Idaho irradiation tests 17-20 February 2015

Introduction

To test the radiation hardness of the spring 2014 produced SIC PbWO4 crystals and the efficiency of an LED-based curing system, 10 crystals were taken to Idaho Accelerator Center, where they were tested with beam on 18 Feb. and 20 Feb. Before the crystals were shipped from JLab to Idaho the following preparation procedures were carried out.

- All $PbWO_4$ crystals were thermally annealed at 200 C° following the procedure that we used earlier: ~10 hour ramp up, ~ 10 hour anneal, and ~10 hour ramp down.
- All crystals' transmission was measured in the transverse direction at 5, 15, 25, 35, 45 and 55 mm from their front face.
    - Data show the uniformity for all crystals along their length, but with noticeable spread from crystal to crystal. The worst quality we found was crystal #9.

Beam properties and Radiation Dose

The Idaho Accelerator Center provides a 20 MeV electron beam with 100 Hz repetition rate, with I_{peak}=111 mA (per pulse) and 100 ns pulse width. The beam is roughly 1mm in diameter and exits through (1/1000)-in thick Ti window, a $x/X_0 = 7.1\cdot10^{-4}$ radiation length. Beam position and profile are measured by shooting a glass plate, some examples of which are shown in Fig. 1. Scanning the plates and fitting the intensity distribution provides a quantitative (though approximate) measurement of the position and size of the beam at the location of the plate.

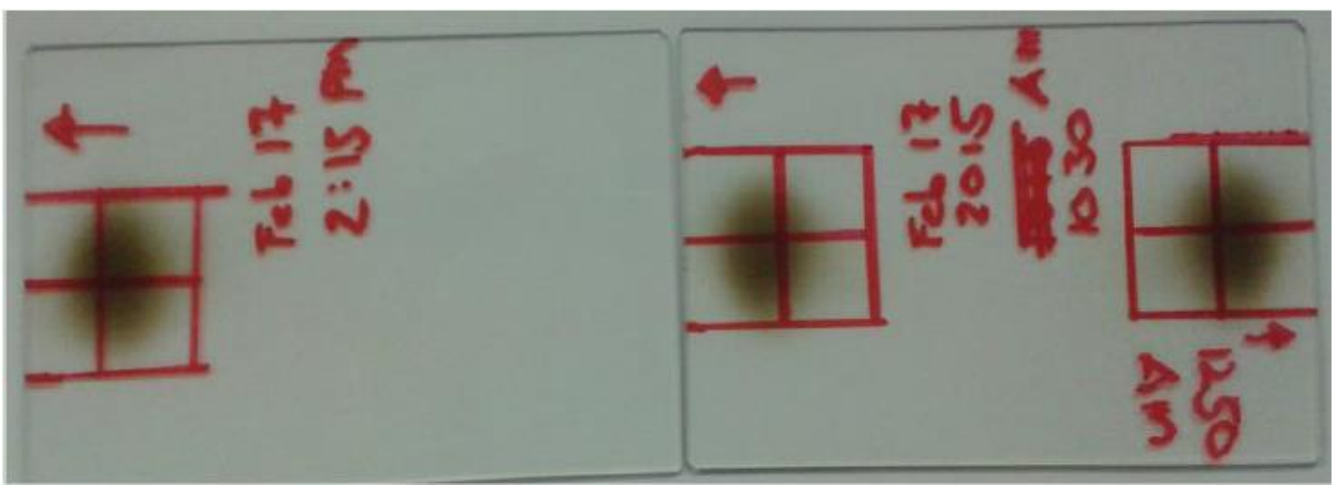

Fig.1: Examples of glass used to position the crystal (block) relative to the beam and estimate the beam distribution.

Fig. 2 documents the beam position and profile as measured during our first day (Feb 17). The front plate was placed at the position of the PbWO4 crystal (block) front faces during irradiation that is 10.75 cm from the beam exit window. The rear plate was located at 51.15 cm from the beam exit, and shows the beam profile expansion. The beam profile at the entrance of the PbWO4 crystals has an approximate size of 0.2-0.3 cm (sigma). This is much smaller than the transverse size of the PbWO4 crystals, so the distance of the PbWO4 crystals was increased the second irradiation day to 33 cm from the exit window (see below). This provides a more homogeneous irradiation and heat load on the crystals.

