Crystal Channeling in Accelerators

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EPAC, Edinburgh 27 June 2006

Crystal lattice can trap and channel particle beams along major crystallographic directions.

In a bent crystal, the channelled particles

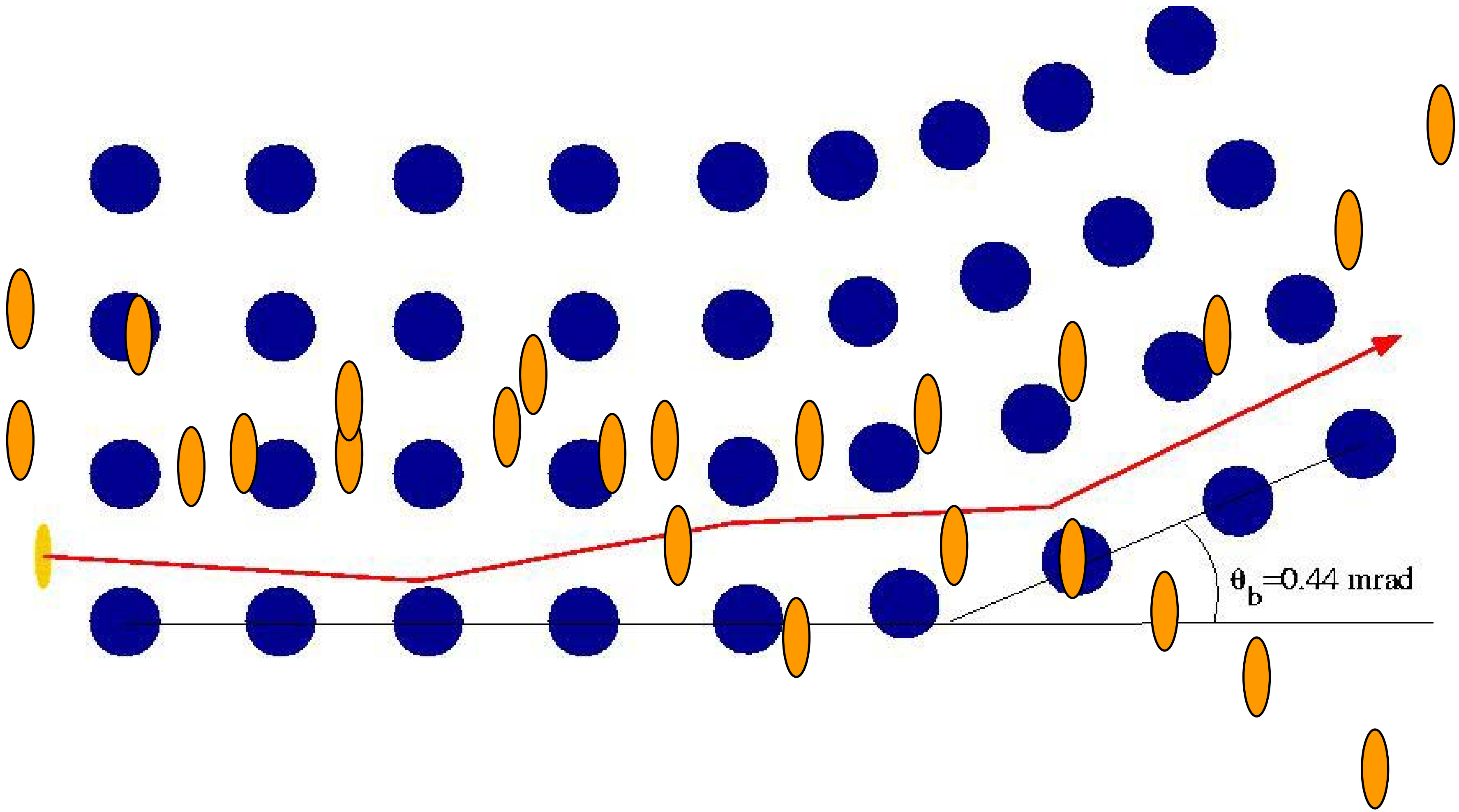
follow the bend !

This makes a basis for an elegant technique of beam steering by means of bent channelling crystals, experimentally demonstrated from 3 MeV to 1 TeV.

This technique was strongly developed in recent studies at CERN, FNAL, IHEP, and BNL, and can lead to interesting applications also at the LHC, such as crystal collimation making a collider cleaner by an order of magnitude.

Bent crystal channeling

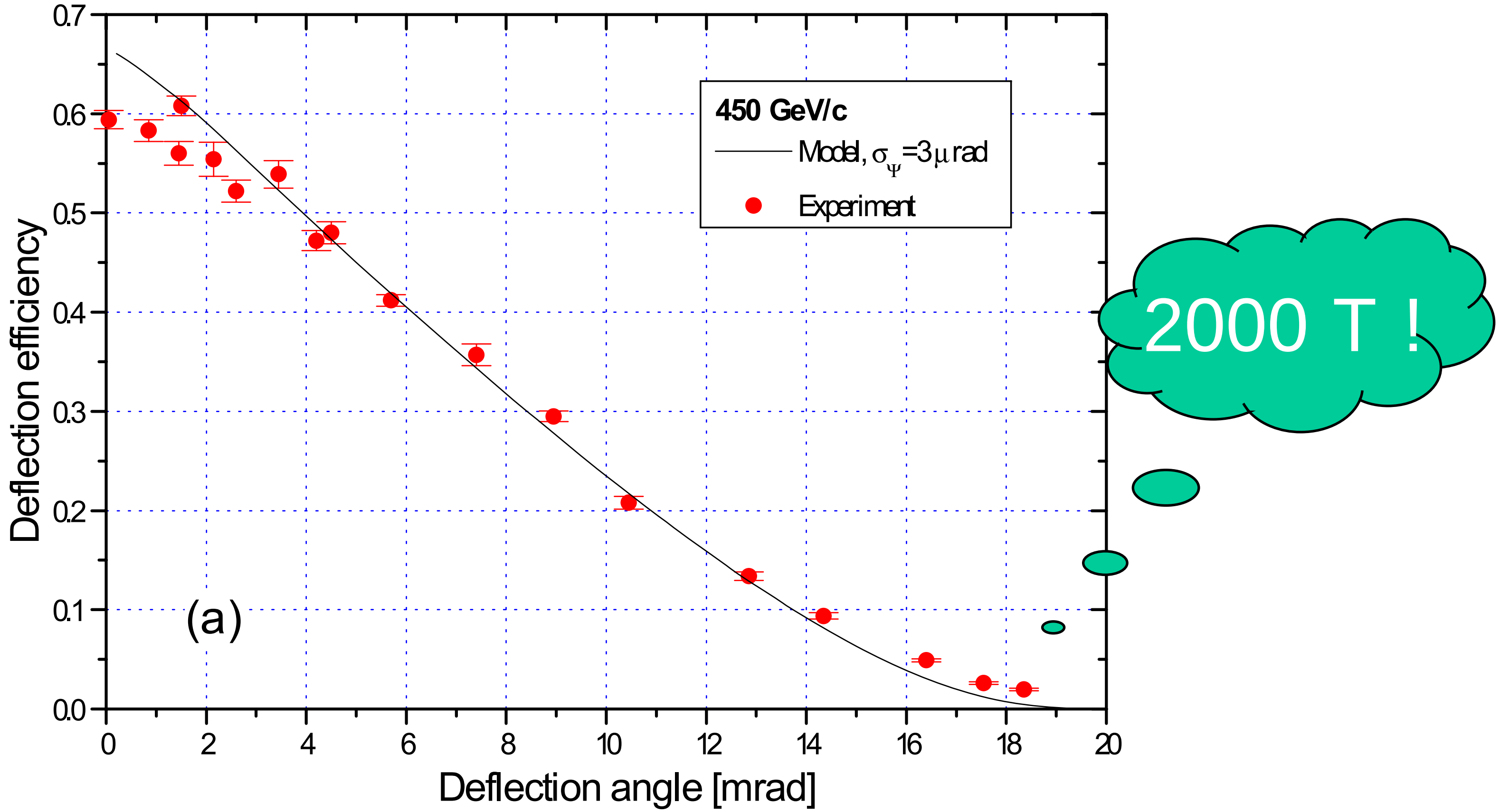
proposed by Tsyganov in 1976,
demonstrated in Dubna in 1979



In the 1990-s, CERN SPS studies made it real efficient

working with many crystal types & projectiles: p^+, π^+.., Pb^{82+}

Here's a nice example with Ge (110), 450 GeV protons:



Radiation Damage

One of Si crystals in CERN SPS was irradiated to

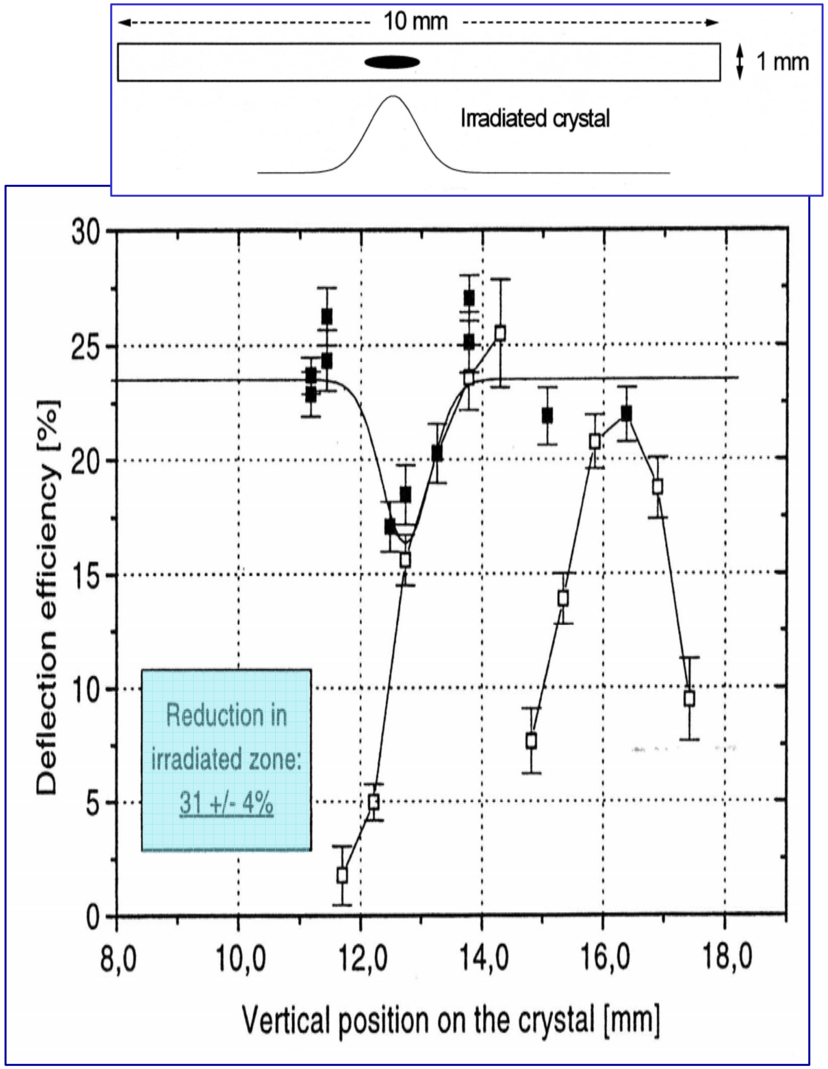
Total dose received :

