HIGH-EFFICIENCY BEAM EXTRACTION AND COLLIMATION USING CHANNELING IN VERY SHORT BENT CRYSTALS

Yu.M.Ivanov, V.V.Skorobogatov, A.A.Petrunin, B.A.Chunin, A.S.Denisov, M.G.Gordeeva

In the last years a new method of beam extraction from accelerator ring based on using bent crystals is successfully developed. The advantages of the method are simplicity of implementation, possibility to combine with collider mode and internal targets, and small magnitude of intensity pulsations in time. The method is also very convenient for applying in a collimation system, a crystal is used to deflect halo particles onto absorber to localize beam losses in this case.

A long time it was a problem to get high efficiency of the particle deflection because only part of incident particles can be captured into channeling regime during single pass through crystal, and this part is further decreased due to dechanneling process in lengthy and bent for large angle crystals.

The idea of drastic improvement of deflection efficiency (for next extraction or collimation) lies in using very short crystals. The advantage in efficiency in this case is provided by increasing a number of particle passes through crystal, which becomes possible due to decreasing of Coulomb scattering (on crystal length) resulting also in decreasing dechanneling losses.

In the first experiments of the IHEP-PNPI collaboration started in 1997, to implement such an extraction regime, short silicon crystals – 7 and 5 mm long – with bending angles of 1.7 and 1.5 mrad, respectively, were used at the 70 GeV accelerator of the Institute of High Energy Physics. For such parameters (which were chosen on the basis of the calculations performed) the average number $\langle N \rangle$ of passes for the channeled particles through the crystal was around 12, while the average number of passes required for a nuclear interaction of the particles in the crystal was ~ 60.

Bending a short crystal in conformance with a number of conditions associated with the mounting of the crystal in the accelerator presents a definite problem. The first Si (111) crystal was made in the form of a strip with dimensions 0.5 mm × 40 mm × 7 mm (thickness, height, length in the direction of the beam). The crystal was bent in the transverse direction using a metal holder shown in Fig. 1 containing a 20 mm slit at the centre for passing the beam. The crystal strip had the shape of a saddle, being bent in both vertical and radial directions. Despite of the presence of bending nonuniformities (twist), encouraging results were obtained with this first crystal: an extraction efficiency ~20% and extracted-beam intensity ~1.9×10^{11} [1].

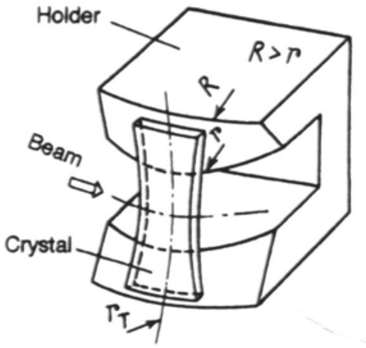

Fig. 1. Bent strip crystal

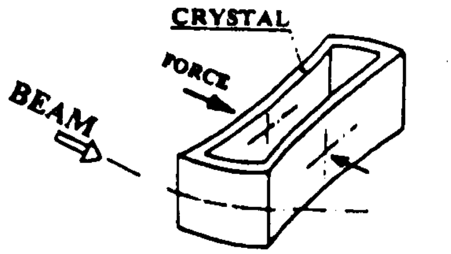

Fig. 2. Bent crystal obtained by compressing a monolithic piece of silicon cut in the shape of the letter O

To increase the extraction efficiency further, a crystal with no "twist" was fabricated in the form of the letter O from a monolithic piece of Si. The crystal is shown schematically in Fig. 2. The dimensions of the working zone (with Si (110) orientation) of the crystal are 0.6 mm × 5 mm × 5 mm (thickness, height, length in the direction of the beam). The required bending of the crystal by 1.5 mrad was produced by compressing the crystal at the centre. The bent part was 3 mm long, and the straight ends were each 1 mm long. With this crystal the extraction efficiency over 40% and extracted beam intensity of 6×10^{11} ppp were obtained [2].

