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Arcing Phenomena on CEBAF RF-Windows at Cryogenic Temperatures*

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Abstract

During the CEBAF commissioning tests some of the superconducting cavities had light emitting discharges (arcing) which were observed in the guard vacuum space between a warm polymeric rf window and the cold ceramic rf window. A dedicated off-line test system was implemented to investigate the conditions under which arcing may occur and to gain some understanding of the mechanisms leading to this phenomenon through optical spectral analysis. This paper reports on the photoemission spectra observed during the dedicated tests on a single cell 1500 MHz niobium cavity with a ceramic window operated at 10 MV/m and 2 K. The light emission was detected using a spectrometer with an intensified photodiode array. The spectral composition of one type of discharge has been measured for standard window material with both TiN_2 and CrO_2 coatings and for a kapton window. Specific spectral lines are identified. The effect of moving the window away from the beam line using a waveguide elbow is also reported.

I. INTRODUCTION

The CEBAF accelerator system uses 338 superconducting niobium cavities at 2 K to provide a continuous electron beam of 200 µA and 4 GeV after 5 recirculations through 2 anti-parallel linear accelerators. Each cavity is equipped with a ceramic rf window located in the input coupler waveguide 7.6 cm away from the beam axis. This window hermetically seals the sensitive superconducting surfaces against the waveguide guard vacuum in line with a 5 kW klystron. The CEBAF rf windows are presently made from a high-purity (99.9%) polycrystalline aluminum oxide (Al_2O_3) sheet of dimensions 13.3 cm x 2.5 cm x 0.4 cm thick, which is brazed to a thin niobium foil frame that is in turn electron beam welded to a solid niobium frame for connection to the waveguide system in a bolted flange joint. This window separates the cavity vacuum space from the guard vacuum space which is separated from the pressurized waveguide by a room temperature polyethylene window.

To insure reliable long term operation of the accelerator with a minimum of interruptions due to interlock trips, several restrictions were placed on the maximum operating gradient in the cavities [1]. One of these restrictions is that an individual cavity not produce an arc more often than once every four days. To meet this goal at the design value of 400 MeV linacs, the maximum gradient obtained in 40% of the cavities was limited by arcing. This arc-rate constraint has limited the operating gradient of 25 cavities to below 5 MV/m. For economic reasons, the maximum klystron power on 288 of the cavities was reduced from the nominal 5 kW to 1.9 kW. This was possible with the commissioning beam current limit of 25 µA with 5 recirulations. With this set of restrictions on the system, the average maximum cavity operating gradient for the 314 operational cavities (two cryomodules not turned on and one cryomodule not installed) is 6.5 MV/m.

In addition to the machine operation issues, these discharges can cause damage to the rf-window, and in several cases we have observed leaks in the bulk ceramic of the window after a large number of discharges. Increasing the machine energy above the design value of 4 GeV will require that more cavities be operated at levels at which arcing may become a problem. Because of the desire for a significant energy upgrade in the future and to improve the reliability of the ceramic window, a better understanding of the phenomena is required.

II. BACKGROUND

These arcing phenomena have been investigated during the past three years, and several reports have been published describing the results [2-8]. Much spectroscopic data presented in this paper were previously presented in reference [8]. They are included in this paper so that the reader may better understand the significance of the recent work. The new work reflects improvement in the diagnostics and techniques which allowed us to better resolve and identify the spectral characteristics of the discharges. Two basic phenomena have been observed which are interpreted to be vacuum discharge phenomena [2–4]. In one type of event, energy stored in the cavity, as measured by the transmitted power signal, is fully dissipated in less than 5 µs . This is accompanied by a large, short duration X-ray pulse of approximately 500 kRad/hr for less than 5 µs and a short intense light pulse which is detected at the beam pipe and on both the cavity and waveguide side of the ceramic window. This class of phenomena, which we call "electronic quench," is interpreted as the effects produced by the sudden injection or liberation of a large number of electrons into the cavity. The electrons and their secondaries quickly absorb the rf energy stored in the cavity and produce an intense bremsstrahlung pulse as they strike the cavity wall, beam pipe, or endplate.

