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SAMPLE TEST SYSTEMS FOR NEXT-GEN SRF SURFACES[*]

T. Oseroff[†], M. Liepe, Z. Sun, CLASSE, Cornell University, Ithaca NY, US

Abstract

With the increasing worldwide focus on the development of new surfaces for SRF cavities, exploring alternative materials and multilayer structures, test systems that allow measuring the RF performance of simple sample geometries (e.g., flat samples) become increasingly essential. These systems provide RF performance results that are needed to guide the development of these surfaces. This contribution gives an overview of sample test systems currently available, including the improved Cornell sample host cavity. Recent advances in this important technology, performance specifications, and current limitations are discussed. In addition, an overview is given of interesting recent RF performance results on samples coated with non-niobium bulk and multilayer films.

INTRODUCTION

The use of three dimensional microwave electromagnetic resonators with superconducting surfaces for accelerating charged particles has a long and successful history [1]. In contrast to normal conductors a superconducting surface exposed to a microwave field will dissipate far less energy. For accelerator applications this propagates into two major advantages. First, a reduction of overall power cost, coming from a net gain of low dissipation in the electromagnetic resonator requiring low input powers to reach a given stored energy (proportional to the square of field magnitude) versus higher refrigeration costs to reach the cryogenic temperatures required for the low T_c superconducting phases employed for this application. Second, less dissipation corresponds to less heating which can be more efficiently removed allowing for continuous wave operation. On the other hand, superconducting RF surfaces are limited to a critical magnetic field above which the low dissipation flux-free Meissner state can no longer be maintained. The optimization of these key metrics; minimizing dissipation (surface resistance) and maximizing accelerating field limitation (quench field) are paramount for advancing SRF accelerator technology.

This regime of minimum dissipation and maximum RF field is unique to the SRF accelerator application and poses major challenges theoretically. At low RF fields accurate estimates of surface resistance can be obtained [2, 3]. Lowering the expected dissipation will increase the role of any defects or material features making accurate estimation increasingly difficult. As the RF field strength is increased dissipation becomes difficult to model as more sources may become relevant and complicated nonequilbrium effects may become important. Unfortunately this regime is of the most practical importance since higher field cavity operation is desired. Thus it is important not only to maximize the limiting field and minimize surface resistance but to do so in the poorly understood high field regime.

The elemental superconductor niobium was a clear initial choice since its properties, compared to other elemental superconductors available at the time, minimize surface resistance and maximize the ideal quench field (superheating field). Over decades niobium processing was advanced to optimize it for accelerator applications [1]. Surface processing techniques have been developed to routinely reduce the surface resistance at high fields in addition to reaching higher quench fields [4, 5]. With cutting edge techniques niobium has been extended further than low-field BCS predictions for surface resistance and very close to predictions for the theoretical superheating field [6]. As such its utility for continuing to meet the ever-rising demands of the future accelerators may be approaching an end.

The potential limits of niobium have refreshed efforts to search for materials or metamaterials that could surpass the capabilities of niobium [7]. Nb_3Sn has emerged as the most successful candidate explored though its measured performance is far below theoretical expectations [8]. At this time it appears that none of the superconducting alloys have demonstrated naive expectations of dissipation or quench field. To assist with field limitations superconductor-insulator-superconductor (SIS') multilayers were proposed [9]. Recently RF measurements have been performed on these metamaterials but benefits have not yet been observed in the presence of an RF field [10].

A major problem with advancing beyond niobium is a lack of measurement of these materials in relevant RF fields. Niobium optimization followed from innumerable and extremely costly RF tests and surface processing trials. In many situations performance improvements are reproducible but the physical mechanisms are not clear. Understanding and identifying positive and negative features will require improved capabilities for measuring surface resistance, quench fields, or other relevant metrics with more diverse samples as a function of more variables. Measurement of flat samples is important for probing more diverse materials and structures without significant investment in specialized deposition systems. Though exposing these surfaces to significant RF fields and obtaining relevant metrics is nontrivial. The purpose of this writing is to present existing systems and methods attempting to perform field-dependent surface resistant measurements on flat samples.