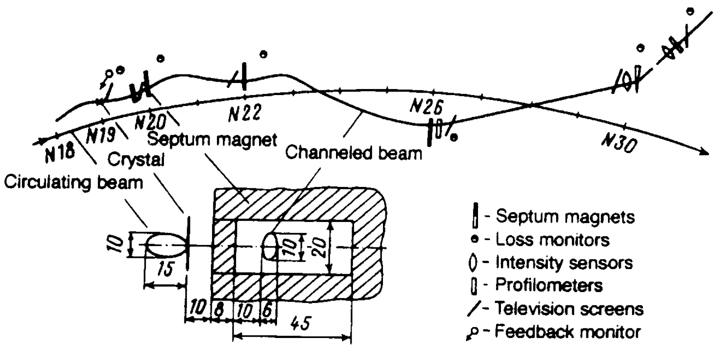

Fig. 3. Experimental arrangement. The dimensions are in mm

The crystal extraction scheme for a proton beam from U-70 at IHEP is shown in Fig. 3. As a deflection at 1.5−1.7 mrad is insufficient for a direct extraction from the accelerator, the crystal served as a primary element in the existing scheme of slow extraction. The crystal was placed in straight section 19 of the accelerator before the septum-magnet OM-20 of the slow-extraction system (the OM-20 barrier thickness is ~ 8 mm) in 60−65 mm from the equilibrium orbit. The precision of the horizontal and angular displacements of the crystal was 0.1 mm and 13 μrad, respectively. The accelerated beam was steered onto the crystal using a local slowly increasing bump. The shape of the bump was chosen so that the circulating beam passed at a sufficient distance from the OM-20 magnet. The relative positions of the circulating and channeled beams with respect to the OM-20 magnet are shown in Fig. 3.

As both channeling regime and the extracted beam characteristics depend essentially on the circulating beam parameters, they were measured before experimenting with a crystal. Results are shown in Fig. 4. The horizontal emittance of the beam was 2π mm × mrad, with the beam divergence at the crystal location of 0.6 mrad, the emittance in the vertical plane did not exceed the beam emittance in the horizontal plane. Approximately 90% of the intensity was contained in ~ 15 mm core. The dense core is surrounded by a halo where the intensity drops off slowly.

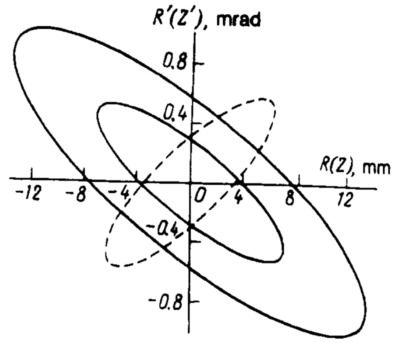

Fig. 4. Phase portrait of the circulating beam in the U-70 at the location of the crystal: the two solid curves (denoting the core and the halo) are in the horizontal plane, the dashed curve is in the vertical plane

A complex diagnostics system, which included a television observation system, loss monitors, profilometers, and intensity meters, was used to control the deflection of the beam onto the OM-20 aperture and guidance of the beam along the extraction path. The arrangement of the diagnostics apparatus along the extraction channel is indicated in Fig. 3. All diagnostics devices were first tested in the fast-extraction regime and calibrated using current transformers. According to the calibration results, the absolute measurement error did not exceed 2% in the intensity range of interest to us. The background conditions were periodically measured without the crystal and with the disaligned crystal at the working measurements, the background level, together with the instrument noise, did not exceed 3% of the useful signal. The fraction of the beam steered onto the crystal was determined by the difference of the measurements of the circulating-beam intensity, performed with the current transformers before and after extraction, with a systematic error of ~ 1% (see Fig. 3.) With all these factors taken into account, the total systematic measurement error was ~ 4%. The extraction efficiency (ratio of the intensity of the extracted beam to the intensity steered onto the crystal) was estimated in each work cycle of the accelerator. For each experimental point, a statistical sample was accumulated over several hundreds of cycles. A feedback monitor based on a photomultiplier tube with a scintillator was used to obtain uniform steering of the beam onto the crystal. The feedback monitor was placed at the level of the orbit near the OM-20 magnet and 10 m downstream the crystal. The total frequency band of the feedback system was ~ 10 kHz.

In Figs.5−8 the results obtained with first O-crystal are presented [2]. The intensity of the accelerator beam was varied during experiment from 1×10^{12} to 2.4×10^{12} protons per cycle, the intensity dumped onto the crystal varied from 16 to 92%. An image of the crystal-deflected beam in front of the OM-20 magnet is shown in Fig. 5. The temporal characteristics of the extraction process are presented in Fig. 6 (information about the intensities of the circulating beam 1 and the extracted beam 2 was displayed on a storage oscilloscope). The duration of extraction in the feedback regime varied from 0.6 to 1.3 s. The flat top of the magnetic cycle of the IHEP accelerator has a duration of 2 s, while the complete accelerator cycle is 9.6 s.

