RRR EFFECT ON THE FLUX TRAPPING OF NIOBIUM SC CAVITIES

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Abstract

We sometimes observe flux trapping phenomena in cold test of niobium superconduction RF cavities. Especially, it is a serious problem with Nb/Cu clad cavities. In this paper, RRR effect on this problem is considered from the theoretical point of view and investigated experimentally.

ADDITIONAL SURFACE RESISTANCE DUE TO FLUX TRAPPING

Cooling down a superconducting (sc) RF cavity in a DC external magnetic field, flux trapping happens below the transition temperature (T_C) as shown in Fig.1 [1]. If the superconducting material is ideal, external magnetic fields less than H_{C1}(the lower critical magnetic field) must be excelled perfectly due to the Meissner effect however, current niobium material used for sc RF cavities usually have imperfections like impurities, lattice defects, other inhomogeneities, and so on. In such a case, external magnetic fluxes are trapped on such pin-centres and produces normal conducting cores. For the frequency range > 100MHz, only the normal cores are responsible for additional surface resistance in RF cavities even in a case Hext < H_{C1}. The surface resistance due to the flux trapping is calculated as following [2]:

$$R_s(H_{ext}) = R_n \cdot \frac{H_{ext}}{H_{c2}(T)} \quad (1),$$

where, H_{c2} is the higher critical magnetic field, H_{ext} an applied magnetic field, and Rn a surface resistance of the material in the normal conducting state, which is calculated as:

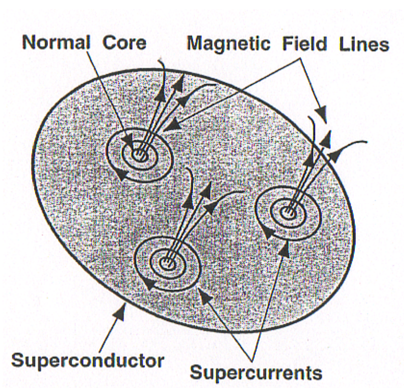

Figure 1: Flux trapping at imperfection in a superconducting material (copied from the ref.[1]).

$$R_n = \sqrt{\frac{\mu\omega}{2\sigma}} \quad (2)$$

where μ is the magnetic permeability of the material, ω angular frequency of the microwave and σ electric conductivity of the normal conducting state. As the flux trapping happens at T_C, σ is the value at T_C. Using the σ, at room temperature (300K), Eq.(1) is rewritten by RRR and σ(300K) [3]:

$$R_s(H_{ext}) = \sqrt{\frac{\mu\omega}{RRR \cdot \sigma(300K)}} \cdot \frac{H_{ext}}{H_{c2}} = R_n(300K) \cdot \frac{H_{ext}}{\sqrt{RRR} \cdot H_{c2}} \quad (3)$$

here, the RRR is defined as:

$$RRR \equiv \frac{\sigma(T \cong T_c)}{\sigma(300K)} \quad (4).$$

RRR strongly depends on the amount of impurities in the niobium material, while the electric conductivity at the room temperature is insensitive to the impurities because electron scattering dominates. H_{c2} also depends on the RRR and temperature, however the temperature is fixed that of the cold measurement. Generally saying, H_{c2} becomes higher with decreased RRR value. Thus the constant term in Eq.(1) depends on only RRR at the fixed temperature. Here, a question happens how H_{C2} depends on RRR.

RRR DEPENDECE OF H_{C2}

We measured the RRR dependence of H_{c2} with niobium material. The result is presented in Fig.2. It was done for niobium materials with RRR=54, 246 and 398 from Tokyo Denkai. Usually KEK makes high gradient measurement of sc cavities at 1.5K. We fix the

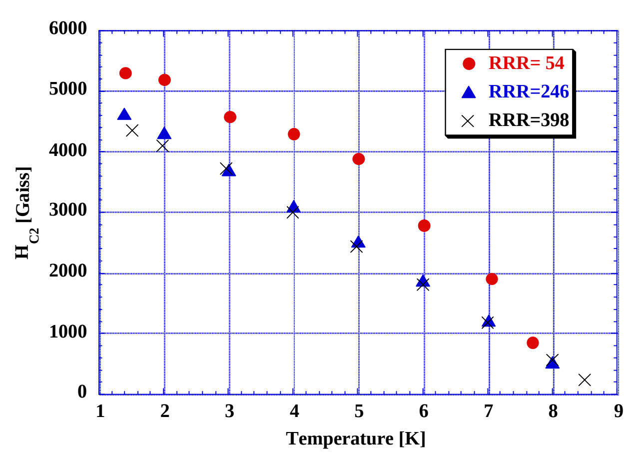

Figure 2: RRR dependence of H_{C2} on niobium.

