# CRYSTAL ASSISTED MANIPULATION OF HIGH ENERGY PARTICLE BEAM IN UA9

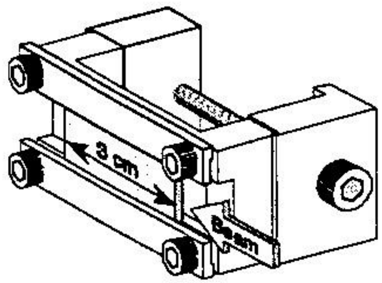
W. Scandale

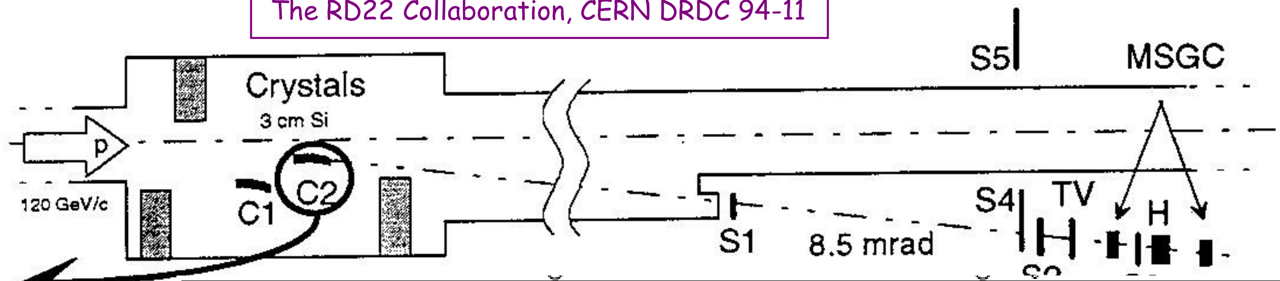
# outlook

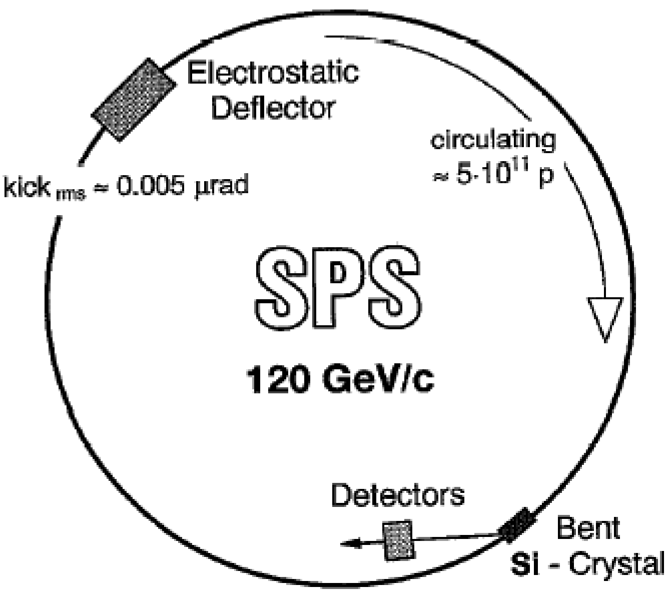
- Historical perspective
  - RD22 at the CERN-SPS as a test bed of beam extraction at LHC
  - E853 at the FNAL-Tevatron as a test bed for the SSC
  - The CERN-INTAS programmes on crystal technology
  - Crystal collimation test at RHIC
  - Crystal collimation test at the Tevatron
- Collimation in LHC
- UA9 as a test bed for crystal assisted collimation at LHC
- Radiation hardness of crystals

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

The RD22 Collaboration, CERN DRDC 94-11



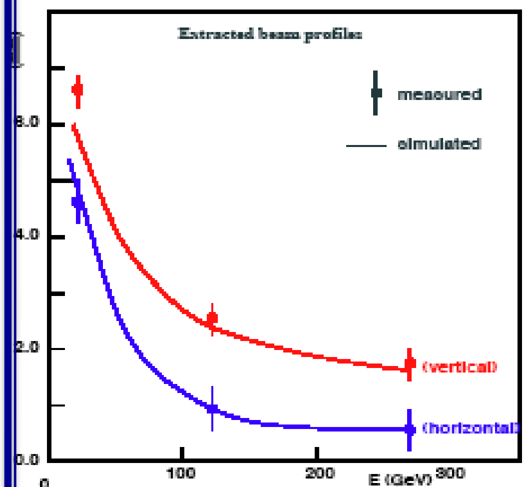

| | Crystal 1 | Crystal 2 |
|---|---|---|
| beam intensity (protons) | $(7.0 \pm 0.1) \cdot 10^{11}$ | $(3.7 \pm 0.1) \cdot 10^{11}$ |
| beam lifetime (hrs) | $20 \pm 2$ | $12 \pm 1$ |
| protons lost per second | $(6.7 \pm 0.6) \cdot 10^{6}$ | $(8.9 \pm 0.7) \cdot 10^{6}$ |
| protons detected per second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

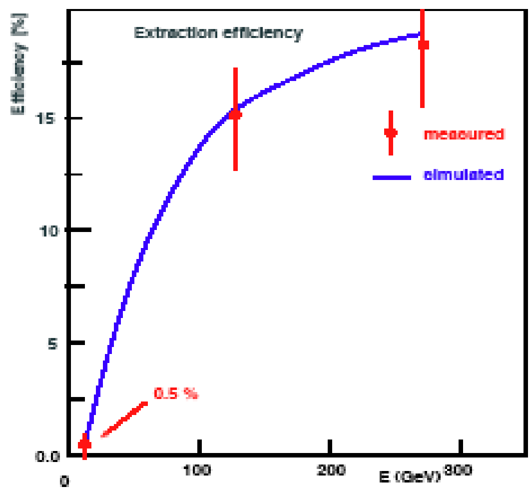
- Large channeling efficiency measured for the first time
- Consistent with simulation expectation extended to high energy beams
- Experimental proof of multi-turn effect (channeling after multi-traversals)
- Definition of a reliable procedure to measure the channeling efficiency

