}/B_p does not exceed 2%. The maximum B-field in the RF joint at B_{ptr1} = 4 mT is 80 μT. An oxide layer of Pb_2O_5 is formed on the tuner plates and gasket on exposure to air. Therefore a network of Josephson junctions or weak links may form in the vicinity of the RF joints. Due to the weak links the magnetic field penetrates much more easily than into a homogeneous superconductor. At extremely low magnetic fields, the magnetic flux may penetrate into the bulk in the form of hyper-vortices [4]. The hyper-vortices movement may be responsible for low-field microwave absorption observed in numerous experiments.

As can be seen from figure 2, the frequency transformation beyond threshold field B_{ptr2} is much more dramatic than the change in R_s. IMD represents the most sensitive characterization of the intrinsic non-linear behaviour in superconducting material. At $B_p < B_{ptr2}$ the IMD products scale with respect to input power at 3:1. For B_p larger than B_{ptr2}, a sudden transition from slope 3 to slope 2 occurs. The behaviour above is similar in SLRs plated under identical conditions as described in [2].

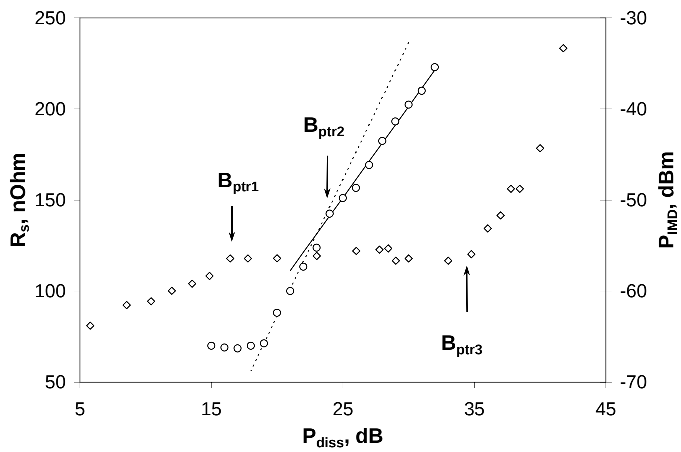

Figure 2. The surface resistance R_s (◇) and the output power of the IMD products P_{IMD3} (○) as a function of the dissipated power at the reduced temperature $t=T/T_c$=0.6. Dashed line illustrates slope 3 and solid line slope 2. The arrows indicate the threshold field $B_p \sim P_{diss}^{0.5}$ separating domains with different nonlinear effects.

Using the harmonic balance algorithm, Mateu *et al* [5] have calculated the power dependence of the IMD products for the power-law nonlinearity in the different forms. These authors have found that the slope 2 of the third-order IMD may correspond to dissipation due to Abrikosov or Josephson vortex [5]. The estimated B_{ptr2} = 9 mT is significantly lower than the B_{c1} = 53 mT value estimated for 96%Pb4%Sn superconducting film. This may be explained by the fact that ANU Pb-Sn coating process involves mechanical hand polishing of the superconducting layer just before deposition of the final cosmetic layer. The mechanical polishing can damage the film and introduce voids and non-superconducting inclusions, the magnetic field can penetrate through the film at much lower field $B_{ptr2} < B_{c1}$.

4. Conclusion

The initial rise in the surface resistance of Pb-Sn films might be caused by low-field microwave absorption due to hyper-vortices movement in the Josephson medium in the vicinity of RF joints.

In low temperature superconducting materials the third-order products must increase with the third power of input main tones. In our case, the IMD slope changes to 2 above transition magnetic field B_{tr2} = 9 mT. This unconventional behaviour in our resonators upon increasing RF power might originate from a hysteresis process dominated by the creation and the irreversible motion and gradual penetration of the Josephson vortices into voids and non-superconducting inclusions introduced by mechanical polishing process.

Acknowledgments

We are grateful to technicians from Nuclear Physics Department J. Heighway, A. Muirhead, A. Cooper and H. Wallace for their important contribution of project.

References

[1] N.R. Lobanov and D.C. Weisser, *Phys. Rev. ST Accel. Beams* **9**, 042002 (2006)

[2] N.R. Lobanov and D.C. Weisser, Accomplishment of Re-plating ANU LINAC, *Proc. 11th Workshop on RF Superconductivity*, Travemunde, Germany 2003

[3] J. Smedley et al, Photoemission Properties of Lead, *Proc. European Particle Accelerators Conference*, EPAC2004, 1126 (2004)

[4] E.B. Sonin and A.K. Taganrtsev, *Supercond. Sci. Technol.* **4** 119 (1991).

[5] J. Mateu, C. Collado, O. Menendez and J. O'Callaghan, *Appl. Phys. Lett.* **82,** 97 (2003).