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IHEP 2004–3

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COMPARISON OF RADIATION DAMAGE IN LEAD TUNGSTATE CRYSTALS UNDER PION AND GAMMA IRRADIATION

Submitted to *Elsevier Science*

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Protvino 2004

UDK 539.1.07 M–24

Abstract

Batarin V.A. Butler J., Chen T.Y. et al. * Comparison of Radiation Damage in Lead Tungstate Crystals under Pion and Gamma Irradiation : IHEP Preprint 2004–3. – Protvino, 2004. – p. 9, figs. 8, tables 1, refs.: 9.

Studies of the radiation hardness of lead tungstate crystals produced by the Bogoroditsk Techno-Chemical Plant in Russia, the Shanghai Institute of Ceramics in China have been carried out at IHEP, Protvino. The crystals were irradiated by a 40-GeV pion beam. After full recovery, the same crystals were irradiated using a ^{137}Cs gamma source. The dose rate profiles along the crystal length were similar in both cases. We compare the effects of the two types of radiation on the crystals light output.

Аннотация

Батарин В.А., Батлер Д., Чен Т. и др. Сравнение радиационной стойкости кристаллов вольфрамата свинца под действием пионного и гамма-излучений: Препринт ИФВЭ 2004–3. – Протвино, 2004. – 9 с., 8 рис., 1 табл., библиогр.: 9.

Исследования радиационной стойкости кристаллов вольфрамата свинца, произведенных Богородицким техно-химическим заводом (Россия) и Шанхайским институтом керамики (Китай), проведены в ИФВЭ (Протвино). Кристаллы были облучены пучком пионов с энергией 40 ГэВ. Эти же кристаллы после полного восстановления подверглись гамма-облучению радиоактивним источником ^{137}Cs. Профили мощности дозы по длине кристалла были одинаковы в обоих случаях. В работе сравнивается влияние двух видов облучения на величину светосбора с кристаллов.

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1. Introduction

In high luminosity collider experiments, lead tungstate ($PbWO_4$) crystals used in electromagnetic calorimeter will be irradiated by high energy particles and accumulate significant absorbed doses, up to a several Mrad. The radiation hardness of $PbWO_4$ crystals has been studied by the CMS group using radioactive sources and electron beams [1] and by the BTeV group using both high energy pion and electron beams, resulting in particle environment that is similar to that expected when running the BTeV experiment [2,3].

The goal of this study is to compare the radiation damages of crystals using two types of irradiation, either a high energy pion beam or a ^{137}Cs radioactive source. If the effects of these two types of radiation are similar, we could use source measurements to classify the radiation resistance of each crystal in the BTeV like environment. This would be considerably easier than using pion beams for this measurement. This is crucial for a crystal quality assurance before assembling the electromagnetic calorimeter. However, the world experience has not the data of a comparative study of the crystals radiation damage under hadron beam and gamma source irradiation. The first attempt in this direction is described in this paper.

The integrated expected dose distribution in the BTeV crystals is shown in **Table 1** assuming a collider luminosity of 2×10^{32} cm^{-2}s^{-1} and a running time of 10^7 s.

Since the BTeV calorimeter starts close to the beam-line, about 15 cm away, and extends to a radius of 160 cm, the amount of radiation varies greatly. Near the beam-line a small fraction of the crystals, ~1% have doses of about 10^4 Gy (1 Mrad), while 90% of the crystals have doses less than 0.1 Mrad. The latter corresponds to a dose rate of 36 rad/h. About 70% of the crystals have dose rates < 4 rad/h.

We used three crystals produced by the Bogoroditsk Techno-Chemical Plant in Russia (denoted as CMS-2442, CMS-2443, Bogo-2313) and three more crystals produced by the Shanghai Institute of Ceramics in China (denoted as Shan-T16, Shan-T19, Shan-T20). All the crystals except those which are marked as CMS were produced at the end of 2000. The CMS crystals were produced in 2001. The dimensions of the crystals were $\sim 27 \times 27$ mm^2 in cross section and 220 mm in length. The CMS crystals had the same length but were tapered with 29×29 mm^2 at the back. Each crystal was wrapped using 170 μm thick Tyvek.

