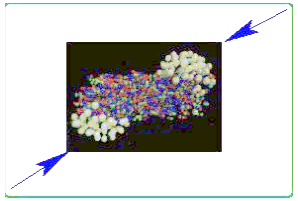


SPS experiments to test crystal collimation for LHC

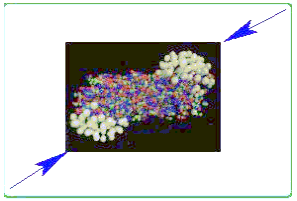
Walter Scandale

CERN

Geneva, 02 February 2006

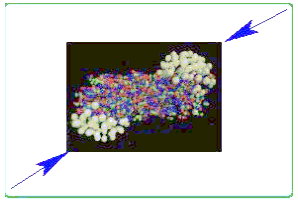
AB & LHC project joint seminar

Outlook

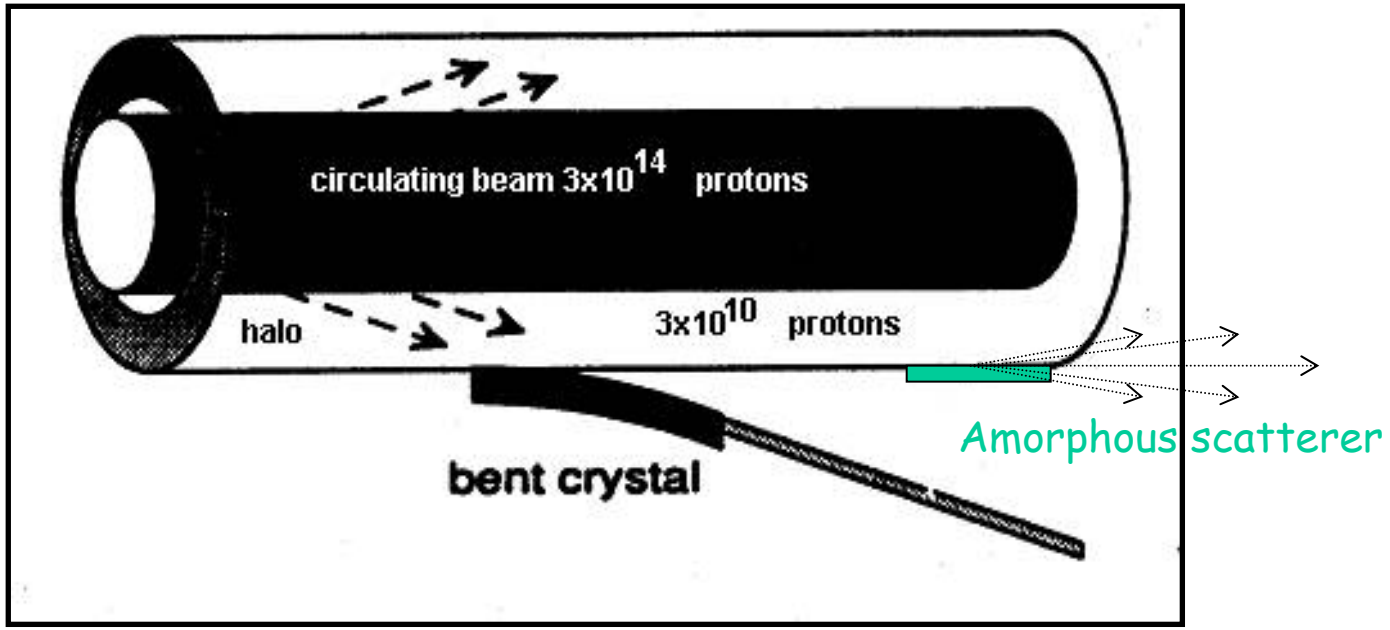


- The concept of crystal collimation
- A review of the activity on crystal channeling relevant for collimation applications
  - RD 22
  - E 853
  - INTAS programmes
  - HCCC-INFN programme
  - CARE-HHH-APD CC-05 workshop March 2005
  - CARE-HHH-APD mini-workshop Dec 2005
  - Crystal collimation at RHIC (did it really fail ?)
  - Crystal collimation at the Tevatron
- A possible experiment in the H8 beam line of the SPS north area
- A possible experiment "à la RD 22" in the SPS ring
- Concluding remarks

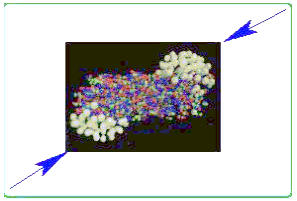
Crystal channeling: a smart approach for primary collimation



- A bent crystal should efficiently deflected halo particles away from the beam core toward a downstream massive absorber
- The selective and coherent scattering on atomic planes of an aligned Si-crystal replaces the random scattering process on single atoms of an amorphous target

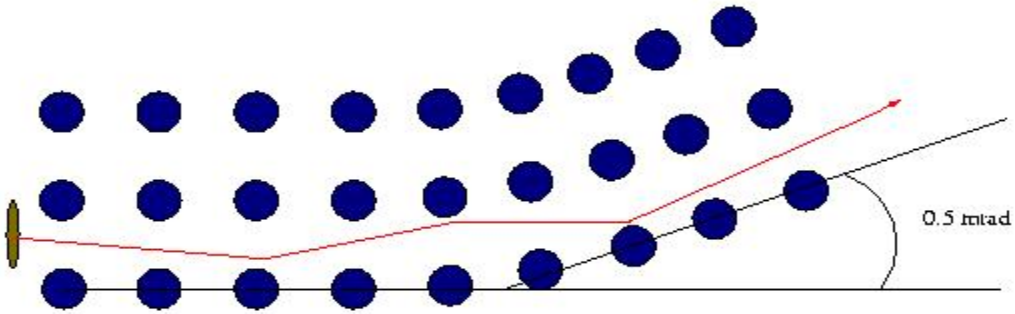


Channeling in bent crystals
Edward Tsyganov (1979)



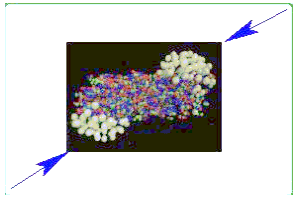
Crystal Channeling

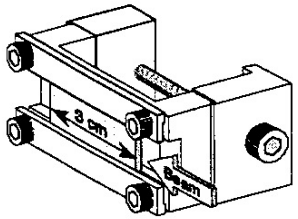
If ions enter a crystal at an appropriate angle, the scattering events are correlated, and the ion is channeled through the crystal planes.



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

RD 22: extraction of 120 GeV protons (SPS: 1990-95)





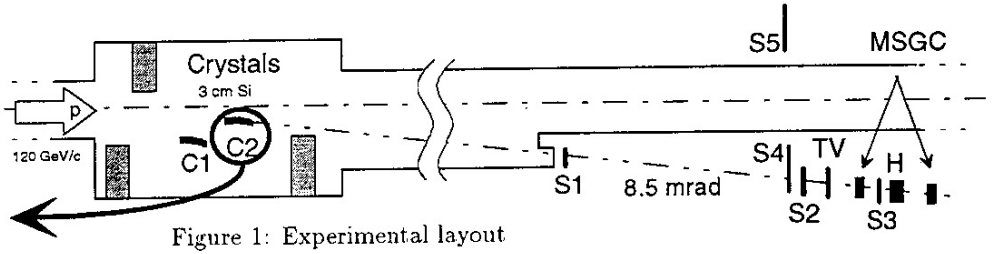
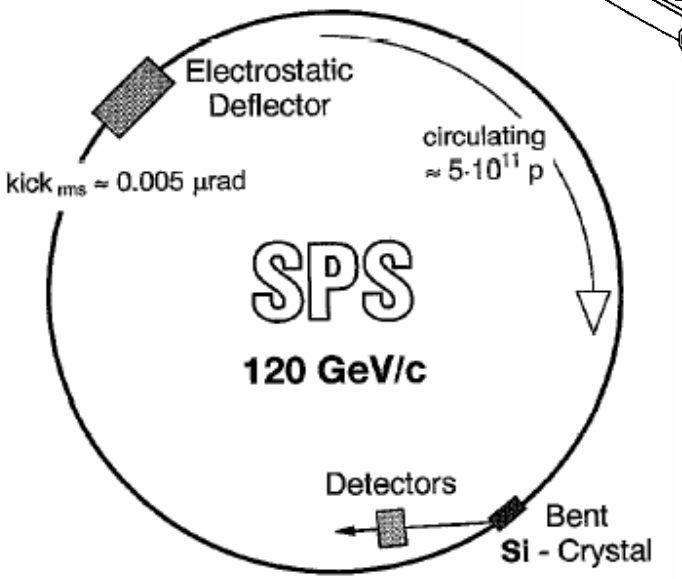


Figure 1: Experimental layout

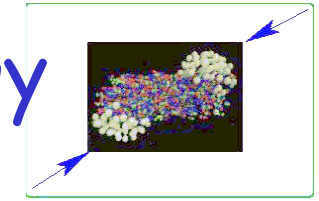


The RD22 Collaboration, CERN DRDC 94-11

	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 (%)	**10.2 ± 1.7**	**9.3 ± 1.6**

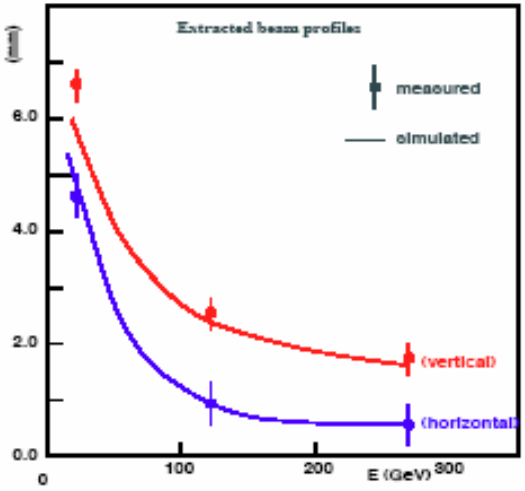
- Large channeling efficiency measured for the first time
- Consistent with simulation expectation extended to high energy beams
- Experimental proof of multi-turn effect (channeling after multi-traversals)
- Definition of a reliable procedure to measure the channeling efficiency

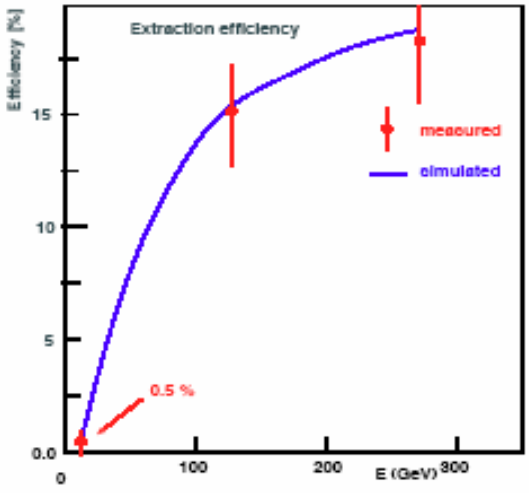
RD 22: varying the proton energy



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

Beam energy (GeV)	Extraction efficiency (%)	Prediction simulation (%)
14	0.55±0.3	0.46
120	15.1±1.2	15.1*
270	18.6±2.7	17.7





Dechanneling vs beam energy

- Critical angle $\psi_c \propto p^{-1/2}$
- Dechanneling is induced by hits on e^- by bending of the atomic planes
  e- hit dech. length --> $L_D \propto p$
  bending dech. length --> $L_B = L_D\,(1-F)^2$

$F = f(p, l, \vartheta) =$ dechanneling factor

Channeling probability

$$P_c = (1-F)\, e^{-l_s/L_D}\, e^{-l_b/L_B}$$

Crystal length:
l_s = straight part
l_b = bent part

Scattering angle

- Gaussian distribution
- $\langle\theta\rangle = 0$
- L_{eff} is the effective scattering length