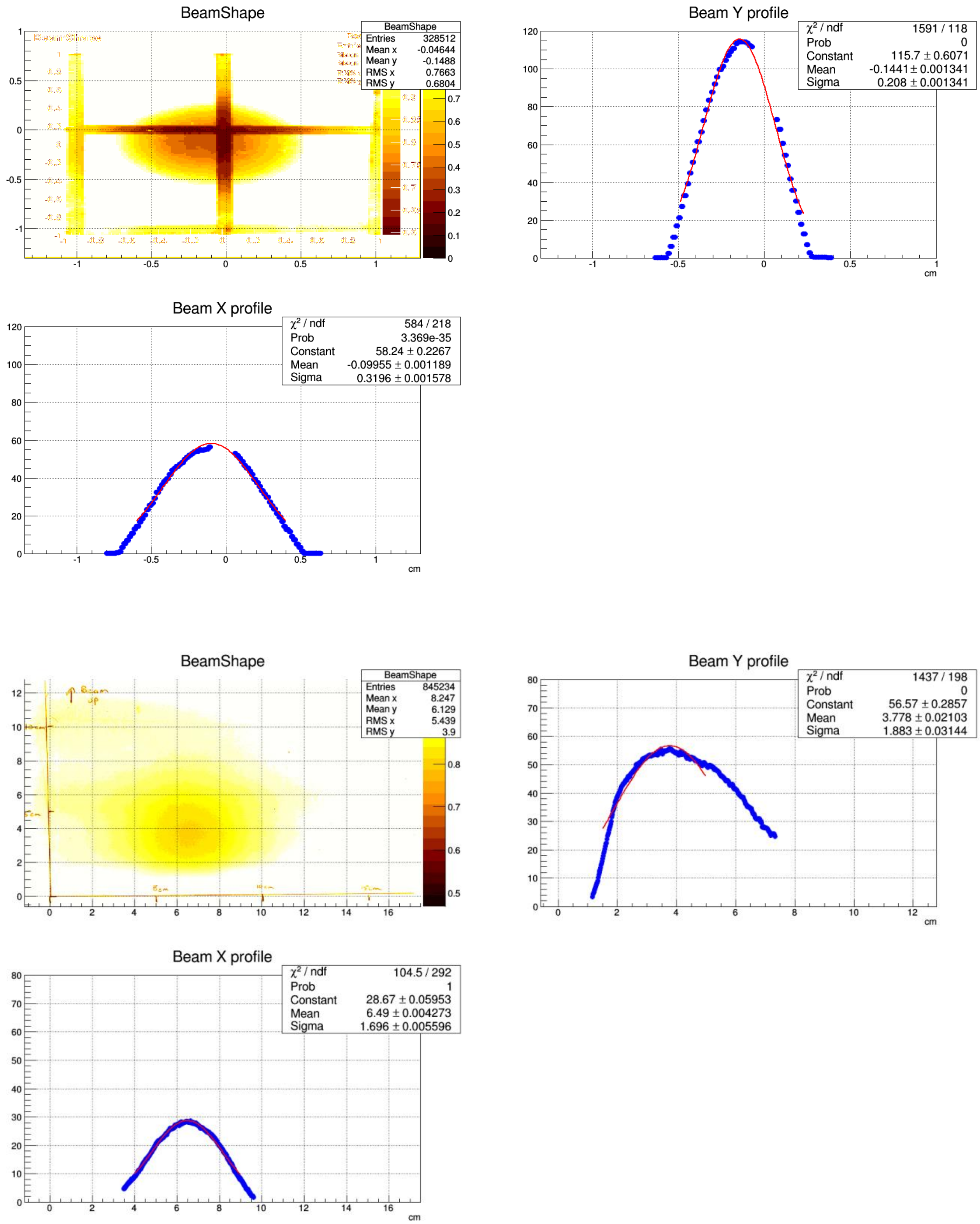

Fig.2: Beam profile during Feb-17's runs reconstructed from 2 plates. The front plate (top three panels) was placed at 10.75 cm from the beam exit, the rear (bottom three panels) plate at 51.15 cm. The beam profile is small at the front face of blocks (0.2-0.3 cm).

Coulomb scattering through the Ti window produces a roughly Gaussian distribution of angular spread of radiation with RMS:

$$\theta_0 = \frac{13.6\,MeV}{\beta cp} z\sqrt{x/X_0}\left[1 + 0.038\log(x/X_0)\right] = 0.0129\,rad \qquad (1)$$

This is, however, smaller than the actual size observed at the glass plates due to the intrinsic size of the beam at the exit window.

A $PbWO_4$ block of mass M_{block} = 0.6 kg at the above mentioned beam parameters will receive a dose:

$$\mathrm{D(Gy)} = \frac{111\cdot 10^{-3}\times 100\cdot 10^{-9}\cdot 3.2\cdot 10^{-12}\cdot 100/1.61\cdot 10^{-19}}{0.6} \approx 36\,\mathrm{Gy/sec},$$

or 216 krad/min. Since such radiation dose rate is too high (~13 Mrad/h), we decided to start our tests at ~1000 times lower dose rates (~13 krad/h). To achieve this dose rates, we requested to reduce the accelerator repetition rate to 0.1 Hz, but kept beam current per pulse and pulse width unchanged (111 mA and 100 ns).

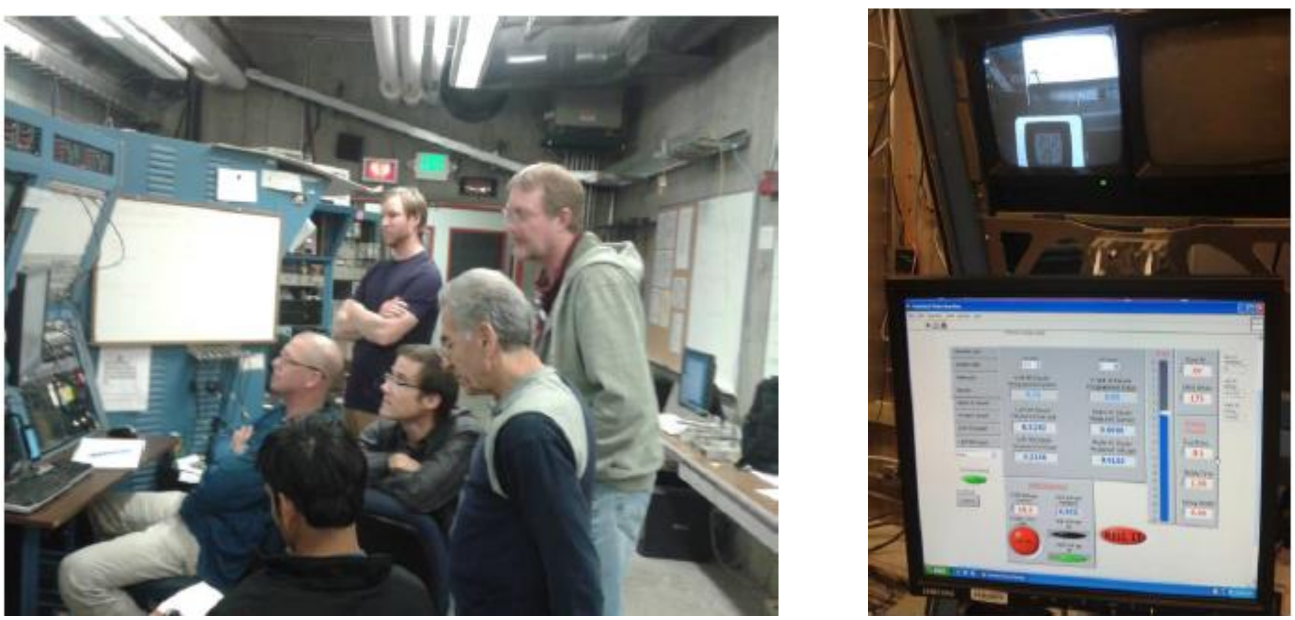

Fig.3: Idaho Accelerator operation room (left) and its main parameter LabVIEW control system (right).

Tests performed in Idaho on 17 February 2015:

- Before irradiation, the crystals' transmission was measured in Idaho using the same setup as the one used prior to shipping the crystals from JLab. This setup is shown in Fig.4.

