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TEST BED FOR SUPERCONDUCTING MATERIALS*

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Abstract

Superconducting rf cavities are increasingly used in accelerators. Gradient is a parameter of particular importance for the ILC. Much progress in gradient has been made over the past decade, overcoming problems of multipacting, field emission, and breakdown triggered by surface impurities. However, the quenching limit of the surface magnetic field for niobium remains a hard limitation on cavity fields sustainable with this technology. Further exploration of materials and preparation may offer a path to surpassing the current limit. For this purpose, we have designed a resonant test cavity. One wall of the cavity is formed by a flat sample of superconducting material; the rest of the cavity is copper or niobium. The H field on the sample wall is 75% higher than on any other surface. Multipacting is avoided by use of a mode with no surface electric field. The cavity will be resonated through a coupling iris with high-power rf at superconducting temperature until the sample wall quenches, as detected by a change in the quality factor. This experiment will allow us to measure critical magnetic fields up to well above that of niobium with minimal cost and effort.

INTRODUCTION

The past decade or so has witnessed considerable progress in the application of superconducting rf cavities to particle accelerators [1]. This has become increasingly the technology of choice, even for linear accelerators such as those of CEBAF, SNS, and now ILC. Fabrication techniques, surface preparation, and cavity shape have evolved to the point where one can speak of sustaining accelerating gradients of up to 35 MV/m in the latter.

Failure of a superconducting rf cavity can result from rf breakdowns due to surface impurities. Multipacting or excessive dark current due to field emission can cause heating beyond the capability of the cryogenics system to remove, causing a cavity to go normal. Aside from these electric field driven failure modes, it is well known that superconductivity can be maintained only below a certain surface magnetic field level, known as the critical field. For rf applications, a lower “superheating field” actually limits operation, typically tenths of a Tesla [2]. Above this limit, the material quenches. Niobium has long been the preferred super-conducting material for accelerator rf applications. A recent proposal to modify the shape of L-band cavities [3] offered the prospect of improving the gradient by trading off a 20% increase in surface electric field for a 10% decrease in surface magnetic field, an indication that this quenching limit is now the main obstacle to reaching higher gradients.

It may be possible to push to higher gradients with different materials, alloys, or treatments. We are establishing an experimental test setup where we will run experiments on different samples to determine their limiting fields at rf frequencies.

EXPERIMENT

Each sample will be mechanically incorporated into an rf cavity fed by a waveguide through an aperture designed to provide close to critical coupling. For reasons of available power sources and of size (our dewar has a one foot interior diameter), we will work around the X-band frequency of 11.424 GHz. This cavity will be encased in a vacuum manifold, lowered into a cryogenic dewar, and evacuated. A copper plug through the manifold wall will tie the cavity thermally to the surrounding bath, and it will be brought down to 4.2 K with liquid helium. From network analyzer measurements, the loaded quality factor of the cavity Q_L, and β, the ratio of unloaded to external quality factors, will be determined, as well as the input waveguide attenuation.

Cavity Characterization

Most techniques used to interpret the reflection data from a high quality factor resonator are based on fitting the so-called Q circle (see [4] and the references cited therein for a review of these techniques). Most of these differ only in the choice of weighting function used to filter the data. We choose the weighting function produced by the Fourier transform of a pulse with a flattop and Gaussian rise and fall; this is a very natural way of getting the total or loaded quality factor, Q_L, of the cavity. The measured frequency response is multiplied by the Fourier transform of such a pulse, modulated at the cavity frequency, f_0, as determined from the resonance minimum. The time response of the cavity is then calculated by an inverse Fourier transform.

Q_L is measured from the decay of the emitted field at the end of the pulse. The coupling parameter, β, and the attenuation of the transfer waveguide, $e^{-\alpha L}$, are calculated by fitting this time response to a cavity model that has the following frequency response.

$$S_{11}(f) = e^{-2L(ik_g+\alpha)}\left(\frac{2i\beta}{(\beta+1)(f_S Q_L - i)}+1\right), \qquad (1)$$

where $f_S = f/f_0 - f_0/f$, and k_g is the guide wavenumber.

