Crystal channeling as a tool to steer particle beams

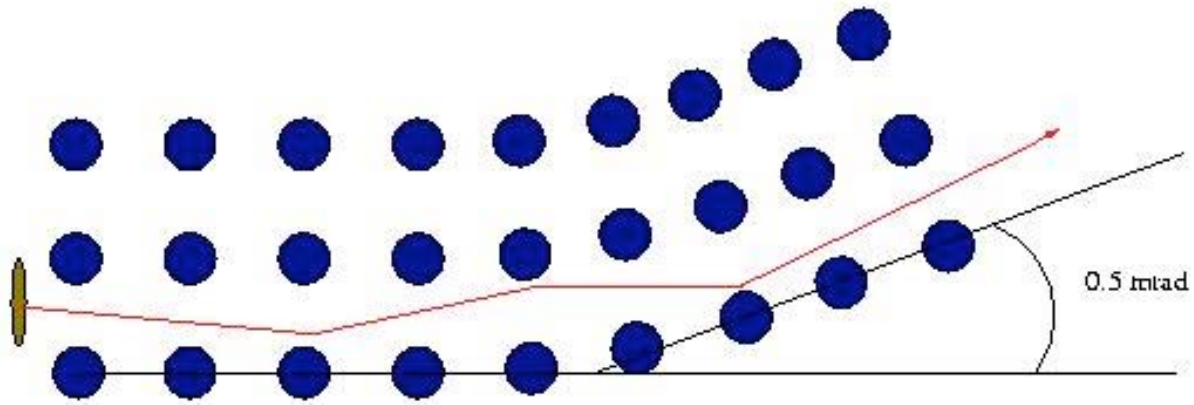
V. Biryukov, Y. Chesnokov

Institute for High Energy Physics, Protvino, Russia

KEK, 2005 October 18

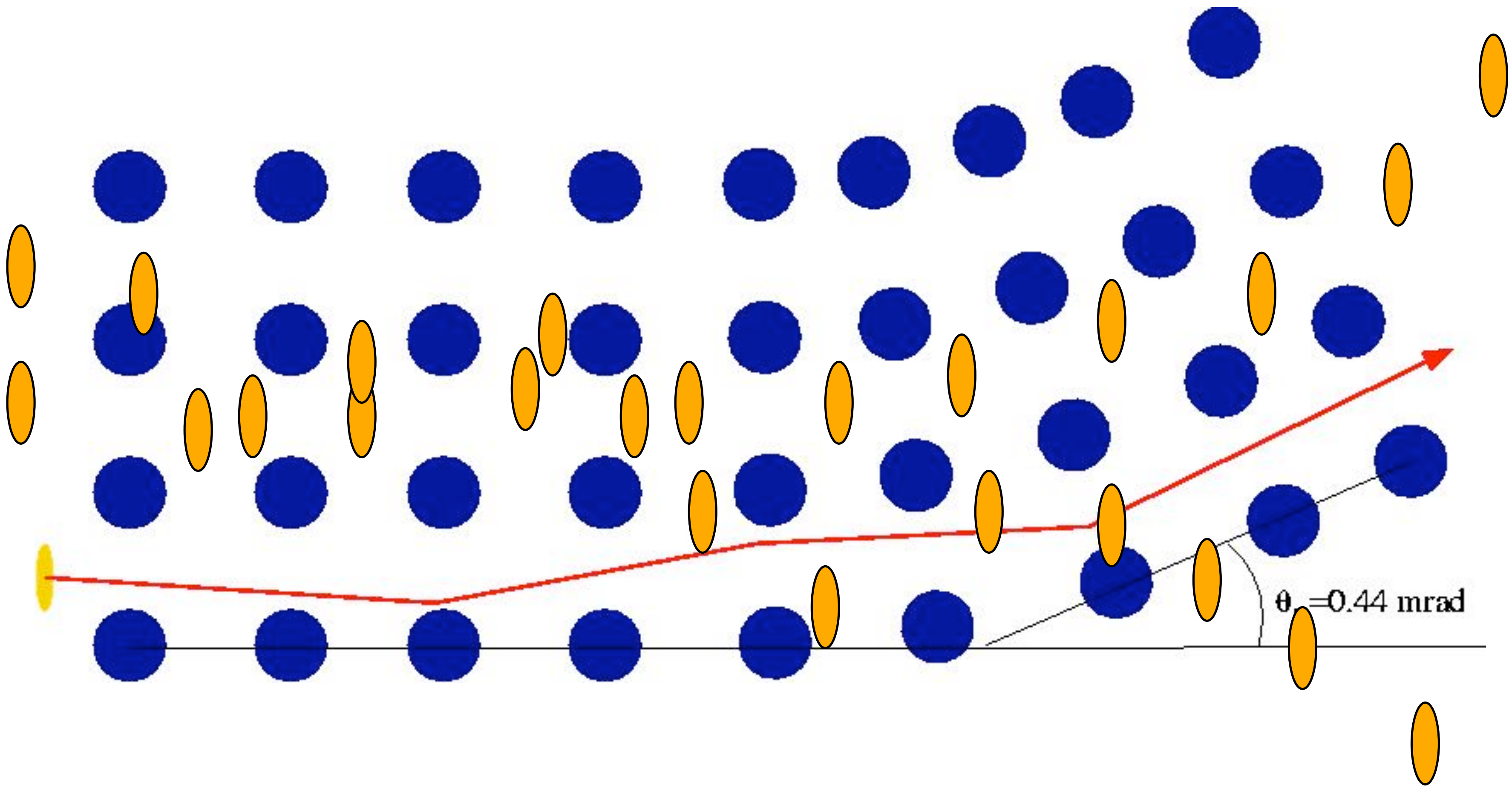
Crystal Channeling

If ions enter a crystal at an appropriate angle, the scattering events are correlated, and the ion is channeled through the crystal planes.



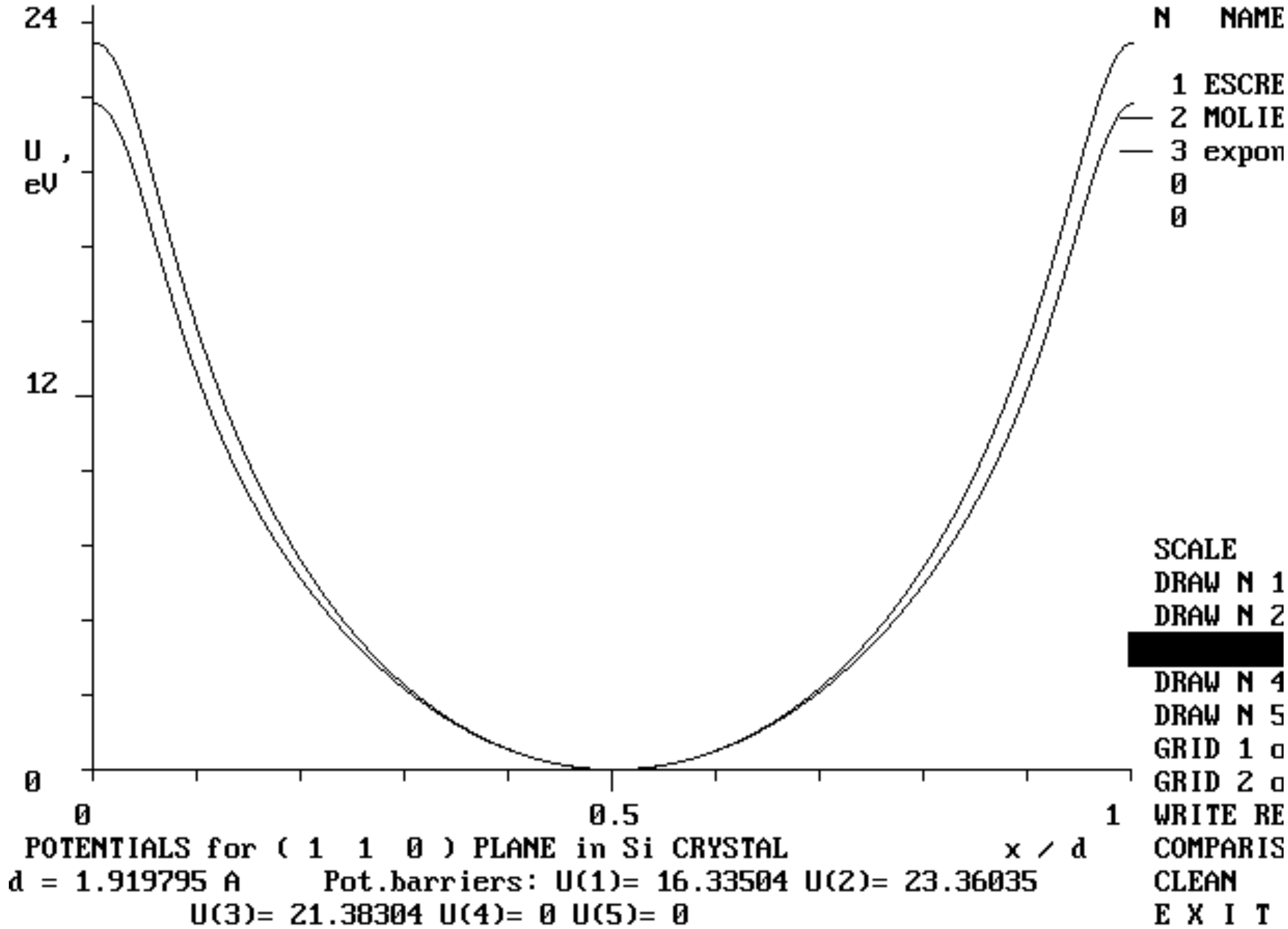
Advantage: The angle of escape from the crystal is known, intercepting the ions now is easy!

Crystal Channeling

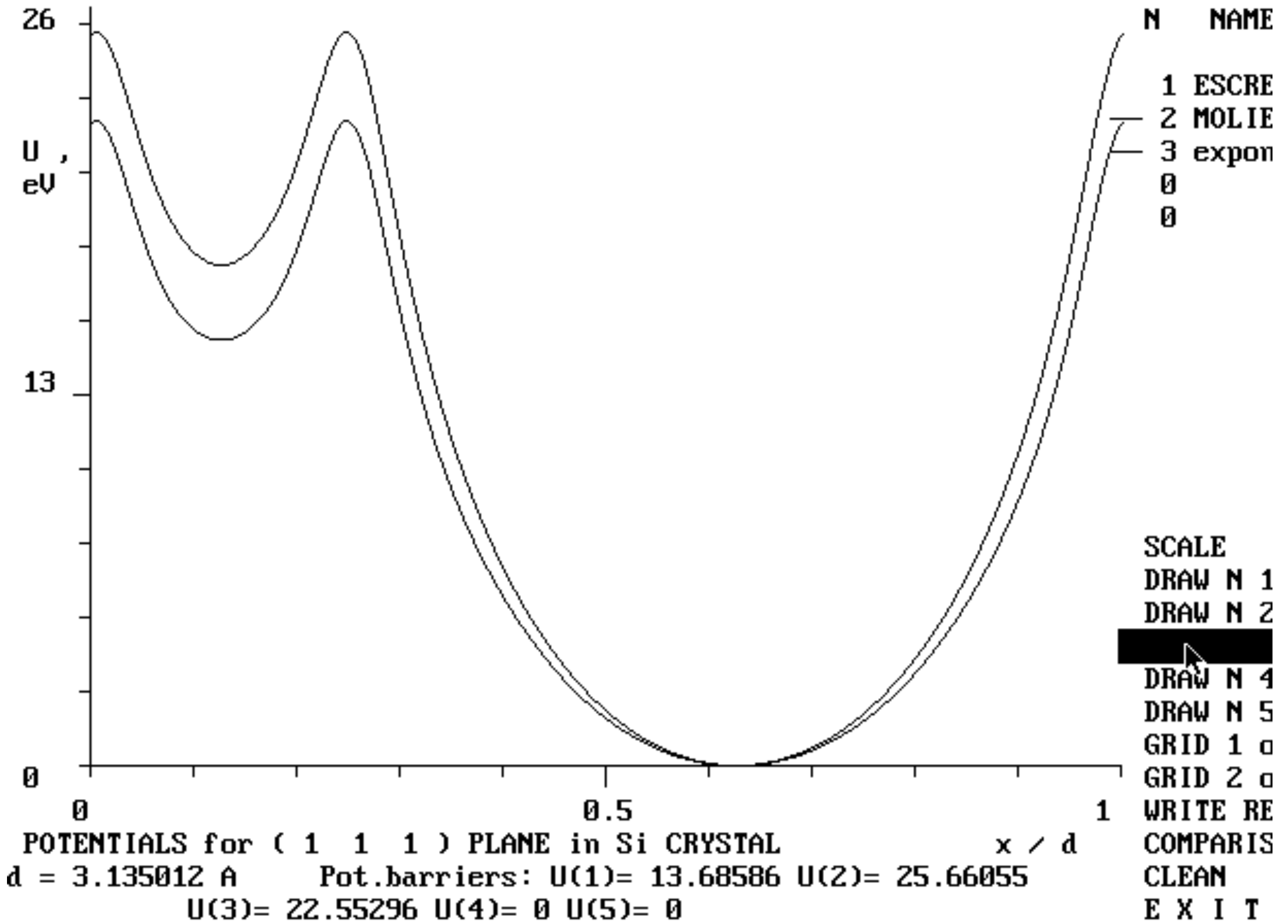


Inter-planar potential well:

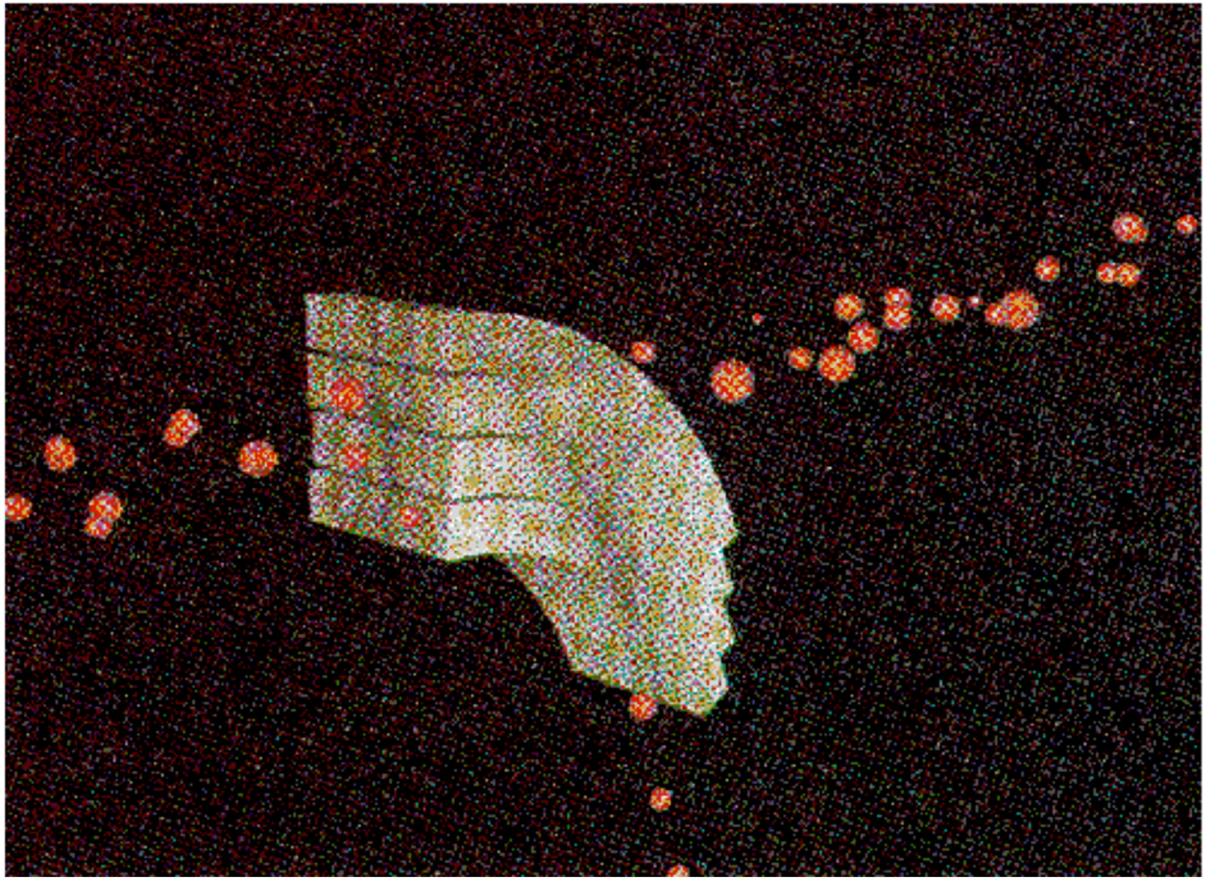
~20 eV deep (in Silicon), ~harmonic



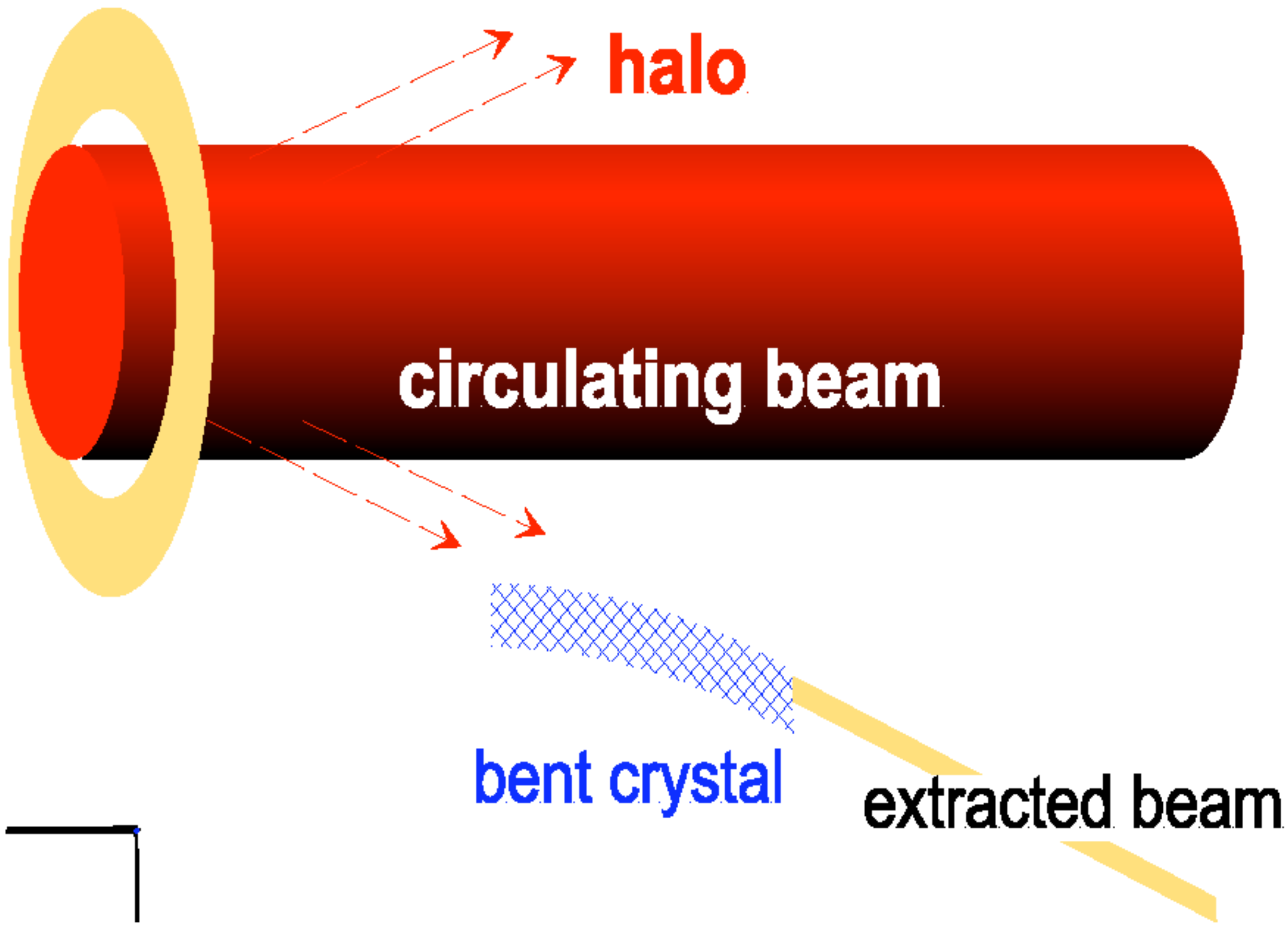
More complicated channels in Silicon (111)



1-st application of bent crystal: beam splitter



Another application: beam extraction



Beam focusing by a channeling crystal

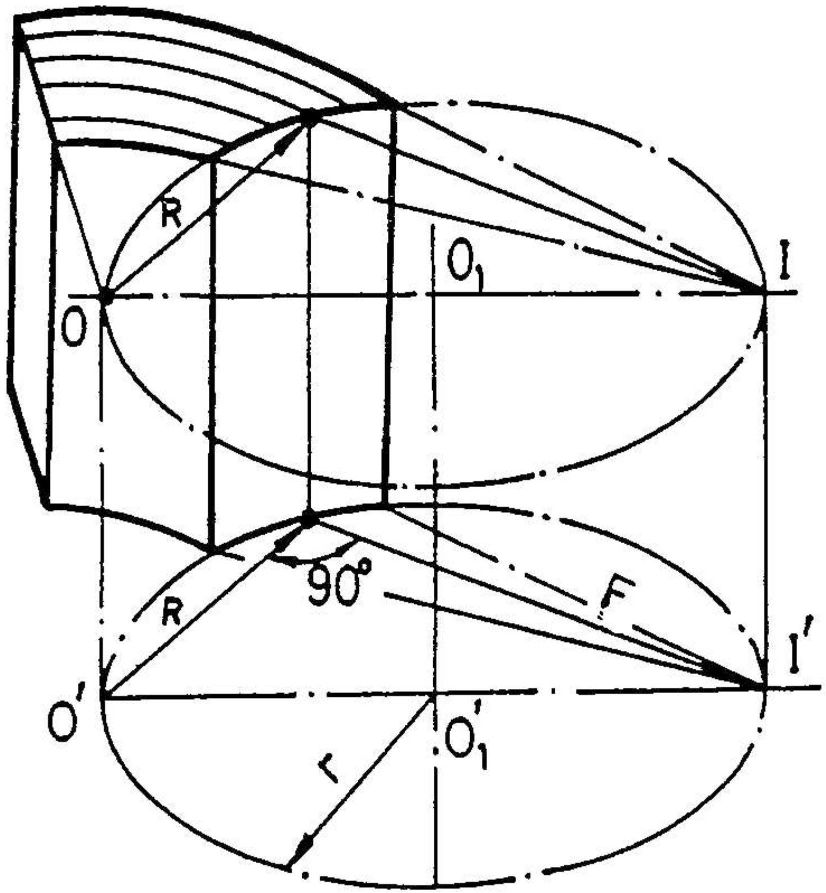


Fig. 11. Principle of focusing of a beam by a crystal. Here, OO' is a line of the centers of curvature of the crystallographic planes; $O_I O_I'$ is the axis of a cylinder of radius r representing the shape which is imposed on the face of a crystal; II' is the focal line where the tangents to the bent planes converge, deduced on the basis of the well-known geometry theorem.

Beam focusing by crystal:

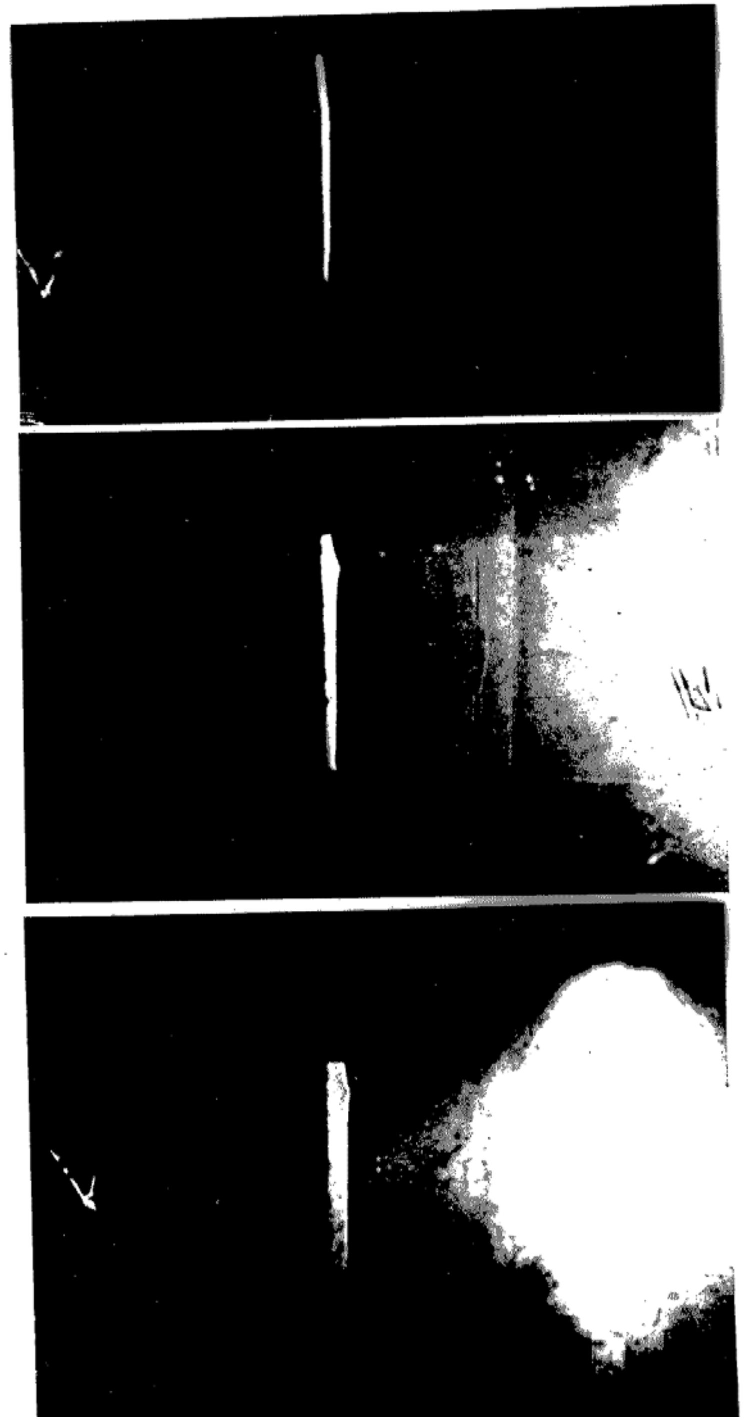
IHEP experiment

beam images

taken at different distances

downstream of

focusing crystal



Beam focusing by a channeling crystal:

focus size 21 μm (r.m.s.)