# 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

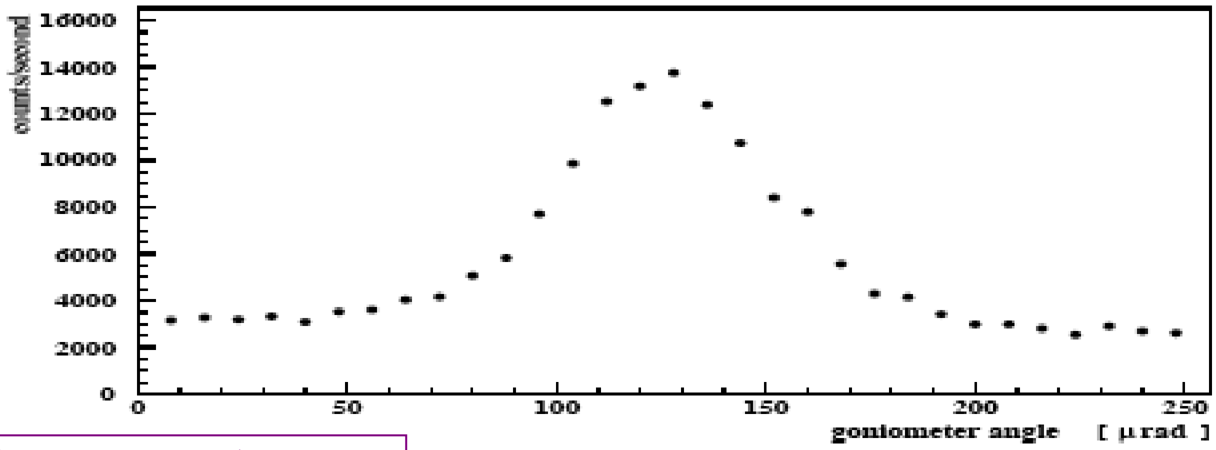
- Gaussian distribution
- $\langle\theta\rangle = 0$
- $L_{eff}$ is the effective scattering length

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

$X_0$ = 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*

# 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

# RD22: what for?

## Extraction scenario from LHC

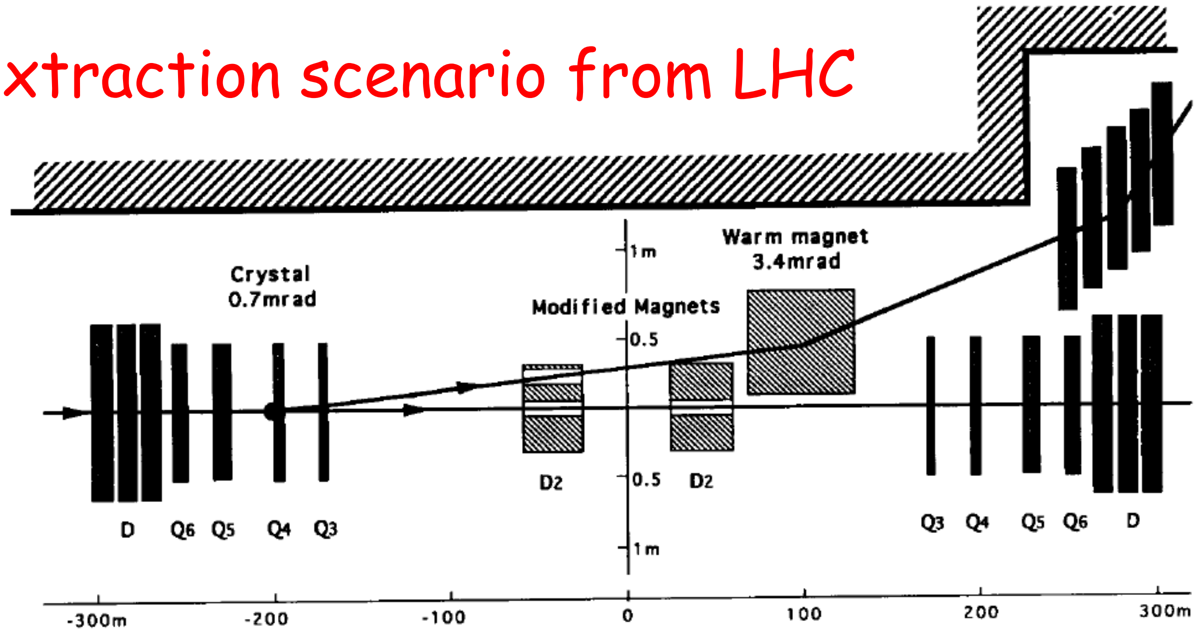
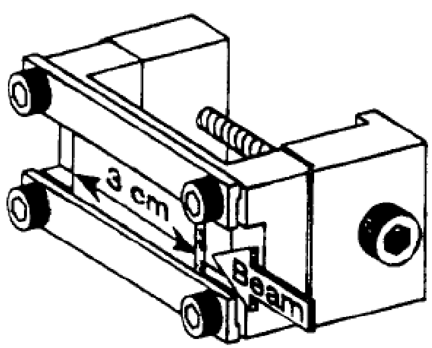
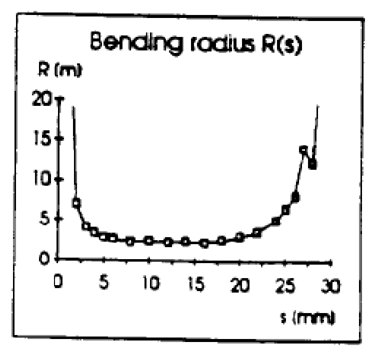
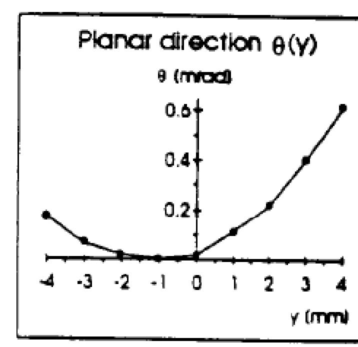



Fig. 2. Schematic layout of vertical halo extraction using channeling in a bent silicon crystal. After the warm septum magnet the extracted beam is bent by a string of five superconducting dipoles of the LHC type [14].