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High Power

High-power pulsed rf will then be fed into the cavity at its resonant frequency and the power level gradually increased. The repetition rate will be kept low enough to avoid any runaway in the cavity temperature, which will be monitored by a thermocouple. The loaded quality factor will likewise be monitored through the reflected waveform. When the surface magnetic field causes the sample to quench, it will be evident from the change in shape of this signal. From the waveform recorded just below this power level, we can calculate the stored energy at which this happens. It is given by:

$$U = \frac{Q_L}{2\pi f_o}\left(1+\frac{1}{\beta}\right)P_e. \tag{2}$$

Here P_e, the emitted power, is measured from the spike just after the input pulse terminates, adjusted for one-way loss in the input waveguide. Q_L, checked by fitting the emitted power decay after the input pulse, to $P_e e^{-\omega t/Q_L}$, should be the same as measured at low power. Finally, cavity simulation gives the proportionality of the square root of U to the peak H field on the surface of the superconducting sample.

CAVITY DESIGN

To test superconducting materials for maximum sustainable surface magnetic field only, it is desirable to eliminate any experimental limitations that might be imposed by surface electric field. To avoid potential problems caused by rf breakdown, multipacting, and heating due to dark current, a test cavity should therefore be designed to utilize a TE_{0nm}-type mode in an axially symmetric geometry. The electric field lines in such modes form self-closing axial rings which do not terminate on any surface.

A further benefit of these modes arises from the fact that their wall currents are also purely azimuthal, making them insensitive to small azimuthal gaps. This facilitates the incorporation of a test sample end plate, which needn't have good electrical contact with, or even touch, the main body of the cavity.

The simplest such cavity is a TE_{011} circular pillbox. It takes on a minimum volume at a radius of 0.7458, with a height of 0.8685, both in units of the resonant wavelength. To maximize the peak H field on the bottom for a given stored energy, one might choose a radius of 0.9658 wavelengths, with a height of 0.6448 wavelengths. Further increasing the radius reduces the contribution of the curved sidewall to the wall loss, and thus its effect on the quality factor. In any case, one has with this geometry the same peak field on the top endplate as on the bottom endplate.

Mushroom Cavity

The approach we took is to focus the magnetic field solely on the bottom plate, formed by the test sample. The geometry arrived at after some experimentation is shown in Fig. 1, along with electric and magnetic field patterns. The mode utilized is TE_{013}-like, but the upper portion of the cavity flares out in a sort of mushroom shape, allowing the upper lobes of the mode to spread out over greater surface area. The cavity is about 4.88 cm high, with a diameter of about 8.26 cm. The bottom has a diameter of only 4.98 cm. The sharp concave corner at the outer radius reflects the intention to form it by joining two separately fabricated pieces, not counting the bottom face, which is formed by connecting a flange with the sample attached.

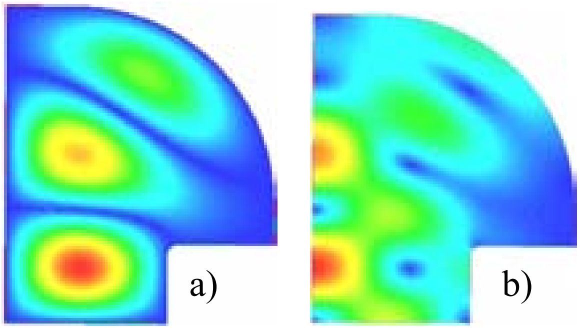

Figure 1: Geometry of our test cavity and false-color plots of the a) E and b) H field patterns for the TE_{013}-like mode. The left edge is the symmetry axis, and the bottom edge is the face of the test sample.

The magnetic field profile along the cavity wall is plotted in Fig. 2, starting at the axis on the bottom and going out and around to the top. The field reaches a peak on the bottom plate significantly higher than anywhere else. The next highest surface fields, on the lower side and the curved area near the top, only reach about 55-57% of this. As noted, the surface electric field is everywhere zero.

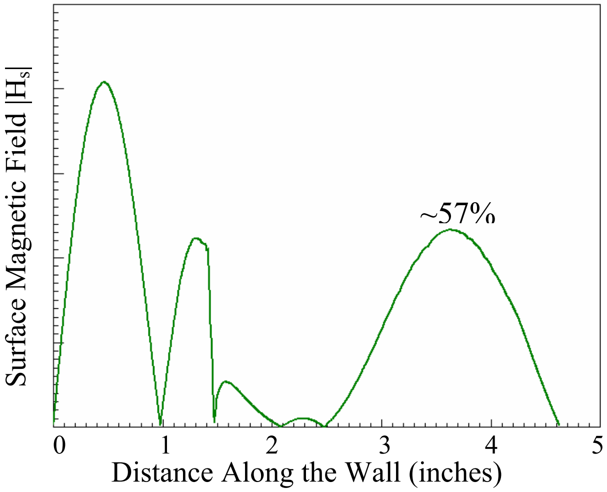

Figure 2: Magnetic field profile (in arbitrary units) along the contour of the cavity wall, beginning at the center of the bottom face. The first peak, and by far the highest, is on the bottom face.

