JLAB-ACT-97-10

SUPERCONDUCTING RADIO—FREQUENCY TECHNOLOGY : UNDERSTANDING AND IMPROVEMENTS OF LIMITATIONS THROUGH APPLICATION OF CRYOGENIC INSTRUMENTATION

P. Kneisel
Thomas Jefferson National Accelerator Facility
Newport News, Virginia 23606

ABSTRACT

A large number of diagnostic methods have been developed during the last two decades to gain insight in limiting phenomena occurring in superconducting rf cavities during operation. Temperature mapping in subcooled and superfluid helium and x -ray mapping have successfully been applied to understand and subsequently prevent or eliminate loss mechanisms present in these devices. Newer techniques specific to problems such as rf window arcing are under development.

This paper reviews various diagnostic techniques and discusses the impact of their application on progress made in SRF technology.

INTRODUCTION

Superconducting Radio—Frequency Technology has been applied successfully in the last decade in several large scale particle accelerator projects such as TRISTAN, HERA, LEP and CEBAF and is being considered seriously for future applications such as Bfactories, proton accelerators for spallation neutron sources or for the production of tritium, TeV linear colliders and free electron lasers. To a large extent this multitude of applications and the renewed interest in this technology are a result of significant progress in understanding and overcoming the limitations encountered since the 1970's. The systematic application of sophisticated diagnostic methods such as temperature mapping and radiation mapping at cryogenic temperatures in conjunction with computer simulation calculations and surface analytical investigations led to the elimination of the most severe performance limitations of superconducting cavities caused by resonant electron loading (" multipacting") and was instrumental in identifying the causes for field emission loading and thermal magnetic breakdowns in cavities. Since the first use of a chain of carbon resistors by C. Lyneis at Stanford University in 1972[1] to detect the location of a quench area on a cavity, a variety of diagnostic methods have been "invented" to gain more insight into phenomena taking place in a superconducting cavity operated at high gradients. Thorough reviews of the "state of the art" between 1981 and 1985 have been given in [2-4]; this paper will mainly concentrate on refinements of diagnostic methods in the last decade, new developments and the progress made in SRF technology by application of these methods.

BEHAVIOR OF AN SC ACCELERATING CAVITY

A superconducting cavity as typically used in particle accelerator application is usually fabricated from niobium or niobium sputtered on copper. Its response to excitation by radio-frequency energy is described by two parameters, its Q-value and its achievable accelerating gradient.

The Q-value of a cavity is defined as the ratio of the stored energy (W) in the cavity to the power (P) lost in the cavity walls per rf cycle ($\omega = 2\pi f$)

$$Q_0 = W / (P/\omega) \qquad (1)$$

The Q_0-value is inversely proportional to the surface resistance (R) of the material of the cavity walls. The proportionality constant is called the geometry factor (G) and depends only on the geometry and the electromagnetic field configuration in the cavity. It is typically of the order of 270 Ω for structures designed to accelerate velocity of light particles:

$$Q_0 = \overset{\uparrow}{G}/R \qquad (2)$$

The accelerating gradient E_{acc} is defined as the maximum energy a charged particle will gain in the time-varying rf fields by traversing an accelerating gap divided by the gap length. The accelerating gradient is proportional to the square root of the stored energy in the cavity.

$$E_{acc} \propto \sqrt{PQ_0} \quad (3)$$

The accelerating gradient is related to the peak surface electric and magnetic fields in the cavity through Maxwell's equations. Since superconductors go from the superconducting state to the normal conducting state, if a critical magnetic field $H_{crit,sh}$ is exceeded, there are fundamental limitations to the achievable accelerating gradients in a superconducting rf cavity. In the case of niobium as the superconducting material the fundamental magnetic field limit is app. 2400 Oe, which in a typical accelerating cavity corresponds to a gradient of $E_{acc} \approx 50$ MV/m. Such gradients are by far beyond the present state of the art and are typically a factor of 3 to 6 higher than present achievements.

The experimentally observed behavior of a niobium cavity deviates from the theoretically expected behavior in four distinct features as shown schematically in the second curve in figure 1:

(a) The observed Q-value is significantly lower than predicted by the microscopic theory of superconductivity (BCS theory) due to the residual surface resistance caused by anomalous losses and defects in the material.