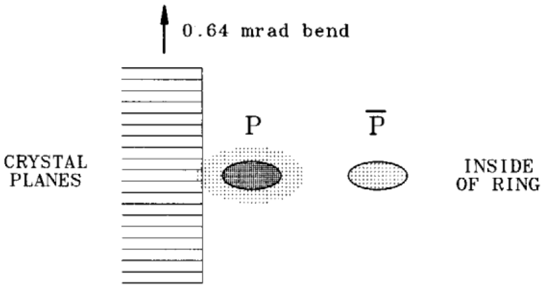
Extraction efficiency
limited by
the crystal technology



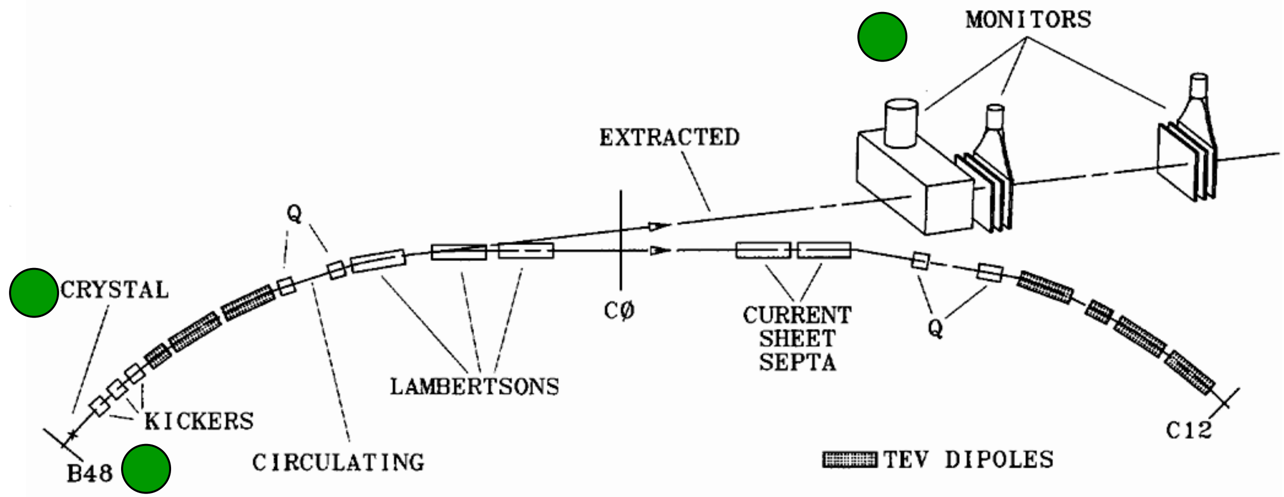



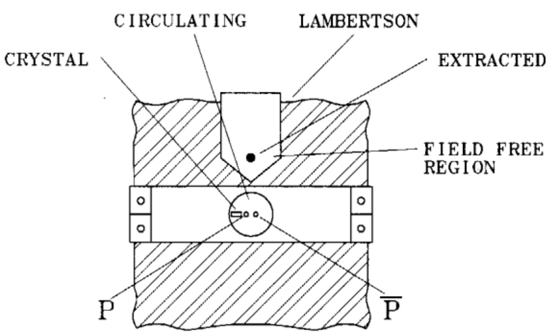



# E853: extraction of 900 GeV protons (FNAL: 1993-98)




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: short crystals (2001)

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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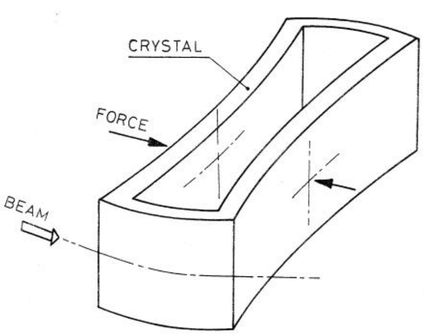
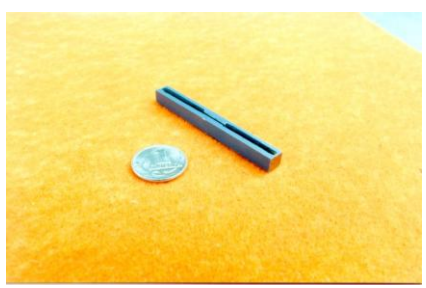
(Received 12 April 2001; published 14 August 2001)

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 $\sim 10^{12}$ 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.

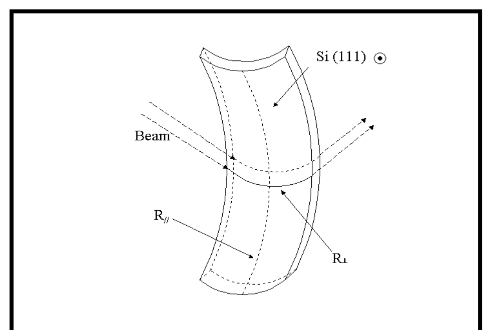
DOI: 10.1103/PhysRevLett.87.094802 PACS numbers: 41.85.–p

