Final Report, 2009-2010 JSA Fellowship

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My 2009-2010 JSA Fellowship facilitated the completion and defense of my PhD dissertation, *Multilayer Thin Films for SRF Cavities*. This interdisciplinary work encompassed extensive hardware design and development, thin film growth and analysis, and RF measurements at cryogenic temperatures. An overview of this work is presented below.

1 Introduction

Particle accelerators requiring high beam currents and high duty factors typically adopt superconducting radio frequency (SRF) technology. That is, accelerating cavities are made from superconducting materials like niobium, and are cooled past their transition temperature \( T_c \) (= 9.2 K for Nb) to allow RF surface currents to flow with negligible resistance. This allows for high beam currents and accelerating gradients. Carefully prepared single-cell niobium cavities may have gradients exceeding 50 MV/m [1].

In principle, there is no limit to the electric field strength in a superconducting cavity. However, the electric field is coupled to a magnetic field which can potentially “quench” the cavity, driving it into the normal-conducting state and seriously degrading its performance. This magnetic field limit is termed the lower critical magnetic field, \( H_{c1} \), above which magnetic flux penetrates the cavity material and dissipates RF power. \( H_{c1} \) then represents an upper limit on the performance of SRF cavities. For niobium, \( H_{c1} = 180 \) mT.

It may be possible to increase the effective value of \( H_{c1} \) (and therefore the accelerating gradient) by coating the cavity interior with alternating layers of thin dielectric and thin superconducting films [2]. This multilayer coating has the effect of screening the cavity fields from the bulk superconducting material (see Figure 1a). In addition, the current distribution in the layers creates a free energy barrier to magnetic flux penetration, further increasing the effective value of \( H_{c1} \) (see Figure 1b). My dissertation established an experimental program to evaluate the efficacy of these multilayer cavity
Figure 1: Effect of multilayer treatment on cavity fields. In Figure 1a, the horizontal axis shows increasing depth into the cavity surface. Fields decay exponentially from the inner surface, through the thin superconducting film (in this case, niobium-titanium nitride) and into the bulk material (niobium). Figure 1b shows the free energy of a magnetic flux vortex moving in the multilayer structure (red line). The free energy is minimized at the inner surface, creating a barrier to flux entry.

2 Experimental Design

Depositing thin films on the interior of a CEBAF-type elliptical cavity is quite complex: material defects introduced during cavity production may affect the overall high-field performance, making systematic error analysis quite difficult. Instead, I have developed an experimental approach based on small, flat samples. These are much easier to prepare and to treat with film coatings.

I built a microstrip disk resonator (4 cm diameter) to apply electromagnetic fields at 2.8 GHz to small, flat samples. The disk operates in the azimuthal TM$_{01}$ mode. A finite difference model of the disk fields is shown in Figure 2a. Figure 2b shows the assembly of the resonator and supporting
hardware. The disk resonator and supporting hardware was cooled to 4.3 K, ensuring that the niobium and thin superconducting films (see below) were well below their critical temperatures. To that end, a cryogenic dewar insert was fabricated for use in the Vertical Test Area (VTA) at TJNAF’s Test Lab [7]. Shown in Figure 3, the dewar insert provides thermal and mechanical stability to the experimental apparatus, as well as electric and mechanical feedthroughs used during cold RF tests. Variable capacitive couplers were installed above the disk resonator so that critical coupling could be achieved during RF measurements. The whole assembly is roughly 2 m tall and 0.5 m wide.

The $Q$ of the disk resonator gives an indication of multilayer performance. That is, $Q$ is measured while the forward power (and therefore the magnetic field under the resonator) is slowly increased. An abrupt drop in $Q$ indicates that the disk field has exceeded $H_{c1}$ and the resonator has quenched. For (Nb,Ti)N (superconducting) and Al$_2$O$_3$ (insulating) multilayers, Figure 4 indicates the expected behavior.
Figure 3: Dewar insert for measurements at the VTA. The disk resonator and supporting hardware are shown in red at the bottom.

Figure 4: $Q$ vs. $H$ curves for three sample configurations. The blue line indicates the behavior of a bulk Nb sample with no thin film coatings. The red line shows the expected behavior of an equivalent resonator fabricated from bulk (Nb,Ti)N. The expected enhanced $H_{c1}$ of the multilayer sample is illustrated by the green line.

3 Thin film deposition

The thin films for this work were deposited by DC and RF magnetron sputtering in the ultra-high vacuum (UHV) multi-technique deposition system at Jefferson Lab [8]. I was able to assist in the commissioning process of that
system by depositing and characterizing many small samples, from which work the repeatability of chamber conditions and film properties was established. Furthermore, I designed and built a UHV sample heater to mechanically stabilize the niobium substrates and hold them at a fixed temperature during deposition (see Figure 5). The conditions during film deposition and the related material analysis are described in detail in my dissertation. Broadly, x-ray diffraction measurements showed I was able to deposit the correct, NaCl-like cubic phase of (Nb,Ti)N. My films had a transition temperature of $13.2 \pm 0.5$ K, in agreement with other, similar work [9].

4 Preliminary RF measurements

Measurements on a bulk Nb “control” resonator (Nb disk, Al$_2$O$_3$ dielectric sheet, bulk Nb ground plane) give results that agree with simulation. Specifically, the TM$_{01}$ mode was found at $2.779 \pm 0.004$ GHz. The apparatus then works as expected. Notably, the coupling mechanism works as designed, and a state of critical coupling was easily found and maintained.

No resonance was observed for the multilayer sample. This gives us important feedback about the UHV system, which is still in its commissioning phase: the thin (Nb,Ti)N films currently made in that system have an anomalously high RF surface resistance, lowering the resonator $Q$ to the point where no resonance is observed.
5 Future work

The experimental apparatus and process developed for my thesis have broad applications at Jefferson Lab and will be useful moving forward, as the Thin Film Group develops deposition processes for (Nb,Ti)N, NbN, and other thin films with promising applications for SRF cavities. In addition, that group is developing other deposition techniques, such as electron-cyclotron resonance. My dissertation work provides a framework for the evaluation of the RF properties of all these thin films: surface resistance as a function of temperature and frequency, for example. Such measurements are not restricted to thin films or exotic superconductors. The RF properties of bulk niobium may also be evaluated using this system. Then the effects of different surface treatments and grain size distributions on the RF surface resistance can be evaluated.

I look forward to a long and productive relationship with the SRF Group at Jefferson Lab, and I’m grateful to JSA for facilitating my work with them.
References