2.4 10^{20} protons/cm^2

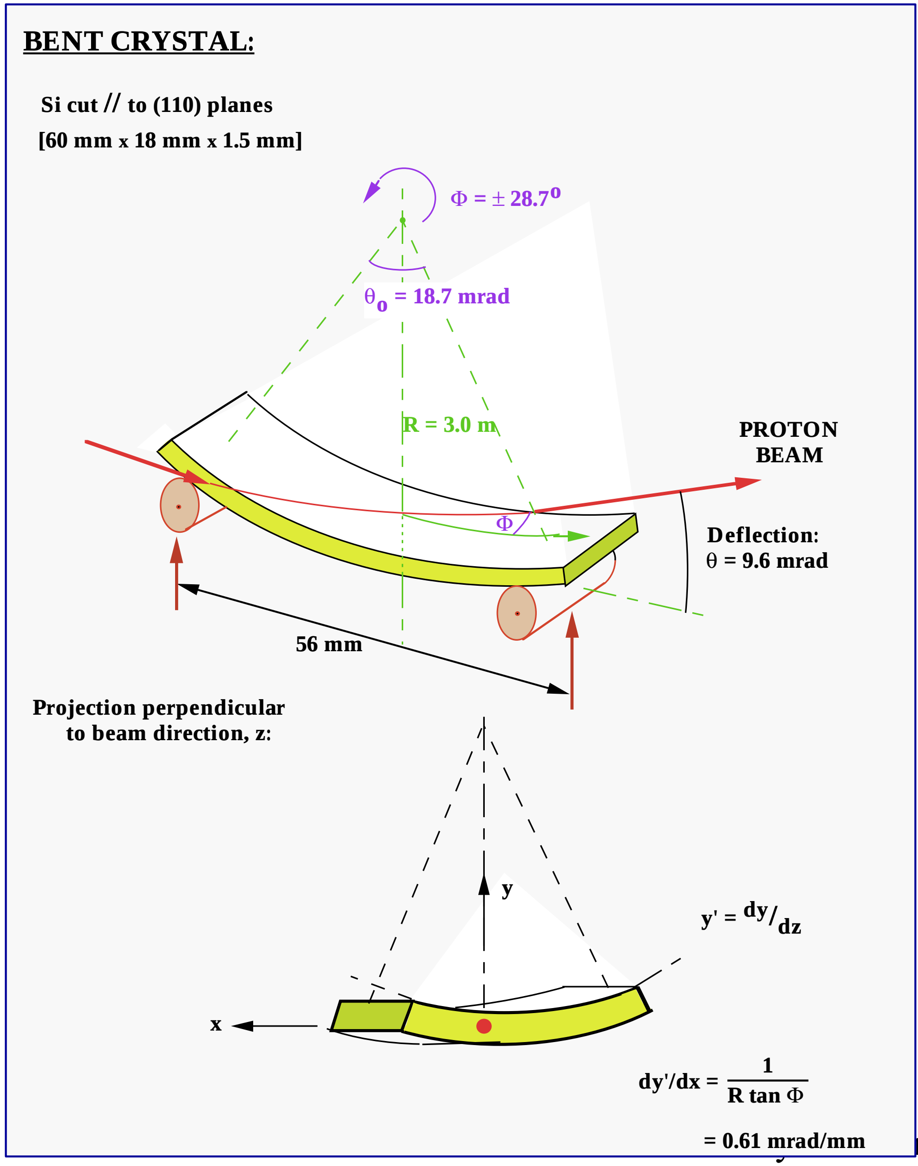
The reduction in deflection efficiency was :

6% / 10^{20} p/cm^2

This means that NA48 could run up to 100 years in the intense proton beam before the crystal needs replacement.



NA48 bent crystal application: two simultaneous Kaon beams, K_L and K_S, as collinear as possible. Beam intensity (K_S) has to be reduced substantially

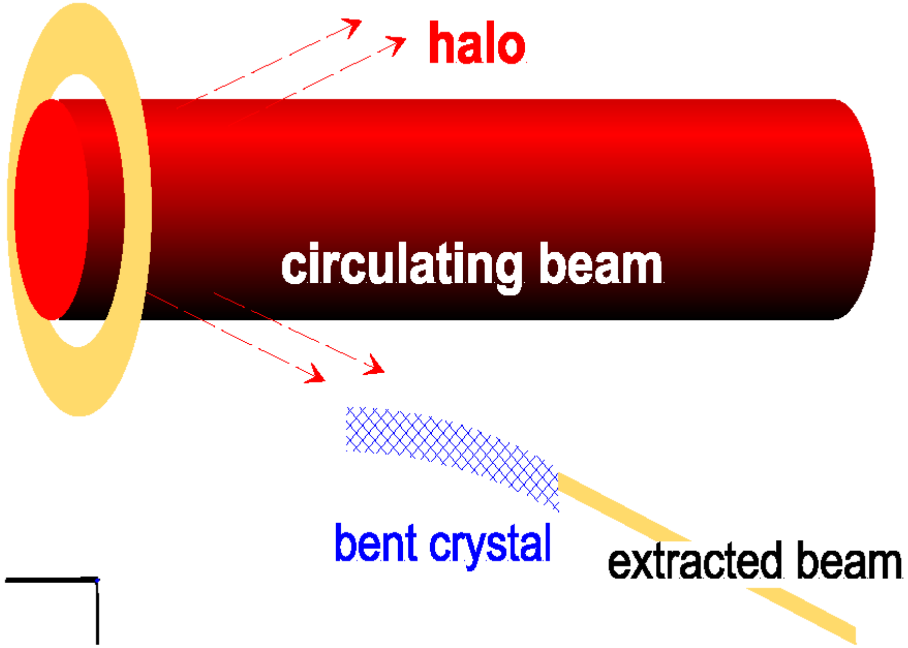


Advantages of using the crystal:

- Deflects cleanly the proton beam in a very short length (equivalent to 14.4 TM)
- Upstream muon sweeping action is not affected
- Splits the desired beam fraction (about 5 10^{-5})
- Garanties a sharply defined emittance of the outgoing beam in both hor. and vert. Planes.

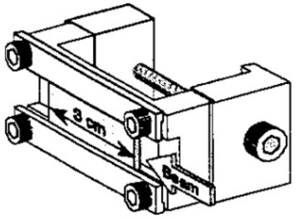
Crystal applied to beam extraction (& collimation)

Major studies - RD22 (CERN) & E853 (FNAL) - started in ~1990
motivated then by possibility of parasitic extracted beam for B-physics



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

RD 22: extraction of 120 GeV protons (SPS: 1990-93)



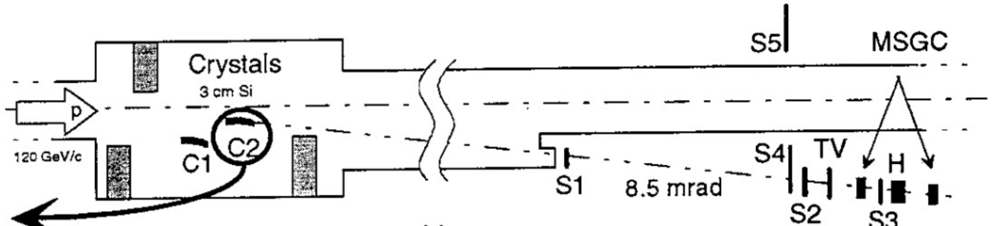
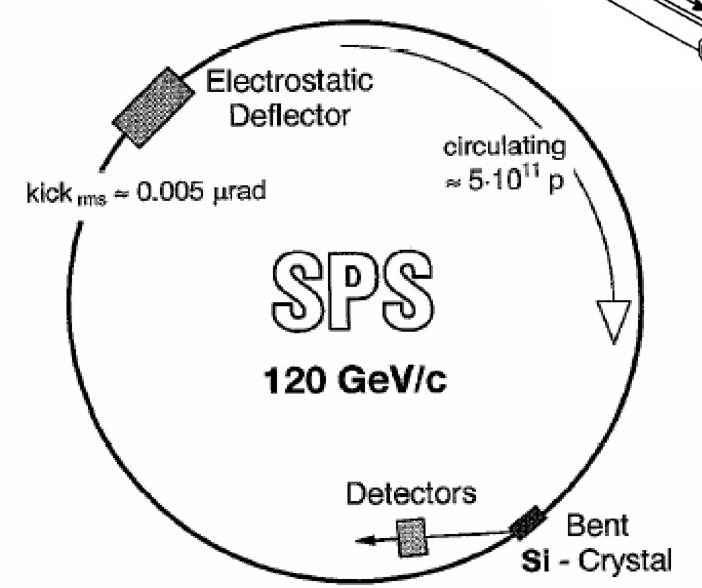


Figure 1: Experimental layout

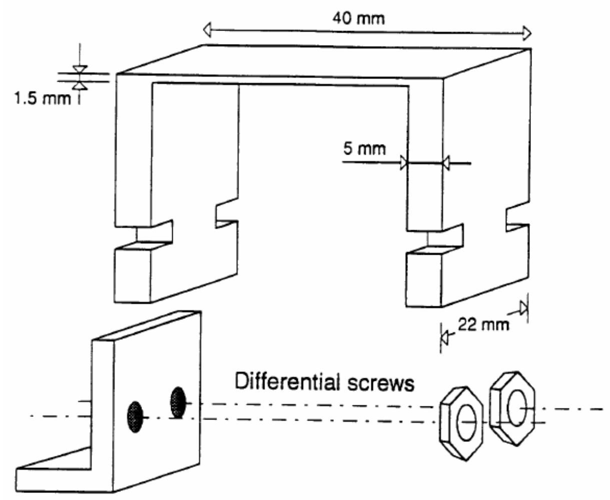


The RD22 Collaboration, CERN DRDC 94-11

	Crystal 1	Crystal 2
beam intensity (protons)	$(7.0 \pm 0.1) \cdot 10^{11}$	$(3.7 \pm 0.1) \cdot 10^{11}$
beam lifetime (hrs)	20 ± 2	12 ± 1
protons lost per second	$(6.7 \pm 0.6) \cdot 10^{6}$	$(8.9 \pm 0.7) \cdot 10^{6}$
protons detected per second	$5.6 \cdot 10^{5}$	$6.6 \cdot 10^{5}$
background (%)	5	2
detection efficiency (%)	78 ± 12	78 ± 12
extraction efficiency (%)	$\mathbf{10.2 \pm 1.7}$	$\mathbf{9.3 \pm 1.6}$

- Large channeling efficiency measured for the first time
- Consistent with simulation expectation extended to high energy beams
- Experimental proof of multi-turn effect (channeling after multi-traversals)
- Definition of a reliable procedure to measure the channeling efficiency

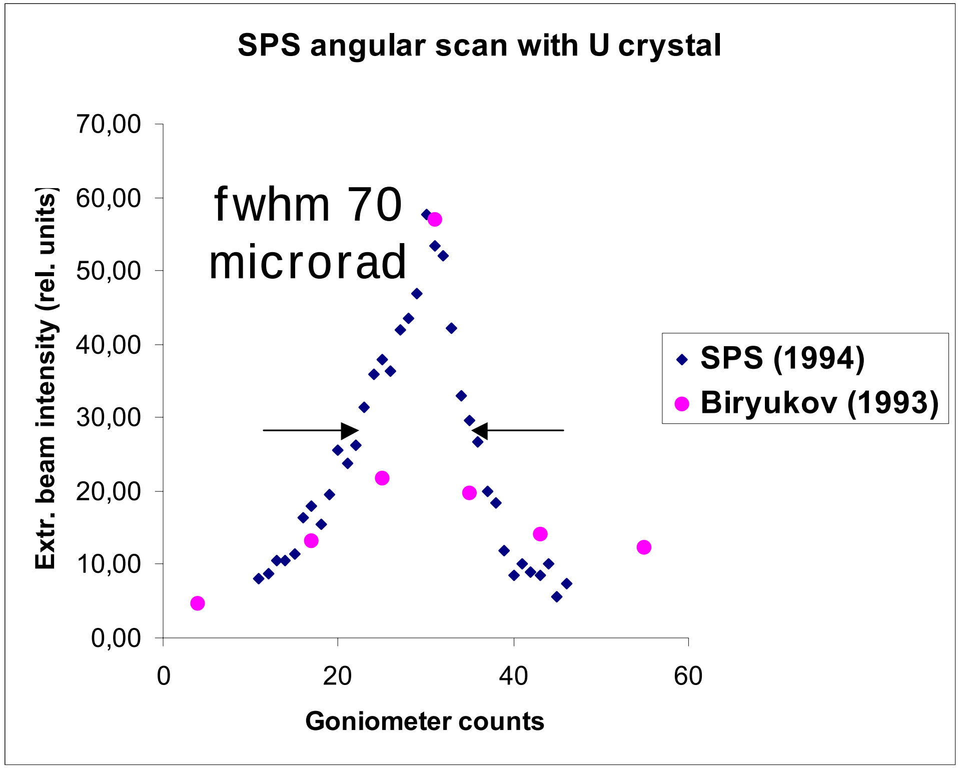
The "perfect" crystal



The U-shaped crystal

- ♦ More constant radius of curvature
- ♦ Less anticlastic curvature

Prediction [1] for the U-shaped crystal agreed with data [2]. Figure taken from ref. [3] :

