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FIELD EMISSION ANALYSIS IN SRF CAVITIES FOR PIP-II USING GEANT4

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ABSTRACT

Field emission (FE) remains a significant hurdle for achieving optimal performance and reliability in superconducting radiofrequency (SRF) cavities used in accelerator cryomodules. A thorough understanding of the generation and propagation of FE-induced radiation is therefore essential to mitigate this problem. The absence of standardized measurement protocols further complicates the comparison of radiation data across different testing phases and facilities. This highlights the need for a precise quantitative method to diagnose and analyze FE-induced radiation. Such efforts could prove beneficial for improving cavity preparation and cleanroom assembly techniques during the prototype and production stages of Fermilab's Proton Improvement Plan-II (PIP-II) project. This study presents the initial steps of detailed Geant4 simulations aimed at analyzing FE-induced radiation in the low-beta 650 MHz 5-cell elliptical (LB650) cavity. Our goal is to combine these results with radiation diagnostics to enhance diagnostic accuracy and optimize detector positioning. This integrated approach ultimately aims to improve the preparation, assembly, and testing procedures for PIP-II SRF cavities, ensuring the delivery of FE-free cryomodules.

INTRODCUTION

- High electric fields in RF cavities can initiate field emission (FE), a quantum mechanical process known as the tunneling effect. This process is often triggered by contaminants like dust, metal flakes, adsorbed gases, or other impurities.
- The RF field accelerates these electrons, draining stored energy and reducing the cavity's quality factor (Q_0).
- When striking the cavity walls, the electrons cause intense localized heating, adding extra load to the cryogenic system, and generate Bremsstrahlung radiation mainly in the form of X-rays.
- The impact point of field-emitted electrons can be far from their emission site, since their trajectories are shaped by the time-varying RF fields inside the cavity.
- X-ray detection outside the cryostat is the most common diagnostic for FE during cavity testing, offering ease of use and quantitative information.
- This study represents an initial effort to reconstruct FE radiation during low-beta 650 MHz (LB650) cavity testing at Fermilab's Spoke Test Cryostat (STC).
- CST Microwave Studio was used to simulate field-emitted electrons and their trajectories in the RF field, providing the impacting electron energies at various emission sites.
- These results were then used as input for Geant4 simulations to model FE-induced radiation and investigate the directionality and propagation of X-ray emission.

SOURCE PARTICLE GENERATION

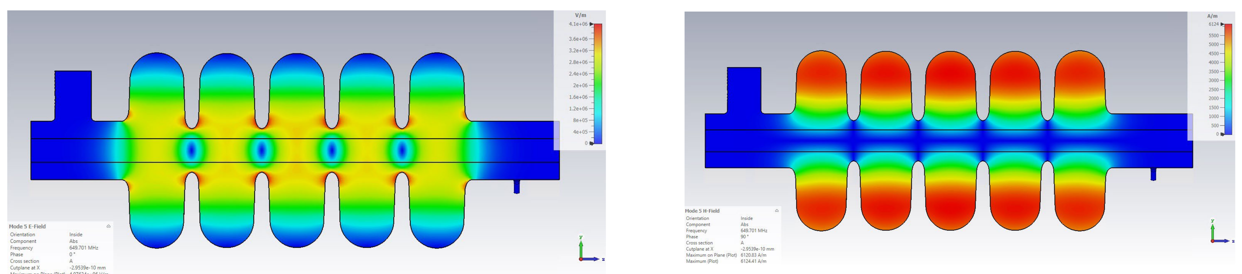

Fig. 01: Simulated electric and magnetic fields (respectively) for the LB650 cavity from CST microwave studio eigen mode solver.

Table 01: LB650 cavity parameters.

Cavity Parameters	LB650
β_G	0.61
β_{opt}	0.65
R/Q(β_G), Ohms	327.4
R/Q(β_{opt}), Ohms	356.3
$E_{surf}/E(\beta_G)$	2.43
$E_{surf}/E(\beta_{opt})$	2.33
$B_{surf}/E(\beta_G)$, mT/MeV/m	4.6
$B_{surf}/E(\beta_{opt})$, mT/MeV/m	4.41
G, Ohms	187

Used the CST particle tracking (TRK) solver to simulate the field-emitted electron trajectories.

- Import E and B fields from the above eigen mode simulations and scale them to the operating Eacc = 16.4 MV/m (for fixed RF phase).
- At least 5E5 emitter locations were placed near the iris.
- The emission model was chosen as field-induced, and the coefficients of the following equation were determined by comparing to the Fowler-Nordheim equation.

