FIELD EMISSION AND CONSEQUENCES AS OBSERVED AND SIMULATED FOR CEBAF UPGRADE CRYOMODULES

F. Marhauser#, R. Johnson, J. Rodriguez, Muons, Inc., Newport News, VA, USA
P. Degtiarenko, A. Hutton, G. Kharashvili, C. Reece, R. Rimmer, JLab, Newport News, VA, USA

Abstract

High gamma and neutron radiation levels were monitored at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Laboratory (JLab) after installation of new cavity cryomodules and initial test runs in the frame of the ongoing 12 GeV upgrade program. The dose rates scaled exponentially with cavity accelerating fields, but were independent of the presence of an electron beam in the accelerator. Hence, field emission (FE) is the source of origin. This has led to concerns regarding the high field operation (100 MV per cryomodule) in the future 12 GeV era. Utilizing supercomputing, novel FE studies have been performed with electrons tracked through a complete cryomodule. It provides a principal understanding of experimental observations as well as ways to mitigate FE as best as practicable by identification of problematic cavities.

INTRODUCTION

After operation of two newly installed 1.5 GHz CW superconducting RF cavity cryomodules (CM) at CEBAF (C100-1, C100-2), prompt gamma dose rates up to 10 rad/h and neutron equivalent dose rates up to 2 rem/h were detected [1]. Gamma spectroscopy analysis revealed various short-lived and long-lived radionuclides produced in CM components [2]. The observations conducted by JLab's radiation control department were analyzed in conjunction with numerical computations. For this purpose, Muons, Inc. collaborated with the SLAC ACD group to enhance Track3P, which is part of the ACE3P supercomputing suite of finite element analysis (FEA) solvers [3]. Improvements were incorporated making feasible - for the first time - to track particles through a principally unlimited number of cavities. This allows changing phase and amplitude of each cavity independently. Hereby, electrons can be seeded at RF interiors and obey the laws governed by the Fowler-Nordheim enhanced field emission.

CODE PREPARATIONS

The Track3P executable provided to Muons, Inc. is installed on the Hopper computer system at the National Energy Research Scientific Computing Center [4]. Though the addressable computing resources on Hopper are vast, simulations need to be constrained in reasonable balance with internal code restrictions. The complete CM RF interior comprising eight cavities has been modeled. Non-relevant geometrical features have been avoided to reduce the number of mesh cells. For instance, fundamental power and higher order mode couplers, which may introduce somewhat asymmetric field effects, were omitted to allow modeling only a slice (20 deg.) of the cavity string. Electrons that are captured by the RF fields accumulate the highest energies and are of most interest. These propagate rather close to the beam axis. Hence, potential asymmetric field effects are of less concern for the objective in this paper.

Figure 1 illustrates the meshing sequence by means of a single seven-cell cavity. It ends with a refined surface mesh discretization. This is particularly important for the cavity cell iris regions in order to seed a larger amount of field-emitted electrons into the calculation domain. The small figure at the bottom represents the full system of computed Eigenmodes in the CM, which is used as input for Track3P. For Fowler-Nordheim FE, both the field enhancement factor and material work function will be set initially, which influences the current density, yet not trajectories or impact energies.

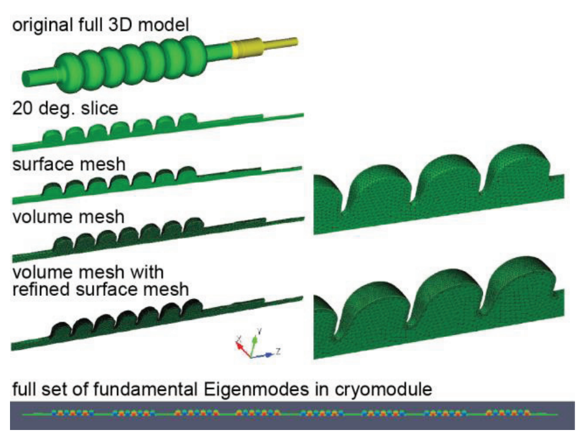

Figure 1: Top left: Modeling and FEA meshing sequence by means of a bare JLab upgrade cavity. Top right: Corresponding close-ups of the mesh. Bottom: Electric field contours of all accelerating modes in the full CM.

