



Radiation Shielding Study for Superconducting RF Cavity Test Facility at Fermilab*

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Abstract

The results of Monte Carlo radiation shielding study performed with the MARS15 code for the vertical test cryostat facility to be installed in the Industrial Building 1 at Fermilab are presented and discussed.

1 Introduction

A vertical test cryostat facility for superconducting RF cavities is planned to be installed in the Industrial Building 1 at Fermilab. The operations will be focused on high accelerating gradients—from 20 up to 50 MV/m. In such a case the facility can be a strong radiation source [1]. When performing a radiation shielding design for the facility one has to take into account photoneutrons generated in photonuclear reactions by gammas which, in turn, are generated due to interactions of accelerated electrons with cavity walls and surroundings (for example, range of 20-MeV electrons in niobium is approximately 12 mm while the thickness of the niobium walls of such RF cavities is about 2.6 mm). The electrons are usually the result of contamination in the cavity.

The radiation shielding study was performed with the MARS15 Monte Carlo code [2]. Due to lack of a reliable model describing the amount and spatial distribution of the field-emitted electrons inside the RF cavities, two the worst case models are introduced and employed in the study. The results of the calculations are normalized using the existing experimental data on measured dose rate in the vicinity of such RF cavities. The tritium production rate in the surrounding groundwater is estimated as well.

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2 Geometry Model

A cross section of the developed three-dimensional model of the test facility is shown in Fig. 1. A fragment of the cross section as well as plan view are shown in Fig. 2. As for the color scheme employed to denote materials in the model, the following convention applies to any system: white, light blue, dark green and grey colors correspond to vacuum, air, soil, and regular concrete, respectively. In addition, in this model the violet, red, light green and brown colors correspond to lead, stainless steel, aluminum and borated polyethylene, respectively. The boundaries between different regions are shown with black lines. It should be noted also that, when the resolution of a figure is inadequate to show small regions, these regions appear as black ones.

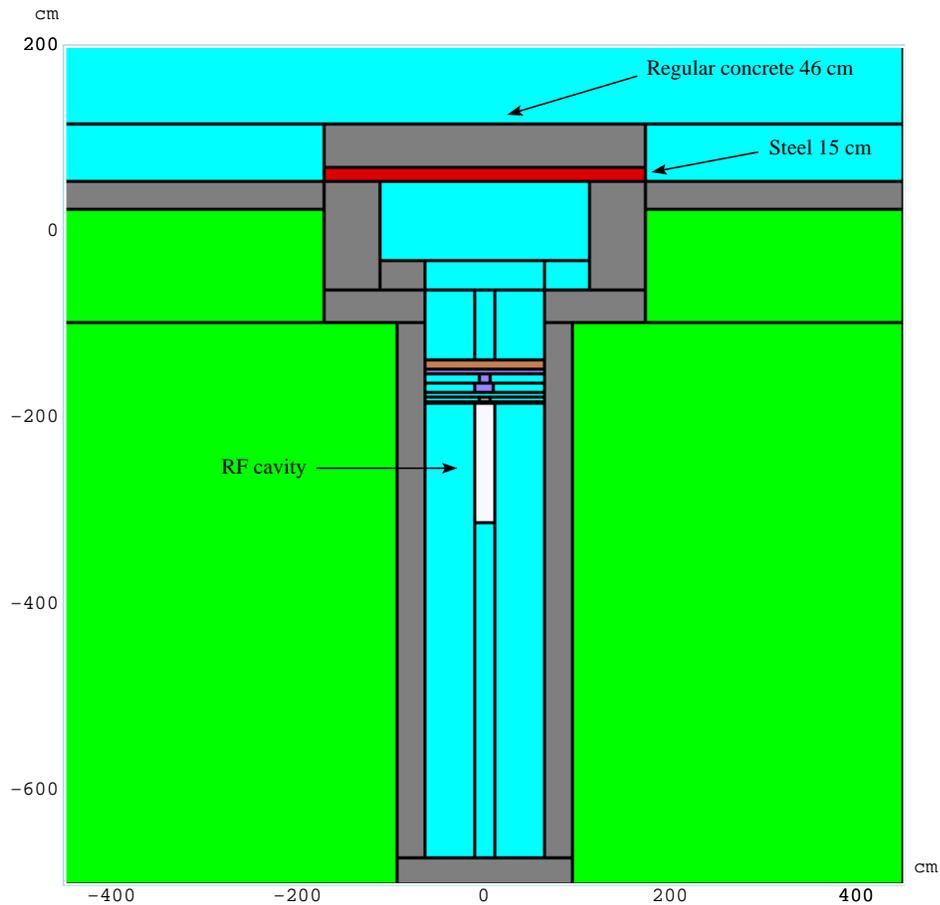


Figure 1: An elevation view of the MARS15 model of the vertical test cryostat facility with an RF cavity in its top position.

