Test plan for Idaho irradiation tests

Introduction

The Idaho Accelerator Facility provides a 20 MeV electron beam with 100 Hz repetition rate, with I_{peak}=111 mA and 100 ns pulse width. The beam is roughly 1mm in diameter and exits through water-cooled window (1mm Al/1mm Water/1mm Al), a total thickness of 0.0253 radiation lengths. Coulomb scattering produces a roughly Gaussian distribution of angular spread of radiation with RMS:

$$\theta_0 = \frac{13.6\,MeV}{\beta cp} z\sqrt{x/X_0}\left[1+0.038\log(x/X_0)\right] = 0.0930\,rad \qquad (1)$$

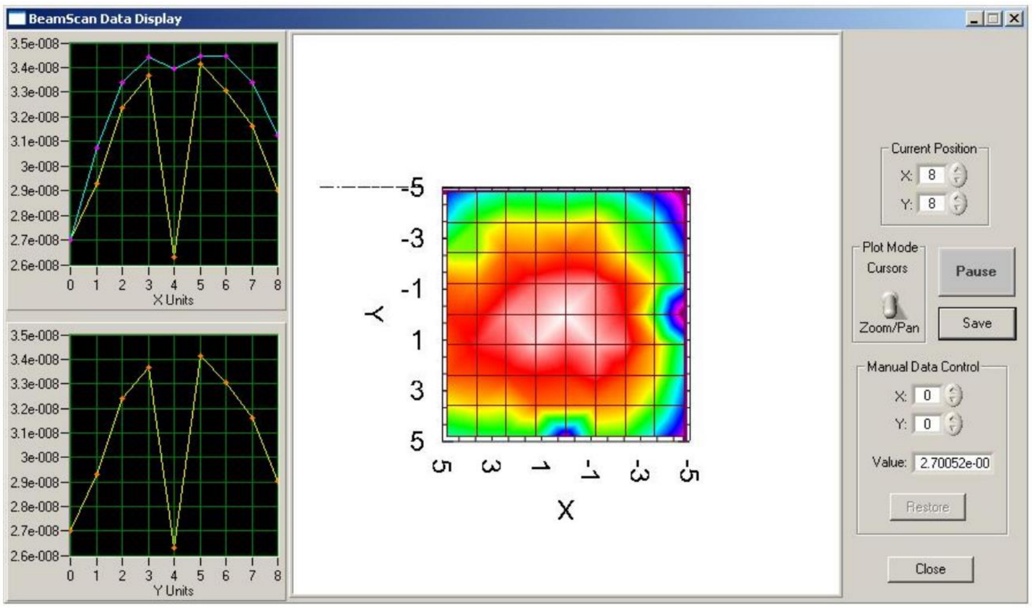

Fig. 1: Beam profile as measured by a Faraday cup mounted on a moving table. The units in X and Y are inches.

The dose received by each block can be estimated as:

$$D(Gy) = \frac{I_{peak}(A)\cdot w_{pulse}(s)\cdot E(J)\cdot N_{pulses}/1.61\cdot 10^{-19}}{M_{block}} \times \frac{1}{4} \times 0.7 \qquad (2)$$

For example, a PbF_2 block of mass M_{block}=1.28 kg will receive a dose of 3.5 kGy during an irradiation period of 20 min (1200 s). The factor ¼ accounts for the fact that 4 crystals are irradiated at the same time, with the beam aiming at the center of assembly (see Fig. 2), and the factor 0.7 is due to the fact that we place blocks within 1σ of the radiation profile (see Eq. 1).