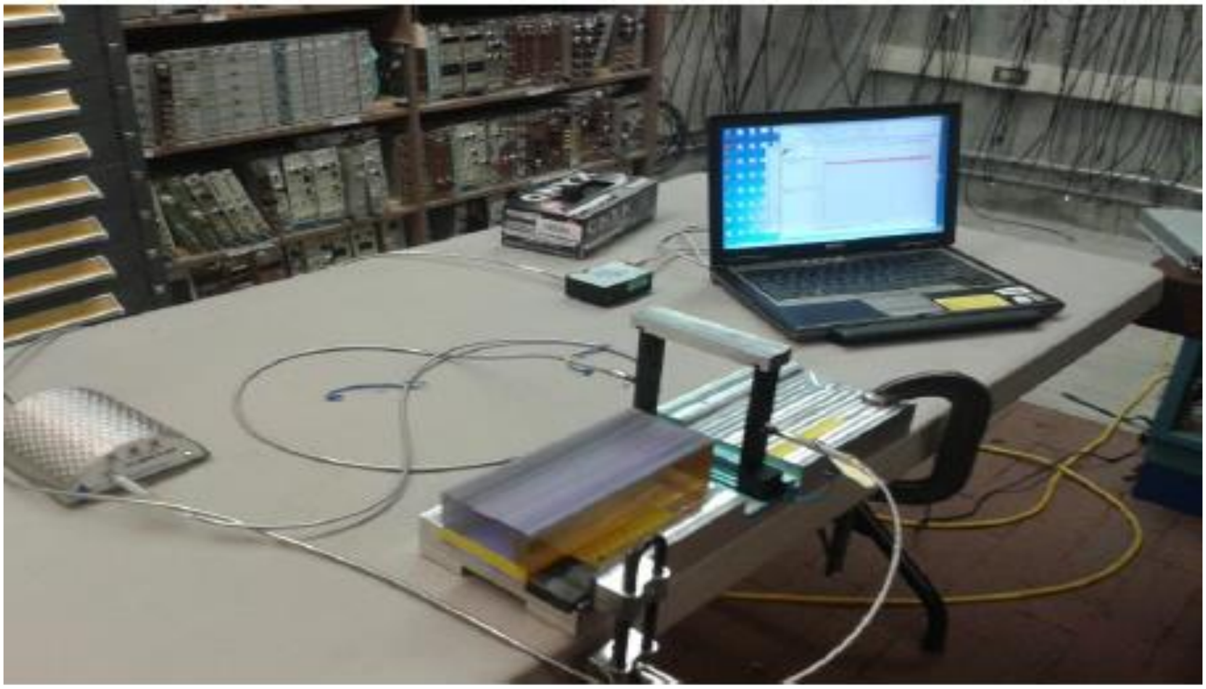

Fig.4: Setup used for crystals transmission measurements at JLab and Idaho.

- We found systematic differences between JLab and Idaho measurements. We found that the accuracy strongly depends on positioning of the crystal relative to the fibers and on the relative adjustment of the fibers.

- Fig. 5 shows the transmittance for crystals #1-3 measured on 16 and 17 February (in Idaho) and their ratios. Comparison of these measurements gives a qualitative number on the accuracy of the transmission measurements performed before irradiation of the blocks. The systematic difference between these two measurements on average ranges between ~5% and ~15%.

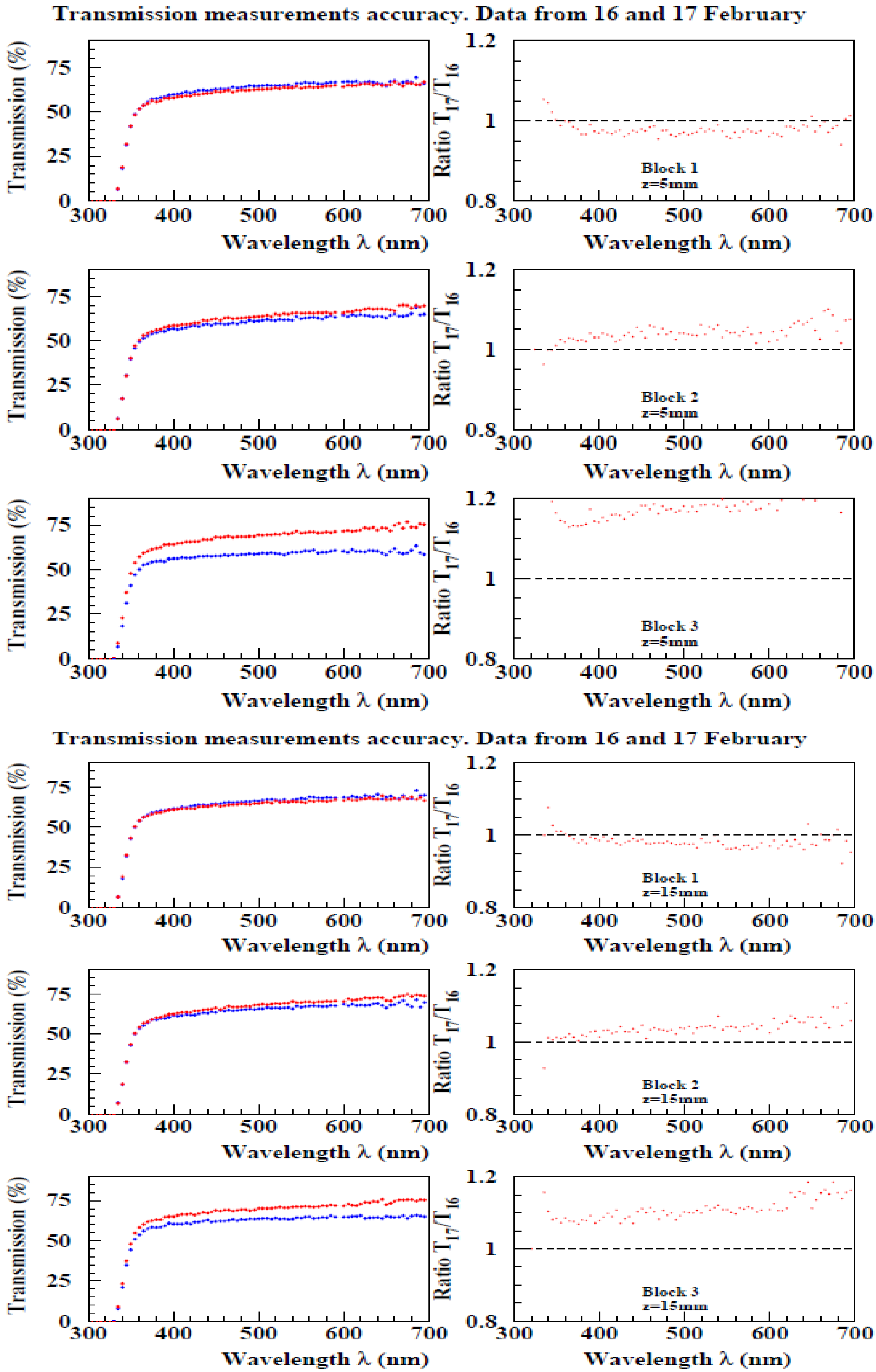

Fig.5: Transmission for blocks #1-3 measured before irradiation on 16 and 17 February and their ratios. (Top panel for the position z=5 mm, and bottom for z=15 mm).