OPERATING SINGLE CAVITIES

All JLab upgrade cavities are routinely tested in the CEBAF tunnel during the RF-commissioning stage before beam operation, i.e. at times when only one cavity is powered. For instance, the radiation dose rates during such a test period are plotted in Fig. 2 for C100-1. Hereby gamma and neutron probes were placed upstream (He supply end can side), underneath the midpoint and downstream the CM (He return end can side). The lateral distance from the beamline was 40”. Due to previous test operations of C100-1, residual activation was observed concentrated mostly at the He supply/return end cans. While short-lived isotopes decay typically within 1-2

frank@muonsinc.com

hours, longer-lived isotopes remain and produce background radiation. This explains the different noise floors of the gamma detectors at low operating field levels depending on the probe location. There are no isotopes produced that emit neutrons, such that the neutron probes have a less noisy background floor than gamma probes.

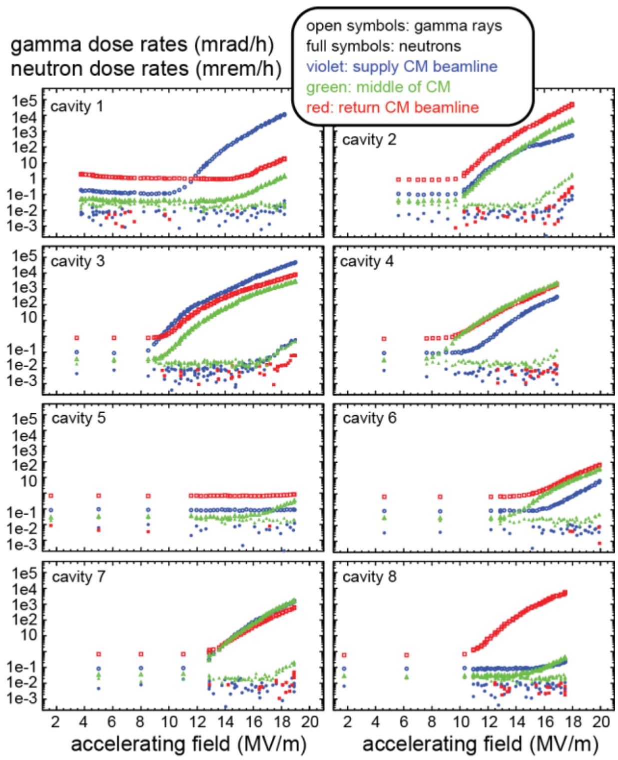

Figure 2: Gamma (mrad/h) and neutron dose rates (mrem/h), respectively, arising from the operation of individually powered cavities in JLab CM C100-1.

Figure 2 reveals that the severity of FE can differ significantly among similar cavities although treated by the same streamlined, elaborated interior cleaning methods. It might generate very high gamma radiation doses in some cavities (e.g. #2, #3), while other cavities (e.g. #5) are spared at the same field levels. Consequently even with state-of-the-art surface treatments, the existence of strong field emitters cannot be excluded. To resemble the observations numerically, the field-emitted electron trajectories and possible impact sites and energies were computed for each cavity. Figure 3 for instance depicts impact energies versus the impact location along the CM, when electrons originate from cavity 2. This specific cavity generated the highest gamma radiation doses with strong bias towards the He return end can of C100-1. The accelerating field (E_{acc}) has been normalized to 16 MV/m. It corresponds to the field level at which the onset for neutron production has been observed, whereas the onset of FE was around E_{acc} = 10 MV/m based on gamma ray signals. The maximum energy that relativistic electrons may gain at E_{acc} =16 MV/m is 11.2 MeV, when traversing a single cavity on axis (0.7 m active cavity length). The calculations reveal that the maximum energy gain is slightly above 10 MeV, when the electrons are emitted from the surface (starting at a few eV). Yet, the achievable energy depends strongly on the site of origin differentiated by the color code in Fig. 3, which covers all eight iris regions of the seven-cell cavity.