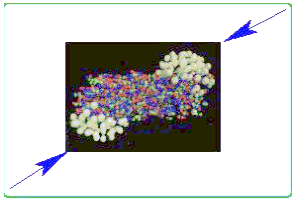
$$\theta_{rms} = \frac{13.6\,MeV}{\beta c p}\sqrt{\frac{L_{eff}}{X_0}}\left(1+0.038\ln\left(\frac{L_{eff}}{X_0}\right)\right)$$

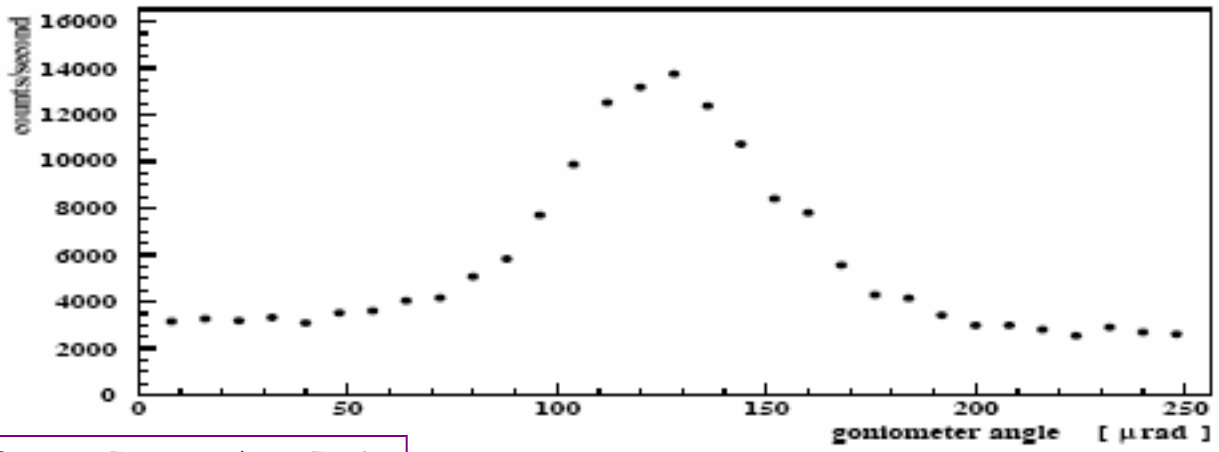
X_0 = rad. length (= 9.7 cm for Si at 120 GeV)

- Multiple scattering and dechanneling determine the dependence of efficiency on energy
- For a given beam energy and crystal bending angle there is an optimal crystal length
- Extrapolations of crystal efficiency to the LHC beam energy can be considered reliable

AT-MAS

RD 22: ion extraction





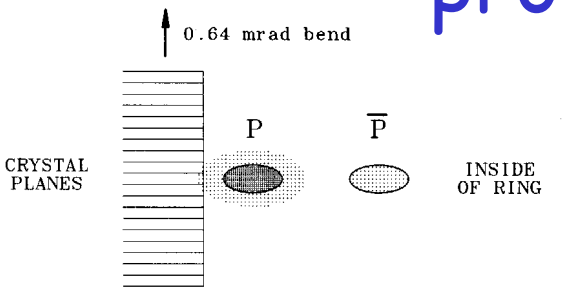
G. Arduini et al., CERN SL 97-036 and SL 97-043

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

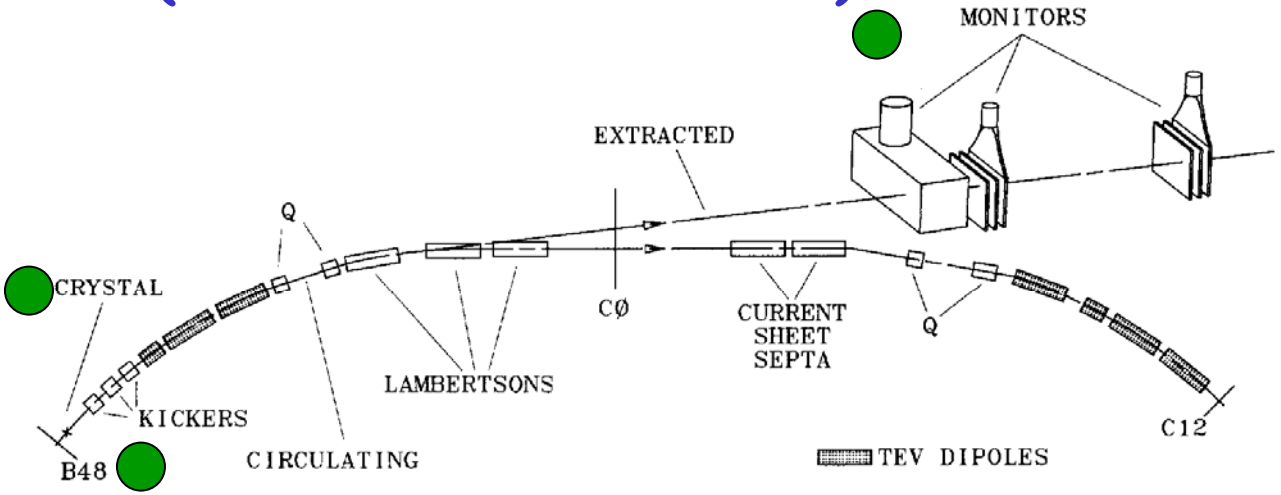
Circulating beam intensity (10^7 ions)	Beam lifetime (hrs)	Extraction efficiency (%)
13.0	2.2	4.0±1.5
10.0	0.3	10.0±3.5
6.7	1.2	9.0±3.0
5.0	0.04	11.0±4.0
5.0	0.23	5.0±2.0

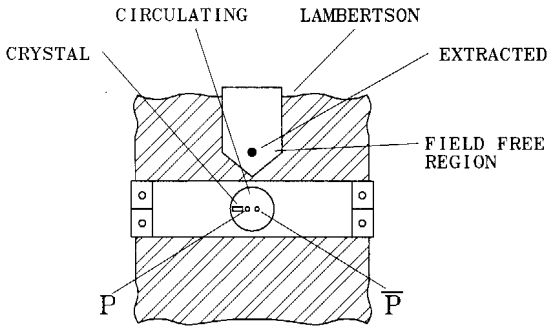
- High energy ions are efficiently channeled
- Angular scan FWHM smaller than with protons
- Electromagnetic break-up cross section large
- Multi-turn effect less effective than with protons

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



At crystal



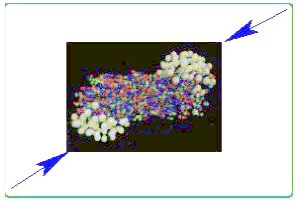


Lambertson, crystal

- 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

INTAS 00-132 (2001-03)

Scientific coordinator: Walter Scandale, CERN



IHEP Protvino:

A.G.Afonin - tuning the accelerator settings
A.A.Arkhipenko - data taking
V.T.Baranov - data taking and analysis
V.M.Biryukov - computer simulations and coordination
M.K.Bulgakov - support of external beam line
V.N.Chepegin - collimator settings and data taking
Yu.A.Chesnokov - major crystal expert; design, realisation, installation and tests of crystals
Yu.S.Fedotov - accelerator settings
V.A.Gavrilushkin - participation in the shifts
V.N.Gorlov - data taking
V.N.Gres - diagnostics guy
V.I.Kotov - support of accelerator experiments
V.A.Maisheev - data taking, external beam line tuning
A.V.Minchenko - accelerator settings
V.I.Terekhov - chief of diagnostics
E.F.Troyanov - accelerator coordination
M.Y.Vrazhnov - participation in the shifts
V.A.Zelenov - participation in the shifts

Ferrara University:

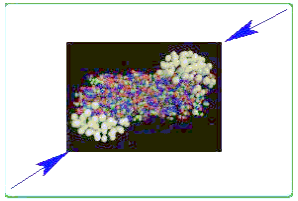
M. Butturi – laboratory esperimentalist
M. Ferroni – structural characterization
V. Guidi – structural characterization and local coordinator
C. Malagù – dicing-machine esperimentalist
G. Martinelli – head of laboratory
M. Stefancich – micromachining esperimentalist
D. Vincenzi – micromachining esperimentalist

PNPI Saint Petersbourg :

B.A.Chunin – optical measurements
A.S.Denisov – electronics
V.V.Ivanov – mechanical design
Yu.M.Ivanov – head of lab, coordination, crystal design, data analysis
M.A.Koznov – optical surface preparation
L.P.Lapina – calculations and data handling
A.A. Petrunin – X-ray diffraction measurements
V.V.Skorobogatov – crystal orientation, cutting and treatment
V.V.Vavilov – data acquisition

Total budget: 120 Keuro

INTAS 00-132: short crystals



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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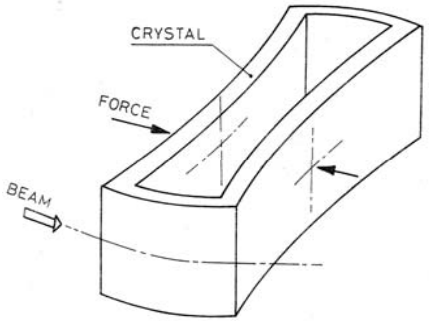
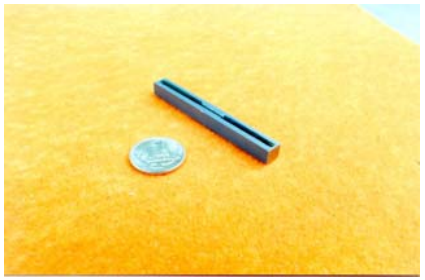
(Received 12 April 2001; published 14 August 2001)

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.

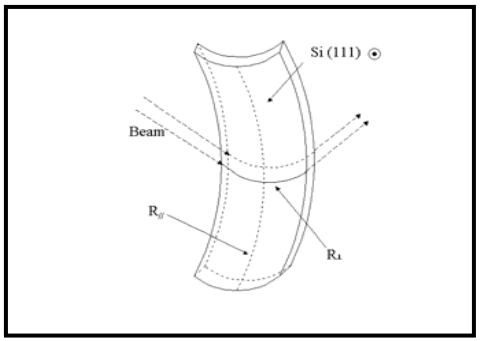
DOI: 10.1103/PhysRevLett.87.094802 PACS numbers: 41.85.–p