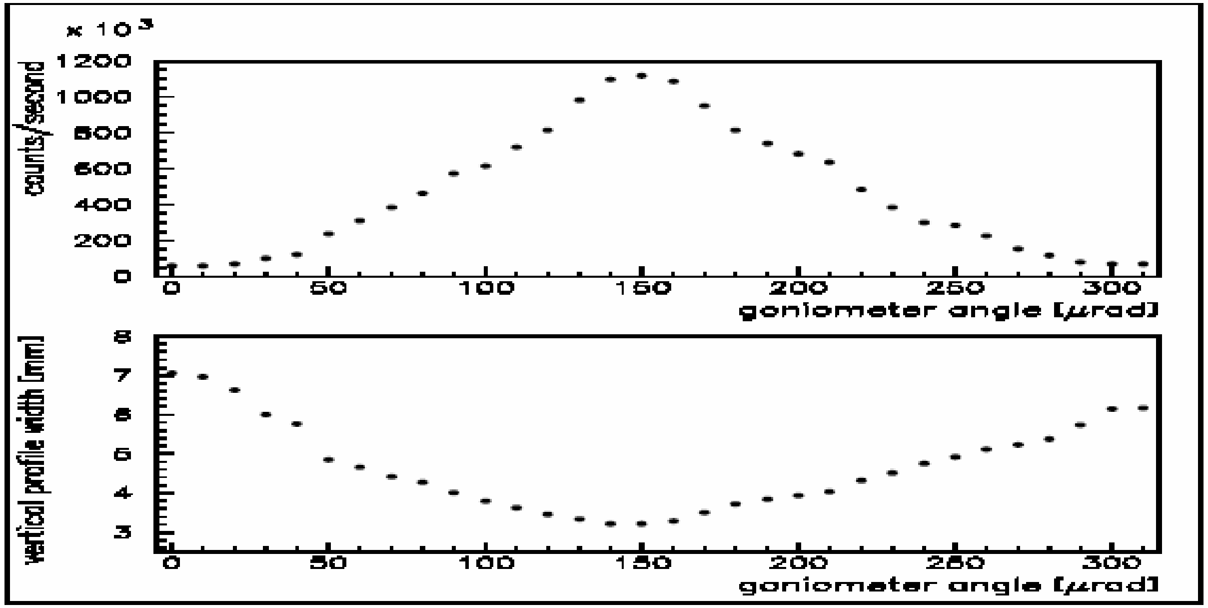


[1] V.Biryukov CERN SL/Note-78 (1993)
[2] CERN-DRDC-94-11
[3] F. Ferroni. NIM A351 (1994) 183

Extraction efficiency

The U-shaped crystals

intensity (10^{11} p)	lifetime (hours)	extracted rate (10^5 p/s)	background (%)	extr. efficiency (%)
4.9	44 ± 8	3.45 ± 0.06	3.2	10.6 ± 2.6
0.13	0.7 ± 0.1	7.88 ± 0.07	4.0	15.4 ± 2.2
0.07	0.9 ± 0.1	2.67 ± 0.04	3.2	12.4 ± 1.4
0.16	0.6 ± 0.1	9.48 ± 0.06	3.1	13.0 ± 2.2

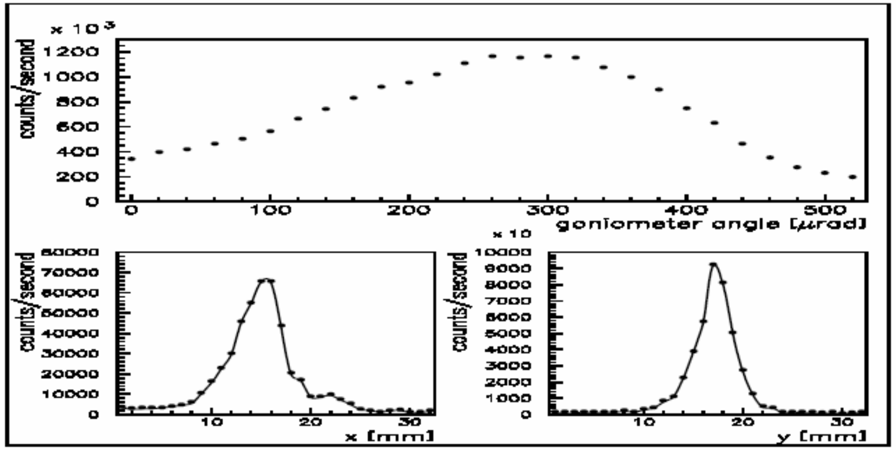


- Higher channeling efficiency measured
- Consistent with expectations (better surface cutting; no anticlastic curvature)
- Large angular response (multi-turn effect)

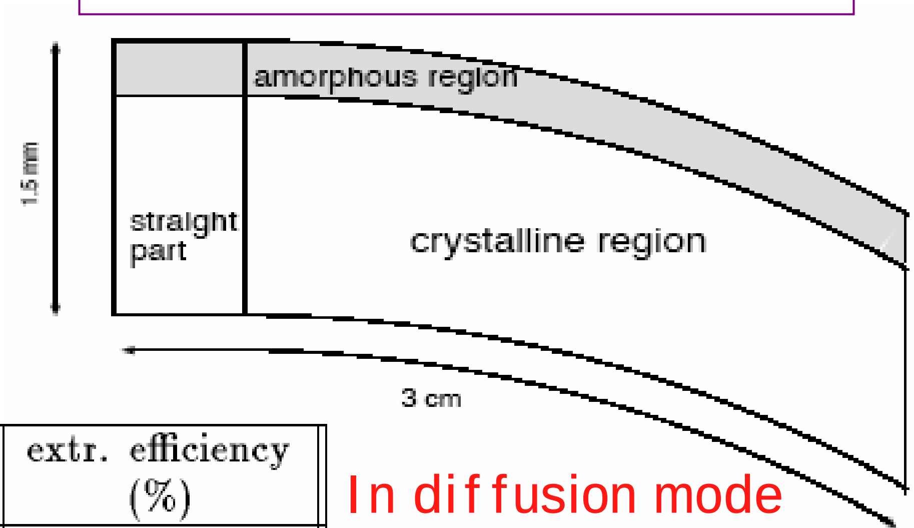
The RD22 Collaboration, CERN SL-95-088

Extraction efficiency

The crystal with 30 μm thick amorphous layer



The RD22 Collaboration, Phys. Lett. B 357 (1995) 671-677



intensity (10^{11} p)	lifetime (hours)	extracted rate (10^5 p/s)	background (%)	extr. efficiency (%)
5.9	33 ± 2	2.07 ± 0.02	13.9	3.6 ± 0.2
5.8	43 ± 10	1.54 ± 0.05	15.2	3.7 ± 0.8
4.4	28 ± 2	2.38 ± 0.03	13.0	4.8 ± 0.3
1.9	5.1 ± 0.2	8.78 ± 0.04	13.8	7.6 ± 0.3
0.6	1.8 ± 2	7.27 ± 0.05	13.3	7.4 ± 0.4

In diffusion mode

- Average impact parameter varying from 0.05 to 1 μm
- Maximum impact parameter varying from 0.5 to 10 μm
- *b* is much smaller that the size of the amorphous layer
- The only possible extraction mechanism should be driven by the multi-pass effect

The same crystal was tested in the SPS at 14, 120, and 270 GeV: The energy behavior of extraction was well reproduced in simulations

G. Arduini et al., CERN SL 97-031 and SL 97-055

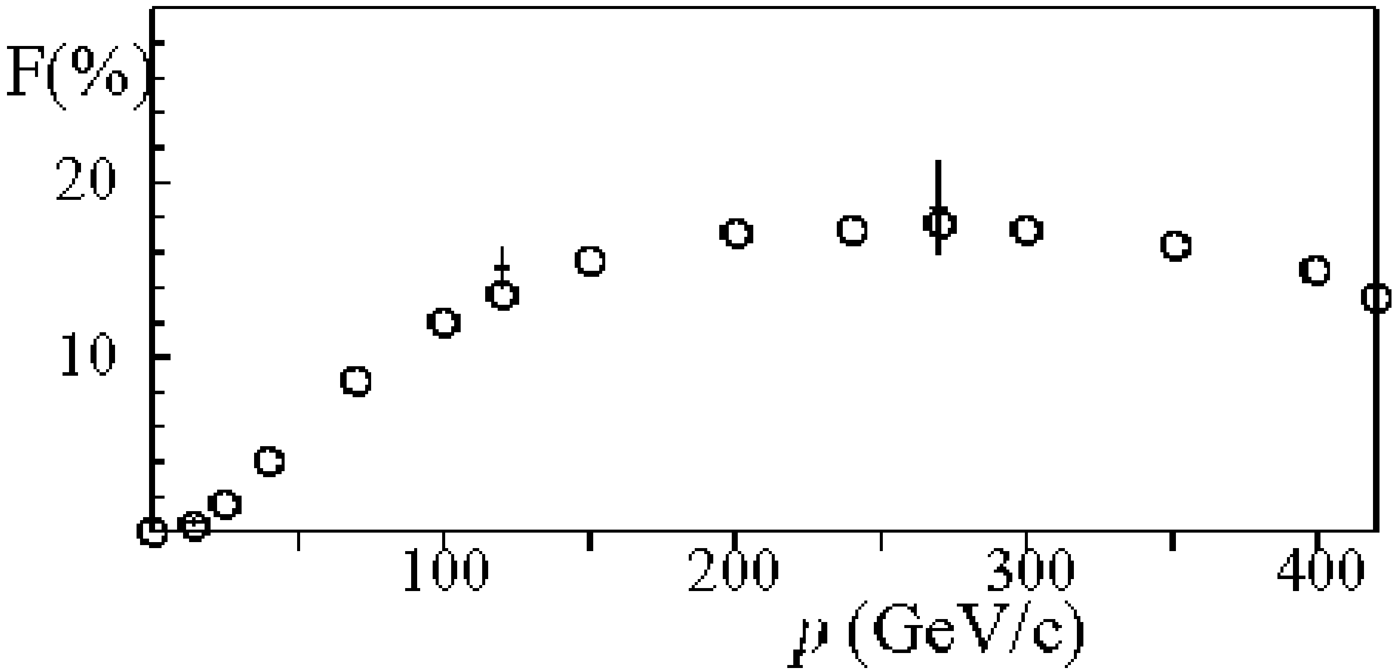
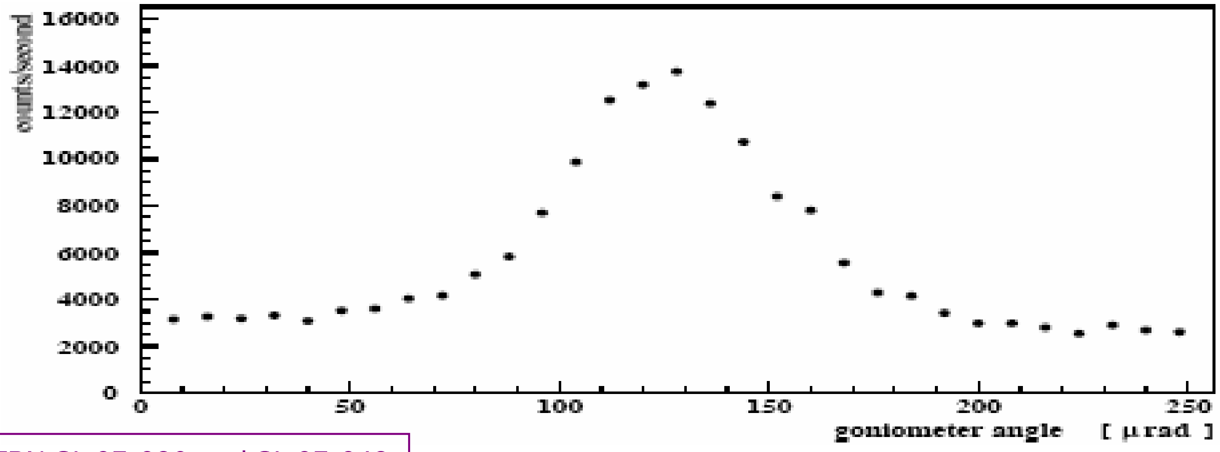


Figure: the crosses are the SPS data for the efficiency, the circles are the absolute figures of efficiency from analytical theory without any fitting parameters like "inefficient layer". See: EPAC 1998 Proc., p.2091.

