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RADIATION TO ELECTRONICS STUDIES FOR CERN GAMMA FACTORY-PROOF OF PRINCIPLE EXPERIMENT IN SPS

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Abstract

The Physics Beyond Colliders is a CERN exploratory study aimed to fully exploit the scientific potential of its accelerator complex. In this initiative, the Gamma Factory experiment aims to produce in the Large Hadron Collider (GF@LHC) high-intensity photon beams in the energy domain up to 400 MeV. The production scheme is based on the collisions of a laser with ultra-relativistic atomic beam of Partially Stripped Ions (PSI) circulating in a storage ring. The collision results in a resonant excitation of the atoms, followed by the spontaneous emission of high-energy photons. A Proof of Principle (PoP) experiment is being planned to study the GF scheme generating X-rays, in the range of keV, from lithium-like lead PSI stored at the CERN Super Proton Synchrotron (SPS). GF-PoP has undergone a series of exhaustive radiation effect studies in view of Radiation to Electronics (R2E) risks. With the use of FLUKA Monte Carlo code, the radiation environment in the laser room and its premises has been estimated during proton and PSI runs. Recorded data from beam instruments has been used to appropriately scale the computed results and to verify the compliance with general R2E limits.

INTRODUCTION

The Physics Beyond Colliders is a CERN exploratory study aimed to fully exploit the scientific potential of its accelerator complex and infrastructure.

In this initiative, the Gamma Factory (GF) experiment proposes to use the unique facilities of the CERN Large Hadron Collider (GF@LHC) to produce γ-beams with high-intensity (1×10^{17} photons/s), in the energy domain up to 400 MeV and with a relatively small energy spread, in the order of 10^{-3} [1]. GF@LHC would open new possibilities across several fields of physics thanks to the leap, by several orders of magnitude, in the photon beam intensity compared to the existing light sources [2].

Commonly, the photon generation is based on the inverse Compton scattering of laser photons on electron beams. In the GF production scheme, the drivers of light source are ultra-relativistic atomic beams of Partially Stripped Ions (PSI), where a heavy nucleus is surrounded by one, or more, electrons. While circulating in a storage ring, the beam collides with laser photons. The interaction results in a resonant excitation of the ions, followed by the spontaneous emission of a secondary photon with energy boosted by a factor up to $4\gamma_L^2$ with respect to the original laser photons, where γ_L is the Lorenz factor of the projectile.

A Proof of Principle (PoP) experiment is planned to study the feasibility of the GF production scheme [3]. The GF-PoP is designed to store lithium-like lead ions, $^{208}\text{Pb}^{79+}$ at the CERN Super Proton Synchrotron (SPS). A pulsed laser will then resonantly excite the $2s \rightarrow 2p_{1/2}$ atomic transition of the PSI, generating X-rays in the keV range.

RADIATION TO ELECTRONICS

Radiation interactions with electronics can commonly induce cumulative effects and Single Event Effects (SEE). The former happen only after a reasonable amount of radiation, on the contrary, SEE can affect the electronics very early during operation and even in low radiation areas [4].

To provide a quantitative description of the Radiation to Electronics (R2E) effects, specific quantities are defined as follows:

1. **Total Ionizing Dose (TID)**, energy deposited in the material of interest.
2. **Silicon 1-MeV Neutron Equivalent Fluence (Si1MN)**, particles fluence weighted with damage function.
3. **High Energy Hadron Equivalent Fluence (HEH)**, fluence of hadrons with energy higher than 20 MeV and neutron of lower energies weighted according to the ratio of their SEE cross section to the one of > 20 MeV hadrons.
4. **Thermal Neutron Equivalent Fluence (ThNeu)**, fluence of thermal neutrons and higher energies neutrons weighted according to the ratio of their capture cross section to the one of thermal neutrons.

The first two quantities are relevant for estimating cumulative damage on the electronics, while the last two are used for SEE analysis. General limits, described in Table 1, are defined on the R2E quantities to identify a particular zone as a radiation-safe area [5].

Table 1: General R2E Limits or Radiation-Safe Areas

Effects	R2E Quantity	General limits
Cumulative	TID	$10\,\text{Gy} \times \text{year}^{-1}$
	Si1MN	$1 \times 10^{11}\,(\text{cm}^2 \times \text{year})^{-1}$
SEE	HEH	$3 \times 10^{6}\,(\text{cm}^2 \times \text{year})^{-1}$
	ThNeu	$3 \times 10^{7}\,(\text{cm}^2 \times \text{year})^{-1}$

For GF-PoP experiment, laser and optical electronics are fundamental components, and therefore, the proper functioning of the systems needs to be ensured. For this reason, R2E studies have been conducted using FLUKA.CERN Monte Carlo code [6, 7] to estimate the radiation environment in

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the laser room and its premises during proton and PSI runs, analysing the compliance with general R2E limits.

Figure 1 describes the FLUKA geometry used for the studies. The location for GF-PoP is the Long Straight Section 6 (LSS6) in the SPS [8]. The area is advantageous since part of the accelerator line is free and the TI18 service tunnel lies along it. The latter is proposed to house the laser room, providing the benefit of shielding the systems from radiation while being connected to the accelerator line through a laser hole.

