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# DEVICES FOR STEERING PARTICLE BEAMS IN THE ACCELERATORS BASED ON CRYSTALS CURVED BY SCRATCHING THE GROOVES ON THE SURFACE

*V.A. Maisheev, Yu.E. Sandomirskiy, M.Yu. Chesnokov, Yu.A. Chesnokov, A.A. Yanovich*

Institute for High Energy Physics named by A.A. Logunov
of NRC "Kurchatov Institute", Protvino of Moscow region, Russian Federation

An interesting method of bending silicon crystal plates by scratching the grooves on the surface mechanically has been presented in the paper. This method appears to have considerable promise for both the U70 accelerator at the Institute for High Energy Physics and the devices at the Large Hadron Collider (LHC). Using the method mentioned above, specific devices were made: a crystalline undulator for 3 GeV positrons, short crystalline deflectors for extraction of 70 GeV proton beam from the U70 accelerator, and multistrip crystals for collimating the 6500 GeV proton beam into the LHC.

**Keywords:** Large Hadron Collider, beam collimation, crystal undulator, multistrip crystal

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# ПРИБОРЫ ДЛЯ УПРАВЛЕНИЯ ПУЧКАМИ ЧАСТИЦ В УСКОРИТЕЛЯХ НА ОСНОВЕ КРИСТАЛЛОВ, ИЗОГНУТЫХ ПУТЕМ НАНЕСЕНИЯ КАНАВОК НА ПОВЕРХНОСТЬ

*В.А. Маишеев, Ю.Е. Сандомирский, М.Ю. Чесноков, Ю.А. Чесноков, А.А. Янович*

Институт физики высоких энергий имени А.А. Логунова
НИЦ «Курчатовский институт»,
г. Протвино Московской области, Российская Федерация

В статье описан интересный метод изгиба кристаллических пластин кремния с помощью нанесения механическим путем канавок на их поверхности. Метод перспективен для применения как в ускорителе У70 Института физики высоких энергий, так и в устройствах Большого адронного коллайдера (БАК). С использованием указанного метода созданы конкретные устройства: кристаллический ондулятор для пучка позитронов с энергией 3 ГэВ, короткие кристаллические дефлекторы для вывода пучка протонов с энергией 70 ГэВ из ускорителя У70, многополосковые кристаллы для коллимации пучка протонов в БАК при энергии 6500 ГэВ.

**Ключевые слова:** Большой адронный коллайдер, коллимация пучков, кристаллический ондулятор, многополосковые кристаллы

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## Introduction

The idea to use channeling in bent crystals to steer particle beams, first proposed by Tsyganov (Joint Institute for Nuclear Research, Dubna, Moscow Oblast) [1], was advanced and tested in many experiments (see [1–3] and references therein). The idea found the widest practical application at the U70 accelerator at the Institute for High Energy Physics (Protvino, Moscow Oblast), where crystals are used in regular sessions for extracting and steering the beams. Problems related to the physics of particle beam channeling were considered in [4, 5].

Our study introduces a method for bending crystals for subsequent use in accelerators. Notably, the efficiency of particle deflection by a bent crystal (for example, see book [4]) is described by the ratio of the critical angle of channeling $\theta_c$ to beam divergence j, decreasing exponentially with crystal length $L$:

$$\text{Eff} \sim (\theta_c / \text{j})\exp(-L / L_d),$$

where the characteristic parameter $L_d$ called the dechanneling length increases linearly along with the particle energy; it amounts to 5 cm in silicon crystals for 100 GeV energy protons.

The critical angle of channeling (the Lindhard angle) is rather small:

$$\theta_c \approx (1/E)^{1/2} = 0.020–0.002 \text{ mrad}$$

for protons with the energies $E$ ranging from 100 to 10 000 GeV, respectively.

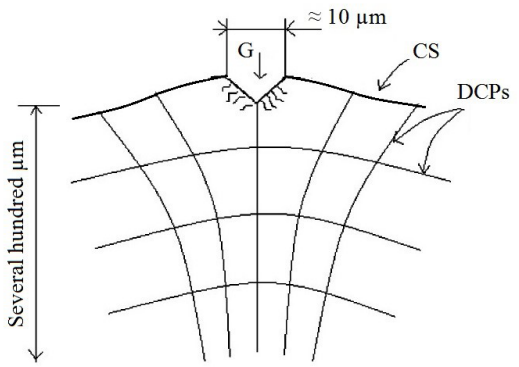


Fig. 1. Effect of deformation of crystal planes from microscratching of crystal surface: groove G, crystal surface CS, deformed crystal planes DCPs

Because the angle is small, this beam steering method is not versatile but can be quite useful in some cases, especially for extraction of circulating beams and their splitting in particle channels where crystals act as miniature magnets.