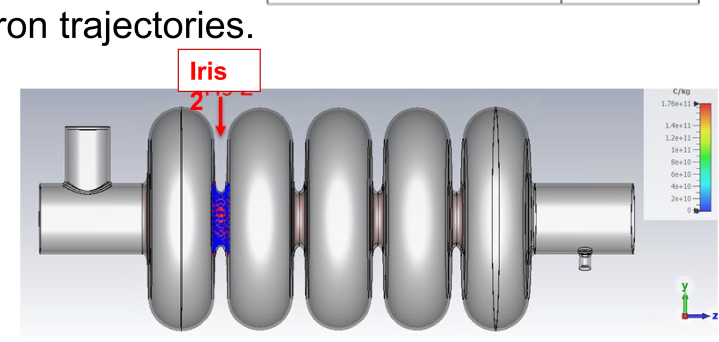

Fig. 02: Particle source area- selected iris2.

$$J = aE^2 exp\frac{-b}{E}$$

β_{FN} (field enhancement factor) = 100
ϕ (metal work function) = 4.3 eV for Nb

$a = 3.58 \times 10^{-3}\frac{A}{V^2}$ and $b = 6.09 \times 10^{8}\frac{V}{m}$

- The initial electron energy is determined by a temperature of 2 K, following the Maxwell-Boltzmann distribution.
- Max energy reached: ~ 6 MV/m, Simulation time: 2.6E-9 s
- Saved the position and momentum of each electron at the end of its trajectory.

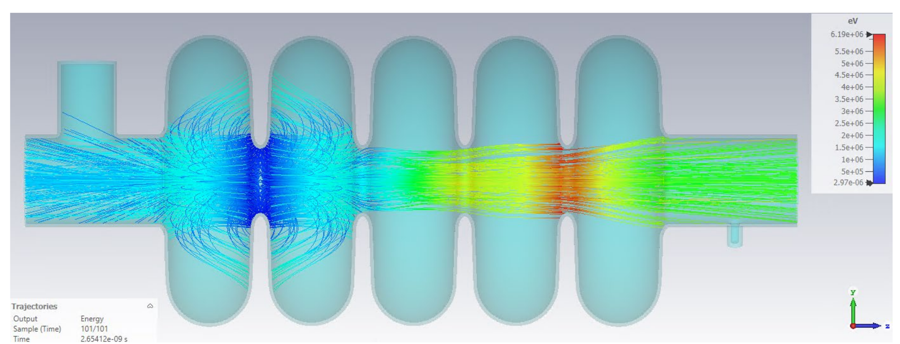

Fig. 03: Electron trajectories.

GEANT4 MODELLING

- The Fermilab Spoke Test Cryostat (STC) consists of several different layers of shielding as shown below.

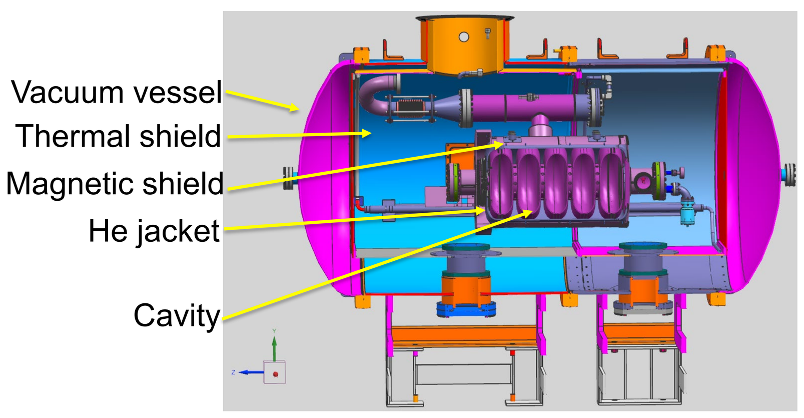

Fig. 04: STC cavity assembly.

Table 02: STC shielding layer details.