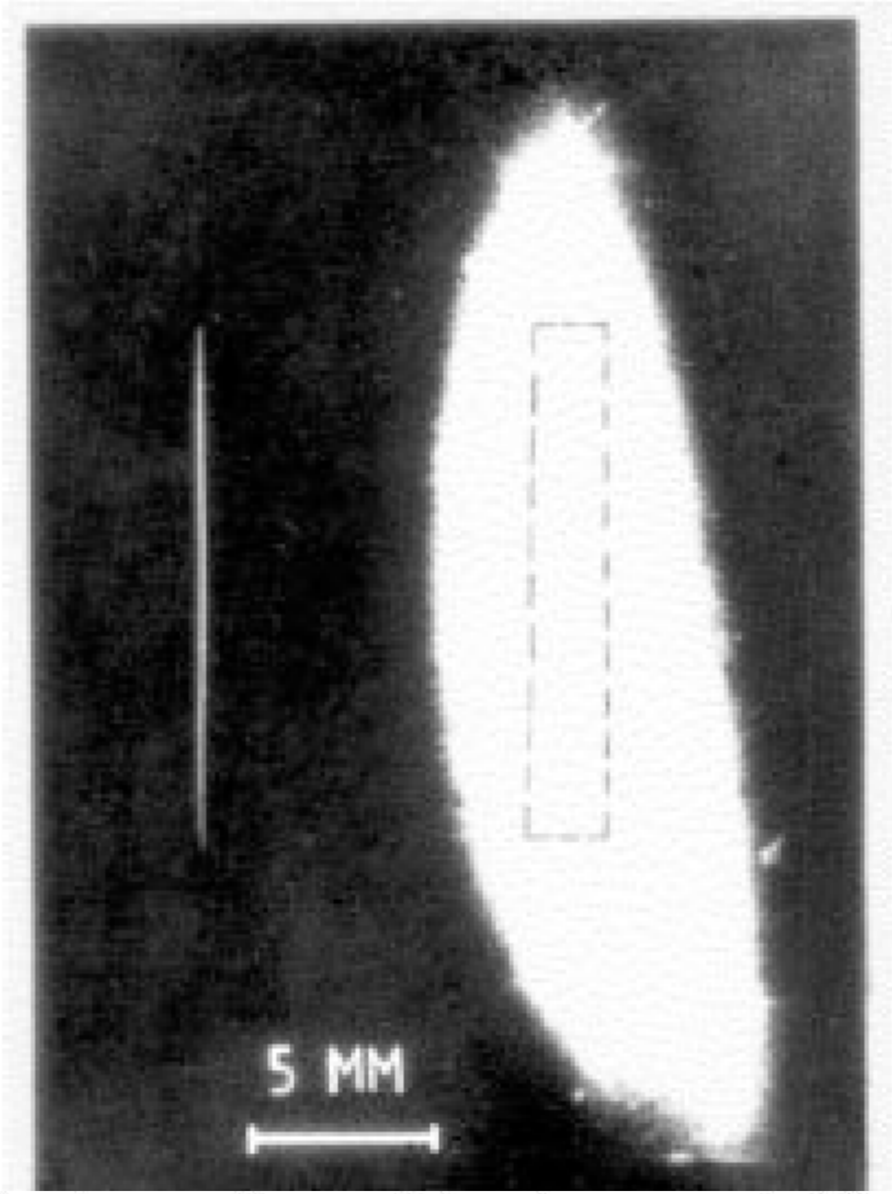


Fig. 12. Image at the crossover of the beam focused by the crystal N3. The profile of the deflected and focused beam can be seen on the left. The dashed rectangle on the right is the crystal cross-section.

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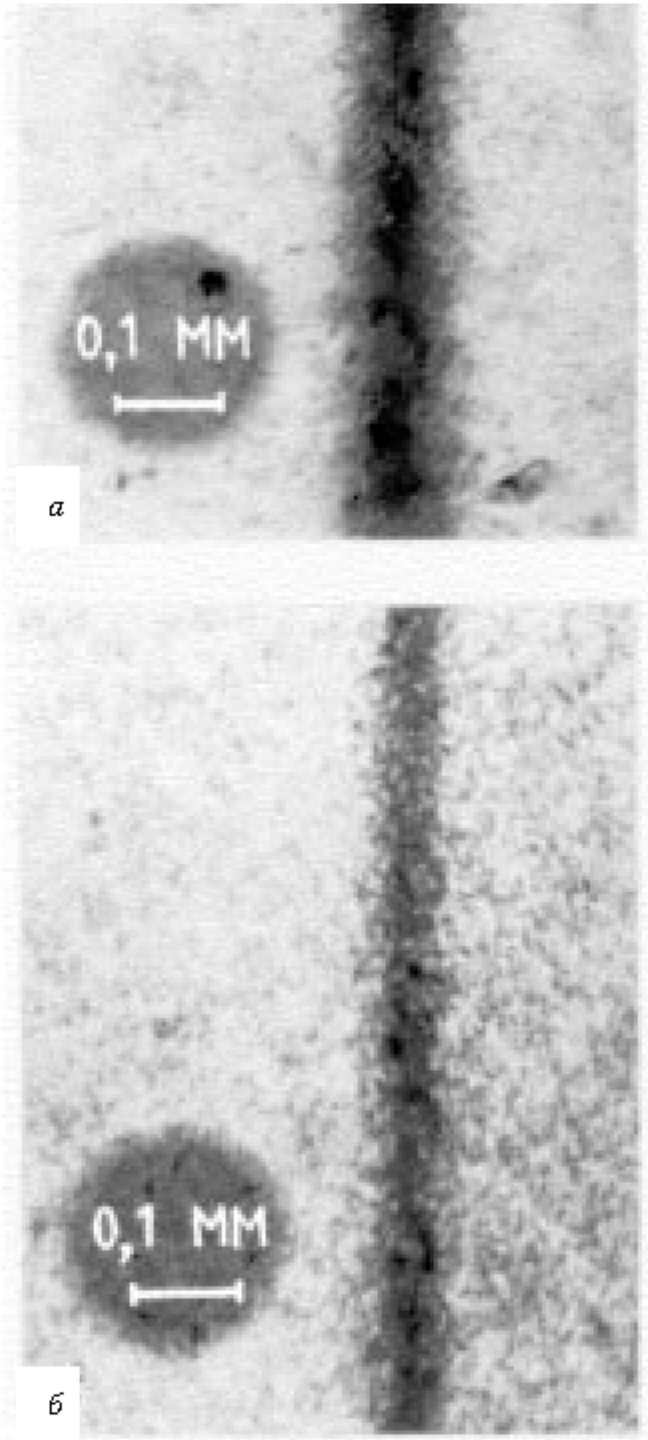
Beam focusing by channeling crystals:

a) F=1.4 m
b) F=0.5 m.

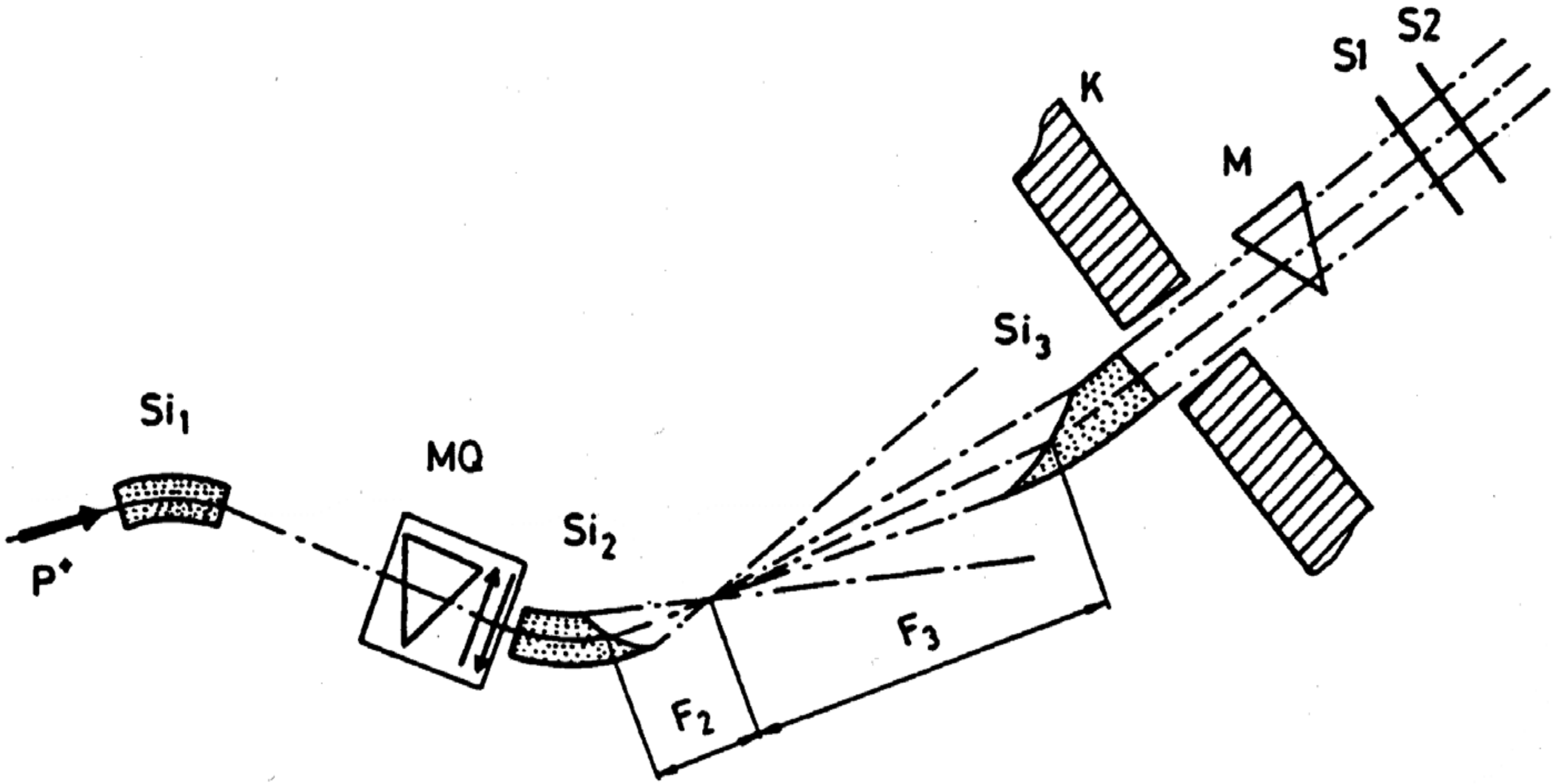


Focus size measured for crystals with focal length 0.5-3.5 m and compared to calculation (Lindhard angle x focal length)

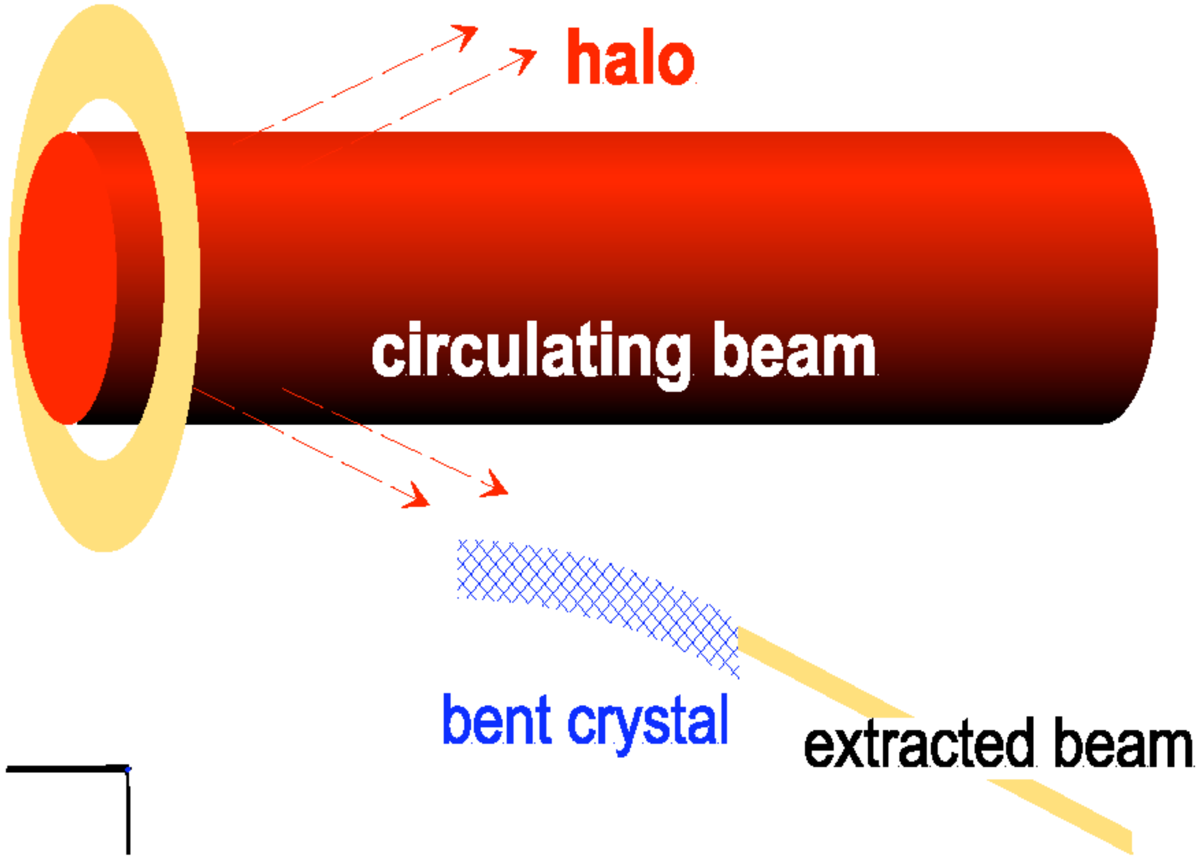
Characteristics of focusing crystals and beam sizes in focus

Crystal N	R [m]	r [m]	α [deg]	F [m]	Focus size $2\sigma_x$ [μm] calculation	measured
1	2.7	2.21	58.2	3.5	175	200
2	2.7	1.52	30.4	1.4	70	80
3	2.7	1.374	11.9	0.5	25	43

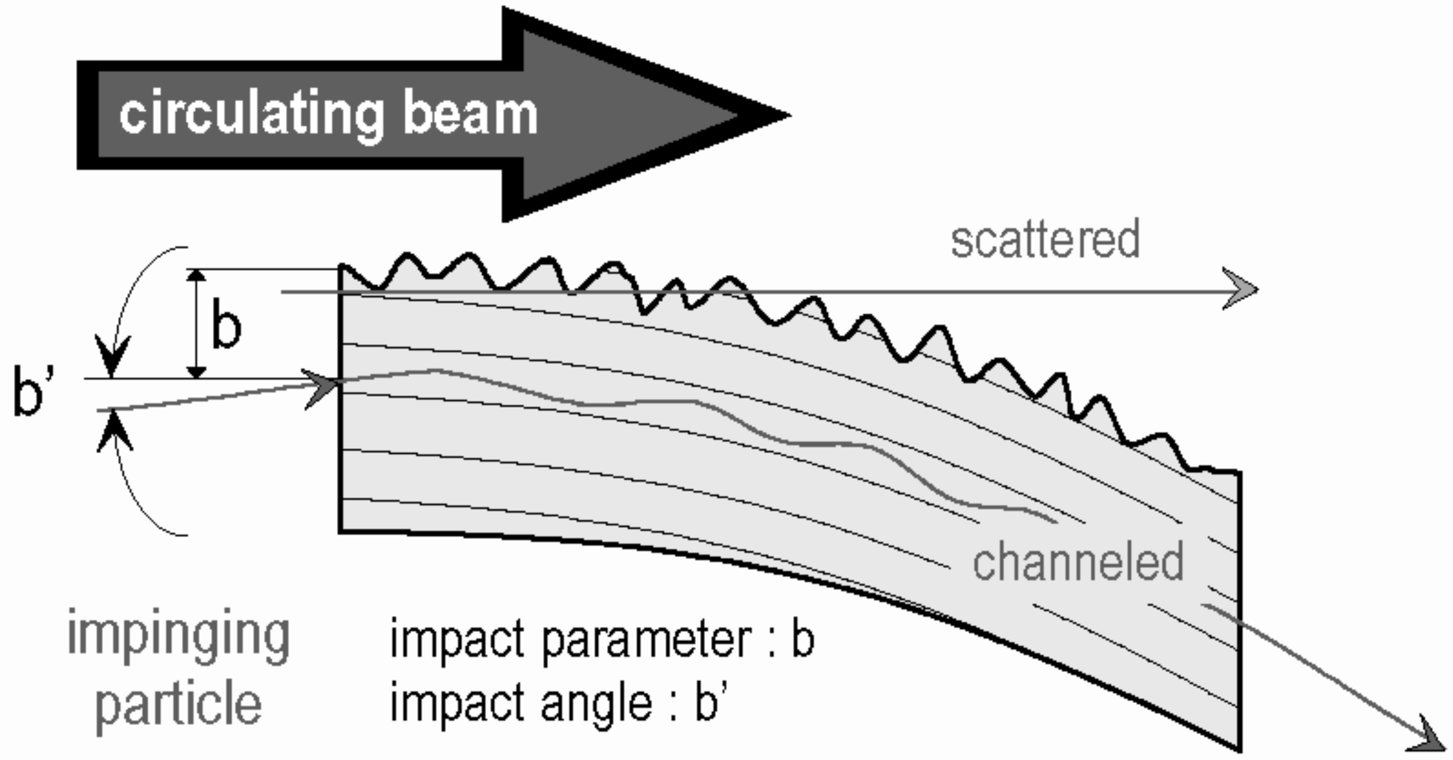
Beam line (70 m long) made of 3 crystals, IHEP



Major application so far: beam extraction



Channeling, scattering, and accelerator dynamics are essential in multi-turn, multi-pass process of crystal extraction and collimation



Physics Letters B 313 (1993) 491–497
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PHYSICS LETTERS B

First results on proton extraction from the CERN-SPS with a bent crystal

H. Akbari [b], X. Altuna [b], S. Bardin [b,1], R. Bellazzini [f], V. Biryukov [b,2], A. Brez [f], M.P. Bussa [h], L. Busso [h], A. Calcaterra [d], G. Carboni [f], F. Costantini [f], R. De Sangro [d], K. Elsener [b], F. Ferioli [b], A. Ferrari [b], G.P. Ferri [b], F. Ferroni [g], G. Fidecaro [b], A. Freund [c], R. Guinand [b], M. Gyr [b], W. Herr [b], A. Hilaire [b], B.N. Jensen [a], J. Klem [b], L. Lanceri [i], K. Maier [j], M.M. Massai [f], V. Mertens [b], S.P. Møller [a], S. Morganti [g], O. Palamara [e], S. Peraire [b], S. Petrera [e], M. Placidi [b], R. Santacesaria [g], W. Scandale [b], R. Schmidt [b], A.M. Taratin [b,3], F. Tosello [h], E. Uggerhøj [a,b], B. Vettermann [b,4], P.F. Vita [f], G. Vuagnin [i], E. Weisse [b] and S. Weisz [b]

[a] *ISA, University of Aarhus, Aarhus, Denmark*
[b] *CERN, Geneva, Switzerland*
[c] *ESRF, Grenoble, France*
[d] *Laboratori Nazionali di Frascati, Frascati, Italy*
[e] *Università di Lecce and INFN, Lecce, Italy*
[f] *Università di Pisa and INFN, Pisa, Italy*
[g] *Università "La Sapienza" and INFN, Roma, Italy*
[h] *Università di Torino and INFN, Torino, Italy*
[i] *Università di Trieste and INFN, Trieste, Italy*
[j] *MPI für Metallforschung, Stuttgart, Germany*

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The feasibility of extracting protons from the halo of a high energy beam by means of a bent silicon crystal has been investigated. Protons diffusing from a 120 GeV beam circulating in the SPS at CERN have been extracted at an angle of 8.5 mrad. Efficiencies of about 10 percent, orders of magnitude higher than the values achieved previously, have been measured. The present results are promising in view of beam extraction from future multi-TeV proton accelerators.

First observation of luminosity-driven extraction using channeling with a bent crystal

R. A. Carrigan, Jr., D. Chen,* G. Jackson, N. Mokhov, and C. T. Murphy
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

S. I. Baker
Argonne National Laboratory, Argonne, Illinois 60439

S. A. Bogacz,† D. Cline, S. Ramachandran,‡ J. Rhoades, and J. Rosenzweig
University of California at Los Angeles, Los Angeles, California 90024

A. Aseev and V. Biryukov
Institute for High Energy Physics, Serpukhov, Russia

A. Taratin
Joint Institute for Nuclear Research, Dubna, Russia

J. A. Ellison
The University of New Mexico, Albuquerque, New Mexico 87131

A. Khanzadeev, Y. Prokofieva, V. Samsonov, and G. Solodov
Petersburg Nuclear Physics Institute, Gatchina, Russia

B. Newberger§
The University of Texas, Austin, Texas 78712

E. Tsyganov
The University of Texas Southwestern Medical Center at Dallas, Dallas, Texas 75235

H.-J. Shih‖
Superconducting Super Collider, Dallas, Texas 75237

W. Gabella
Vanderbilt University, Nashville, Tennessee 37235

B. Cox, V. Golovatyuk,¶ and A. McManus**
The University of Virginia, Charlottesville, Virginia 22901
(Received 2 September 1997; published 26 June 1998)

Luminosity-driven channeling extraction has been observed for the first time using a 900 GeV circulating proton beam at the superconducting Fermilab Tevatron. The extraction efficiency was found to be about 30%. A 150 kHz beam was obtained during luminosity-driven extraction with a tolerable background rate at the collider experiments. A 900 kHz beam was obtained when the background limits were doubled. This is the highest energy at which channeling has been observed. [S1098-4402(98)00003-2]

1993-1998: measured data at FNAL and CERN are found in good agreement with Monte Carlo predictions

PRST-AB 1 R.A. CARRIGAN *et al.*

shown in Fig. 3 (bottom). No time dependence in the data was discernible.

In two stores in which the extraction was luminosity driven, the channeling efficiencies were 24 ± 8% (Fig. 3) and 35 ± 11%. During the 84-bunch proton-only fill, the efficiency was 32 ± 9%. The errors in these efficiencies are derived from the rms scatter of the many data points about their average value. The simulation [8] predicted an extraction efficiency of 35% for a realistic crystal. The same simulation program gives a value consistent with the efficiency measured at 120 GeV at CERN [10].