The sizes of crystal plates (along the beam) range from 0.1 mm to 10 cm depending on the degree of bending and the type of problems solved. A commonly used bending method consists in applying the bending moment generated by a metal holder to the crystal [4, p. 85]. A method involving mechanical scratching of grooves on the surface of crystals was used in several cases for small bending angles.

## Basic principles of the groove scratching method

The Twyman effect, known in optics [6], is a phenomenon when small mechanical damage to the surface from microgrinding produces stresses causing the surface structure to bend, in some cases substantially. It is important that these deformations are smooth for channeling high energy particles. Experiments on particle deflection with crystals conducted at IHEP [4] revealed interesting phenomena in the end face of crystal, when the trajectories of channeled particles escaping the crystal are generated specifically depending on the microscratches present on the surface (i.e., the trajectories are sensitive to microscratches).

The explanation for the effect is that protons near, for instance, scratches are channeled in deformed layers of the crystal and move around these scratches. Reconstruction of deflection angles of the particles indicates that deformation of the crystal planes penetrates to substantial depths, up to a few hundred microns (Fig. 1). This effect was successfully applied to solving several acceleration problems for silicon crystals bent by periodic microgrooves scratched mechanically on the surface (using a diamond blade).

## Example applications of the method in accelerators

A method for creating a crystalline undulator, i.e., a periodically bent crystal, by mechanically scratching grooves on the faces of the crystal was first considered in

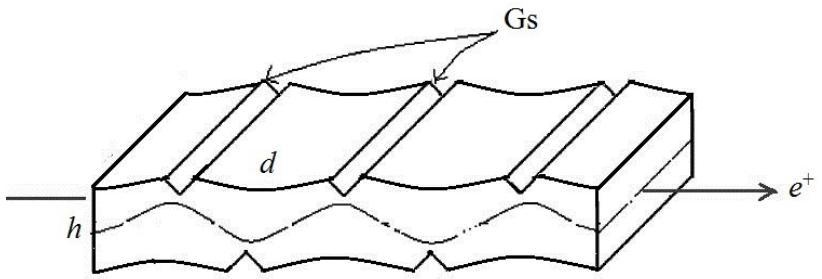


Fig. 2. Schematic representation of crystalline undulator:
grooves are denoted as Gs, $d$ is the groove period, $h$ is the thickness of the crystal plate, $e^+$ is the positron beam. The sinusoid corresponds to the bent crystal planes in the bulk of the crystal

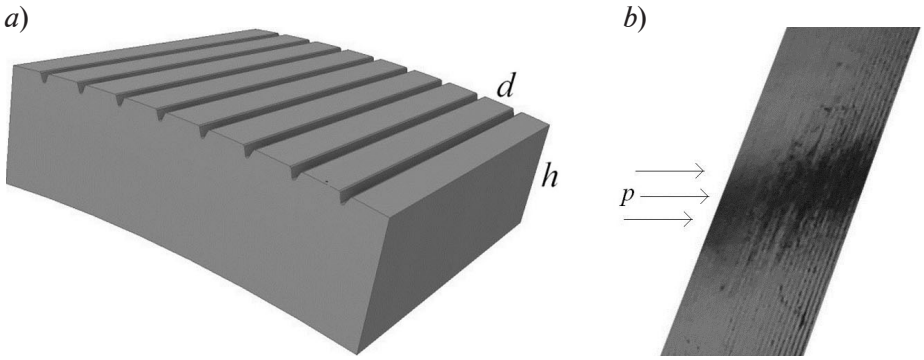


Fig. 3. Schematic representation of bent silicon crystal plate:
smooth bending obtained by periodic scratching of grooves on the surface (*a*);
plate fragment in the region of interaction with proton beam *p* (*b*)

[7]. An X-ray diffractometer was used to establish that the deformation amplitude of 40 E was reached in 10 periods with a 0.5 mm step, which is sufficient for generation of hard photons. The first experiment with such an undulator was carried out at the U70 accelerator with a 10 GeV positron beam [8]. Fig. 2 shows a scheme of the undulator with grooves developed at the IHEP.

