FIELD EMISSION RADIATION CHARACTERIZATION OF LCLS-II CAVITIES*

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Abstract

LCLS-II xFEL facility at SLAC will accelerate 300 µA, 4 GeV CW-beams in a new superconducting linac. Cavities and full cryomodules will be tested at Fermilab and JLAB, including radiation levels generated by dark current. The latter parameter needs to be controlled to ensure safe operations, and a broad lifetime of radiosensitive components near the cavities.

We describe the studies performed for LCLS-II, from which an acceptable dark current limit was established, and the subsequent simulations of vertical tests that will serve to indirectly determine via radiation measurements whether cavities meet this limit.

RADIATION STUDIES FOR LCLS-II COLD LINAC

Field Emission Generation and Extraction

Field emission generation and extraction was computed with Track3P [1], a 3D finite element particle tracking code with a grid of curved elements that fits the curvature of the boundaries, thereby allowing high-fidelity modeling of the geometry and correct emission angles for particles.

Primary emission of electrons from RF fields is computed according to the standard Fowler-Nordheim [2] formula, where the emission current (J[A/m^2]) as a function of position and time *(r, t)* is determined by the work function of the material (φ [eV]) and the product of the strength of the surface electric field (E [V/m]) and the local field enhancement factor (β):

$$J(r,t) = 1.53 \cdot 10^{\left(-6+\frac{4.52}{\sqrt{\varphi}}\right)} \cdot \frac{(\beta \cdot E(r,t))^2}{\varphi} \cdot e^{\left(-\frac{6.53\cdot 10^9 \cdot \varphi^{1.5}}{\beta \cdot E(r,t)}\right)} \quad (1)$$

The RF fields were imported from SLAC finite element field solvers [3]. Primary field emission particles were generated within one quarter of the cross section whenever the electric field exceeded the emission threshold, and tracking was performed for up to 60 RF cycles. Randomization over the 2π angle was carried out during post-processing.

Particle conditions were dumped into impact files that record dark current impacts on cavity walls, as well as current escaping at the ends of the 8-cavity string in a cryomodule.

Tracking Field Emission and Its Radiation Showers

Fluka [4–6] is an intra-nuclear Monte Carlo radiation transport code that uses microscopic models to simulate interactions with matter and with magnetic fields of about 60 particles in a wide energy range generally spanning between 1 eV and 10000 TeV. Numerous subroutines are configurable by users, allowing for the extensive customization that was required for these studies.

Field emission collision or cavity exit events generated by Track3P were imported into FLUKA to perform the radiation transport. Those electrons that made it to neighboring cryomodules were written into data files an imported back to Track3P to perform the transport under fast-cycling EM fields in the cavities. The resulting impact files were in turn used again as seed in FLUKA. This process was repeated up to 9 cycles. Thus, the two codes were actually hard-coupled, i.e. there were no calls between the two. Instead, in a first 9-step pass, all impact files were pre-computed, and in a second phase FLUKA would randomly select events from within those source files.

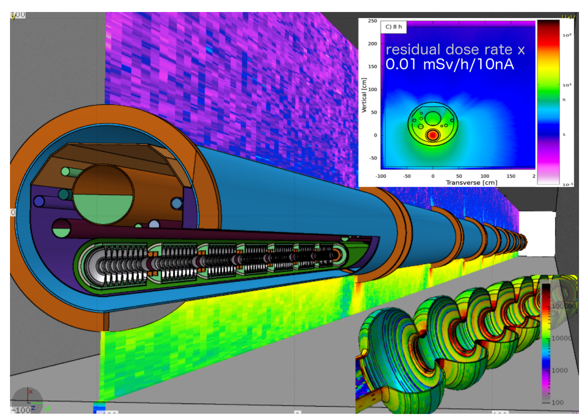

Figure 1: A detailed model of 9 cryomodules (CM) was used in Track3P & FLUKA simulations to define radiation/machine protection levels for a maximum captured current of 10 nA/CM.