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In the second type of event, the cavity stored energy is dissipated in several hundred microseconds (typically 500 μs) and there is an increase in the pressure of the guard vacuum from about 10^{-9} Torr to 10^{-6} Torr. During this time, light is observed in the waveguide vacuum space. When the cavity energy reaches a minimal level, the discharge is extinguished. This type of event is interpreted as a discharge occurring in the window/rf-coupler region which is sustained by the stored energy in the cavity. It has been observed that the discharge may be sustained indefinitely by rf energy supplied by a 2 kW klystron [2]. The light emission during this type of discharge has three different temporal phases. During the first 5 μs a relatively large light pulse, which has the same temporal and spectral characteristics as that of an electronic quench, is observed. For the next 500 μs an emission, with distinctly different spectral characteristics from an electronic quench is observed. This is followed by a long tail which has spectral similarities to the long decay tail of the electronic quench. [3]

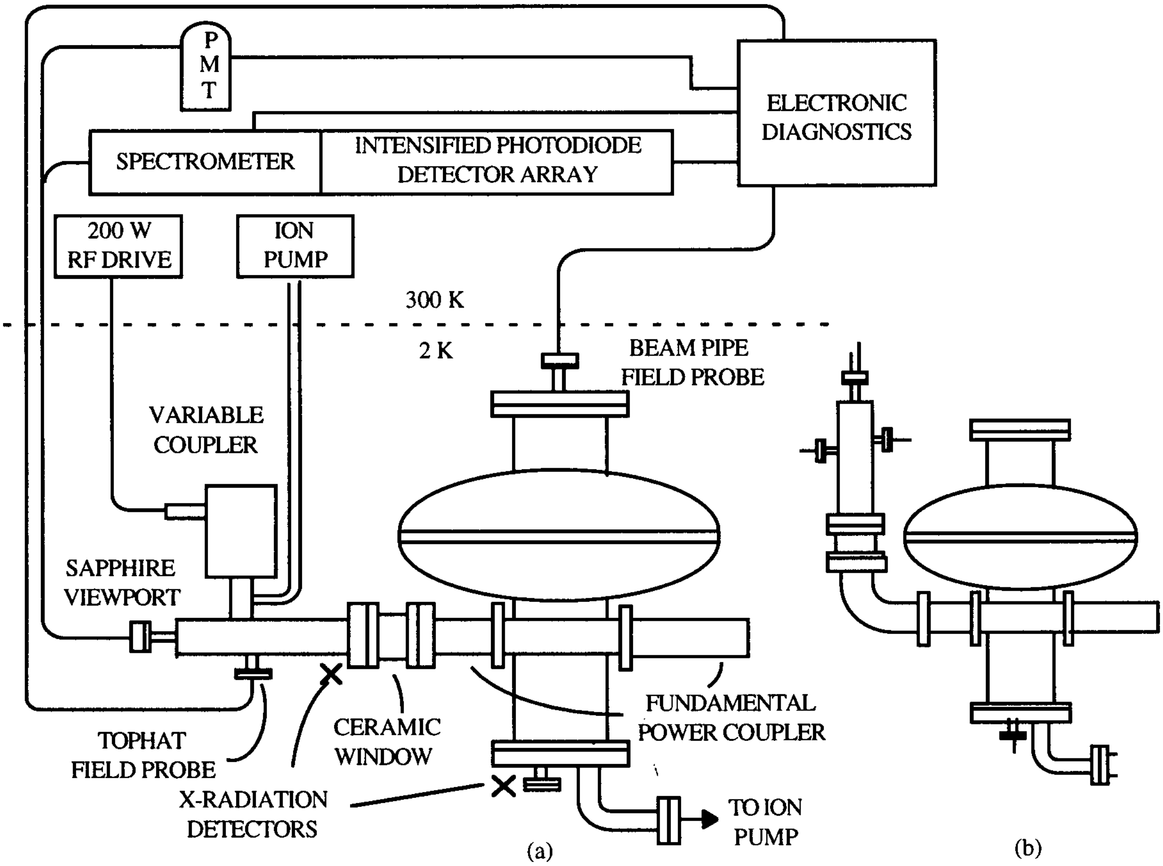

Figure 1. Single-cell cavity configurations used in arc rate and spectroscopic experiments (a) experimental setup with window in standard position, (b) cavity with waveguide elbow.

II EXPERIMENTAL STUDIES

In an effort to better understand the arcing phenomena, off-line spectroscopic studies of the light emitted by the discharge have been performed. The basic experimental setup which used a single cell CEBAF-style cavity is shown in Figure 1(a). The light produced in the waveguide vacuum space was monitored through a sapphire viewport mounted on the coax-to-waveguide adapter. This light was transmitted from the viewport to a PMT and, through a 300 ns optical delay line, to an 0.275 m spectrometer. Commercial grade acrylic fibers which provide reasonable transmission from 350 nm to 720 nm [2] were used as an optical media. The spectrometer was configured with a 990 element intensified photodiode array which allowed the available spectrum to be recorded with resolution up to 0.06 nm. Most data were taken with 0.6 nm resolution. Absolute accuracy was verified using a mercury vapor source. Through the use of gating and delays, different temporal regions of the discharge were examined.