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temperature at 1.5K to see the RRR dependence on H_{C2}. Fig3 shows the RRR dependence of H_{C2} at 1.5K. It is well fitted as a function of RRR:

$$\begin{aligned} \boldsymbol{H_{c2}(1.5K)} &= \boldsymbol{H_{c2}(RRR)} \\ &= 7089.7 - 1072.3\,\mathbf{log}(\boldsymbol{RRR}) \end{aligned} \quad (5).$$

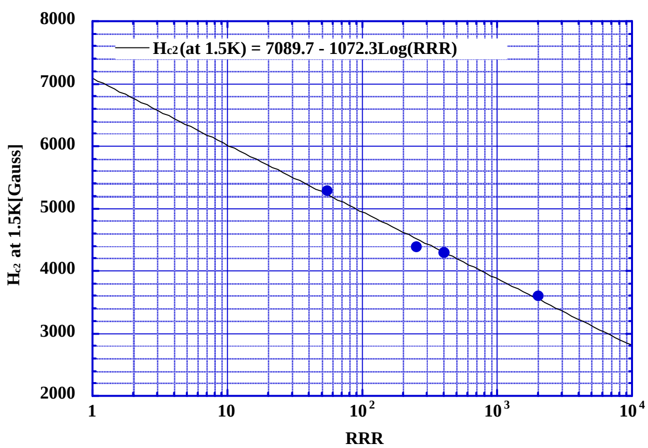

Figure 3: RRR dependence on $H_{C2}(1.5K)$ with niobium bulk material.

RRR DEPENDENCE OF FLUX TRAPPING

Putting Eq.(5) into Eq.(3), one has the following formula:

$$\boldsymbol{R_s(Hext)} = \frac{\boldsymbol{R_n}(300\boldsymbol{K})}{\sqrt{\boldsymbol{RRR}} \cdot [7089.7 - 1072.3\,\mathbf{log}(\boldsymbol{RRR})]} \cdot \boldsymbol{H_{ext}} \quad (6)$$
$$= \boldsymbol{R_o(RRR)} \cdot \boldsymbol{Hext}$$

here R_O depends on only RRR value. For niobium, $R_n(300K)$ is 2.53E-2 Ω at 1300MHz. Using the number, $R_O(RRR)$ is calculated in Fig.3. R_O is fitted as the function of RRR by a much simple experimental formula:

$$\boldsymbol{R_o(RRR)} = 3.15 \cdot \boldsymbol{RRR}^{-0.394} \quad (7).$$

For 1300MHz sc niobium cavity, thus the additional surface resistance due to flux trapping is calculated as:

$$\boldsymbol{R_s(H_{ext})[n\Omega]} = 3.15 \cdot \boldsymbol{RRR}^{-0.394} \cdot \boldsymbol{H_{ext}\,[mGauss]} \quad (8).$$

COMPARISON WITH EXPERIMENTAL RESULTS

We measured the surface resistance due to the external magnetic field for 1300 MHz niobium cavities with RRR=100 and 400 [4, 5]. In those measurements external magnetic fields were applied in parallel with cavity beam axis. The results were:

$$\boldsymbol{R_s(n\Omega)} = 10.8 + 0.56 \cdot \boldsymbol{H_{ext}}\,[\text{mGauss}] \quad \text{for RRR=100},$$
$$\boldsymbol{R_s(n\Omega)} = 3.3 + 0.43 \cdot \boldsymbol{H_{ext}}\,[\text{mGauss}] \quad \text{for RRR=400}.$$

Similar measurements have been done at CEBAF [3] or Saclay [6] for 1500MHz niobium cavities. CEBAF result was R_O=0.25nΩ/mG with RRR ≧ 500 and Saclay 0.35nΩ/mG with RRR=180. When these results are scaled for 1300MHz by $\omega^{1/2}$ dependence of R_n, the results are 0.23nΩ/mG and 0.33nΩ/mG. These results are also plotted in Fig.4. Experimental formula (9) can reasonably fit all the data.

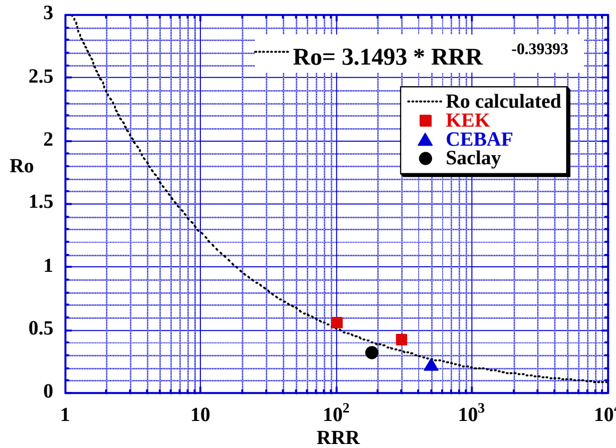

Figure 4: RRR dependence of the slope on the surface resistance with the strength of external magnetic fields.

DISCUSSION

The formula (8) shows that the higher RRR material has a benefit against frozen flux trapping. Nb/Cu clad cavities have shown a serious frozen flux tapping after quenches [5]. If this problem is caused by the same mechanism here described, cure against it is to use higher RRR niobium material. If the niobium with RRR=500 is used for Nb/Cu clad tubes, then R_O will be reduced to 0.27 nΩ/mG. The problem will be suppressed to one half of that in the case of RRR=100. Of course making a tight magnetic shielding is another important cure.

So far we investigated the effect on external magnetic field parallel with cavity beam axis. How is the perpendicular case? P.Kneisel has measured for this case with 1500MHz cavity [3]. R_O was 0.22nΩ/mG, which corresponds to 0.20nΩ/mG for 1300MHz. It is close to the parallel case. The frozen flux tapping has the same effect in both parallel and perpendicular cases.

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