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Ultraviolet Transmissivity of Quartz Optical Fibers Under Proton Bombardment BRIAN DIDONNA, ROBERT W. BRUMLEY, SAPS BUCHMAN, *W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, U.S.A.* — We present a study of the ultraviolet transmissivity of multi-mode quartz optical fibers under proton bombardment. The motivation for this work is to verify the functionality in space (650 km polar orbit) of an ultraviolet system for the charge control of precision gyroscopes. Proton bombardment of the optical fibers, used to transport the ultraviolet light, can cause ionization, lattice displacements, and nuclear interactions in the fiber core and cladding. A 5 meter long sample of 300 μm core quartz fiber was exposed to proton fluxes of 10^5 to 10^7 protons/cm²/s at kinetic energies of 2-7 MeV and 63 MeV while transmitting 1-2 μW of 254 nm light. Transmission attenuation was exponential in time, with the strongest effect (about 2.5 dB asymptotic attenuation) produced, as expected, by the highest flux of 2-7MeV protons. Transmission recovery after proton exposure was also exponential, with a time constant of about 1.5 hours. Permanent transmission loss was measured to be about 0.1 dB. We discuss experimental results and compare them to theoretical models of radiation-induced fiber damage.

Prefer Oral Session
 Prefer Poster Session

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Ultraviolet Transmissivity of Quartz Optical Fibers Under Proton Bombardment

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BACKGROUND - GRAVITY PROBE B

- Sensitive measurement of the precession of a satellite's local inertial frame due to the Earth's gravity.
- Employs four cryogenic ultra-precise electrostatically suspended gyroscopes and one drag-free proof mass.
- To minimize torques on gyroscope and keep suspension system stable, rotor voltage must be kept to within 15 mV of local ground. However, method of charge control must be non-contact.
- Solution: Ultraviolet light at 254 nm, fed into gyroscope through fiber optic cables, induces photoemission from surface of rotor and gyroscope housing. Adjustable biasing leads to a net positive or negative current between rotor and housing.

❖ All systems must function continuously for 2 years in orbit ❖

SPACE RADIATION ENVIRONMENT

- Low, continuous flux of protons with wide range of KE
- Little shielding for fiber optics on spacecraft exterior
- Concern: fiber optic transmission attenuation due to proton radiation may hinder system performance.

EFFECT OF PROTON BOMBARDMENT ON FIBER TRANSMITTANCE

(Calculations preformed for fused quart fibers)

SHORT TERM

- Coulomb interaction between incident protons and atomic electrons result in ionization and atomic displacement, opening new photon absorption bands.
- Strongest interactions take place at lower proton KE's.

LONG TERM

- Incident protons interact with Si and O nuclei to form other elements. This introduces permanent impurities into the fiber which attenuate transmission and decrease overall lifetime.
- Threshold for overcoming Si nucleus coulomb barrier: 8 MeV.

OUR TESTING

(performed at Crocker Nuclear Laboratory, U.C. Davis)

TARGET

- Fiber: 300 micron fused silica core, 360 micron doped fused silica cladding.
- Approximately 5 meters wound into a flat coil with minimum bend radius = 2.5 cm
- Target coil irradiated by proton beam at various energies and fluxes.
- Fiber coupled to a mercury arc lamp source and a CsTe photodetector to measure transmitted intensity at 254 nm. Initial intensity of 1-2 μW .