(b) At certain distinct fields the Q-value might drop to lower values caused by resonant electron loading (" multipacting")

(c) Above a certain field level in the cavity—typically 5 MV/m $\leq E_{acc} \leq$ 15 MV/m— the Q-value decreases exponentially due to non -resonant electron loading ("field emission")

(d) The experimentally observed field, at which the superconducting state disappears ("quench") is significantly lower than the theoretically predicted field as already mentioned above.

All the above listed deviations from the ideal behavior are to a large extent caused by the surface conditions of the superconducting material. This knowledge has been gained through systematic application of diagnostic methods such as prominently temperature mapping or x-ray mapping in conjunction with scanning electron microscopy and elemental surface analysis as well as computer simulation calculations. Whereas the Q_0 vs E_{acc} behavior of a cavity gives a "global" picture of the cavity as a whole—some conclusions of phenomena such as multipacting, field emission or quenching can be deduced from the rf-signal response of the cavity—the application of diagnostics led to significant progress in understanding of localized phenomena in these cavities.[5]

DIAGNOSTIC METHODS

The diagnostic methods, which have been developed during the last two decades can be categorized into three main groups as follows:

a). **Thermal methods**: temperature mapping and use of second sound signals in the helium bath.

b). **Detection of ionizing radiation**: x-radiation mapping, measurements of x-ray energy spectra, electron currents , x-ray photography.

c). **Optical methods**: measurements of optical spectra of light emitted from areas of a cavity via fiber optic cables or the use of "warm" and "cold" optical devices such as a miniature CCD camera.

In the following several of these methods will be described and their usefulness in advancing the understanding of limiting phenomena encountered in these accelerating cavities will be discussed.

Thermal Methods

As described by the BCS theory, an ideal superconductor in a high frequency electromagnetic field has a finite surface resistance, which vanishes exponentially as the temperature approaches absolute zero. In practice however, every superconducting cavity contains on its rf surface small areas, which are either normal conducting or are only weakly superconducting and become normal conducting in electromagnetic fields well below the critical field of the superconducting material. They can also be produced by the impact of high energy and high intensity electron currents during the operation of a cavity.

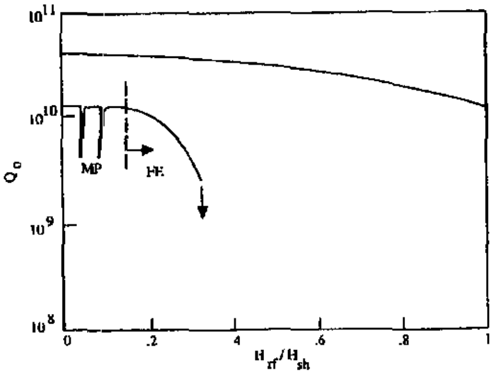

Figure 1. Schematic behavior of a sc cavity in electromagnetic fields

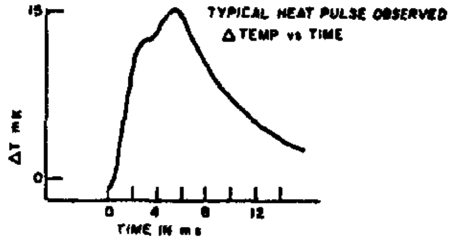

Figure 2. First observed heat pulse from a sc cavity[1]

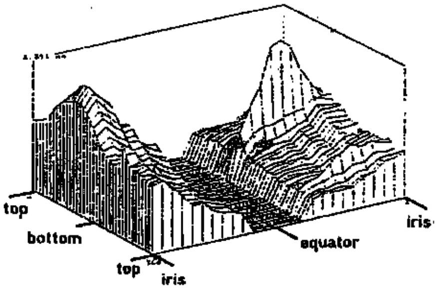

Figure 6. X-ray map[17]