Table 1. Fraction of BTeV crystals with given absorbed doses and dose rates estimated at the maximum of the dose profiles inside the crystals (100 rad = 1 Gy).

Relative number (%)	Absorbed dose (krad/year)	Dose rate (rad/h)
33	0.3 - 2	0.11 - 0.72
27	2 - 5	0.72 - 1.8
12	5 - 10	1.8 - 3.6
16	10 - 50	3.6 - 18
6.2	50 - 100	18 - 36
3.2	100 - 200	36 - 72
2	200 - 500	72 - 180
0.4	500 - 1000	180 - 360
0.2	1000 - 2000	360 - 720

The crystals were irradiated by a 40 GeV π^- beam, four of them in April 2001 and the other two CMS crystals in April 2002. After the recovery process at room temperature the crystals were irradiated by ^{137}Cs gamma source in May and June 2003. We provided very close irradiation conditions, dose rates and absorbed doses in crystals, for both cases. Two types of measurements were done on each crystal both before and after the gamma irradiation:
a) light output (LO) measurements using a radioactive source for crystal excitation, and
b) crystal transparency measurements using a spectrophotometer.

2. Irradiation by pions

A pion irradiation was carried out at the IHEP (Protvino) 70-GeV accelerator. The size of the 40 GeV π^- beam was 8 cm horizontally and 6 cm vertically, i.e. 90% of the beam was contained within these dimensions. The beam was present in 1.2 second interval of the full accelerator cycle of 9 sec. Six crystals were irradiated with a dose rate ranging from 30 to 60 rad/h. The crystals light output signals were monitored using the minimum ionizing particles (MIP) in pion beam running and electron beam data from separate low-intensity calibration runs. The LeCroy 2285 15-bit integrating ADC was used to measure the signal using a 150 ns integration time. The Protvino testbeam setup was described in detail elsewhere [3,4,5].

3. Irradiation by ^{137}Cs source

We used a gamma radioactive source ^{137}Cs (E = 0.661 MeV) with activity of $5 \cdot 10^{12}$ Bq to irradiate the crystals. The geometrical setup for each crystal position is shown in **Fig. 1**. Each crystal was irradiated separately. Commercial dosimeter DKS-AT1123 was used to measure the dose rate (in air) in proximity to the crystals. The accuracy is better than 25% [6].

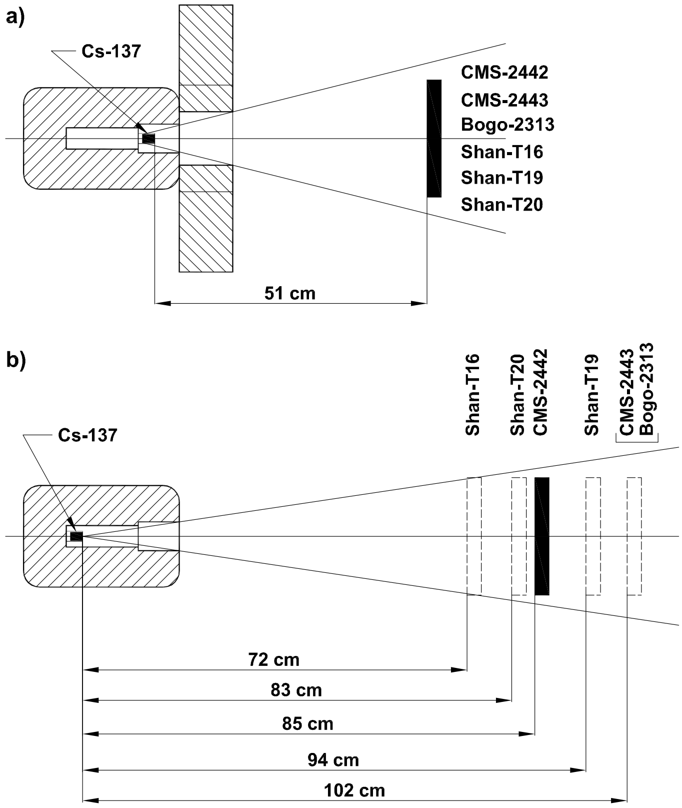


Figure 1. Setup of the crystal gamma irradiation at the dose rate of 110 rad/h (a), and the dose rates of 30–60 rad/h (b).