RD 22: ion extraction



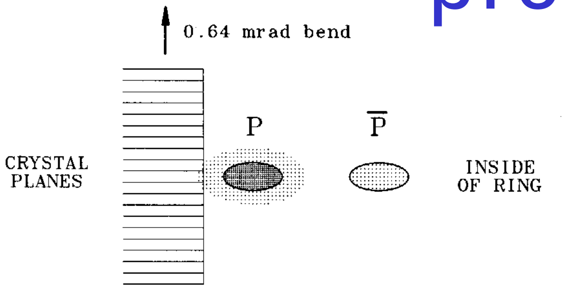
G. Arduini et al., CERN SL 97-036 and SL 97-043

Table 2: Extraction efficiences for Pb ions at 22 TeV/c.

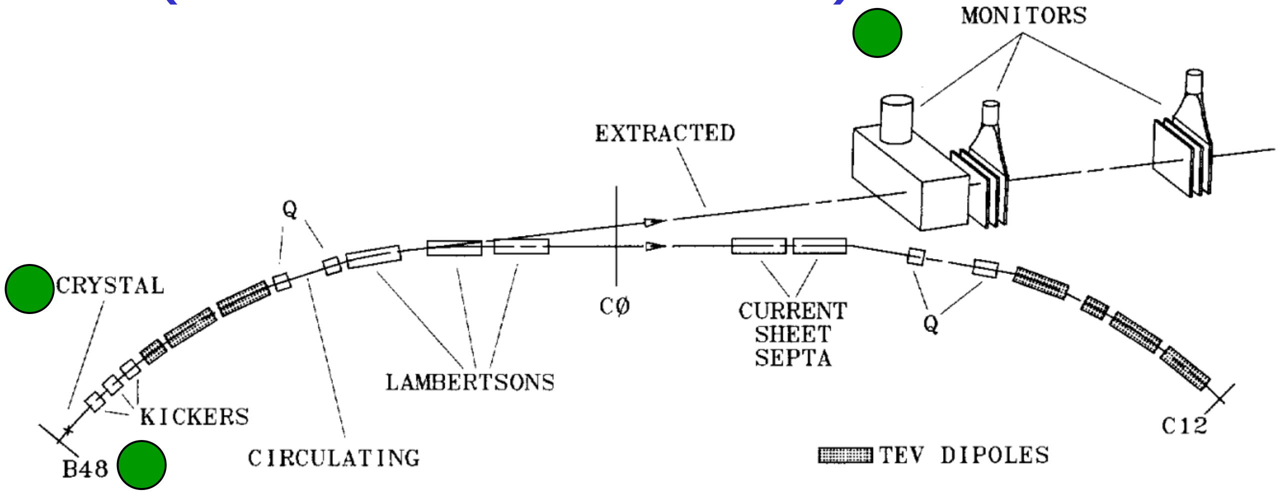
Circulating beam intensity (10^7 ions)	Beam lifetime (hrs)	Extraction efficiency (%)
13.0	2.2	4.0 ± 1.5
10.0	0.3	10.0 ± 3.5
6.7	1.2	9.0 ± 3.0
5.0	0.04	11.0 ± 4.0
5.0	0.23	5.0 ± 2.0

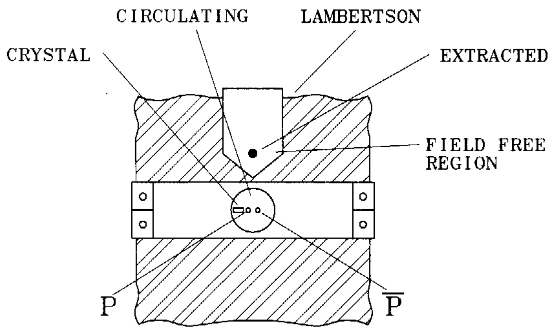
- High energy ions are efficiently channeled
- Angular scan FWHM smaller than with protons
- Electromagnetic break-up cross section large
- Multi-turn effect less effective than with protons

E853: extraction of 900 GeV protons (Tevatron: 1993-98)



At crystal





Lambertson, crystal

- Extracted significant beams from the Tevatron parasitic, kicked and RF stimulated
- First ever luminosity-driven extraction
- Highest energy channeling ever
- Useful collimation studies
- Extensive information on time-dependent behavior
- Very robust

FNAL Tevatron: the nearest to the LHC in energy. Good agreement observed (1998) with Monte Carlo predictions (1995)

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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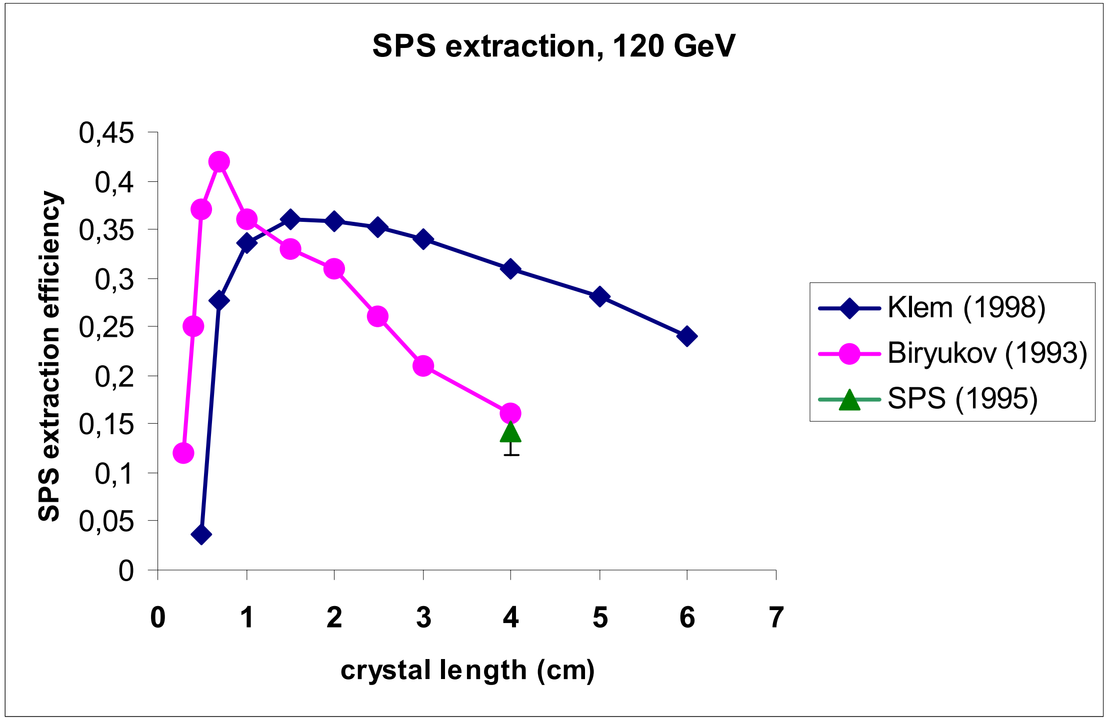
New ideas for efficient channeling came from simulations:

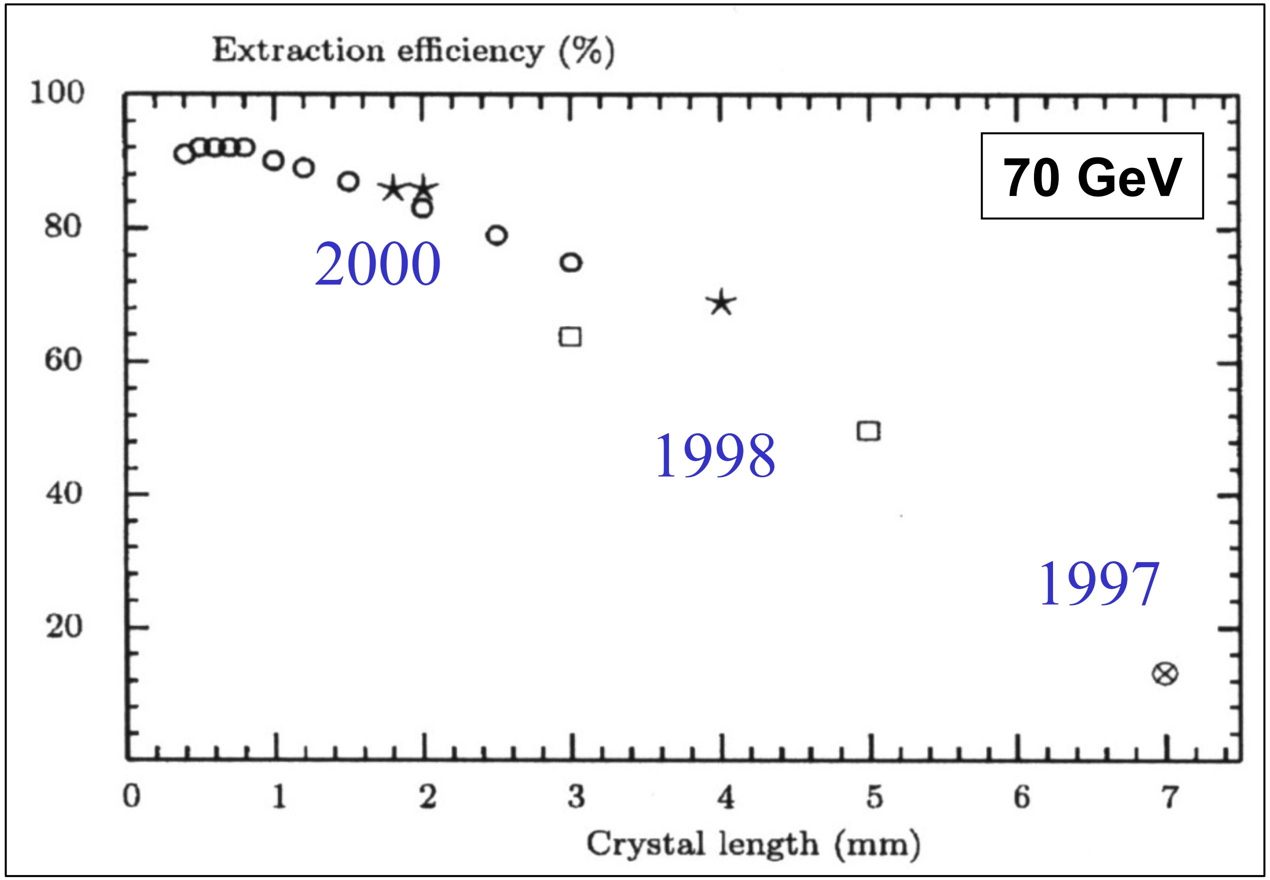
a) **Real crystal extraction is a multi-pass thing, not a single-pass**
(this changed radically the requirements to crystal and expectations of efficiency)

b) **For extraction, crystal must be shortened dramatically**
(in the following, the crystals were shortened from 40 mm → 2 mm,
bringing efficiency up from ~20% → 85%; SPS, Tevatron → IHEP)



Different models predicted different gain from a short crystal:
from just 15%
to <u>factor of 2-3</u>
rise in efficiency
in the SPS case

New experiment started at IHEP in 1997



Measured efficiency of 85 % for 2 mm long crystals (highest ever)

IHEP: collimation / extraction efficiency for 70-GeV protons.

Measurements (*, □, ⊗) and MC predictions (o) for perfect crystal

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

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]

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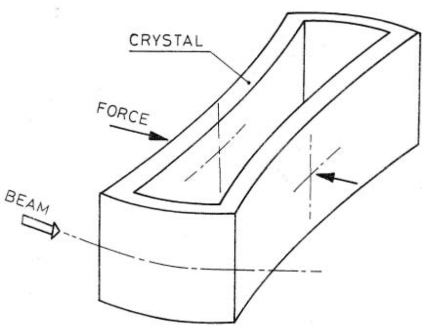
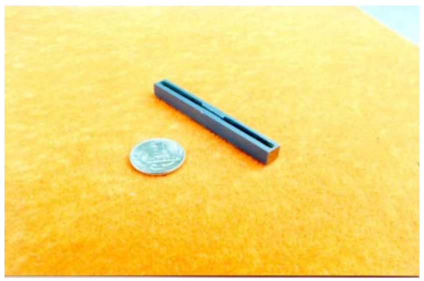
(Received 12 April 2001; published 14 August 2001)

A silicon crystal was used to channel and extract 70 GeV protons from the U-70 accelerator with an efficiency of 85.3 ± 2.8%, as measured for a beam of ~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.