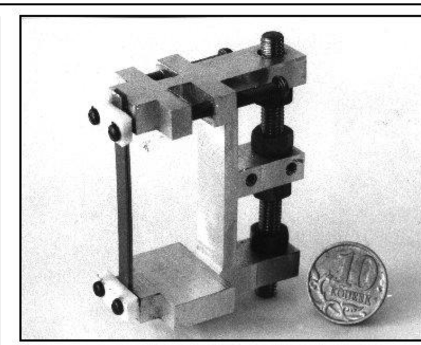
## Two examples of bent short crystals



O-shaped crystals 3÷5 mm long

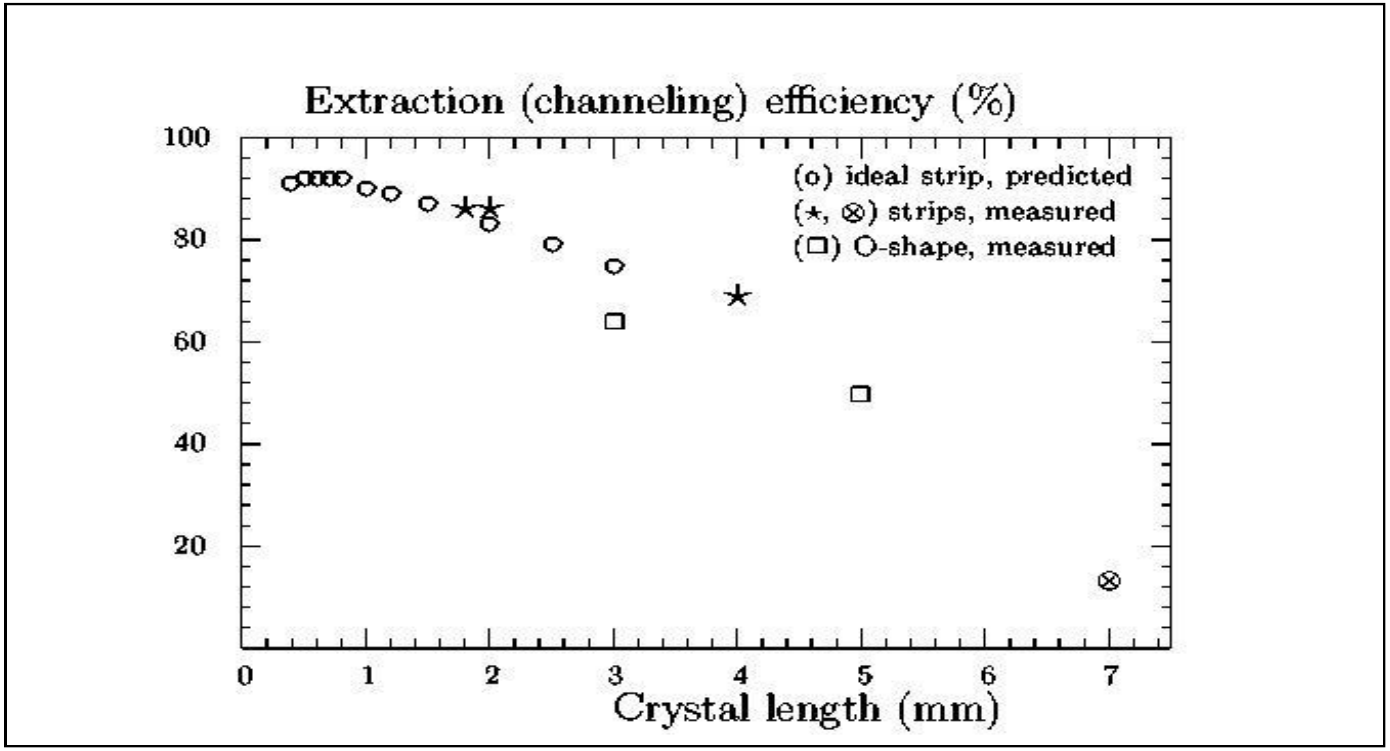


Saddle shaped crystals 0.5×2 ×50 mm$^3$.

The saddle shape is induced by anticlastic forces

# INTAS 00-132: short crystals (2001)



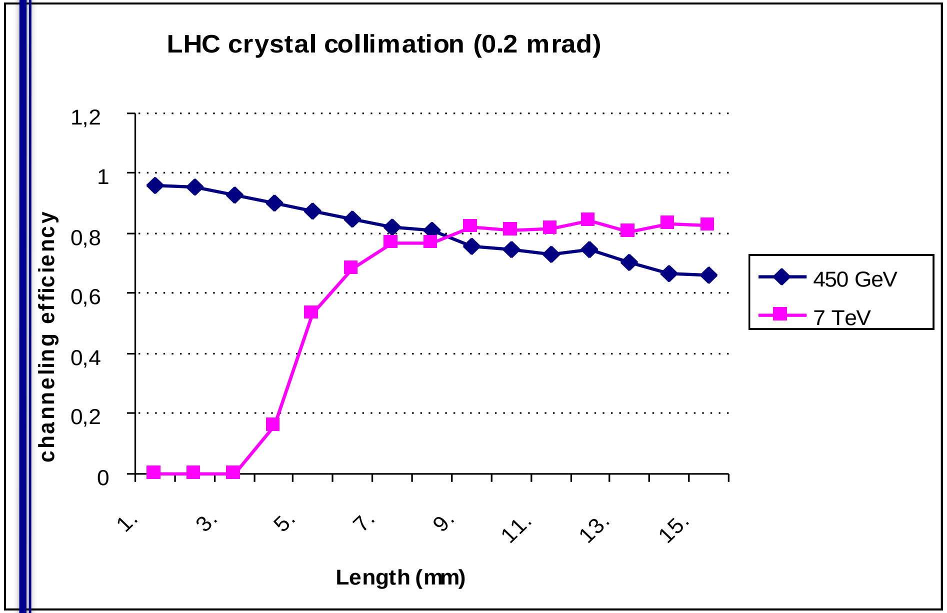

- Efficiency predicted in a perfect strip crystal with 0.9 mrad bending (" ○ ")
- Efficiency measured using 70 GeV protons in IHEP U-70 (" ☆ □ ⌖ ")
- Crystal bending angle varied from 0.8 to 1.7 mrad

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

# INTAS 03-51-6155: extraction efficiency (2003)

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.



# RHIC crystal collimation (2001/05)

- Indirect experiment (measure particles disappearance) with Au and p runs
- Si crystal 5×1 mm with $\theta_B$=465 mrad located in interaction region matching section
- Positioning not optimal (large beam divergence and $\alpha \neq 0$)
- Crystal bends in the same plane where it scrapes ⇒ sensitivity to horiz. halo

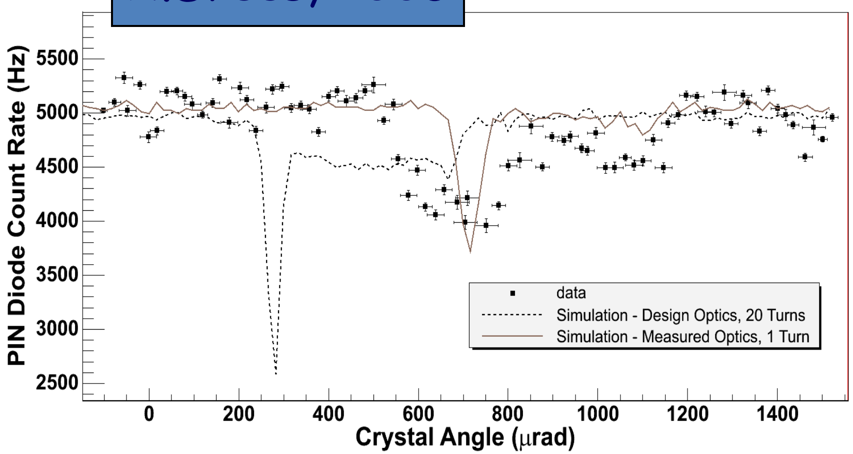
***No clear interpretation of the results!***