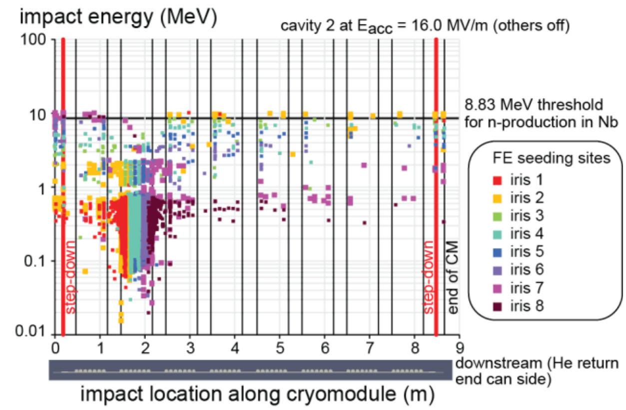

Figure 3: Impact energy versus impact location along the cryomodule. Emitters start in cavity 2 (E_{acc} = 16 MV/m for cavity 2, zero for all others) distinguishing between iris 1 through iris 8 (see color code in legend).

Only electrons emitted from both of the outer cells (irises 1&2 and 7&8) may exceed the threshold for photo-neutron production in Nb indicated by a horizontal line (~9 MeV). Furthermore, the probability for such electrons to traverse the whole CM and hit walls at the ends of the module or escape through the CM is highest, when they originate from iris 2 or 7, respectively. Yet, the monitored gamma dose was about two orders of magnitude higher at the downstream than at the upstream end of the CM. Moreover, neutrons were detected dominantly between the mid and the downstream end of the CM. Consequently, the first cell - specifically iris 2 - is identified as the most probable site for dominant FE. It should be noted that both CM ends exhibit distinct locations, where the beam tube steps down in diameter by more than a factor of two. This step has been introduced to limit the heat conduction from the warm CM inter-connecting beam tubes into the cryogenic enclosure. The black vertical lines in Fig. 3 mark the start and end position of each cavity, while the two red vertical lines correlate with these step-down locations. It clarifies that a significant portion of the high energy electrons are scraped off at these positions. This is rather unfavorable since field-emitted electrons are eventually stopped in thick copper walls used as thermal heat intercepts. Radionuclides with the highest radioactivity have indeed been measured arising from Cu (among other metals like Al, Nb, stainless steel) concentrated at the downstream end of C100-1 [2].

OPERATING ALL CAVITIES

While the neutron yield is yet rather low during RF-commissioning (one cavity powered at a time), the situation changes once all cavities are powered and relative phases of cavity fields are set for 'on crest' conditions. This is the normal operational scenario in

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CEBAF with beam. This case has been resembled numerically, e.g. for Fig. 4 with all cavities operating at E_{acc} = 16 MV/m (90 MeV energy gain). The focus is again on cavity 2 with emitters seeded on iris 2.

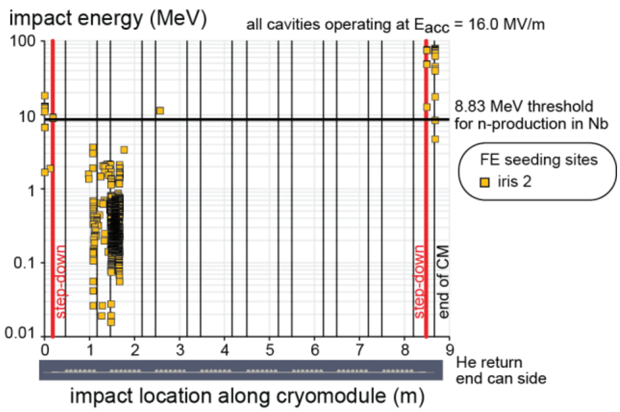

Figure 4: Impact energy versus impact location along the CM. Emitters start in cavity 2 at iris 2 (E_{acc} = 16 MV/m).