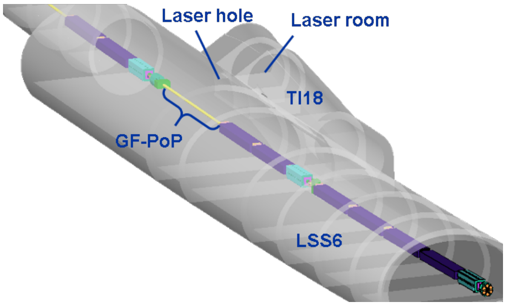

Figure 1: FLUKA model for SPS-LSS6 and TI18.

PROTON RUN

The CERN accelerator complex can accelerate protons, and nuclei of ionized atoms. While protons are accelerated, the electronic components for GF-PoP will not be active but are already installed in TI18 tunnel. Hence, it is requested to evaluate the cumulative effects to the electronics, due to proton losses.

The SPS can accelerate proton from an injection energy of 14 GeV/c to a maximum energy of 450 GeV/c. For this study protons of 400 GeV/c have been assumed to be lost uniformly along the line due to interaction with the residual gas present in the beam pipe. The 400 GeV/c protons have been chosen since they correspond to the typical beam extracted from SPS to CERN North Area, which is the main SPS user receiving yearly more than 85 % of the protons injected in the accelerator. Instead, the uniform distribution of losses is because of the constant gas pressure in the considered zone.

Different beam instruments are installed in the accelerator tunnel to monitor the beam losses. Some examples are the Beam Loss Monitor (BLM), Optical Fiber Dosimeters (OF), Radiation Monitors (RadMON), and Radio-Photo-Luminescence dosimeters (RPL). They provide useful information on the radiation environment in the tunnel. From the recorded data it can be determined that losses happening during the acceleration of the North Area beam are the main contributor to the radiation levels in SPS [9].

Moreover, the BLMs data have been used for the normalization of the results obtained by MC simulations. FLUKA estimation on BLMs recorded values has been compared and adjusted in order to best match the data, as shown in Fig. 2. The comparison resulted in a normalization factor used to rescale the FLUKA results.

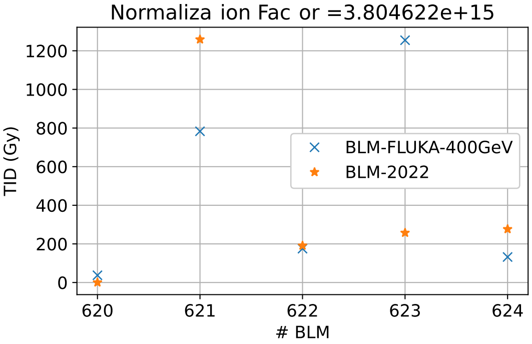

Figure 2: Comparison of FLUKA results with recorded data.

Figure 3 shows the R2E results depicting a cross view of the accelerator tunnel and the laser room, connected through the laser hole. In the plots, Si1MN and TID values are shown, the R2E quantities used for the estimation of cumulative damage to the electronics.

The laser room is found to be safe for the electronics. The computed values have a statistical uncertainty lower than 10 % and they are below the proposed limits for an R2E safe area. A possible optimization would be to add shielding in the laser hole during the proton run, to reduce the radiation levels in the service tunnel.

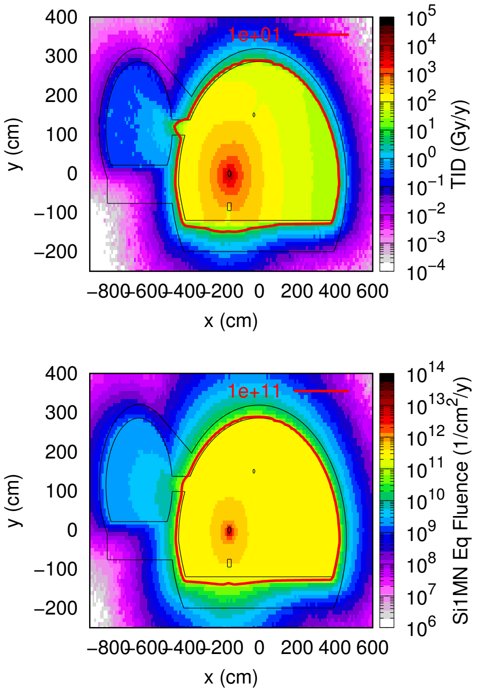

Figure 3: Tunnel cross view at laser room showing TID (top) and Si1MN (bottom) results with proton run.

PSI RUN

In the collision between a Partially Stripped Ion (PSI) and atoms, charge-changing events can arise causing the loss of a particle beam along the circular accelerator. The main processes are electron capture by the PSI and electron stripping from the PSI. In both channels, one or more electrons can be involved, but single-electron stripping is the main process once the accelerated particle is at relativistic energies [10].