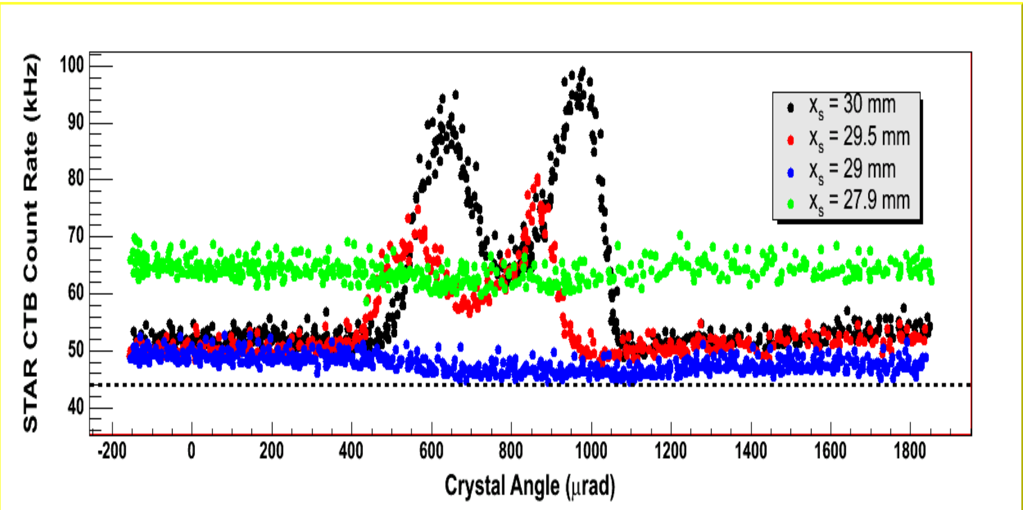
- Measured ch. efficiency (~25%) doesn't match theoretical predictions ( 56% with nominal machine optics). Better agreement and consistency when using measured beam divergence  need accurate knowledge of lattice functions.
- Multipass physics and halo distribution models too simplistic?
- Low channelling efficiency ⇒ collimation not successful & increased backgrounds !!

R.Fliller III, A.Drees, 2005

*STAR Background during crystal collimation*

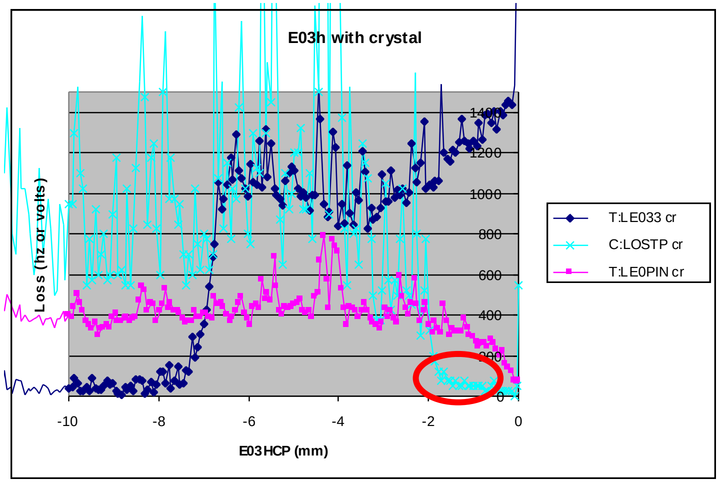
**Not conclusive & abandoned !**

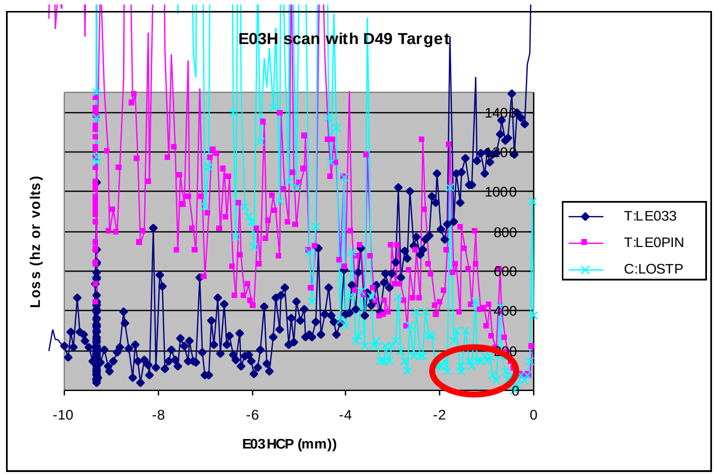


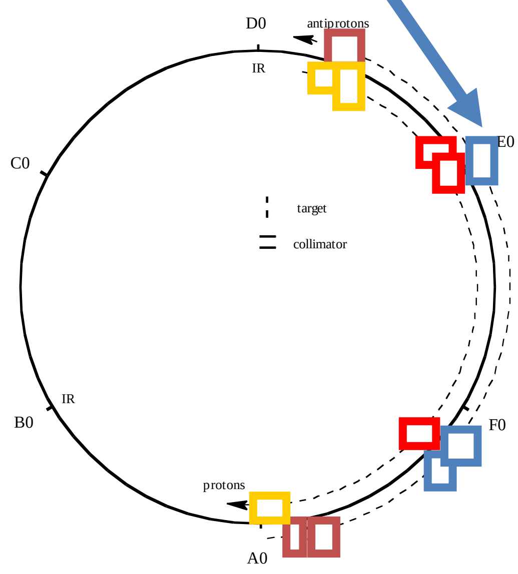
# FNAL crystal collimation (2005-2011)