COMPLICATIONS AND STRATEGIES FOR FLAT SAMPLE RF CHARACTERIZATION

The primary difficulty of experimentally probing materials for SRF accelerator application is exposing them to

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[†] teo26@cornell.edu

sufficiently large amplitude microwave fields. In accelerator cavities surface magnetic fields greater than 100 mT are routinely achieved. To our knowledge the only methods of producing microwaves with this magnitude using reasonable power sources are with resonators (as is done for accelerators to begin with) or near-field antennas. The secondary difficulty is performing relevant measurements. As discussed previously accelerator applications most directly make use of measurements of surface resistance and magnetic field applied to a surface. But other measurements can provide information about superconducting materials and surface features. Specifically measurements of fast (compared to the RF period) nonlinearities are routinely used for characterization of high T_c superconductors [11, 12]. Regardless of measurement varying more parameters enhances comparisons to models to gain understanding and increases chances of novel observations. The goal of sample RF characterization therefore is the measurement of relevant metrics (surface resistance, penetration depth, surface field amplitude, intermodulation distortion, third harmonic response, etc) over as many extrinsic variables (temperature, frequency, RF field strength, DC field strength, pressure, etc) and material properties as possible.

RF Characterization Using a Resonator

Resonator-based measurements demanding an interchangeable sample with a flat surface require the use of a host structure which takes the form of a complete resonator missing one face. The sample to be tested is joined to the host structure at this opening to close the cavity. This joint must be robust enough to support ultra high vacuum (UHV) since providing sufficient cooling for high field measurement requires the immersion in liquid helium often in a superfluid phase. The sample-host flange must be located for a given resonant mode such that currents do not flow through it causing spurious dissipation. Edges of the sample must be outside of the cavity interior or adequately screened to avoid field enhancement. Resonant excitation will limit the frequency range to discrete values immediately eliminating detailed studies of this important variable. To our knowledge no flat surface RF characterization methods expose the sample area to uniform fields which can complicate analysis of samples with field-dependent effects.

With a few exceptions the host structure RF surfaces are constructed with niobium to enable high fields with reasonable power sources. This creates a fundamental limitation on the range of fields that can be explored since the niobium host structure can quench at a lower value than the sample material. Many designs have been optimized to maximize the ratio $H^{max}_{sample}/H^{max}_{host}$ but none have succeeded in reaching comparable maximum fields to those of accelerator cavities. Some systems have been created using copper to avoid host structure quench limitations but because of the low quality factor reaching relevant sample fields requires megawatt sources that are not commonly available.

TE$_{01n}$ mode resonators Historically the standard cylindrical TE$_{01n}$ cavity modes have been frequently employed for RF characterization. For high field characterization where minimizing sharp edges in the resonator is desired the end plate replacement method is employed as shown in Fig. 1. In this configuration current does not pass through the flange which reduces the risk of spurious dissipation. Electric field lines form closed circles which reduces the risk of field emission issues as the component of the electric field normal to the surfaces is ideally zero.