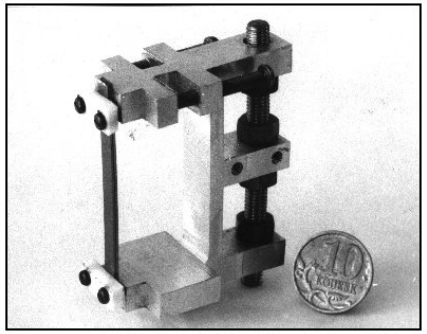
Two examples of bent short crystals





O-shaped crystals 3÷5 mm long



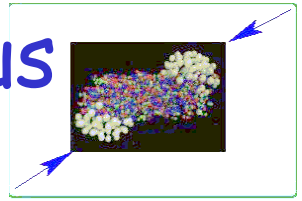


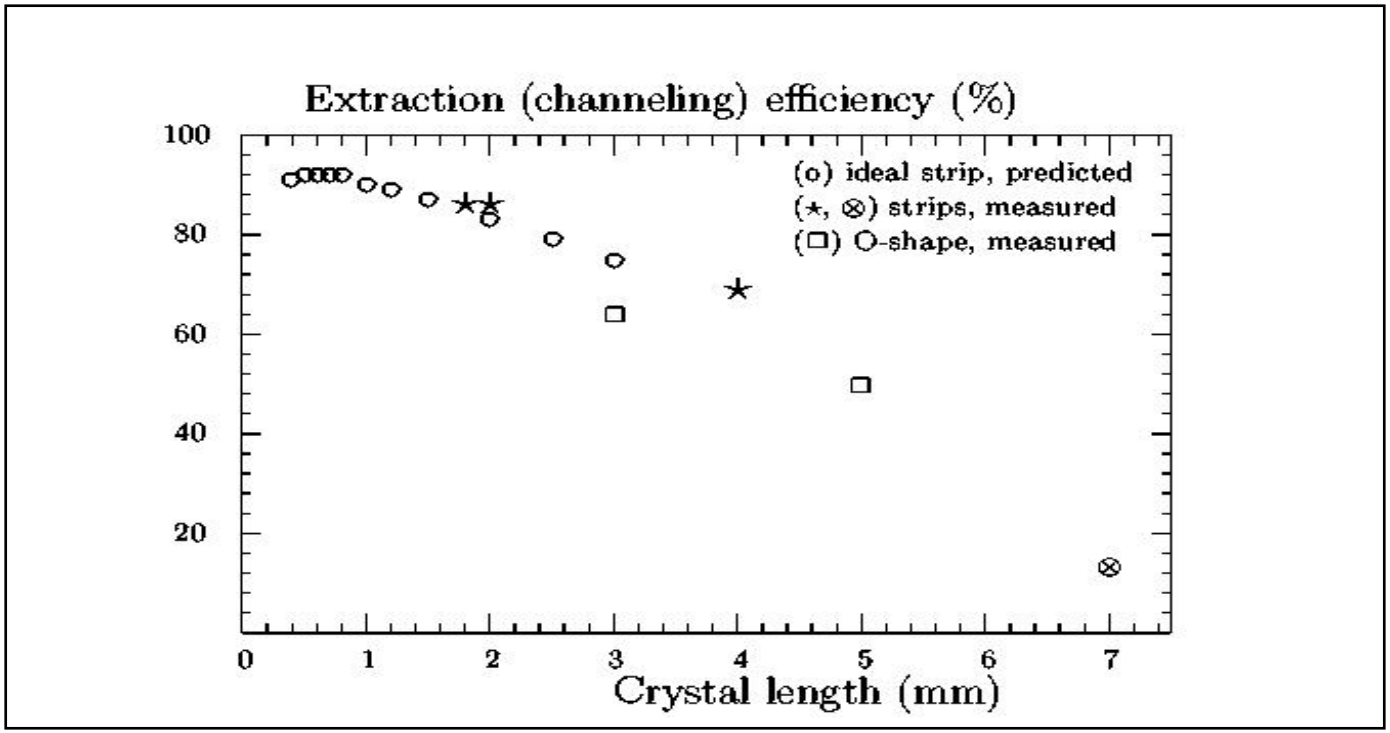
Saddle shaped crystals 0.5×2 ×50 mm³.

The saddle shape is induced by anticlastic forces

AT-MAS

INTAS 00-132: simulations versus experimental data



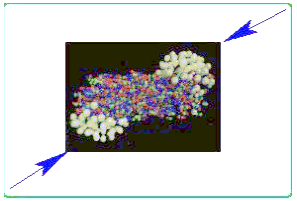


In the graphics:

- Efficiency predicted in a perfect strip crystal with 0.9 mrad bending (" ○ ")
- Efficiency measured using 70 GeV protons in IHEP U-70 (" ☆ □ ⌖ ")
- Crystal bending angle varied from 0.8 to 1.7 mrad

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

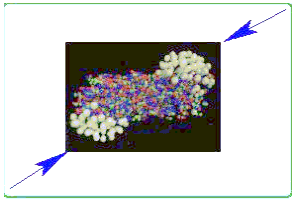
Outcomes of INTAS 00-132



- Channeling efficiency can reach 85 % : good perspectives for crystal collimation.
- Crystal works efficiently at very high intensity with a lifetime of many years at least for 70 GeV protons.
- Crystal can survive to an abnormal dump with a large safety margin at least for 70 GeV protons.
- Monte Carlo model successfully predicts the particle channeling in the crystal.
- Simulations show that the same crystal scraper may work in LHC with more that 85 % efficiency over the full LHC energy range, from injection through ramping up to top energy.
- Bent crystal of low-Z and high-Z material are available with efficiency similar to silicon.

HCCC (2004-on-going)

Halo Collimation through Channeling in Crystals



SPECIAL PROJECT NTA-INFN (approved in 2004 - Budget about 70 Keuro/Y)

PARTECIPANTS:

Ferrara

Andrea Antonini
Mariangela Butturi
Vincenzo Guidi
Francesco Logallo
Cesare Malagù
Giuliano Martinelli
Emiliano Milan
Marco Stefancich
Donato Vincenzi

LNL (Laboratori Nazionali Legnaro)

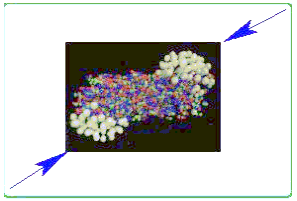
Gianantonio Della Mea
Alberto Quaranta
Alberto Vomiero
Fabiana Gramegna
Valentino Rigato
Alessandro Patelli
Enrico Boscolo Marchi
Marco Bonafini
Enrico Negro

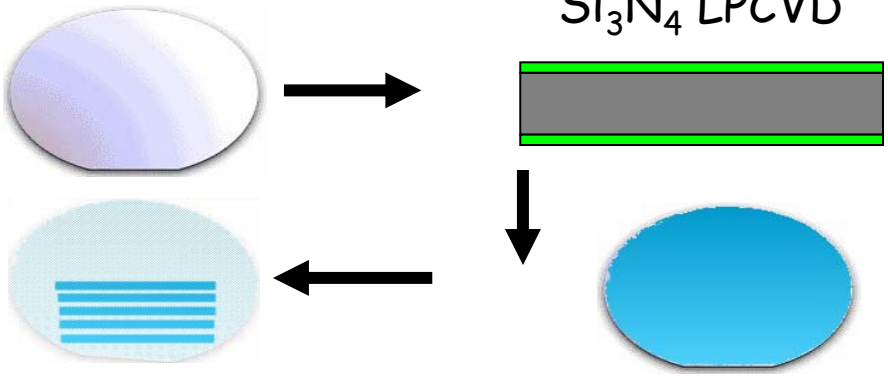
Collaborations :
CERN, Geneva, Switzerland
Institute for High Energy Physics (Protvino)
Petersburg Nuclear Physics Institute (Gatchina)

Goals :

- Chemical etching of crystals
- Crystal characterization with p, n, α (LNL, Italy)
- Special holders for crystal bending

HCCC: chemical etching

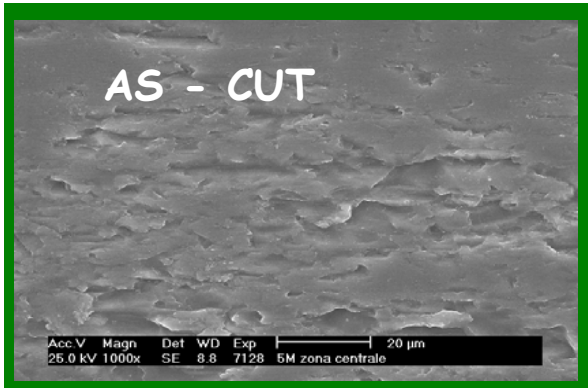




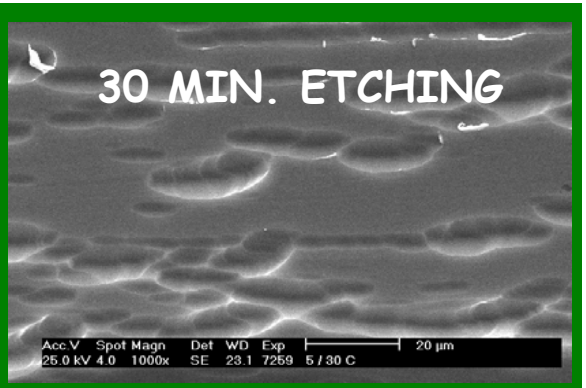
preparation and characterization of crystals

The samples are cut by a dicing saw

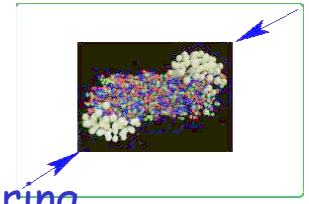
Chemical etch to remove of in-depth lattice imperfections induced during the slicing.



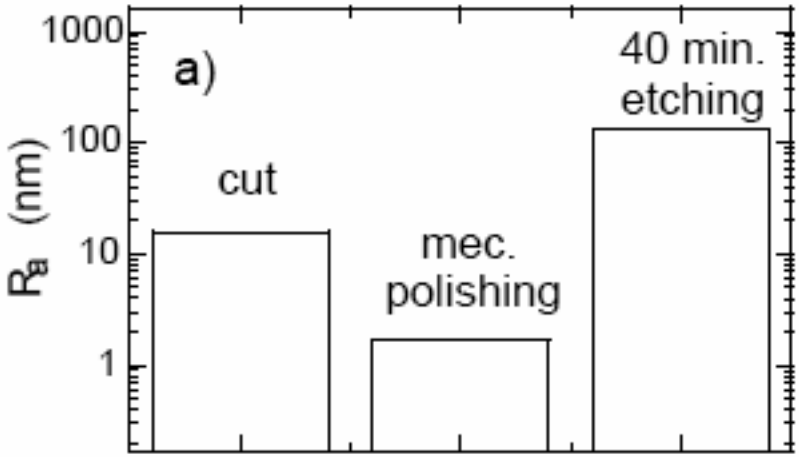
SEM images of the surface as-cut (left) and after 30 minutes of chemical polishing (right)

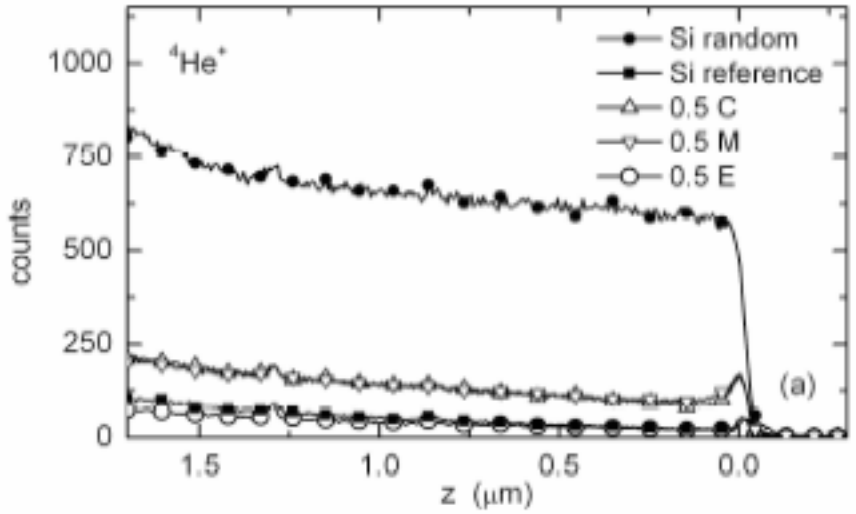


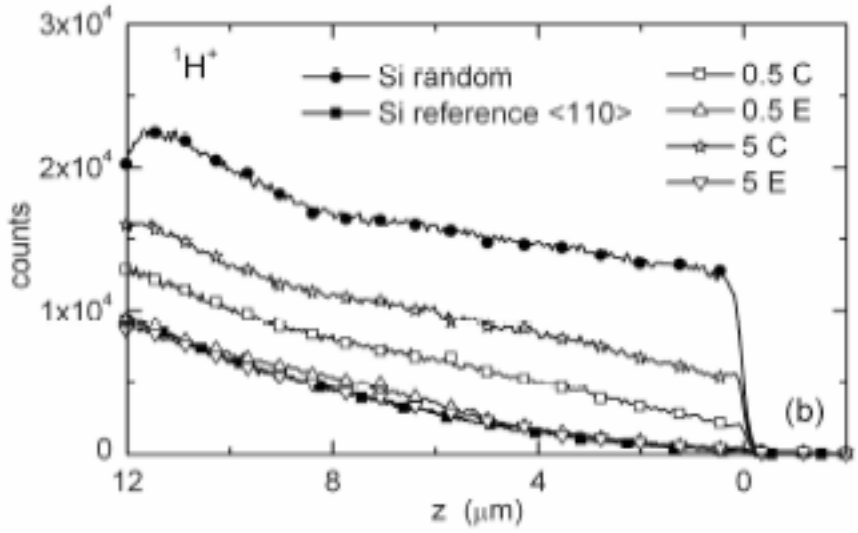
HCCC: crystal characterization



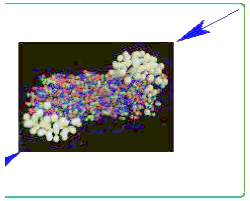
Rutherford back-scattering







INTAS 03-51-6155: the team



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V.T.Barakov - data taking and analysis
V.M.Biryukov - computer simulations and coordination
V.N.Chepegin - collimator settings and data taking
Yu.A.Chesnokov - major crystal expert;
V.I.Kotov - support of accelerator experiments