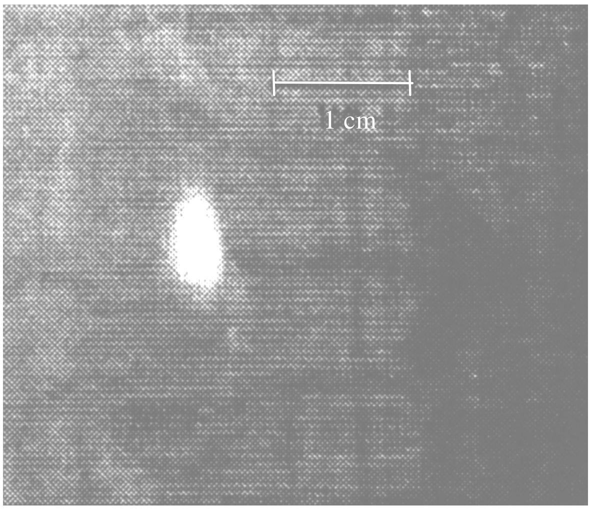

Fig. 5. Image of the deflected beam in front of the OM-20 magnet

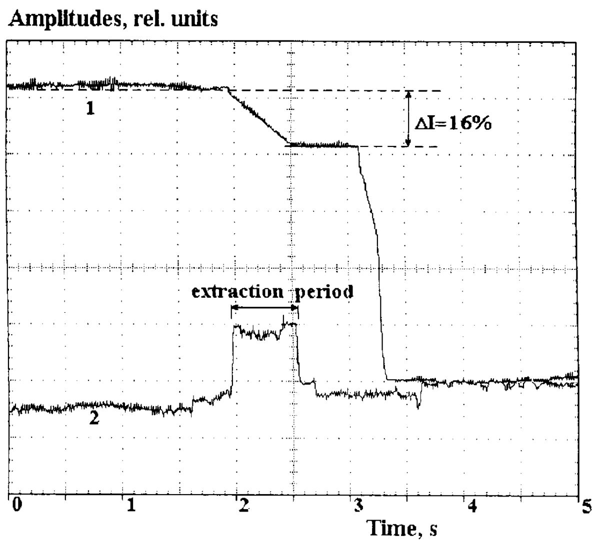

Fig. 6. Time dependence of the circulating (1) and extracted (2) proton beam intensities

The direct proof, that the extracted beam was channeled, is the so called angular scan – the dependence of the extracted beam intensity on orientation of the crystal which shown in Fig.7. The bottom plot of Fig.7 shows the measured scan in comparison with simulation results, the top plot of Fig.7 shows the reduction in the circulating beam intensity as a function of the crystal orientation, under conditions of the feedback system when the nuclear interaction rate at the crystal remains constant. These data also prove a high efficiency of extraction (the channeled beam does not affect the feedback monitor). The extraction efficiency evaluated from this plot as $(I_{max} - I_{min})/ I_{max}$ is equal to 36%, well matching the directly measured efficiency of 32% in this case.

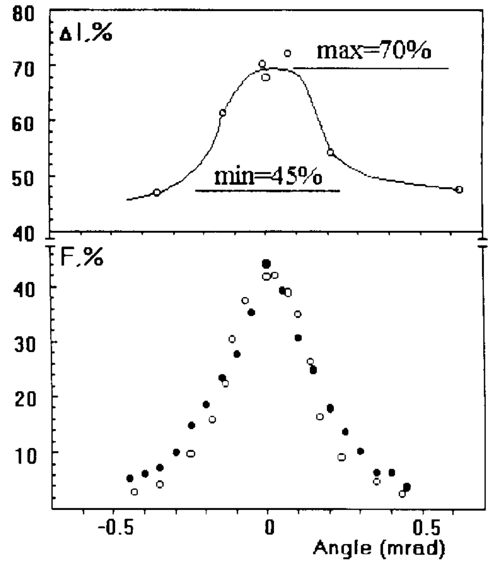

Fig. 7. Bottom: the extraction efficiency as a function of the crystal angle; the measurements (open circles) and simulations (dots). Top: the reduction in the beam store as a function of the crystal angle under conditions of a feedback system