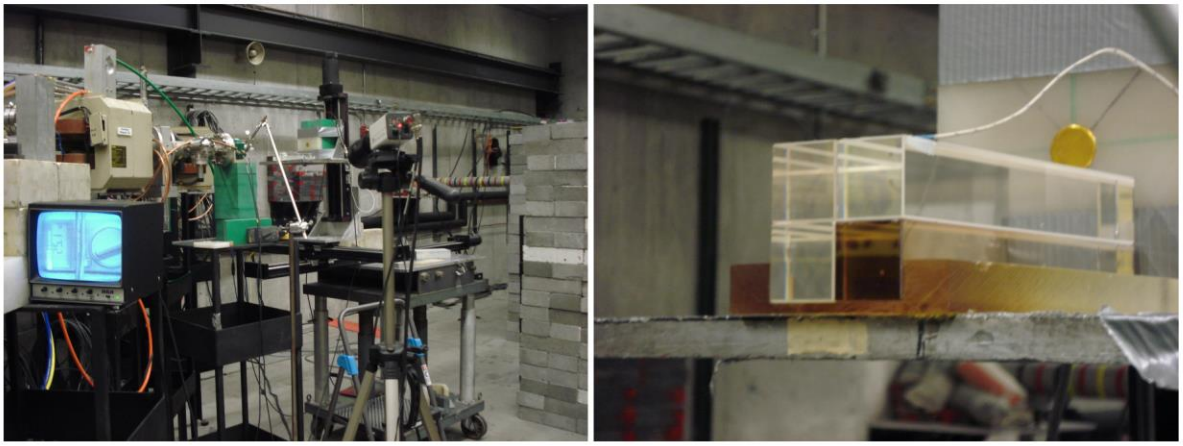

Fig. 2: Experimental setup: Overview (left) and a batch of 4 crystals placed in front of the beam. The Faraday cup is in the same plane as the back side of the blocks.

Therefore, the dose rate is about 1 Mrad/h. In the NPS setup we expect doses of up to 1krad/h, so we can irradiate 1000 faster than the real experiment. We can irradiate blocks at different rates by moving the crystals further away from the beam exit or decreasing the repetition rate of the beam. Setting and removing blocks in the Hall is a very rapid procedure (around 15min, including shutting down the beam and restoring it later).

General information about Idaho Accelerator Complex

a) 25 MeV LINAC
- RF Frequency: 2856 MHz
- Energy range: ~4-25 MeV
- Average current: ??
- Pulse width: ~50 ns to 4 μsec
- Repetition rate: single pulse to 360 Hz
- Ports: 0 degree, 45 degree and 90 degree

b) 44 MeV Short-Pulse Electron LINAC
- RF Frequency: 1300 MHz
- Energy range: ~2-44 MeV
- Pulse width: ~60 ps (2 μsec bunches)
- Repetition rate: single pulse to 180 Hz
- Ports: 0 degree and 90 degree
- Beam energy resolution: ~1±15%

c) 48 MeV, >6 kW Electron LINAC
- RF Frequency: 2856 MHz
- Energy range: ~25-48 MeV
- Average current: 10-150 μA
- Pulse width: ~1 to 9 μsec
- Repetition rate: single pulse to 300 Hz
- Ports: 0 degree and 45 degree
- Beam energy resolution: ??

Pulse width	Maximum current	Charge/Pulse	Peak e-dose	Peak γ-dose
50 ps	100 A	5 nC	2×10^{13} rad/s	2.5×10^{8} rad/s
2 ns	3 A	20 nC	1×10^{12}	1.2×10^{7}
20 ns	1 A	60 nC	6×10^{11}	7.5×10^{6}
100 ns	1 A	100 nC	2×10^{11}	2.5×10^{6}
2μs	0.5 A	2000 nC	1×10^{11}	1.25×10^{6}

Overview Crystal Quality Control Measurements

following studies performed by PANDA collaboration (R. Novotny, V. Dermenev, PANDA-EMC Internal Report: 2014/1, 03.07.2014)