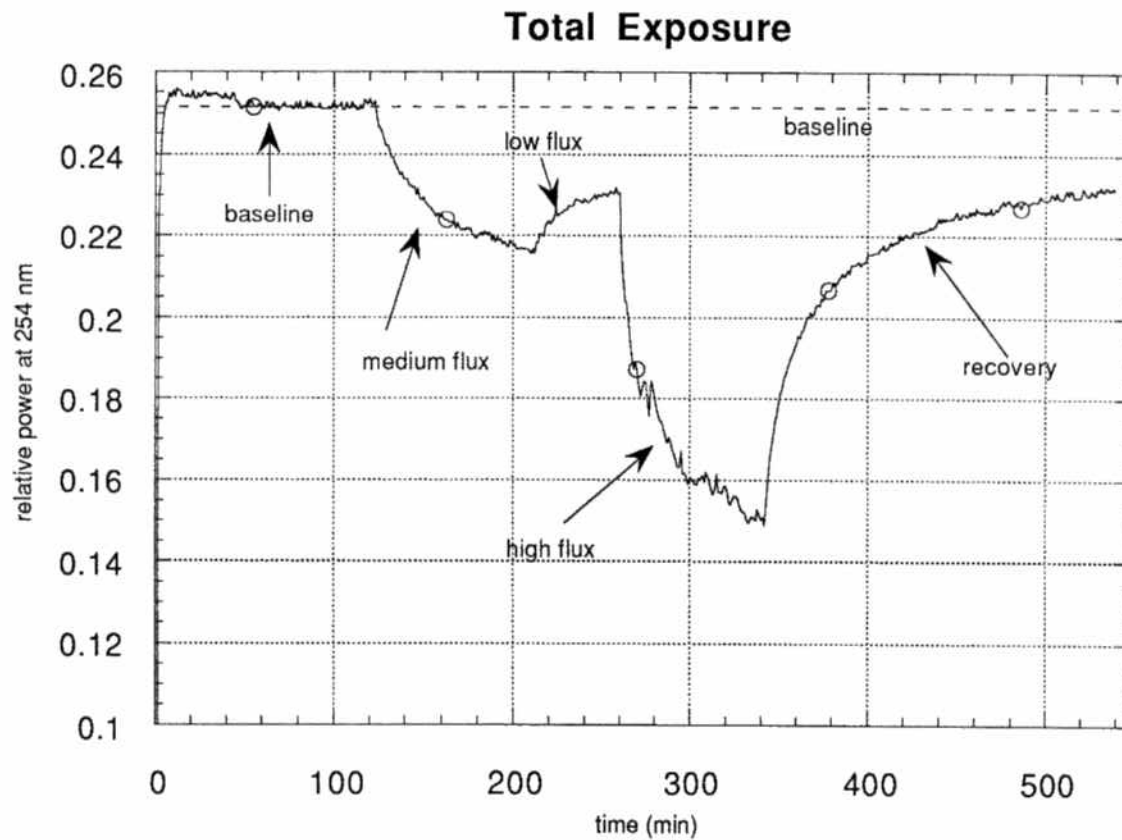
Low Energy Testing

- Anticipated flux on orbit: 25 protons/cm²/sec
- Protons with KE between and 2 and 7 MeV will stop somewhere within the fiber core or cladding. They will transfer the greatest amount of energy to the atoms around them just as they come to a stop.
- Fiber coil bombarded by 2-7 MeV protons at fluxes of 10⁵, 10⁶ and 10⁷ protons/cm²/sec for periods of up to 90 minutes.
- Transmission data taken for three hours after bombardment in order to characterize fiber self-annealing.

High Energy Testing

- Tested at highest available proton energy, 63 MeV.
- Our concern was mainly with the amount of permanent damage, so that total dose was more important than flux.
- Total dose for 2 year space mission: 7.2×10^8 protons/cm.
- Total dose delivered in lab: 3.6×10^9 protons/cm at a flux of 10^6 protons/cm/sec.
- Again, recovery was observed for a 2.5 hour period.

RESULTS - LOW ENERGY



ANALYSIS - LOW ENERGY

Observations:

- Though the decay curve is not a clean exponential, it did approach an asymptotic value.

