GRAD-LEVEL RADIATION DAMAGE OF SiO_2 DETECTORS*

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Abstract

SiO_2 quartz fibers of the LHC ATLAS Zero-degree Calorimeter (ZDC) anticipated to experience integrated doses of a few Grad at their closest position were exposed to 200 MeV protons and neutrons at the Brookhaven National Laboratory (BNL) Linac. Specifically, 1mm- and 2mm- diameter quartz (GE 124) rods were exposed to direct 200 MeV protons during the first phase of exposure leading to peak integrated dose of ~28 Grad. Exposure to a primarily neutron flux of 1mm-diameter SiO_2 fibers was also achieved with a special neutron source arrangement. In a post-irradiation analysis the quartz fiber transmittance was evaluated as a function of the absorbed dose. Dramatic degradation of the transmittance property was observed with increased radiation damage. In addition, detailed evaluation of the fibers under the microscope revealed interesting micro-structural damage features and irradiation-induced defects.

INTRODUCTION

The power dissipated in the ZDC calorimeter (Fig. 1) during the LHC p-p runs is expected to reach ~6W/Kg or ~6 krad/s [1]. For year of p-p running at a luminosity 10^{34} cm^2/sec the expected dose will reach ~15 Grad. While quartz (SiO_2) has been assessed to exhibit high radiation damage resistance, the Grad-level dose may have serious performance consequences as a result of the interaction of energetic particles (protons and neutrons primarily) with the quartz material causing serious light transmission degradation which is the primary function of the detector. Due to the fact that extrapolation from previous lower-dose experience may not be appropriate, or even misleading, a comprehensive experimental effort was undertaken at BNL to assess the Grad-lever radiation damage on light transmittance of the SiO_2 quartz fibers that will form the ZDC. Figure 2 depicts the anticipated dose levels in reference to the nominal beam position.

Prompted by the important role of silicon detectors and the need to identify radiation tolerant materials to play such role, studies have been conducted in the past. In particular interest has been focused in the past on the use of silicon in the CMS tracker of the LHC [2], the super-LHC [3] as well as space mission detectors and fusion reactor diagnostics. Regarding the LHC, fluences associated with the LHC upgrade and 10 years of operation are of the order of $3 \cdot 10^{15}/cm^2$ and for 5 years of super-LHC operation $1.6 \cdot 10^{16}/cm^2$. In order to push the dose limits to these extreme levels, the current study exposed silicon fibers to 200 MeV direct-on protons as well as to a cocktail of neutrons, secondary protons, electrons and gamma-rays reaching doses that exceed even those anticipated in the super-LHC and studied the light transmittance degradation including the effect of the interaction of the different particles with the detector material and structural damage that was induced as a result of the exposure.

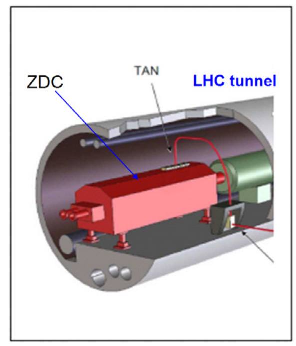

Figure 1: Configuration of ZDC Calorimeter in LHC.

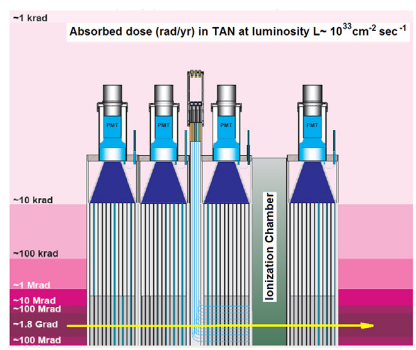

Figure 2: ZDC layout and anticipated dose in SiO_2 fibers.

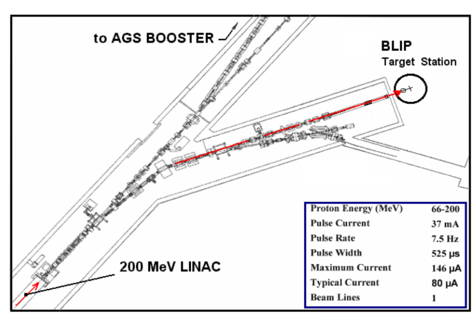

Figure 3: Schematic of the BNL BLIP irradiation facility.