PNPI Saint Petersbourg :
Yu.M.Ivanov – head of lab, coordination
L.P.Lapina – calculations and data handling
A.A. Petrunin – X-ray diffraction measurements
V.V.Skorobogatov – crystal cutting and treatment

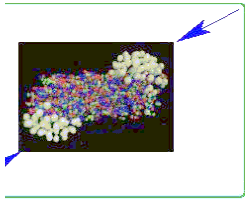
RINP Minsk :
Vladimir Baryshevsk – head of lab, coordination
Andrey Grubich
Alexandra Gurinovich
Sveltlana Siahlo
Viktor Tikhomirov

Ferrara University:
M. Ferroni – structural characterization
V. Guidi – structural characterization and coordination
C. Malagù – dicing-machine esperimentalist
G. Martinelli – head of laboratory
M. Stefancich – micromachining esperimentalist

University of Witwatersrand :
S. Connel– coordination,

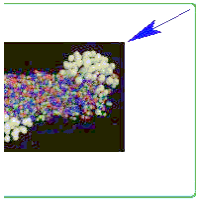
EU budget: 130 K€ in 36 months
Start date: July 2004

INTAS 03-51-6155: the basic goals



- Monte Carlo simulations for crystal channeling
  - Crystals with imperfections (IHEP)
  - Proton and Ion beams at various energies (IHEP)
  - Predictions for various experimental tests (IHEP)
- Crystal design and manufacture
  - Crystals with improved mosaic properties (PNPI)
  - Chemical etching of the crystal surface (Ferrara University)
  - Holders to bend the crystal with constant angles (IHEP & PNPI)
  - Diamond crystals (University of Witwatersrandz)
- Crystal characterization
  - Electron microscopy (Ferrara University)
  - X-rays (Ferrara University & PNPI)
  - Beams of α (Ferrara University using LNL - Legnaro infrastructures)
- Provide scenarios to use the crystals
  - High efficient extraction (IHEP & PNPI & RINP)
  - Collimation (CERN)
- Use the U70 accelerator in IHEP as a test bed for extraction and collimation

INTAS 03-51-6155: the achievement of the first year



- Proposal to

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 234, Issues 1-2 , May 2005, Pages 23-30
Relativistic Channeling and Related Coherent Phenomena in Strong Fields

doi:10.1016/j.nimb.2005.03.003 Cite or Link Using DOI

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- Full Text + Links
- PDF (310 K)

Actions
- E-mail Article

Crystal collimation as an option for the large hadron colliders

V.M. Biryukov[a], V.N. Chepegin[a], Yu.A. Chesnokov[a], V. Guidi[b] and W. Scandale[c],

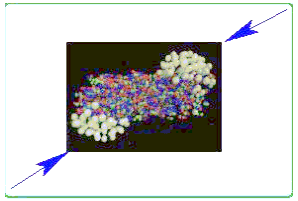
[a]Institute for High Energy Physics, 142281 Protvino, Russian Federation
[b]Department of Physics and INFN, Via Paradiso 12, I-44100 Ferrara, Italy
[c]CERN, Geneva CH-1211, Switzerland

Received 9 September 2004; revised 28 February 2005. Available online 23 May 2005.

iders

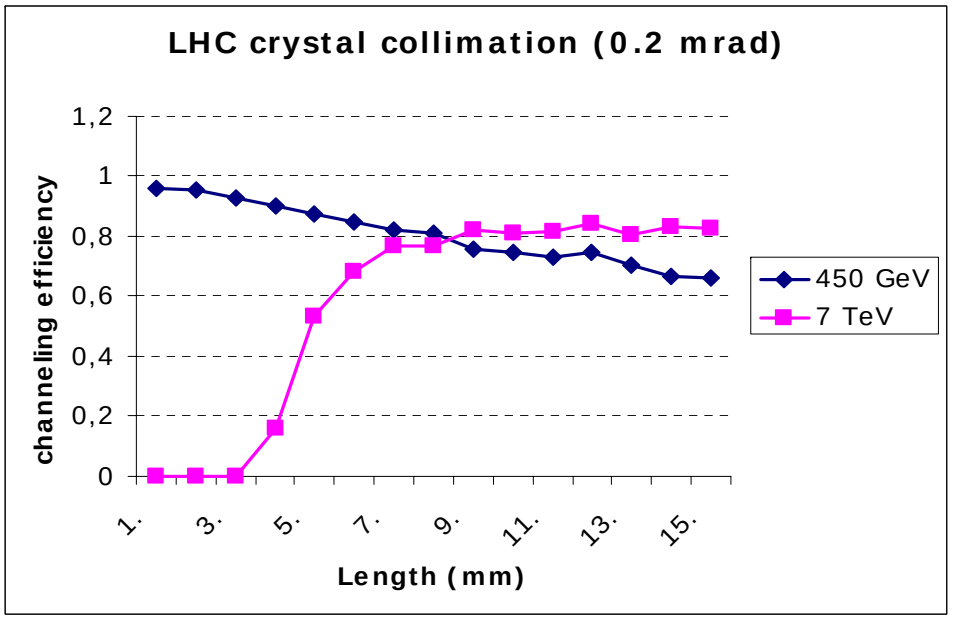
- Active participation to a CARE-HHH-APD *workshop* on Crystal Collimation in LHC http://care-hhh.web.cern.ch/CARE%2DHHH/CrystalCollimation/
- Contribution to the proposal of a *crystal channelling experiment at the CERN-SPS* to check the collimation efficiency - *simulations & hardware design*

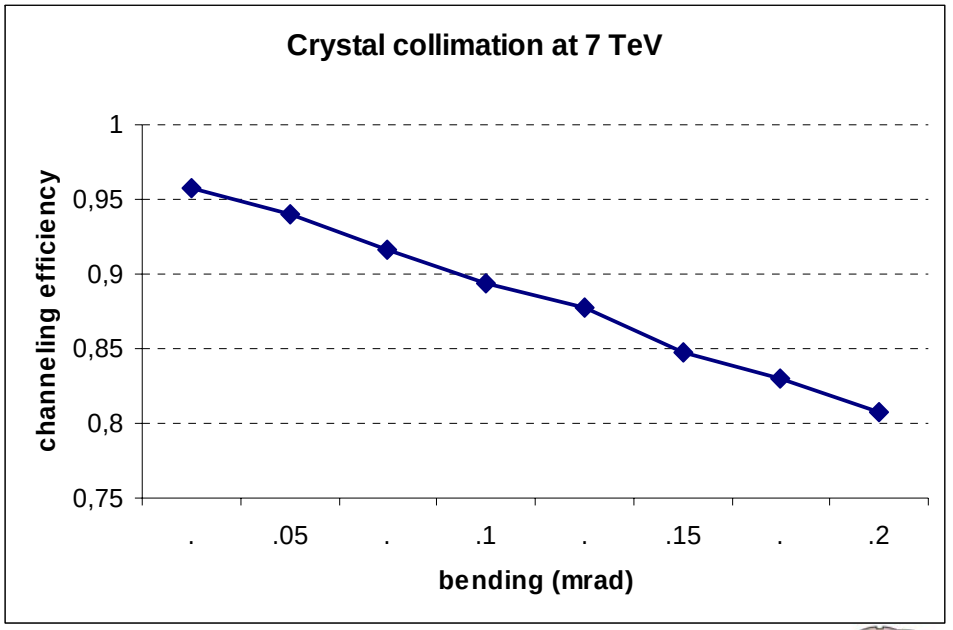
INTAS 03-51-6155: LHC collimation efficiency



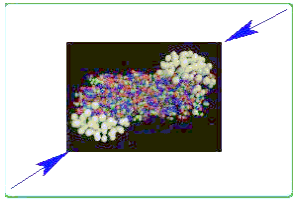
Channeling efficiency computed as a function of the crystal length along the LHC beam: at flattop 7 TeV and at injection 450GeV
The chosen bending angle is 0.2mrad.

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





CARE-HHH-APD CC05 workshop (March 2005)



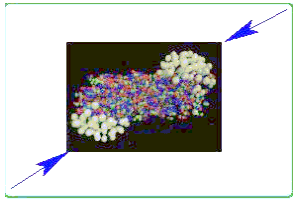
Proposal of a crystal collimation test in the SPS ring

'a new experiment should be proposed in the SPS to clarify issues related to small angle and large angle deflection in a primary collimator made by a state-of-the-art crystal in view of a possible use in the LHC collimation system'

Why a new experiment ?

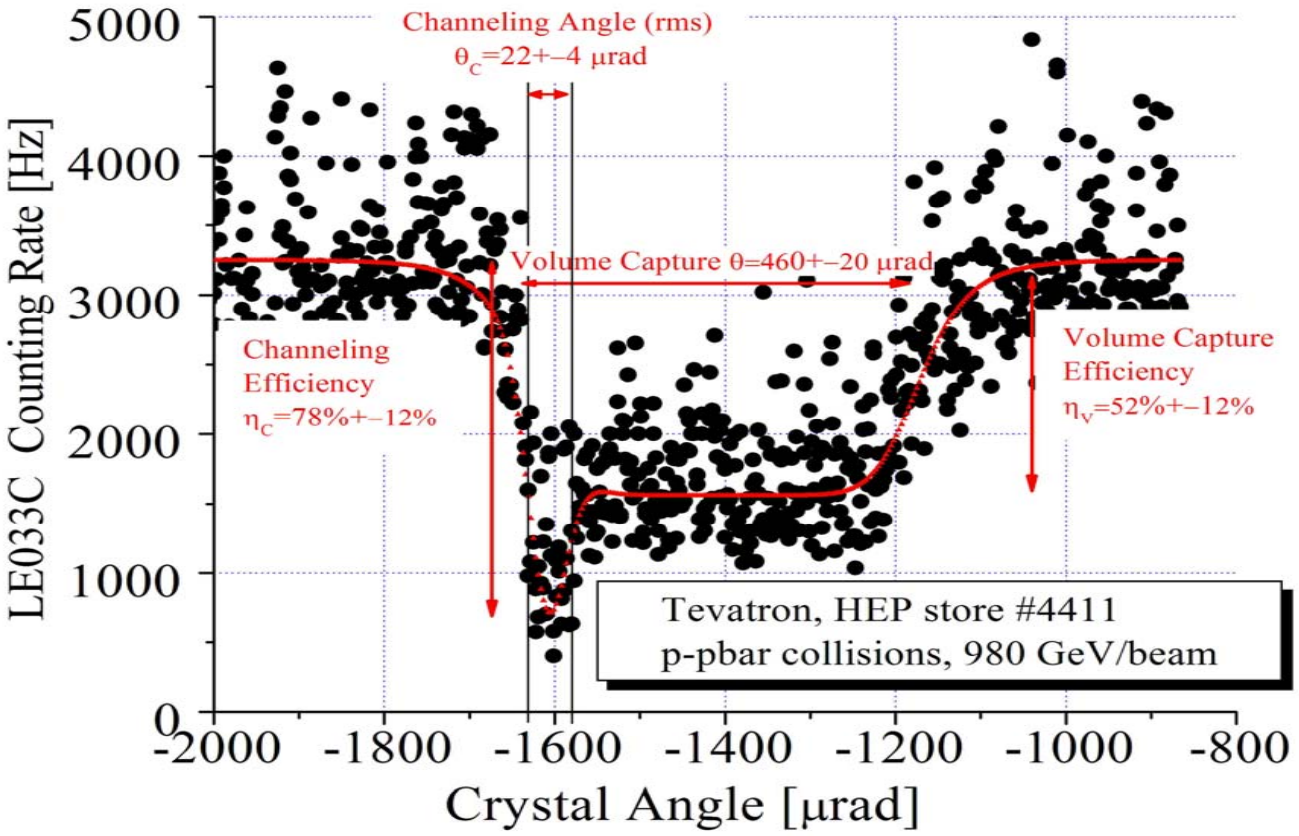
- The experience at U70 is very promising
- There is a strong incentive to propose collimation upgrade (we need however guidance from RHIC ad FNAL experiences)
- There are proposals to exploit crystal in LHC experiments (ATLAS CMS and TOTEM)
- Considerable improvement were made in crystal production
  - More homogeneous bending radius using strip crystals with anticlastic curvature (the Russian way)
  - "perfect" surface with no amorphous layer using chemical etching (the Italian way)