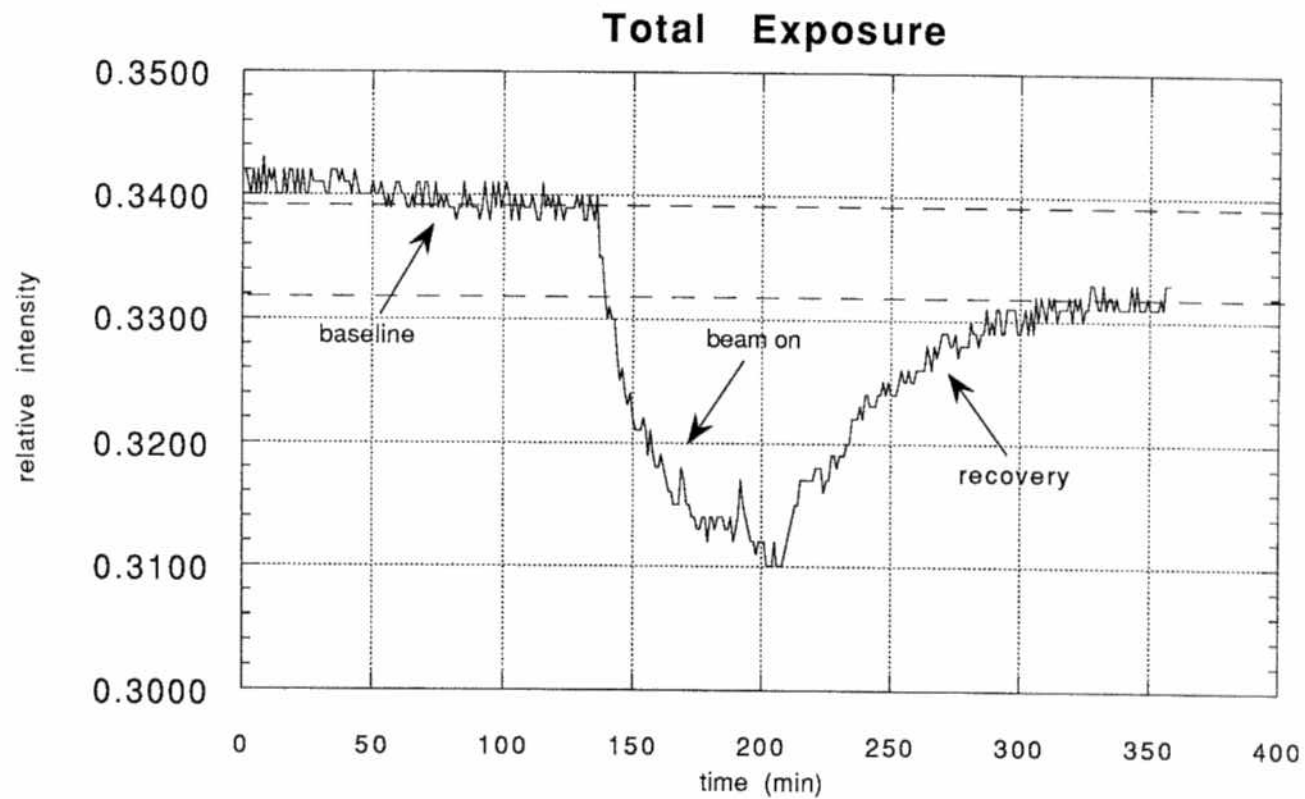
PROTONS/CM ² /SEC	ATTENUATION (%)	ATTENUATION (dB/m)
10 ⁵	6.7 %	0.06
10 ⁶	17 %	0.16
10 ⁷	48 %	0.56

Initial transmitted power: 0.252

Final transmitted power: 0.234 \Rightarrow 0.064 dB/m permanent attenuation.

- Transmissivity attenuation determined by balance between rates of damage and recovery.

RESULTS - HIGH ENERGY



ANALYSIS - HIGH ENERGY

Problems with accelerator prevented us from getting clean data. However, we can see that:

- Beam-on attenuation was less than for lower energy protons at the same flux (at most 11% attenuation, compared to 17% for lower energy).
- Permanent attenuation < 0.02 dB/m.

CONCLUSIONS

- Low energy coulomb interaction has much greater effect on transmission than does high energy atomic interactions at the same proton fluence (nuclear cross section $\approx 10^5$ times smaller than atomic cross section).
- There is an equilibrium point between fiber self-annealing and radiation induced damage.
- At high fluxes, transmission attenuation is dominated by flux dependence (as opposed to smaller levels of permanent damage which depend on total dose).
- Conclusion for satellite application: At expected orbital proton fluxes, system performance will not be affected by radiation induced transmission attenuation.

PROPOSAL

Proton Irradiation of Optical Fibers

Attn: Dr. Carlos Castineta
Crocker Nuclear Laboratory,
U.C. Davis

Dear Sir,

It was good talking to you on Wednesday, 6/28 and afterwards. We have decided to take advantage of your facilities for proton irradiation testing. Below is a formal work proposal detailing our motivations and concerns.

Background:

The Gravity Probe B project is a sensitive satellite test of General Relativity. At the heart of the experiment are four ultra precise gyroscopes with spherical, electrostatically suspended rotors. For the suspension system to remain stable, the rotor voltage must be kept to within 0.1 V of satellite ground. In order to add or remove electrons from the rotor, UV light is directed onto the rotor and the housing to induce photoemissions from both, then a bias voltage is used to move the resulting electron cloud either onto or away from the rotor. The UV light is transmitted to the rotor through fused silica optical fibers.