V. CONCLUSIONS

In summary, this experiment has observed luminosity-driven crystal extraction and demonstrated crystal extraction in a superconducting accelerator for the first time. No

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High-Efficiency Beam Extraction and Collimation Using Channeling in Very Short Bent Crystals

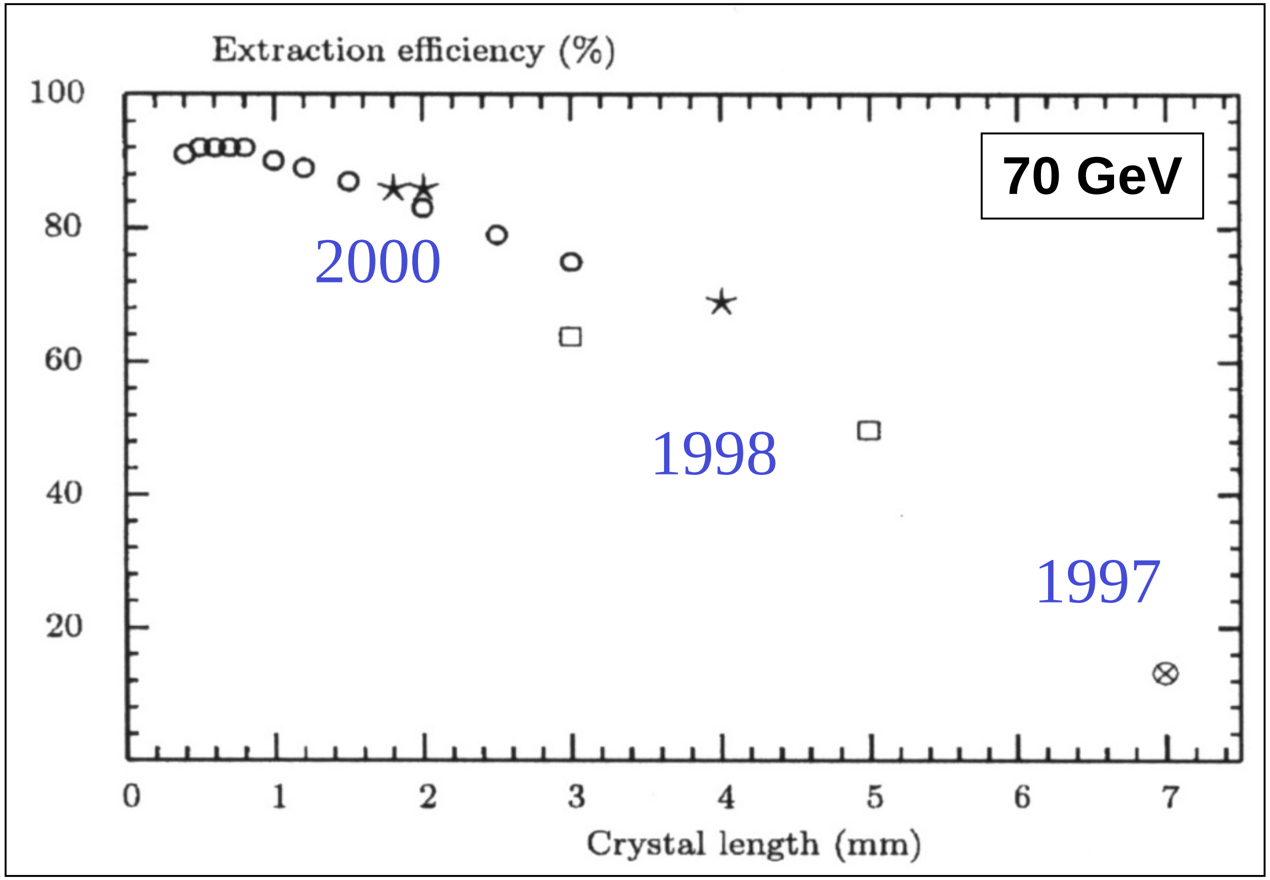
A. G. Afonin,[1] V. T. Baranov,[1] V. M. Biryukov,[1] M. B. H. Breese,[2] V. N. Chepegin,[1] Yu. A. Chesnokov,[1] V. Guidi,[3] Yu. M. Ivanov,[5] V. I. Kotov,[1] G. Martinelli,[4] W. Scandale,[6] M. Stefancich,[4] V. I. Terekhov,[1] D. Trbojevic,[7] E. F. Troyanov,[1] and D. Vincenzi[4]

[1]*Institute for High Energy Physics, Protvino, 142281, Russia*
[2]*Surrey University, Guildford, GU2 5XH, United Kingdom*
[3]*Ferrara University, Department of Physics and INFN, I-44100, Italy*
[4]*Ferrara University, Department of Physics and INFM, I-44100, Italy*
[5]*Petersburg Nuclear Physics Institute, Gatchina, 188350, Russia*
[6]*CERN, Geneva 23, CH-1211, Switzerland*
[7]*Brookhaven National Laboratory, Upton, New York 11973*
(Received 12 April 2001; published 14 August 2001)

A silicon crystal was used to channel and extract 70 GeV protons from the U-70 accelerator with an efficiency of $85.3 \pm 2.8\%$, as measured for a beam of $\sim 10^{12}$ protons directed towards crystals of ~ 2 mm length in spills of ~ 2 s duration. The experimental data follow very well the prediction of Monte Carlo simulations. This demonstration is important in devising a more efficient use of the U-70 accelerator in Protvino and provides crucial support for implementing crystal-assisted slow extraction and collimation in other machines, such as the Tevatron, RHIC, the AGS, the SNS, COSY, and the LHC.

DOI: 10.1103/PhysRevLett.87.094802 PACS numbers: 41.85.–p

IHEP started new experiment in 1997

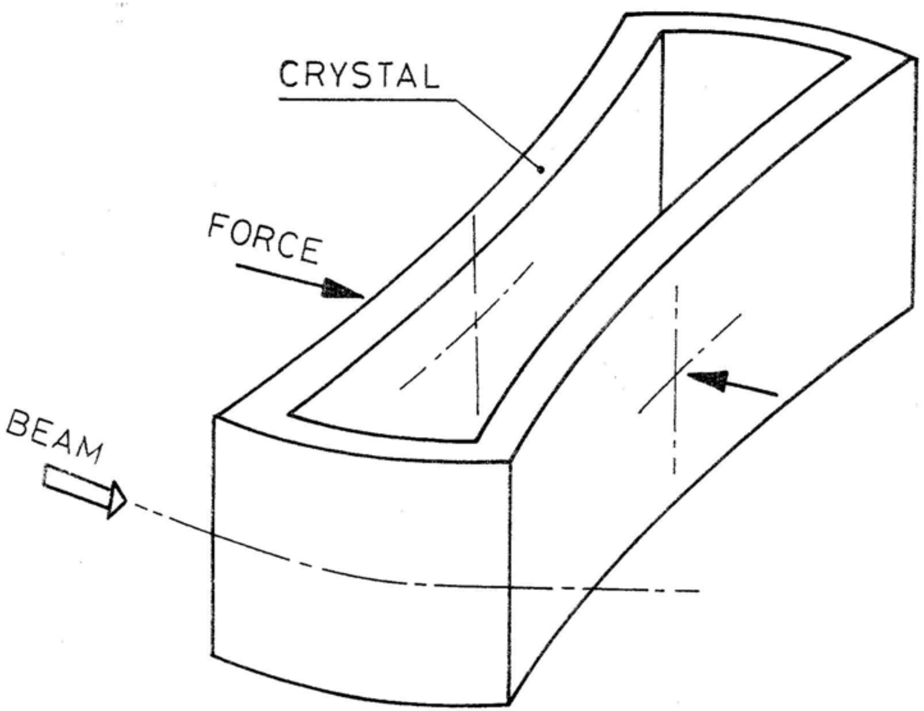


Crystals shortened by factor of 20 from SPS and Tevatron cases.
Efficiency increased by factor of 5.

IHEP: collimation / extraction efficiency for 70-GeV protons.
Measurements (*, , ⊗) and MC predictions (o) for perfect crystal

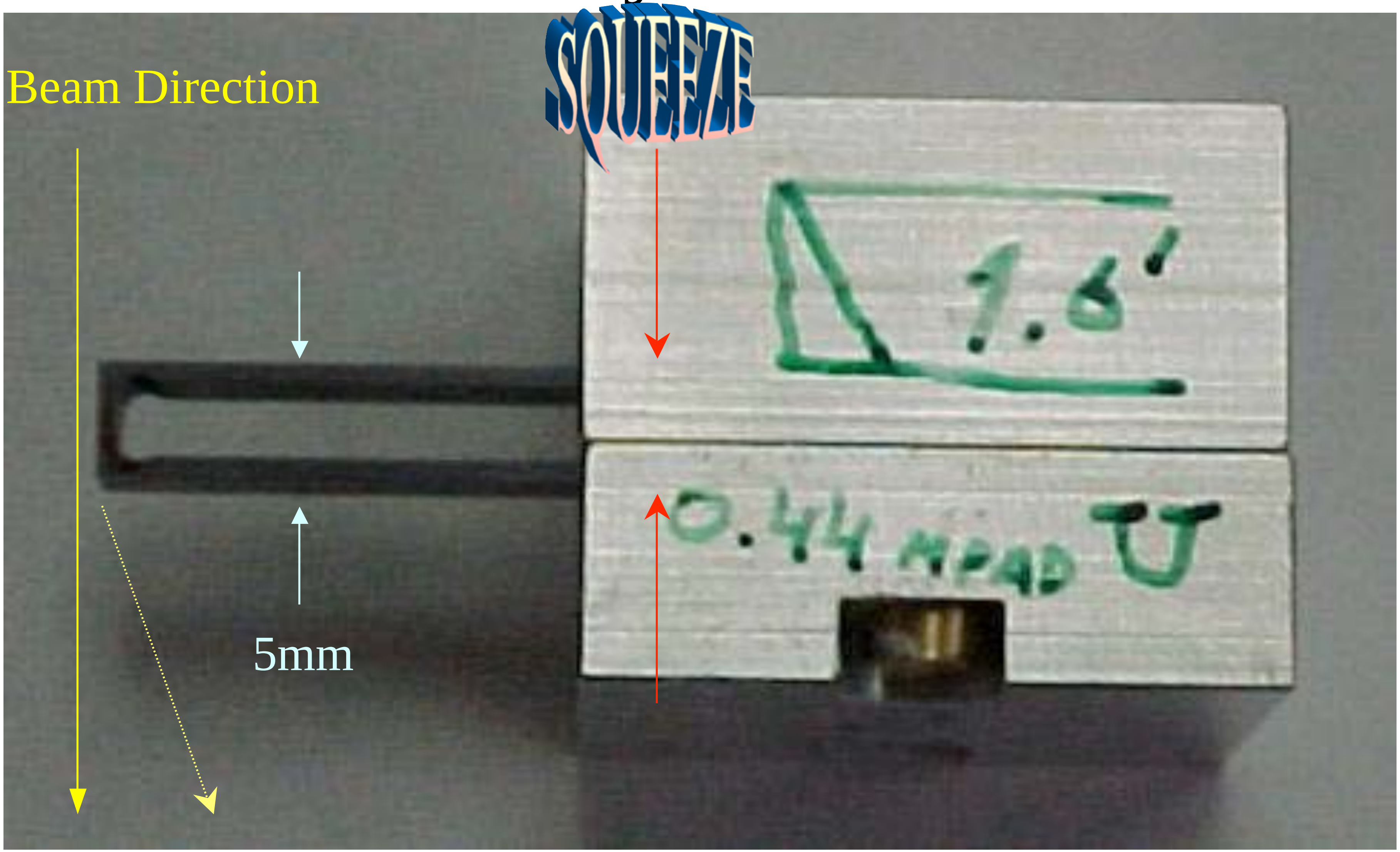
DIFFERENT BENT CRYSTAL DEVICES APPLIED AT IHEP FOR BEAM STEERING (EXTRACTION FROM MAIN RING AND BEAM SPLITTING IN BEAM LINES)

O-shaped crystal design as used at IHEP Protvino, RHIC and Tevatron



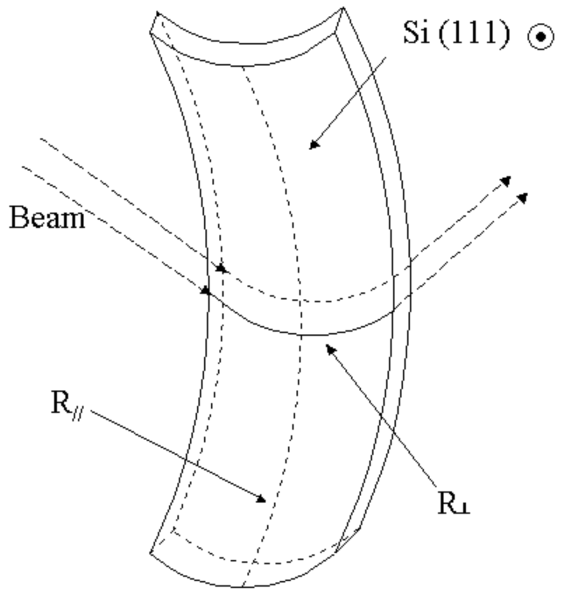
Crystal is 3 to 5 mm along the beam

Crystal



Although the way to ~90% efficiency was predicted by theory, the dramatic boost in crystal efficiency is realised by a breakthrough in bent crystal technology in IHEP

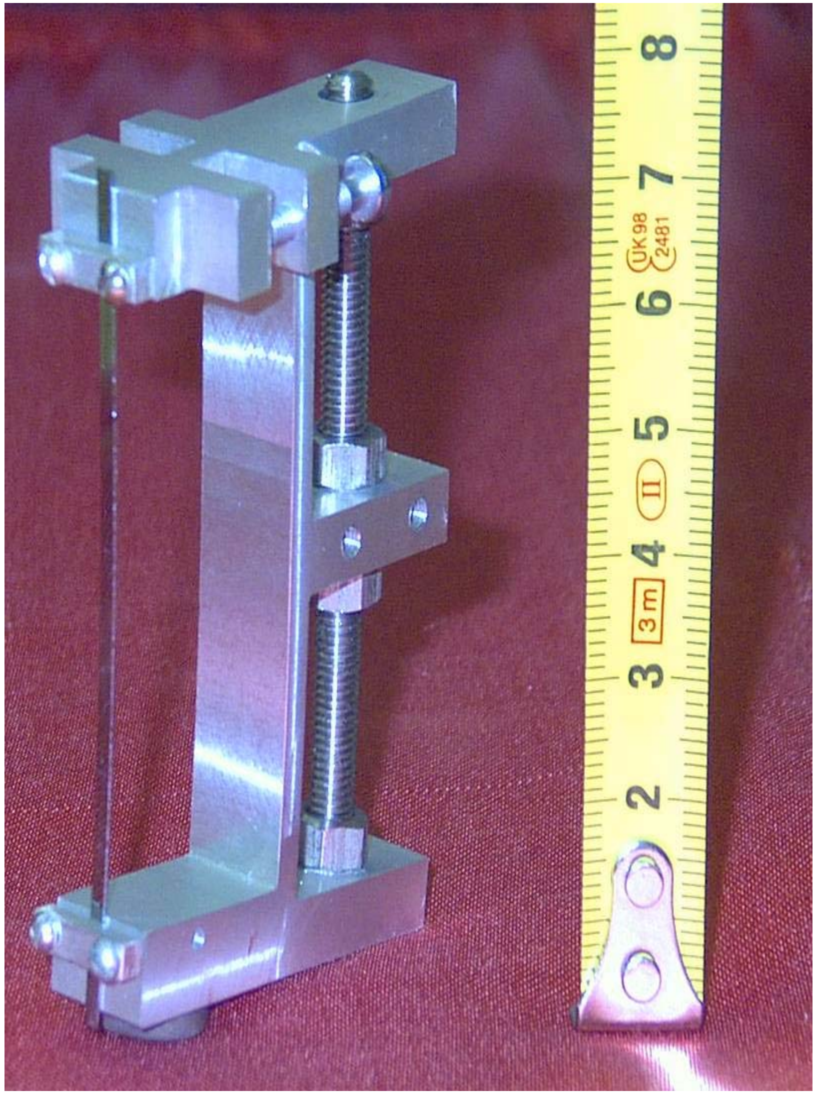
IHEP:
Basic idea is the use of anticlastic bending.
The real know-how behind the idea was thoroughly developed and tested.



One of realizations of Strip-type bent crystals

This is IHEP device N1
for efficient (85%)
extraction

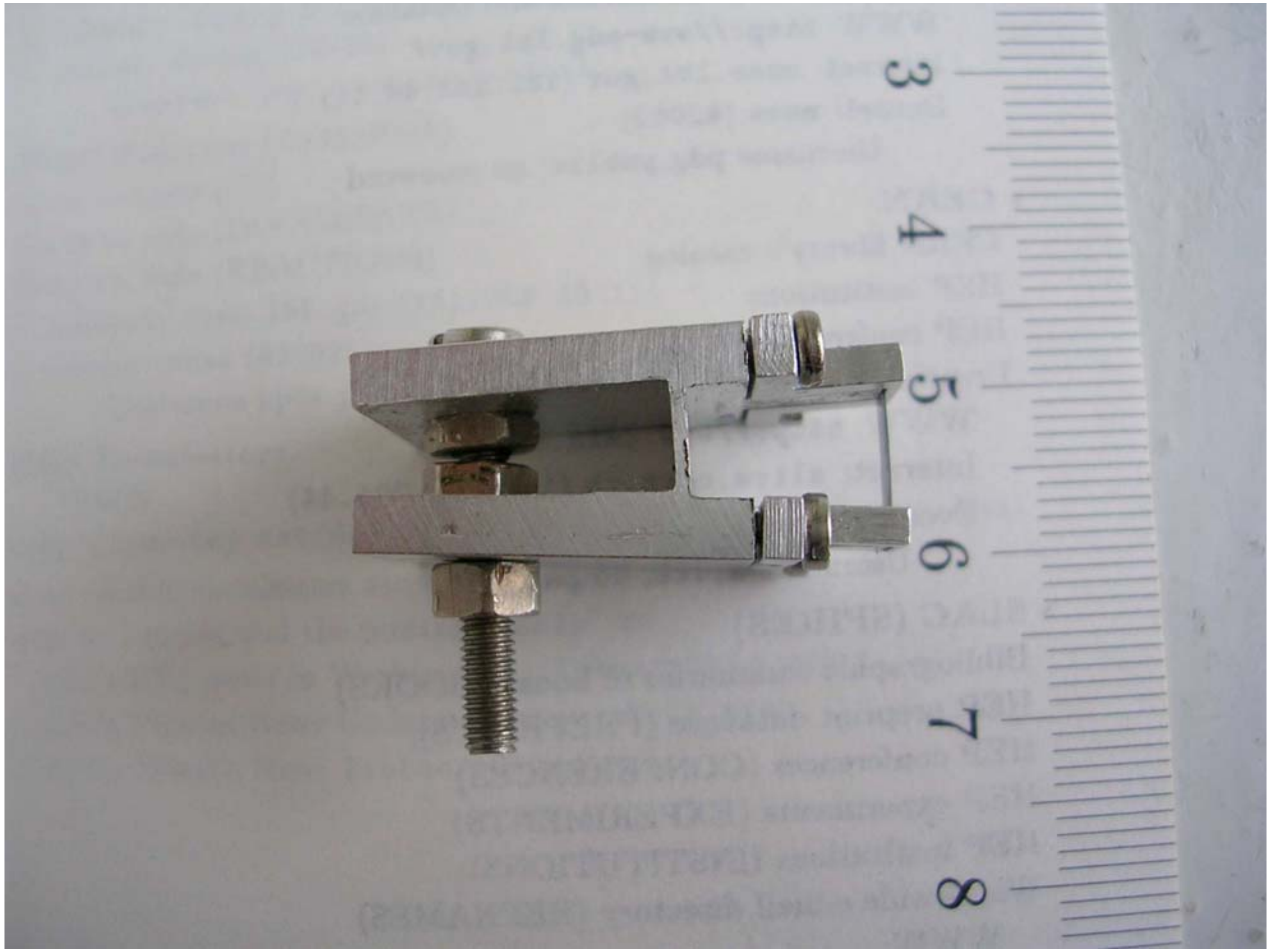
Small angle - few mrad
minimal material



Device N2 - big angle, long crystal.

Bent crystal parameters are: 150 mrad bend, 100 mm length and 12 mm width

Device N3 – strong curvature.
Big angle over short length.



The scheme of 150-mrad crystal beam line operated at IHEP at 10^6 protons in 1994-2004

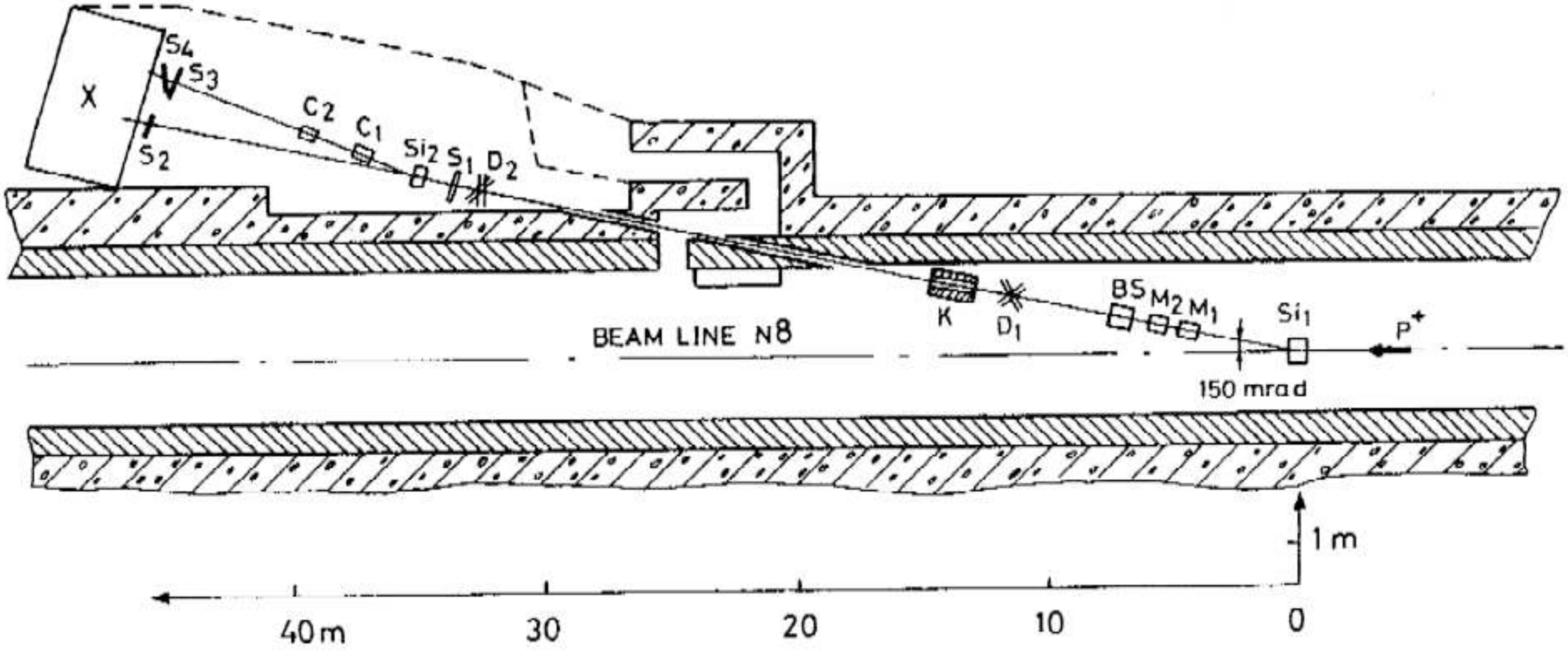
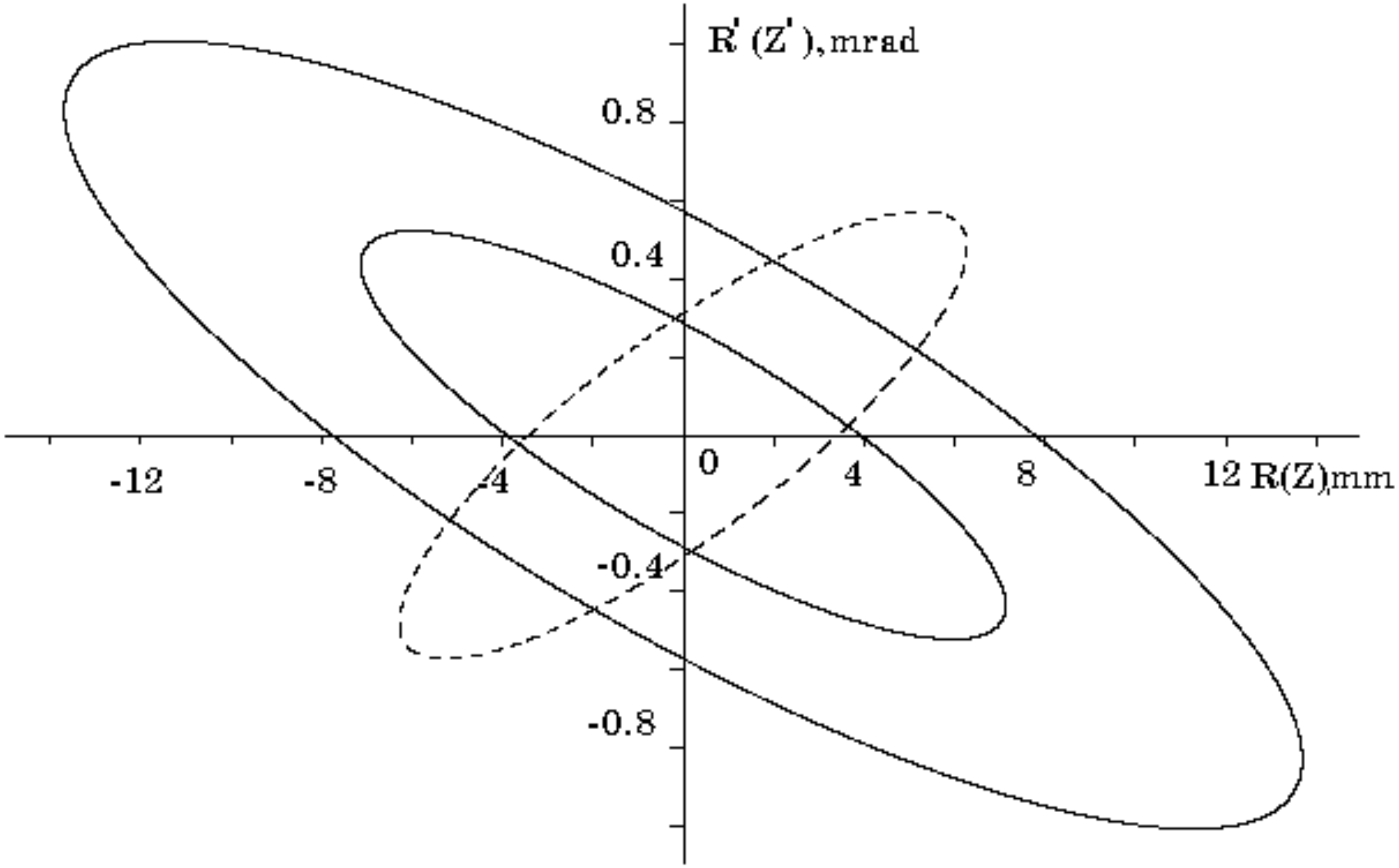
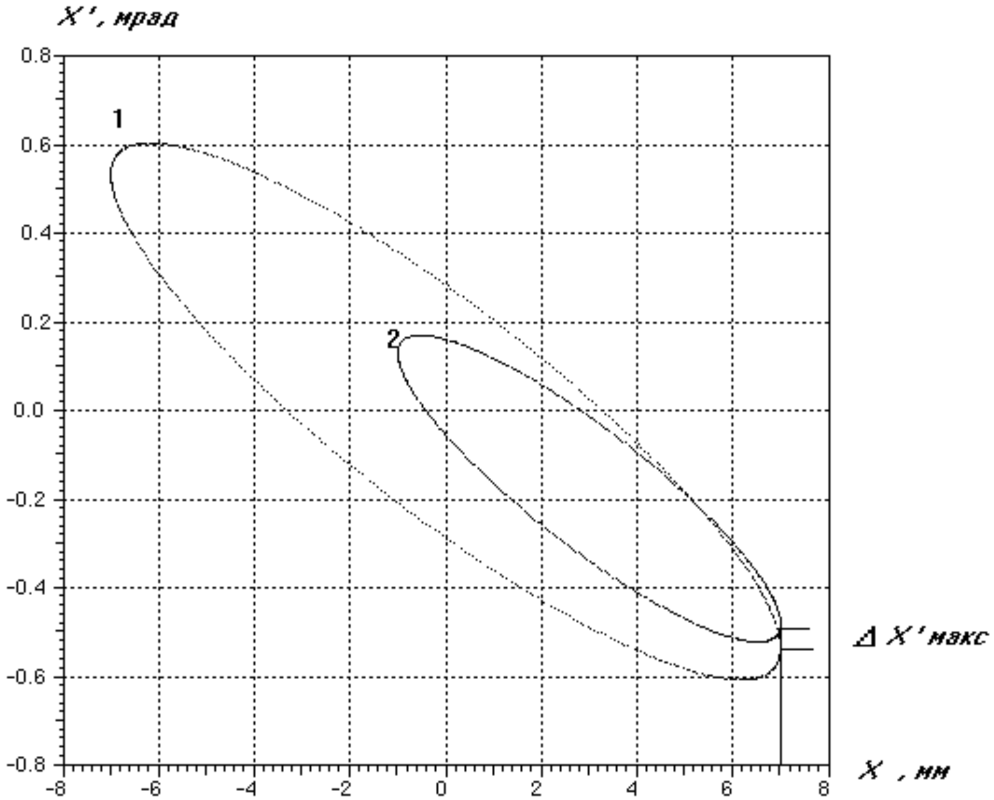


Fig. 1. The scheme of crystal beam line and experimental setup: Si_1, Si_2 - deflecting and testing crystals, M_1, M_2 – corrector magnets, BS – beam stopperp, D_1, D_2 – proportional chambers, K – a collimator, $S_1 - S_4$ – scintillator countes, C1, C2 – microstrip detector stations, X – a beam absorber.