	Thickness [mm]	Material
Vacuum vessel	12.7	Stainless Steel
Magnetic shield	1.6	FeMnCrNi
Thermal shield	4.8	Al
Magnetic shield	1.5	FeMnCrNi
He jacket	5.0	Ti
Cavity	4.7	Nb

- **Purpose of Geant4:** Geant4 is a Monte Carlo–based software toolkit designed to simulate the transport and interaction of elementary particles through matter.
- **Physics Processes:** The main physics processes of interest are bremsstrahlung, Compton scattering, and ionization.
- **Physics List:** The G4EmStandardPhysics_option4 (including multiple scattering) was used to accurately model electromagnetic interactions.
- **Design Construction:** The G4Polycone class was used to create the LB650 cavity geometry, while G4Tubs were implemented to represent the shielding layers with their actual dimensions and materials.
- **Primary Particle Generator:** Electron details were imported from the above CST simulations for each iris location. Generated 1 M electrons through random resampling and utilized the NERSC HPC facility to run the simulation.
- **Particle Tracking:** Particles were tracked two different ways: as they exited the cavity volume and the vacuum vessel and traveled up to 2 m (rad detector location).

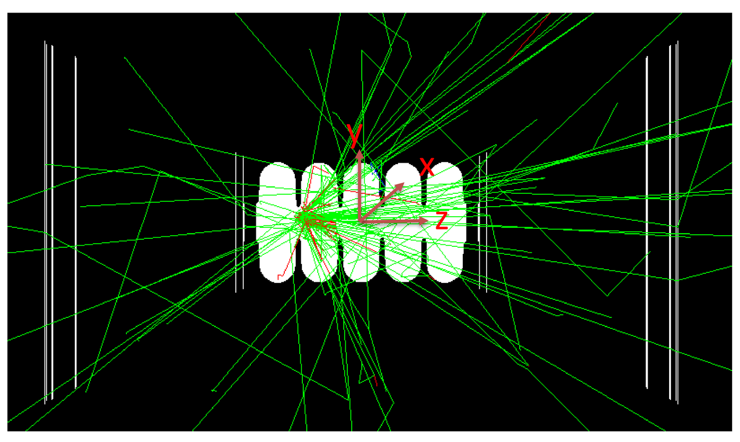

Fig. 05: Geant4 simulation.

RESULTS ANALYSIS

- Results are shown for the iris 2 location.

Particle tracked exiting the cavity volume.

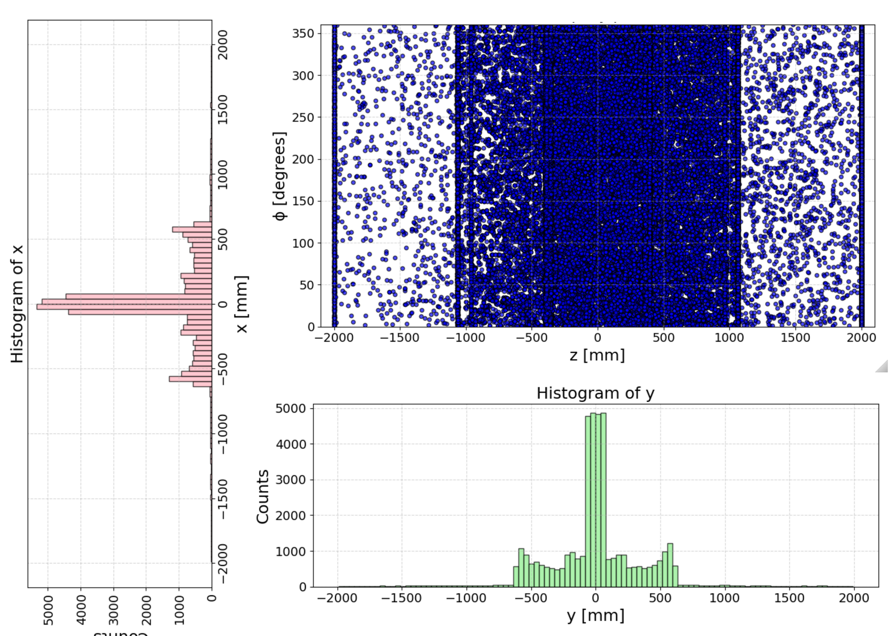

Fig. 06: Simulation of gamma ray collection, the histogram represents the photon count on the x and y axes.