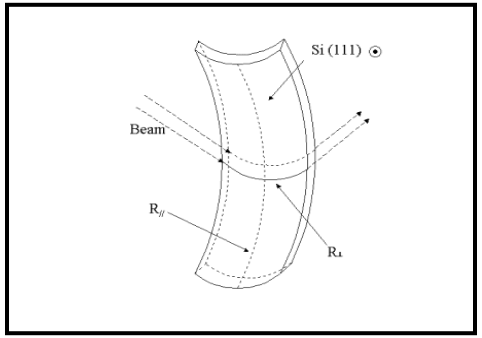
DOI: 10.1103/PhysRevLett.87.094802 PACS numbers: 41.85.–p

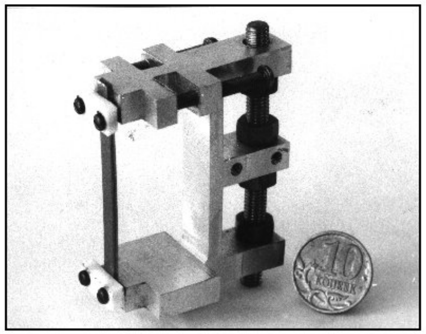
Two examples of bent short crystals





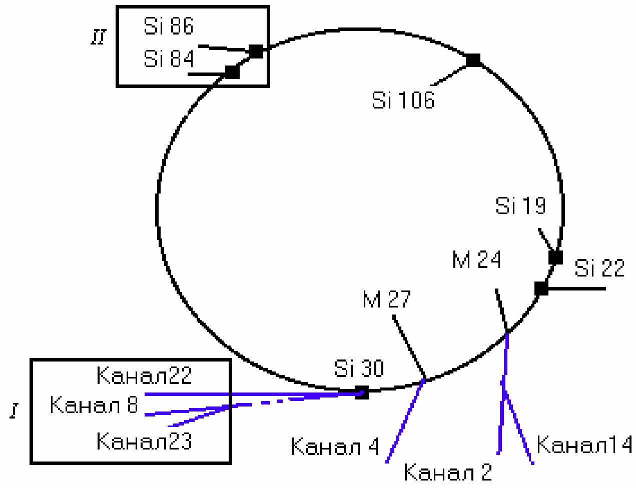
O-shaped crystals 3÷5 mm long



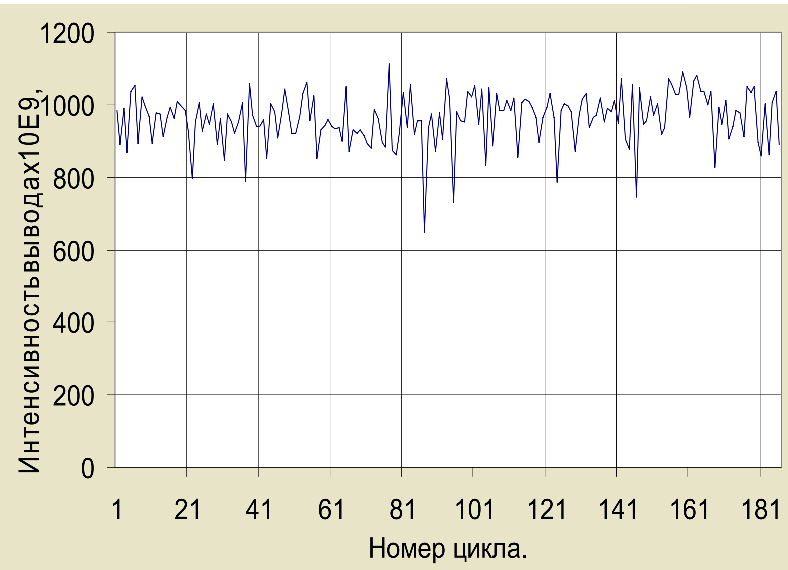


Saddle shaped crystals 0.5×2 ×50 mm^3.

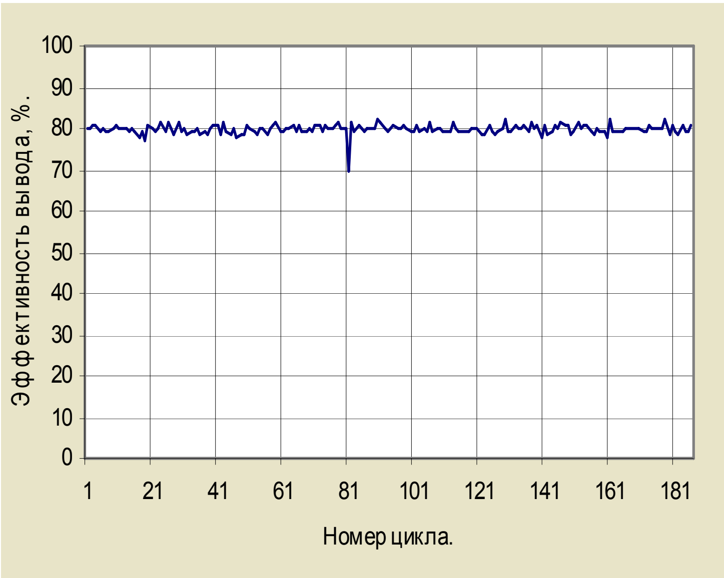
The saddle shape is induced by anticlastic forces



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



Extracted beam intensity per cycle



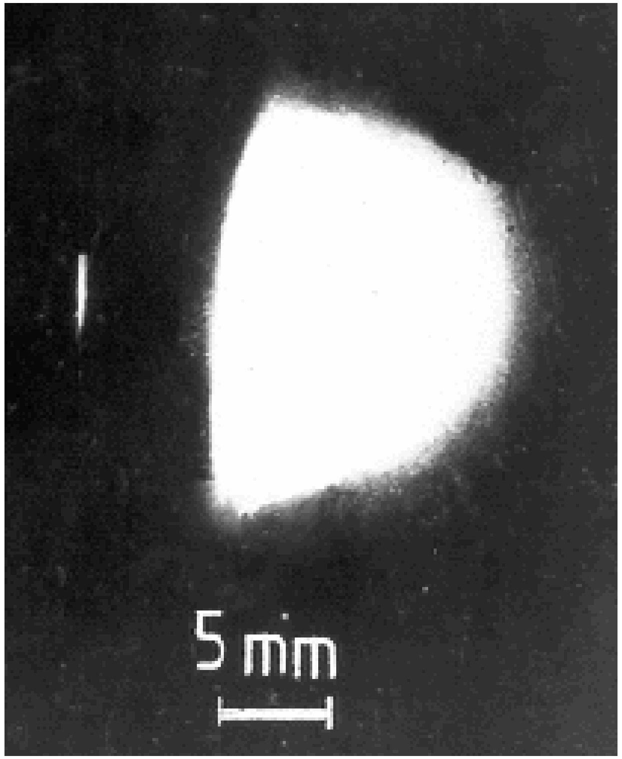
Extraction efficiency measured by cycle

High intensity test:

⇒

The IHEP crystal survives "an instant dump of 1000 bunches of the LHC"

- The crystal exposed to 50-ms pulses of **very intense beam** (10^{14} proton hits per pulse). **No damage** seen.



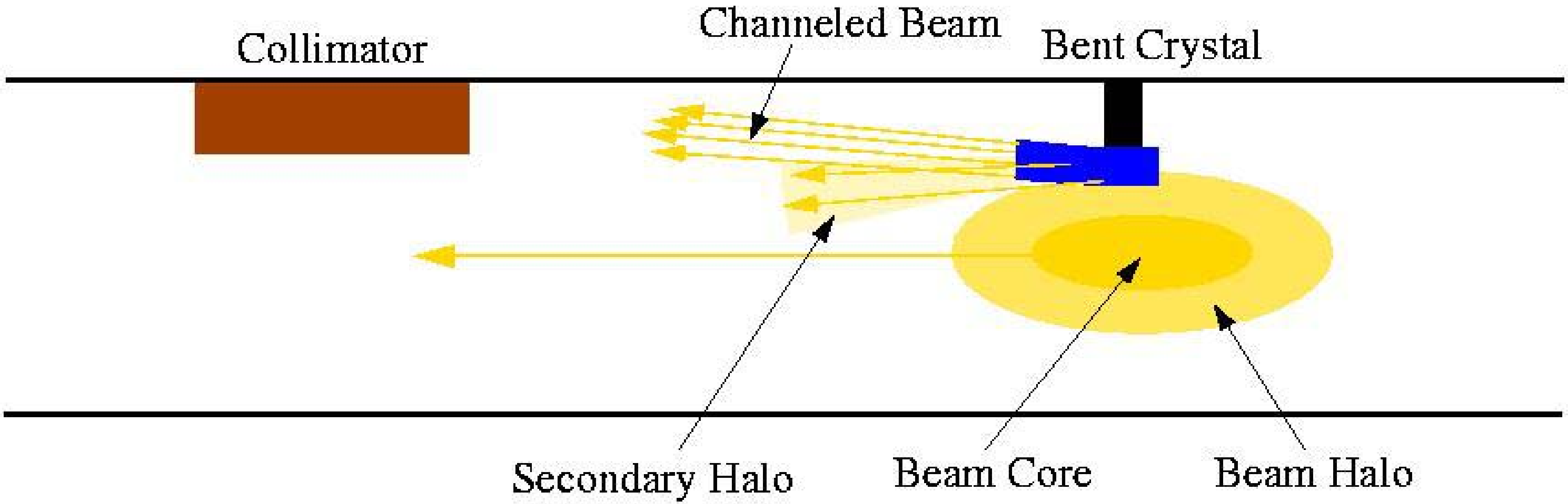
IHEP crystals channel ~10^{12} protons (up to $4{\cdot}10^{12}$ in some runs) in a spill of 0.5-1s.

Let us illustrate it in the following way. Suppose, all the LHC store of $3{\cdot}10^{14}$ protons is dumped on our single crystal in 0.2 hour. This makes a beam of $4{\cdot}10^{11}$ proton/s incident on the crystal face. In IHEP, this is just routine work for crystal, practiced every day.

IHEP experience can serve for J-PARC etc.