- Nevertheless, when we carefully adjusted the setup, the reproducibility of the measurements was ~±5%. Transmissions for all 10 crystals before irradiation are shown in Fig.6.

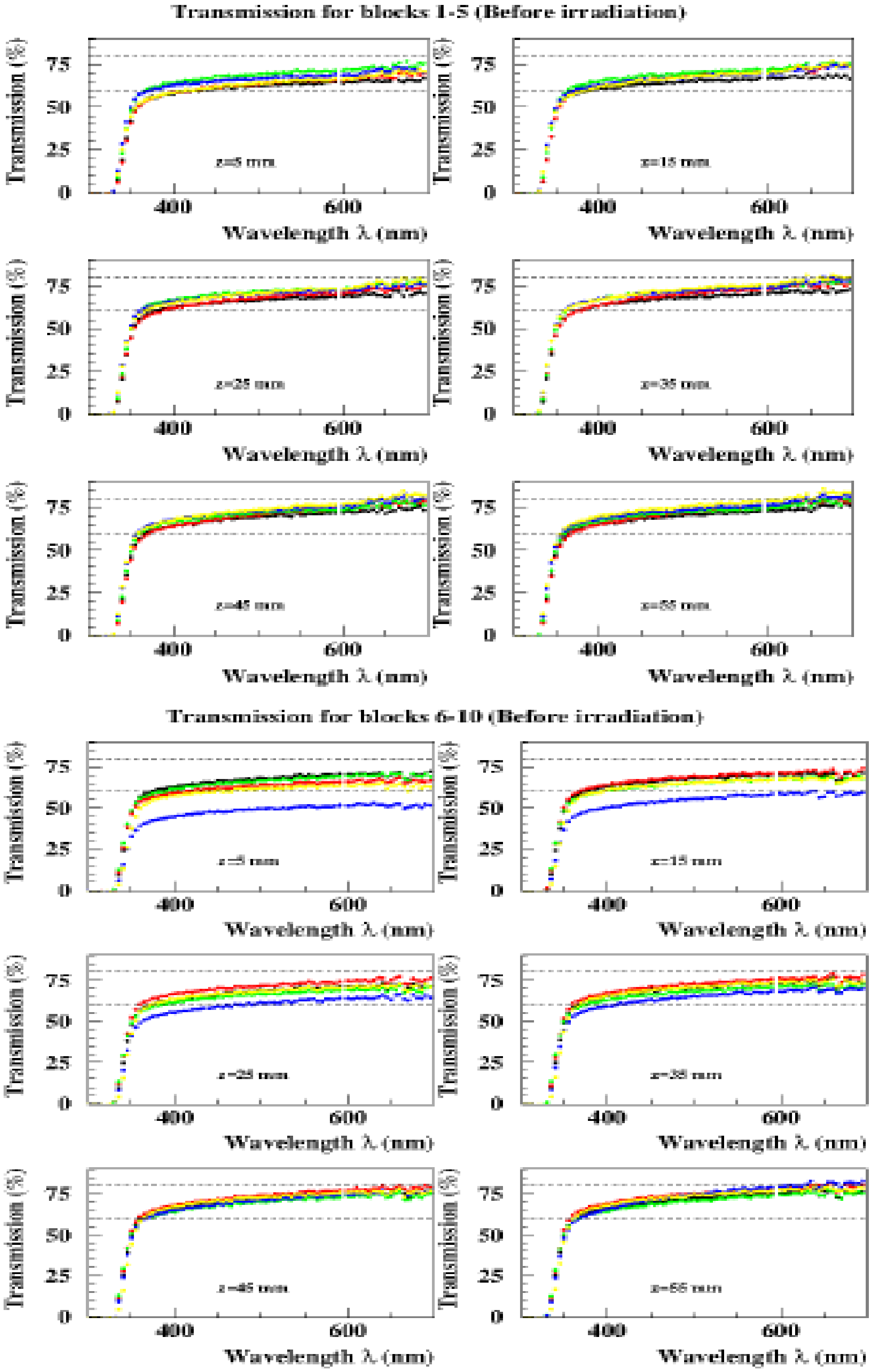

Fig.6: Transmission of $PbWO_4$ in the transverse direction at different distances from the front of crystals measured in Idaho before irradiation. Data for different crystals are plotted in colors. Blue indicates crystal #9 – the crystal with the worst transmittance of this batch.

- We installed an adjustable table as close to the beam pipe as possible and positioned the crystal support at 10.75 cm from the beam exit window.

Fig.7: Details of the installation and positioning of the crystal relative to the beam.

- Started irradiation tests of crystal #1:
    - First, we set the dose rates to ~13 krad/h (0.1 Hz, 111 mA, 100 ns, E=20 MeV) and exposure time to 10 min.
    - Then we increased the dose rate to ~130 krad/h (increased by factor 10 just by increasing operation rate from 0.1 to 1 Hz) and irradiated for an additional 10 min.
    - On step three, we increased beam frequency to 10 Hz which yielded a dose rate of 1.3 Mrad/h and irradiated the crystal for 10 more min.
    - After each step of irradiation we did transmission measurements in the transverse direction at all z-positions, and not found any noticeable sign of radiation damage. Small changes within 5-10% were attributed to the accuracy of our measurements.
    - Then we increased beam rate to 100 Hz keeping the beam current and width unchanged (111 mA per pulse and 100 ns). Temperature of the crystal near frontal area increased from ~25°C to ~42°C in less than 10min, and crystal cracked sooner than we stopped beam (see figure Fig.8 below).

Fig.8: Block #1 damage due to irradiation at dose rate ~13 Mrad/h. Rapid and not uniform rise temperature cracked the crystal sooner than we could stop the beam.

  - After such a fiasco (crystal #1 cracked) we decided not to exceed the dose rate of 1.3 Mrad/h, and test all other 9 crystals at this dose rate, but doubling the exposure time (from 10min to 20 min) and keeping our eyes on the thermometer during the run.
- Crystals #2-10 were irradiated at a dose rate of 1.3 Mrad/h for 20 min. On average, the temperature near the frontal area of the crystals during exposure increased from 74-77°F (at start) to 97-98°F (at the end). Beam parameters and conditions of irradiation are listed in Table I.

