OPTIMIZATION STUDIES FOR RADIATION SHIELDING OF A SUPERCONDUCTING RF CAVITY TEST FACILITY*

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Abstract

Test facilities for high-gradient superconducting RF cavities must be shielded for particle radiation, which is generated by field emitted electrons in the cavities. A major challenge for the shielding design is associated with uncertainty in modeling the field emission. In this work, a semi-empirical method that allows us to predict the intensity of the generated field emission is described. Spatial, angular and energy distributions of the generated radiation are calculated with the FISHPACT code [1]. The Monte Carlo code MARS15 [2] is used for modeling the radiation transport in matter. The detailed distributions of the generated field emission are used for studies with 9-cell 1.3 GHz superconducting RF cavities in the Fermilab Vertical Cavity Test Facility. This approach allows us to minimize the amount of shielding inside cryostat which is an essential operational feature.

INTRODUCTION

The vertical cavity test facility (VCTF) for superconducting RF (SRF) cavities at Fermilab has been in operation since 2007. The facility currently consists of a single vertical test cryostat VTS1. Radiation shielding for VTS1 was designed for single 9-cell 1.3 GHz cavities using a simplified field emission model as the radiation source [3, 4]. Two additional cryostats with common design, VTS2&3, are being procured, and are sized such that six 9-cell cavities can be installed per cryostat (see Fig. 1). VCTF test throughput will be gained through common cooldown and warmup time, with cavities tested sequentially. Space for additional shielding, either internal or external to the cryostat, is limited. An evaluation of the radiation shielding was performed, to minimally extend the VTS1 shielding design to a six-cavity configuration in VTS2&3 which attenuates radiation consistent with personnel safety standards.

An essential part of the present analysis is in using realistic models for cavity geometry and spatial, angular and energy distributions of field-emitted electrons inside the cavities. The calculations were performed with the computer codes FISHPACT and MARS15.

GEOMETRY MODEL

The full cross section and fragments of the three-dimensional shielding model, showing a simple extension to the VTS1 shielding, are shown in Figs. 2 and 3, respec-
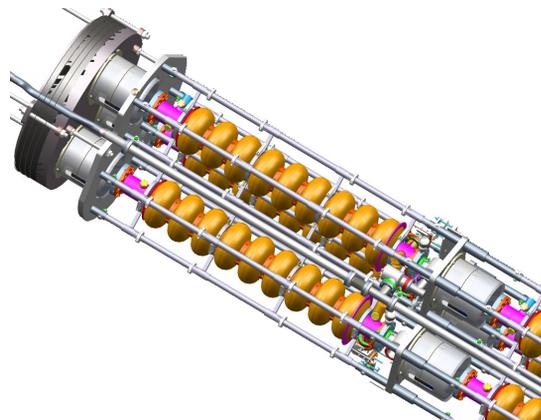
Figure 1: A fragment of a model VTS2 or VTS3 insert with six SRF cavities, showing a simple extension of VTS1 internal shielding, consisting of one stainless steel and borated polyethylene plug, and a lead block at each cavity.

tively. The color scheme denotes materials in the model: white, light blue, gray, red, violet, brown, and pink correspond to vacuum, air, regular concrete, stainless steel, lead, borated polyethylene, and superfluid helium, respectively.
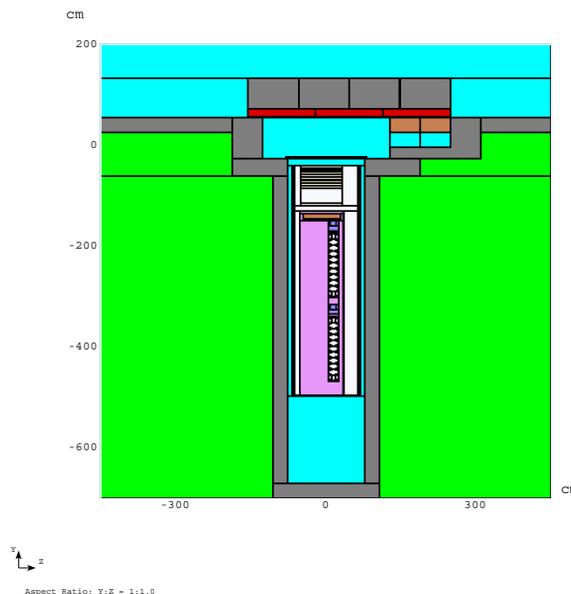

Figure 2: An MARS15 model elevation view of the VTS2 or VTS3 cryostat configuration with six SRF cavities in a simple VTS1 shielding extension.