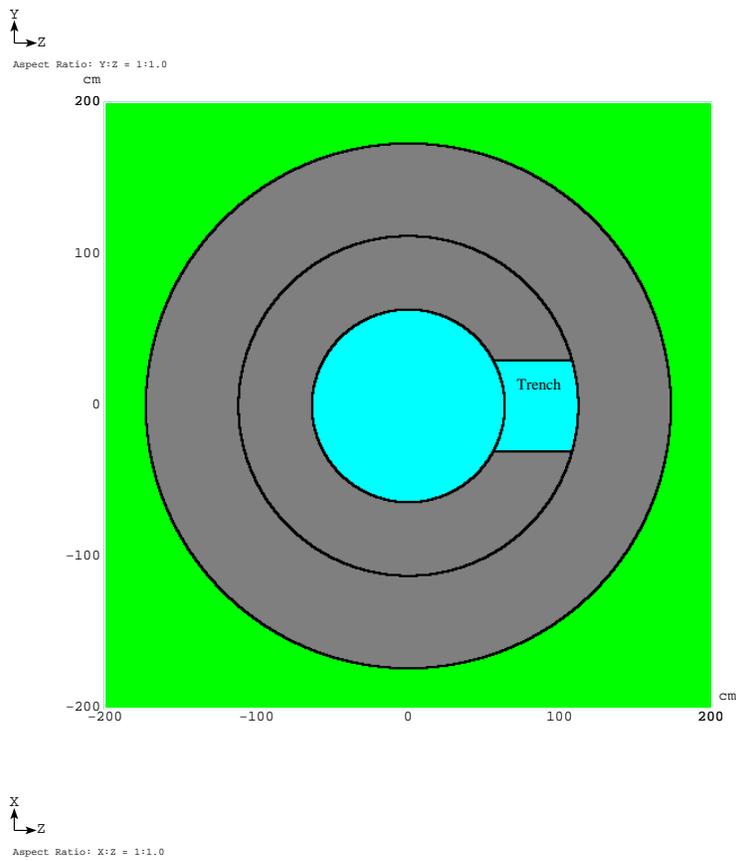
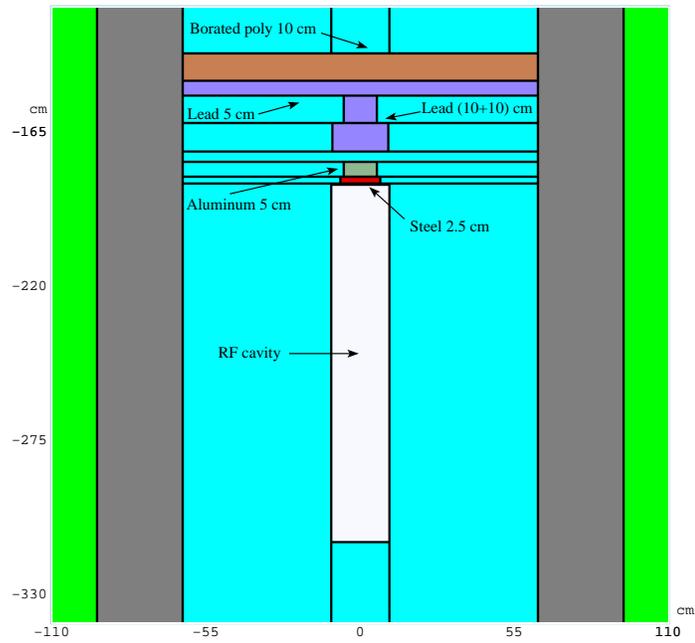


Figure 2: A fragment of the elevation view of the model (top) showing the details around the RF cavity and fragment of the plan view (bottom) taken at $Y = -45\text{cm}$ (see Fig. 1).