A series of four spectroscopic experiments were performed. In the first experiment, a standard ceramic window configuration was used. In the second, a right angle elbow of about one-half of a wavelength was placed between the fundamental power coupler (FPC) and the same window top hat configuration, see Figure 1(b). In the third experiment, the window frame assembly was removed and a 127 µm sheet of kapton® was placed between the FPC and the tophat, using indium seals. In the fourth experiment a standard window with a CrO_2 coating was used. The spectroscopic data taken for each of the experiments are presented as Figures 2 and 3. Each of the spectral plots for the TiN_2 window and the kapton window represents the average of individual spectra. In the experiments using the CrO_2 coated window the 300 ns delay line was not used and the resultant signal did not require averaging for resolution of the signal.

For the purpose of identifying observed spectral lines, electroluminescence measurements were made on the ceramic material. For this experiment, a sample of the ceramic material was placed in an electron microscope and irradiated with a 100 pA 30 keV beam. The emitted light was collected and transmitted using UV grade fused silica optics and fibers. The results of this data is presented as Figure 4. Arc rate measurements, presented as Figure 5, were taken for the two ceramic window configurations. The standard position test was performed both before and after the elbow experiment to insure that the cavity arcing characteristics were not effected by the experiment.

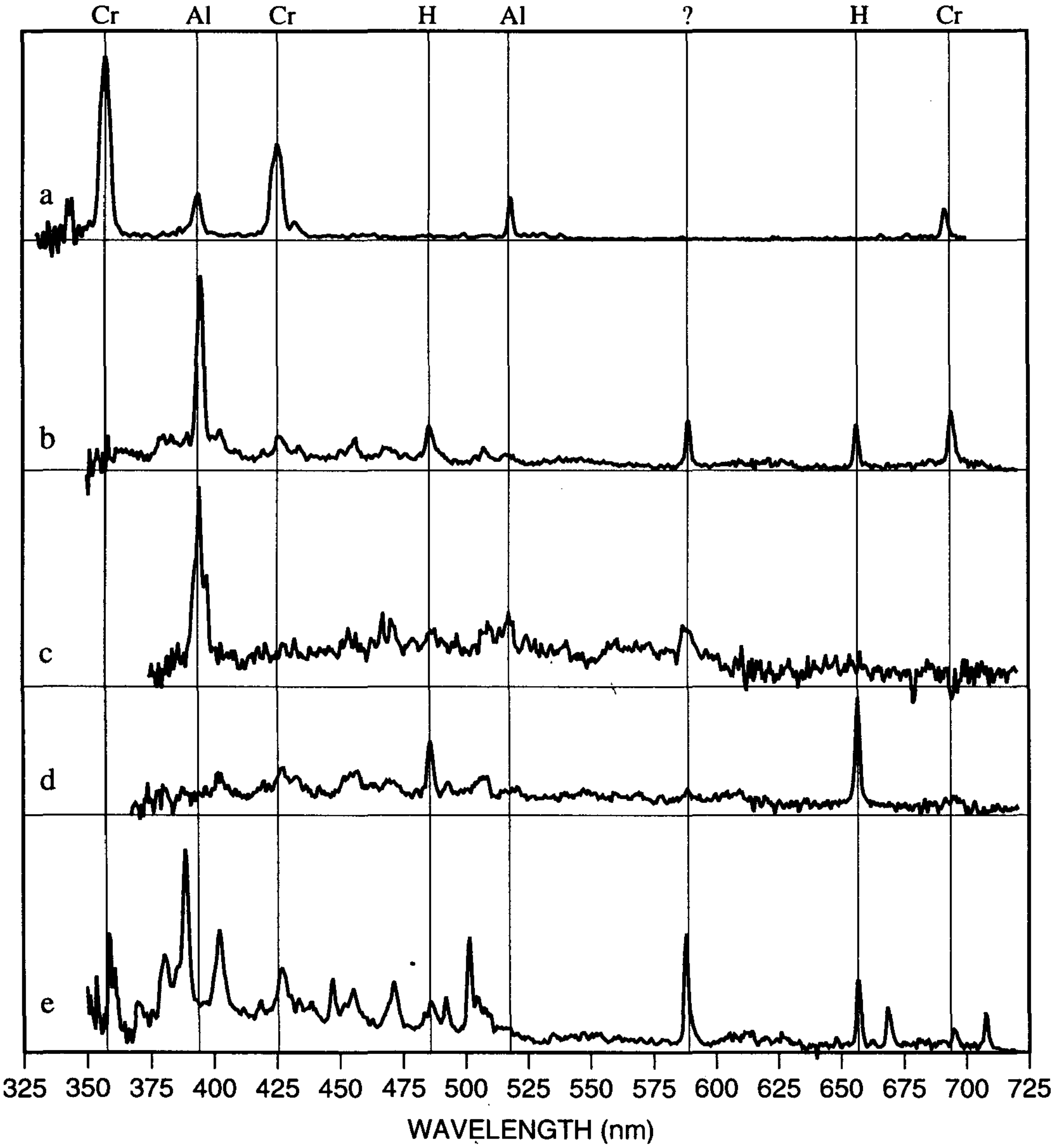

Figure 2. Optical spectra of waveguide vacuum discharges for a) Alumina window, CrO_2 coating, 800 µs gate, b) Alumina window, TiN_2 coating, 800 µs gate c) Alumina window, TiN_2 coating, 1 µs gate, d) Alumina window with elbow, TiN_2 coating, 300 µs gate, e) kapton window, 800 µs gate. Marked spectral lines indicate Cr @ 359.5 nm, Al @ 395.5 nm, Cr @ 427.5 nm (see figure 3 for enhanced resolution), H @ 486.4 nm [9], unknown @ 589.9 nm, H @ 656.3 nm [9] Cr @ 694.1 [10]).

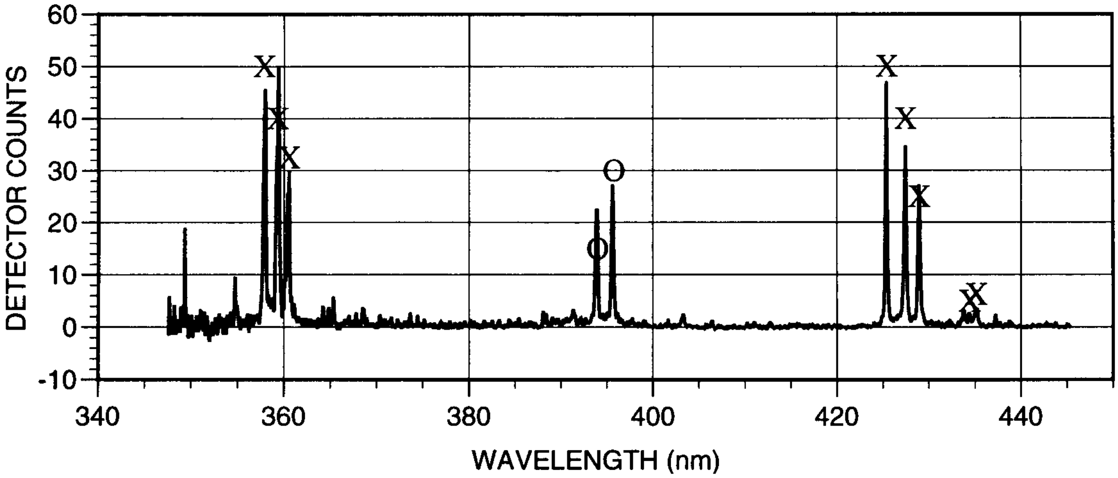

Figure 3. Optical spectra of waveguide vacuum discharge with enhanced resolution showing the chromium spectral lines (357.87 nm, 359.35 nm, 360.533 nm, 425.44 nm, 427.48 nm, 428.97 nm, 434.45 nm and 435.18 nm) and the Aluminum spectral lines (394.40 nm and 396.15 nm) [11].