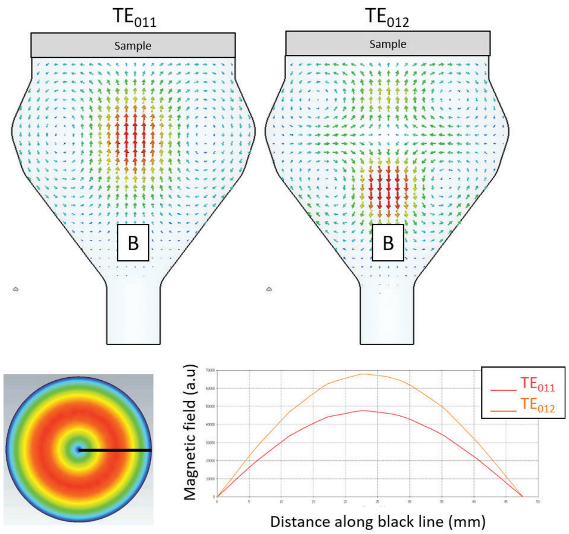

Figure 1: Cornell sample host cavity magnetic fields demonstrating typical TE$_{01n}$ sample host cavities in SRF. In the top images a geometry that optimizes field focusing to the sample is demonstrated showing the fields for two modes and the position of the sample in the end plate replacement method. The lower image shows the magnetic field amplitude on the sample RF surface for the TE$_{011}$ mode and the right shows the field along the black radial line for the TE$_{011}$ and TE$_{012}$ modes demonstrating little variation in their profile on the sample.

With the sample configured as an end plate of a cylindrical cavity operating with higher frequency TE$_{01n}$ modes allows for exploring more frequencies with similar field configurations at the sample as is shown in Fig. 1. Practically this does become limited to low n as it becomes more difficult to identify higher order modes as the total mode density becomes large. SRF applications typically employ relatively low frequencies (0.1 GHz - 2 GHz) to maintain low dissipation. For the TE$_{011}$ mode with the sample at the end plate reaching these frequencies requires a large diameter sample. It is often required to choose a rather large sample to push frequencies somewhat close to this range but is still small enough to be suitable for deposition systems.

The cylindrical TE$_{01n}$ modes with the sample at the end plate are not very efficient since most of the electromagnetic energy is near the center and is far from the sample. This results in a low filling factor: $H^{max}/\sqrt{U}$ leading to higher input powers required for reaching a given sample field. More importantly the previously discussed ratio $H^{max}_{sample}/H^{max}_{host}$ is small which would lead to lower maximum sample fields before being limited by reaching a quench field on the host structure. These issues can be improved by changing the cylindrical shape into a "mushroom" shape so that the diameter near the sample is larger than the diameter further away. This shifts the energy towards the plate focusing the field to the sample more effectively. An example of an optimized pillbox geometry is shown in Fig. 1.

Quadrupole resonators A more modern approach that has demonstrated improved capabilities towards reaching SRF sample study goals is the quadrupole resonator (QPR). A brief overview is presented but for more complete descriptions and discussions see the following references [13–16]. The idea stems from placing a current carrying loop very close to the sample surface where the current loop is positioned at the end of a transmission line onto which a standing wave is excited with its anti-node at the current loop. This configuration is identified as a dipole resonator. A second current carrying loop with corresponding transmission lines allows for operation of a quadrupole mode which has a higher cut-off frequency [13]. A cartoon of this RF excitation is shown in Fig. 2. A very small gap ($<$ 1 mm) between the sample and the current loops focuses the field very effectively on the sample as is demonstrated in Fig. 2 and allows for reaching high fields. For SRF application this method of RF excitation allows for a relatively small sample diameters while maintaining low frequencies of operation since the resonances depend primarily on the length of the transmission lines. In practice up to three modes with similar sample field distributions are employed. The QPR does not have the same field emission reduction effects from electric field configurations of TE_{01n} modes and it has been suggested that multipacting could be an issue [17].