S. Sawada et al., to be published.

The idea of crystal collimation was around since ~1991

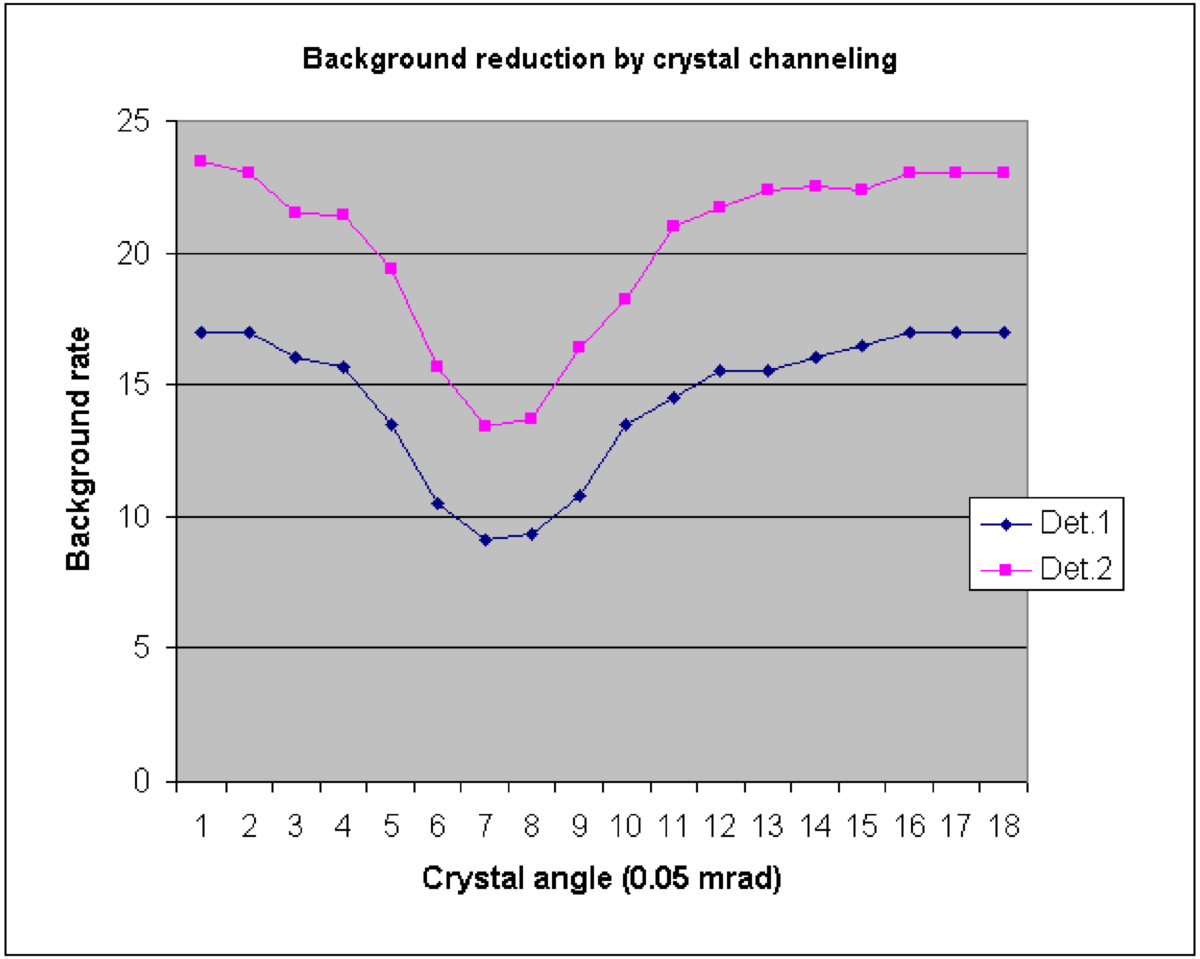


- Crystal bends halo particles toward a downstream absorber
- Coherent scattering on atomic planes of aligned crystal replaces the random scattering process on single atoms of an amorphous target

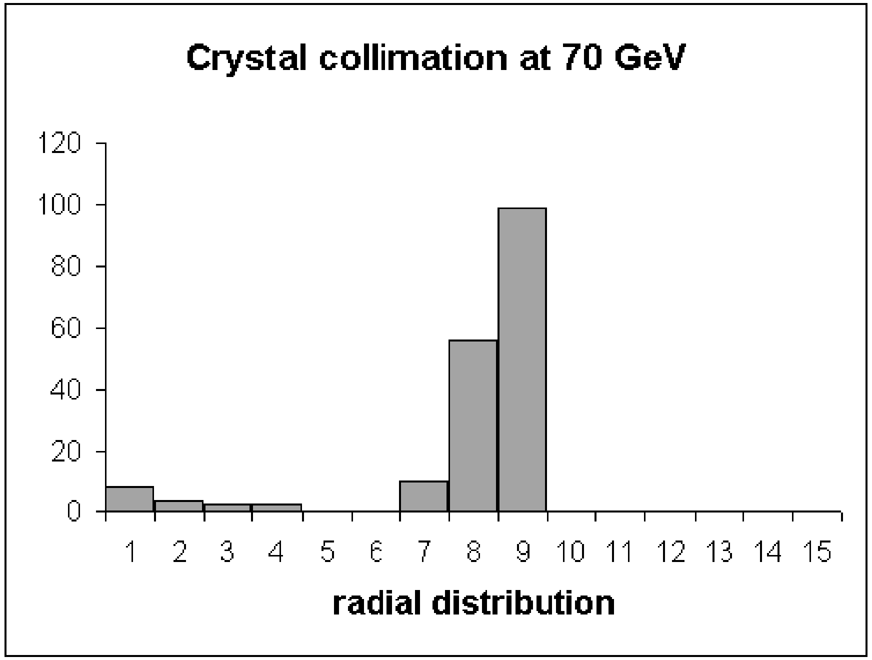
World first demonstration of crystal collimation: IHEP (1998)

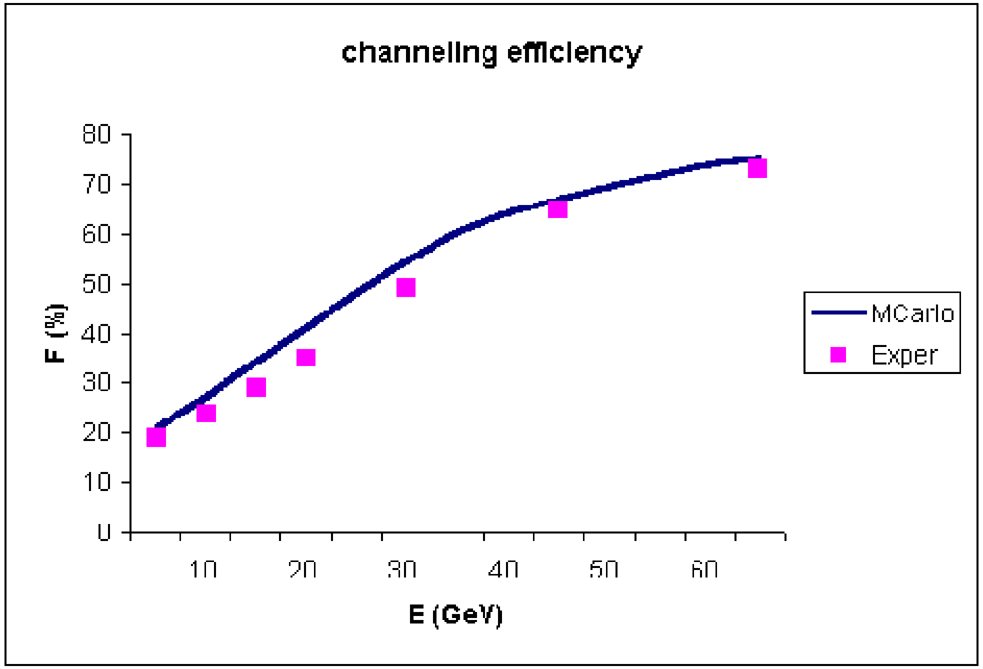
Background measured downstream of the scraper (detectors 1,2) vs crystal angle:

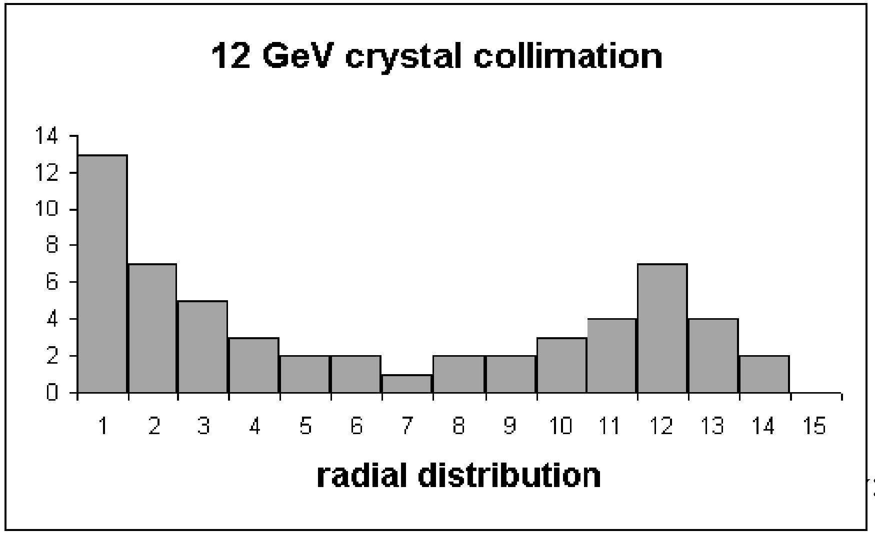
<ins>Factor of 2 gained due to channeling with 50% effy</ins>



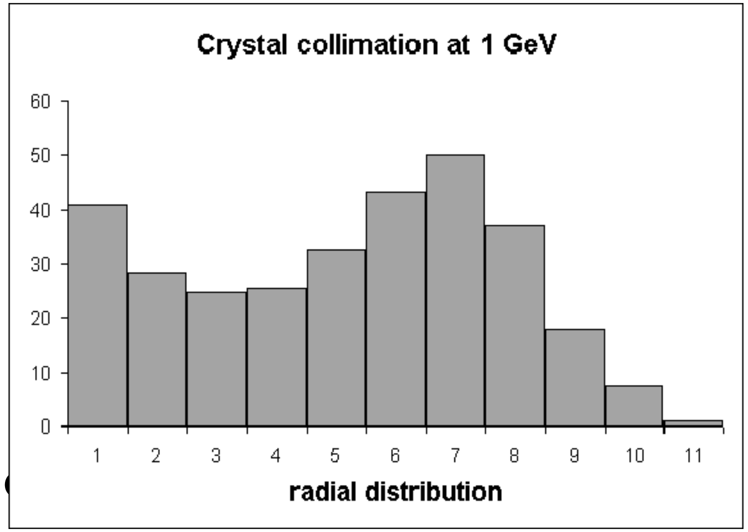
IHEP: crystal collimation studied over full energy range 1 to 70 GeV







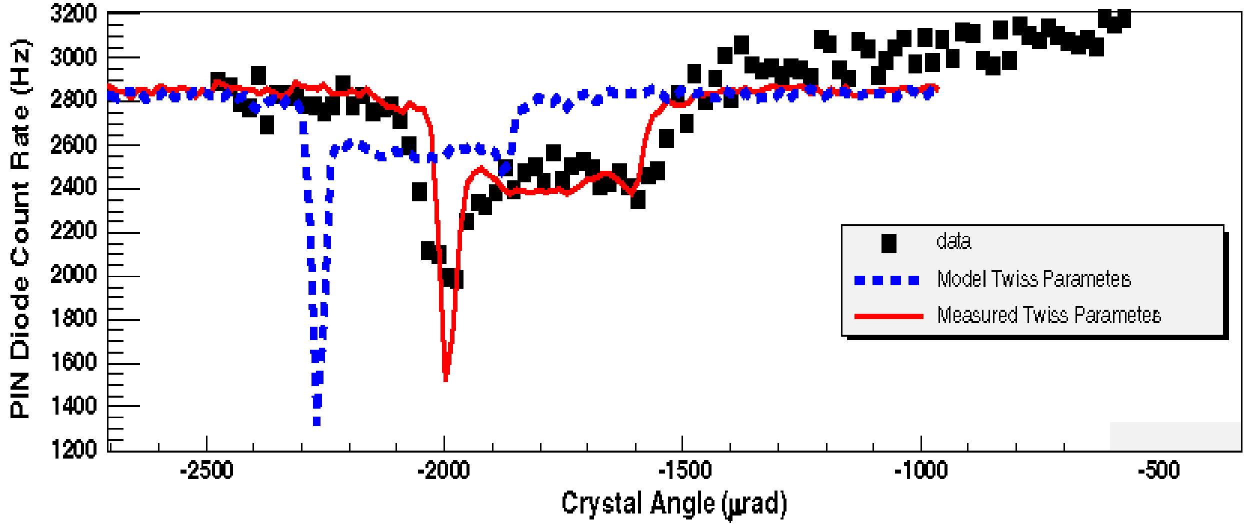
: Crystal



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 efficiency over 2003 RHIC run measured 26%, theory predicted 32% for Au ions. [PAC 2003 Proc.]