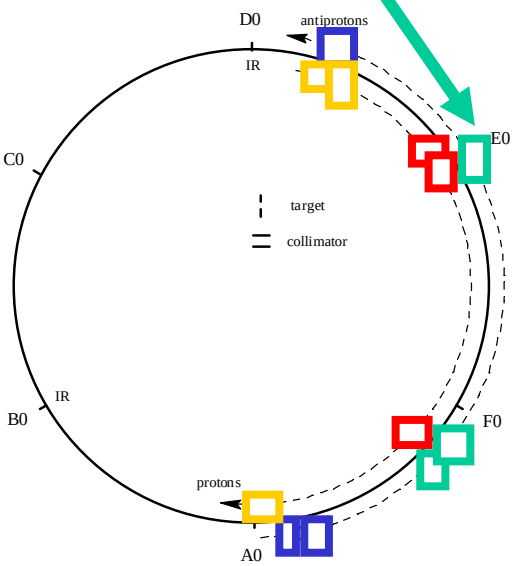
Mini workshop on crystal channeling (December 2005)



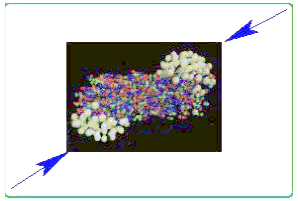
Crystal Collimator in E0 replacing a Tungsten Target

FNAL results (2005)

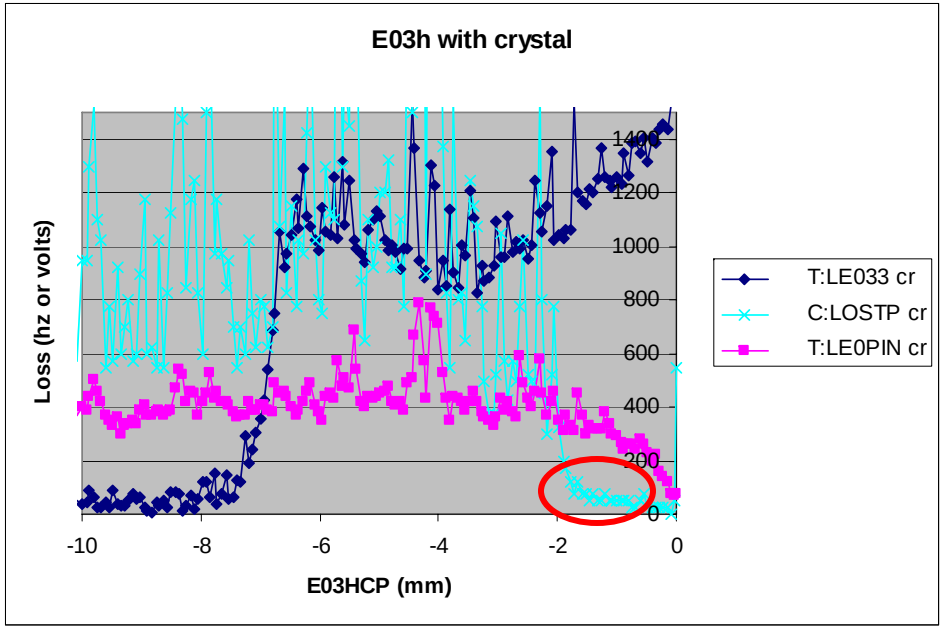


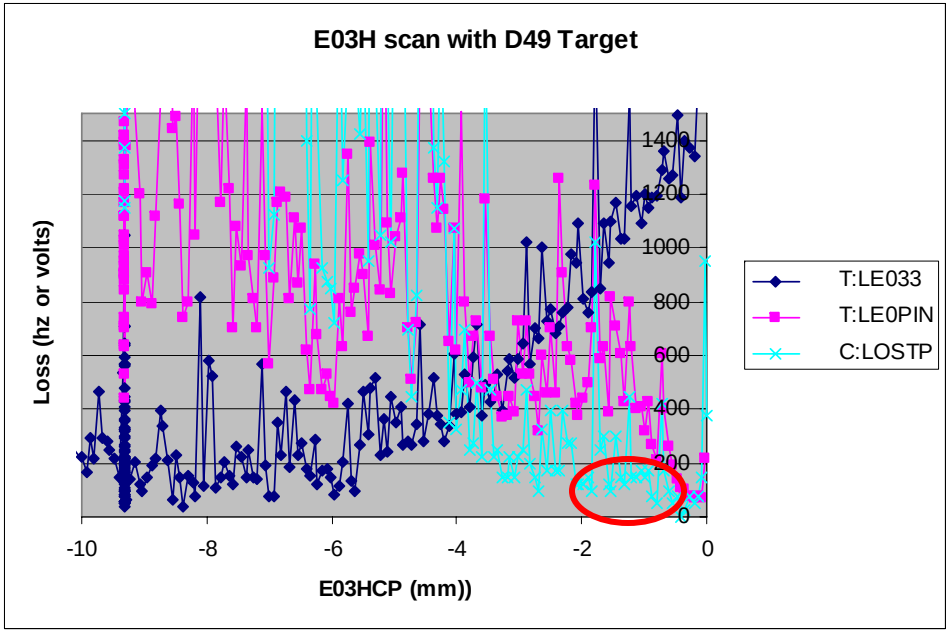


Mini workshop on crystal channeling (December 2005)



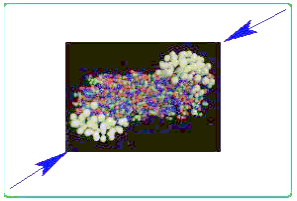
Crystal versus Tungsten target performance at FNAL (2005)



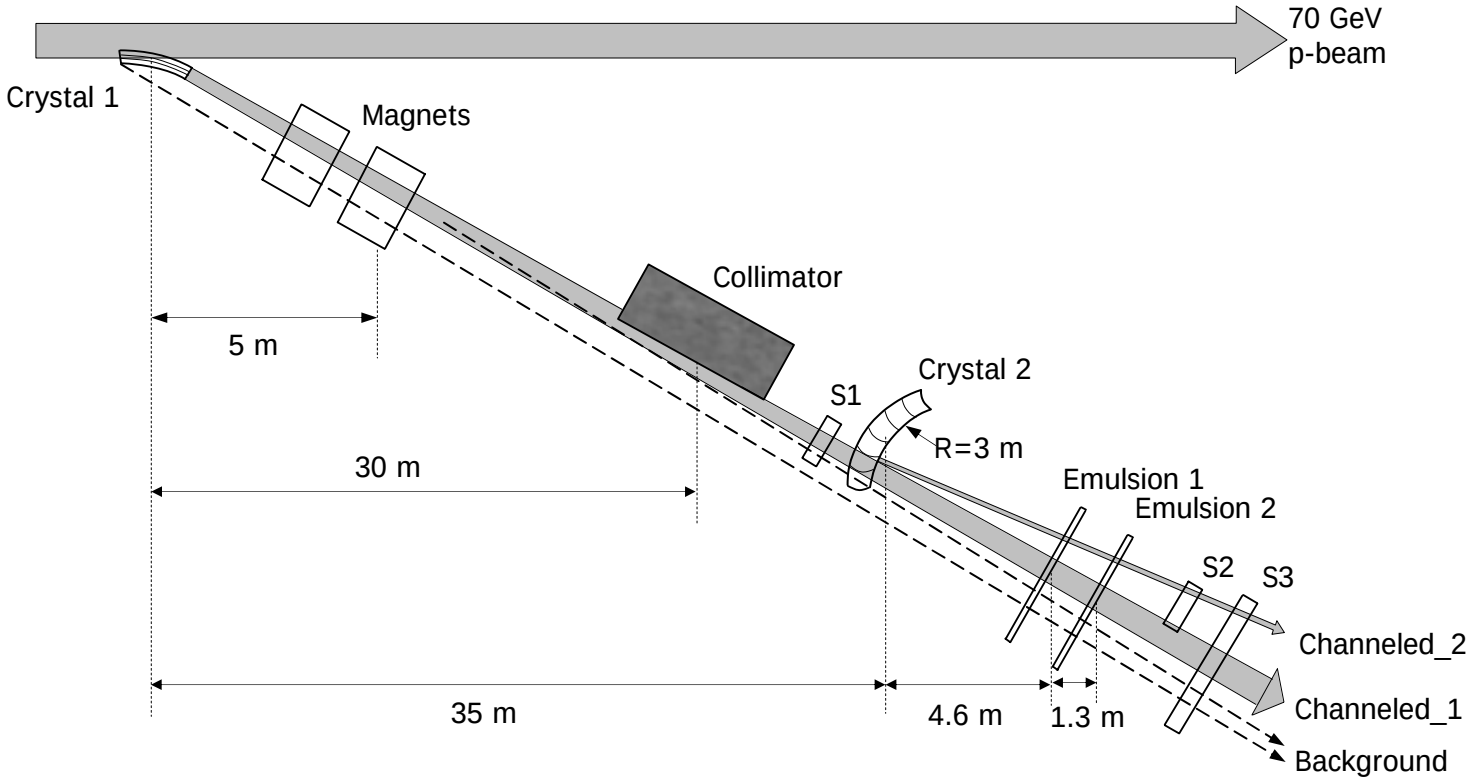


Using the crystal, the secondary collimator E03 can remain further (-1 mm or so) from the beam and achieve almost a factor of 2 better result!

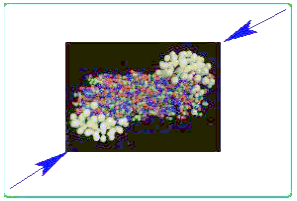
Mini workshop on crystal channeling (December 2005)



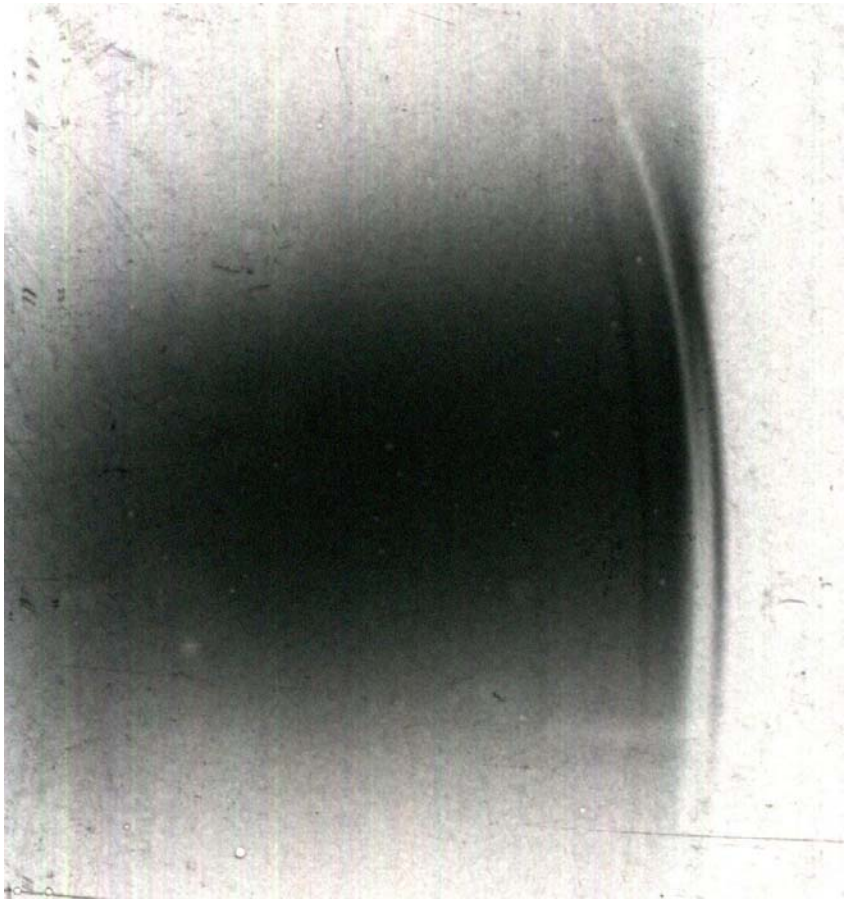
Scheme of experiment crystal extraction at IHEP with 70 GeV protons