The period $d$ of bilateral groove scratching has to be no less than the thickness $h$ of the crystal plate for the sinusoidal deformations to penetrate deep into the entire bulk of the crystal according to the Saint-Venant's principle, known from elasticity theory [9]. If the grooves are scratched with a small period, so that $d << h$, then the stresses become uniform at a depth approximately equal to $d$, producing a smooth bend in the crystal (Fig. 3,a).

The thickness of the layer with efficient channeling equals $h - d$. This method of crystal bending was first applied using a 70 GeV beam splitting station at the U70 accelerator [10]. The bending angle of a crystal 16 mm long and 0.5 thick amounted to 10 mrad. The experience with proton beams with an intensity of $10^{12}$ particle/(cm$^2$·s$^{-1}$), accumulated since 2009, indicates that the crystal preserves its bending and channeling properties, splitting the beam with the same efficiency. Fig. 3,*b* shows a fragment of the crystal after irradiation with protons (dose of $5 \cdot 10^{19}$ particles).

Notably, the method of bending the crystal by scratching grooves on the surface is also applicable for production of crystal strips with a small bending angle (around 50 μrad), optimal for TeV energies. Such crystals were tested with a 400 GeV proton beam at the Super Proton Synchrotron (SPS) at the European Organization for Nuclear Research (CERN, Switzerland) via particle deflection by multiple volume reflection [11].

Fig. 4,*b* shows a photograph of the silicon crystal plate with periodic grooves serving as a deflector, prepared by the IHEP team for the experiment. Fig. 4,*a* shows a schematic for the deflector's operation during multiple volume reflection of particles. Deep grooves with a rough surface were made by a triangular cutter with diamond grit, providing sufficient curve bending of the strips produced on

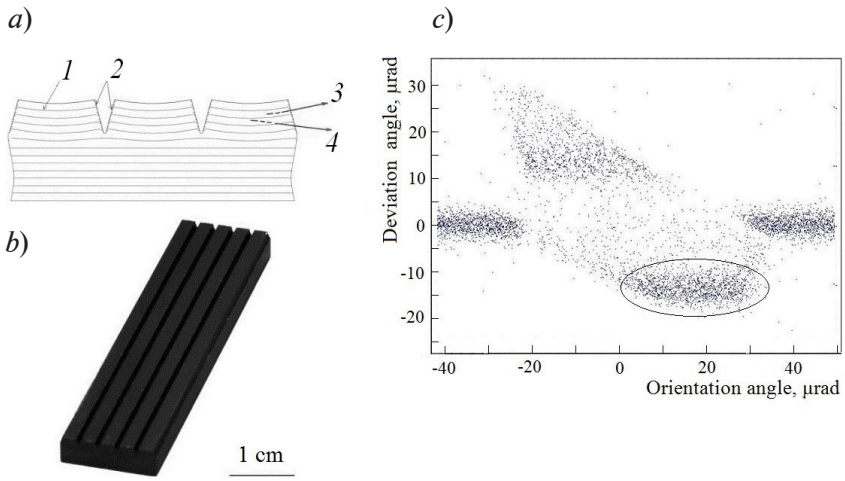


Fig. 4. Thick bent silicon multistrip crystal with periodic grooves scratched on the surface: operation sequence for multiple volume reflection (*a*); photograph of crystal (*b*); computational results for efficient 6.5 TeV proton deflection by multiple volume reflection in bent strips (*c*): Monte Carlo simulation and SCRAPER code were used. Fig. 4,a shows bent crystal planes (*1*); triangular grooves (*2*); tracks of particles deflected due to channeling (*3*) and multiply reflected by bent planes (*4*); the oval in Fig. 4,*c* marks the reflection region

the polished face of a thick silicon plate. The beam in the experiment described in [11] was deflected at an angle of 50 μrad and agreed with the calculated value with an efficiency of about 90%.

Bending of separate strips and their mutual orientation was studied with the Kurchatov Synchrotron Radiation Source (Kurchatov Institute, Moscow) using a parallel X-ray beam [12]. Analysis of the results showed that this structure, i.e., a series of bent strips formed between large grooves on a thick plate, is aligned perfectly, fitting for collimation of 50 TeV proton beams at the Large Hadron Collider (LHC, CERN) and even the Future Circular Collider (FCC, CERN), using multiple volume reflection of particles. The parameters of the crystal device can be easily adapted to this energy by varying the size of the grooves and the distance between them.