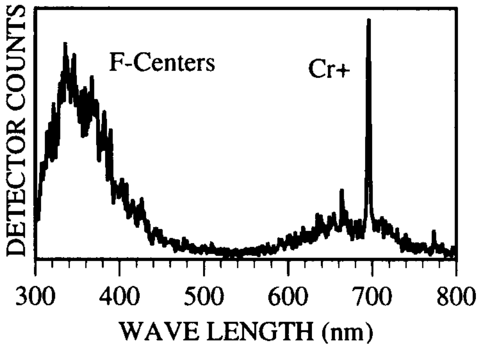

Figure 4. Optical emission spectra from an alumina sample irradiated with a 100 pA, 30 keV electron source. The Cr+ line is located at 694.1 nm. [10]

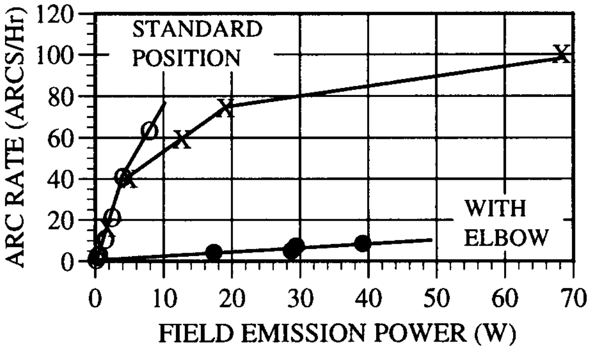

Figure 5. Arc rate as a function of additional power dissipated due to field emission for the same ceramic window with and without a waveguide elbow where the data for the standard position was taken before and after the data with the elbow.

Discussion

The irradiated alumina samples, Figure 4, show the commonly present electroluminescence spectra of alumina [10, 12, 13]: a Cr+ impurity line located at 694.1 nm and a broad spectra centered at 340 nm caused by F-centers. This Cr+ electroluminescence line was again observed in the spectra of Figure 2(a) and 2(b). In the CrO_2 coated window, see figure 2(a) and 3, there were also strong sets of chromium lines centered at 359.5 nm and 427.5 nm. All three of discharges which involved ceramic windows in the standard position, see figures 2(a), 2(b), 2(c), and 2(d) had a set of aluminum emission lines centered at 395 nm. All of the other lines observed in the ceramic window discharges were also present in the kapton window discharge. The hydrogen lines and the line located at 589.9 nm seem to be present independent of the window material. These lines are probably due to desorbed gases which contribute to sustaining the discharge. The group of unidentified spectral lines between 375 nm and 500 nm on the kapton window are assumed to be generated by the kapton, but they have not been identified. Further, the occurrence of the aluminum lines in the data taken during the first 1 μs of the discharge in the ceramic window test (standard position) indicates that the process which generates it may have a significant roll in the initiation of the discharge. The Cr+ line in the more sustained portion of discharges, figure 2(a) and 2(b), is indicative of possible electron bombardment. The additional Cr lines observed with the CrO_2 coated window indicate that the coating is contributing to the discharge.

As can be clearly seen in Figure 5, the displacement of the window further away from the beam axis significantly reduces the arcing rate. The absence of the aluminum line in the spectra of these discharges seems to indicate that the arcing phenomenon might be different in nature than in the standard configuration. The spectral data taken during this experiment show only the hydrogen lines. This further indicates that the discharge process in this configuration is different than the configuration in which the window is exposed to direct secondary electron flux and soft x-radiation.

While the exact mechanisms which initiate the discharges observed in these tests are not well understood, two mechanisms which probably contribute are x-radiation and electron bombardment of the ceramic material. Trajectory calculation of electrons accelerated in the cavity fields indicate that secondary electrons, created when field emitted electrons from within the cavities strike the irises adjacent to the fundamental power coupler, can strike the ceramic window [14]. An additional source of electrons is x-radiation-induced photoemission. Electron currents on the order of 10 nA have been measured on an electrically insulated window frame assembly with a correlation to field emission in the cavity. Some current flow does occur when there is direct radiation through the walls of the cavity [7]. The introduction of a waveguide elbow between the cavity and the window reduces the measured currents.

IV CONCLUSIONS

The spectra measured during a waveguide vacuum arc for four different window configurations has been presented. Several spectral lines have been identified. Lines for aluminum (395 nm) and Cr (359.5 nm and 427.5 nm) have been resolved and confirmed. The aluminum lines centered at 395 nm have been identified as an indicator of a possible arc initiation mechanism when the ceramic window is located in the standard position. Other observed spectral lines were also present in the discharges involving kapton window material and a ceramic window in an alternate location. Electroluminescence measurements were performed which confirm the presence of a Cr+ line at 694.1 nm and a broad F-center emission located at 340 nm consistent with previously seen emission from warm resonant ring studies [13]. The location of the window has a major impact on arcing rate for this cavity. A reduction of arcing rate by an order of magnitude was seen when a window was separated from the cavity by a half-wave right angle waveguide elbow, which eliminated the possibility of direct electron impact of the window. More detailed work is required to understand the complex interdependencies involved in the arcing process.

V REFERENCES

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