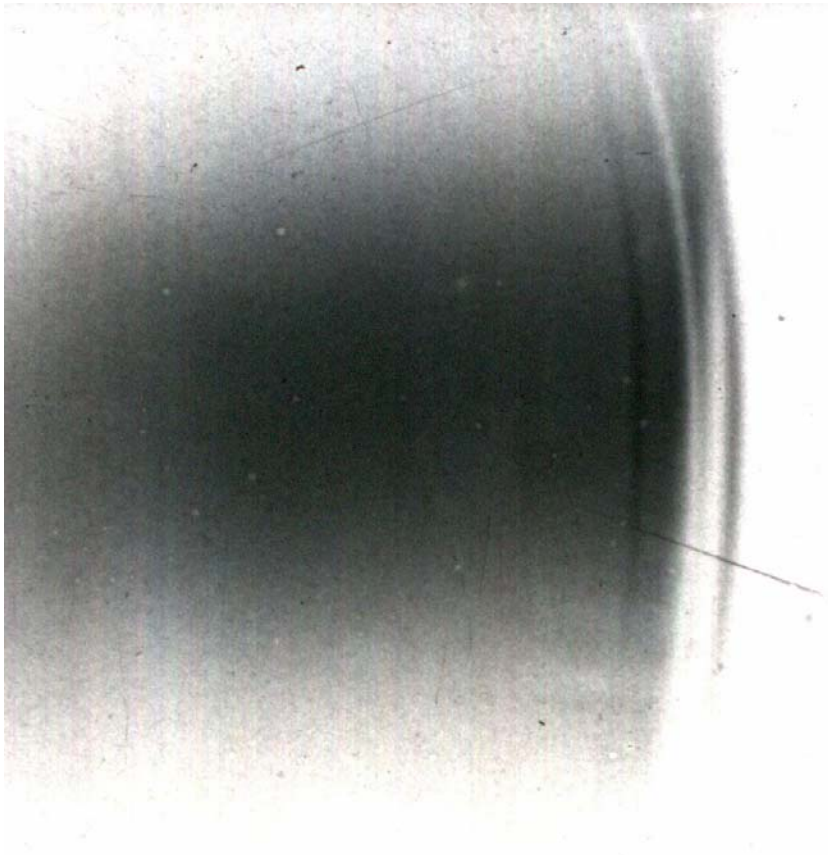


Mini workshop on crystal channeling (December 2005)

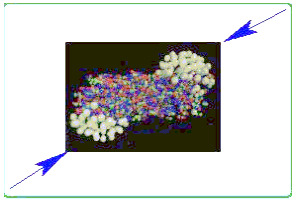


Exposure of emulsions 1 and 2 made at IHEP in 2002

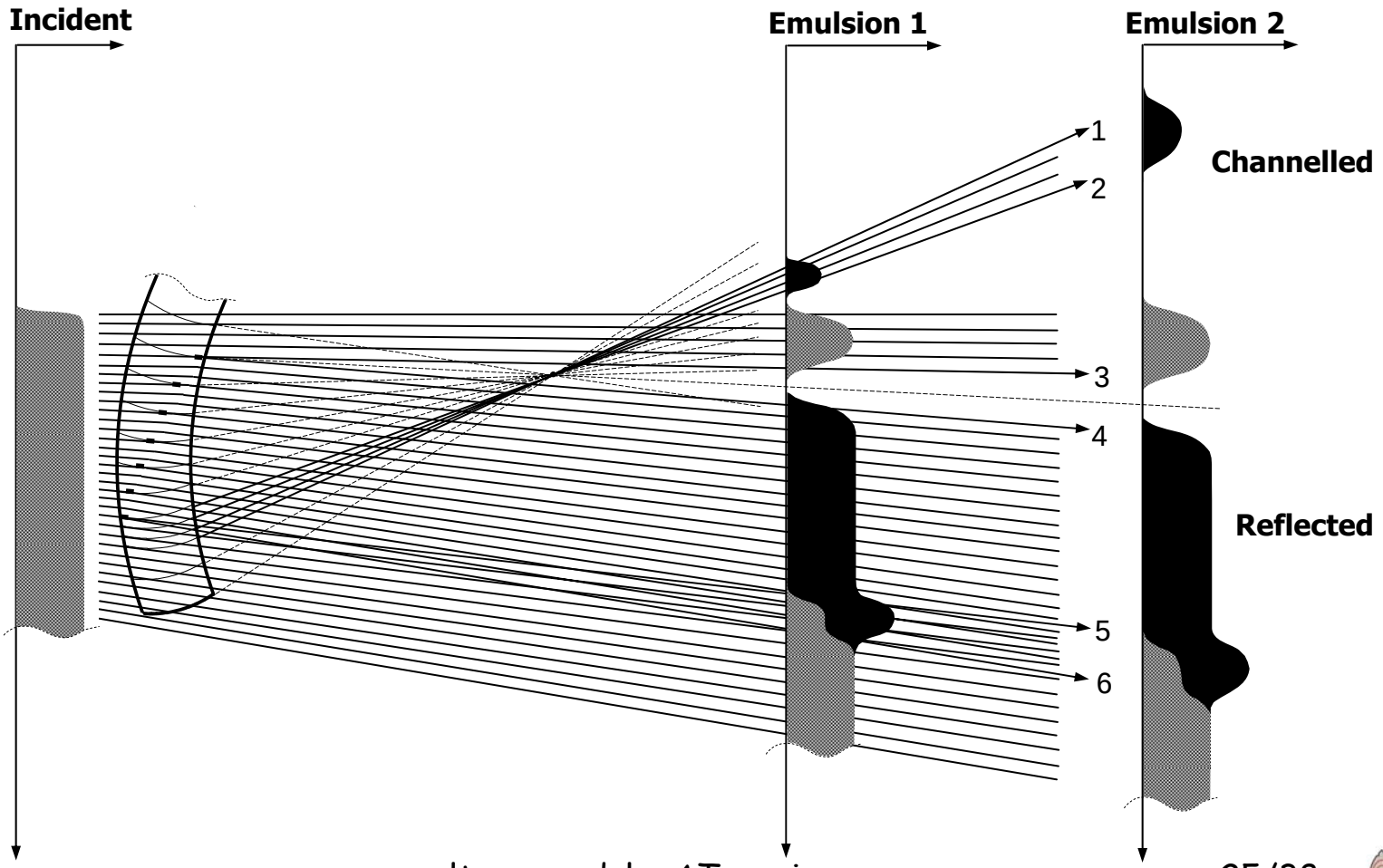




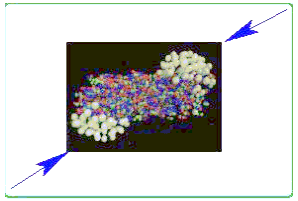
Mini workshop on crystal channeling (December 2005)



Interpretation of the IHEP results



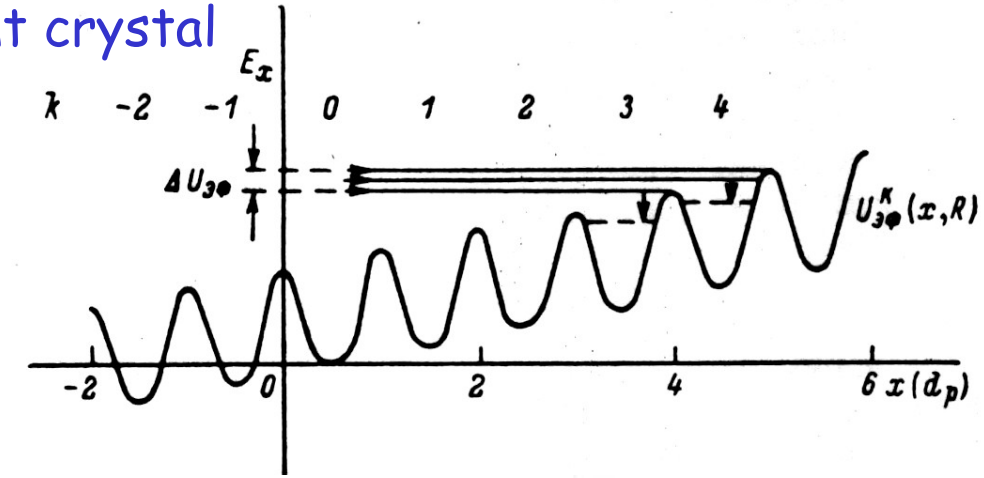
Mini workshop on crystal channeling (December 2005)



Prediction of beam reflection in bent crystal

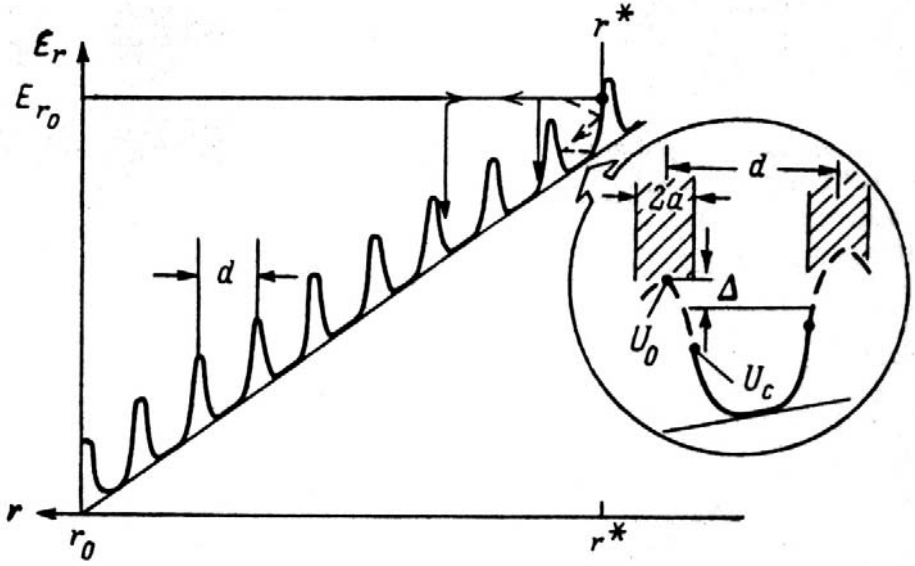
A.M.Taratin and S.A.Vorobiev,

Sov. Journal of Technical Physics, v.55, p.1598, 1985 (in Russian)

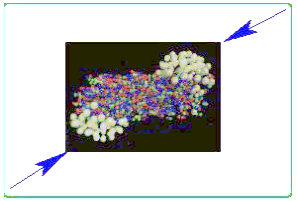


O.I.Sumbaev,

The theory of volume capture by a curved crystal in the channeling regime, Preprint LIYaF-1201, 1986 (in Russian)