The main task in the experiments at IHEP was to determine the extraction efficiency defined above as a ratio of the extracted beam to reduction in the beam store. We measured both the efficiency averages over a spill, and the efficiency as a function in time. Fig. 8 shows the measured efficiency, spill-averaged, for several beam intensities at the same crystal, as in Figs.5–7, with corresponding results from simulation. The highest efficiency of extraction, 42 ± 2%, was obtained for a small fraction, 23%, of the beam store directed onto the crystal. With increasing the beam store fraction taken from the accelerator, the averaged-over-spill efficiency decreases, in agreement with computations, because of a significant drift (0.3 mrad) of the proton incidence angle at the crystal as the beam moves radially toward the crystal. This phenomenon is due to the fact that the beam was steered onto the crystal in a radial direction with an inclined phase ellipse. For the same reason the extraction efficiency varies in time during the spill (Fig. 6), especially for a large beam fraction used. Notably, the peak extraction efficiency in the spill was the same, 47±3%, irrespective of the beam store fraction.

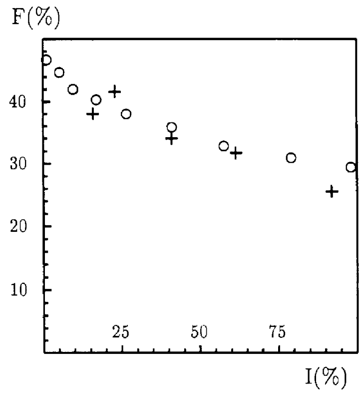

Fig. 8. Extraction the efficiency as a function of the beam fraction incident on the crystal (+ – experiment, o – computer simulation)

The divergence of the beam circulating in the IHEP accelerator was ≈ 20 times greater than θ_L (≈ 20 μrad at 70 GeV), so only a few percent of the beam particles may satisfy the channeling criteria in the first passage. The high overall efficiency of extraction was essentially due to the high multiplicity of proton encounters with the crystal.

The intensity of the extracted beam was equal to 6×10^{11} in first measurements and later improved to 10^{12} ppp [3], which is 5–6 orders of magnitude higher than previous results at CERN and FNAL. The crystal worked in hard regime a long time, it had an estimated temperature of several hundred degrees C but retained the same high channeling efficiency. The parameters of extracted beam were stable and well reproducible, the beam spot sizes on a target were 4×4 mm^2 (FWHM).

After first successful experiments [1–3] the technologies of fabricating bent crystals were further developed. With new crystals, more short, better polished and bent, the extraction efficiency up to 85% was achieved [4, 5].

There are several crystals mounted in accelerator U-70. The places of these crystals were chosen to provide their using as first steps of slow extraction system. Parameters of the mounted crystals are presented in Table. Crystals in shape of strip (S-type) have orientation Si(111), O-crystals have orientation Si(110).

Table

Parameters of the mounted crystals.

Crystal number	Place, number of magnet	Type	Bending angle, mrad	Length × Height × Thickness, mm	Efficiency, %	Comment
1	106	S	1.0	2.035 × 0.5	85	Extraction scheme: 106-24-26
					80	Extraction scheme: 106-20-22
2	106	O	0.7	3.5 × 5.0 × 0.7	60	
3	19	S	2.0	5.0 × 45 × 0.5	67	
4	19	O	2.1	5.0 × 5.0 × 0.7	65	
5	19	O	2.3	5.0 × 5.0 × 0.6	45	Particle fluence ~ 2×10^{20}/cm^2
6	84	S	0.8	1.8 × 27 × 0.5	85	70 GeV
					20	1.3 GeV
7	84	O	1.7	2.5 × 5.0 × 0.5	60	
8	86	S	1.4	4.0 × 45 × 0.5	65	

The best results were obtained with the most short crystals 1 and 6 with lengths 2 mm and 1.8 mm, respectively, both of the S-type. The experimental data for crystal 1 are shown in Fig. 9. Extraction efficiency of (85 ± 2.8)% was obtained with beam intensity in accelerator ring of 1×10^{12} protons per cycle.