Table I: Beam parameters and conditions of irradiation for blocks #2-10
E=20 MeV, Pulse width=100 ns, current =111 mA/pulse, Dose Rate=216 krad/min

Run #	Block #	Start Time	Initial T1 - (⁰F)	Initial T2 (⁰F)	End Time	Final T1(⁰F)	Final T2 (⁰F)	Pulse Count
6	2	12.21	76.1	76.9	12.41	97.7	76.3	12003
7	3	12.54	74.3	76.6	1.14	95.0	76.3	12005
8	4	1.20	75.0	76.5	1.40	95.0	76.3	12006
9	5	1.47	76.0	75.0	2.07	95.0	76.3	12004
10	6	2.29	74.5	75.4	2.49	97.5	76.3	12002
11	7	2.48	77.2	76.5	3.08	96.4	76.5	12011
12	8	3.12	76.3	76.5	3.32	96.6	76.8	11989
13	9	3.38	75.9	76.8	3.58	96.3	76.6	12016
14	10	4.02	~76	76.5	4.23	98.1	76.3	11974

- Transmission some of blocks changed more than 15% after an accumulated dose of 432 krad (at a dose rate of 1.3 Mrad/h). Some of blocks can handle this dose without noticeable damage.

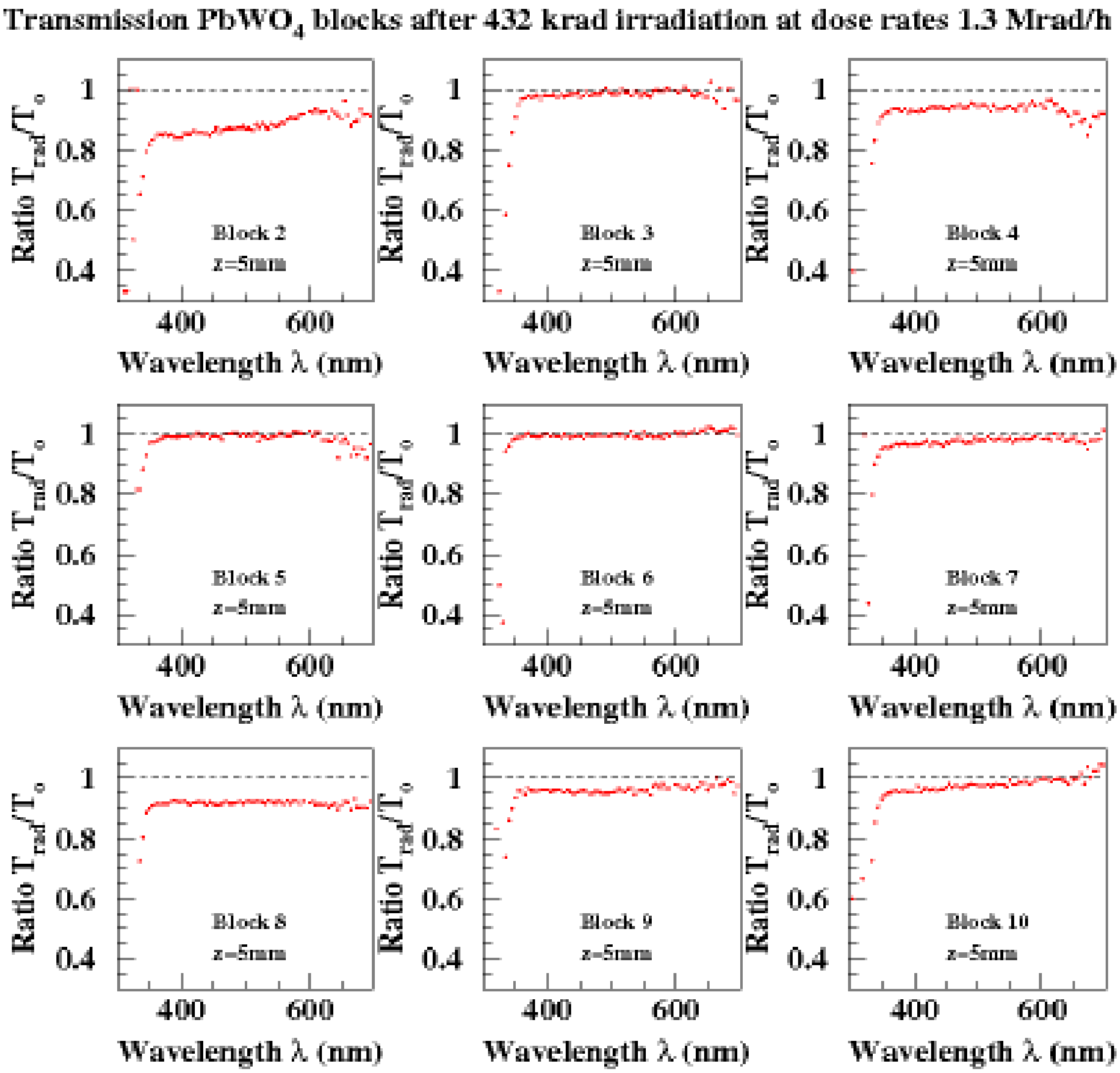

Fig.9: Transmission degradation of the PbWO4 blocks after 432 krad accumulated dose at dose rates of 1.3 Mrad/h. Ratio of transmissions after and before irradiation reflects the level of crystal degradation. For example, crystal #6 shown in the center panel was not damaged significantly.

- Degradation of transmissions for positions far from the front of crystals decreases with the distance and are comparable to the accuracy of our measurements.
- After irradiation tests of all 9 crystals with a dose rate of 1.3 Mrad/h and 20 min exposure, we returned to find out a higher dose rate regime acceptable for crystals (since the goal was to find the maximum dose rate limits for crystals, reach a noticeable radiation damage and study the curing systems). The simplest way to double dose rates relative to 1.3 Mrad/h was to just change the beam rate from 10 Hz to 20 Hz (keeping 111 mA current per pulse and pulse width 100 ns).
- Since this study was potentially dangerous for crystals, we first tested the damaged crystal #1. We used the other end of crystal #1, set two thermometers on top of the crystal, one on the front face area, the second on the middle of the crystal. The plan was to expose the crystal for 20 min at a dose rate of ~2.6 Mrad and follow the rise of temperature. After 13 min exposure at dose rates of 2.6 Mrad/h, the temperature of crystal #1 increased from 76.3 °F to 115.2 °F and crystal cracked.