Fig. 4,c shows the calculated deflection angles of beam particles at 6.5 TeV depending on the orientation of the crystal plate in a form of two-dimensional density marked with dots. The calculations were performed using our SCRAPER software and the Monte Carlo method [14]. Evidently, the particles at the edges of the beam (on the right and left)

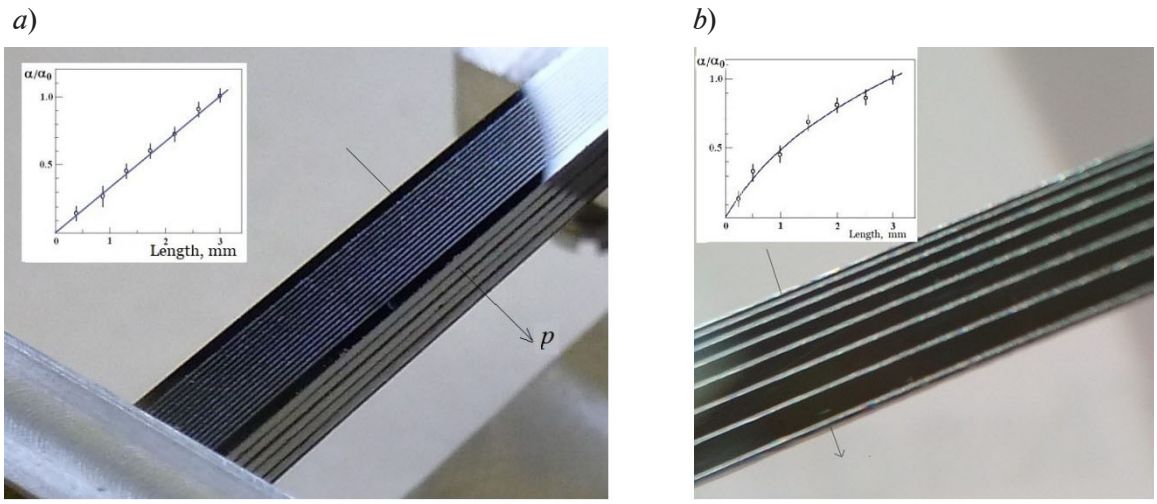


Fig. 5. General view of silicon crystals with periodically (*a*) and aperiodically (*b*) arranged grooves The insets show distributions of the bending angle along the length of the crystals

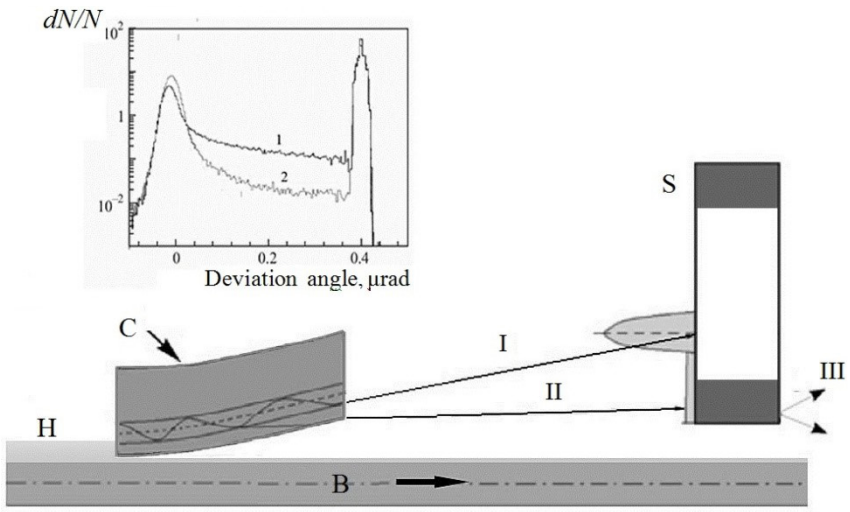


Fig. 6. Schematic layout for beam extraction by crystal (C): peak of channelled particles efficiently extracted (I); fraction of dechanneled particles (II); losses at the septum S (III); H, B denote halo and beam, respectively.
The inset shows distributions of particles deflected by the crystals with constant (curve *1)* and dropping (curve *2*) curvature; computed using Monte Carlo method with our SCRAPER software [14]

are not deflected as they do not fall within the range of the strip bending angles. Almost the entire beam in the reflection region marked in the figure shifts down by an angle of 15 μrad corresponding to multiple reflection on five crystal strips. According to our estimations, the calculated efficiency of beam deflection amounts to 92%.