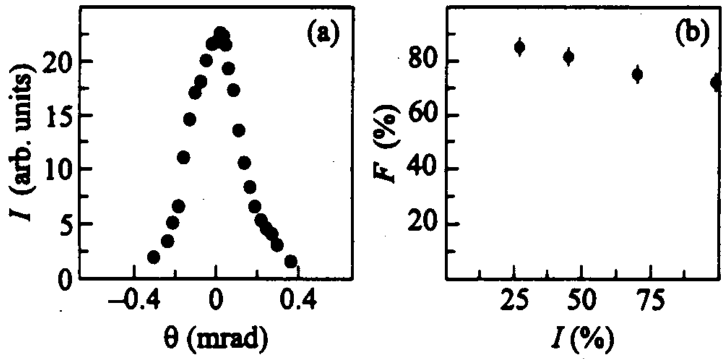

Fig. 9. (a) Dependence of extracted beam intensity on orientation of crystal 1;
(b) Dependence of extraction efficiency F of crystal 1 on beam intensity I incident on the crystal (in percents from total circulating beam)

Crystal 6 was used in a beam losses localization system as coherent scattering target. It was mounted in 20 m upstream of beam collimator, and it channeled the 85 ± 2.8% of incident particles in depth of the collimator. In Fig.10 there are shown results of measurements of the beam profile on the entry face of the collimator in different cases, in each case, the amount of incident beam was about the same.

First, an amorphous collimator is used as primary target while the crystal is kept outside of the beam. As expected, the beam profile is peaked at the collimator edge (Fig.10a). In the second case (Fig.10b), the crystal is used as a primary scraper but it is not aligned to the beam. Third, when properly aligned, the crystal channels most of the incoming beam into the depth of the collimator (Fig. 2c). In the fourth case (Fig.10d), the beam is simply kicked by a magnet towards the secondary collimator, while the crystal is retracted (this mode was used to calibrate the beam deflected by the crystal).

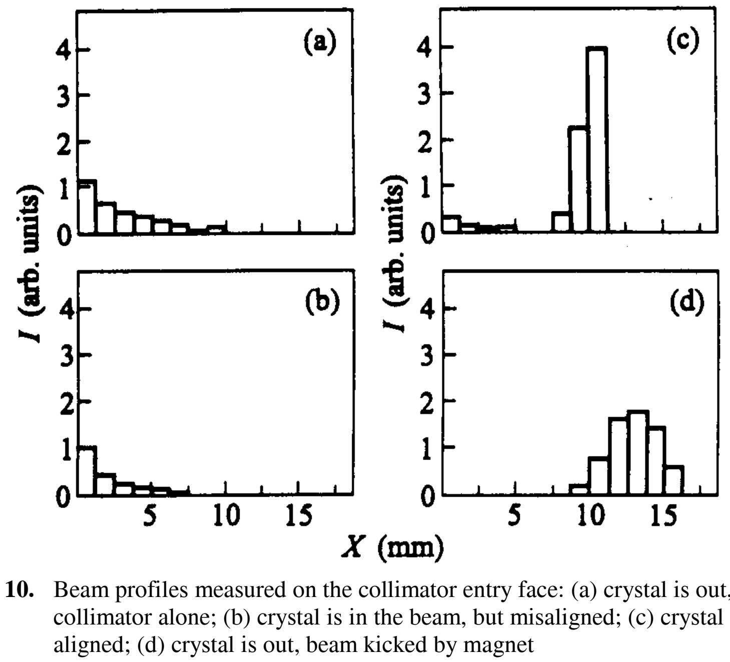

Fig. 10. Beam profiles measured on the collimator entry face: (a) crystal is out, beam scraped by collimator alone; (b) crystal is in the beam, but misaligned; (c) crystal is in the beam, aligned; (d) crystal is out, beam kicked by magnet

The using of crystal resulted in decreasing radiation level behind the collimator by several times.

In Fig.11 the summary of extraction efficiencies, measured and calculated, with crystals of different lengths are presented. The bending angle of the crystals varied from 0.8 to 1.7 mrad while the theoretical efficiency curve was calculated for 0.9 mrad. Expected dependence of the efficiency on the bending angle is weak because the crystal curvature in all cases is far from critical one for 70 GeV protons. The agreement between measurements and calculations is good.