To perform the radiation transport, a prototype of an LCLS-II cavity was implemented in FLUKA geometry by fitting the surface profile of each of its nine bulb-shaped cells with eleven quadrics (cylinders, ellipsoids, cones and paraboloids), and then adding other components like the helium cooling tank, flanges, etc. Instructions were coded in Fluka particle source subroutine to recurrently apply micro adjustments to Track3P impact coordinates so that those

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would be within a small tolerance of the cavity inner surface. The cavity model was then copied and translated as necessary into respective three-dimensional descriptions of a string of cryomodule tanks, for LCLS-II Linac studies, or of a vertical test setup, such as that described in next section.

The final setup allowed deriving multiple conclusions [7] about the survivability of radio-sensitive components installed by the cryomodules, the transport of dark current along the linac, and the expected prompt and residual dose rates in different locations.

INDIRECT MEASUREMENTS OF DARK CURRENT

The studies described above were normalized to a maximum field-emission captured current (CC) per Cryomodule (CM) of CC =10 nA/CM, i.e. ≃ 1 nA/cavity. Cavities above that threshold should be identified as early as possible in the fabrication process. In the vertical tests at Fermilab and Jlab, individual cavities will be examined for multiple performance criteria, including how much radiation they generate at different field gradients. Here we provide the calibration values to compute the capture current of a cavity for a given detector reading anywhere around the dewar where cavities are cooled with liquid helium.

Baseline Calibration of Radiation vs. Dark Current

Track3P was used to generate the impact file of a single cavity with no local defects. The Fermilab vertical test bench geometry, including the dewar, containers containers, shielding layers and penetrations was implemented in FLUKA, and the existing model of the LCLS-II cavity was moved into the model. Moreover, the response functions of Canberra GP110 detectors, Fig. 2, that will be used for the tests were programmed in FLUKA on-line fluence weighting routine.

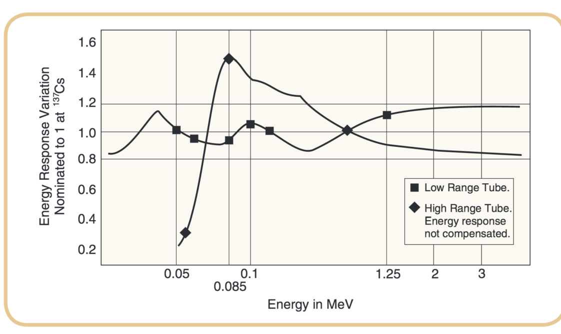

Figure 2: Efficiency curves for CR110 instruments to be used at Fermilab vertical tests.

Figure 3 shows the geometry of the vertical test setup along with a 2D map [μSv/h/nA] which should allow estimating the captured current of a uniformly emitting cavity for any position of a *CP110-High Range Tube* radiation detector. Positions D1-D4 marked in the figure are then referred at in Table 1, showing different types of readings at those locations for "well behaved" cavities.

Table 1: Photon fluence [cm^{-2} h^{-1}/nA] and expected signals at CP110 HR or LR tubes installed at D1 position normalized to 1 nA captured current, and (unnormalized) ratios D1/D2, D2/D3 and D1/D4

Measure	D1/CC [μSv/(h·nA)]	D1/D2	D1/D3	D1/D4
Fluence	177	2.00	5.12	5.34
CP110-HR	202	1.69	4.45	5.32
CP110-LR	189	2.01	5.36	5.44

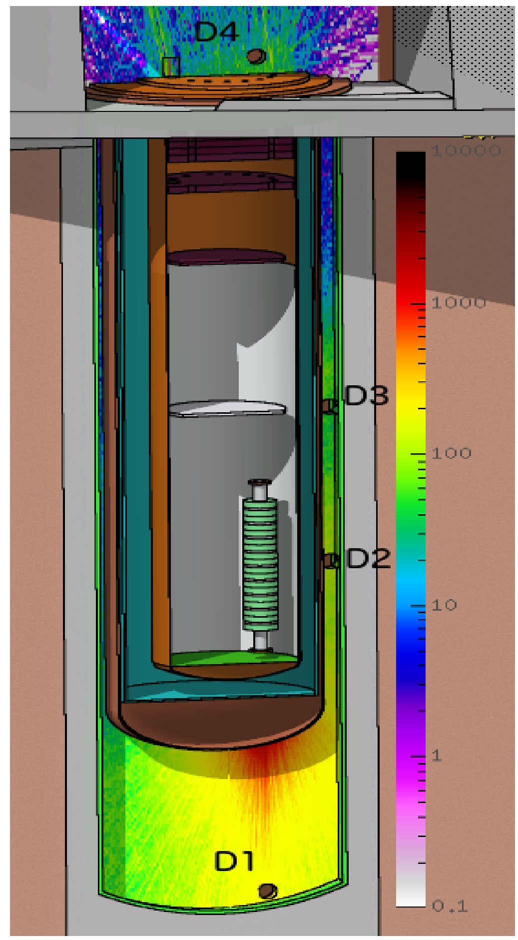

Figure 3: Implementation of Fermilab vertical test setup showing the expected signal [μSv/h] for a Canberra CP110-HR detector per 1 nA captured current.

