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Grad-Level Radiation Damage of SiO_2 Detectors

**N. Simos¹, G. Atoian¹, H. Ludewig¹, S. White¹, J. O'Connor¹,
N.V. Mokhov²**

¹Brookhaven National Laboratory, Upton, NY 11973, USA

²Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

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Energy Sciences and Technology Department

Brookhaven National Laboratory

P.O. Box 5000

Upton, NY 11973-5000

www.bnl.gov

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GRAD-LEVEL RADIATION DAMAGE OF SiO₂ DETECTORS*

N. Simos[#], G. Atoian, H. Ludewig, S. White and J. O. Conor, BNL, Upton, NY 11973, USA
 N. V. Mokhov, FNAL, Batavia, IL 60510, USA

Abstract

SiO₂ 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 SiO₂ 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 10³⁴ cm²/sec the expected dose will reach ~15 Grad. While quartz (SiO₂) 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-level radiation damage on light transmittance of the SiO₂ 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 · 10¹⁵/cm² and for 5 years of super-LHC operation 1.6 · 10¹⁶/cm². 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.

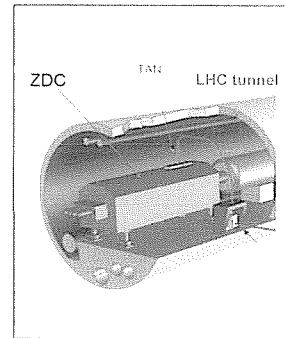


Figure 1: Configuration of ZDC Calorimeter in LHC

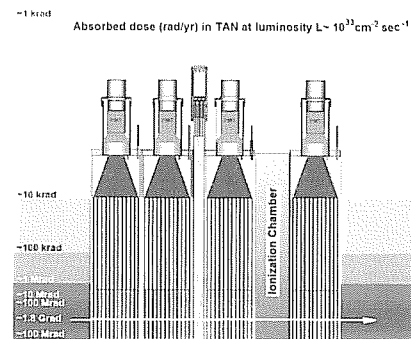


Figure 2: ZDC layout and anticipated dose in SiO₂ fibers

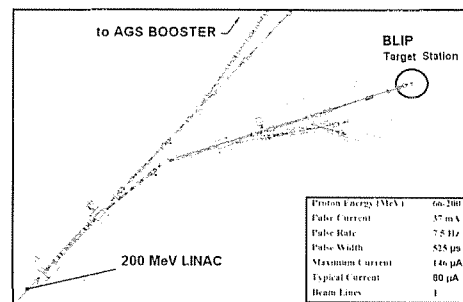


Figure 3: Schematic of the BNL BLIP irradiation facility

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 SiO₂ 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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[#] simos@bnl.gov

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/cm², $7.3 \cdot 10^{16}$ p/cm², $2.6 \cdot 10^{16}$ p/cm². 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.

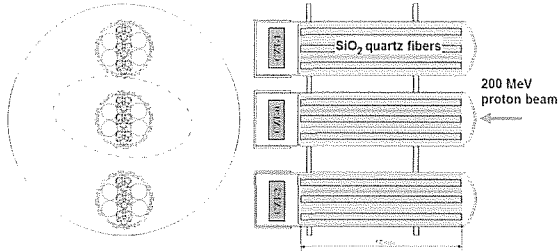


Figure 4: Fiber arrangement for the 200 MeV irradiation

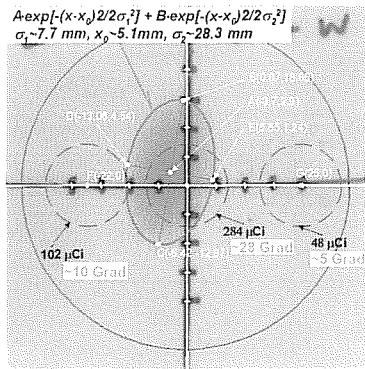


Figure 5: Beam profile and measured peak dose

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.

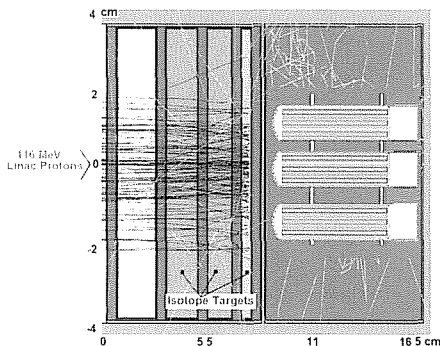


Figure 6: Particle tracks generated by the MARS15 code

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.