To modify the spatial dose distribution from the source in order to make it as similar as possible to pion beam, we used a lead screen placed between the source and the crystals and also rotated the crystals along their longitudinal axes at a rate of 2 turns per minute. The lead screen was made using four lead plates with varying dimensions [7]. The dose rate distributions along the length of crystal are compared for both the pion and source irradiation in **Fig. 2** using the lead screen and rotating the crystals. We see that the profiles are quite similar. The rotation is even more important for insuring a uniform irradiation transverse to the crystal axis when using the source.

In **Fig. 3** we show the transverse radiation profiles for case (a), where the crystal was not rotated and for case (b), where it was rotated. Since pion irradiation uniformly illuminates the crystals in transverse direction, we use the crystal rotation for all the source results in this paper. The MARS and ROZ-6 codes, were used for simulations of the dose profiles in crystal under pion and gamma irradiation respectively [3,8].

Two sets of gamma irradiation were carried out. One of them was done using dose rates of 30–60 rad/h, and the second one at the dose rate of 110 rad/h for each crystal. The crystals were allowed to recover during two weeks, at room temperature, between the first and the second sets of irradiation. After each exposition the crystal was removed from the place of irradiation to dedicated test stands for light output and transmittance measurements. This procedure usually took about 1 to 1.5 hours.

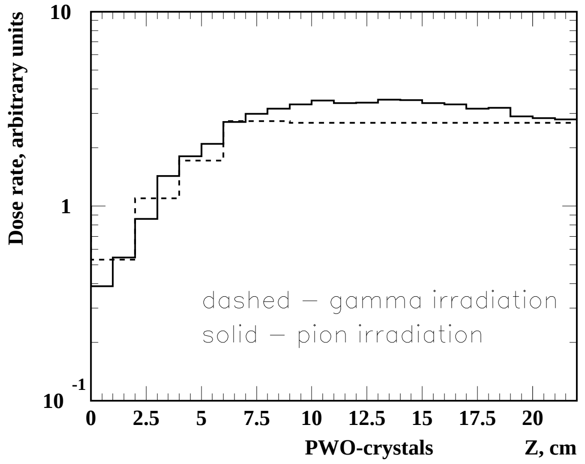


Figure 2. Longitudinal dose rate profiles for crystal under pion and gamma irradiation (Z near 22 cm corresponds to the phototube front).

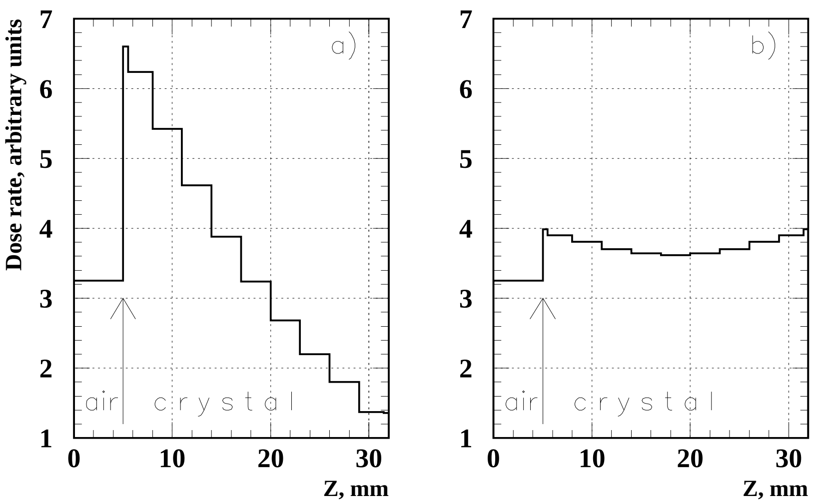


Figure 3. Transversal dose rate profiles for crystal under ^{137}Cs gamma irradiation: a) side irradiation without crystal rotation, b) side irradiation with crystal rotation. Dose estimations were made in both "air" and "crystal", as indicated.