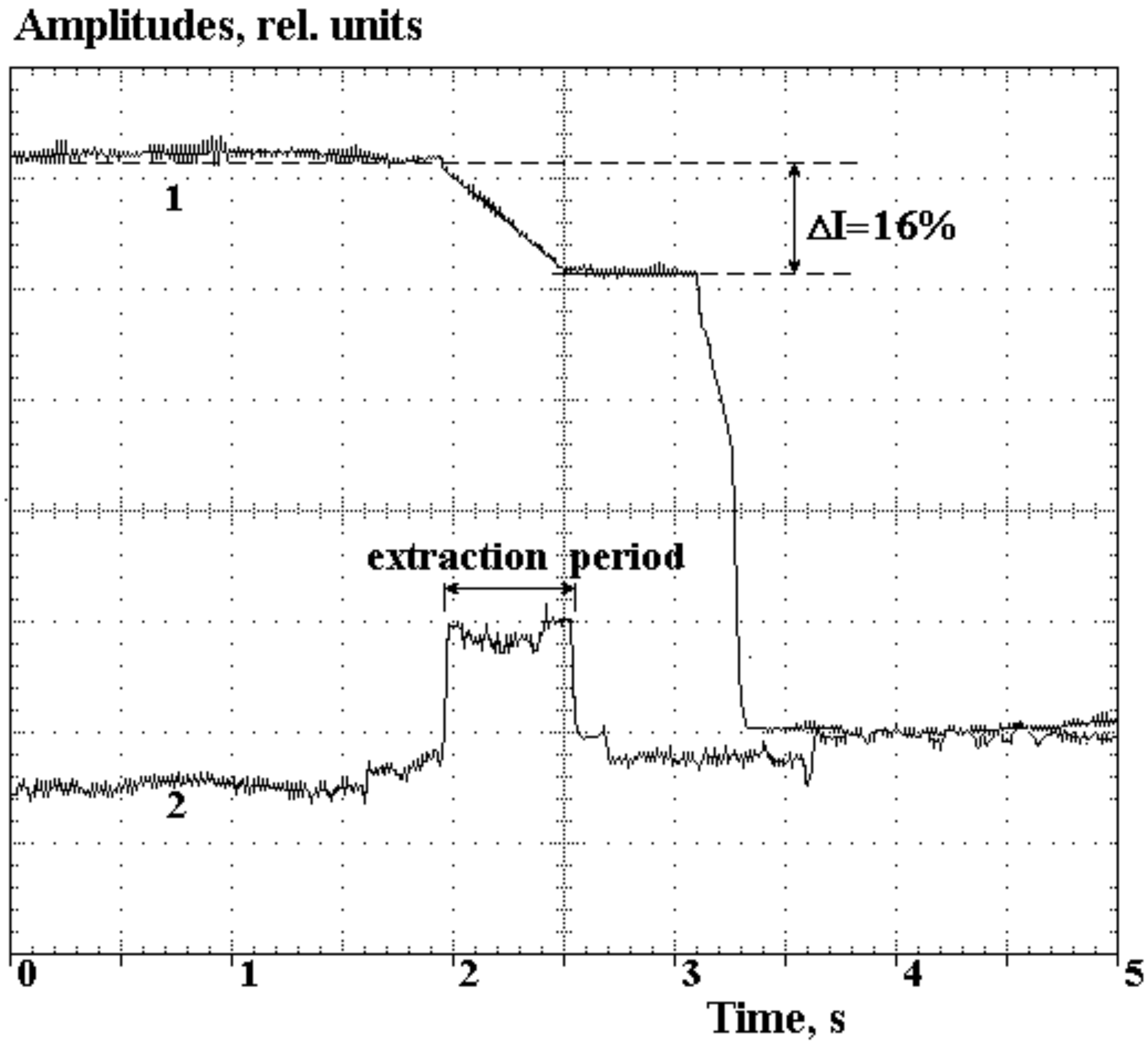
Typical beam phase space at crystal location in IHEP ring



Beam is gradually shifted to crystal location

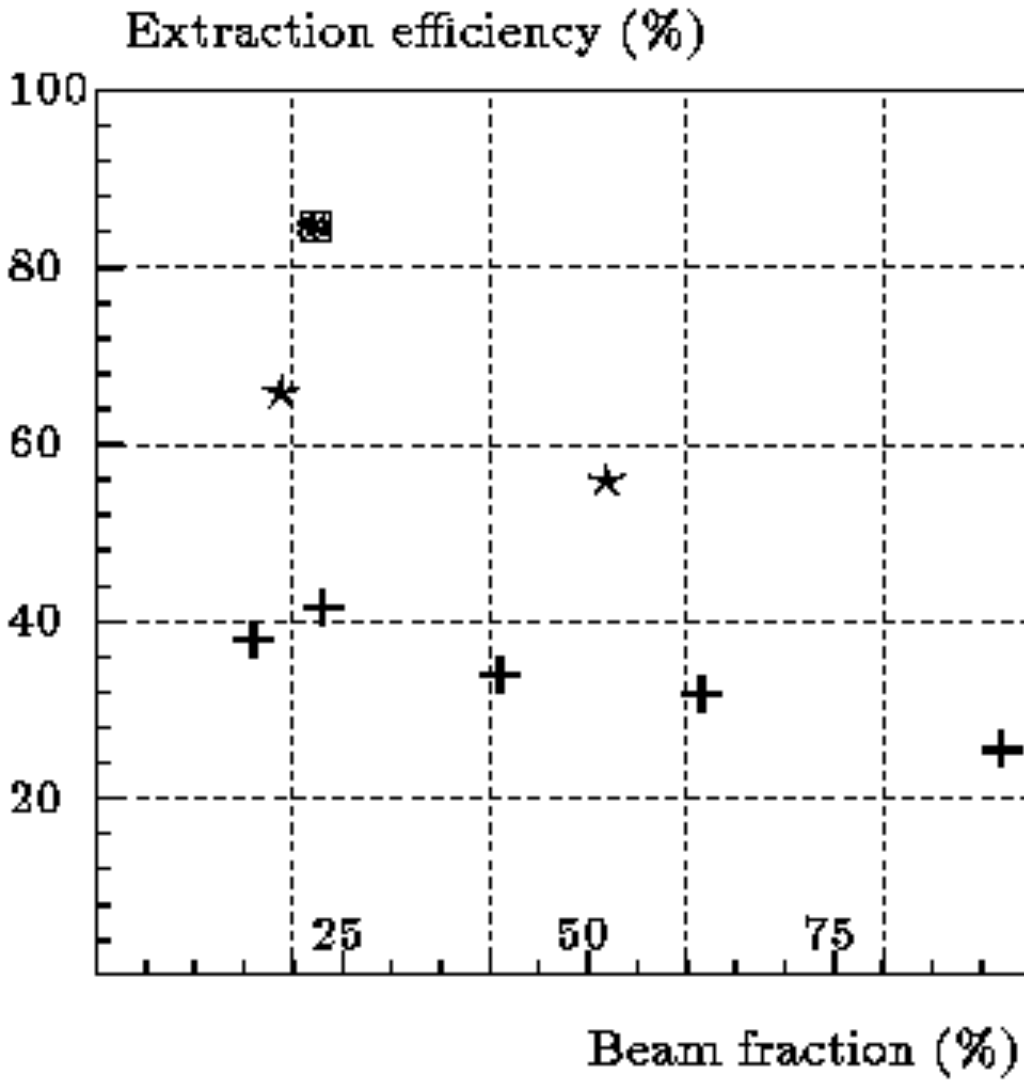


1- circulating beam, 2- extracted beam, IHEP



Crystal extraction efficiency as measured since Dec 1997.

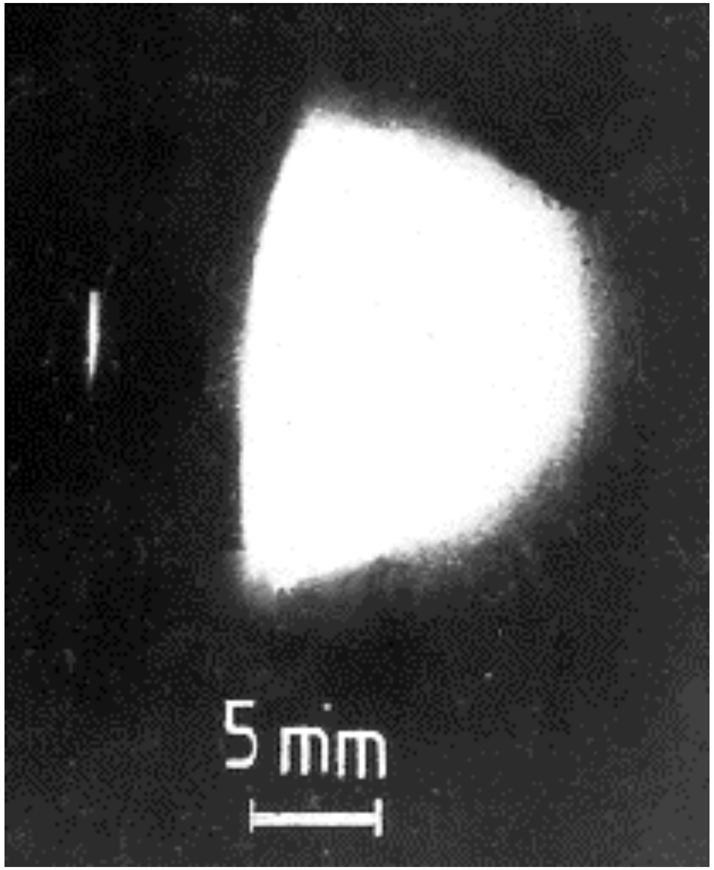
85% is measured even when all stored beam is dumped onto crystal !!



Deflected (left) and incident (right) beams as seen downstream of the crystal

- Prior to the test, the crystal was exposed in the ring to 50-ms pulses of **very intense beam** (about 10^{14} proton hits per pulse).

- **No damage** of crystal was seen in the test, after this extreme exposure.



Crystal lifetime is order of $5*10^{20}$ proton/cm^2

IRRADIATION DOSE

AT IHEP still $\sim 10^{20}$ p/cm^2

Efficiency didn't change:

44% in the beginning of run

43±2% in the end of run

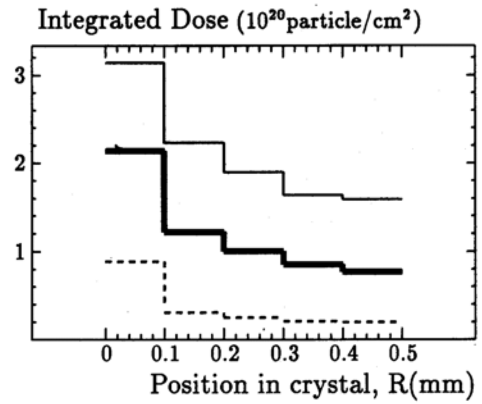


Figure 4: Irradiation of the crystal entry face (O-shaped crystal, 3 mm along the beam) in proton hits per square centimeter, after 100 000 machine cycles (~1 month of accelerator run) with dump of 10^{12} proton/cycle. Shown for typical extraction efficiency 43% (thick line, middle); for misaligned crystal (thin line, top); for extraction efficency 73% (dashed, bottom).

WORLD TOP RESULTS:

4×10^{20} p/cm^2 (1994)
S.I. BAKER et al., BNL
28 GeV

5×10^{20} p/cm^2 (2000)
A. BAURICHTER et al., CERN
450 GeV

IRRADIATED CRYSTAL
REDUCED EFFICIENCY
BY 30%

At ~1 GeV crystal is
less sensitive to lattice
misalignment

450 GeV : 5 μrad
1 GeV : 100 μrad

Expect $\sim 10^{21}$ p/cm^2 lifetim
at SNS

1 year lifetime in SNS ?

It took several years in IHEP to approach the target set by theory. First IHEP crystal was a kind of strip, 7 mm along the 70 GeV beam.

Then we turned to analog of U-shaped crystals of SPS; the required deflectors designed in IHEP were cut and polished in the optical workshop of PNPI chosen among other workshops because of their long experience in channeling.

The decisive step was invention in IHEP of strip-type deflectors, very short – down to ~2 mm along the beam, without straight parts and uniformly bent.

We produced in IHEP many strip deflectors from commercially available wafers. Crystal systems extract 70 GeV protons from IHEP main ring with efficiency of 85% at intensity of 10^{12}. Today, six locations on the IHEP 70-GeV main ring are equipped by crystal extraction systems, serving mostly for routine applications rather than for research

The **station of crystal deflectors** mounted at U-70 (left), and **bent crystals** mounted on the station (right)

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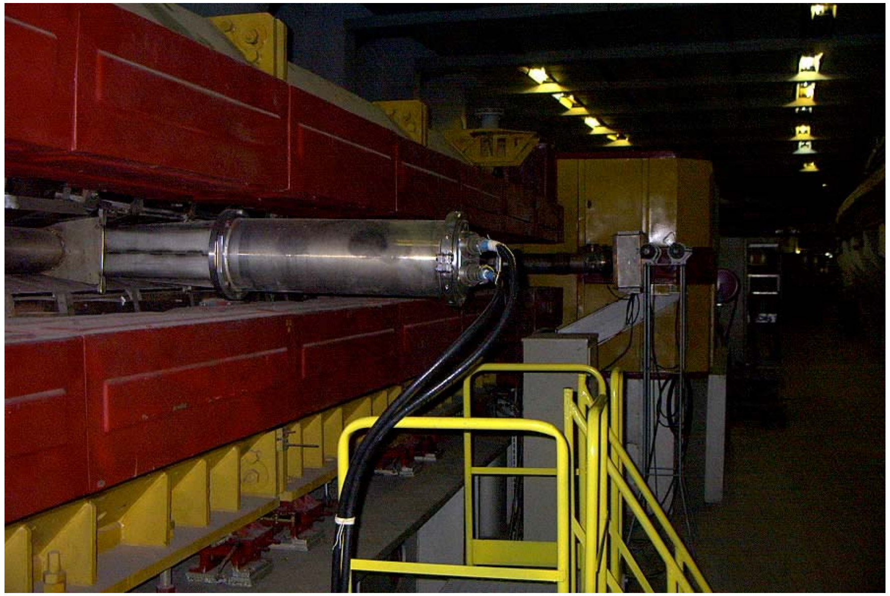

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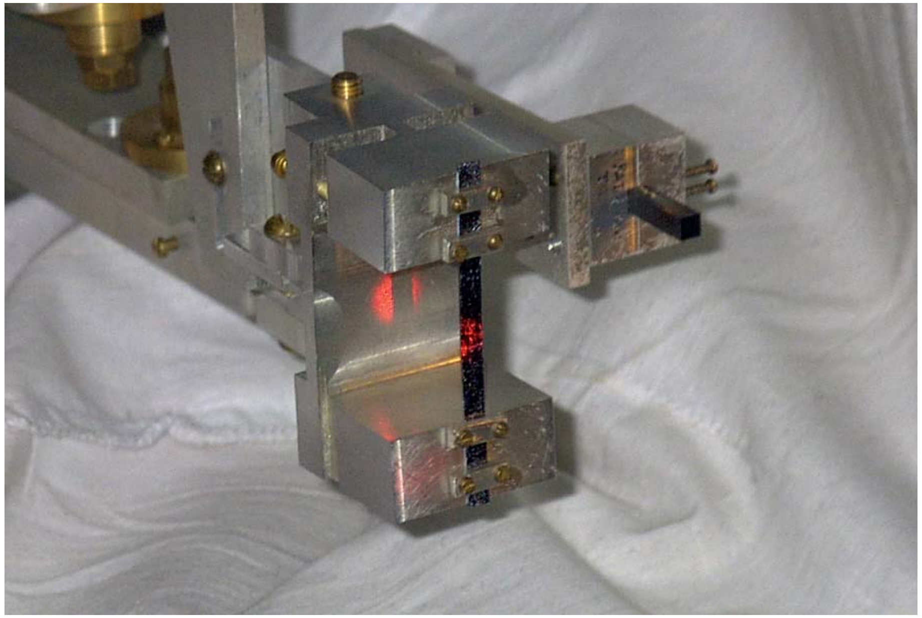
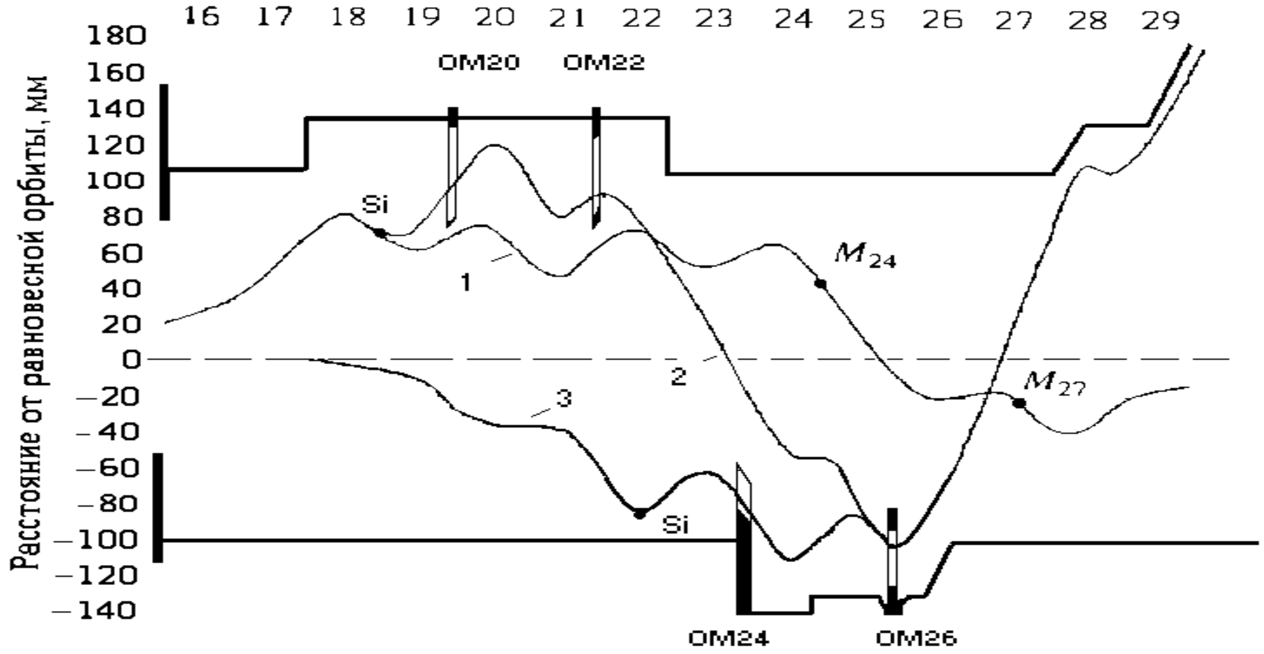