The external shielding consists of a concrete/steel movable shielding lid and borated polyethylene in instrumentation feedthrough regions. The internal shielding con-

sists of cylindrical lead blocks above each of the cavities and cylindrical layers of steel and borated polyethylene above the upper cavities. Other cryostat components also serve as radiation shielding: (i) layers of copper and G10 above the internal shielding and under the top plate; (ii) the steel top plate; (iii) several cylindrical shells around the SRF cavities—magnetic shield of Cryoperm-10® with aluminum support liner, helium vessel, copper thermal shield, and steel vacuum vessel. Various small components like cables and pipes are not included in the model. The boundaries between different regions are shown with black lines; when the resolution of a figure is inadequate to show small regions, these regions appear black. The realistic cavity geometry was taken from the TESLA design [5].
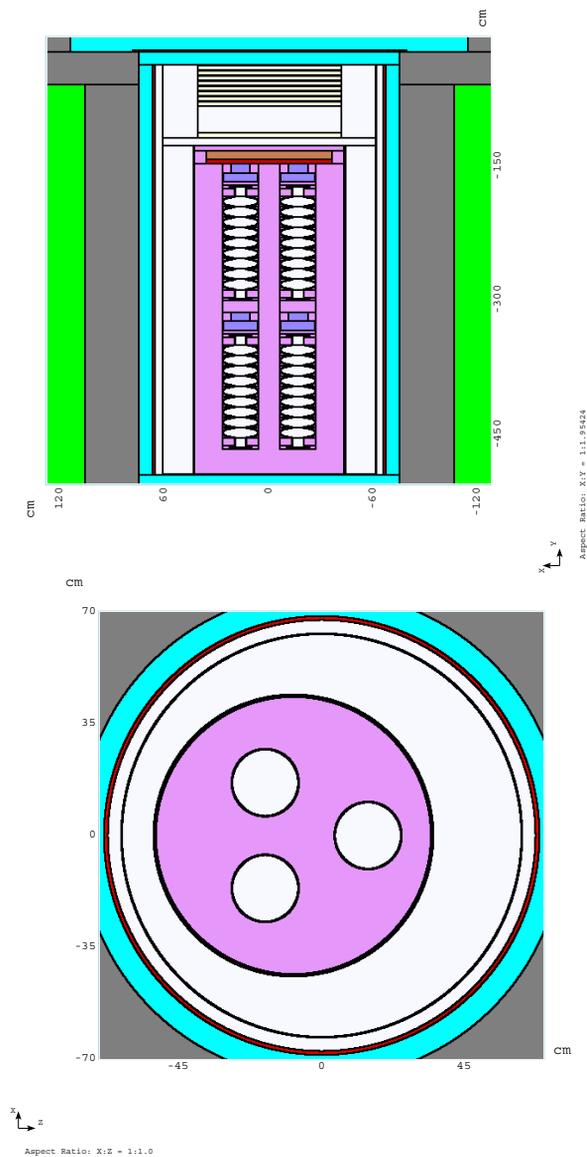

Figure 3: Fragments of the MARS15 model of the VTS2 or VTS3 facility with six SRF cavities: vertical (top) and horizontal (bottom) cross sections.

SOURCE TERM

A realistic two-dimensional model for the radiation source term was developed to describe the trajectories and energy distributions of field emitted electrons generated in SRF cavities at high accelerating gradients. The FISHPACT code has been used to model field-emitted electrons. FISHPACT is interfaced with POISSON SUPERFISH [6], a simulation package used to calculate RF electromagnetic fields. Although the simulation provides a field emission current, given input field emission parameters, only the electron trajectories and energies have been used here. The dose estimated in the simulation using standard parameters from literature [7], was found to be substantially higher than justified by existing data, so data have been used to normalize the predicted dose, as discussed later.

The cavity cell structure and simulated surface electric field are shown as a function of cavity Z in Fig. 4. Electrons emitted from iris regions may be accelerated along the cavity axis and acquire significant energy. An example of simulated trajectories for an emission site in which electrons can reach an energy almost as high as the cavity accelerating gradient is shown in Fig. 5.
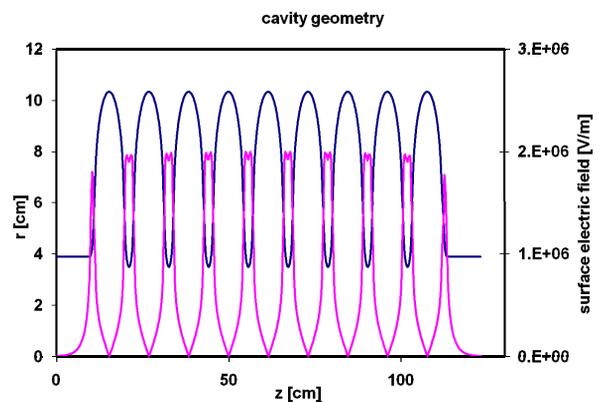

Figure 4: The cavity surface electric field (pink, normalized to 1 MV/m gradient), and the cavity cell structure (blue) as a function of cavity Z from a SUPERFISH simulation. The electric field peaks in the cavity iris regions.

The maximum gradient of 30 MV/m has been chosen to correspond to the largest gradient at which field emission is likely to result in a substantial dose rate immediately above the cryostat, as determined from data. In addition, this is approximately the largest gradient for which the facility must be able to test typical cavities without interrupting the RF system with radiation monitoring system trips.