4. Light output and transmittance measurements

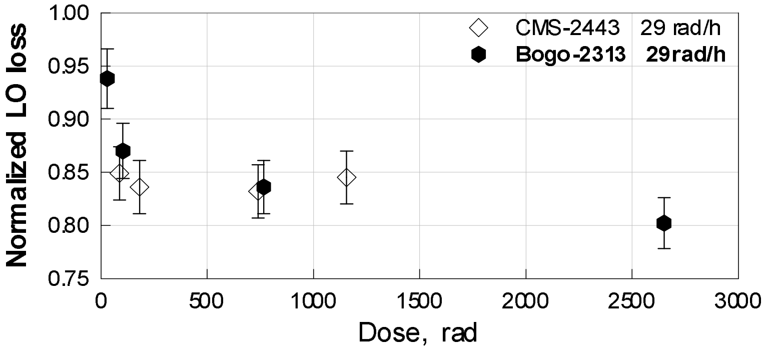
A stand with a radioactive source was designed to study a changes in the crystal light output due to radiation damage. Scintillation light was detected by a XP2020Q photomultiplier tube (PMT). The PMT output was connected to a 20 kOhm load. The mean current through this load was measured by a 11-bit ADC read out by a computer. The PMT high voltage value was of 1.5 kV. The PMT nonlinearity in the direct current mode was less than 1% in the range of 1.2 to 2 kV. The dark current was $\sim 2 \cdot 10^{-3}$ relative to the average signal level. The background current, mostly due to direct PMT irradiation by the source was $\sim 5 \cdot 10^{-3}$ of the average signal at the worst. The gamma radioactive source ^{137}Cs ($7 \cdot 10^{8}$ Bq) was installed inside a cylindrical lead collimator, 30 mm in diameter and 40 mm in height with aperture diameter of 5.3 mm. The crystals, were wrapped by a Tyvek, except for one end which was attached to the PMT without optical grease. The source was moved longitudinally along the central line of the crystal with a step of 2 cm. The distance between the source and the crystal surface was 5 mm. The measurements of the average direct current were provided in the same way for each of the 9 position along the crystal. The mean value over these 9 measurements gives us a value of a light output signal of each crystal. The light output measurements were monitored using a non-irradiated reference crystal. Performing measurements on non-irradiated crystals, we estimate the systematic error to be at most 3% of the relative light output degradation. The temperature was measured during irradiation and during light output monitoring. The temperature variations were ~ 1 degree on average, and up to 2 degrees in the worst case. There were no corrections for the temperature variations. The full systematic errors of the monitoring measurements include the effects of the temperature differences.

To measure a light transmittance curve of each crystal, a commercial spectrophotometer SF-26 was used in the wave length region from 340 up to 700 nm with a steps of 10 nm. The spectrophotometer light spot was 5 mm in diameter with a negligible angular dispersion. The measurement accuracy at each point was 1%.

5. Results and discussion

The dependence of a signal loss on the accumulated dose (at a fixed dose rate) for six crystals irradiated by ^{137}Cs source is shown in **Fig. 4**. Two crystals lost 10% of their signal or less under the source irradiation and four other crystals lost 15–25 %. The signal loss in transmittance curves at wavelengths of 420–550 nm measured with the use of the spectrophotometer is one order of magnitude less. For example crystal CMS-2442 showed losses between 2–2.5% (see **Fig. 5**). This difference might be due to different optical paths in crystal taken by the injected spectrophotometer light as compared with the scintillation light. From now on we will show only the results from the radioactive source measurements that are more sensitive than the spectrophotometer measurements in indicating the effects of radiation.

It has been shown that $PbWO_4$ transmission damage occurs in the crystal when valence electrons are trapped in metastable states around crystal defects. Thus, the irradiation of $PbWO_4$ crystals creates so called color centers which reduce the light attenuation length. When the rate of color centers production (proportional to the dose rate) equals to natural recovery rate, the crystal light output will reach a saturation level [9]. Fig. 4 shows that the signal degrades relatively rapidly with the absorbed dose up to 100–200 rad and then degrades at a significantly slower rate until the saturation level is reached. The light loss has a tendency to exhibit saturation when the dose rate is kept at a constant level. Each crystal demonstrates a different level of light loss in the saturated state. We found that the saturation level is reliably reached after $\sim$10 hours of continuous irradiation at the fixed dose rate. We did not observe a significant difference in radiation hardness of the crystals from different manufacturers.