Surface resistance measurements In contrast to accelerator cavity tests where the material to be studied is the dominant surface of dissipation, sample host systems are complicated by the need to separate the response of the sample of interest from that of the host structure. The basic method is a calibrated quality factor measurement where a sample with known surface resistance (typically a material as identical as possible to the host structure material) is first measured and used in conjunction with known field distributions to identify dissipation on the host structure. Assuming no significant errors in the calibration sample resistance, no changes occur on the host structure between tests (flux trapping, contamination, etc), and ignoring field dependent effects this knowledge is then combined with a measurement on a sample of interest to isolate the response of the sample. This method immediately limits the temperature range to that of the host structure restricting a full range of measurement for higher T_c samples. The range of surface resistances the method can resolve is limited to those greater than that of the host structure since as the dissipation of the sample becomes smaller it will become more difficult to separate changes in it from measurement error. This is improved by minimizing uncertainty and by designing the cavity to more effectively focus magnetic fields onto the sample [18]. The limitation introduced by this uncertainty does limit the theoretical application of this system. Though currently very few materials have demonstrated resistance comparable to niobium at low temperatures so systems utilizing this measurement method do have utility for optimizing materials and eventually validating their performance if there is success. In addition one can imagine alternative measurements on higher dissipation materials that may provide understanding surface resistance from different perspectives.

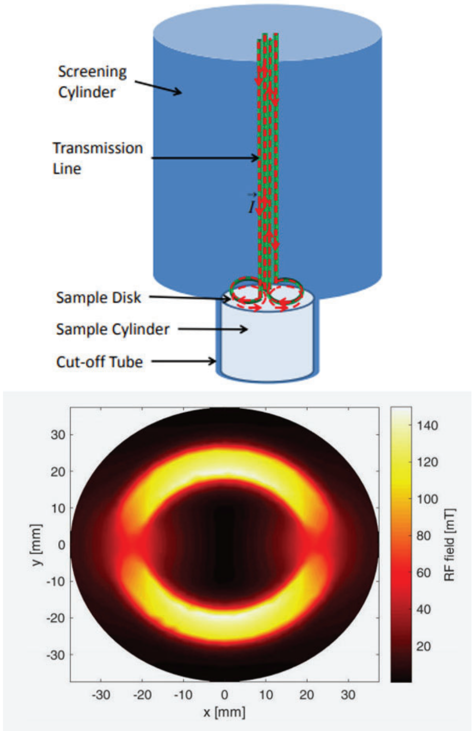

Figure 2: (Top) principle of QPR operation: a standing wave along a transmission line ending in a loop near the surface of the sample [13]. (Bottom) Quadrupole resonator sample magnetic field [16]. Note that the field is essentially unchanged for different modes.

A more sophisticated approach for measuring sample surface resistance is the calorimetric measurement where heating on the sample from the applied RF field is more directly measured. Most commonly this is done through an RF-DC heating compensation technique requiring thermal isolation of the sample from the host structure and a limited connection to the bath. A DC heater is used to independently control the sample temperature. When the RF field is turned on the DC heater is adjusted to maintain temperature and the difference in required power is attributed to the sample. Another method requiring vacuum on the outer surface of the sample has also been demonstrated but is likely not optimal for high field studies. The calorimetric methods require

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precise design to ensure thermal isolation and minimize spurious heating. Operation can be complicated and is more naturally done with pulsed RF where potential complications regarding pulse period and length require careful analysis. The RF-DC compensation method of calorimetric measurement has demonstrated extremely high resolution of heating measurement which would correspond to surface resistance resolution $< 1\,\mathrm{n\Omega}$ assuming successful design of thermal and RF isolation. However in most cases nontrivial residual resistances seem to be present in at least some of the modes of operation indicating the possibility of persistent issues with this measurement. A major advantage is the thermal isolation of the sample allows for independently varying the temperature of the sample from that of the host.

RF Characterization Using Near-field Antennas

The use of resonator host structures with superconducting surfaces has significant limitations. Frequency dependence is limited to a discrete range of resonant frequencies with resolution ultimately confined by size constraints. Maximum sample fields are limited by quenching on the host structure. Some spatial resolution can be obtained using temperature mapping systems on the outside of the cavity but this is limited to ~ 1 cm and information is diluted as the heat must propagate through millimeters of material [19].