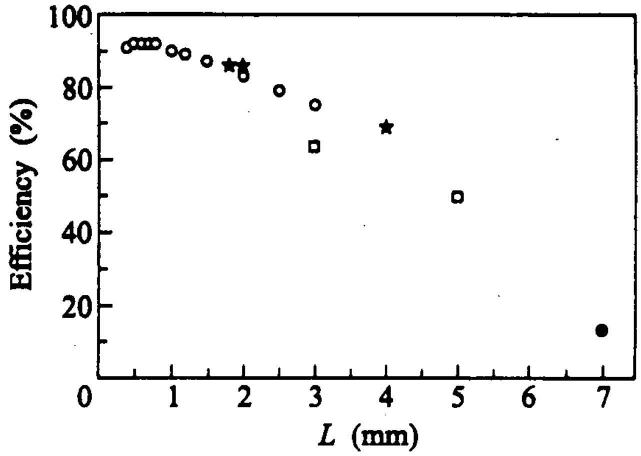

Fig. 11. Crystal extraction efficiency for 70 GeV protons: (*) – results for S-crystals 1.8, 2.0, and 4 mm, results for O-crystals 3 and 5 mm, (⊛) – result for S-crystal 7 mm, (o) – Monte Carlo prediction for a perfect crystal with 0.9 mrad bending

Short crystals with length of 1 mm along beam can be used not only for multi-GeV energy protons, but also for particles with energies in GeV region. The first tests on deflection of 1.3 GeV (energy of injected protons at U-70) were successfully done with crystal 6 (length 1.8 mm), the experiment practically repeated the crystal collimation one at the injection flattop of U-70.

With the crystal aligned with the incoming halo particles, the radial beam profile at the collimator entry face showed a significant channelled peak far from the edge (Fig.12). The feature of this case is significant Coulomb scattering of protons on the crystal: the mean squared scattering angle is about 1 mrad and is comparable with crystal bending angle. Nevertheless the channelled peak contains about half of the protons incident on the collimator. Corresponding to this case the crystal deflection efficiency is estimates as 20%. This figure is orders of magnitude higher than previous world data for low-GeV energy range.

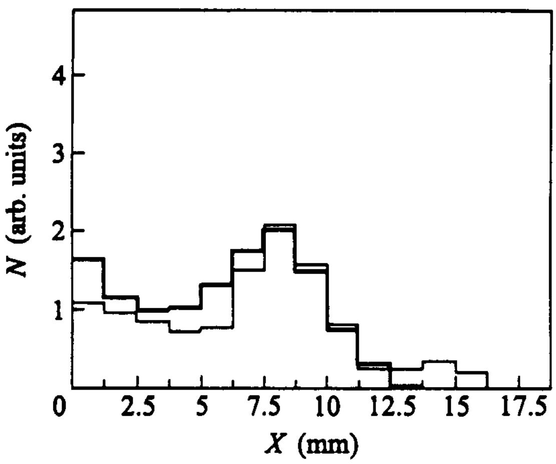

Fig. 12. Beam profile as measured on the collimator entry face with 1.3 GeV protons. Fine line shows result of calculations

In summary, the crystal channeling efficiency was significantly improved both at top energy and at injection energy during work presented. The same 2-mm-long crystal was used to channel 70 GeV protons with an efficiency of 85% during several weeks of operation and 1.3 GeV protons with an efficiency of 20% during some test runs. Crystals with a similar design were able to withstand radiation doses over 10^{20} proton/cm^2 and irradiation rates of 2×10^{14} particles incident on crystal in spills of 2 s duration without deterioration of their performances.

As calculations show, extraction and collimation with efficiencies over 90–95% are feasible. The high figures obtained experimentally in present work provide a support for application of this technique in beam cleaning systems at RHIC, Tevatron and LHC. Applications in sub-GeV accelarators also are possible, but require further researches and developments.

References

[1] A.G.Afonin, …, M.G.Gordeeva, A.S.Denisov, Yu.M.Ivanov, A.A.Petrunin, V.V.Skorobogatov, and B.A.Chunin, Pis'ma v ZhETF **67**, 741 (1998) [JETP Lett. **67**, 781 (1998)].

[2] A.G.Afonin, …, B.A.Chunin, A.S.Denisov, M.G.Gordeeva, Yu.M.Ivanov, A.A.Petrunin, and V.V.Skorobogatov, Phys. Lett. **B 435**, 240 (1998).

[3] A.G.Afonin, …, M.G.Gordeeva, A.S.Denisov, Yu.M.Ivanov, A.A.Petrunin, V.V.Skorobogatov, and B.A.Chunin, JETP Lett. **68,** 568 (1998).

[4] A.G.Afonin, …, Yu.M.Ivanov, … *et al.*, Phys. Rev. Lett. **87**, 094802 (2001).

[5] A.G.Afonin, …, Yu.M.Ivanov, ... *et al.,* Pis'ma v ZhETF **74**, 57 (2001) [JETP Lett. **74**, 55 (2001)].