For GF-PoP, lithium-like lead ion has been selected as PSI: a lead nucleus surrounded by three electrons, Pb^{79+}. The choice of the beam particle is purely technical, aiming to minimize the cost and the required technology. Once in the SPS, the PSI reaches ultra-relativistic energies (E = 18.652 TeV). Therefore, in the interaction with the residual gas, the single-electron stripping channel ($Pb^{79+} \rightarrow Pb^{80+} + e^-$) is expected to be the dominating process [10].

The evaluation of R2E risk during the PSI run has been conducted with the use of FLUKA4-3.3. In the considered version, it is possible to define only fully stripped ions. This implies that both transport and interaction models for PSI are not implemented in the code. Hence, to evaluate the radiation levels in the laser room, a workaround has been exploited considering a 2-steps FLUKA simulation.

In the first step, the PSI loss map was evaluated by tracking protons equivalent to the PSI in magnetic rigidity. Defining the momentum as p and the charge as q, a proton equivalent should have a momentum equal to:

$$p_{\text{proton}} = \frac{q_{\text{proton}}}{q_{\text{PSI}}} \times p_{\text{PSI}} \tag{1}$$

The proton equivalent and original PSI follow the same trajectory, and therefore the loss points will be consistent.

Initially, assuming the interaction between Pb^{79+} and the residual gas as the main source of beam loss, three possible channels have been considered:

1. Single-electron stripping: $Pb^{79+} \rightarrow Pb^{80+} + e^-$
2. Two-electrons stripping: $Pb^{79+} \rightarrow Pb^{81+} + 2e^-$
3. Three-electrons stripping: $Pb^{79+} \rightarrow Pb^{82+} + 3e^-$

Then, to compute the loss map, a model of the SPS line was defined in FLUKA with the main optics set to store lithium-like lead ions. In this model, protons equivalent to the ions resulting from the described interactions have been sampled uniformly along the nominal trajectory, taking into account the betatron oscillation and dispersion effects. The protons equivalent were then tracked until impacting with the beam pipe. This particular location has been saved as the loss point.

Results from the simulations conclude that the only situation where there are significant losses in the region of interest for GF-PoP is considering the case of a three-electron stripping process resulting in a Pb^{82+} being transported.

The second step aims to compute the radiation environment in the tunnels: fully stripped lead nuclei have been transported starting from the loss map computed in step-1. Once the PSI impinges on bulky material, it will undergo nuclear and electromagnetic interactions. The use of nuclei for step-2 simulation is based on this consideration.

Results of step-2 are shown in Fig 4. They have been obtained considering the beam life-time (expected to be 100 s [3]) to depend solely on the three-electrons stripping process in the interaction between PSI and H2-like gas, which is the main component of the residual gas in SPS. This assumption results to be conservative since, as described at the start of this chapter, the PSI in SPS reaches relativistic energies, and therefore the main channel in the interaction with the residual gas should be the single-electron stripping [10]. Together with this consideration, the FLUKA results have been normalized considering a constant pressure in the beam pipe, and the PSI expected intensity, 4.6×10^{13} PSI/year.

During PSI run, the electronics will be active and subject to SEE. Hence, Fig 4 shows the normalized results of HEH and ThNeu fluences in the tunnels. As a consequence of the conservative assumption, the hadron fluence value is slightly above the general limit. Therefore, some precautions might be taken to lower the radiation level, for example, placing additional shielding around critical electrical components, but the area is generally expected to be R2E radiation-safe.

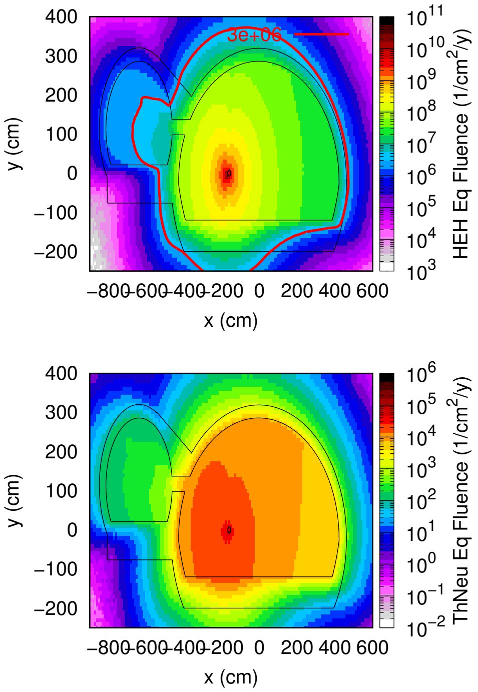

Figure 4: Tunnel cross view at laser room showing HEH (top) and ThNeu (bottom) results with PSI run.

CONCLUSION

In this paper, we have reported simulation results scaled to recorded data to estimate the cumulative damage to the not-active electronics during proton run. Based on conservative assumption on the loss mechanism for PSI, we have also estimated the R2E risk during PSI run. The conclusions indicate that the laser room, required for the GF-PoP experiment, is found to be radiation-safe for the electronics operation during both proton and PSI runs, as it is compliant with standard R2E limits.

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