### Novel approaches introduced at the U70 accelerator using the proposed method of crystal bending

**Optimized beam extraction from the accelerator.** Beam extraction by short silicon crystals has been used at the U70 accelerator since 1998 [13]. The new bending method is aimed at increasing the efficiency of extraction by reducing the length of the crystals while preserving the required bending angle, since the surface grooves increase the crystal curvature. Moreover, if the grooves are arranged aperiodically, a bend with decreasing curvature can be achieved. This also suppresses particle dechanneling along the length of the crystal, which in turn reduces particle losses [14].

We prepared several samples of crystals bent by scratching grooves on the surface, including those with aperiodic scratching (Fig. 5). We conducted an optical test of the bend using a laser device (the technique is described in [4]). The insets in the figure show distributions of the bending angle along the length of the crystals. Apparently, periodic grooves produce uniform bending, while aperiodic grooves result in a decreasing curvature. Fig. 5,a also shows that identical crystals are stacked to increase the transverse size of the crystal beam deflector, thus additionally improving its efficiency.

Fig. 6 shows a schematic layout for beam extraction with the improved crystals, illustrating how the beam extraction efficiency can be improved by reducing the share of dechanneled particles. The inset in Fig. 6 shows distributions of particles deflected by the crystals with constant (curve *1*) and decreasing (curve *2*) curvature calculated by the Monte Carlo method and our SCRAPER software [14]. It is apparent that decreasing curvature results in reducing the share of dechanneled particles by several times. Experiments aimed at improving the crystal extraction at U70 are planned as soon as the accelerator equipment is upgraded. The SCD19 crystal station uses a crystal 5 mm long with a bending angle of 2 mrad. The prepared crystals (see Fig. 5) allow to reduce their length down to 3 mm, which will increase the extraction efficiency from 70 up to 85%.

**Testing the crystal undulator with a 3 GeV positron beam.** The energy of photons generated by the undulator is proportional to the squared Lorentz factor of a $\gamma$ particle and inversely proportional to the undulator period $L$. The period of a simple electromagnetic undulator reaches several centimeters. Thus,

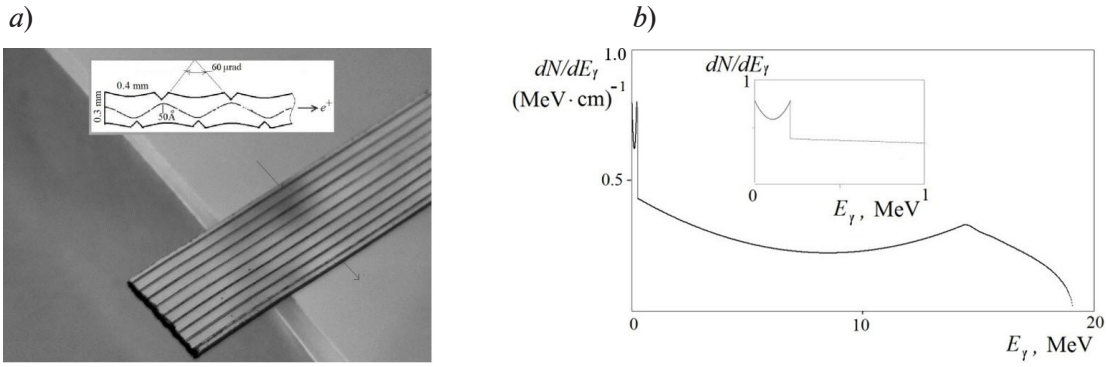


Fig. 7. Crystal undulator with 3 GeV positron beam: photograph and schematic cross section (inset) (*a*); calculated spectrum of photons obtained with the undulator and undulator peak around 0.23 MeV (inset) (*b*)

photons with the energies of several keV reach approximately 1 GeV in the beam of the electron accelerator. Consequently, crystal undulators with submillimeter periods are the subject of intense scrutiny because of the potential they hold for increasing photon energies.