Crystal Collimator in E0 replacing a Tungsten Target (2005)



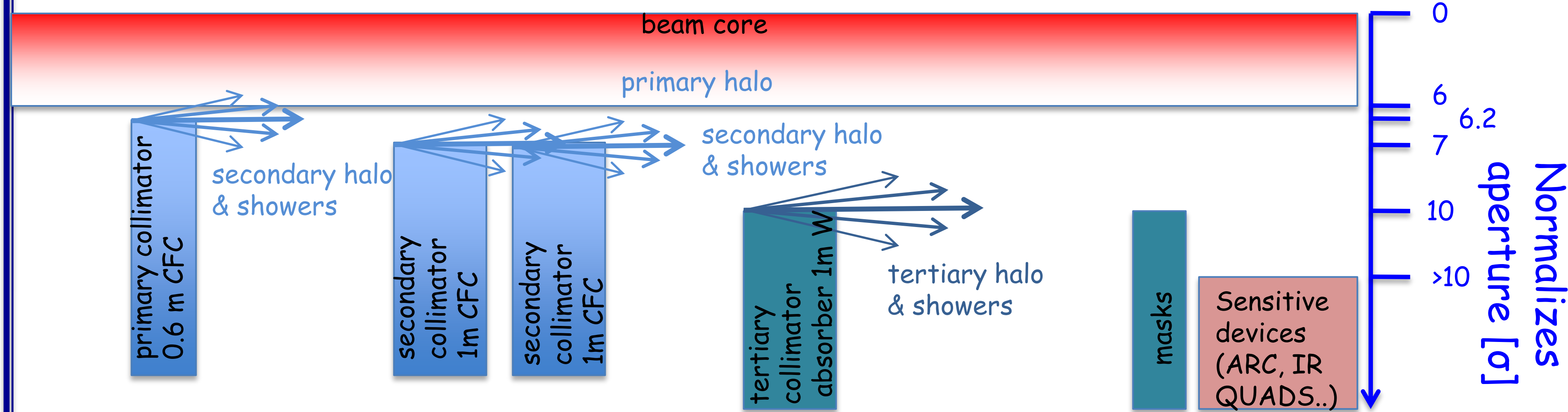

Tungsten scatterer




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!

# Multi stage collimation as in LHC

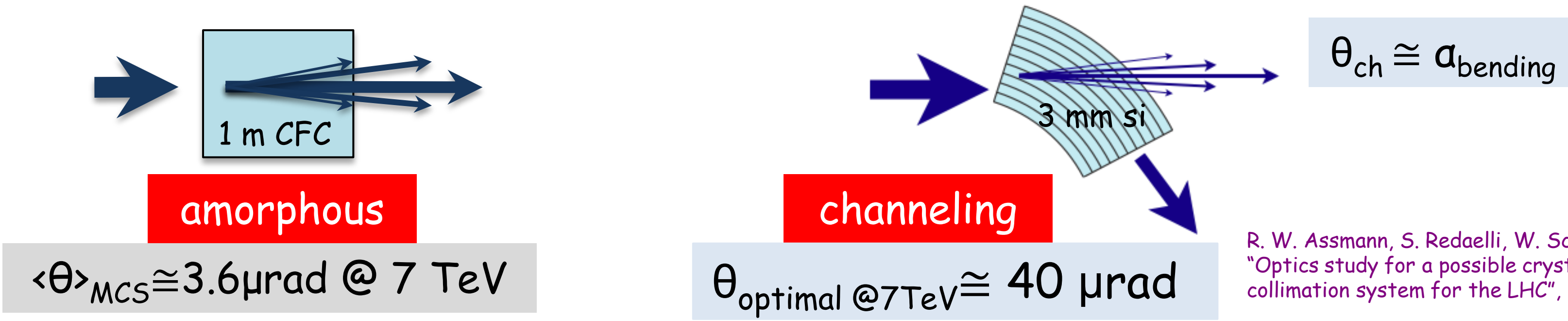
- The halo particles are removed by a cascade of amorphous targets:
  1. Primary and secondary collimators intercept the diffusive primary halo.
  2. Particles are repeatedly deflected by Multiple Coulomb Scattering also producing hadronic showers that is the secondary halo
  3. Particles are finally stopped in the absorber
  4. Masks protect the sensitive devices from tertiary halo