The same crystal gave 42% efficiency for protons at IHEP. [PLB **435** (1998) 240]

Earlier measurements: CERN SPS, efficiency 4 to 11% for Pb ions. [PRL **79** (1997) 4182]

world first crystal collimation for heavy ions, top efficiency

INTAS-CERN projects 00-132 (2001-03) and 03-51-6155:

“Crystal technique for halo cleaning in the LHC”

Scientific coordinator: Walter Scandale, CERN

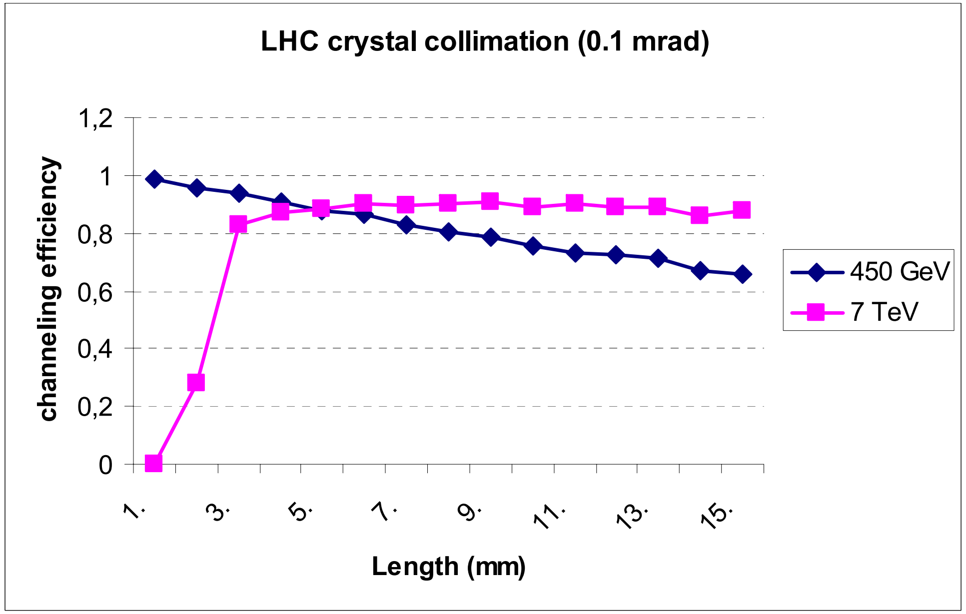
Simulations of LHC crystal collimation

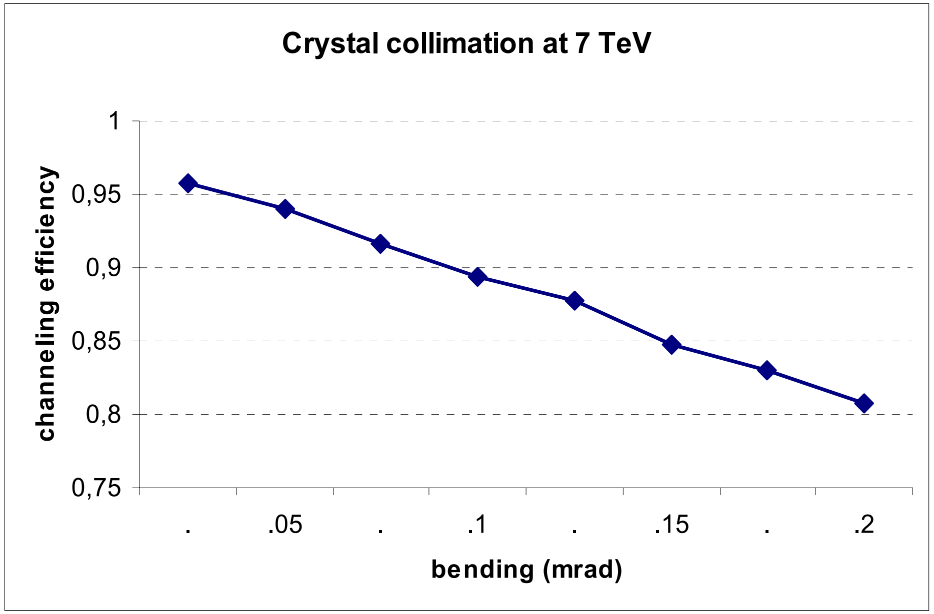
We applied the same computer model verified at the IHEP, CERN SPS, Tevatron, and RHIC experiments in order to evaluate the potential effect of crystal collimation for the LHC. In the model, a bent crystal was positioned as a primary element at a horizontal coordinate of 6 σ in the halo of the LHC beam, on the location presently chosen for an amorphous primary element of the LHC collimation system design. The LHC lattice functions were taken corresponding to this location.

LHC collimation efficiency

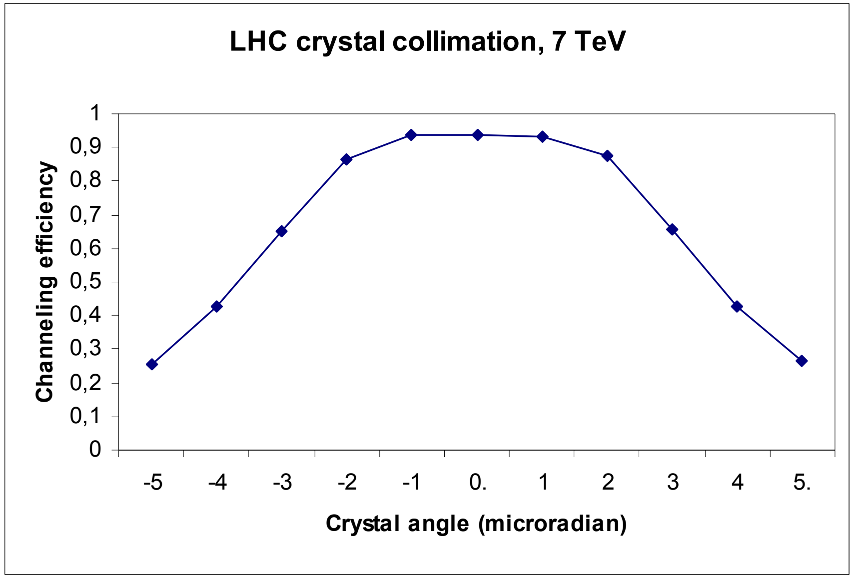
Channeling efficiency computed as a function of the crystal length along the LHC beam: at flattop 7 TeV and at injection 450GeV.
The chosen bending angle is 0.1mrad.

Channeling efficiency computed as a function of the crystal bending angle. Silicon crystal (110) with a 1μm thick rough surface.

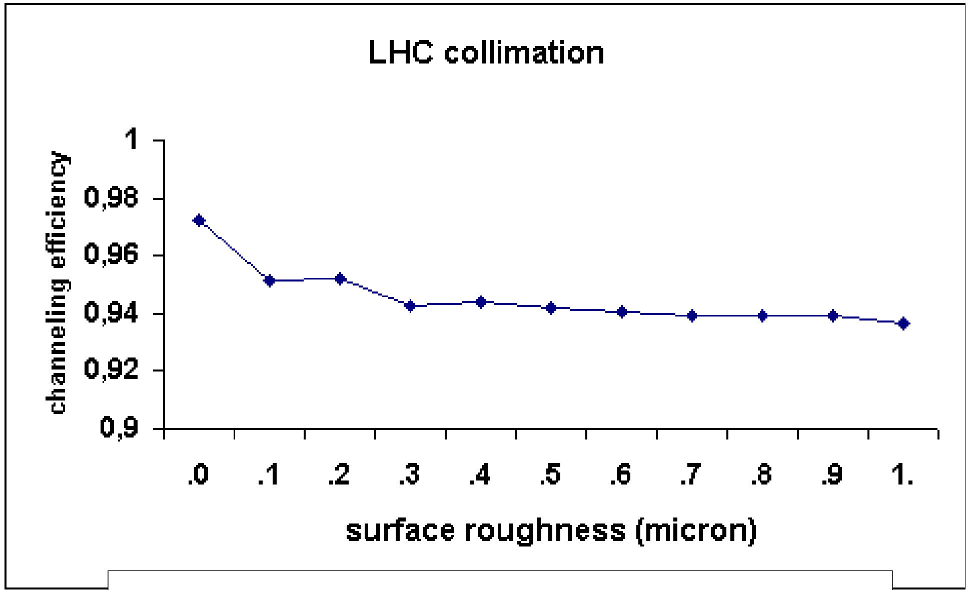




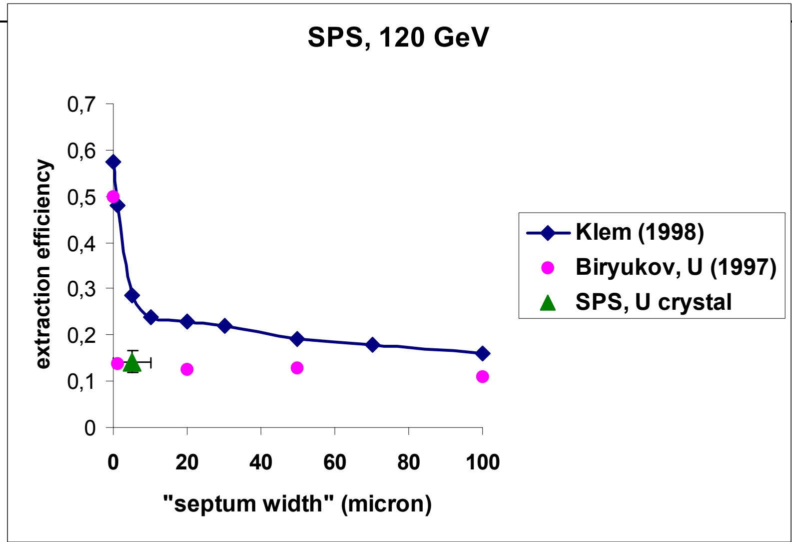
Channeling efficiency as a function of the crystal orientation angle. The orientation curve has FWHM = 7 μrad at top energy.



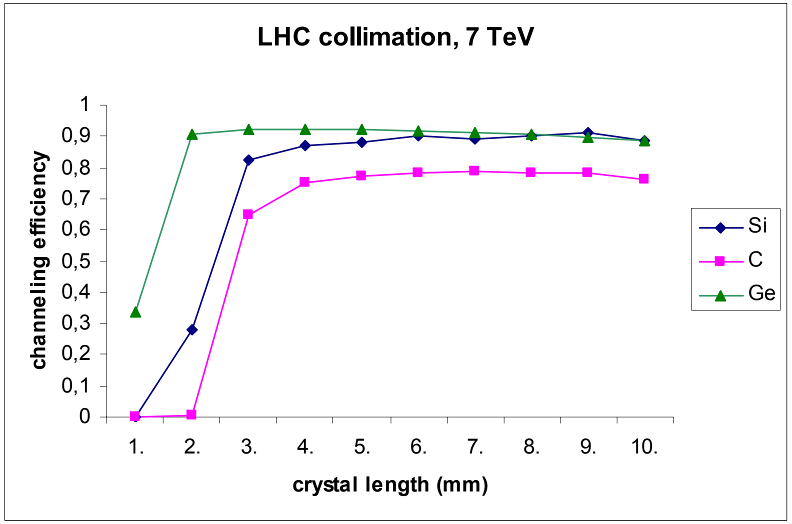
Requirement on crystal surface at the LHC: weak dependence on it

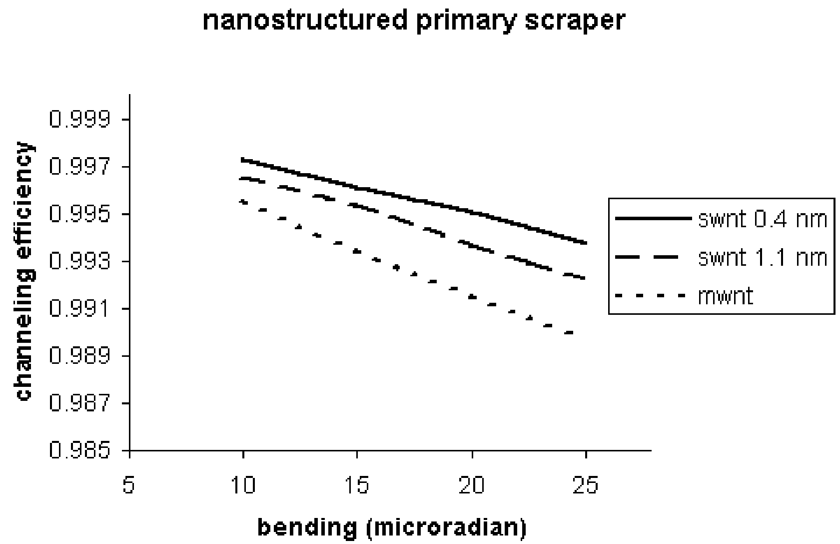


Similar dependences were earlier found for the SPS → weak dependence on surface quality