Channeled beam transfer through IHEP accelerator lattice



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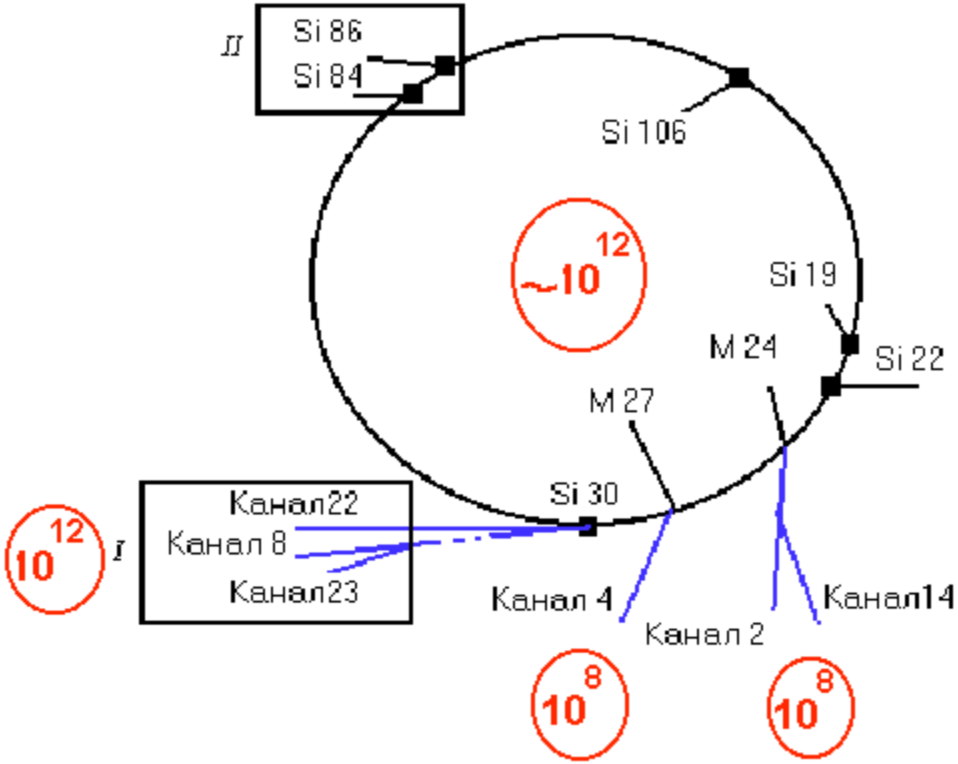
Proton extraction with crystals from 70 GeV accelerator

crystals installed on 6 locations in the IHEP ring



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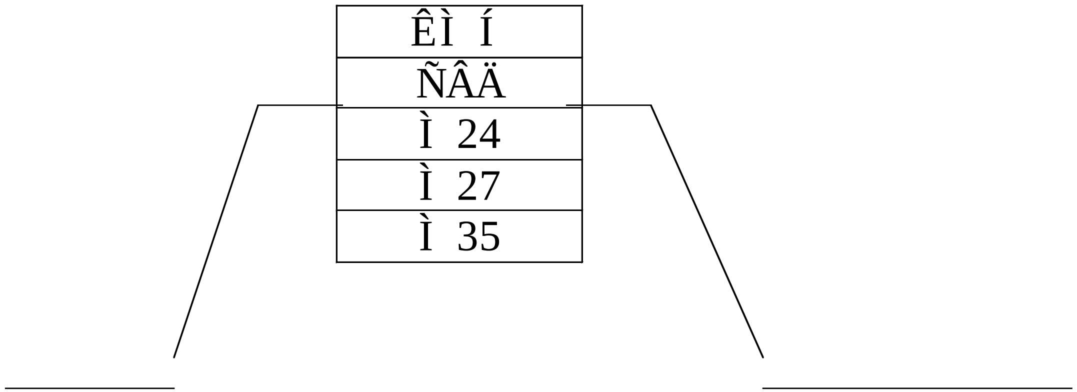
Five particle physics experiments can be run simultaneously

at IHEP thanks to parasitic crystal extraction



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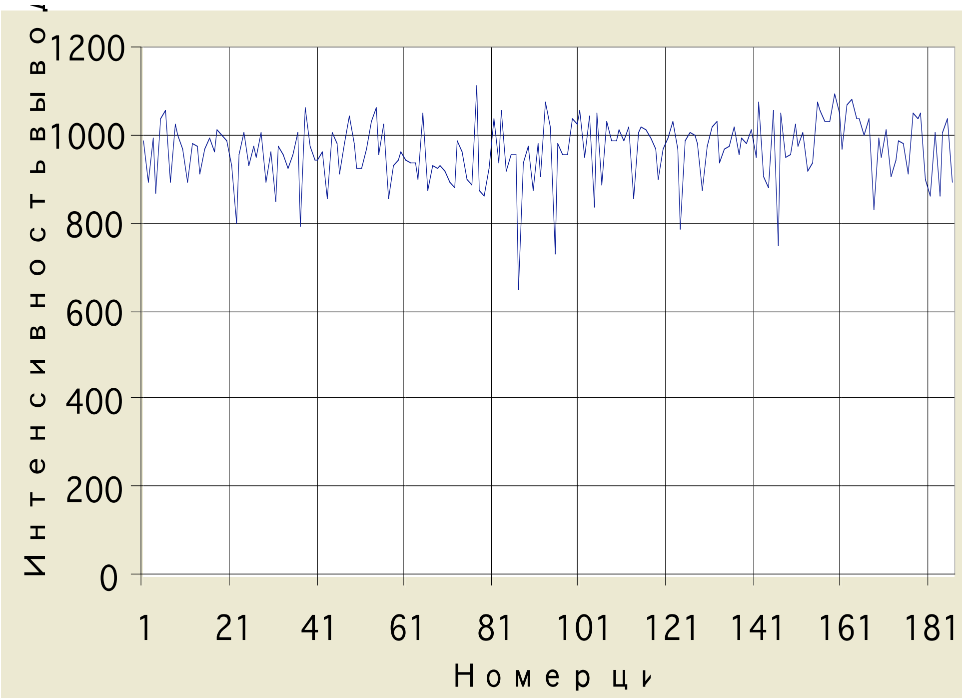
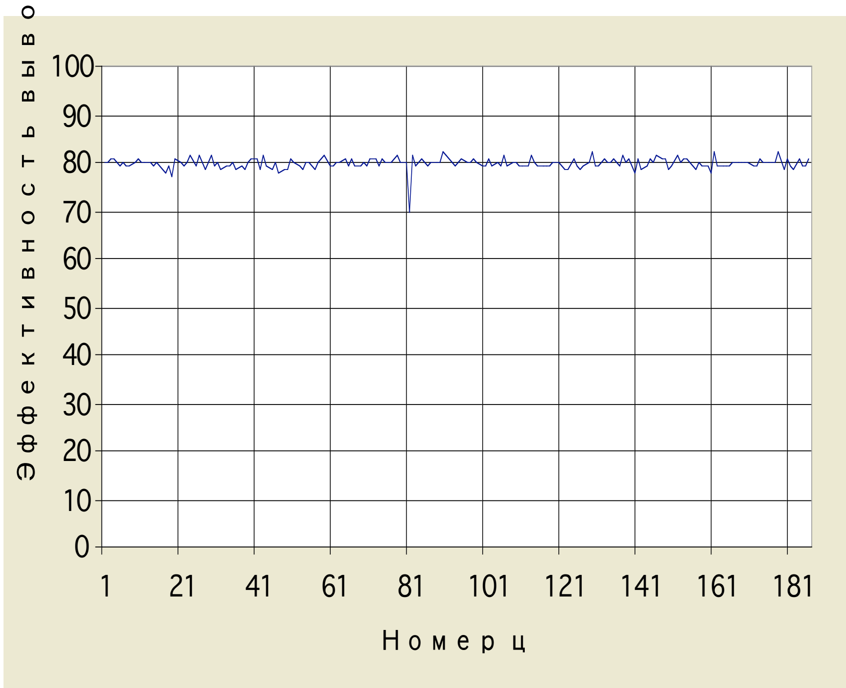
Intensity (left) and **efficiency** (right) of 50 GeV proton extraction by the scheme 22-24-26





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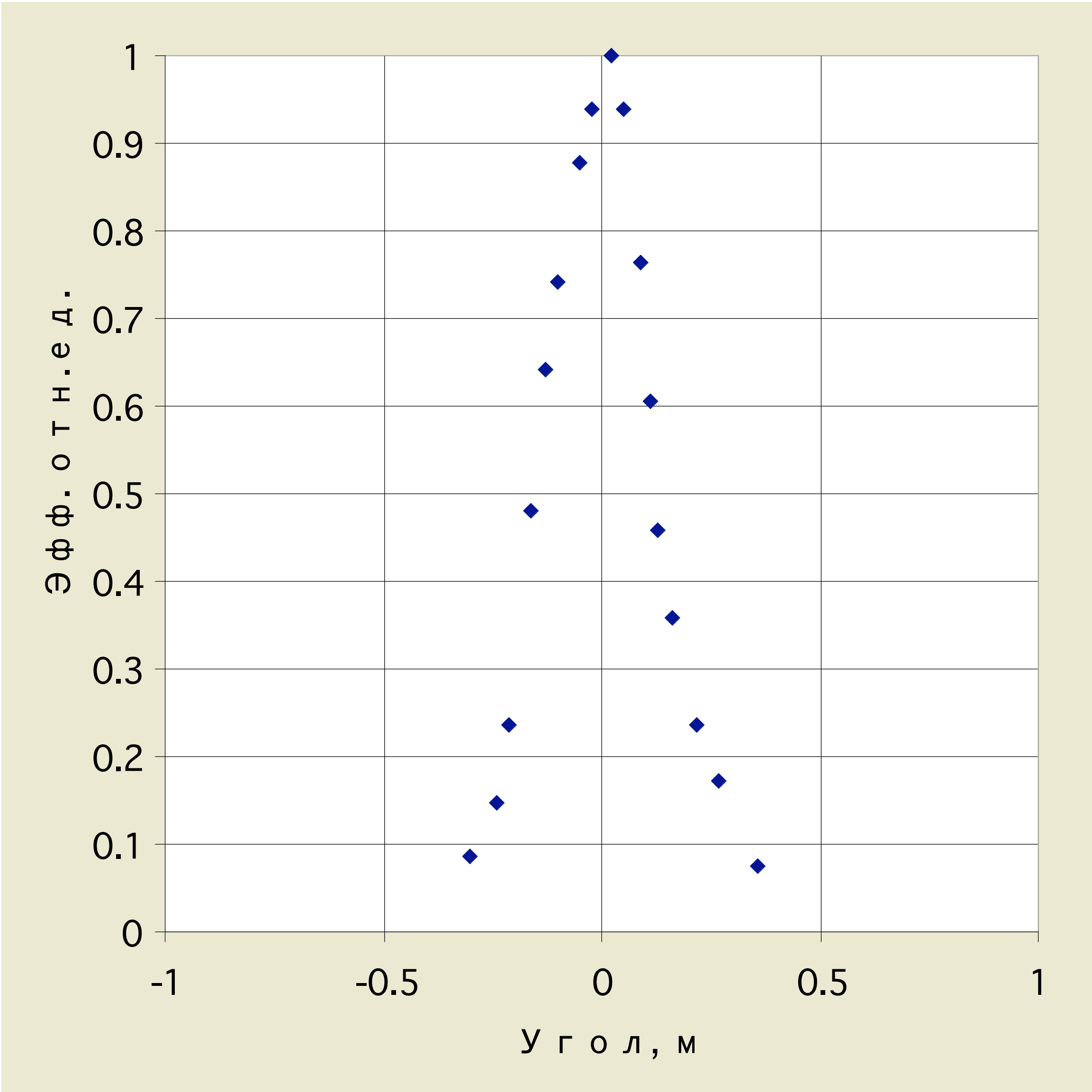
Example of the angular scan

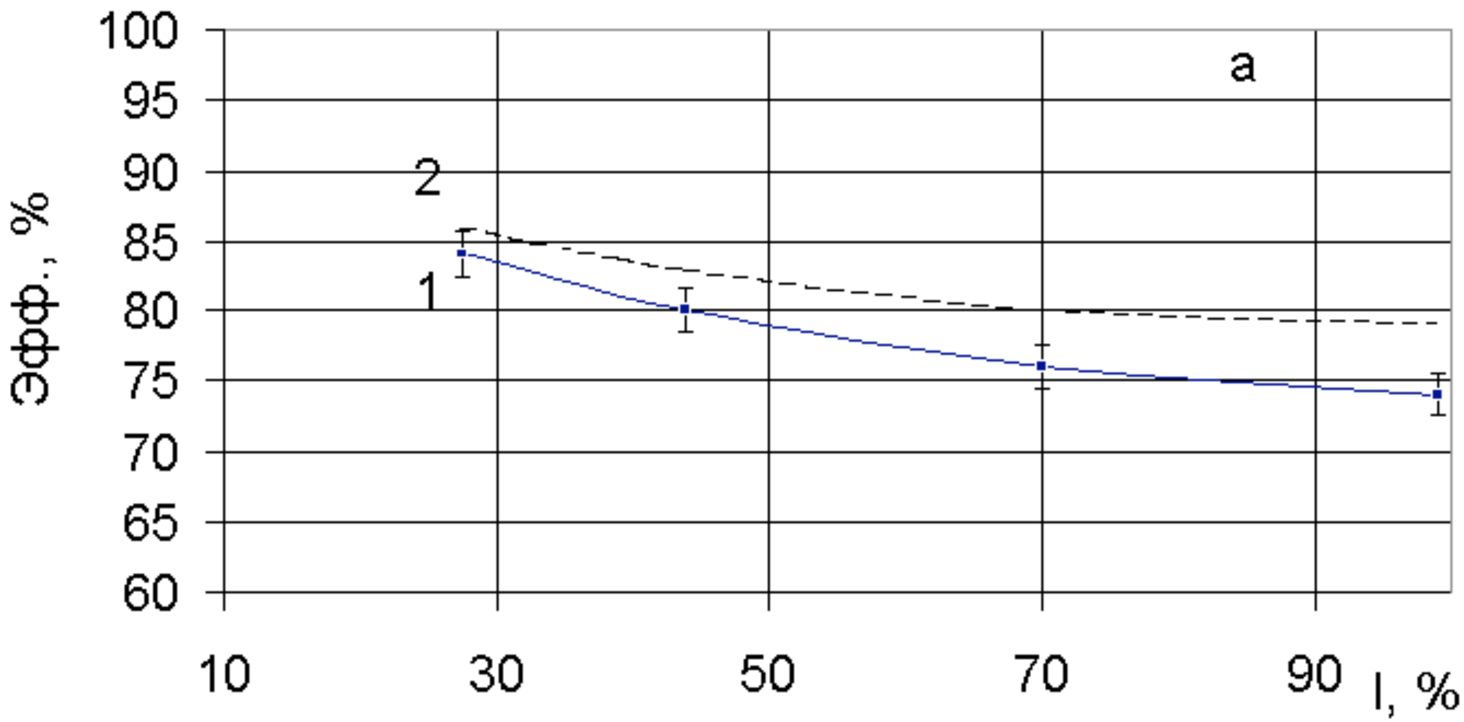
(dependence on crystal orientation)



Efficiency measured vs beam store fraction used.

Extraction scheme 106-24-26

Experiment (1, solid) and Monte Carlo (2, dash)



Çàâèñèì îñòü ?ô ôåêòèâí îñòè âû âî äà î ò äî ëè ï ó÷êà, í àáî äèì îãî í à ê∂èñòàëë:

à – ñõåì à âû âî äà 106-24-26; **á** – ñõåì à âû âî äà 22-24-26.

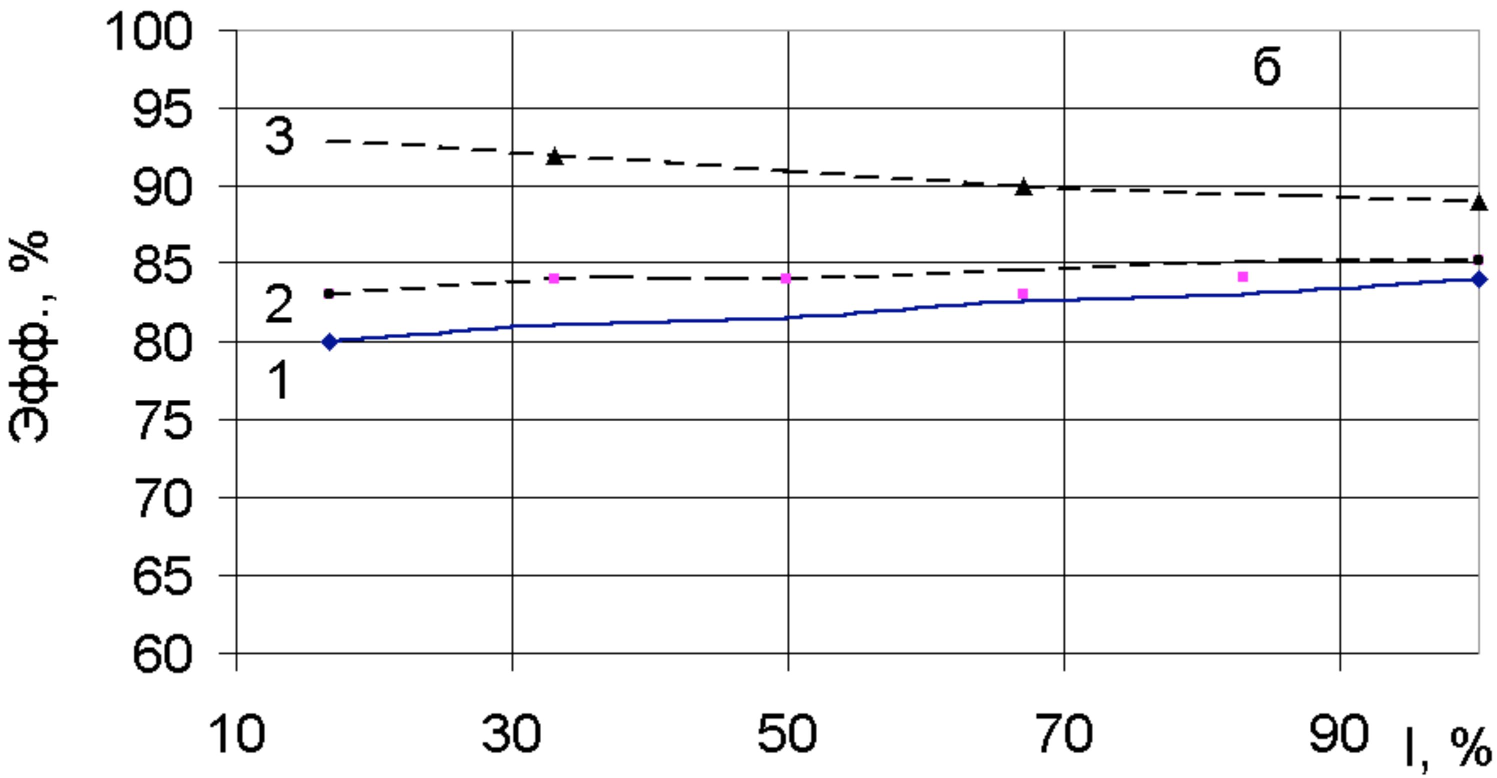
Dàñ÷åòí àÿ ê∂èâàÿ (ï óí êòè∂)

Efficiency measured vs beam store fraction used.

Extraction scheme 22-24-26

Experiment (1, solid) and **Monte Carlo** (2, dash).

Curve 3 is MC prediction for crystal reinstalled closer to the orbit.



Çàâèñèìîñòü ?ôôåêòèâíîñòè âûâîäà îò äîëè ïó÷êà, íàâîäèìîãî íà êðèñòàëë:
à – ñõåìà âûâîäà 106-24-26; **á** – ñõåìà âûâîäà 22-24-26.

Åñëè èçìåíèòü ïîëîæåíèå êðèñòàëëà, ïðèáëèçèâ åãî ê ðàâíîâåñíîé îðáèòå íà âåëè÷èíó ≥0,3 ìì, òî íàáë?äàåìûé ?ôôåêò ïðîïàäàåò, à ?ôôåêòèâíîñòü âûâîäà óâåëè÷èâàåòñÿ äî 90% (ïóíêòèðíàÿ êðèâàÿ 3). Òàêèì îáðàçîì, õîòÿ ìû è äîñòèãëè äîñòàòî÷íî âûñîêîé ?ô-ôåêòèâíîñòè âûâîäà ~85%, êàê ïîêàçûâà? ò ðàñ÷åòû, åå ìîæíî ïîïûòàòüñÿ äîâåñòè äî 90%.

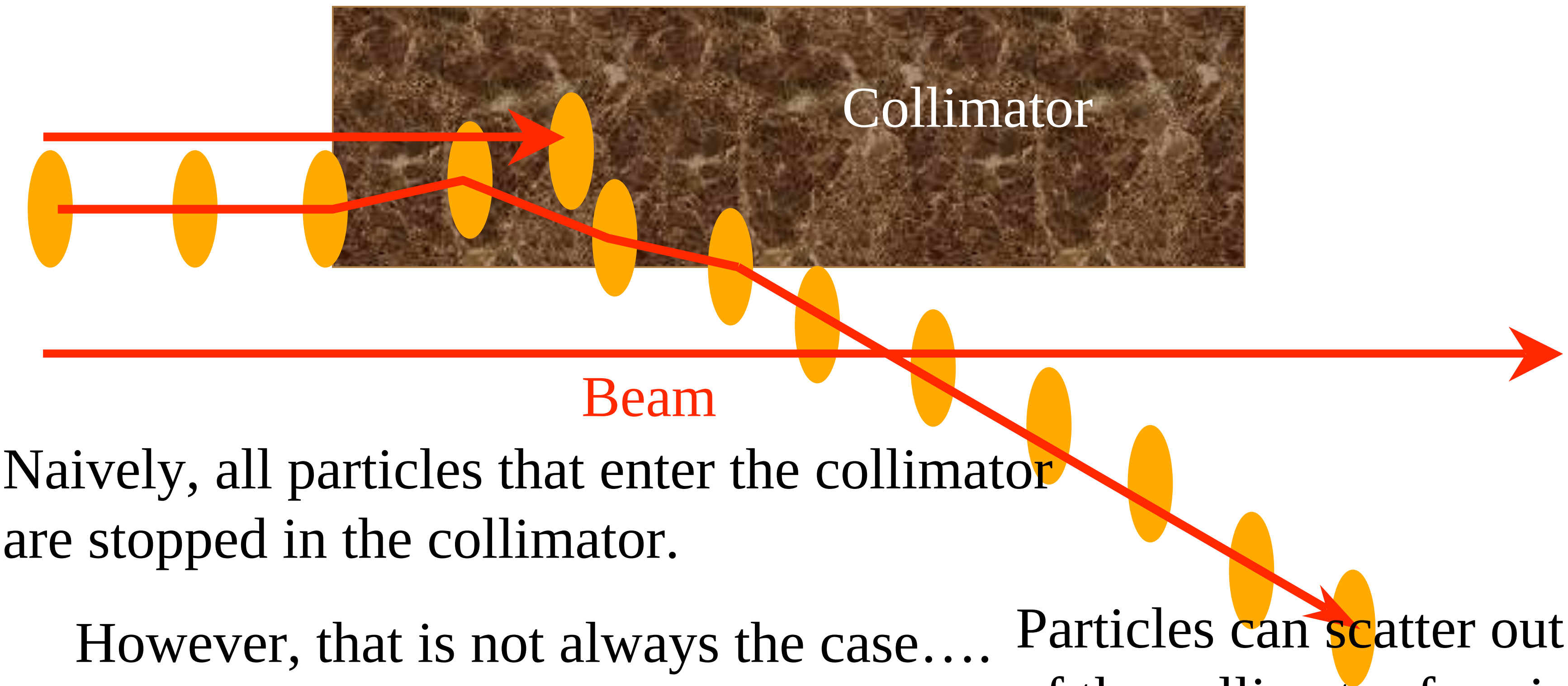
Apart from extraction, we developed **crystal use in collimation systems**

Various processes cause particles to enter into unstable orbits and large betatron amplitudes, causing beam halo formation. These halo particles cause:

- Background in experiments
- Excessive radiation in uncontrolled areas of the tunnel
- Magnet quenches in superconducting machines
- Equipment malfunction, damage

The job of the collimation system is to remove the halo and alleviate these problems. In addition, it should provide a well defined location for beam losses in case of equipment failure.

Conventional Collimation



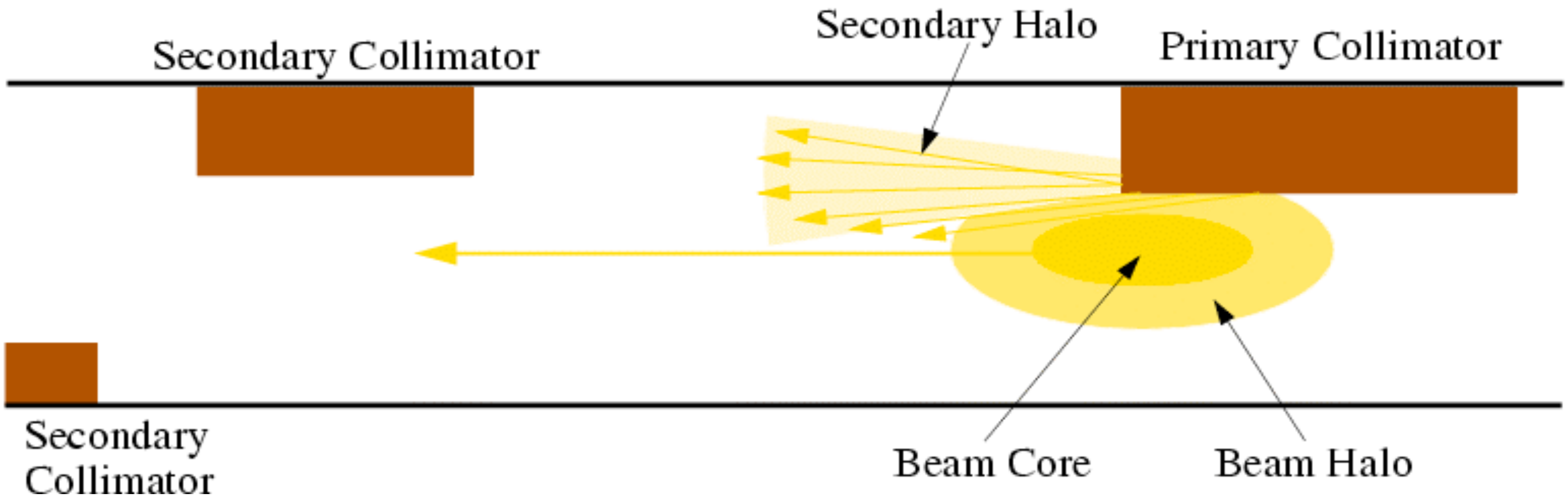
Naively, all particles that enter the collimator are stopped in the collimator.

However, that is not always the case….

Particles can scatter out of the collimator forming secondary halo!

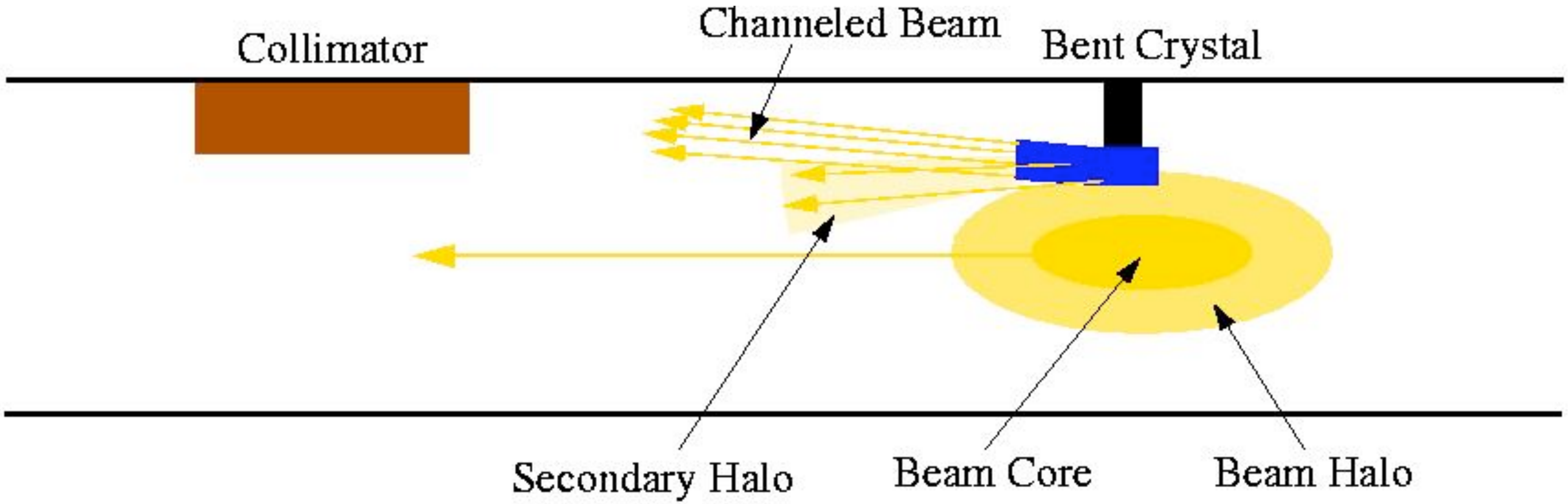
Two Stage Collimation

To deal with secondary halo, secondary collimators are needed.