- **Measure optical transmittance and light output before and after irradiation.**
  - Transmission variation along the axis will reflect non-uniformity of the crystals and indicate difference in their growing methods.
  - The longitudinal optical transmission of the crystals before irradiation must be measured in the range of wavelengths between 300 nm and 900 nm. Care must be taken to mark exact position of the crystals (side, orientation and coordinate) relative to the light beam and to reach reproducibility of positioning of the crystals prior to all measurements (before and after irradiation). Special attention must be taken to transmission near absorption edge (~360 nm) where significant differences between crystals (related to the growing procedure) may show up.
- **Measure transmission in transverse direction (perpendicular to the longitudinal axis of a crystal) at 5-6 positions in steps of ~5 mm before and after irradiation** to study the depth dependence of absorbed radiation dose in the first 2-3 cm from the frontal (radiated) side
- **Measure the light-output at room and low temperature (stability on the level of 0.1 C°) to determine the contribution of slow components (strongly depends on impurities, specifically on contamination from Molybdenum)**
  - Gamma radioactive source, such as ^{137}Cs (energy of emitted photons ~662 keV) can be used for this measurement.
  - The PMT signals must be calibrated in units of photoelectrons (by single photo-electron peak positions defined in separate measurements). We can measure the light yield after wrapping the crystals (in ~8 layers of Teflon foil and one additional layer of aluminum foil) and optically coupling with PMT by Si-grease.
  - To determine the light yield "Y" per 1 MeV energy deposit (the number of phe/MeV) and ratio Y_{short}/Y_{long} for each crystal from measurements, the charge from PMT's anode signal can be measured by QDC within two different integration gates: "short" (~60 ns) and "long" (which must be varied in range ~1−4 μs).

To minimize systematic errors and maximize reproducibility of such measurements we need to keep crystals light tight during and after irradiation until the transmission measurements and at low temperature (to minimize spontaneous recovery). For example, transmission of a PbF_2 crystal from SICCAS, irradiated with a dose of 10 krad increased from 91% to 93% at 300 nm after 15 days of storage, while heavily irradiated Korth crystals recovered by 10-15% after 4 days (Achenbach, NIM A416-1998, p357). Similar spontaneous recovery of transmission has been observed in PbWO4 crystals kept in dark at room temperature. For a λ in the range ~550-650 nm initial transmission from ~50% dropped down to ~18% after 1 Mrad accumulated doses. No recovery was noticed after 4 days. But after 18 days transmission of the crystal kept at room temperature in darkness has reached ~30% (C. Woody et al., IEEE Trans. Nucl. Science 43, 1996, p1585).

The results of transmission measurements before and after irradiation will demonstrate the impact of radiation. For comparison with existing data and different samples of crystals, we may present results by using the absorption coefficient k. dk is deduced from the longitudinal transmission spectra before and after irradiation as:

$$dk = \left[\ln\left(T_{before} / T_{after} \right)\right] / d$$, given in m^{-1}, where d is the total crystal length.

For comparison of radiation hardness of crystals, the change in the optical absorption coefficient "dk" needs to be calculated at three wavelengths (360nm, 420nm and 620nm).

Idaho Test Plan

What will be shipped:

- A mix of $PbWO_4$ (produced by SICCAS in 2014) and PbF_2 crystals. Totally we will test 10 crystals: 8 $PbWO_4$ (5 taken from the NPS prototype, 3 from the new delivery), and 2 PbF_2 crystals from DVCS.
- All crystals will be labeled (for example SIC-2014-1, SIC-2014-2 and so on), measured and packed.

Questions:

- Can we take blocks offsite right away after irradiation? Will the blocks be activated?
- How we will keep crystals after irradiation and during transportation?
- Can we use traditional "cooler box" at ~0 C° to prevent fast crystal recovery?
- Can we just drive NewportNews-Idaho-NewportNews? (Note, the distance is ~2266 miles, or 33 hours of driving time. This may take 3-4 days!)