Dark current generation is assumed to be equiprobable for regions around irises with high surface electric field. For a given emission site, however, the probability of field-induced electron emission depends greatly on the magnitude and phase of the surface electric field (see, e.g., [7]). Therefore the relative probabilities of possible electron trajectories differ significantly, and the most probable trajectories usually do not correspond to the highest electron en-

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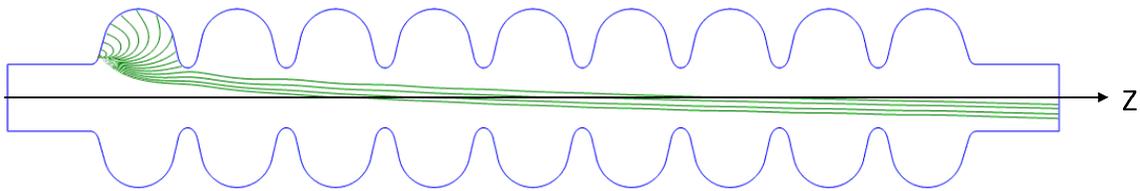
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Figure 5: Simulated electron trajectories generated in a 9-cell SRF cavity with an accelerating gradient of 30 MV/m. The green curves correspond to electron trajectories for 10 degree increments in the RF phase, for the half period in which the electric field has the correct sign to pull electrons from the surface.

ergy gain in the accelerating field. The field emission was generated with azimuthal symmetry.

CALCULATED DOSE DISTRIBUTIONS

The calculated dose distributions were normalized using the measured dose rates for similar SRF cavities obtained from the DESY/TTF vertical test facility [3, 4], in which the dose rate above the cryostat (within the external shielding) did not exceed 5 rem/hr for 90% of the measurements. In the case of the simple VTS1 shielding extension, the predicted dose rate outside the external shielding is less than 0.1 mrem/hr, well within the safety target of <5 mrem/hr.

The internal radiation shield in VTS1 occupies about an hour, or about 35%, of the total cooldown time; for the larger VTS2&3, it is highly desirable to reduce the internal shielding thermal mass as much as possible. Because the lead blocks are such an effective attenuator of radiation, and are so massive, we considered a scenario in which all lead is removed. In this case, the highest dose rate outside the external shielding is ∼40 mrem/hr. The dose distributions around the facility without the lead blocks are shown in Fig. 6. This dose rate can be reduced to acceptable levels using additional steel on the movable external shielding lid; the exact dimensions are yet to be determined but are expected to be well within the shield's load tolerance.

ACKNOWLEDGMENTS

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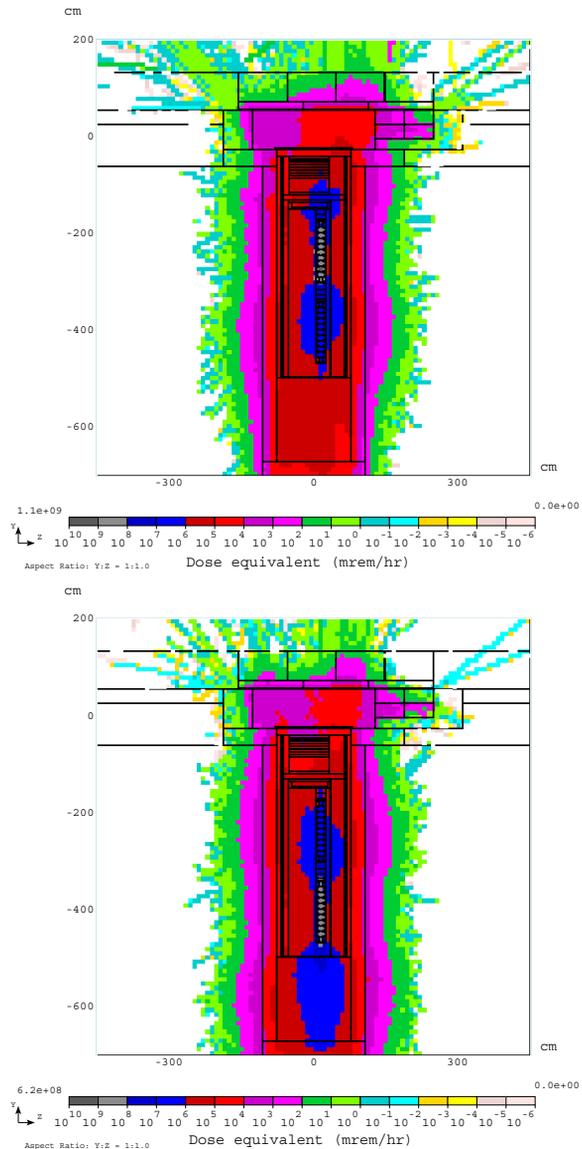

Figure 6: The calculated prompt dose rate distributions with an upper (top) and lower (bottom) SRF cavity tested, for a model with all lead shown in Figs. 1-3 removed.

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