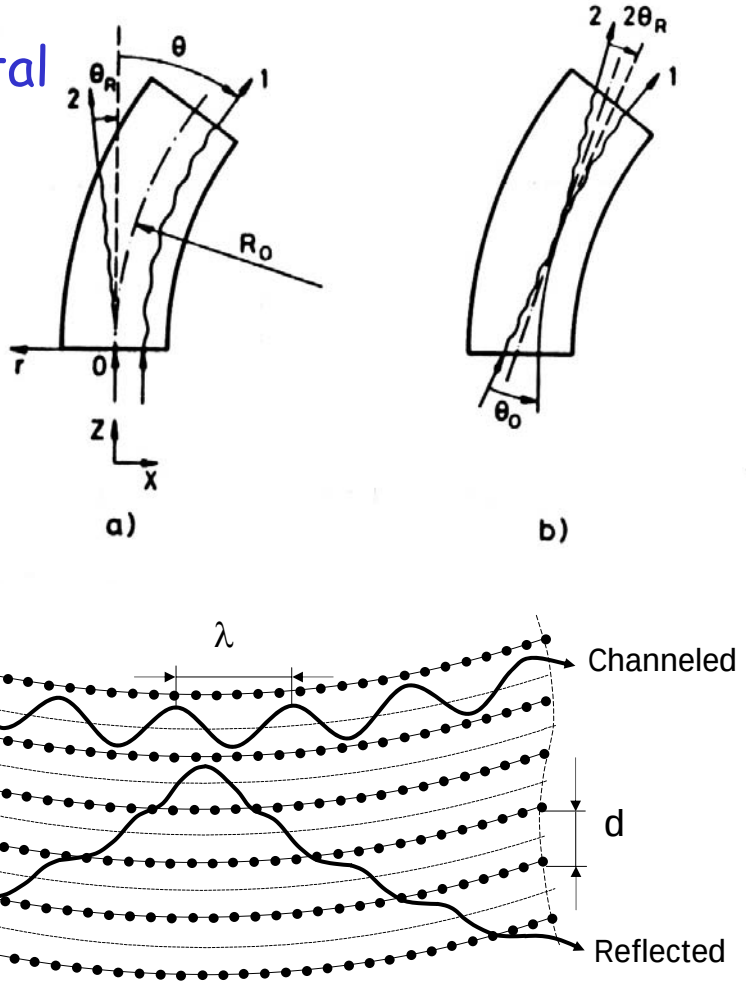


Mini workshop on crystal channeling (December 2005)

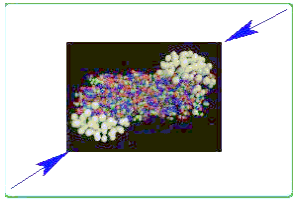


Prediction of beam reflection in bent crystal

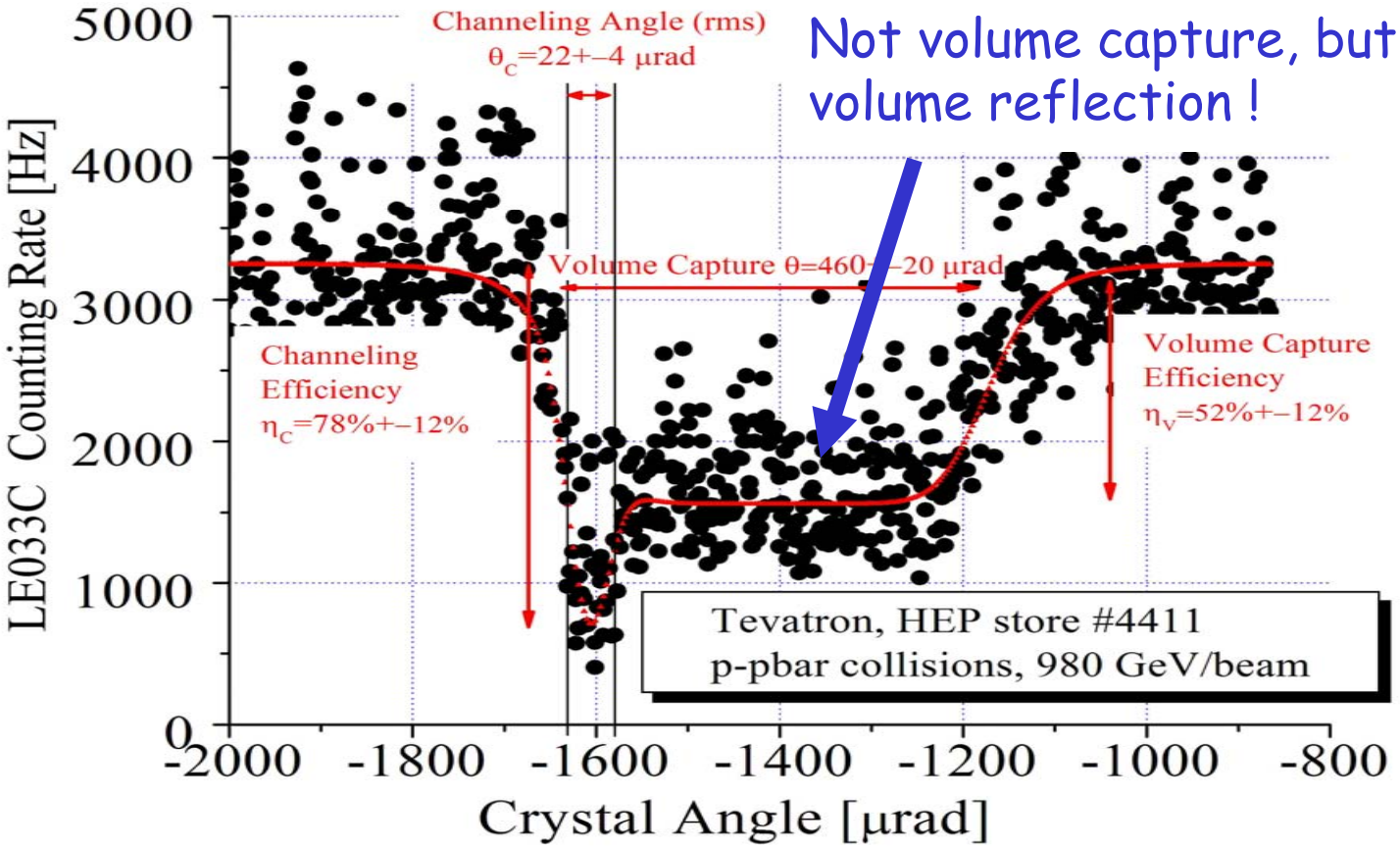
A.M.Taratin and S.A.Vorobiev,
Phys.Lett. A119 (1987) 425
and
A.M.Taratin and S.A.Vorobiev,
NIM in PR B26 (1987) 512



Mini workshop on crystal channeling (December 2005)

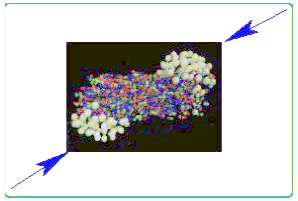


1 TeV Channeling at the Tevatron, October 5, 2005

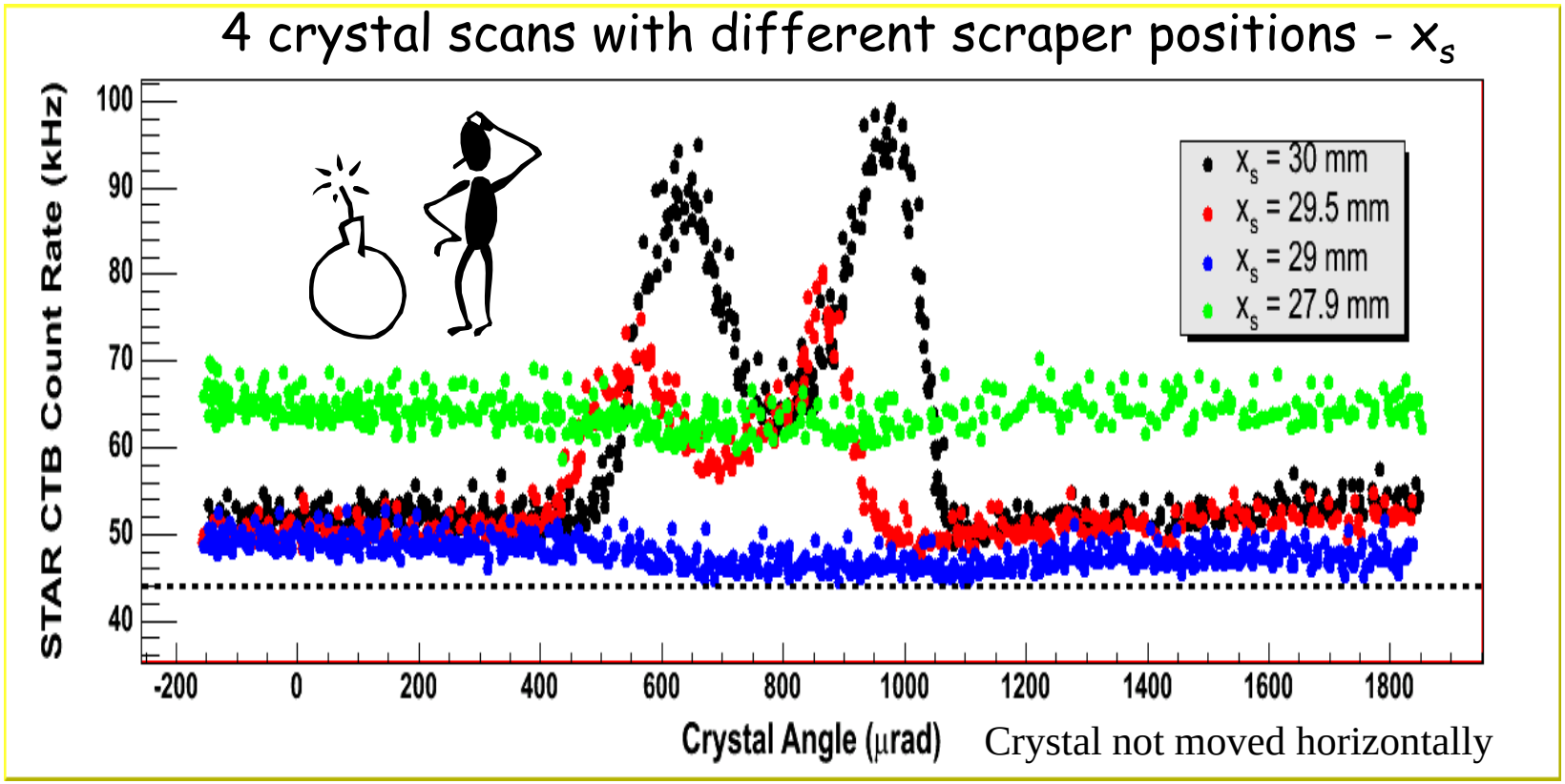


The observed tail beside the channeling peak is most likely induced by beam reflection into the crystal itself

Mini workshop on crystal channeling (December 2005)

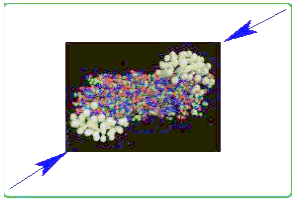


STAR Background during crystal collimation test at RHIC



The observed increase of background (black and red plots) is most likely induced by beam reflection into the crystal itself

Where do we stand ?



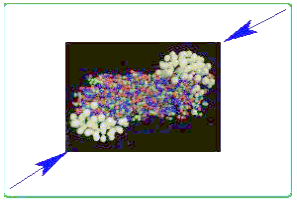
- Crystal collimation is considered promising for LHC
  - To increase collimation efficiency in "phase II"
  - To ensure ion collimation with a reasonable efficiency
- We still miss a fully convincing feasibility proof
  - The crystal collimation test at RHIC produced a negative evidence
  - The test at FNAL produced moderately positive results in collision mode only
- The crystal reflection phenomenon is a crucial new finding
  - The effect has been observed in emulsions
  - Its probability is unknown: emulsions are not suited to evaluate flux
  - If neglected reflection may hamper collimation efficiency (see RHIC experience)

New experiments are needed to clarify the open issues

Resources available:

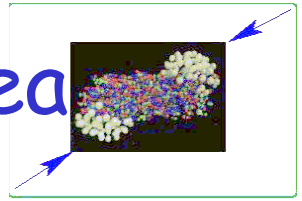
- CERN/EU-INTAS/INFN
  - INTAS 03-6155: funded for another 18 months
  - INTAS 05-7525: just approved for 36 months
  - HCCC-INFN: operational for the second year
- FNAL
  - An experiment is on-going, but with a mediocre and non characterized crystal
  - The instrumentation is not adequate to measure the extraction nor the collimation efficiency

What to do at CERN ?