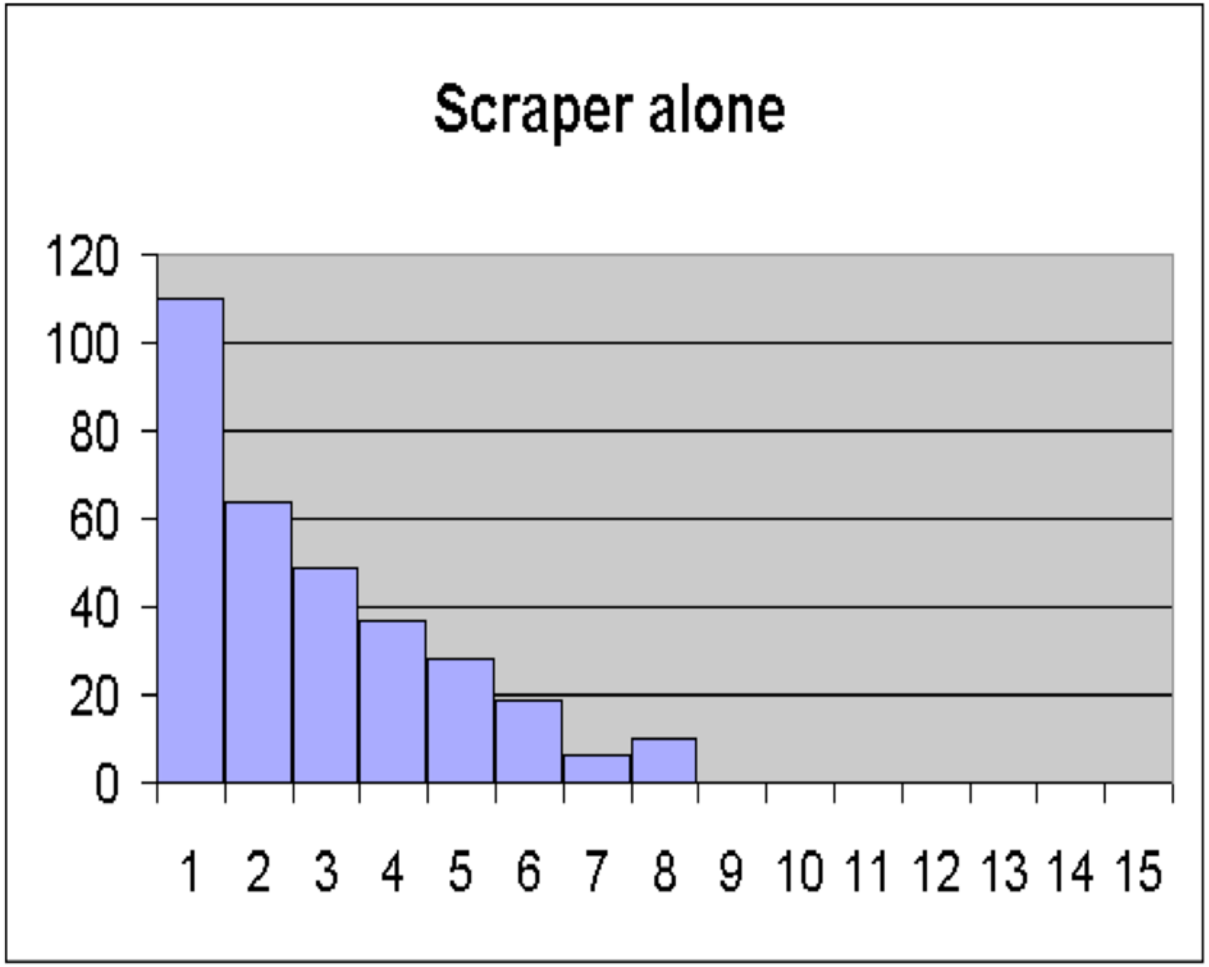
The number of secondary collimators grows quickly when background or machine protection requirements are strict and a high collimation efficiency is required.

A simpler way



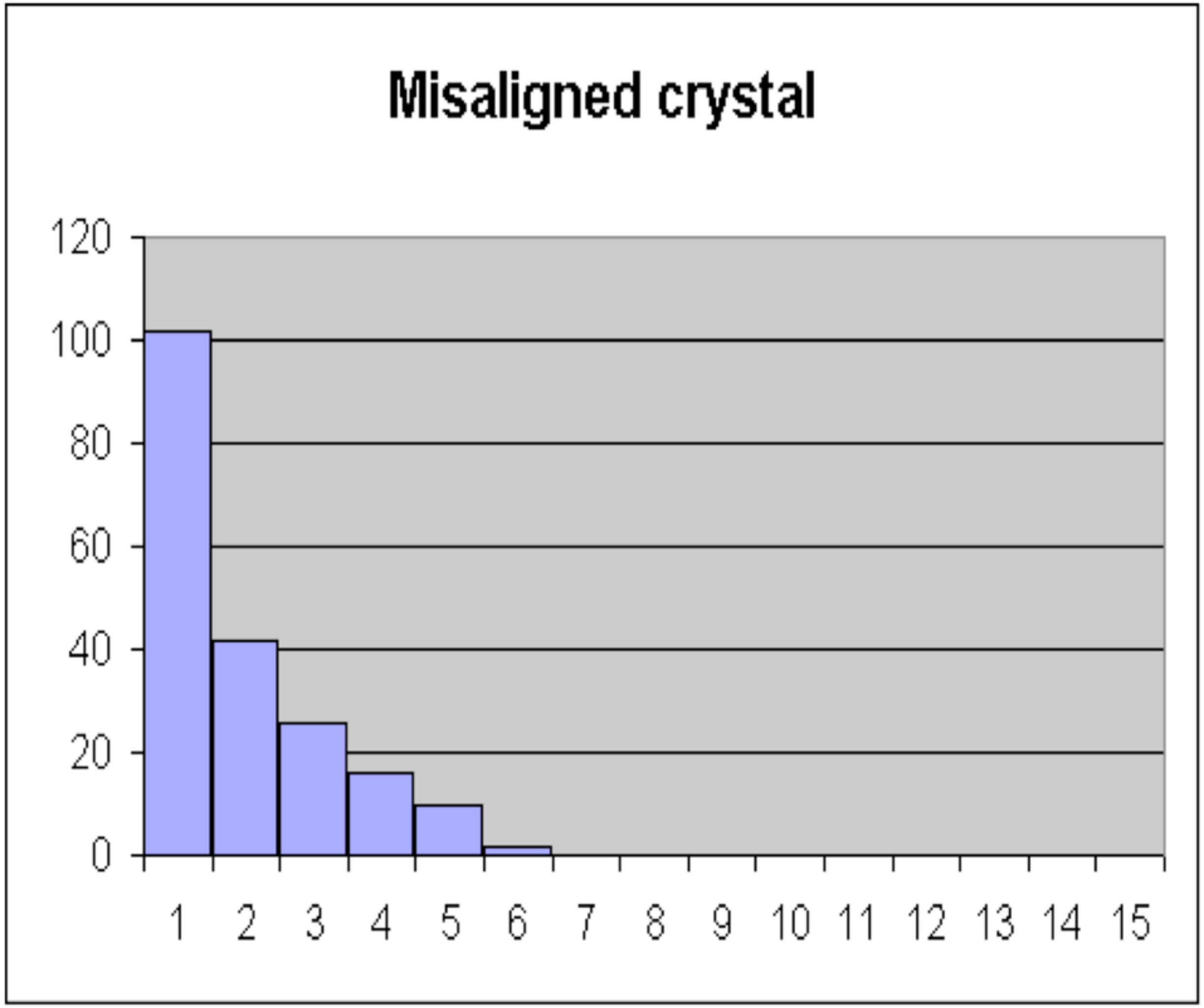
Use a bent crystal to channel halo away from the beam core, intercept with a scraper downstream. Number of secondary collimators can be greatly reduced.

Beam profiles measured at collimator face
(70 GeV, IHEP) illustrate the physics:
first case without crystal



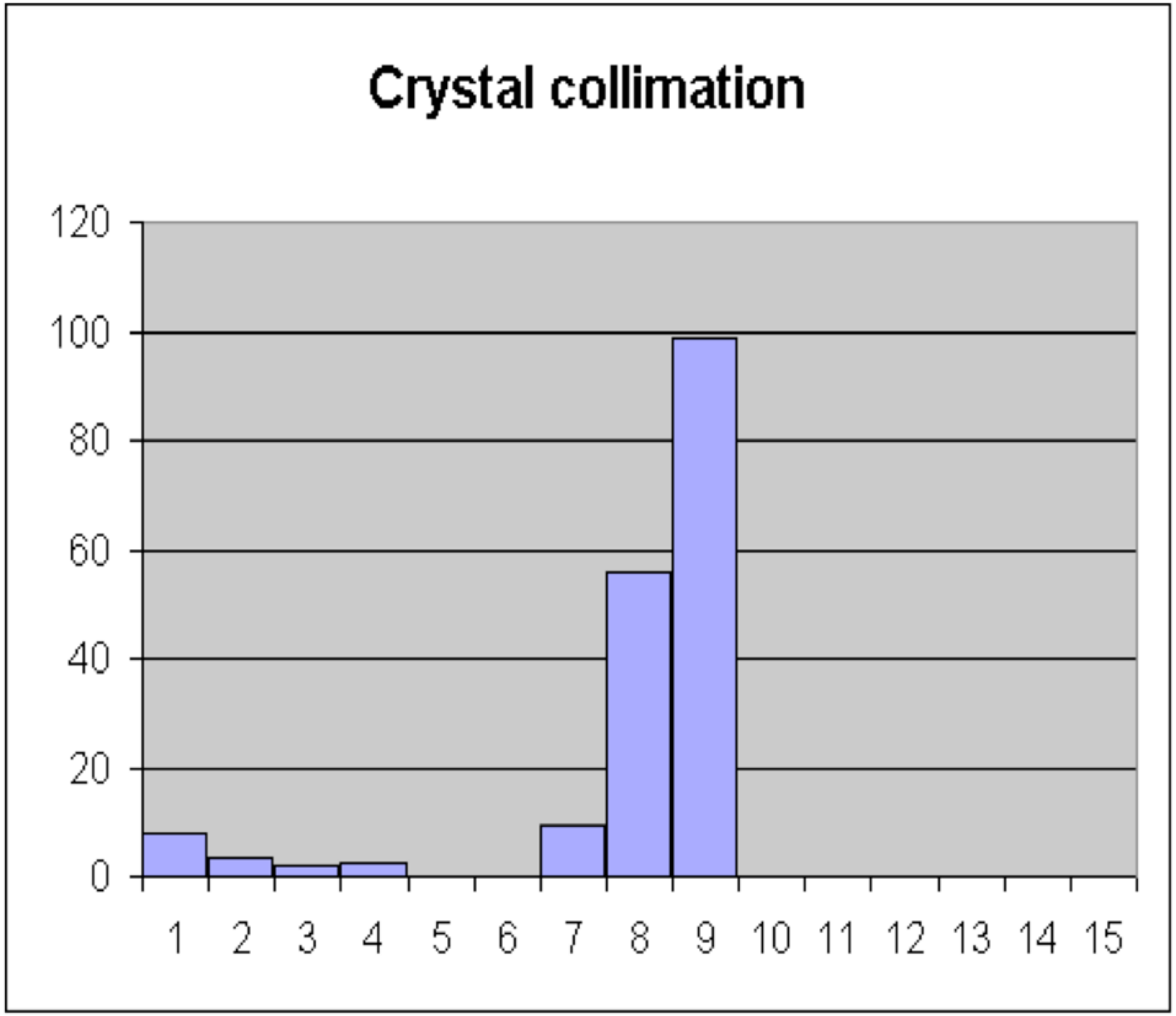
Radial coordinate

Now crystal installed, but misaligned



Radial coordinate

Crystal aligned → **Crystal collimation**



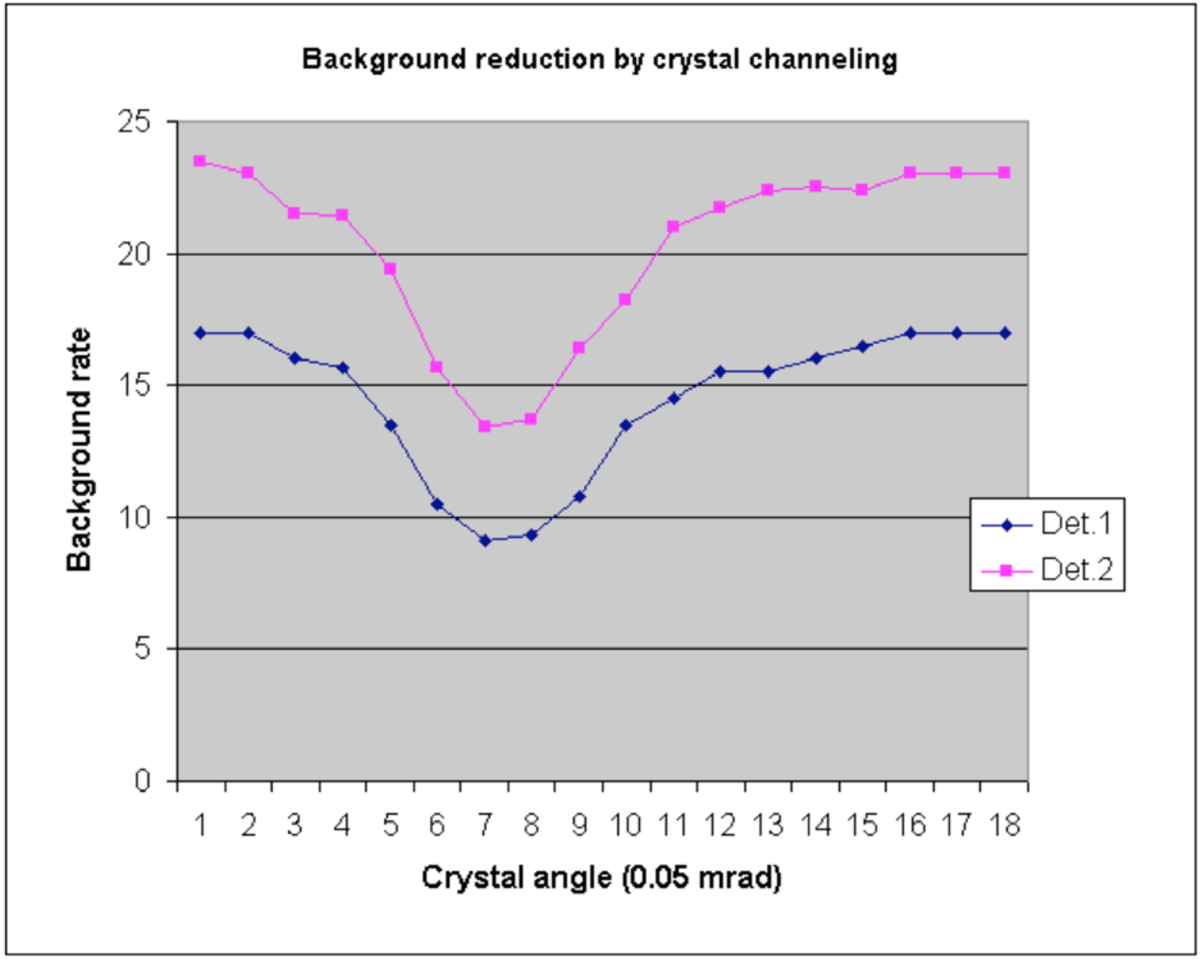
Radial coordinate

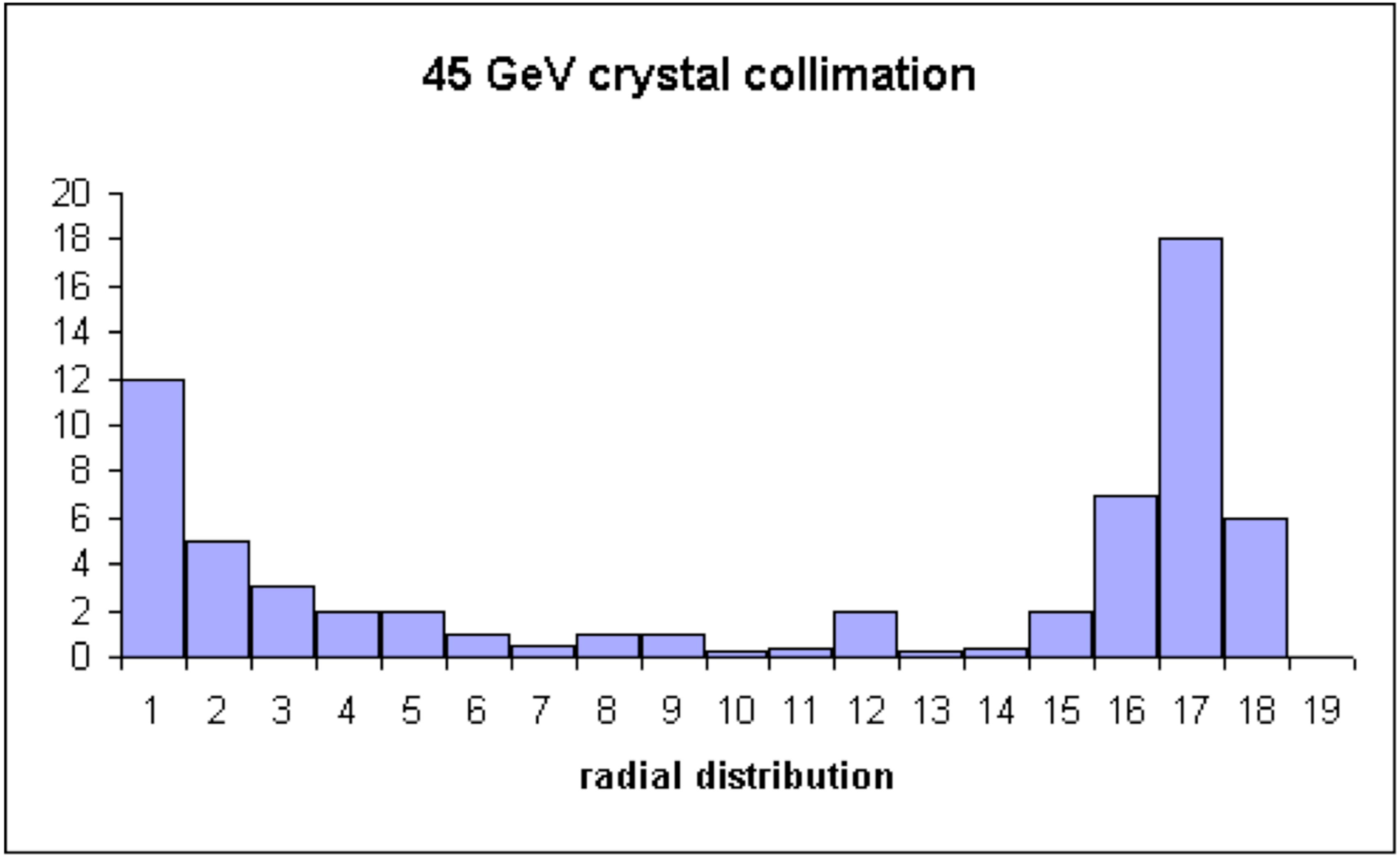
World first demonstration of crystal collimation: IHEP (1998)

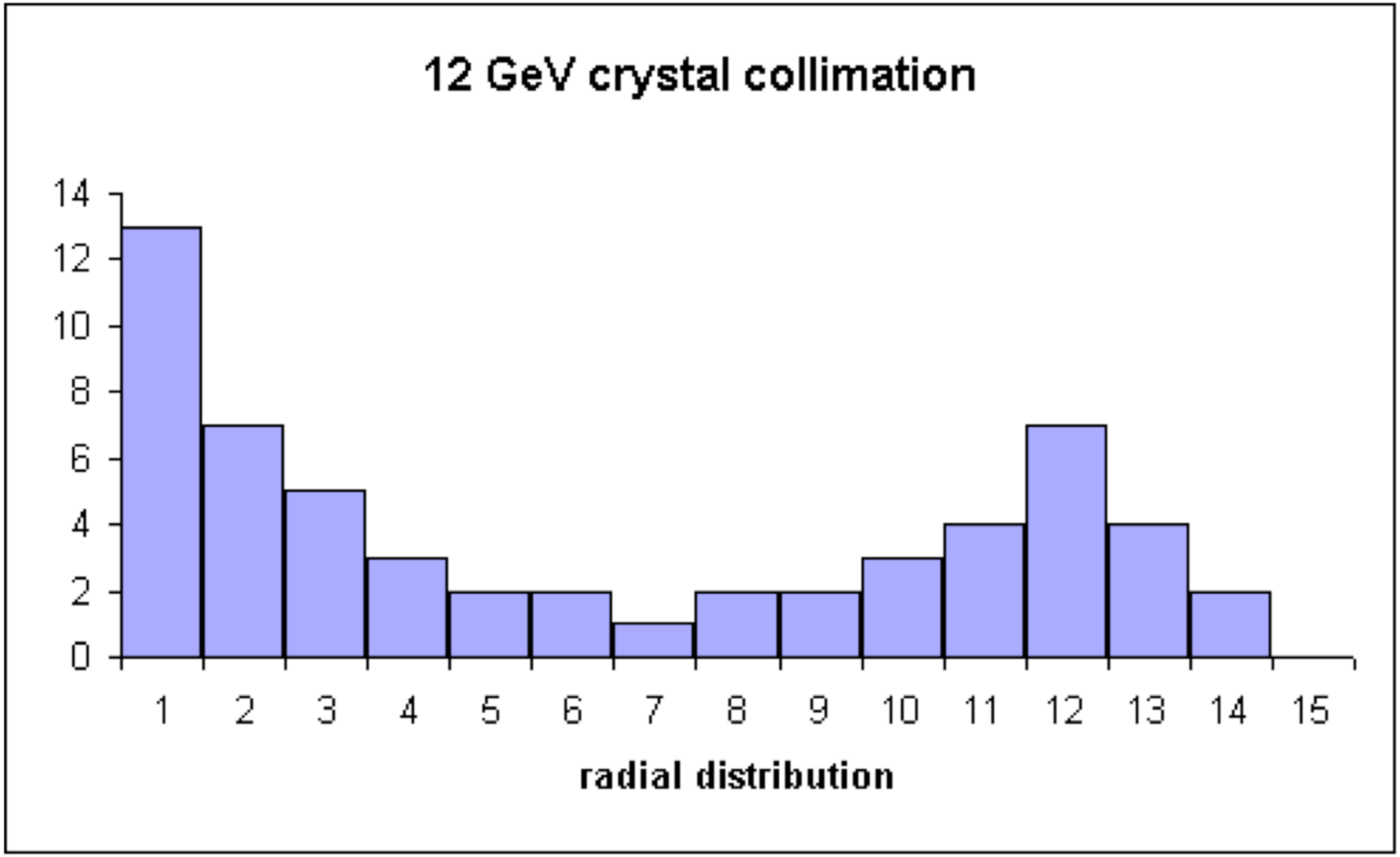
Background measured downstream of the scraper (detectors 1,2) vs crystal angle:

<u>**Factor of 2 gained**</u>

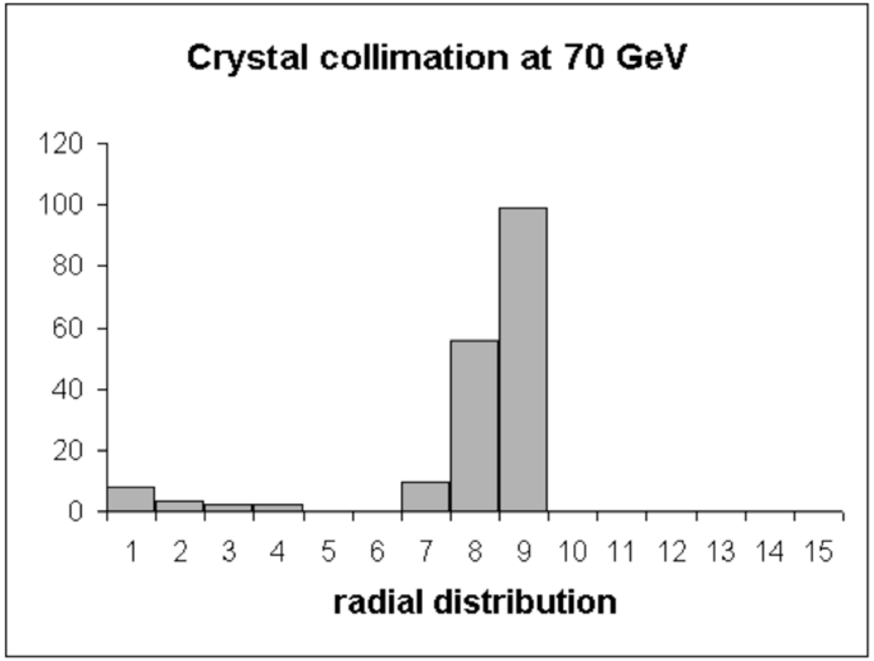
<u>due to channeling with 50% effy</u>

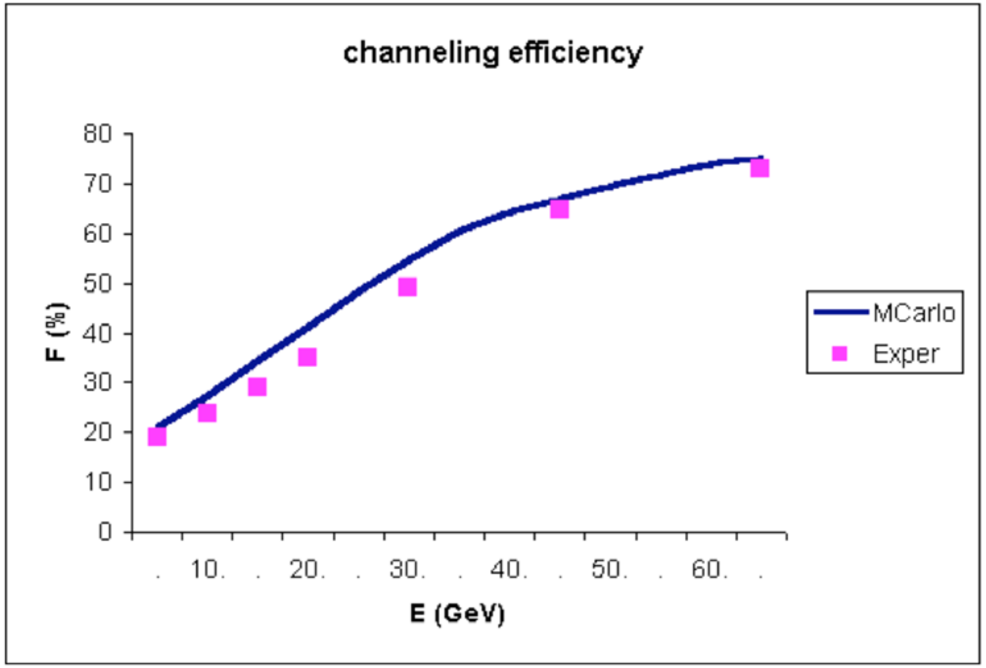


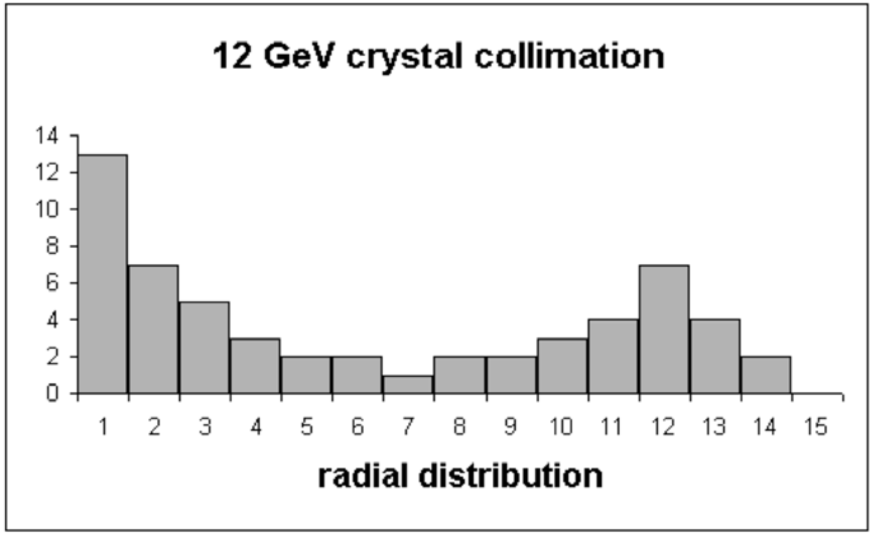

45 GeV crystal collimation
20
18
16
14
12
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
radial distribution

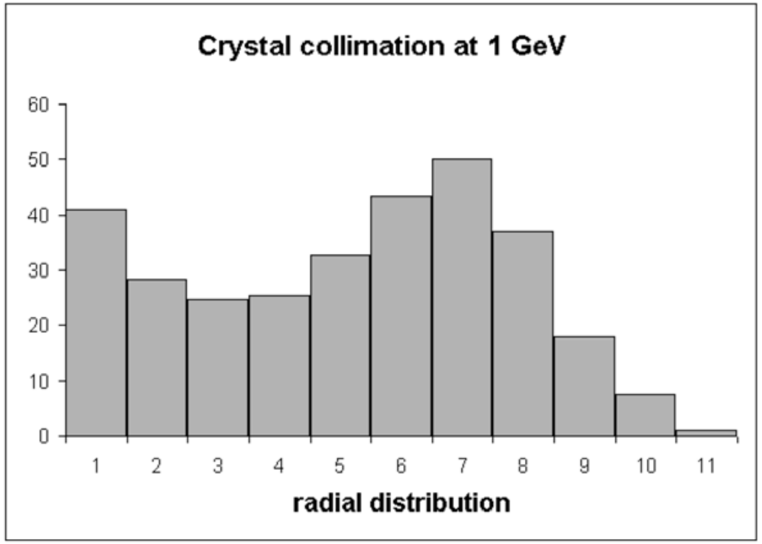

12 GeV crystal collimation
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
radial distribution

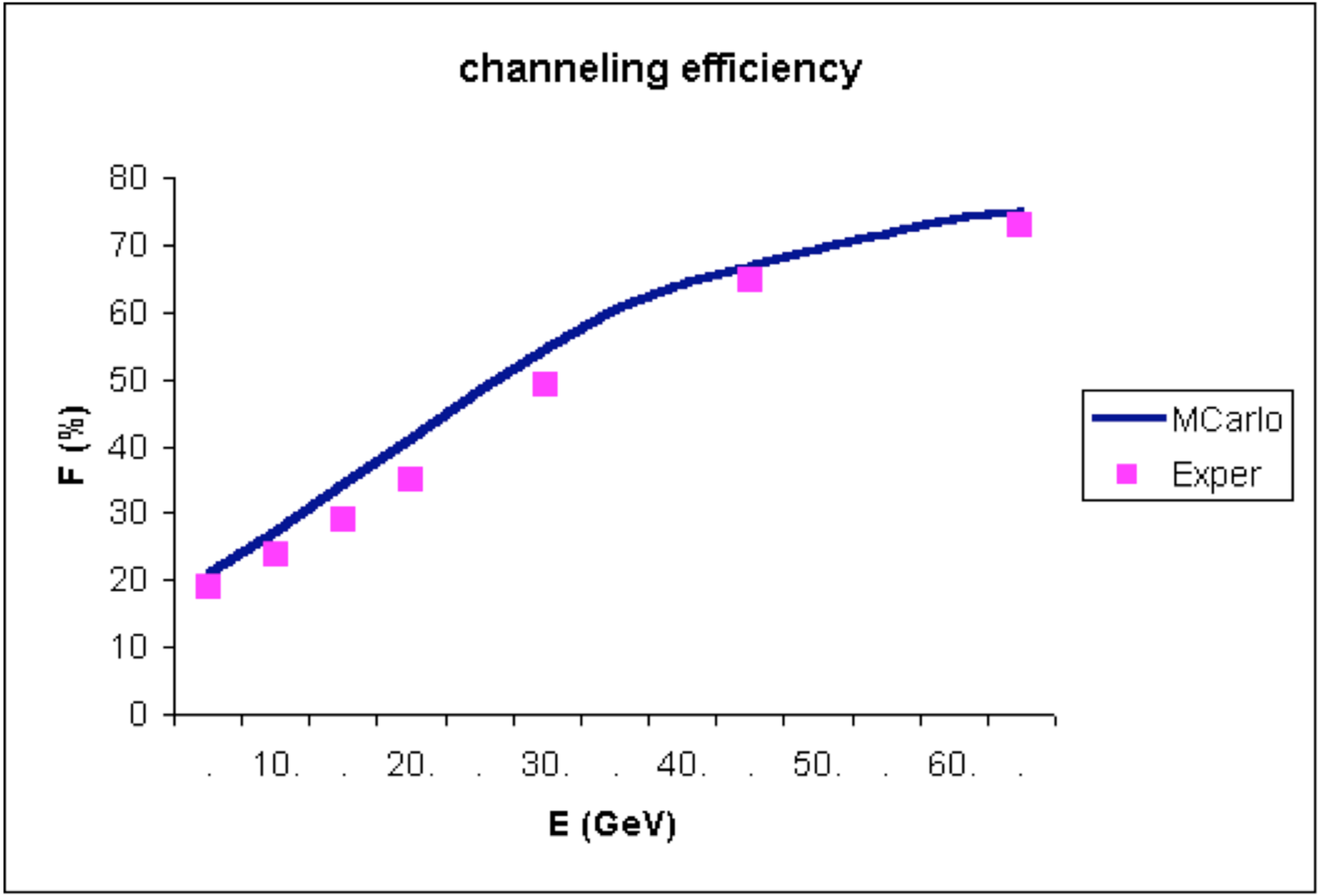
IHEP: crystal collimation studied over full energy range 1 to 70 GeV





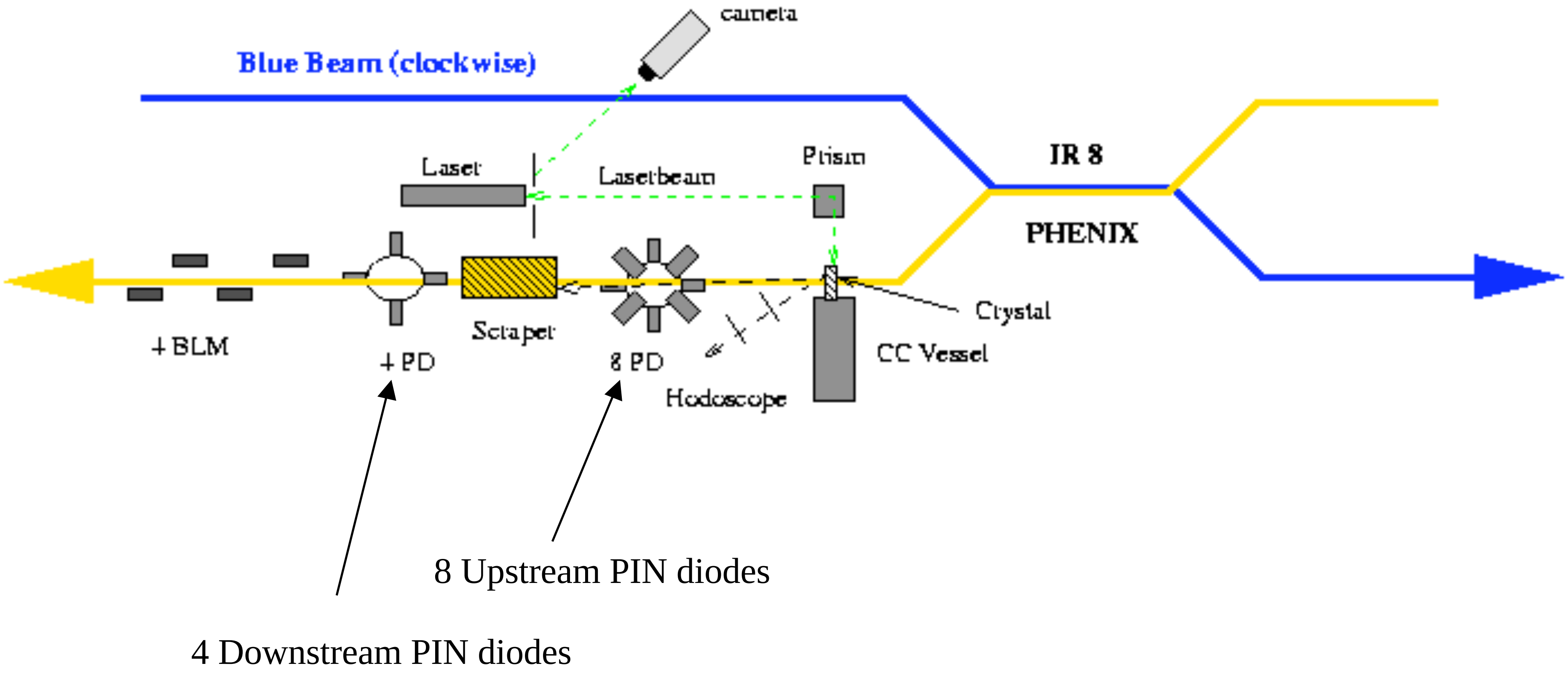






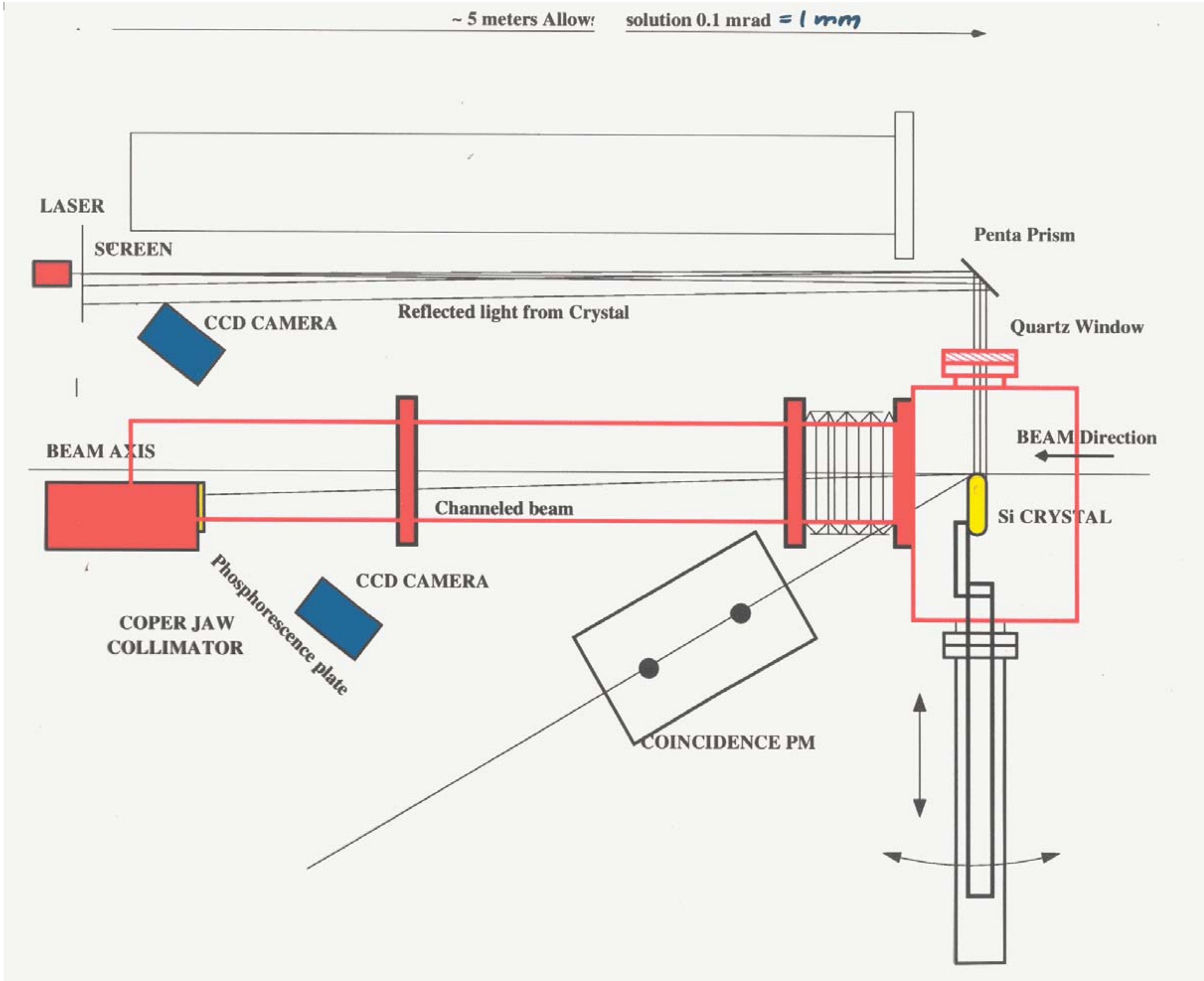
channeling efficiency
80
70
60
50
40
30
20
10
0
F (%)
. 10. . 20. . 30. . 40. . 50. . 60. .
E (GeV)
MCarlo
Exper

RHIC Crystal Collimator Setup used for Au ions and protons (250 GeV)



Data fill focus on upstream PIN diodes

Layout of RHIC experiment on crystal collimation



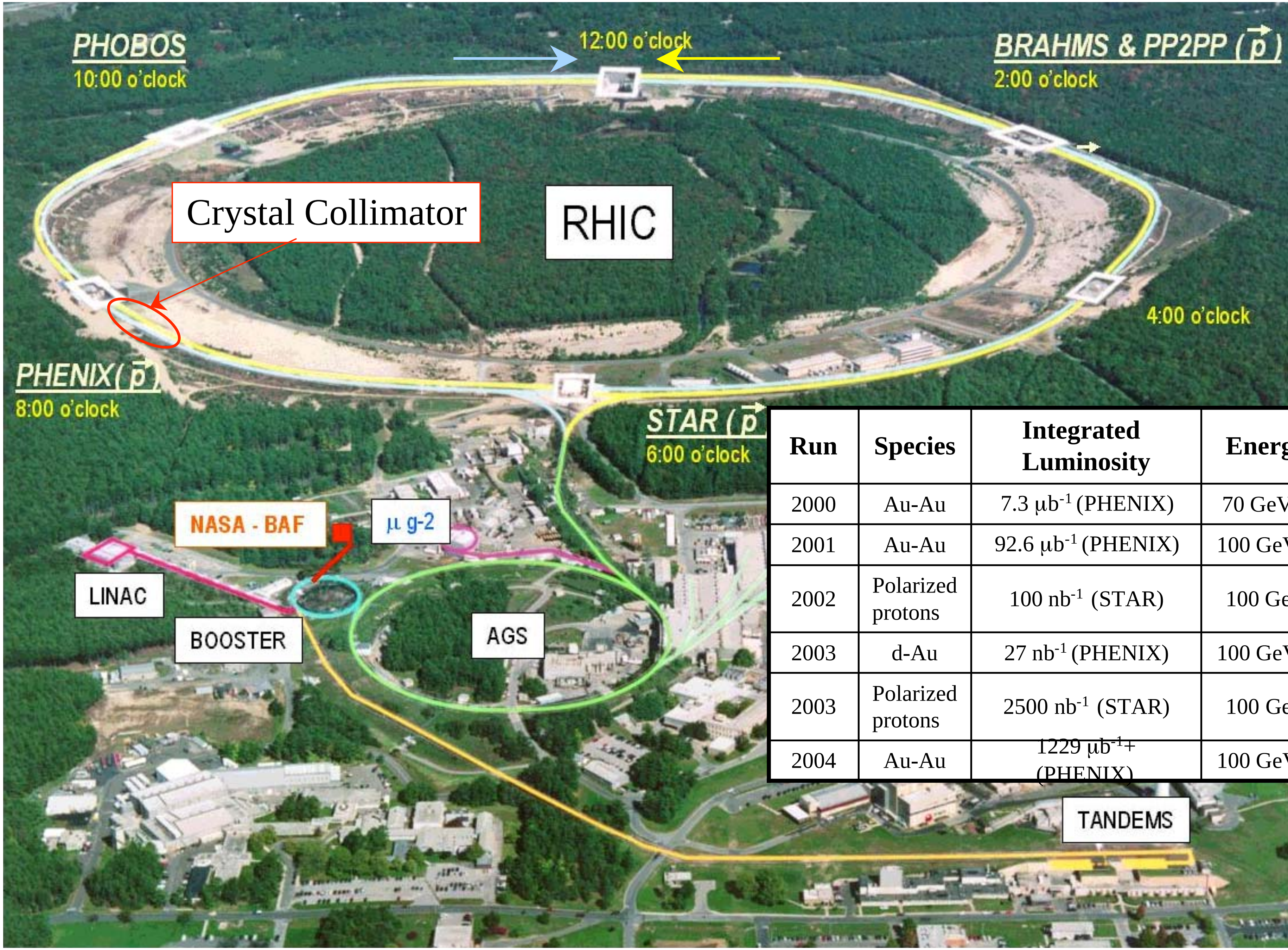
Collaborators

BNL

- Angelika Drees
- Dave Gassner
- Lee Hammons
- Gary McIntyre
- Steve Peggs
- Dejan Trbojevic

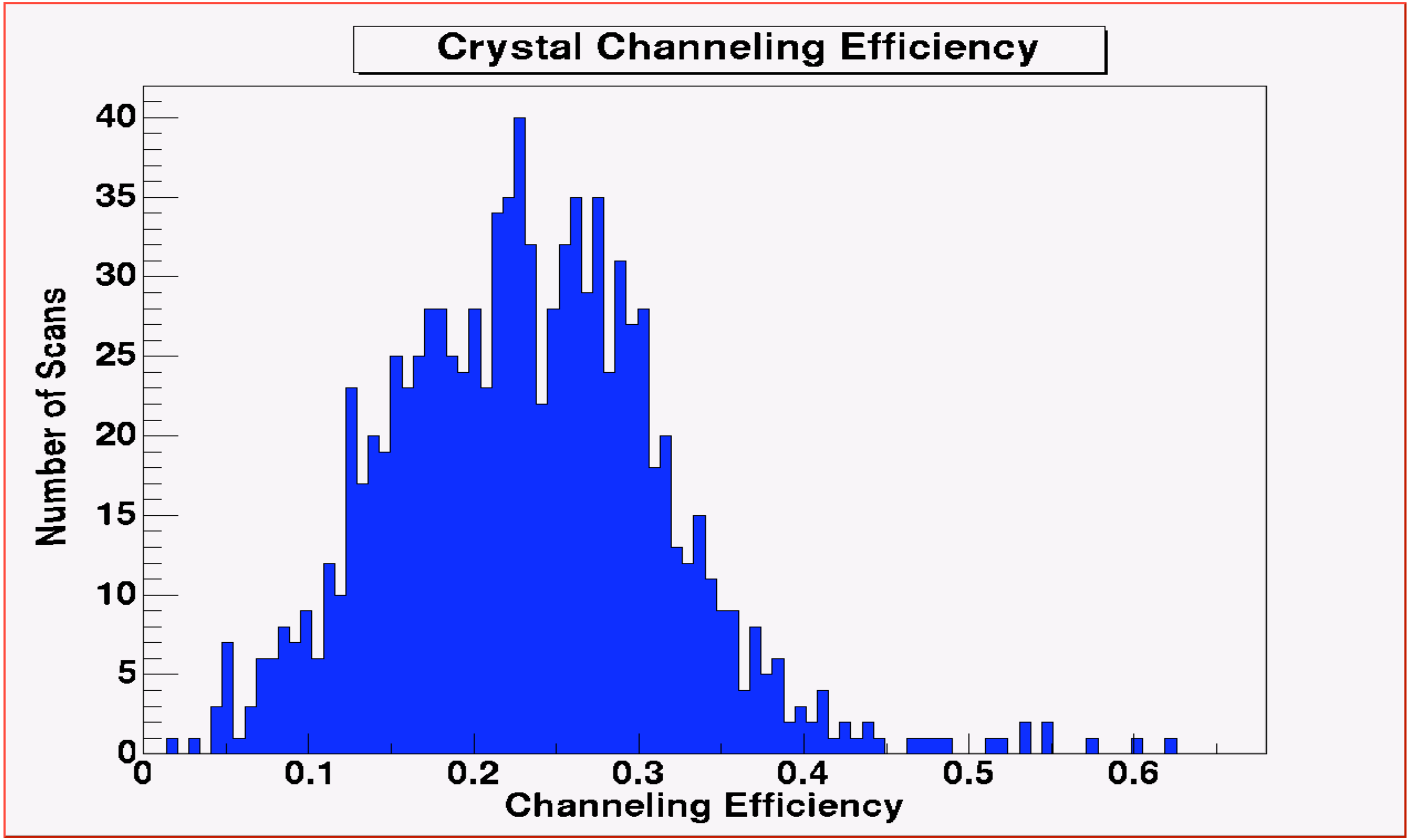
IHEP – Protvino

- Valery Biryukov
- Yuriy Chesnokov
- Viktor Terekhov



Run	Species	Integrated Luminosity	Energy
2000	Au-Au	7.3 μb^{-1} (PHENIX)	70 GeV/u
2001	Au-Au	92.6 μb^{-1} (PHENIX)	100 GeV/u
2002	Polarized protons	100 nb^{-1} (STAR)	100 GeV
2003	d-Au	27 nb^{-1} (PHENIX)	100 GeV/u
2003	Polarized protons	2500 nb^{-1} (STAR)	100 GeV
2004	Au-Au	1229 μb^{-1}+ (PHENIX)	100 GeV/u