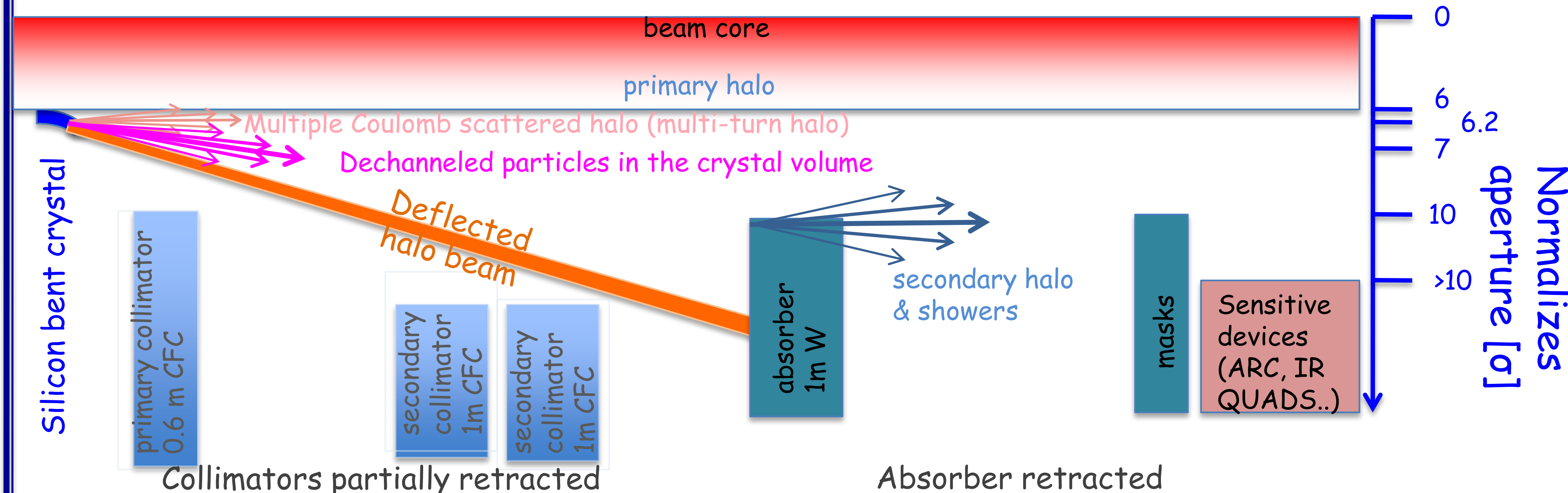

- Collimation efficiency in LHC ≅ 99.98% @ 3.5 TeV
  - ✓ Probably not enough in view of a luminosity upgrade
  - ✓ Basic limitation of the amorphous collimation system
    - ✧ p: single diffractive scattering
    - ✧ ions: fragmentation and EM dissociation

# Crystal assisted collimation

- Bent crystals work as a "smart deflectors" on primary halo particles
- Coherent particle-crystal interactions impart large deflection angle that minimize the escaping particle rate and improve the collimation efficiency



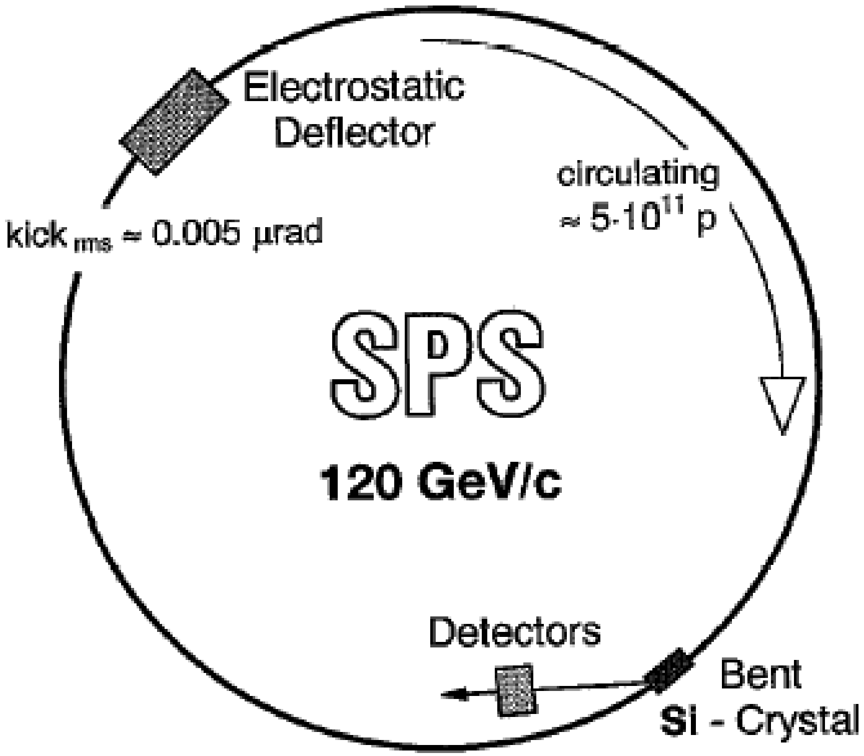

R. W. Assmann, S. Redaelli, W. Scandale, "Optics study for a possible crystal-based collimation system for the LHC", EPAC 06

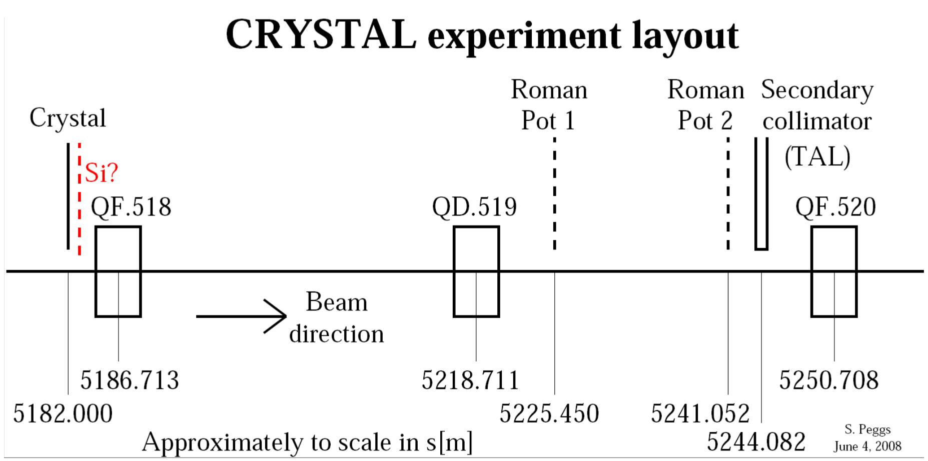


# UA9 crystal collimation in the SPS (2008-…)

Goals:

- Demonstrate loss localization
- Measure channeling and collimation efficiency
- Measure the single particle dynamics (later ?)

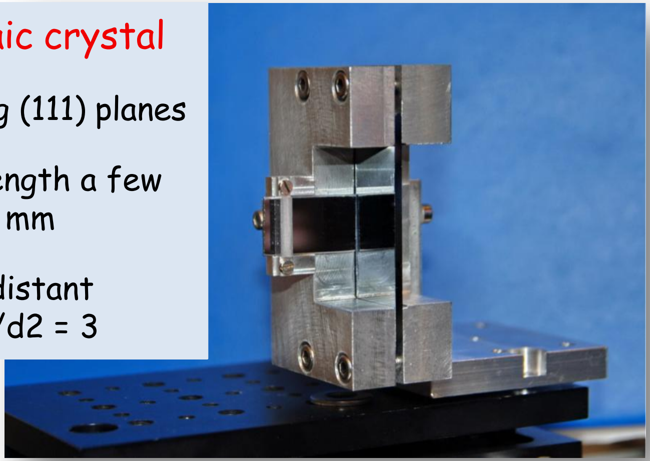


# Crystals to assist collimation

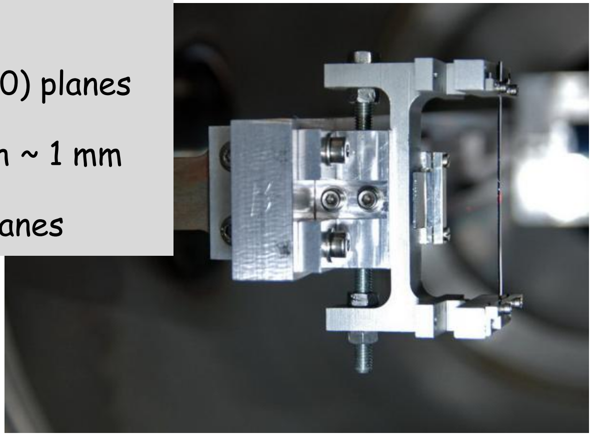
## Quasimosaic crystal

- Bent along (111) planes
- Minimal length a few tenths of mm
- Non-equidistant planes d1/d2 = 3