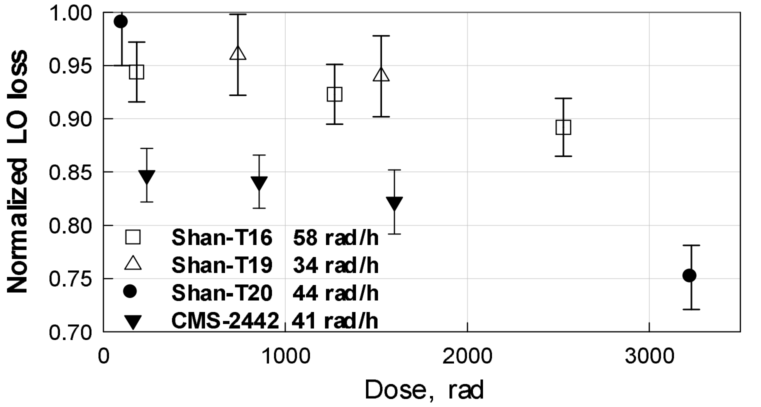


Figure 4. Light output loss for six crystals versus absorbed dose under gamma irradiation at the fixed dose rate for each crystal. There were several measurements for the two crystals, CMS-2443 and Bogo-2313 (upper part). The results of measurements for other four crystals (bottom part) are consistent with the first two, but were taken at longer intervals.

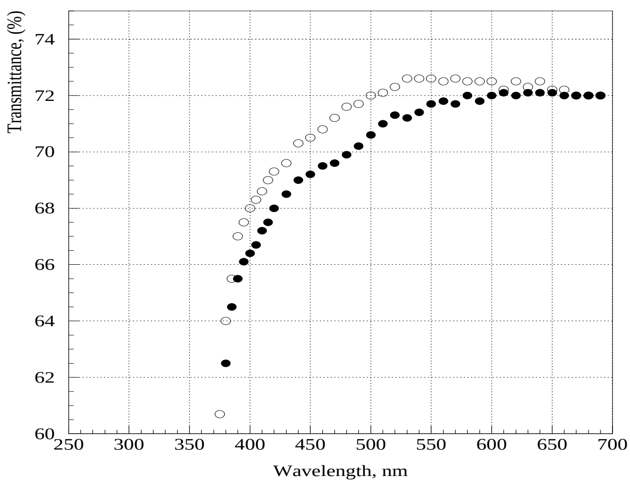


Figure 5. Transmittance of the CMS-2442 crystal before (open circles) and after (filled circles) gamma-irradiation at 41 rad/h dose rate and 4.4 krad of absorbed dose.

The second round of gamma irradiation was done with the dose rate of 110 rad/h for each crystal after two weeks of crystals recovery at room temperature. Because we irradiated the crystals with 110 rad/h gamma-source for a long time, ∼60–70 hours, we believe that we reached the signal loss saturation level for each crystal at this high dose rate. The dependence of the normalized signal loss (in state of saturation) on a dose rate for the six crystals under gamma irradiation is shown in **Fig. 6**.

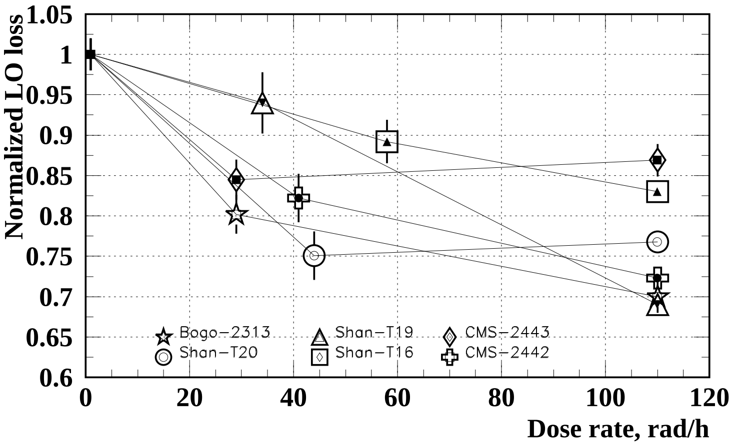


Figure 6. Dependence of the normalized light output loss (in state of saturation) on a dose rates for six crystals for gamma irradiation using ^{137}Cs source.