Near-field antenna RF excitation provides an interesting solution to the above limitations. Microwaves generated by an antenna extremely close to the sample can expose the surface to high magnitude fields without requiring excessive power or resonance. Without the need for resonance a continuous range of frequencies can be explored limited only by the impedance of the antenna. The spatial extent of these excitations does not extend far allowing for sub-micron spatial resolutions directly on the RF surface.

Near-field antenna excitation has the potential to provide much needed measurement and understanding for SRF accelerator goals but has not yet demonstrated measurement of surface resistance or the surface field amplitude. Current systems rely on measurement of third-harmonic response which probes fast nonlinearities of the sample [11]. This is a very powerful measurement on superconducting surfaces that possess powerful sources of nonlinearity from both intrinsic superconducting properties and extrinsic sources such as vortices or defects. Measurements of third harmonic response have been used to compare to models of SRF surfaces with great success and as such they can provide understanding to the SRF community [20] but are not as directly applicable as surface resistance.

EXISTING FLAT SAMPLE RF CHARACTERIZATION SYSTEMS

Many systems have been designed for measuring flat samples at high RF fields and used for novel measurements. In this section some relevant systems are presented to demonstrate the strengths, weaknesses, and capabilities of the various methods for RF characterization discussed above. Table 1 lists some basic features of all RF characterization systems considered in this section. For an excellent summary refer to the following [21].

TE$_{01n}$ Mode Sample Host Cavities

Basic TE$_{01n}$ mode sample host cavities are at SLAC [22], Cornell [18, 23], and IMP [24]. At SLAC two host structures designed to focus the field on the sample are in operation. They use a very high frequency of 11.4 GHz and accept small diameter samples. One is made of niobium and the other of copper. The copper system requires a 50 MW klystron for high field operation but can reach extremely high sample fields without host structure quench. The Cornell and IMP host cavities have very similar designs though the IMP system has not yet reported measurements so this discussion will focus on the Cornell system. It operates at two medium frequencies of 4.0 GHz and 5.2 GHz with similar sample fields. These frequencies are near to SRF accelerator applications while allowing for a sample diameter of 12.4 cm. The geometry, shown in Fig. 1, is optimized to reach maximum field on the sample before quenching on the host structure [23]. Temperature mapping has been demonstrated and can be used to provide local information on heating of the sample. In practice it reaches ~ 80 mT and ~ 50 mT for the 4.0 GHz and 5.2 GHz modes respectively. Residual resistance on samples has been a persistent issue though it has recently been traced to contamination occurring in the furnace [18]. Performing the relevant heat treatments with the samples wrapped in niobium foil seems to reduce the residual but it is still present. A light electropolish after the bake can reduce the residual as shown in the top of Fig. 3 where it is demonstrated to be very low at 4 GHz

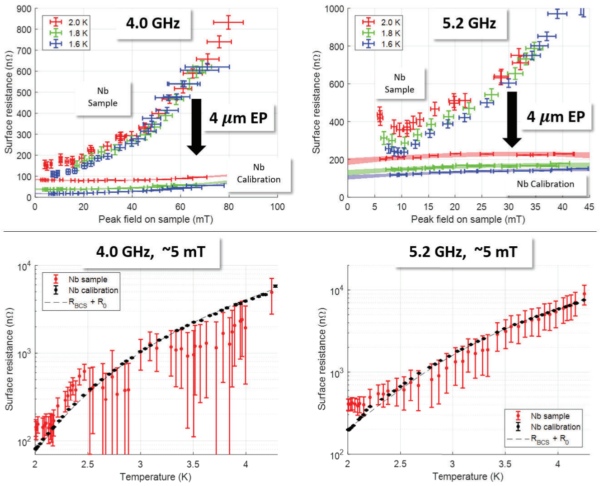

Figure 3: Cornell sample host cavity results of fine grain 5 hr 800° C vacuum baked niobium samples (Top) Residual resistance introduced by furnace and removed by a light electropolish. Higher fields are limited by quench. (Bottom) Uncertainty introduced by the calibration procedure for a niobium sample with the same preparation as the calibration plate.