Radiation Concern

The fiber optics cables on the outside of the satellite will be exposed to high levels of cosmic radiation. It is imperative that they still transmit enough UV light to adequately control the rotor voltage for the entire two year space mission. Ultraviolet light is especially problematic since it tends to amplify defect in the fiber cables into "color centers," larger phosphorescent defects which decrease fiber transmission efficiency. The effects of gamma and beta radiation on fused silica fibers is well documented. For our purposes, however, it would be useful to gather data on fused silica fibers that are exposed to proton radiation *while they are transmitting* UV radiation. It is believed that the UV radiation may turn otherwise transient ionization defects in the fiber into permanent damage. Therefore, for an accurate simulation of the actual operating environment, the fiber sample must be irradiated while transmitting.

Proposed Experiment

Using your facilities, we would like to expose a long sample of FiberGuide SFS300/360/460 fused silica optical fiber to the full expected total dose of protons it would encounter over the two year mission. During the exposure, we would be continuously feeding UV light through the fiber and monitoring its intensity at the other end. It is important that the UV lamp and electronics are not exposed to the proton bombardment. If the fibers were completely unshielded from cosmic rays, the total radiation dose for the two year period would be not more than 10^{10} protons/cm² (with individual proton energies ranging from 2 to >400 MeV). So that we can witness the interaction of the UV light with the proton induced defects in the fiber, in the simulation this total dose shall be delivered over a period of **three hours**. This amounts to a proton flux of $\approx 10^6$ protons/cm²/s. For a **7 cm diameter beam**, an exposure area of only 40 cm² and therefore a beam current of **4×10^7 protons/sec** is required. It is believed that the most

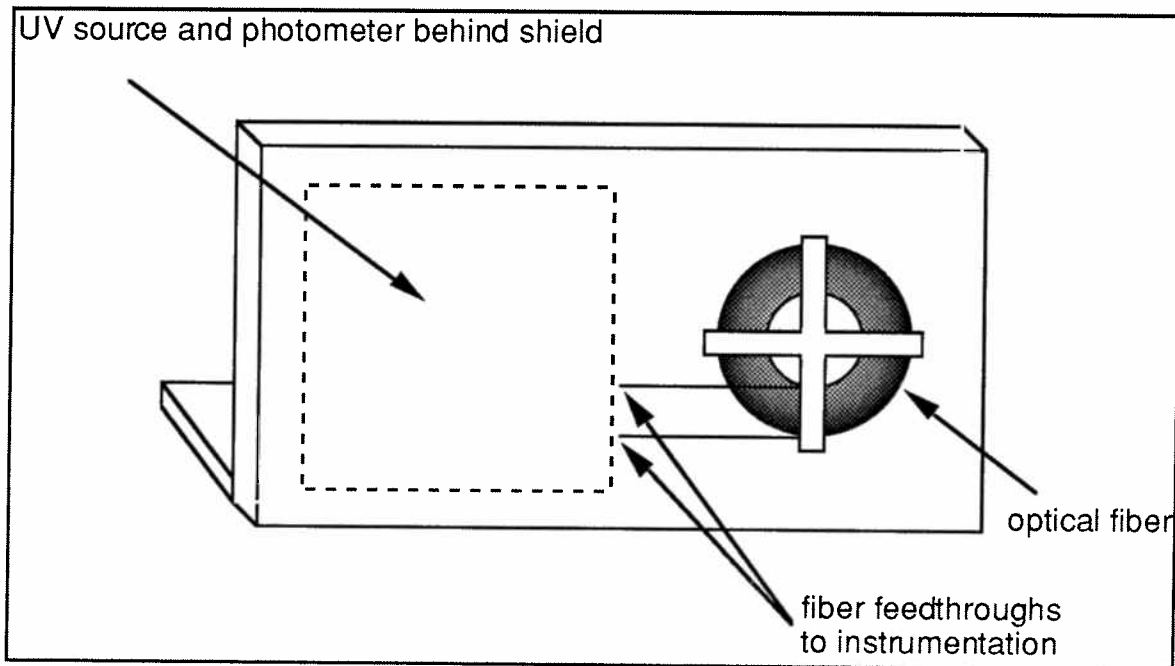
damage will be done by the protons which deposit the greatest amount of energy in the fiber: namely those that come to a halt within the fiber core. Therefore, for a worst case simulation, we require that the proton energies be centered around **6.5 MeV**, with a standard deviation less than 0.5 MeV.