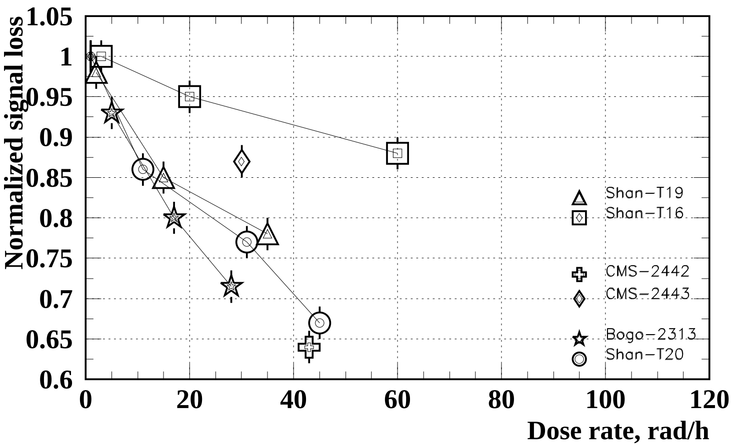


Figure 7. Dependence of the normalized signal loss (in state of saturation) on a dose rates for 40 GeV pion irradiation.

The normalized signal loss versus of the absorbed dose under 40 GeV pion irradiation for the same crystals is presented in **Fig. 7**. The points on the plot represent the level of signal loss in state of saturation at the fixed dose rates. The rate of the signal degradation is practically the same for both irradiation procedures up to the dose rates of 60 rad/h. Using gamma irradiation at a dose rate of 110 rad/h does not lower the saturation level of some of the crystals, while others are affected (see Fig. 6). This is an indication that the relative difference of the crystal signal losses demonstrated at dose rates of 30-60 rad/h might change at larger dose rates.

Ratios of pion/gamma signal losses at saturation, caused by irradiation at the same dose rates, for the six crystals are shown in **Fig. 8**. We see that these ratios are close to each other and are in the region between 0.8 and 1. Thus we can conclude that a pion and a gamma irradiation at the same dose rates affect radiation hardness of lead tungstate crystals similar way.

We shall continue our study. The major goal of the further measurements is to carry out crystal radiation studies for significantly larger number of crystals using the light output measurements continuously during the gamma irradiation process.

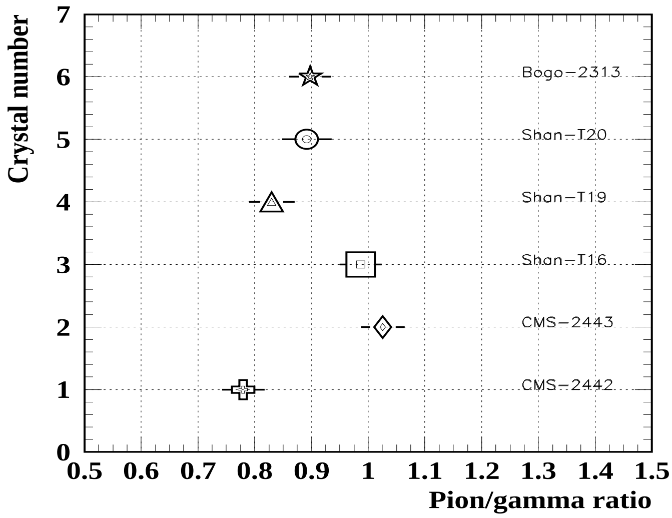


Figure 8. Ratios of two signal losses at their saturation levels, under pion and under gamma irradiation for the same dose rates (30–60 rad/h) for six crystals.