Table 1: Table comparing high level features of flat sample RF characterization systems considered in this section. Values come from references of each system given in the text. Some educated guesses are made on temperature ranges and some important distinctions regarding the type of calorimetric measurement are ignored

Location	RF excitation	R_s measurement	f (GHz)	Sample ∅ (cm)	T range (K)	Field limit (mT)
SLAC (Cu)	TE_{013}	Calibrated Q_0	11.4	5.1 - 7.6	> 4	400 (est) / power
SLAC (Nb)	TE_{013}	Calibrated Q_0	11.4	5.1 - 7.6	4 – 9	
Cornell	TE_{01n}	Calibrated Q_0	4.0, 5.2	12.4	1.6 – 4.2	80 / quench
IMP	TE_{011}	Calibrated Q_0	3.9	11	1.5 - 4.2	Untested
Orsay	TE_{01n}	Calorimetric	3.9, 5.2	12.6	1.6 – 4.2	20 / power
JLab	TE_{01n}	Calorimetric	7.4	7.5	~ 2 – 40	14 / power
CERN 1	QPR	Calorimetric	0.4, 0.8, 1.2	7.5	~ 2 – 20	70 / quench
HZB	QPR	Calorimetric	0.4, 0.8, 1.3	7.5	~ 2 – 20	120 / quench
CERN 2	QPR	Calorimetric	0.4, 0.8, 1.2	7.5	~ 2 – 20	
DESY	QPR	Calorimetric	0.4, 0.9, 1.3	7.5	~ 2 – 20	Untested
Daresbury	TM_{010}	Calorimetric	7.8	10	> 2	Untested
UMD	MM	N/A	2 – 25	variable	cryostat	> 400 (est) / power

(< 10 nΩ) but is still somewhat large at 5.2 GHz (100 nΩ). All of these systems make use of a calibrated quality factor measurement which limits their utility for measuring low resistance samples. At Cornell numerous upgrades have been made to minimize measurement error in an attempt to reach the best case of this method [18]. The bottom of Fig. 3 demonstrates the impact of a calibration procedure for a sample with similar resistance to that of the host structure. At 4.0 GHz systematic errors cause some deviation from the true value though this may be an operation issue. For the 5.2 GHz mode it is found that measurements of a niobium sample can be carried out with reasonable accuracy due to better sample field focusing.

A sample host cavity at Orsay [25] has similar RF excitation to the Cornell and IMP host cavities but makes use of a vacuum calorimetric surface resistance measurement that provides some local information. A sizable residual resistance over 100 nΩ has been reported on both its 3.9 GHz and 5.2 GHz modes. The highest field reported is 20 mT at 5.2 GHz.

At Jefferson Lab a 7.4 GHz partially dielectric-loaded TE_{011} mode sample host cavity called the surface impedance characterization system (SIC) was designed and built implementing an RF-DC compensation calorimetric measurement [26, 27]. For RF excitation the system makes use of a sapphire rod to focus the field onto a small portion of the sample. In addition it makes use of RF chokes to ensure even less RF leakage in unwanted regions. Despite excellent design work the system has reported anomalously high residual resistances exceeding 1 $\mu\Omega$ on niobium samples and has been limited to 14 mT due to power limitations. The author assumes the presence of sapphire in the cavity leads to a low quality factor and potentially heating issues at high fields as the loss tangent of sapphire should lead to significant dissipation. On the other hand the filling factor would increase allowing for higher fields at a lower stored energy. Indeed despite these reservations a sapphire loaded cavity at MIT Lincoln lab has reported high fields [12] though we have been unable to find relevant details. The Jefferson lab system has been used for important validation work on MgB_2 [28] and Nb_3Sn [29] samples and demonstrated measurements up to 40 K.