FUSED SILICA IRRADIATION

Using the BNL accelerator complex (Fig. 3) and the Isotope Production Facility (BLIP) two irradiation exposures were achieved. In the first exposure 200 MeV Linac protons showered an array of 1mm and 2mm diameter SiO_2 fibers as shown in Fig. 4 for a total beam current of 72.24 μA-hrs. Based on the beam profile

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situated upstream of the array recorded on the foil shown in Fig. 5, the corresponding fluences over the three canisters were $2.5 \cdot 10^{15}$ p/cm^2, $7.3 \cdot 10^{16}$ p/cm^2, $2.6 \cdot 10^{16}$ p/cm^2. Following irradiation, the residual activity of each fiber was measured and based on its position on the beam footprint the corresponding dose was estimated. As shown in Figure 5, fibers within the one sigma of the beam received a dose of ~28 Grad. Fibers in the other two positions (or canisters) received 10 and 5 Grad respectively.

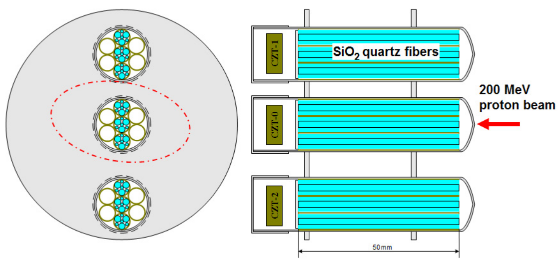

Figure 4: Fiber arrangement for the 200 MeV irradiation.

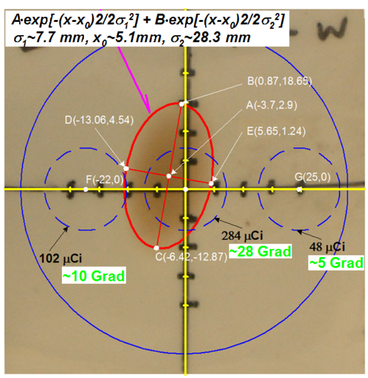

Figure 5: Beam profile and measured peak dose.

To address the combined effect of neutrons, secondary protons, photons and electrons, a special arrangement in the target station was introduced that allowed the generation of high neutron fluxes. Specifically, the upstream isotope production targets were utilized and enabled the stopping of the primary protons resulting in a uniform flux of neutrons, photons, and electrons at the location of the fused silica fibers. For this irradiation only 1mm diameter fibers were used while the primary proton beam was reduced to 116 MeV.

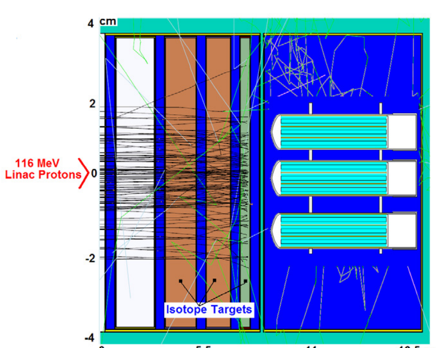

Figure 6: Particle tracks generated by the MARS15 code.

Figure 6 depicts the isotope target arrangement generated by the MARS15 Monte-Carlo code [4] used to generate the combined flux superimposed by the fused silica fiber layout. Neutron and photon fluxes behind the isotope targets are shown in Fig. 7. Secondary proton and neutron energy spectra are shown in Fig. 8.

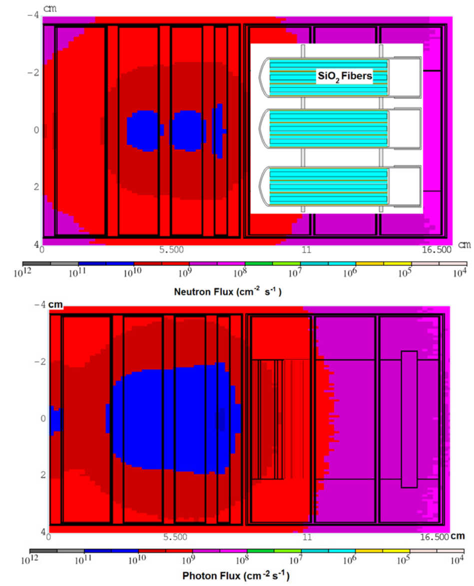

Figure 7: Estimated neutron, photon and proton fluxes in the target irradiation arrangement (MARS15 code).

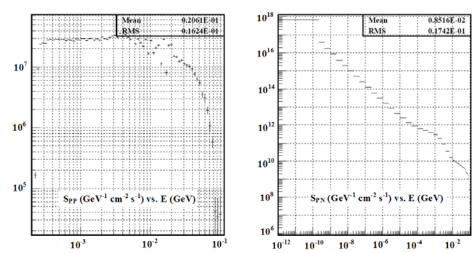

Figure 8: Estimated proton and neutron energy spectra.

POST-IRRADIATION RESULTS

The degradation of the light transmittance in the fused silica fibers as a result of the two radiation environments and as a function of the accumulated radiation dose was evaluated using the set-up shown in Fig. 9. Figures 10 and 11 summarize the post-irradiation transmittance exhibited by the exposed fibers.

