USING CERENKOV LIGHT TO DETECT FIELD EMISSION IN SUPERCONDUCTING CAVITIES

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Abstract

We propose a method that could become the most sensitive diagnostic tool for measuring dark currents in superconducting cavities and help detect the onset of field emission accurately.

INTRODUCTION

Superconducting radio frequency (SRF) technology is used for most next generation scientific facilities that accelerate particle beams including light sources, neutron sources and high energy colliders. The production chain for SRF cavities is quite complicated with the final stages of preparation still performed at research facilities as they are not fully industrialized. There are many process control parameters in production that affect the final performance and many of these are either poorly understood or possibly still unknown and there is a large spread in performance (in terms of maximum achievable accelerating electric field) in a batch of cavities going through an identical process chain. The yield versus performance is a critical issue that will determine the feasibility of the International Linear Collider (ILC) [1] and other future scientific facilities. Failure modes for SRF cavities that don't make the design gradient in testing include quenches due to local heating and running out of RF power due to field emission (which may also trigger a quench). The onset of field emission in a cavity is an important diagnostic indicator in the final stages of production and testing.

Testing Superconducting Cavities

Present diagnostics for superconducting cavity operation include

- forward/reflected power and cavity field probes to detect power dissipation
- temperature mapping to see hot spots (direct contact, infrared emission from surface or second sound)
- Faraday cups and similar devices to measure on-axis dark current of field-emitted electrons
- x-ray detectors to measure the rate and spectrum of secondary x-rays generated by bremsstrahlung of field-emitted electrons going through various metal parts

These are all relatively crude measurements that rely on the high intensity of the dark current signal. Cavities are typically buried inside several radiation lengths of metal making x-ray measurements indirect. An example of a practical configuration is shown in Fig. 1.

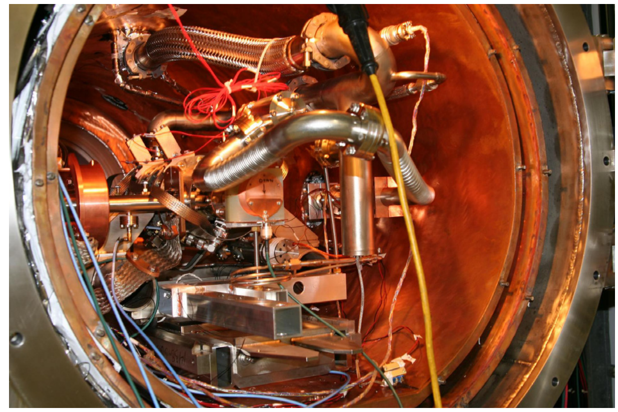

Figure 1: Typical layout showing an rf cavity (in the center) buried inside layers of heat shield and rf and cryo plumbing in a cryostat (from the Fermilab ILCTA-MDB Horizontal Test Stand). X-ray detectors are outside the cryostat.

FIELD EMISSION

Field emission is a result of electrons tunneling through the few-eV potential barrier (work function ϕ) at a metal surface due to the rf electric field E and is described [2] by the Fowler-Nordheim current density j

$$j(E) = \frac{A}{\phi}(\beta_s E)^2 exp\left(-\frac{B\phi^{3/2}}{\beta_s E}\right)$$

where β_s is the electric field enhancement factor at the surface and A and B are constants. To show the very steep dependence of this current on electric field, we can write the exponent m in $j \sim E^m$ as

$$m = \frac{E}{j}\frac{\partial j}{\partial E} \simeq 2 + \frac{67.4\text{ GV/m}}{\beta_s E}$$

using typical values for the constants. For a pure Nb cavity, the average electric field on the surface is limited to about 50 MV/m beyond which the rf magnetic field exceeds 200 mT and penetrates the bulk causing a quench [3]. The enhancement factor β_s is 1 for a flat perfectly smooth surface and inversely proportional to the local radius of curvature, so small features on the surface can create field emission sites with effective $\beta_s E$ of several GV/m. Another limiting factor is the local tensile stress σ caused by the interaction of the dark current with the electric field given by

$$\sigma = \frac{1}{2}\epsilon_0(\beta_s E)^2$$

which exceeds the tensile strength of Nb at about 4 GV/m, limiting the exponent m to about 19. Typical values measured for m are 10-20 [4]. Due to the large dynamic range of the dark current signal, covering a useful range in accelerating field usually requires use of multiple detector technologies [4, 5]. It is desirable to detect the dark current signal closer to the source. We propose a method to accomplish this in the next section.