6. Summary

We have observed that a relative signal loss under 40-GeV pion irradiation and under ^{137}Cs radioactive source irradiation looks similar at the dose rate of 30–60 rad/h.
We consider that gamma-source might be used for a crystal quality control. Approximately 10 hours irradiation at the fixed dose rate will be enough to reach a saturation plateau for each crystal.
The dose rate can be chosen in the range of 60–100 rad/h because the most of the crystals will be suffering from the lower dose rates at the BTeV experiment.

Acknowledgments

We would like to thank the management of IHEP Radiation Research Department for providing us a ^{137}Cs radioactive source for our gamma irradiation studies, as well as PHENIX (RHIC, BNL) group in IHEP (Protvino) for providing us hard/software for LO measurements. We thank O. Sumaneev for calculation of the dose profiles in crystal at the gamma irradiation.

This work was partially supported by the U.S. National Science Foundation and the Department of Energy as well as The Russian Foundation for Basic Research grant 02-02-39008.

References

[1] CMS. The Electromagnetic Calorimeter Project Technical Design Report. CERN/LHCC 97-33, CMS TDR 4 (1997);
S.Baccaro et al. Further understanding of $PbWO_4$ scintillator characteristics and their optimization. CERN, CMS NOTE 2000/002 (2000);
S. Gascon-Shotkin. Recent Developments in Crystal Calorimeters (featuring the CMS $PbWO_4$ Electromagnetic Calorimeter). CERN. CMS CR 2003/001 (2003);
G.Davies et al. A study of the monitoring of radiation damage to CMS ECAL crystals, performed at X5-GIF,CERN, CMS NOTE 2000/020 (2000);
H.F.Chen et al. Measurements of $PbWO_4$ crystals behavior under irradiation. CERN CMS CR 1999/027 (1999).

[2] A. Uzunian, A. Vasiliev, J. Yarba. First results on simulation of radiation environment at BTeV electromagnetic calorimeter. IHEP preprint 2001-24, Protvino, 2001.

[3] V.A.Batarin et al. Study of Radiation Damage in Lead Tungstate Crystals Using Intense High Energy Beams. e-Print ArXiv hep-ex/0210011; Nucl. Instr. and Meth. A 512 (2003) 488.

[4] V.A. Batarin *et al.* Development of a Momentum Determined Electron Beam in the 1-45 GeV Range, e-Print Archive hep-ex/0208012; Nucl. Instr. and Meth. A 510 (2003) 211.

[5] V.A. Batarin *et al.* Precision Measurement of Energy and Position Resolutions of the BTeV Electromagnetic Calorimeter Prototype. e-Print Archive hep-ex/0209055; Nucl. Instr. and Meth. A 510 (2003) 248.

[6] http://www.atomtex.com/.

[7] The lead screen was formed of plates with dimensions (thickness, length, height)xmm^3: 19x20x40, 12x20x50, 7.5x20x50 and 2x30x50.

[8] A.V Averin, A.M. Voloschenko, E.P. Kondratenko*et al.* The ROZ-6 One-Dimensional Discrete Ordinates Neutrons, Gamma-Rays and Charged Particles Transport Code. – In: Proc. Int. Topical Meeting on Advaces in Mathematics, Computations and Reactor Physics, Pittsburgh USA, 1991, vol.5.

[9] A.A Annenkov, M.V. Korzhik, P. Lecoq. Lead tungstate scintillation material. Nucl. Instr. and Meth. A 490 (2002) 30.

Received January 13, 2004.

Препринт отпечатан с оригинала-макета, подготовленного авторами.

В.А. Батарин, Д.Батлер, Т.Я. Чен и др.
Сравнение радиационной стойкости кристаллов вольфрамата свинца под действием пионного и гамма-излучений.

Оригинал-макет подготовлен с помощью системы **LaTeX.**

Подписано к печати 16.01.2004. Формат $60 \times 84/8$.
Офсетная печать. Печ.л. 1,15. Уч.-изд.л. 0,9. Тираж 160. Заказ 184.
Индекс 3649.

ГНЦ РФ Институт физики высоких энергий
142284, Протвино Московской обл.

Индекс 3649

П Р Е П Р И Н Т 2004–3, И Ф В Э, 2004