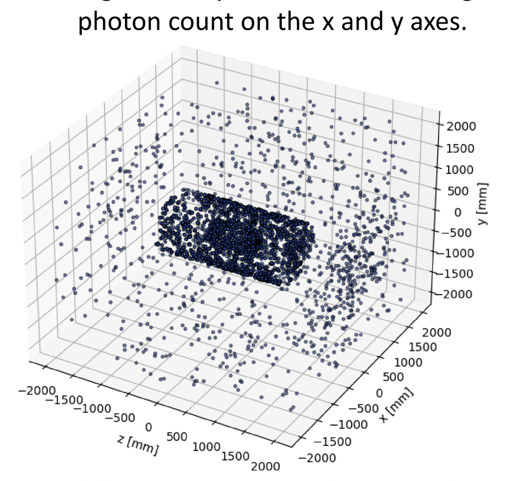

Fig. 07: Illustration of the gamma ray distribution in the STC cave up to 2 m.

Particle tracked exiting the vacuum vessel.

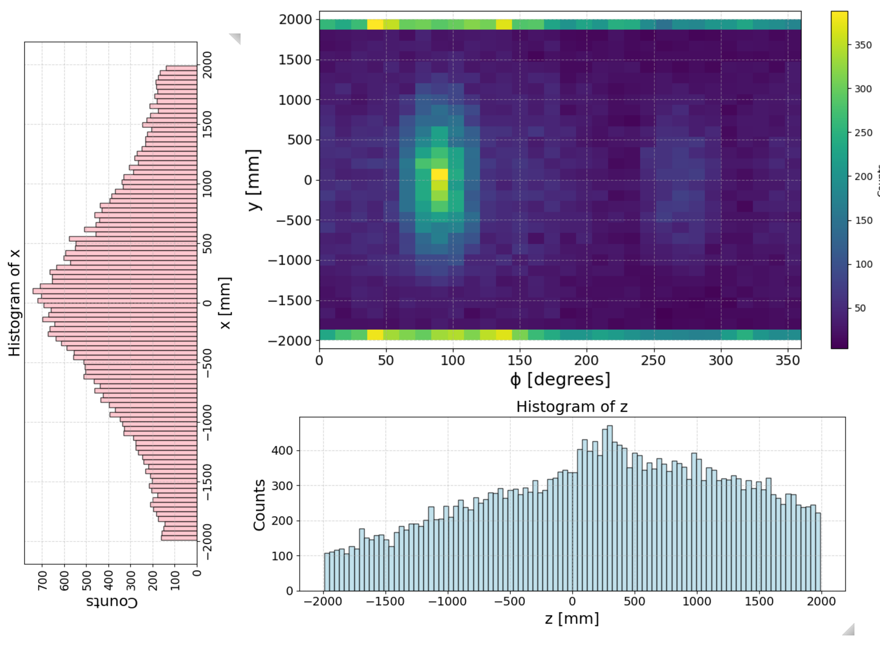

Fig. 08: Simulation of gamma ray collection, the histogram represents the photon count on the x and z axes.

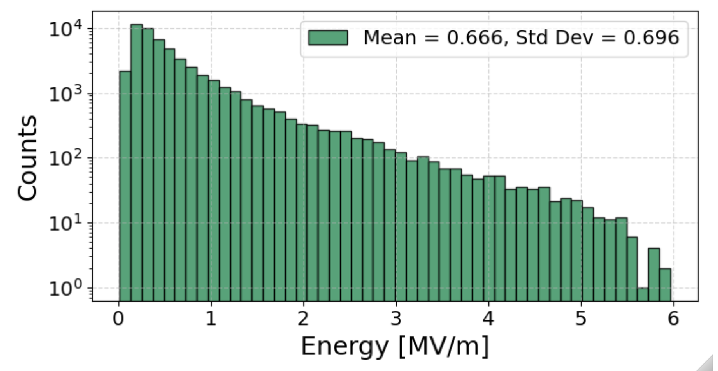

Fig. 09: Emitted gamma ray energy distribution. Less than 1% of gamma particles have energy > 5 MV/m.

- Different shielding layers have absorbed most gamma rays.
- Simulation shows ~5% of gamma particles, generated by primary electrons, penetrate the vacuum vessel and reach the 2 m boundary.

SUMMARY AND OUTLOOK

- Successfully developed a simulation model using CST and Geant4 software to analyze the FE in LB650 cavities at STC.→ first step toward understanding X-ray directionality and propagation.
- Performed systematic FE radiation analysis at different iris locations over the full RF phase → to identify the most probable field emission sites.
- Integrate radiation detectors into the Geant4 model and compare with LB650 cavity radiation measurements → enhance diagnostic accuracy, optimize detector placement
- Extend simulations to SS1, SSR2, and HB650 cavity assemblies at STC and compare with corresponding radiation measurements.
- Extend the simulation model to analyze FE in PIP-II cryomodules.

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