- The experiment at FNAL needs crystals of better quality, perfectly characterized
  - ➔ They can be provided within INTAS and HCCC programmes
  - ➔ A test facility in the SPS North experimental area will be of a crucial interest to evaluate the probability of crystal reflection and the other crystal properties
- The possible use of crystal for phase II collimation at LHC is to be extensively tested
  - ➔ A test "à la RD 22" to be implemented in the SPS, complementing the FNAL experiment

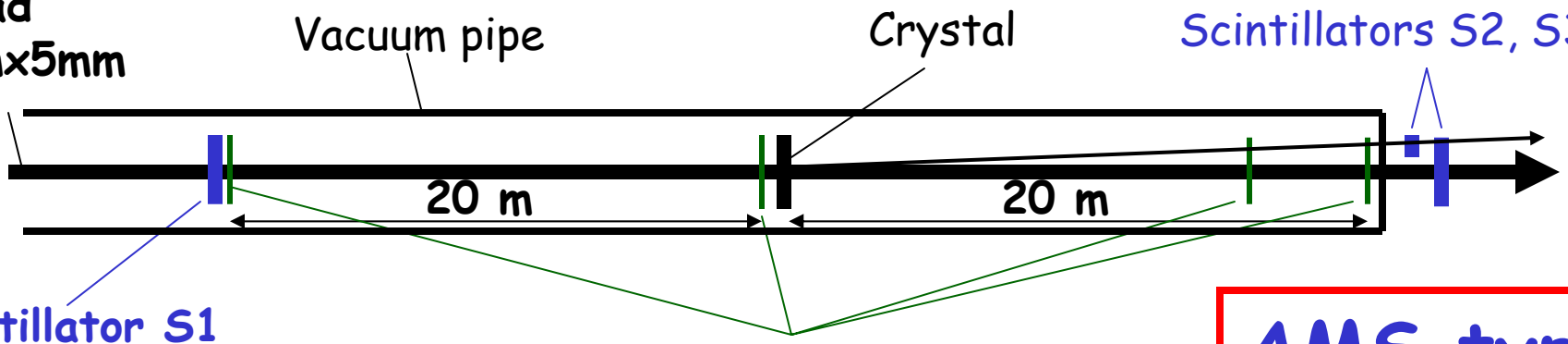
Experiment in the SPS north area



H8 Beam Line - 400 GeV, low divergency protons

10^5 protons/s
400 GeV/c
3μrad
5mmx5mm

Beam line parameters taken from
C.Biino et al., PL B403(1997)163



Scintillator S1
0.5 mm (1 μrad)

Silicon with X- and Y-strips
X-position resolution 30 μm
0.3 mm thick (1.5 μrad)

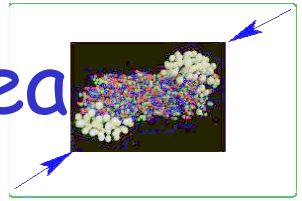
AMS type detector

$\psi_{critical} \approx$ **10 μrad**

$\theta_{bending} \approx$ **100 μrad**

Angular resolution=√2x30μm/20m ≈ 2 μrad

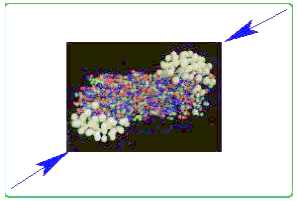
Experiment in the SPS north area



Resources requested

- INFN should provide the experimental set-up
  - ➔ A funding request is pending in the "gruppo I", with a favourable preliminary decision, still conditioned to the formal approval of the experiment
- The beam line should be adapted and refurbished
  - ➔ 100 kCHF and 6 men-months (to be funded by CERN)
- The experiment should last a few years with 2 to 4 weeks of beam availability per year
  - ➔ 7 FTE (to be funded by INFN) for the procurement, the installation and the operation of the experimental set up
  - ➔ 2 FTE (to be funded by CERN) for coordination, data taking, data analysis and beam line maintenance
  - ➔ 5 FTE (to be funded by INTAS and HCCC) for the refined experiment design, computer simulations, crystal procurement, preparation and pre-characterization, and for mechanical supports, motors and goniometers

Collimation test in the SPS: preliminary analysis



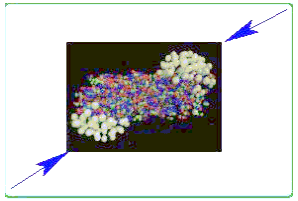
Goals

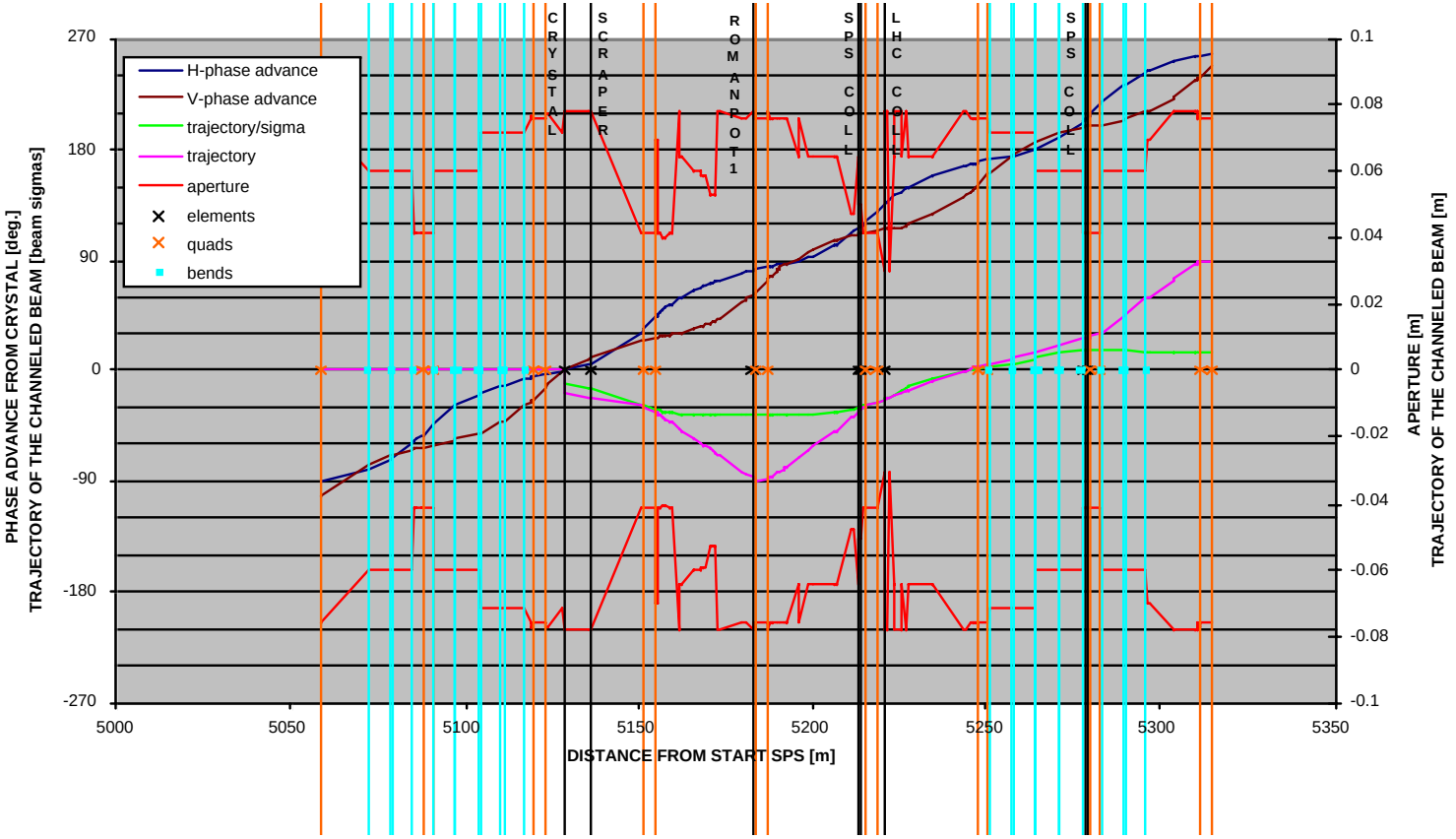
- Propose and implement sound ways to establish the collimation efficiency
- Determine the collimation efficiency at about 0.2 and 4 mrad as requested for LHC
- Long-term performance studies

Possible implementation

- Two different crystals and experimental set-ups required to study large/small angle channeling/collimation
- For the small angle set-up ➔ compromise (not optimum)
- Use of the old RD22 set-up and of the 2004 Roman pot impossible ➔new set-up requested
- Detailed simulations of crystal behaviour in progress ➔ Feodotov-IHEP
- Detailed engineering/integration and "aperture compatibility study" in progress ➔INFN team
- Compatibility with near-by instrumentation (BDI/VAC) acceptable

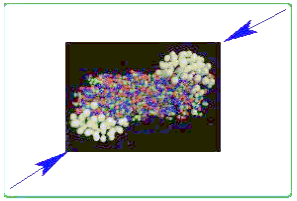
Collimation test in the SPS: proposed scenario in LSS5





The crystal is sitting at 10 sigmas from the beam centre

Collimation test in the SPS: resources



CERN contribution over 3 years (1.5 MCHF total)

- 5 men-years: 1 for coordination, 1 for installation, 1 for controls, 2 for handling the experiment and analysing the results (1.25 MCHF)
- 250 k CHF in kinds

INTAS/CERN programmes

- 25 men-years funded over 3 years (230 kEuro total)
  - Programme 03-6155 on-going with 130 k Euro funding
  - Programme 05-7525 just approved with 130 k Euro funding

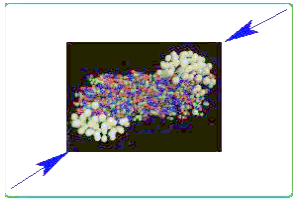
INFN gruppo I

- Preliminary request to fund the detector: informal approval for funding

INFN HCCC programme

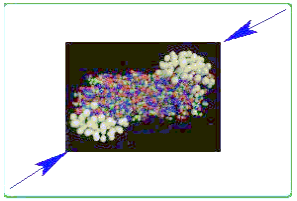
- Funded with about 100 k Euro/y (for travels and kinds) + 4 FTE

Collimation test in the SPS: resources in kinds



ITEM	Cost (CHF)
Build new vacuum tanks for Goniometers	CHF 15,000
2 Goniometers	CHF 15,000
Stepping motors for crystals orientations	CHF 2,500
Control electronics	CHF 6,000
Cabling	CHF 6,000
Roman pot station mechanics	CHF 100,000
Stepping motors	CHF 4,000
Cooling if needed	CHF 20,000
Cabling	CHF 6,000
Mechanics for Silicon in roman pot	CHF 5,000
Printed board with Silicon bonded	CHF 10,000
Analog electronics	CHF 15,000
Cabling	CHF 6,000
Readout electronics for analog	CHF 30,000
GEM for external telescope	CHF 50,000
Assembly	CHF 10,000
Analog electronics	CHF 50,000
Cabling	CHF 10,000
Readout electronics	CHF 20,000
total in kinds	CHF 380,500
contingency	CHF 119.500
TOTAL	CHF 500.000

Conclusive remarks



- Some international experts are convinced that crystal collimation may work and may be beneficial for LHC
- However a solid experimental evidence is still missing.
- On-going programmes over the word (FNAL, INFN, INTAS) are focused on the specific goal of providing this evidence
- CERN management should decide if this matter is of interest for LHC performance and if there are enough resources to complement the on-going international effort
- A scenario with a minimal effort from CERN is to launch and support the H8 experiment in view of a collaboration with FNAL for the final proof of the crystal collimation in the Tevatron
- A more ambitious scenario is to launch ALSO the SPS experiment to enhance and complement the on-going international effort on this matter

The right time for a decision is NOW