Crystals of **low-Z and high-Z** material are available, e.g. diamond and Germanium: they demonstrate efficiency similar to Silicon





Nanostructured channeling material could be used for primary scraper
NIM B 230 (2005) 619

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

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

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

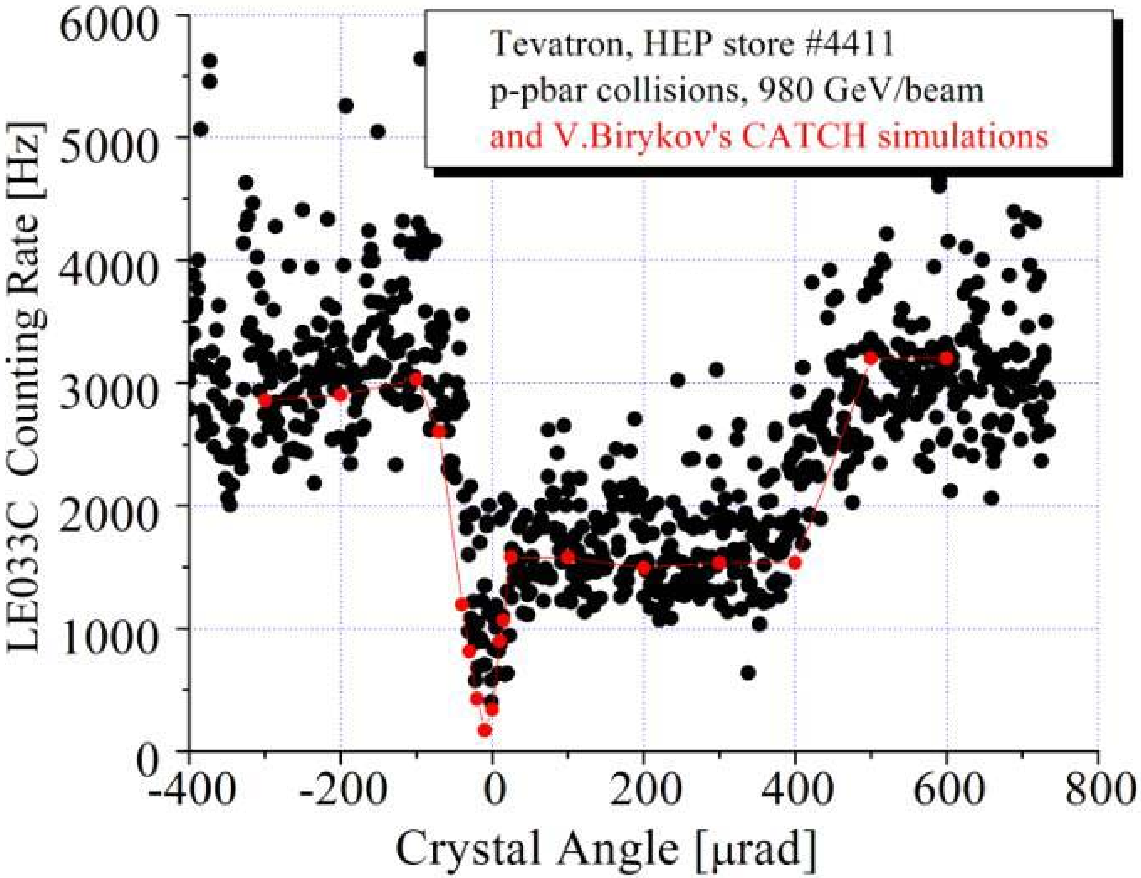
	with target	with crystal		
		amorphous layer thickness		
		10 μm	5 μm	2 μm
DØ	11.5	1.35	1.60	1.15
CDF	43.6	5.40	3.20	3.43
N	270	82.4	70.6	50.3

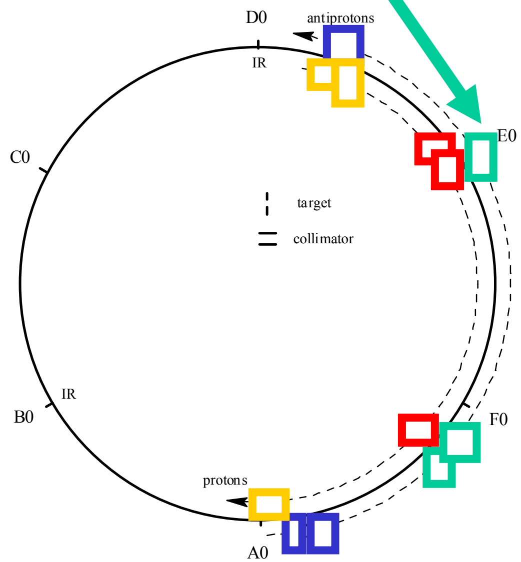
Crystal reduces background in D0 and CDF by a factor of 10 (simulation). Experiment started in 2005 at the Tevatron.

D. Still, N. Mokhov, V. Shiltsev, R. Carrigan, R.Flliller, V.Biryukov, Y. Chesnokov, Y. Ivanov, talk at Channeling 2006

Crystal Collimator in E0 replacing a Tungsten Target

1 TeV crystal collimation at the Tevatron

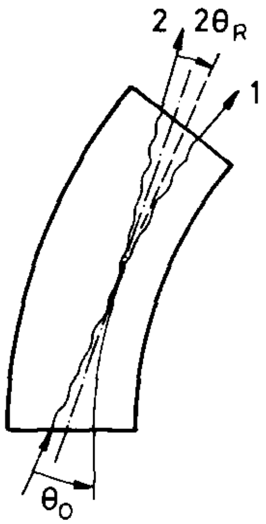


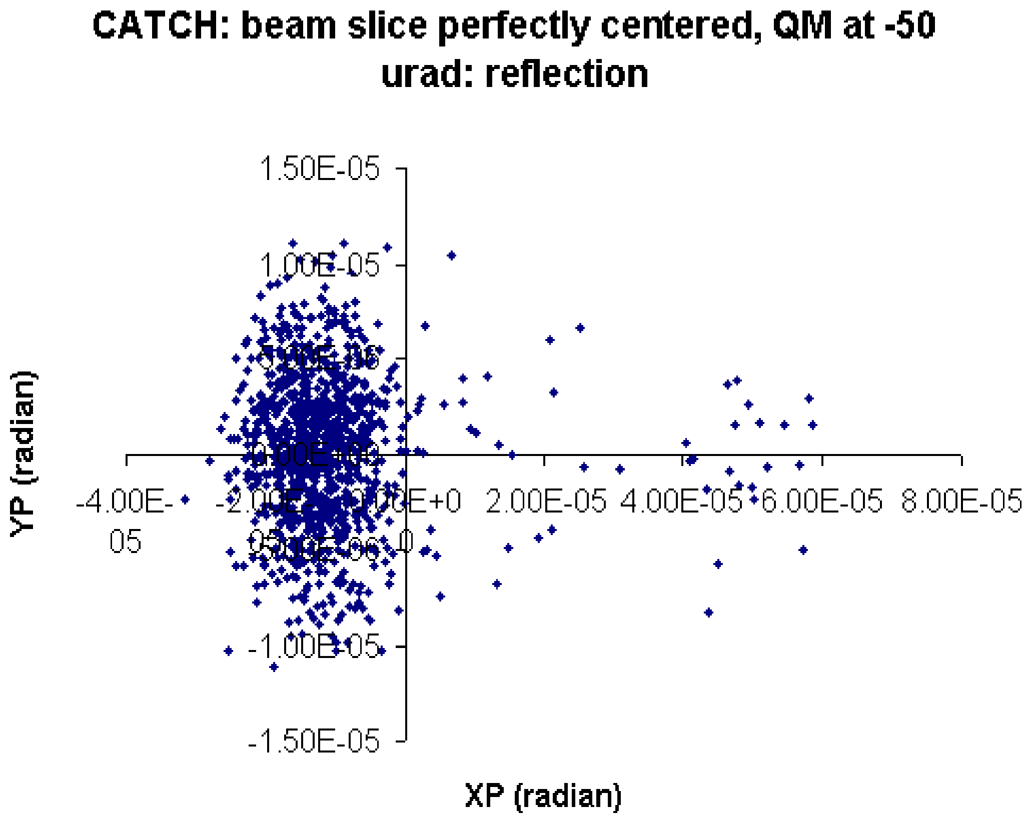


Crystal "volume reflection" predicted by Taratin & Vorobiev (1987): the whole beam is reflected in bent crystal by a ~critical angle

RHIC, Tevatron collimation experiments gave first observation.

Experiment started at CERN SPS for first direct measurement

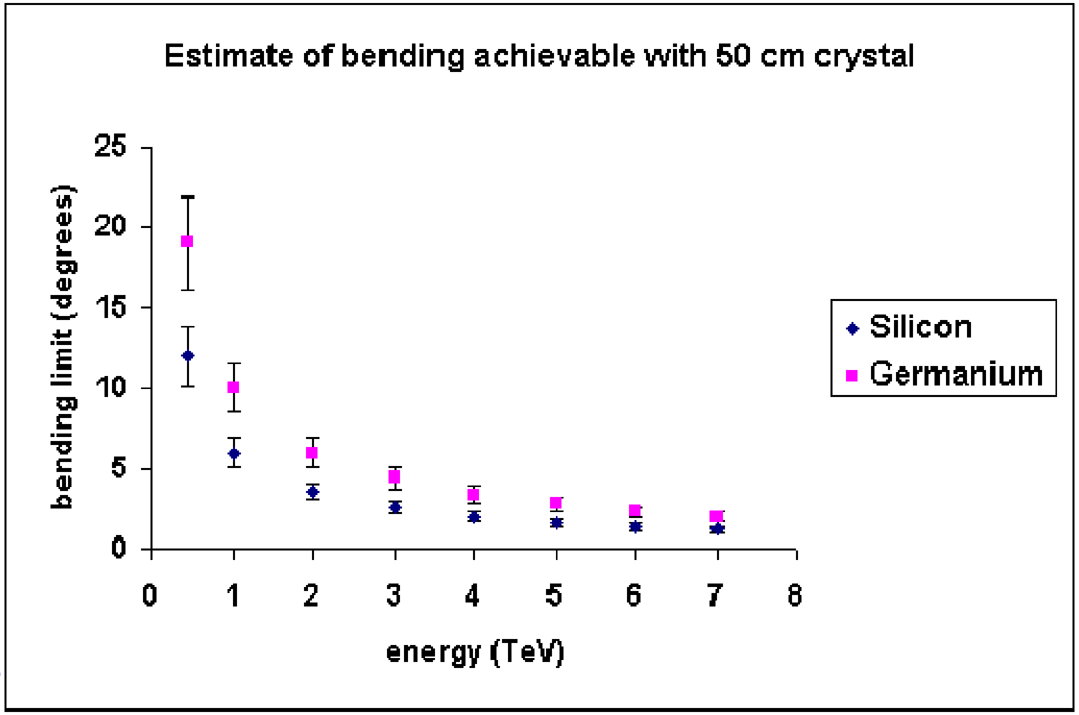




Sketch of a channeled (1) and reflected (2) particle. Predicted volume reflection for the SPS.

Apart from collimation & extraction, more crystal applications are developed for the LHC, for instance:

- ATLAS & CMS calorimeters can be calibrated *in situ* by channeling the LHC protons (ions) of 0.45-7 TeV right into calorimeters, irradiating them cell by cell, with a crystal bent a very large angle, ~ 1 to 20 degrees



IHEP has bent a 70 GeV beam at 9 degrees (150 mrad) by a crystal

Conclusions

Crystal works in efficient, predictable, reliable manner with beams of very high intensity (~10^{12}) with a lifetime of many years (IHEP)

Monte Carlo model successfully predicts crystal work

The same crystal scraper works efficiently over full energy range, from injection through ramping up to top energy

Crystal would be very efficient in the LHC environment. The expected efficiency figure, ~90%, is already experimentally demonstrated at IHEP and being confirmed at the Tevatron.

This would make the LHC 10-40 times cleaner.

Thank you