Quadrupole Resonators

The quadrupole resonator was proposed at CERN [30] and then later designed and implemented with success [13]. This system could be measured with three frequencies at 400 MHz, 800 MHz, and 1200 MHz with similar field configuration. Its maximum field is limited by a host quench to around 80 mT. A second QPR was made at Helmholtz-Zentrum Berlin (HZB) that most notably made optimizations allowing it to reach a higher host structure quench at a sample field of 120 mT [31]. A second QPR has been built at CERN with some optimizations however it is currently reporting high residual resistances and work is being done to understand and remove the source [32]. Finally a QPR has been constructed at DESY with similar design to HZB and it may become operational within a year of this writing [33].

All QPRs make use of RF-DC compensation calorimetric measurements allowing for high resolution surface resistance measurement and can explore temperatures beyond the critical temperatures of niobium host structures. To provide the necessary thermal isolation a coaxial gap used between the niobium host structure and a sample cylinder. The sample geometry is a cylinder which requires electron beam welding and is not compatible with all deposition systems. While having excellent resolution some issues with residual resistance have been observed especially at the higher frequency modes. Possible sources for this include RF leaking through the coaxial gap [34] or multipactng effects [17].

Utilizing the high resolution measurement the QPR at HZB has reported novel measurements that exemplify the potential of these systems. Figure 4 shows measurements of a NbTiN-AlN-Nb SIS' multilayer sample. The measure-

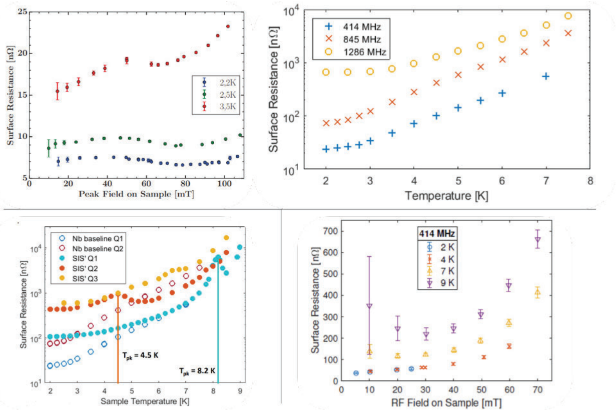

Figure 4: HZB quadrupole resonator results (Top) 120° C vacuum baked niobium demonstrating high field operation to 120 mT [31] and nontrivial residual resistance on higher frequency modes [34]. (Bottom left) NbTiN-AlN-Nb SIS' multilayer surface resistance temperature dependence at three frequencies (Q1 = 414 MHz, Q2 = 845 MHz, Q3 = 1286 MHz) compared to baseline niobium demonstrating unique measurement capabilities [10]. (Bottom right) Nb_3Sn measurement demonstrating capability to reach high sample fields at high temperatures [35].

ments reported cover all three frequencies, temperature dependence, and field dependence. Observations of interesting resistance field dependence and sample quench limitation were obtained in addition to anomalous frequency dependent peaks in the resistance as temperature is varied [10]. This measurement indicates advantage over traditional accelerator cavity tests as it explored the temperature dependence of a single surface with similar field configuration at different frequencies. This is not something that could be done with traditional accelerator cavity tests and has given the observation of novel physics that could be important for understanding the response of SIS multilayers. In addition the sample is a metamaterial that would be challenging to deposit on a cylindrical geometry. Measurements using the HZB QPR on Nb_3Sn [35] demonstrate the advantages of thermal isolation by reaching high RF fields on a sample while bringing it to temperatures higher than the boiling point of helium. While this is pulsed RF operation it is a natural measurement for the QPR while it is not something typically explored with accelerator cavities. In addition the sample's thermal isolation from the bath allows for rapid thermal cycling through its critical temperature without the need to boil away all helium in the cyrostat which is time-consuming and potentially costly. In the Nb_3Sn study this allowed for rapid measurement of quench fields without concerns of heating due to trapped flux dissipation introduced from prior quenches.