While we will construct our initial cavity out of copper, the true benefit of this design will be realized in a niobium version. With the cavity completely superconducting, the fall off in Q will be very pronounced when a quench occurs. With the surface magnetic field so maximized on the sample face, it should be possible to measure on sample materials superheating fields up to 75% higher than that of niobium before the test cavity itself quenches.

Coupling

For simplicity, our cavity will include only one rf coupling, through a centered circular aperture in the top. A second coupling aperture would be useful for diagnostics, but would need to either be made through the center of the material sample or break the axial symmetry of the cavity.

The former would unduly complicate the sample preparation and introduce a machined edge on which field enhancement would increase uncertainty. The ability to test materials with simply a flat, replaceable three inch disk (with screw holes beyond the cavity region), is a great asset of this test setup.

The latter coupling option of breaking symmetry by coming in through the side is a bad idea in an overmoded high-Q resonator. Unintentional excitation of non-axisymmetric cavity modes and evanescent fields from such an aperture or probe could affect the Q and alter the surface fields. This would limit the accuracy and usefulness of experimental results. Problems of anomalous loss were experienced during an initial cryogenic Q-test, in which we used a side-coupled TE_{011} pillbox designed and previously used for pulsed heating experiments [5].

The cryogenic apparatus, as well as the cavity, is simplified by using only one waveguide feed-through. As described above, we should be able to determine the quality factor well enough from S_{11}, using low-power frequency data along with high-power measurements, although this method is not as straight-forward as measuring S_{21} resonance widths.

The cavity was designed with a flat region on top of the dome to facilitate machining of an iris of the necessary radius through a constant thickness wall. The electric and magnetic fields are both zero at the top center of the cavity. Furthermore, the flared shape of the cavity pulls the upper lobe of the mode away from the center, requiring a rather large hole, nearly a centimeter in radius, to achieve critical coupling for copper. This corresponds to a loaded quality factor of ~22,800 at room temperature or ~51,600 at 4.2 K. The latter number is based on the observed change in the surface resistivity of copper during our cool down of the X-band pillbox cavity mentioned above.

Taking the bottom face as an essentially lossless superconductor, the critically coupled loaded Q would approach ~80,900. Fig. 3 shows the dependence of the external Q on iris radius, roughly a 13-14th power dependence over eight orders of magnitude, according to HFSS calculations. This sensitivity makes our geometry ideal for a wide range of unloaded Q's, so that we should be able to approach critical coupling with a reasonable hole radius even with a fully superconducting niobium cavity. It also tends to overcouple other modes.

Mode Launcher

To couple to this cavity mode through a centered iris requires the same field pattern on the waveguide side, namely an incident TE_{01} wave. Furthermore, to avoid excitation of other potentially high-Q cavity modes, this waveguide mode should be as pure as possible. We plan to use a mode converter of a new design to launch TE_{01} in a 1.5 inch diameter waveguide, connected by a vacuum flange to the top of the cavity.

The input of the mode converter is standard WR90 X-band rectangular waveguide. A very compact section converts the fundamental TE_{10} mode to TE_{20}. This is followed by a height tape and a multi-section taper from rectangular to circular cross-section designed to launch TE_{01}. Simulation shows resulting parasitic mode levels to be on the order of -60 dB.

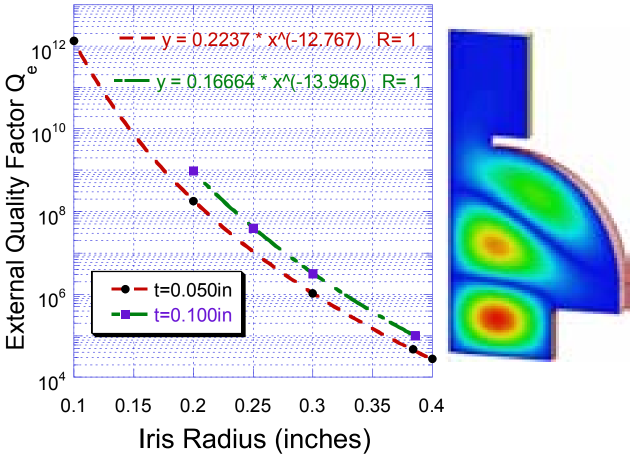

Figure 3: Dependence of the external quality factor, $Q_e=\omega U/P_e$, on the iris radius, with two iris thicknesses. Also shown is the final geometry for copper.

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