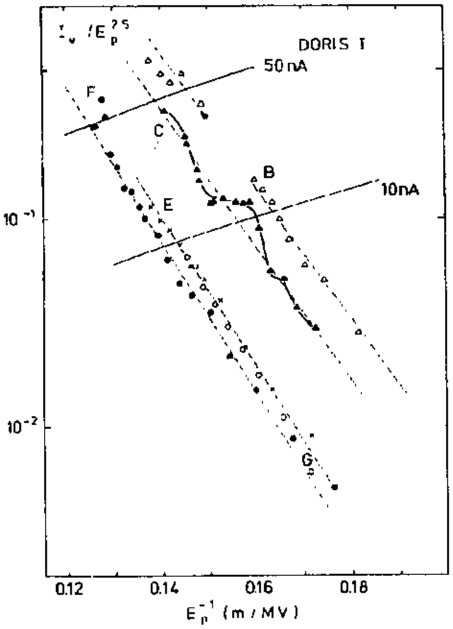

Figure 7. Fowler-Nordheim-Plot from electron current measurements[24]

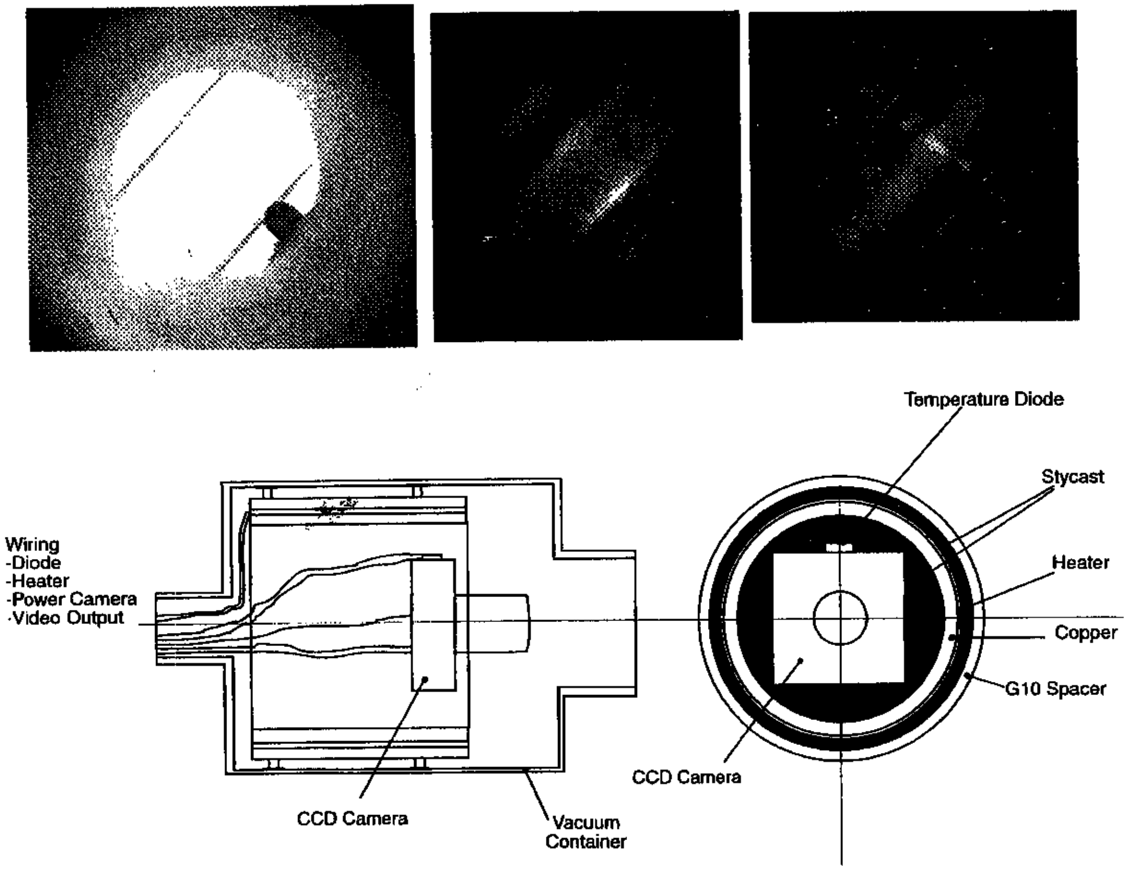

Figure 8. Arcs on an alumina window detected with "cold" CCD camera