The first data on radiation produced with a crystalline undulator were obtained for a 10 GeV positron beam at IHEP [8]. However, the majority of electron accelerators where crystalline undulators can be used operate at energies below 6 GeV. We prepared novel samples of crystal undulators (Fig. 7,a) optimized for positrons at lower energies achievable by the electron accelerators currently available. The first tests are planned to take place at IHEP's Crystal setup at the energy of 3 GeV. Given the achieved parameters, specifically, a period of 0.4 mm, an amplitude of 50 E, and the number of periods equal to 9, we plan to obtain a photon peak at approximately 0.23 MeV with the undulator. Fig. 7,*b* shows the calculated photon spectrum obtained using the software described in [15]. This software implements an algorithm for simulating undulator radiation in the crystal taking into account rather strong radiation during positron channeling, proposed in [16]. The undulator peak around 0.23 MeV is shown in detail in the inset to Fig. 7,*b*. The background radiation up to 20 MeV is due to channeling.

## Conclusion

The paper presents an interesting method for bending silicon crystal plates by mechanical scratching of grooves on the surface. This method has already been applied for a number of problems related to steering particle beams but we also propose vital improvements for potential applications in new problems described in the study. The method was used to construct novel devices: a crystal undulator for 3 GeV positrons, short crystal deflectors for extraction of 70 GeV proton beams at the U70 accelerator, and multistrip crystals for collimation of 6500 GeV proton beams at the LHC. The latter show promise for solving the global problem of beam collimation at future multi-TeV colliders.

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## THE AUTHORS

**MAISHEEV Vladimir A.**
*Institute for High Energy Physics named by A.A. Logunov of NRC «Kurchatov Institute»*
1, Nauki Sq., Protvino of Moscow Reg., 142281, Russian Federation
maisheev@ihep.ru

**SANDOMIRSKIY Yury E.**
*Institute for High Energy Physics named by A.A. Logunov of NRC «Kurchatov Institute»*
1, Nauki Sq., Protvino of Moscow Reg., 142281, Russian Federation
Yury.Sandomirskiy@ihep.ru

**CHESNOKOV Mikhail Yu.**
*Institute for High Energy Physics named by A.A. Logunov of NRC «Kurchatov Institute»*
1, Nauki Sq., Protvino of Moscow Reg., 142281, Russian Federation
Michail.Chesnokov@ihep.ru

**CHESNOKOV Yury A.**
*Institute for High Energy Physics named by A.A. Logunov of NRC «Kurchatov Institute»*
1, Nauki Sq., Protvino of Moscow Reg., 142281, Russian Federation
chesnokov@ihep.ru

**YANOVICH Andrey A.**
*Institute for High Energy Physics named by A.A. Logunov of NRC «Kurchatov Institute»*
1, Nauki Sq., Protvino of Moscow Reg., 142281, Russian Federation
yanovich@ihep.ru

## СПИСОК ЛИТЕРАТУРЫ


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## СВЕДЕНИЯ ОБ АВТОРАХ

**МАИШЕЕВ** Владимир Александрович – *кандидат физико-математических наук, ведущий научный сотрудник Института физики высоких энергий имени А.А. Логунова НИЦ «Курчатовский институт», г. Протвино* Московской обл., *Российская Федерация.*

142281, Российская Федерация, г. Протвино Московской обл., пл. Науки, 1
maisheev@ihep.ru

**САНДОМИРСКИЙ** Юрий Евгеньевич – *инженер-технолог Института физики высоких энергий имени А.А. Логунова НИЦ «Курчатовский институт», г. Протвино* Московской обл., *Российская Федерация.*

142281, Российская Федерация, г. Протвино Московской обл., пл. Науки, 1
Yury.Sandomirskiy@ihep.ru

**ЧЕСНОКОВ** Михаил Юрьевич – *инженер-исследователь Института физики высоких энергий имени А.А. Логунова НИЦ «Курчатовский институт», г. Протвино* Московской обл., *Российская Федерация.*

142281, Российская Федерация, г. Протвино Московской обл., пл. Науки, 1
Michail.Chesnokov@ihep.ru

**ЧЕСНОКОВ** Юрий Андреевич – *доктор физико-математических наук, главный научный сотрудник Института физики высоких энергий имени А.А. Логунова НИЦ «Курчатовский институт», г. Протвино* Московской обл., *Российская Федерация.*

142281, Российская Федерация, г. Протвино Московской обл., пл. Науки, 1
chesnokov@ihep.ru

**ЯНОВИЧ** Андрей Антонович – *научный сотрудник Института физики высоких энергий имени А.А. Логунова НИЦ «Курчатовский институт», г. Протвино* Московской обл., *Российская Федерация.*

142281, Российская Федерация, г. Протвино Московской обл., пл. Науки, 1
yanovich@ihep.ru