The bulk of electrons that can hit the step-down at the He return end can side accumulate energies up to about 75 MeV. This can create an elevated neutron dose compared to the upstream end with energies up to ~20 MeV only. In fact, such a bias has been observed during test runs of C100-1 as plotted in Fig. 5 covering a full month of operation. Due to Fowler-Nordheim scaling, the neutron yield increases significantly with the total energy gain. At 90 MeV the neutron equivalent dose rate exceeds 1,000 mrem/h at the He return end can compared to only ~200 mrem/h at the He supply end can side. Note that the envisaged energy gain of JLab CMs is 100 MeV.

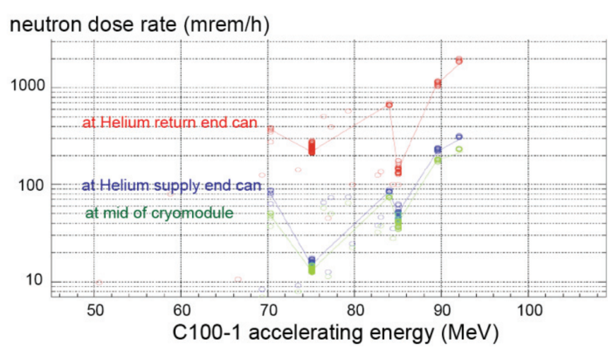

Figure 5: Neutron dose rates arising from the operation of C100-1 at various total energy levels.

Yet, during some test periods the neutron dose rate dropped considerably, in contrast to the exponentially increasing trend. The most pronounced dip is visible at 85 MeV with roughly a factor of five dose rate reduction compared to the operation at merely 1 MeV below. It should be emphasized that at no point was the radiation survey correlated to the more prioritized physics run in CEBAF such that the operating field conditions changed frequently. To understand Fig. 5, individual field amplitudes were analyzed covering a full month period (Fig. 6). It reveals that cavities 2 and 3 were operated merely within E_{acc} = 12-13 MV/m, when the total energy gain was 85 MeV (cf. blue line), i.e. lower than the field levels in all other cavities. At times corresponding to a gain < 85 MeV however, the fields were usually higher by a few MV/m provoking a stronger, dominant FE. This explains the much higher neutron dose rates at 84 MeV compared to 85 MeV energy gain. The dip at 75 MeV (Fig. 5) is explainable by similar arguments [5].

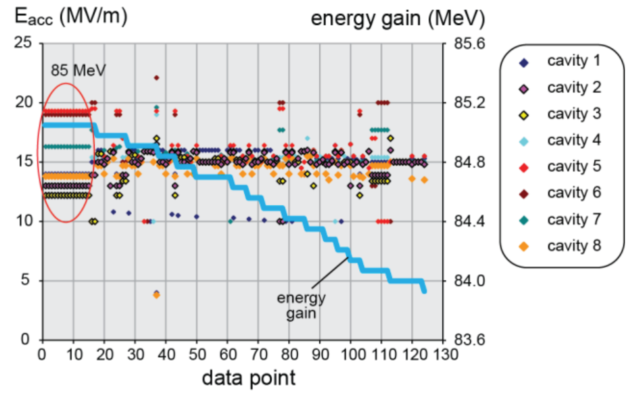

Figure 6: Field levels in individual cavities during radiation surveys (covering a full month) with C100-1 delivering an energy gain (blue line) of 83.9-85 MeV.

SUMMARY

RF field emission studies have been carried out for a full JLab upgrade SRF cavity cryomodule utilizing the supercomputing code Track3P. Track3P has been recently enhanced by the SLAC code developers with the help of Muons, Inc. to allow such novel calculations. Results were correlated with radiological, location-dependent dose rate pattern gathered for the first CEBAF upgrade cryomodule (C100-1) during initial test runs. It explained the biased topology of measured dose rates and allowed to identify the most problematic cavities in C100-1 that carry dominant field emitters (down to a single cavity cell or iris region). Diagnostics engaging neutron probes as field emission indicators have been found to be very helpful, particularly when cavities are powered individually. A significant suppression of the FE-induced dose rates is to ramp down the fields in the problematic cavities only (few MV/m), while trying to compensate for the lost energy gain operating 'quiet' cavities at higher field levels. More detailed studies, which could not be addressed here, can be found in ref. [5].

ACKNOWLEDGEMENTS

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