In this model the floor level is at $Y = 56\text{cm}$. The asymmetry in the recessed region is due to the existence of an instrumentation trench. The model includes all the components essential from the standpoint of correct description of radiation transport: the RF cavity itself, additional components inside the shaft immediately above the cavity (2.5 cm thick steel plate, 5 cm thick aluminum holder, 20 cm thick lead cylindrical shielding block, 5 cm thick lead layer, and 10 cm thick layer of borated polyethylene above the latter), regular concrete walls, movable shielding block at the floor level, as well as surrounding soil. The cavity itself is modeled as a hollow cylinder 1.3 m long with a radius of 10.5 cm and niobium walls as thick as 2.6 mm. It is supposed that the interior of the cavity is vacuum. The model shown in Fig. 1 corresponds to the most recent design [3]. A real dewar can contain two RF cavities. Only one cavity in its top position is shown in Fig. 1. When in its bottom position, the cavity itself as well as all the layers of the local shielding shown in Fig. 2 (steel, aluminum, lead, and borated polyethylene) are under their corresponding top positions by 130 cm, so that all the relative positions are kept unchanged. In this study, we performed calculations for the facility containing just one RF cavity in its either top or bottom position.

3 Two worst case models

Due to lack of a reliable model describing the amount and spatial distribution of the field-emitted electrons inside the RF cavities, we use two worst case models to calculate dose distributions around the facility and tritium production in the surrounding groundwater.

In the first model we assume that a monodirectional beam of electrons of certain energy (30, 40, or 50 MeV) is going upward and hitting the upper (inner) wall of an RF cavity being tested. Such a scenario implies that the electrons, generated with kinetic energy equal to zero, are accelerated up to the maximum possible energy. It is assumed also that spatial distribution of electrons in the beam to be uniform over a circle with a radius of 5 cm. This is a very conservative model because it gives rise to an overestimate of the dose in the building above the movable shielding block.

In the second model we assume that the electrons of the same energies (30, 40, or 50 MeV) are generated uniformly over the volume of the cavity. This implies an additional conservative factor because it is impossible to generate such high-energy electrons in all regions of the cavity—for example, 30 MeV electrons for the accelerating gradient of 30 MV/m can appear only in the upper region of the cavity. Angular distribution is assumed to be uniform within a solid angle of 0.293π which corresponds to a cone with an opening angle of 45° . Such an angle, probably, overestimates a realistic angular spread of the beam. At the same time, one can estimate the sensitivity of the results to the beam profile.

4 Normalization of calculated data

The level of the electron current that should be used to normalize the predicted dose and tritium production rate is not known. Twelve years of experimental data from the DESY/TTF

vertical test facility were analyzed, and are used to make realistic predictions. The x-ray dose rate was measured 5 cm off axis on top of the stainless-steel top plate (approximately 1 m to 1.5 m from the cavity), *i.e.*, between the radiation shielding internal to the dewar and the shielding outside the dewar. An analysis of the maximum x-ray dose rate, at maximum accelerating gradient, showed that the dose rate was less than 5 rem/hr 90% of the time [4]. The maximum x-ray dose rate ever measured was 58 rem/hr. Although 1 kW is available, the forward power was limited to 250 W at the cavity for equipment safety reasons. For a single cavity, the x-ray dose rate as a function of accelerating gradient increases approximately exponentially; however, the maximum dose rate varies from cavity to cavity and cannot be correlated directly with accelerating gradient. In addition, it was found that the cavities reaching the highest gradients do not field emit significantly; indeed cavities which put substantial forward power into field emission cannot reach high gradients, so any field-emitted electrons would have lower energy.

Therefore, the experimental upper limits are taken independent of the maximum accelerating gradient, which provides a conservative estimate of the x-ray dose rate at highest electron energies. The consideration of different accelerating gradients is only to show the difference in the secondary particle production for the different electron energies. The maximum gradient achieved was 41 MV/m; a 50 MeV upper limit for electron energy is also very conservative.

5 Calculated dose distributions around the facility

The calculations have been performed for the accelerating gradients of 30, 40, and 50 MV/m with the cavity in its either top (see Fig. 1) or bottom position. An example of the calculated dose distribution around the facility for the gradient of 30 MV/m is shown in Fig. 3. Table 1 lists the calculated highest dose rates on the top of the movable shielding block (15 cm of stainless steel and 46 cm of regular concrete) for all the cases considered.