Study of Radiation Fields for Single Emitters

The previous section describes the radiation field from a cavity with a uniform field enhancement factor (β). This is not always the case, as defects or contamination on the niobium surface, lead to local emitters that may dominate the overall dark current pattern from a cavity. If the number of emitters is low, and most specially if it is just one, then the conclusions from section are no longer applicable. Here we provide some guidelines to identify such situations.

FLUKA subroutines were further customized to first latch impact events read from Track3P dump files with the corre-

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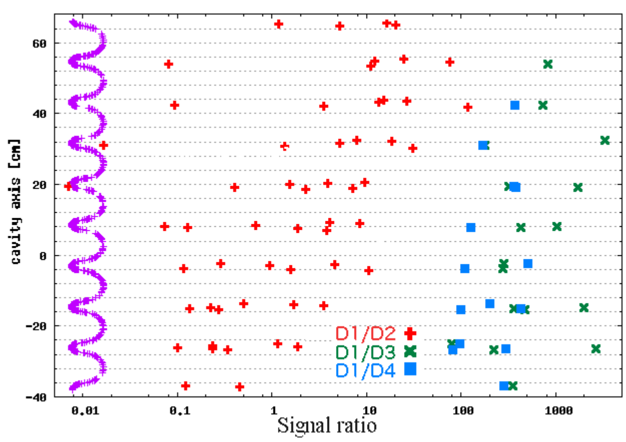
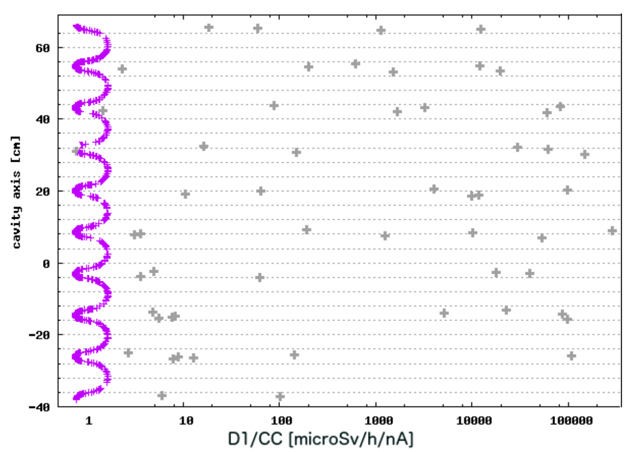
sponding electron birth coordinates, and then to discriminate the signal in the detectors as a function of those coordinates. The results are summarized in Fig. 4, where the vertical axis is the dark current origin projected on the axis of cavity, the profile of which is superimposed in magenta. These data can help determine if, where, and eventually to which degree a cavity is contaminated. For any given cavity, if ratios from dose measurements at positions D1 through D4 differ substantially from those in the last three columns of Table 1, then the cavity likely has one or few single emitters. By searching the closest fit of the ratios D1/D2, D1/D3 and D1/D4 in Fig. 4(a) the location of the emitter could be identified. If such position is clearly established, then the captured current intensity could be computed by dividing the reading of D1 by the corresponding value in Fig. 4(b).



(a) **D1 vs D2-D4 signal**



(b) **D1/Captured Current [μSv/h/nA]**

Figure 4: Detector signal dependance on single field emitter position

CONCLUSIONS

The expected radiation near LCLS-II SCRF linac was computed by coupling Track3P and FLUKA. Results were normalized to a maximum captured current that can be inferred from radiation measurements at vertical tests via similar simulations. In some cases, cavities have surface defects that manifest in vastly different radiation patterns, which have been surveyed to assist in the diagnosis of such pathologies.

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