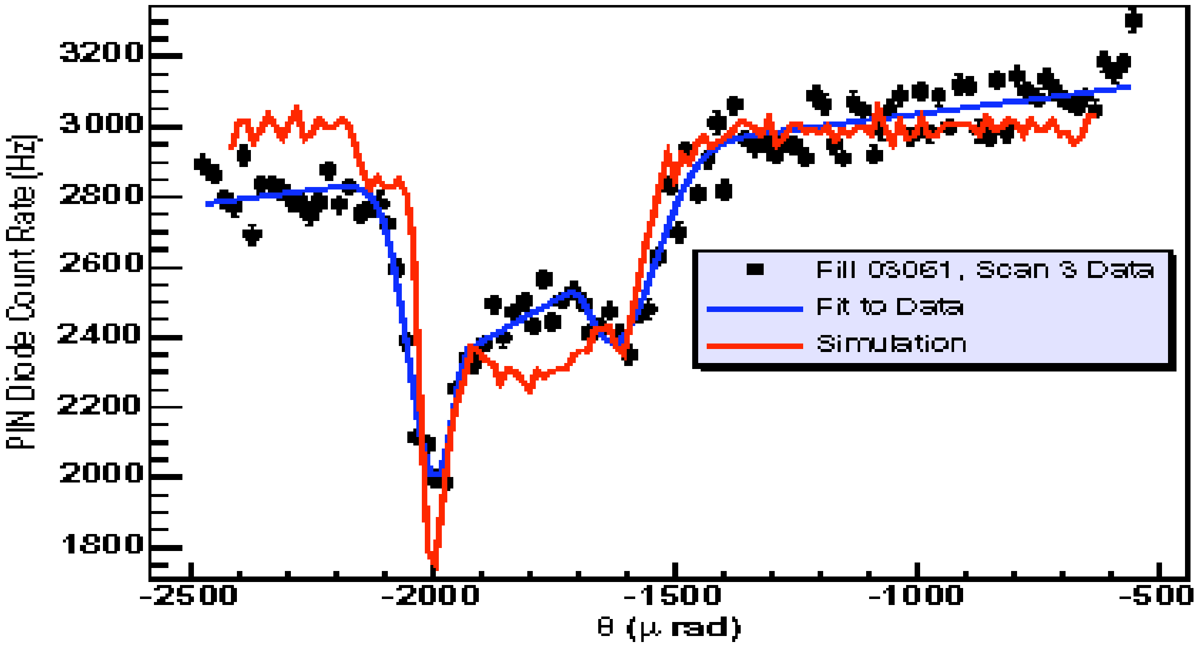
RHIC measurements, EPAC 2002



CRYSTAL COLLIMATION AT RHIC *

R. P. Fliller III†, A.Drees, D.Gassner, L. Hammons, G. McIntyre, S. Peggs, D. Trbojevic,
BNL, Upton, NY, 11793, V. Biryukov, Y. Chesnokov, V. Terekhov, IHEP, Protvino, Moscow Region

Average over 2003 RHIC run measured crystal effy 26%, theory predicted 32% for Au ions.
[PAC 2003 Proceedings]



The same crystal gave 42% effy for protons at IHEP.
[Phys.Lett.B **435** (1998) 240]

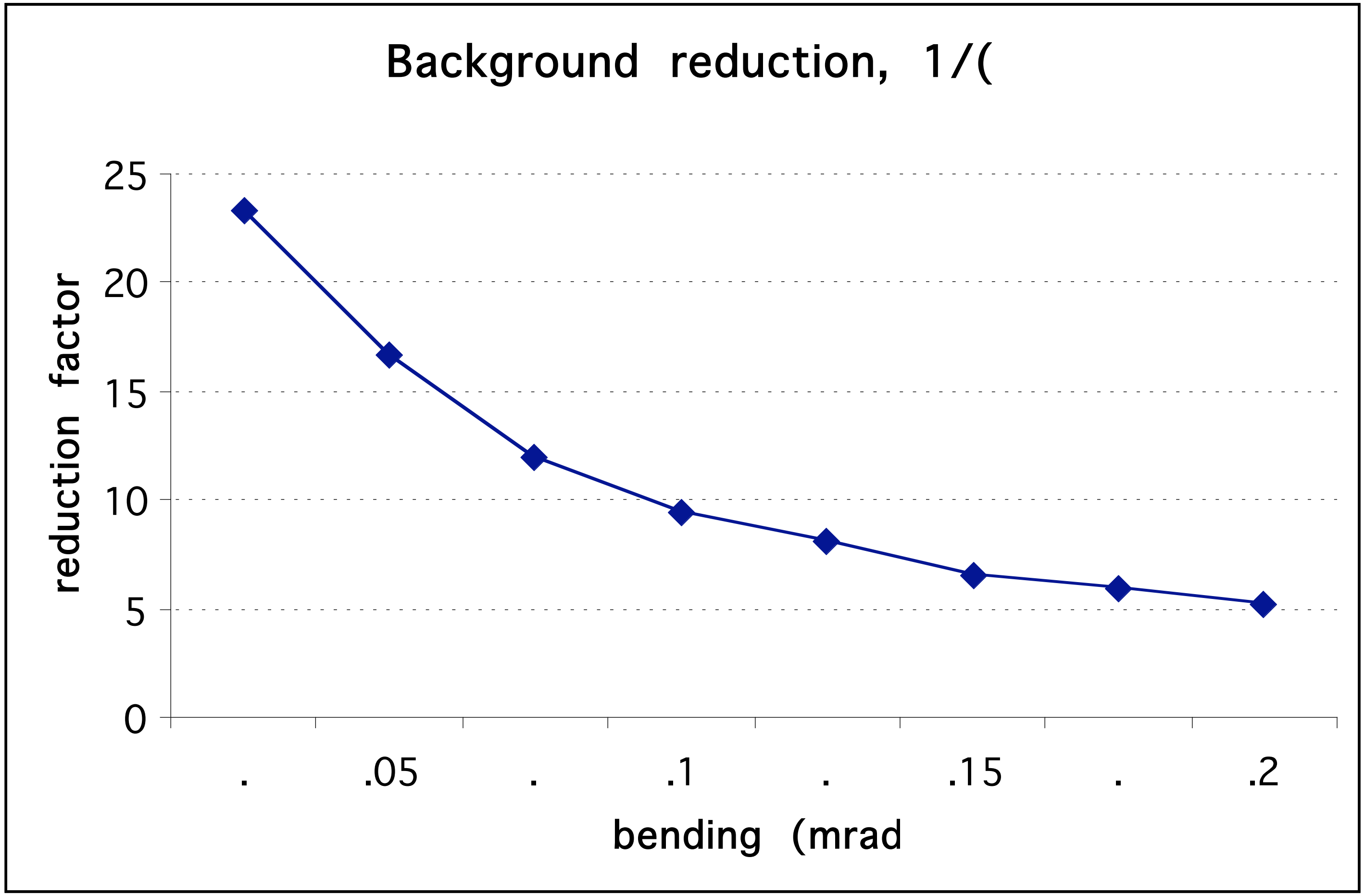
CERN SPS measured effy 4 to 11% for Pb ions.
[PRL **79** (1997) 4182]

world first crystal collimation for heavy ions, top efficiency

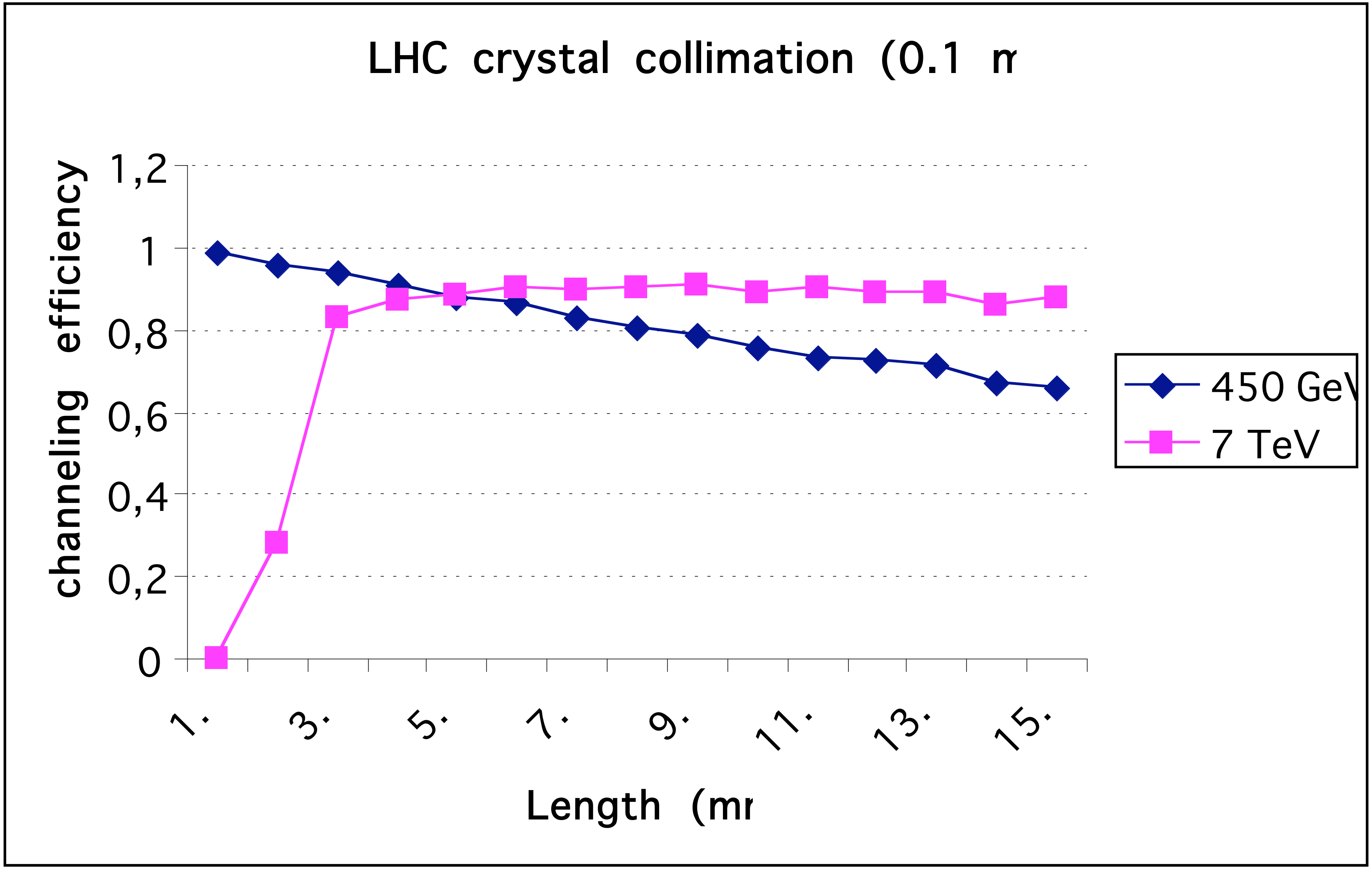
We are running CERN-INTAS project

“Crystal technique for Halo Cleaning in the LHC”

Here’s LHC background reduction factor expected from crystal use:



Efficiency simulation with crystal bending of 0.1 mrad:
5 mm Si crystal is enough at 7 TeV



2006:
we start new SPS experiment with bent channeling crystals - test bench for the LHC

Collaboration CERN-INFN-IHEP-JINR-PNPI

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

ON POSSIBLE USE OF BENT CRYSTAL TO IMPROVE TEVATRON BEAM SCRAPING *

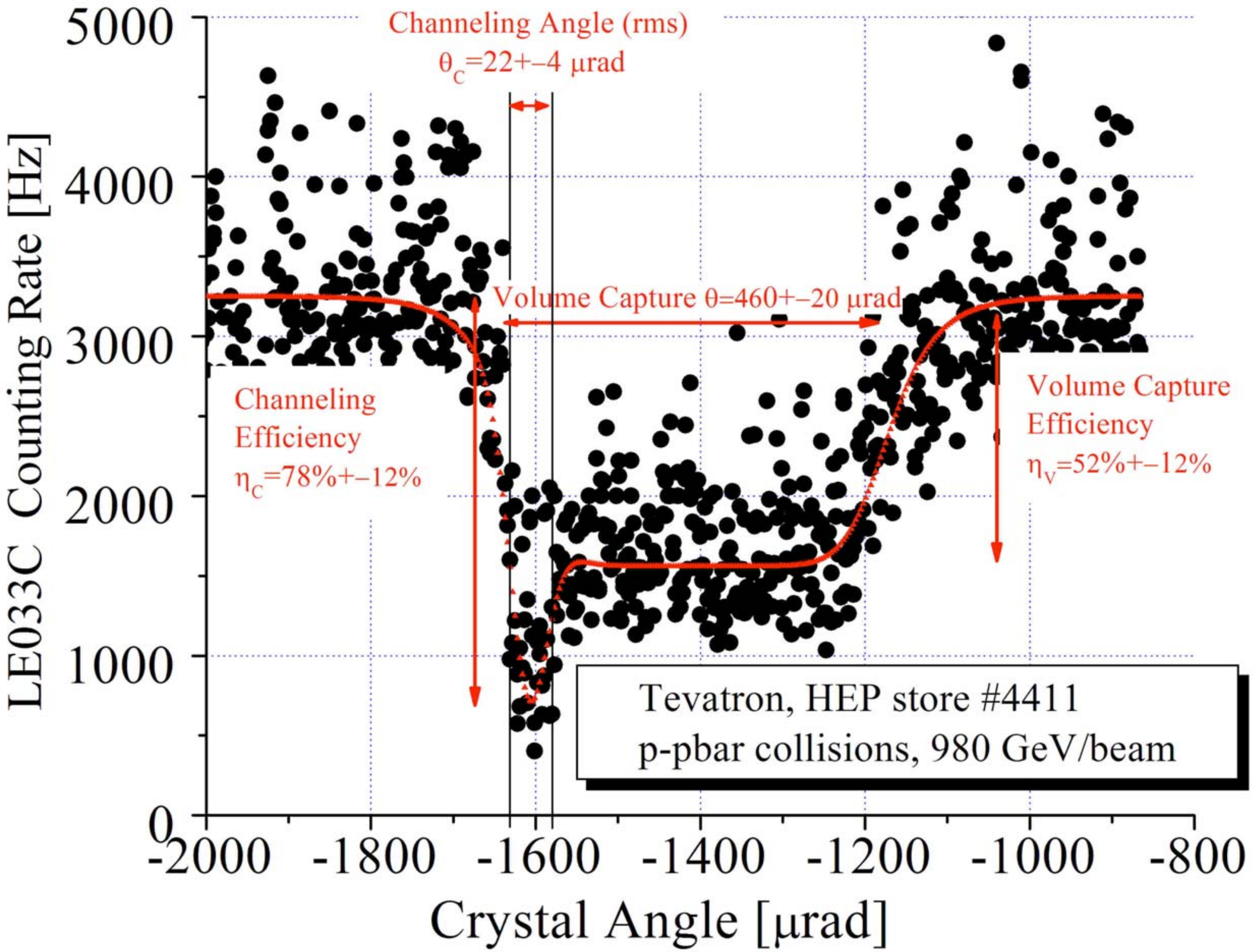
V. M. Biryukov†, Institute for High Energy Physics, Protvino, Russia
A. I. Drozhdin, N. V. Mokhov, FNAL, Batavia, IL

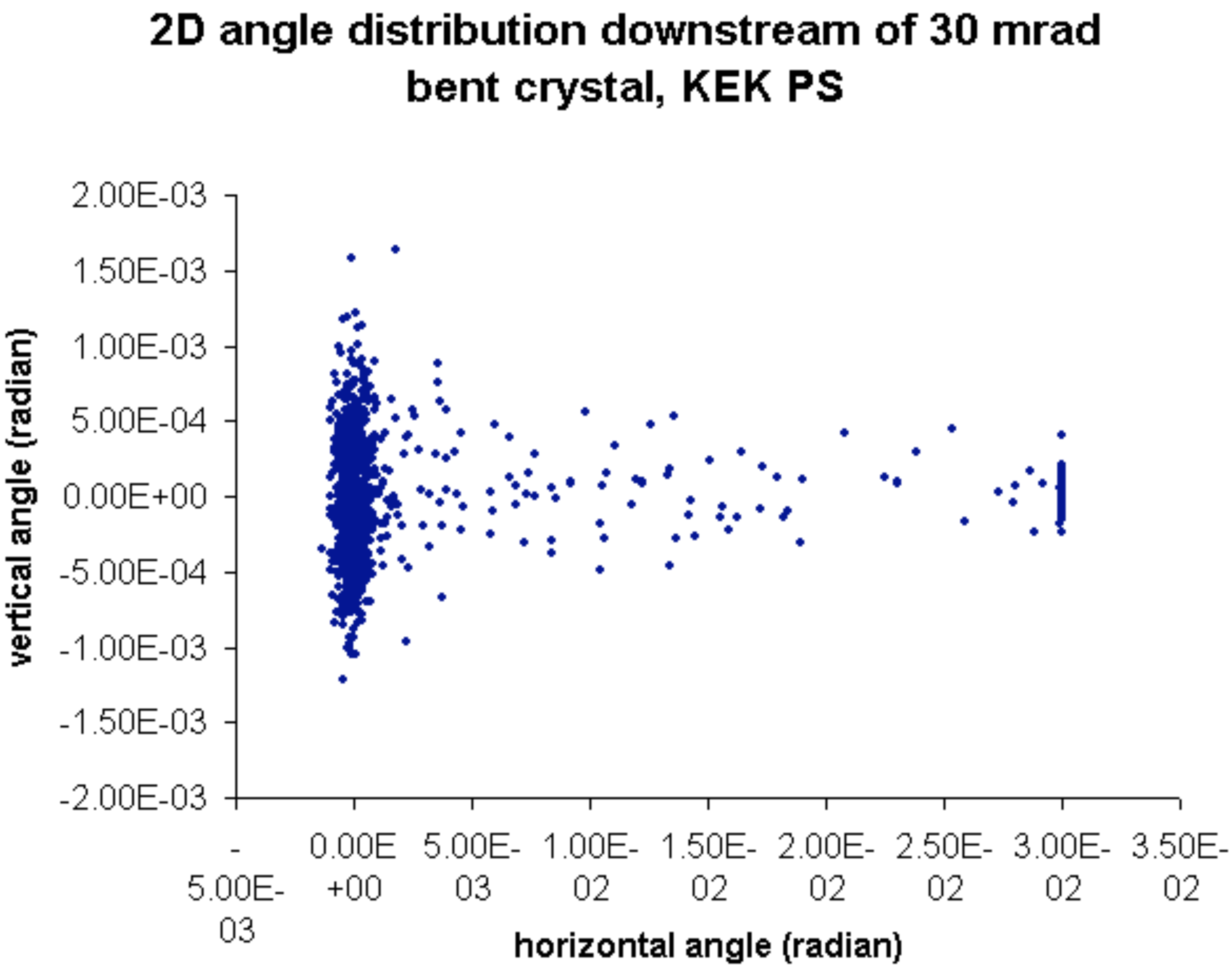
Table 1: Halo hit rates at the DØ and CDF Roman pots and nuclear interaction rates N in target and crystal (in $10^4 p/s$)

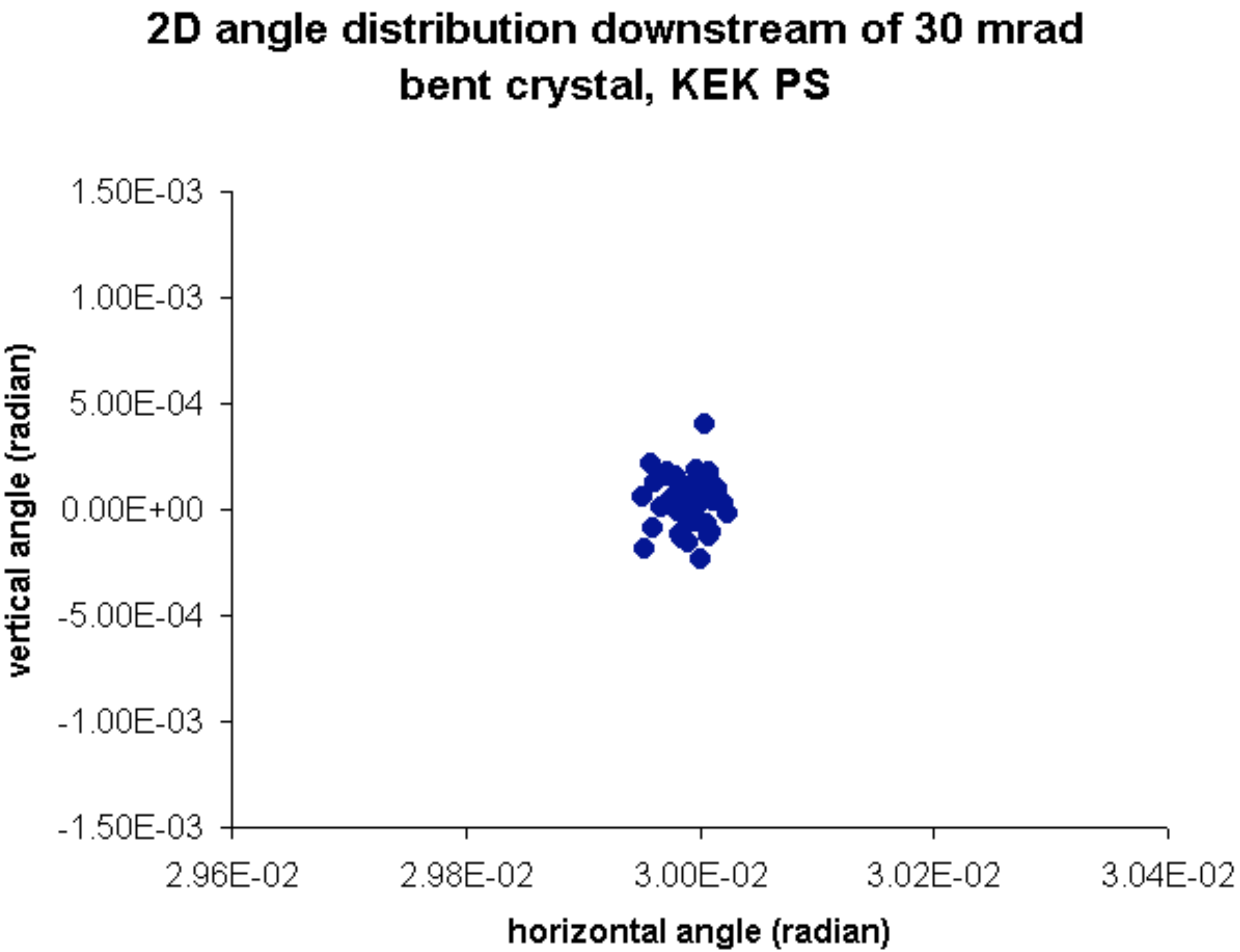
	with target	with crystal		
		amorphous layer thickness		
		$10\ \mu m$	$5\ \mu m$	$2\ \mu m$
DØ	11.5	1.35	1.60	1.15
CDF	43.6	5.40	3.20	3.43
N	270	82.4	70.6	50.3

Crystal reduces background in D0 and CDF by a factor of 10 (simulation). Experiment started in 2005 at Tevatron.

Experiment: 1 TeV Channeling, October 5, 2005




2D angle distribution downstream of 30 mrad bent crystal, KEK PS
vertical angle (radian)
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
-5.00E-04
-1.00E-03
-1.50E-03
-2.00E-03
-5.00E-03
0.00E+00
5.00E-03
1.00E-02
1.50E-02
2.00E-02
2.50E-02
3.00E-02
3.50E-02
horizontal angle (radian)


2D angle distribution downstream of 30 mrad bent crystal, KEK PS
1.50E-03
1.00E-03
5.00E-04
0.00E+00
-5.00E-04
-1.00E-03
-1.50E-03
vertical angle (radian)
2.96E-02
2.98E-02
3.00E-02
3.02E-02
3.04E-02
horizontal angle (radian)

Conclusion

Crystals can be **very efficient** in accelerators. The efficiency figure of ~80-90% is already experimentally demonstrated at IHEP, seen at Tevatron and confirmed by simulations.
If used for collimation, this will make accelerator 10 times cleaner.
Monte Carlo **model successfully predicts** the crystal work in the circulating beam, as shown in crystal experiments at CERN SPS, IHEP, Tevatron and RHIC at up to 1 TeV.
Crystal **works efficiently at very high intensities** (~10^{12}) with a lifetime of many years.
Crystal **survives an instant dump of ~10^{14}** protons as seen experimentally at 70 GeV.
The same crystal **works efficiently over full energy range**, from injection through ramping up to top energy, as demonstrated experimentally at IHEP from 1 thru 70 GeV and as seen in simulations for the LHC.
Bent **crystals of low-Z and high-Z** material are available, e.g. diamond and germanium, and they demonstrate efficiency similar to that of silicon.
Even when a crystal is misaligned, nonchanneling, it still works as an amorphous scatterer so the collimation system returns to its traditional scheme. This **makes it safe**.

Conclusion from IHEP applications:

- IHEP Protvino 70 GeV accelerator is **largely crystallised** and became a **fabric of channeling!**
- **Five** physics **experiments** can be run **simultaneously**
- **Efficiency 85%** is routinely obtained for **10^{12} beam**
- **The same crystal** works efficiently **at 1 thru 70 GeV**
- No problems with high intensity or lifetime.
- Many types of deflectors tested
- Work on bringing regular intensity to **10^{13}**
- Crystal extraction and collimation are **established beam instruments**