## Strip crystal

- Bent along (110) planes
- Minimal length ~ 1 mm
- Equidistant planes

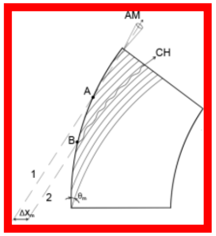


## Crystals

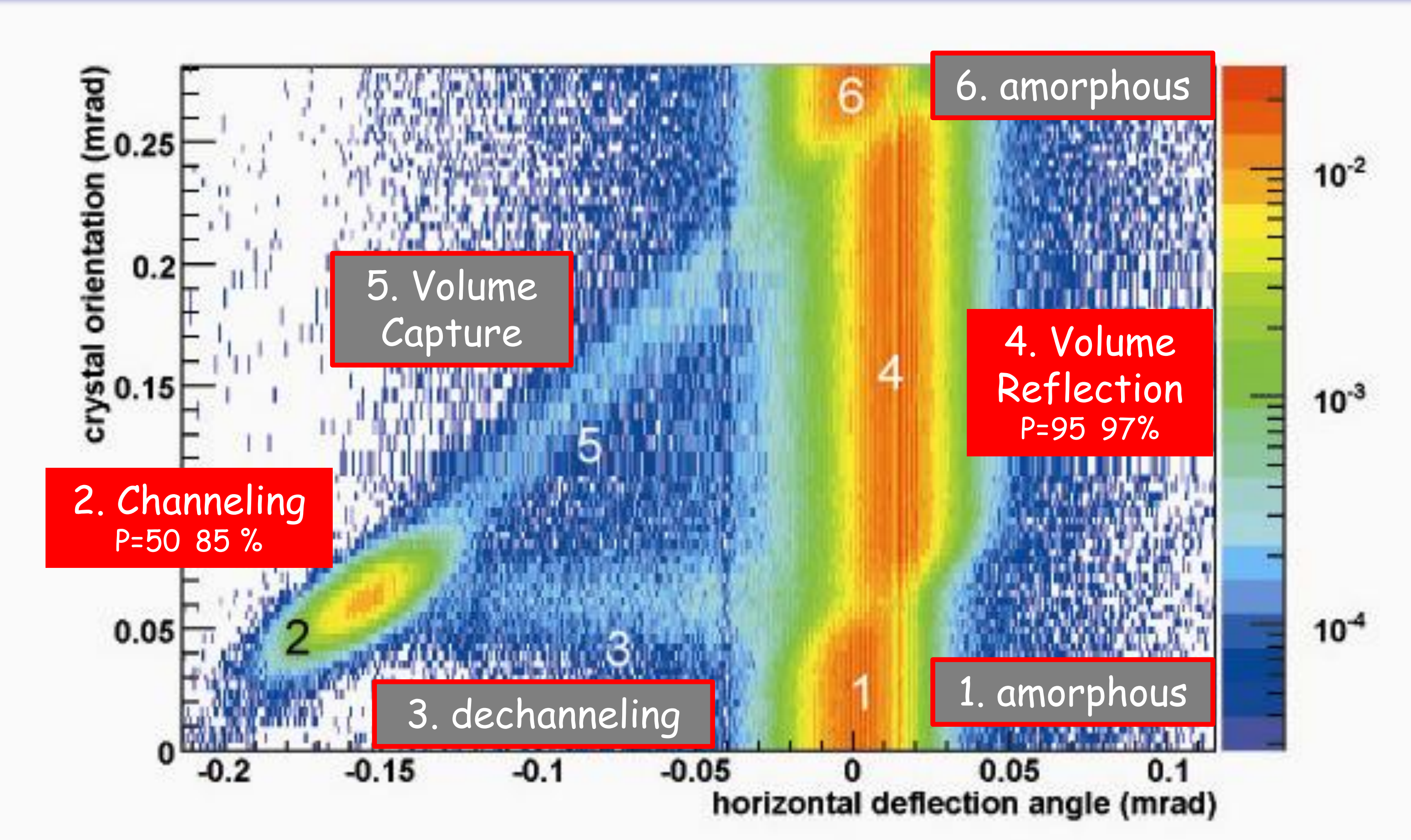
- Dislocation-free silicon crystals plates or strips
- for optimal channeling efficiency
  - ✓ short length (few mm)
  - ✓ moderate bending radius 45  70 m

> - SPS at 120  270 GeV) 1  2 mm length, 150  170 μrad angle
> - LHC 3  5 mm length, 40  60 μrad angle

- Mechanical holders with large C-shape frame imparting the main crystal curvature
  - ✓ Strip crystal: (110) planes are bent by anticlastic forces
  - ✓ Quasimosaic crystal: (111) planes are bent by 3-D anticlastic forces through the elasticity tensor
- Expected crystal defects:
  - ✓ Miscut: can be ≈100 μrad, but negligible effect if good orientation is applied
  - ✓ Torsion: can be reduced down to 1 μrad/mm ➔ UA9 data in the SPS North Area
  - ✓ Imperfection of the crystal surface: amorphous layer size ≤ 1 μm



# Coherent interactions in bent crystals




- ❑ Two coherent effects could be used for crystal collimation: W. Scandale et al, PRL 98, 154801 (2007)
  - ✓ Channeling → larger deflection with reduced efficiency
  - ