X-RAY TOMOGRAPHY OF SUPERCONDUCTING RF CAVITIES*

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Abstract

Field emission loading limits the performance of a significant fraction of the cavities in existing superconducting accelerators. The field emission produces an additional load to the cryogenic system; it is a source of dark current and background radiation in the accelerator; and it can lead to RF breakdown if the cavity is pushed to its limits. The field-emitted electrons are accelerated by the RF field and strike the cavity wall, generating Bremsstrahlung x-rays. The regions of x-ray emission (intensity and energy spectrum) can be located by using a collimated NaI detector placed outside the cryostat and radiation shield. The x-ray emission sites can be reconstructed using tomographic techniques. Particle tracking simulations can be used to trace the field emission electrons back to their source in order to help identify the locations of the surface defects.

INTRODUCTION

Field emission (FE) in superconducting radio frequency (SRF) cavities is a primary factor that limits the surface electric field. Sources of field emission include surface roughness, dust or micro-particles, grain boundaries, adsorbed gas and impurities in the metal itself. Additional sources of electrons such as antenna discharge and multipacting can also limit cavity performance.

FE is normally a steady state phenomenon, but RF breakdown can occur when regular FE currents increase exponentially. RF breakdown further limits the operation of accelerators and can cause irreversible damage to their physical structures. The sequence of events leading to RF breakdown is varied, but typically when under high gradient operation dark current, x-rays, pressure and temperature changes appear before a structure begins to break down.

The field-emitted electrons are accelerated by the RF field and strike the cavity wall, generating Bremsstrahlung x-rays. The x-rays have been detected on general radiation monitoring systems and coincide with a fall of the quality factor (Q) value while the electric field is increased [1]. Though a good determination of cavity performance, the location of the x-rays and the possibility of multiple sources cannot be determined.

X-ray images of a single-cell cavity were taken through a Dewar and magnetic shield using a lead “pinhole camera” and high sensitivity re-useable x-ray film [2]; this approach has proven successful but lacks three-dimensional and energy information.

Carbon resistors placed on the cavity wall have been used for thermometric diagnostics of cavities in identifying the actual electron impact location(s). Field emission simulations are used to locate the source of the field-emitted electrons [1,3]. This system has proven successful also, and has been used by several labs.

In utilizing x-ray tomography, the regions of x-ray emission (intensity and energy spectrum) can be located by using a collimated sodium iodide (NaI) detector placed outside the cryomodule and radiation shield. By positioning the detector in each plane a tomographic image of the cavity can be reconstructed. The image will accurately locate the source(s) and energies of x-rays in SRF cavities being tested or in operation. Knowing the location of the x-rays and the maximum electron kinetic energy, field emission simulations can be used to determine the location of the source of electrons and thus surface defects. Other than FE from the cavity wall the electron source may be discharge from the antenna, multipacting, discharge from the window, residual gases (plasma) in the cavity or residual gases in the cavity that adsorb to micro-particles and change the potential barrier.

When successful, x-ray tomography should make it easier to identify defects and greatly facilitate superconducting radio frequency research and development.

DESIGN

A horizontal test of the β_g=0.47 6-cell cavity for the Rare Isotope Accelerator (RIA) is being planned [4]. This provides good opportunity for x-ray imaging, as the detector assembly can be placed within 50mm of the cryomodule wall. This will provide good spatial resolution of the cavity inside.

A detector with slit collimation, moving perpendicular to slit orientation along the entire cavity length, will locate the source of x-rays in one plane (see Fig. 1a). A 1.5mm slit collimator through 102mm of lead will provide full width half maximum horizontal resolution of 3.3mm to 8.4mm.

The slit will then be replaced with a parallel hole collimator and positioned at the plane of the x-ray source. An angular scan over the cavity diameter will locate emission along a chord (see Fig. 1b). Additional scans will provide three dimensional or tomographic imaging and resolve multiple sources (see Fig. 4). A parallel seven-hole collimator with 1.5mm hole diameter and 1.8mm septa thickness through 102mm of lead will provide full width half maximum resolution of 9.9mm to 15.0mm.

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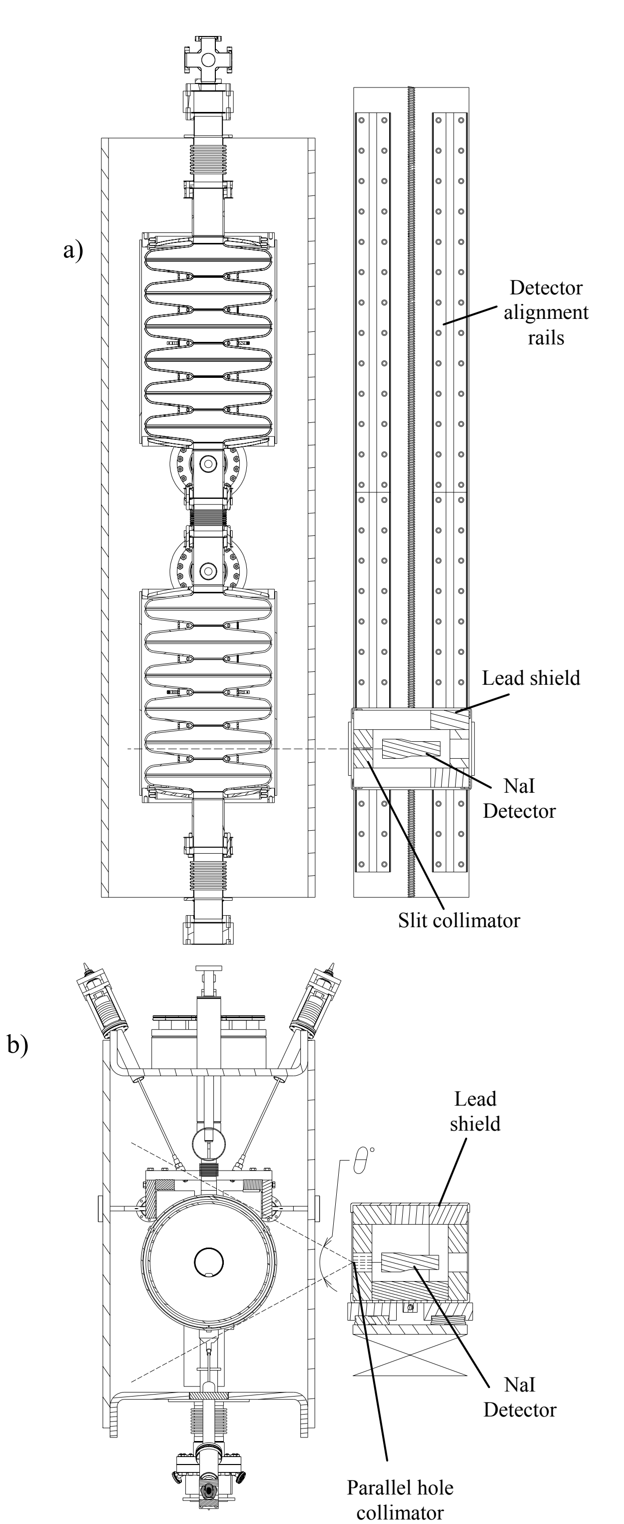

Figure 1: (a) Top view of slit collimator scanning the cryomodule in the horizontal direction [4,5]. (b) End view of parallel hole collimator scanning the diameter of the cavity [4,5].

Detector

The x-ray spectrum is measured with an ORTEC 50mmx50mm integral sodium iodide (NaI) crystal and photomultiplier tube (PMT). Sodium iodide was chosen as the scintillator since it provides adequate energy resolution and good efficiency. Sodium iodide can be obtained in almost any shape and size so it is possible to arrange an array of detectors along the scintillator to form a gamma camera [6].

Data Acquisition

Data is acquired with a digiDART portable multi-channel analyzer (MCA). The portable MCA is connected to a host computer via a universal serial bus (USB) port. The host computer, running a MAESTRO-32 software package, emulates an MCA and is used to display and archive the spectra.

Data Analysis

Energy spectra from a β=0.47 single cell cavity [7] inside a dunking Dewar that was housed in a 0.8m concrete walled bunker were measured. A typical energy spectrum measured with an unshielded, non-collimated Bicron 76mmx76mm integral NaI crystal and PMT located on top of the Dewar lid is shown in Figure 2. An energy spectrum of x-rays decreases monotonically as photon energies increase, and goes to zero at the energy of the electrons generating the x-rays. That is, measuring the x-ray spectrum and locating the endpoint energy determinations the maximum electron kinetic energy. This energy can be compared to that which is predicted.

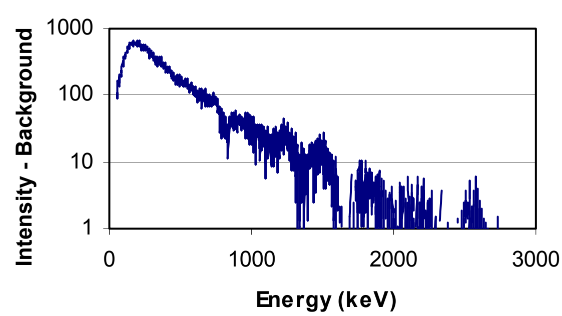

Figure 2: A typical x-ray energy spectrum from a β=0.47 single cell cavity measured on top of the Dewar lid [2]. The peak electric field level in the cavity was 21.88MV/m and the maximum electron kinetic energy 1200keV.

The regions of x-ray emission (intensity and energy spectrum) for the 6-cell β_g=0.47 cavity will be located from outside the cryomodule [4]. Compton scattering will be the predominant x-ray interaction for the range of energies expected and cryomodule materials. When an x-ray is Compton scattered only a fraction of its energy is imparted to an electron. The x-ray travels on in the material at a lower energy and on a different trajectory. The electron travels a short distance losing energy in ionizing and radiative collisions. Therefore Compton scattering increases the intensity of x-rays in low energy channels at a higher rate than the reduction in higher energy channels. Thus binning of the data is necessary to distinguish an actual x-ray source from Compton scattered x-rays. The detector assembly will be placed in a lead housing to essentially eliminate many of the low energy scattered x-rays. A lead filter in front of the detector will allow x-rays above a certain energy to pass and attenuate those below that energy.

Energy spectra from the β=0.47 single cell cavity were measured through a 0.8m concrete wall. The shielded Bicron 76mmx76mm integral NaI crystal and PMT was slit collimated. The slit was moved horizontally, perpendicular to the slit orientation. When the x-ray source was out or range of the slit resolution the intensity of x-rays in the low energy bins increased at a higher rate than the reduction of intensity in higher energy bins due to Compton scattering (see Fig. 3).

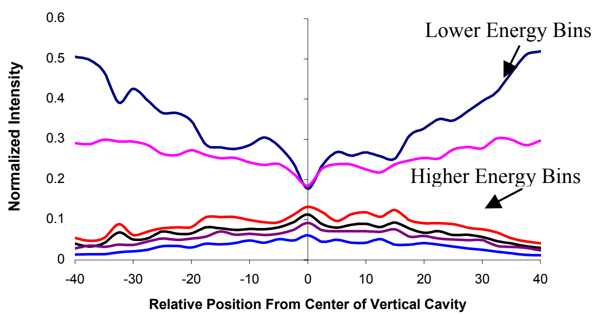

Figure 3: Binned and normalized x-ray energy spectrum from a β=0.47 single cell cavity measured through 0.8m of concrete [2]. The peak electric field level in the cavity varied between 38.22-38.48MV/m.

Image Reconstruction

The initial horizontal scan of the cryomodule, with a slit-collimated detector, will determine the plane where the x-ray source(s) reside. Tomography reconstruction expresses the x-ray emission as a set of pixels covering some mesh. Each pixel then corresponds to a function that is dependent upon position and ΔI, where I is x-ray emission intensity in an energy bin (see Fig. 4).

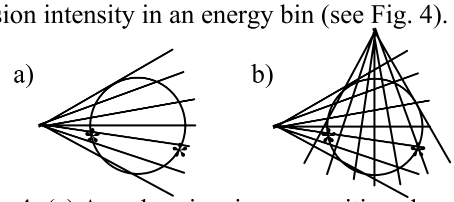

Figure 4: (a) Angular view in one position showing two x-ray sources. (b) An additional view will provide three dimensional information and resolve multiple sources.

Field Emission Simulation

Multipacting/field emission simulation software [3] is used to trace the source of electrons, producing the Bremsstrahlung x-rays, to their point of origin. The software not only predicts the trajectories of field-emitted electrons, but their impact locations, impact energies and the resulting power deposition along the inner surface of the cavity as well (see Fig. 5).

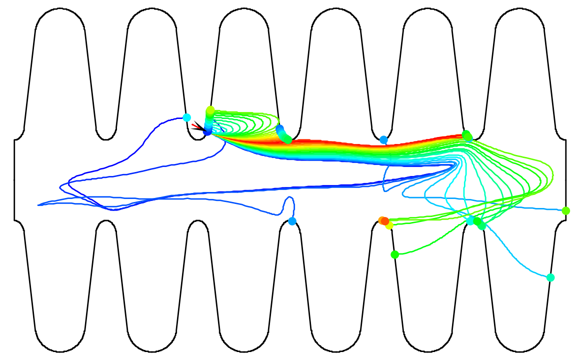

Figure 5: Field emission simulation. The electron emission site is near the iris in the third cell. Primary clusters of electron impact, or primary x-ray emission sources, are seen in the third and fifth cells [3].

FUTURE PLANS/STATUS

When successful, x-ray tomography will make it easier to identify defects and greatly facilitate superconducting radio frequency research and development. The alignment rails and the detector angle positioner are projected for assembly in September 2003. Calibration measurements and data acquisition tests with known sources will follow around November 2003. Test of the 6-cell cavities in the cryomodule is planned for 2004 [4,5]. X-ray tomography will be demonstrated at that time.

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