Table 1: Calculated highest dose rate (mrem/hr) on the top of the movable shielding block for several accelerating gradients (MV/m) and for the two models described above (see section 3).

Position of the cavity	Accelerating gradient	Model 1	Model 2
Upper	50	5.7	1.4
Upper	40	5.0	1.1
Upper	30	4.2	0.81
Lower	50	3.3	0.78
Lower	40	3.1	0.70
Lower	30	2.7	0.58

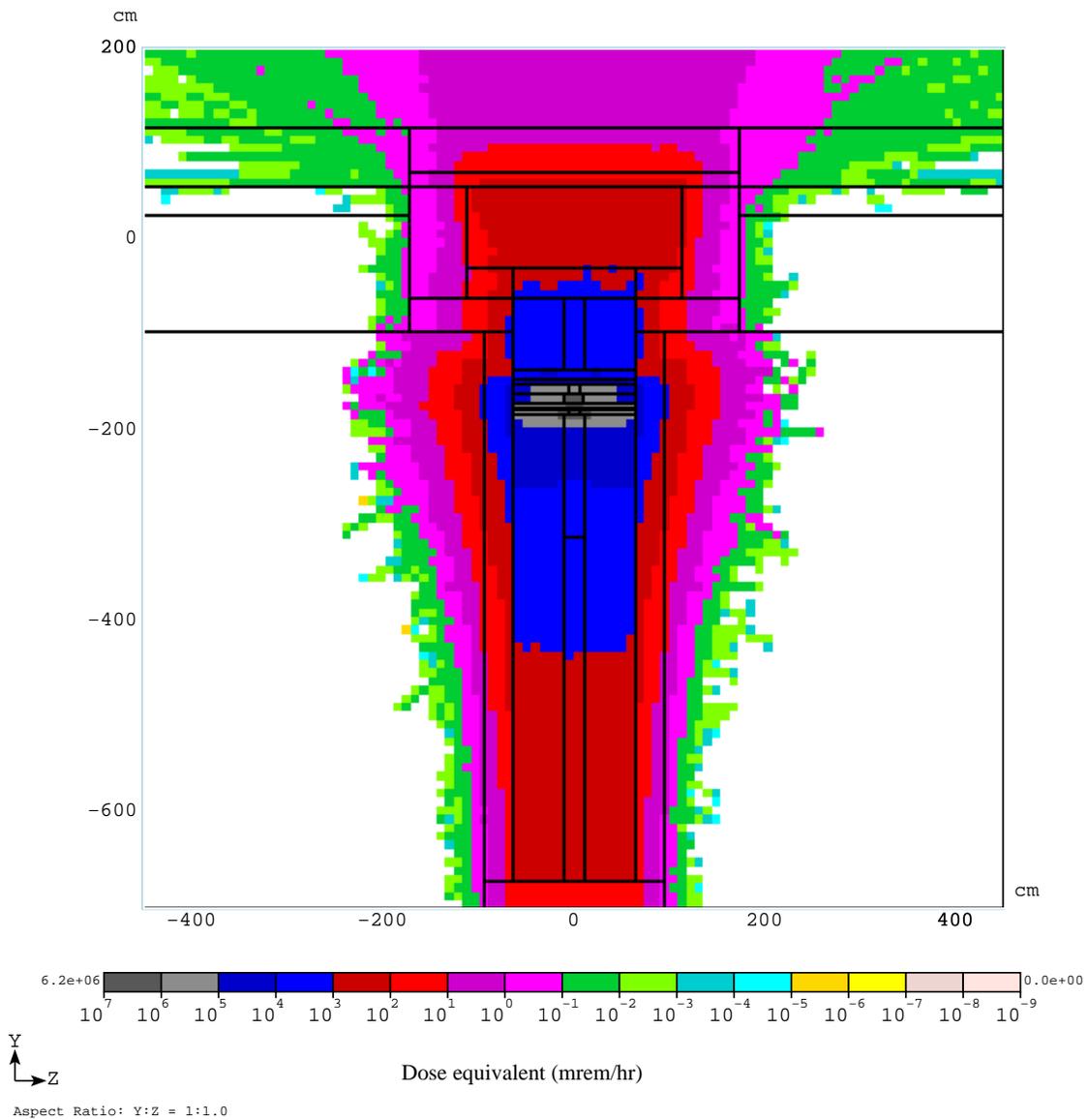


Figure 3: The calculated dose rate distribution around the facility according to the model 1 (see section 3) for the accelerating gradient of 30 MV/m and with the RF cavity in its top position.