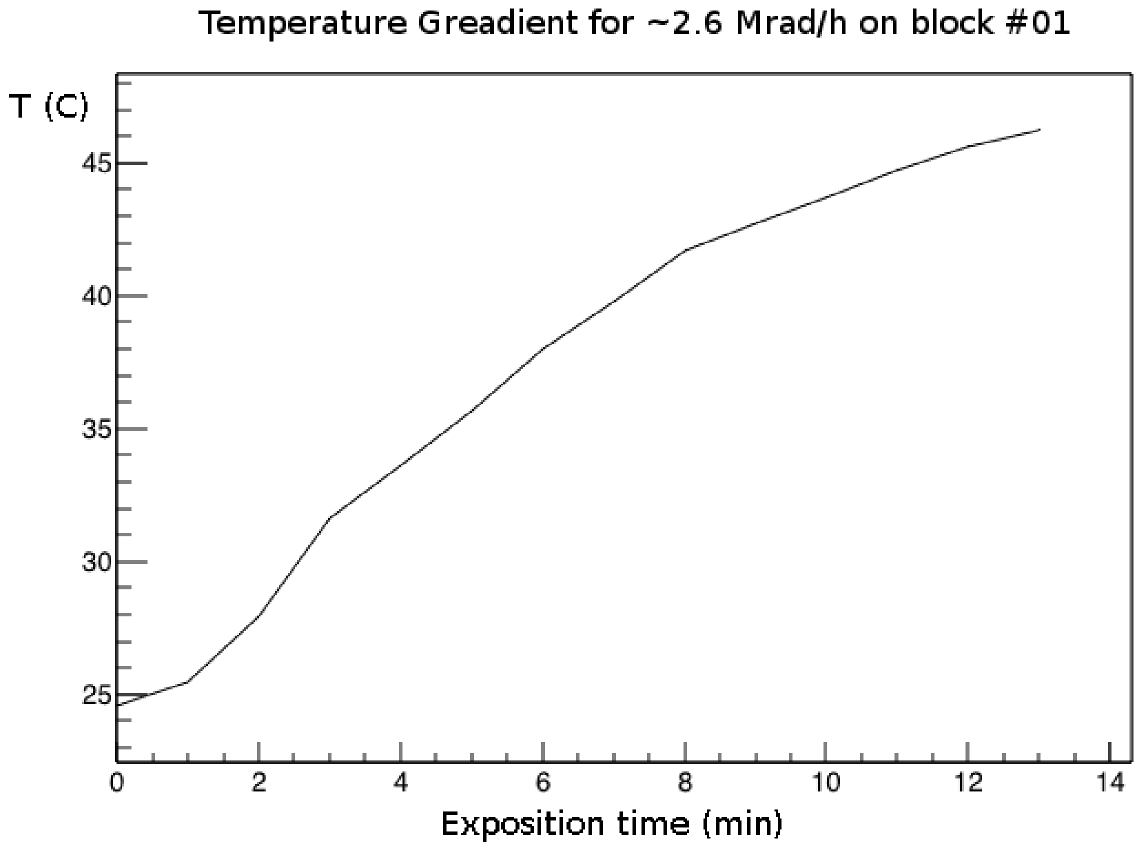

Fig.10: Temperature increase for the block #1 during irradiation at dose rate of ~2.6 Mrad/h. Crystal cracked after ~13 min, when the temperature near the frontal area ramped up from 25 °C to 48 °C.

- This test made it clear that we could not go to higher dose rates, but we could potentially increase the exposure time.
- To reach higher level of accumulated dose we exposed each crystal several times with a 20-30 min pause. (For example, expose crystal #2 for 20 min at a dose rate of 1.3 Mrad/h, then take out crystal #2 and expose crystals #3 and #4 each for 20 min. While we expose crystals #3 and #4, the temperature of crystal #2 will decrease and the block would be ready for the 2nd exposure).

<u>Tests performed at Idaho on 20 February 2015:</u>

- Since after 17 February tests we found that the beam profile was too small (σ_x and σ_y~2-3 mm), we decided to place the blocks further (~33 cm) to get a more homogeneous irradiation (and heat load) on the crystal.
- Beam profile was measured by two plates located on front and back of the crystal. The front plate at 33cm from the beam exit (σ_x ~ 0.8 cm, σ_y ~ 0.7 cm). The rear plate at 53 cm from the beam exit window (σ_x ~2.8 cm, σ_y ~2.1 cm).
- Beam profiles as measured on Feb-20's tests are shown in Fig.11.