So that the effects of proton irradiation are not confused with light source startup transients or swift initial fiber darkening, the entire UV lamp, fiber and detector circuit must be continuously running for a period of 1-2 hours before the proton beam is turned on. Allowing one hour to set up the apparatus, this adds to a total of 2-3 hours set up and initialization time in the laboratory before the beam is activated. We would also like to run the lamp for an additional hour after the beam is shut off, to study the relaxation time of any fiber damage which is only temporary. The entire experiment would therefore require 6-7 hours in the laboratory.

Experimental Apparatus

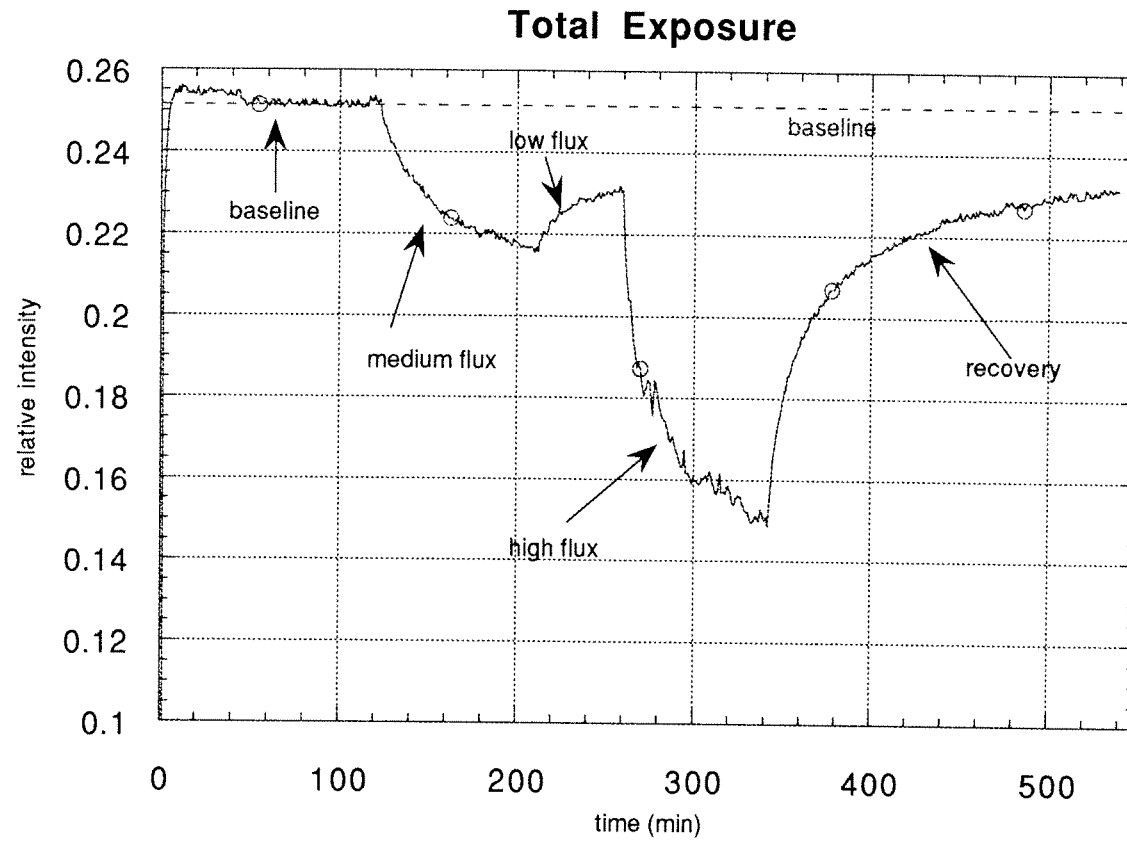
A rough sketch of the probable instrument design is pictured below (the actual part design will be left to another student here). The main structure will be an aluminum el which will provide a support for the fiber coil as well as shielding for the photometer and UV source which will be built into the apparatus. The optical fiber will be wound into a coil one layer thick (0.5 mm) with an inner diameter of 5 cm and an outer diameter of 7 cm. It will be held in place against an aluminum backing by a raised crossbar. The dimensions of the source and photometer are less than $7 \times 8 \times 15$ cm and $6 \times 6 \times 8$ cm respectively.