CERENKOV LIGHT FROM DARK CURRENT

The proposed technique is shown in Fig. 2. A superconducting cavity assembly can be viewed as a Cerenkov radiator, liquid He, between a set of mirrors: the cavity outer surface (Nb), the He vessel inner surface (typically Ti or stainless steel) and the endcaps [6]. Cerenkov radiation is emitted at an angle θ_c with

$$\cos\theta_c = \frac{1}{\beta n}$$

where β is the speed of the charged particle in units of the speed of light and n is the index of refraction of the medium. The yield N_c of Cerenkov photons per unit energy dE and path length dx is given by [7]

$$\frac{d^2 N_c}{dE\,dx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c \simeq \frac{370}{\text{eV cm}}\sin^2\theta_c(E)$$

for a singly-charged particle. Some of the relevant quantities for different cryogenic liquids are listed in Table 1. The

Table 1: Cerenkov Data for Some Cryogenic Liquids

Radiator	Index n	Cerenkov angle $\theta_c(\beta=1)$	Yield N_{pe} (/cm)
LH2	1.112	26^o	19.1
LHe	1.024	12^o	4.6
LN2	1.205	34^o	31.1
LNe	1.092	24^o	16.1
LAr	1.233	36^o	34.2

photoelectron yield is calculated using the typical quantum efficiency of 0.27 for a photomultiplier tube (PMT) with bialkali cathode. One can improve this by about a factor of 3 by using the higher efficiency VLPC readout technology which naturally works at LHe temperature. An optical port integrated into the helium vessel coupled to a photodetector can be used to provide an electronic signal that could be fed out of the cryostat. The photon yield will be attenuated at the metal surfaces which have a reflectivity of about 0.5 and covering a large area with photosensitive detectors would not be cost-effective or practical in a cavity assembly. The reflectivity can be improved by polishing or coating the vessel interior. The geometric efficiency for light collection is not included in the table and would have to be calculated using ray tracing for the specific cavity, vessel and readout geometry. While the optics of the multiple mirror system is not well-suited for this purpose, a yield of order 1% is plausible.

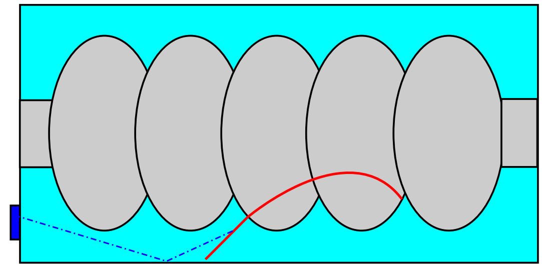

Figure 2: Sketch of the basic concept. An electron emitted from the surface gets accelerated and goes through the cavity wall. It emits a Cerenkov photon which gets reflected from the inner surface of the helium vessel into the optical port where it can be seen by a photodetector.

Application to ILC Cavities

The TESLA design ILC main linac cavities [8] are made up of 9 11.5-cm-long cells made from deep-drawn Nb sheet e-beam welded together at the equators. Cavity walls are mostly 2-3mm thick Nb and an electron would need 2-4 MeV of kinetic energy to punch through. The Cerenkov threshold for an electron in LHe is only 0.3 MeV. The range (due to ionization energy loss) for a 0.3 MeV electron in LHe is over 5 meters. Thus, a field-emitted electron that gets accelerated to a few MeV would create tens of detectable photoelectrons on its way through the LHe with a path length of order 10 cm. The class of field emitted electrons that get enough energy to get through cavity walls depends on cavity design and can only be found by detailed simulation similar to the ones for dark current transport [9]. This diagnostic capability could be engineered into production cavities and provide real-time data in an operating Linac. The signal could also be used as part of the beam protection system. Although this technique should provide a very sensitive indicator for the onset of field emission using a simple integrated optical port, pinpointing the location of the emission site requires a segmented and/or special shaped light detector. More complex arrangements with fibers and strips may be designed. Due to limited space between the cavity outer surface and the He vessel inner surface as well as the extra cost and complexity, such systems are probably not practical for mass production. For vertical test facilities, a more sophisticated system can be designed and integrated into the instrumentation. The gap filled with LHe is usually much larger in that case which should improve the light yield from the extra path length and more favorable optics. A segmented photosensitive surface in a vertical test cryostat can be used to pinpoint the source. The cavity wall is a fraction of a radiation length, so the low energy electrons would receive substantial angular kicks from multiple scattering before getting into LHe.

R&D PLANS

The performance of the technique prooposed here is hard to estimate without detailed simulation including tracking electrons through the rf field inside the cavity, through the cavity walls and LHe and tracking Cerenkov photons through multiple reflections. A detailed model has been built for simulation of electron and photon transport in a TESLA-type cavity assembly based on the GEANT4 toolkit [10]. This will allow evaluation of the light collection efficiency for a realistic geometry. In addition, a cosmic ray test is in preparation for detecting Cerenkov light in liquid cryogens. It is possible to carry out some initial tests with a normal conducting Cu cavity (for higher dark current) in LN2 (for enhanced Cerenkov light yield). Such a configuration may also be applicable in muon ionization cooling [11] where higher gradients from cryogenically cooled normal conducting cavities could provide better beam cooling performance. Detailed design of a practical diagnostic setup will be driven by simulation and hardware test results.

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