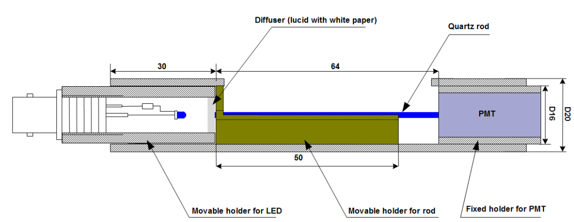

Figure 9: SiO_2 fiber transmittance evaluation set-up.

As seen in Fig. 10, fibers that were situated within the beam first σ during the 200 MeV proton irradiation and have seen a dose of ~28 Grad have completely lost all transmittance. The same is true for the 1mm fibers that were exposed to the cocktail of fluxes (primarily neutron) and were situated at the central location of the arrangement (uniform flux in neutron irradiation). Transmittance in this case was approaching 0%. The relation between dose and light wavelength transmittance observed in post-irradiation analysis is depicted in Fig.11.

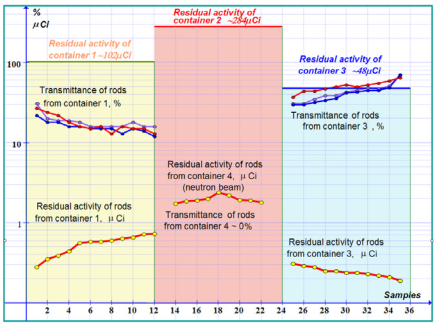

Figure 10: Transmittance of irradiated SiO_2 fibers.

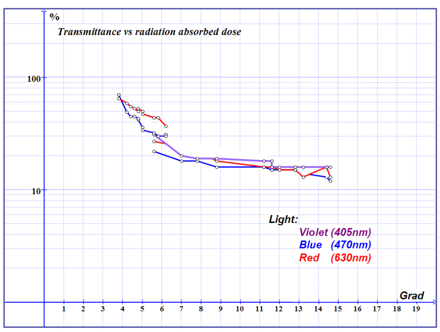

Figure 11: Light wavelength transmittance vs. dose.

Microscopic Assessment of Damage

The interaction of the energetic particles with the crystal atoms and the structural disorder that results is responsible for the scattering and the loss of transmission. Interesting features that constitute damage have been seen in crystals through TEM. In addition a number of theoretical models were used to explain the observable effects. Filaments of atomic disorder or fragment tracks have been observed in non-metals as well as thermal spikes resulting in localized material phase transformation. To examine if similar features are observed following the SiO_2 irradiation a microscopic analysis was performed.

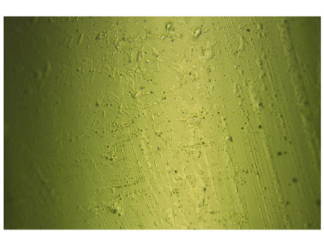

Figure 12: Un-irradiated SiO_2 crystal surface.

Fig. 12 depicts an un-irradiated crystal surface. Fig. 13 shows the damage at the surface which confirms the presence of fragment tracks. Damage was observed also within the bulk of the material. Fig. 14 depicts a "thermal spike" of a fragment whose track is visible. Energy deposition (loss of kinetic energy) of a fragment on the surface of the crystal is in view in Fig. 15.

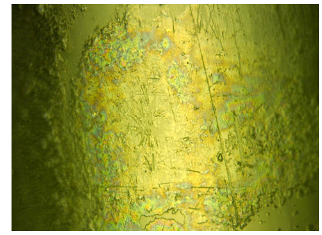

Figure 13: Crystal surface damage and fragment tracks.

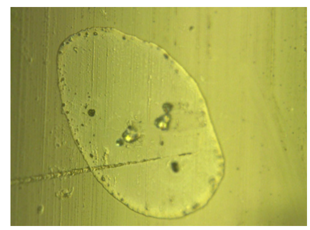

Figure 14: Thermal spike on the fiber surface.

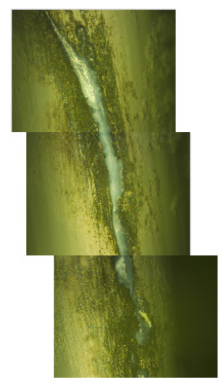

Figure 15: Fragment track and damage on crystal surface.

SUMMARY

The experimental effort focusing on radiation damage on SiO_2 crystal fibers of the LHC ZDC detector showed that Grad-level irradiation has a detrimental effect on the fiber light transmittance. Microscopic analysis has revealed that lattice disorder is the main cause. Assessment of annealing for transmittance recovery is planned.

REFERENCES

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