Preliminary Apparatus Design

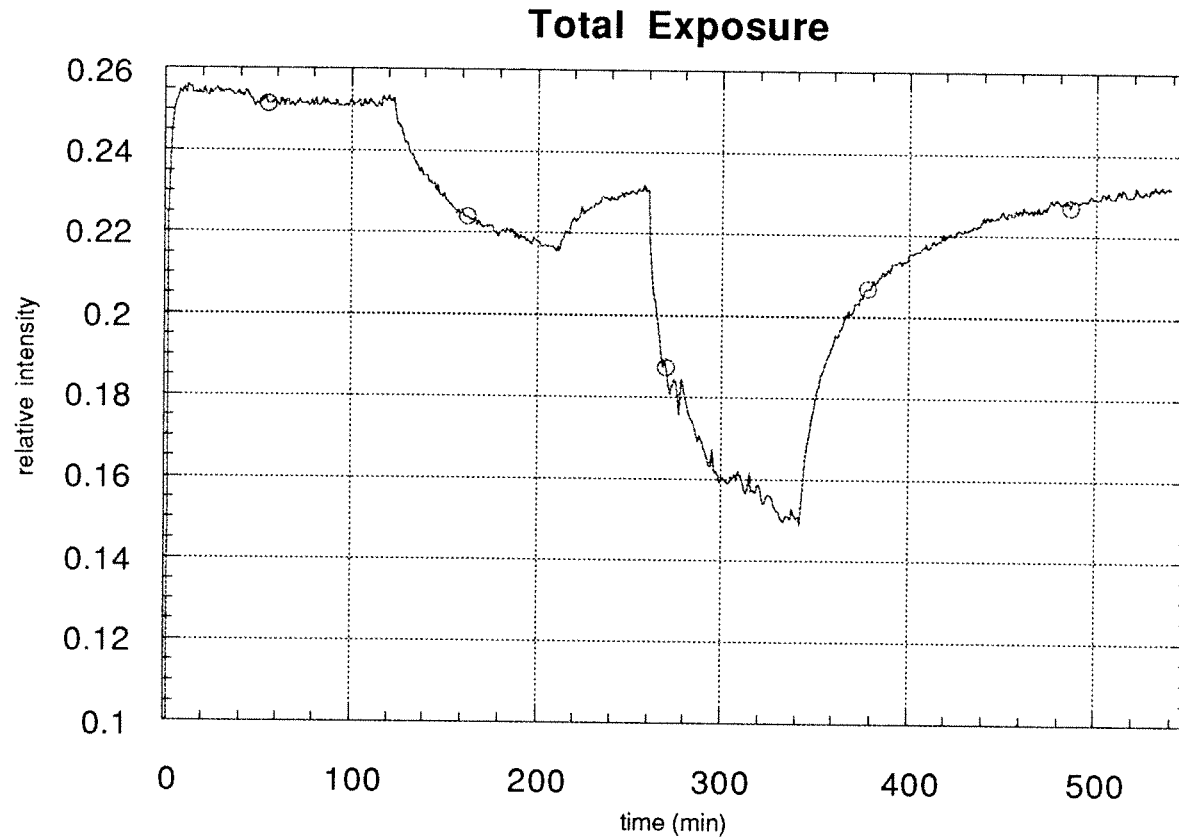


PROTON RADIATION EXPERIMENT

- **PURPOSE: TO STUDY THE ULTRA-VIOLET TRANSMITTANCE OF OPTICAL FIBER IN SIMULATED SPACE RADIATION ENVIRONMENT.**
- **INITIAL TESTING: LOW ENERGY PROTONS (2 - 7 MEV)**
- **EXPECTED EFFECT OF LOW ENERGY PROTON RADIATION:
IONIZATION: ($\text{SiO}_2 \rightarrow \text{SiO}_2^+$, $\text{SiO}_2 \rightarrow \text{Si} + \text{O}_2$)
CHANGE IN ABSORPTION SPECTRUM
LITTLE PERMANENT DAMAGE**
- **ANTICIPATED FLUX: 25 PROTONS/CM²/S**
- **TESTED AT: 10^5 , 10^6 & 10^7 PROTONS/CM²/S**



RESULTS



INITIAL VALUE: 0.252

FINAL VALUE (EXTRAPOLATED): 0.234