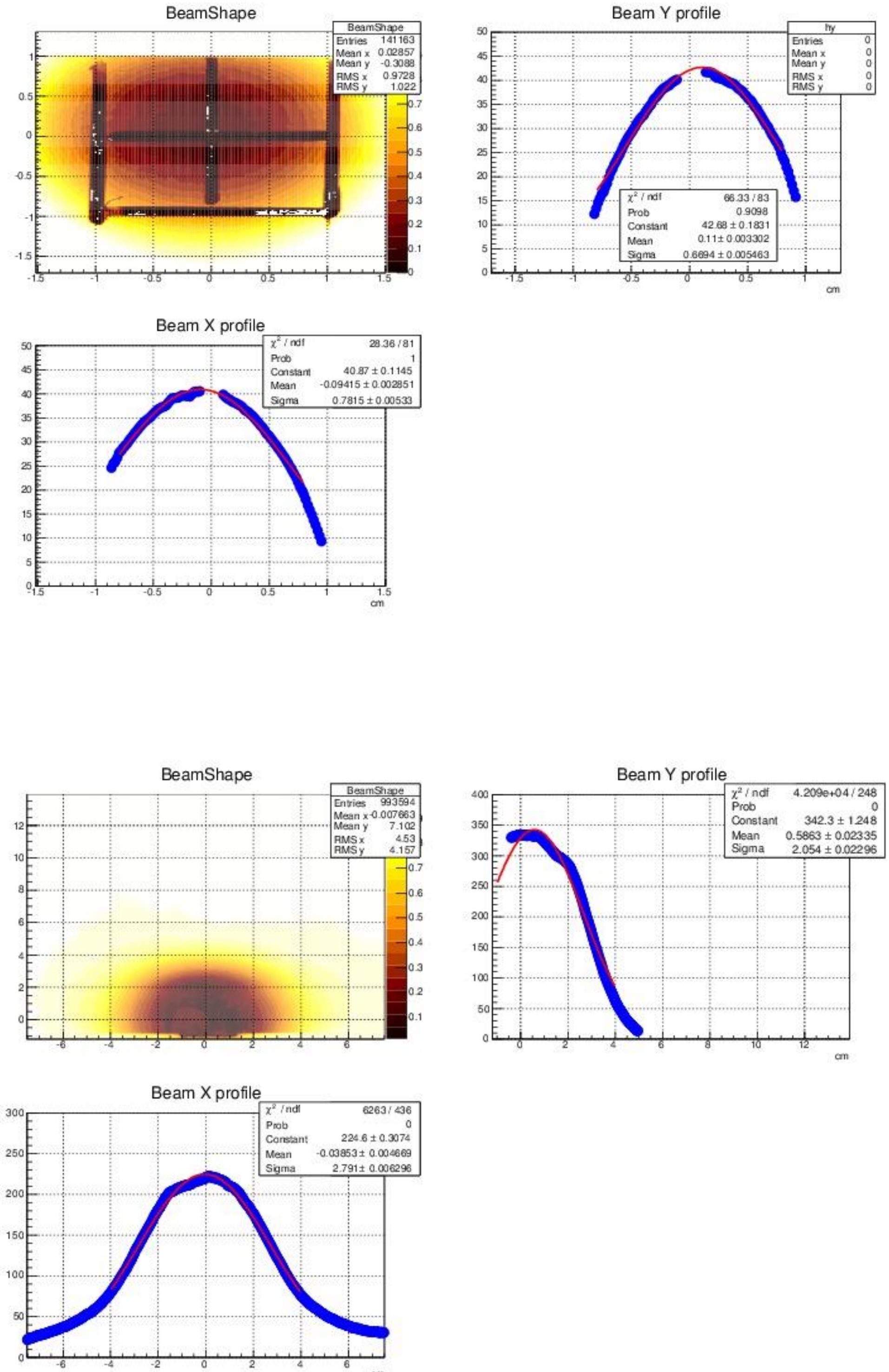

Fig.11: Front (top) and rear (bottom) profile of the beam at the beginning of Feb-20's tests. Front plate was located at 33cm from the beam exit (σ_x ~ 0.8 cm, σ_y ~ 0.7 cm), the rear plate at 53 cm from the beam exit window (σ_x ~ 2.8 cm and σ_y ~ 2.1 cm).

- Since beam time was limited on Feb 20, we selected pair of crystals: #2 and #3, and #6 and #8. One crystal from each pair (#3 and #6) did not show noticeable damage after 432 krad dose received on 17 February, while the second (#2 and #8) was damaged about 10-15% (see Fig.9).
- Before the start of the irradiation tests we did transmission measurements of these crystals. The goal was to estimate the level of their spontaneous recovery after 60 hour of receiving a 432 krad dose (on Feb 17) and to determine the starting condition of the crystals.
- As we expected, the transmission of some of the crystals improved within 2 days due to spontaneous recovery. Fig.12 shows the ratios of transmission for crystals 2, 3, 6, 8 and 10 measured after 60 hours of receiving a dose of 432 krad and before being irradiated again.

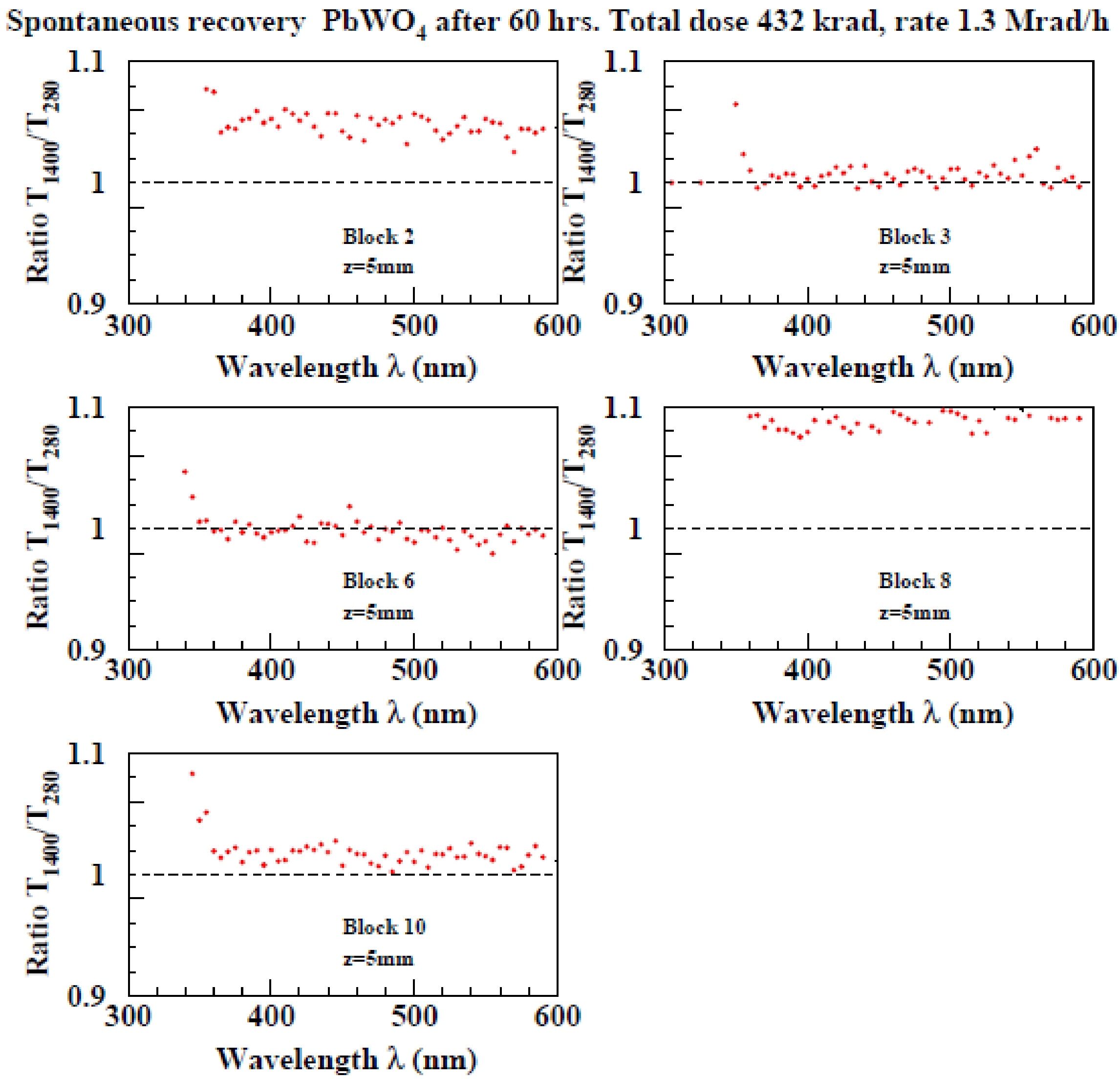

Fig.12: Spontaneous recovery of crystals from a 432 krad dose damage, 60 hours after irradiation.