Alternative Resonant Structures

Not many host structures making use of other RF excitation modes have been constructed to our knowledge. An interesting exception is a choked TM_{010} resonator at Daresbury [36, 37]. The concept centers around a gap separating the host structure and sample with each independently cooled by cryocoolers. This has numerous potential advantages including elimination of liquid cryogens and preventing flange dissipation that would likely be an issue if the sample and host made direct contact in the presence of TM_{010} fields. The surface resistance can be readily measured via a calorimetric method since the sample is completely thermally isolated from the host structure. These benefits could allow for accurate surface resistant measurements with high throughput since the cavity need not be brought to UHV and no liquid cryogens are required. The cost of these advantages is limited field capabilities since the gap will cause significant energy loss resulting in low quality factors and current cryocooler technology does not provide enough refrigeration power.

Microwave Microscopy

Microwave microscopy is a near-field antenna RF excitation technique that has been developed and utilized over recent decades for numerous applications [38]. At University of Maryland (UMD) there have been recent and continuing efforts to employ the technique for superconducting RF characterization [20, 39–41]. The antennas are write heads used for magnetic hard drives. Despite differences in intended application it has been demonstrated that these are compatible with microwave operation over a wide band of frequencies (2 GHz - 25 GHz) and can generate strong and local RF magnetic fields. Expected spatial resolutions are sub-micron and simulations predict support for surface fields exceeding 400 mT [39]. This requires the magnetic write head to be very near the sample (~ 100 nm) which makes it sensitive to surface roughness and error. These issues should be readily solvable by employing mature microscopy techniques for controlling probe-sample distance.

Microwave microscopy could prove essential for the detection and identification of surface defects and features relevant for SRF. The third harmonic response of local defects should have unique signatures that could be used for identification [42] as has been demonstrated by the group at UMD [20]. While the technique has advantages for RF excitation and spatial resolution it seems difficult to obtain surface resistance or surface field amplitude measurements. Without measurement of the applied field strength the information it can provide may be somewhat limited.

CONCLUSION

The primary goal of the SRF accelerator community is to optimize materials for its application. This involves reaching higher accelerating gradients (increasing maximum surface magnetic field supported by flux-free Meissner state) and minimizing dissipation on the surface. With the decades of improvement of niobium it appears to be reaching a point where further significant improvement will require a new material or metamaterial. Measurements of these candidates for next generation SRF surfaces indicate the need for

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identification of relevant surface features and, if possible, optimization. As such the need for rapid development of samples and quality measurements for improved understanding of the response of more complicated superconductors to significant RF fields has never been greater.

Flat samples provide a vessel for exploring a wide range of interesting surfaces without time consuming and costly deposition system development. Relevant RF characterization of interchangeable samples with flat surfaces has proven to be a challenging task and none of the existing resonator-based attempts have fully succeeded. With remarkable work at all stages, from concept to design to implementation to operation and commissioning, some quadrupole resonators are able to deliver high quality measurements in at least some of their intended variable ranges. Other systems have more conceptual limitation but have demonstrated accurate measurements of samples with resistances greater than that of the host structure. Many systems have demonstrated the ability to probe the response of samples with more temperature range and frequencies (with nearly identical sample field distributions) than the traditional accelerator cavity tests. Improved variable range could be instrumental for understanding the physical mechanisms and surface features leading to benefits or identifying those that cause degradation or limitations. While resonant sample host structures are now ready to perform interesting measurements they still have many obstacles to overcome.

Microwave microscopy has been demonstrated as a powerful supplemental measurement to resonant systems promising to fill in some of the experimental gaps including high field excitation with extreme spatial resolution and wide band frequency dependence. This kind of measurement, or other novel techniques that could provide new perspectives to the SRF community, could be essential for understanding limitations that are preventing the implementation of more complicated superconducting materials or metamaterials.

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