Tests to be done at Idaho:

- Irradiate blocks uniformly (both sides) at fixed dose rates for different durations (total doses);
- Irradiate blocks with different radiation rates up to equilibrium;
- Transmission measurements of the crystals right after irradiation (or after a ~30 min later);
- Several crystals irradiate with dose rates ~1-2 krad/h up to accumulated doses of ~1 Mrad (for future tests of efficiencies of blue and IR curing systems);

It would be best if we can organize first transmission measurements at Idaho after irradiation, and do next more detailed set of measurements at JLab with 5-7 days delay. In Idaho we can start transmission measurements after irradiation with the ~30 min delay after the end of radiation (as this was done by R. Novotny), and keep this delay time same for all crystals. This delay allows a partial recovery of color centers with extremely fast relaxation times. All measurements that we can do are at room temperature (~18 C°).

Questions:

- Are we planning irradiate crystals uniformly or only from the front? From the experimental point of view, more important is frontal radiation, but for studies of crystal quality and for comparison with existing data, uniform irradiation is needed. For uniform irradiation we will need to rotate crystals by 180° at least after half-time of its exposure (*doing both front and back irradiation*).
- Do we have other plan *if* we find that the small spectrometer is very unreliable compared to the setup at JLab? (We would measure "big radiation effects". Do we need high accuracy!).
- After transportation all measurements will be done at JLab again, but with the delay time ~5-7 days or more. Would be this problem? How we will calibrate setups in Idaho and JLab?

Preparations needed before shipping

- Thermally anneal all crystals at 200 C° following the procedure that we used earlier: ~10 hour ramp up, ~10 hour anneal, and ~10 hour ramp down. This thermal annealing will fully recover possible damages of radiated crystals and also will reduce mechanical stress in the new produced crystals.

- Measure transmission of all crystals to select samples for Idaho tests, e.g., crystals with similar transparencies. Crystals with similar or very close transmittances can be used for studies of the rate dependence of radiation damage. At each dose rate the crystals will be radiated for accumulated doses to reach level of equilibrium.
- Develop simple means for transmission measurements which we can take to Idaho, e.g., a mini-spectrometer based on LEDs with Photodiode
- Light yield measurements
- Time property studies
- Calibrate the device by doing transmittance measurements with it and with more accurate Zorn's system;
- Prepare another option to measure transmittance similar to what we have used for LED intensity studies (shown in Fig.3).
  - Light produced by three different LEDs (Blue, Green and Red) will be delivered by fiber onto front of crystal. Each time only one type LED will be ON. Intensity of the light passing through the crystal will be measured by Photodiode (combined with pico-amperemeter). Two measurements in each case most be performed: without crystal and with crystal. **Note, such setup can measure only average transmission in the range of LED spectrum!**

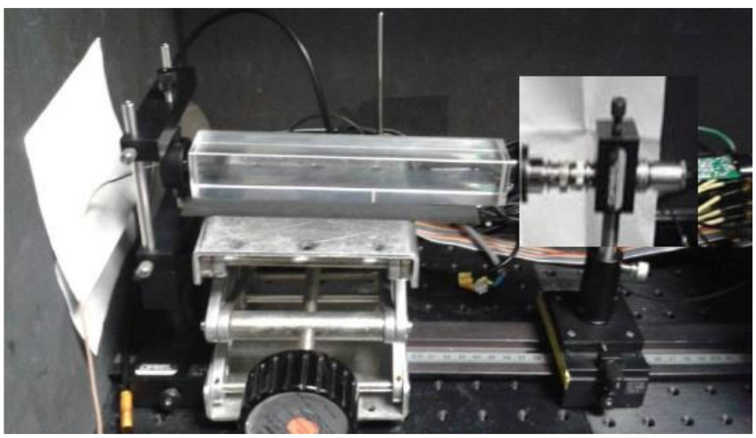

Fig.3 Possible variant of simple setup for relative transmission measurements

Who will go to Idaho for the tests?

- Carlos can potentially go to Idaho for the tests.
- At least 1 or 2 more people would be needed. **Does anyone volunteer?**