- To reach higher level of accumulated dose but avoiding crystal overheating, we exposed each crystal to a dose rate of 1.3 Mrad/h several times with 20 min pauses (for the crystal to cool down). For example, expose crystal #2 for 20 min, then take out crystal #2 and expose crystal #3 for 20 min, then back to irradiation crystal #2, and so on.

- While we exposed one of the crystals, we did transmission measurements for the crystal which had already been irradiated.
- By swapping and periodically irradiating crystals we reached accumulated doses of ~2 Mrad. Meanwhile, transmission measurements showed no further degradation. Moreover, some of the crystals showed improvements relative to their condition after the initial dose of 432 krad.
- For some of the crystals, after a ~864 krad dose, we observed a slightly yellow color on the frontal area, within ~1-2 mm from the surface. This yellow color disappeared during further irradiation.
- Fig.13 shows the ratios of crystal transmission after an accumulated dose of 2160 krad with respect to the transmission measured after 60 hours of spontaneous recovery from a 432 krad dose. All irradiation took place at a dose rate of 1.3 Mrad/h.

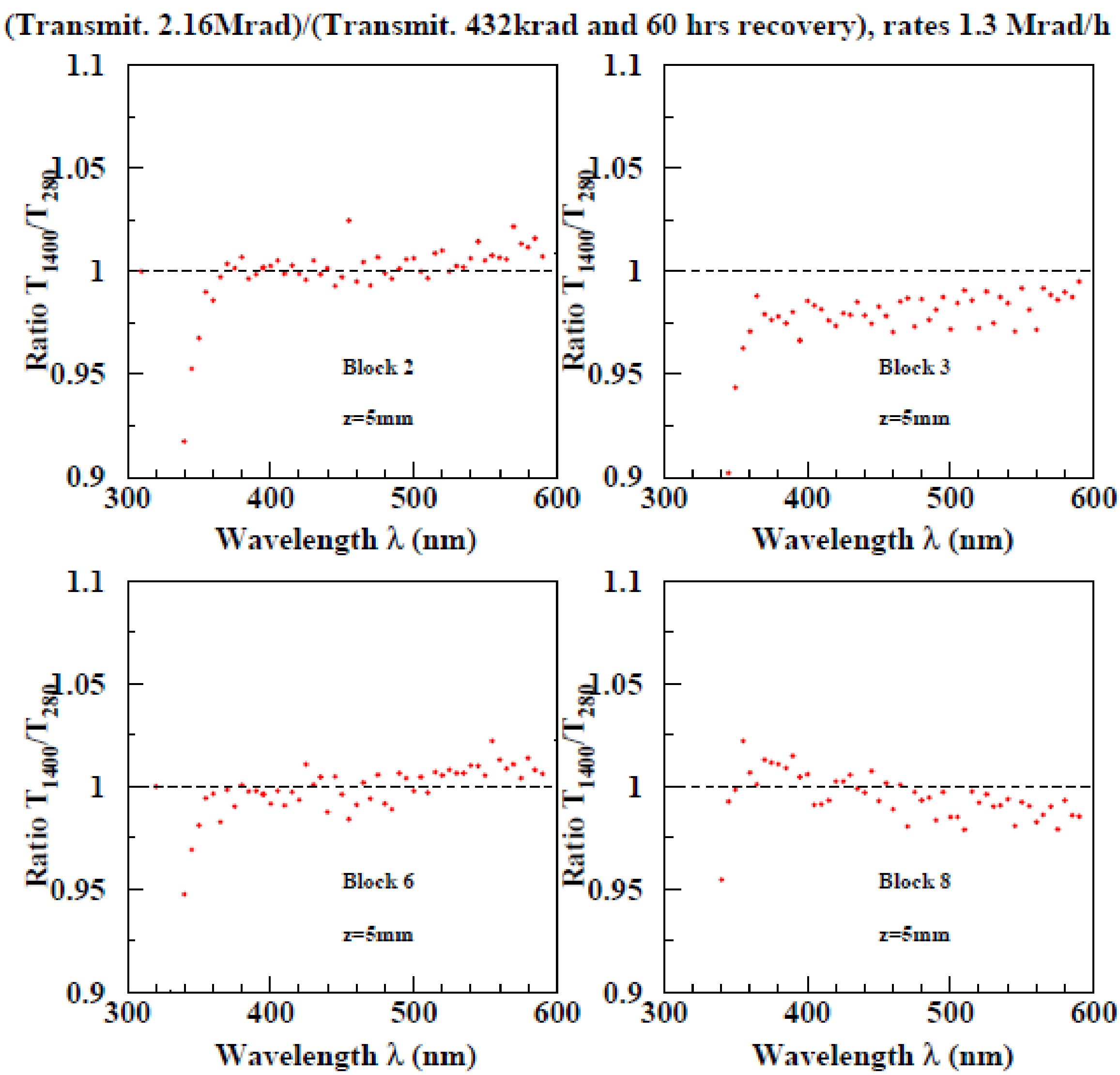

Fig.13: Ratios of crystal transmissions after an accumulated dose of 2160 krad with respect to the transmission measured after 60 hours of spontaneous recovery from a 432 krad dose. All irradiation took place at a dose rate of 1.3 Mrad/h.

GENERAL CONCLUSIONS FROM IDAHO TESTS:

- No noticeable damage to the crystals was observed after irradiation, up to an accumulated dose of ~2 Mrad at a dose rate of 1.3 Mrad/h.
- Some of the crystals show ~10-15% damage after a 432 krad dose, which partly spontaneously recovered after 60 hours.
- Prior to irradiation with a dose rate of 1.3 Mrad/h, the temperature in the frontal area of the crystals ramped up at a rate of ~0.5 °C/min. A rise in temperature in the frontal area of more than ~12-15 °C may crack the crystal due its bad thermo-conductivity.
- After an accumulated dose of ~2.1 Mrad, the crystal frontal area shows a 55-60 mkrad γ-activity.

Tests curing systems:

- We took 3 curing systems to Idaho (OSRAM blue lamps from Julie and a set of blue and infrared LEDs). Since no noticeable damage was observed, we have not used either of these curing systems.

Packing crystals and equipment for shipping back to JLab:

- At the end of Feb 20, we asked RadCon IAC to do a check of the radiation conditions of the crystals. The blocks activation was ~55-60 mkrad in the frontal side and below 20 mkrad at the rear.
- At such levels of activation, crystals must be kept in a special controlled area for about one week.
- We packed crystals in the cooler box and all equipment in the wooden box. Hopefully, they will be shipped to JLab within the next 7-10 days.

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