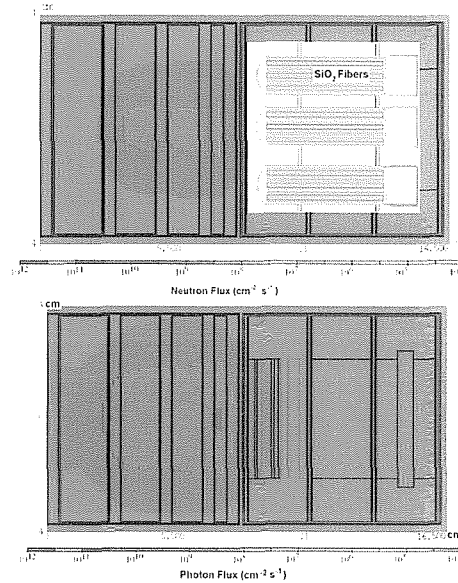


Figure 7: Estimated neutron, photon and proton fluxes in the target irradiation arrangement (MARS15 code)

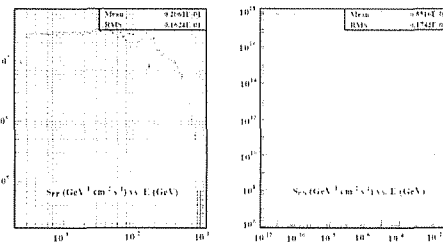


Figure 8: Estimated proton and neutron energy spectra

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.

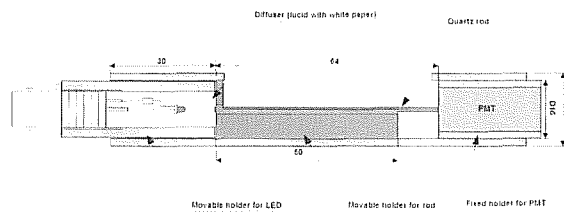


Figure 9: SiO₂ fiber transmittance evaluation set-up

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.

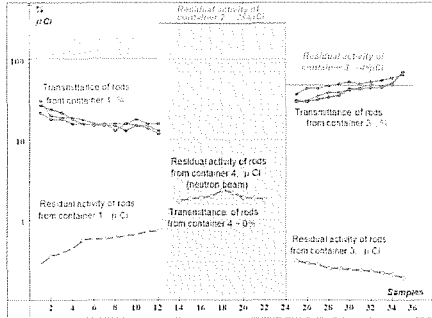


Figure 10: Transmittance of irradiated SiO₂ fibers

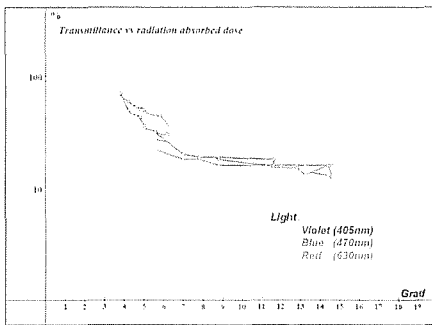


Figure 11: Light wavelength transmittance vs. dose

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 SiO₂ irradiation a microscopic analysis was performed.

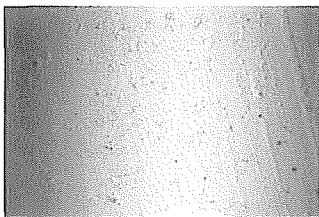


Figure 12: Un-irradiated SiO₂ crystal surface

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

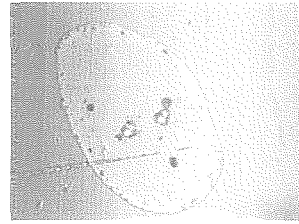


Figure 14: Thermal spike on the fiber surface

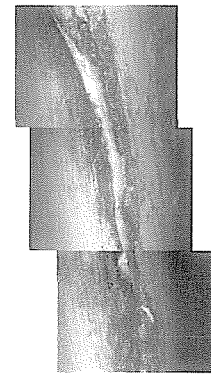


Figure 15: Fragment track and damage on crystal surface

SUMMARY

The experimental effort focusing on radiation damage on SiO₂ 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.

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