The employed normalization means that for all the considered accelerating gradients and without the 5-cm layer of lead and 10-cm layer of borated polyethylene (see Fig. 2) the dose rate approximately 1.25 m above the cavity should be equal to 5 rem/hr. However, even with such a normalization the higher accelerating gradients corresponding to higher electron energies give rise to higher energies of secondary gammas and photoneutrons. Therefore, the dose rates presented in the Table follow the trend. Anyway, the bottom position of the RF cavities is preferable from the standpoint of better radiation shielding.

According to the Fermilab Radiological Control Manual [5], the dose rate above 0.25

mrem/hr and below 5 mrem/hr corresponds to a controlled area of *minimal* occupancy, while the dose rate above 0.05 mrem/hr and below 0.25 mrem/hr corresponds to a controlled area of *unlimited* occupancy. The calculated data reveal that the top of the movable shielding block corresponds to the former definition. One can see also that the dose rate at $Z \simeq 230$ cm is about 0.25 mrem/hr and, when going upward in the air, 60 cm along the Y axis provide for the dose reduction factor of about two. The data means that normal working areas such as offices will be maintained at a radiation level lower than 0.25 mrem/hr, so that they can be qualified as controlled areas of *unlimited* occupancy.

6 Calculated tritium production rate

Due to generation of gammas with energies potentially up to 50 MeV and, consequently, photoproduction of neutrons one has to calculate the tritium production rate in the surface water and groundwater. For this purpose one has to determine first the so-called “99% volume” in the surrounding uncontrolled soil that contains approximately 99% of all stars generated in the soil. After that one needs to calculate activity of the tritium generated in the volume. The details on how to determine the “99% volume” can be found in Ref. [5]. However, there is an uncertainty in determining the volume because usually a “star” refers to an inelastic nuclear interaction with kinetic energy above 50 MeV per nucleon [5]. At the same time, there will be no neutrons above 50 MeV around the facility and, following the definition, no stars. To avoid the uncertainty, we prefer to use the 30 MeV star production threshold according to an approach used in other related studies [6]. The amount of generated tritium nuclei does not depend on the star production threshold because the realistic excitation functions taking into account realistic threshold behaviour of the tritium production in nuclear reactions are used in these calculations.

It has been determined in our calculations, performed for the most conservative case of 50 MV/m, that the “99% volume” corresponding to the 30 MeV star production threshold is a cylindrical layer a few feet thick and about 16 feet in height. The amount of tritium nuclei generated in the volume is equal to 9.43×10^{-9} per electron generated in the RF cavity being tested. After proper normalization (see section 4) this gives rise to the production rate of 1.76×10^3 $^3\text{H}/\text{sec}$. According to an estimate based on experience at JLab, the facility will be in operation, most likely, for about 80 hours a year [7]. Then the latter rate yields 5.15×10^8 $^3\text{H}/\text{yr}$ which means the activity of 3.40×10^{-7} $\text{pCi}/\text{g} \cdot \text{yr}$. If one takes into account that soil contains about 10% of water, the conservative estimate will give rise to the generated tritium activity of 3.40×10^{-6} $\text{pCi}/\text{ml} \cdot \text{yr}$. For any reasonable lifetime of the facility, the latter is significantly lower than the allowed limit of 2000 pCi/ml [5], so that the tritium production around the facility can be neglected.

7 Conclusions

The radiation shielding study performed with the MARS15 Monte Carlo code for the vertical test cryostat facility revealed that, in the worst case scenario, the tritium production

around the facility can be neglected. Taking into account all the uncertainties of the employed models as well as the conservative style of our approach, one can state that the suggested shielding will provide for the dose rate in the building not exceeding 5 mrem/hr in the immediate vicinity of the shielding and not exceeding 0.25 mrem/hr in normal working areas such as workbenches and offices. According to the Fermilab Radiological Control Manual, this corresponds to the definition of a controlled area of *limited* and *unlimited* occupancy, respectively.

8 Acknowledgements

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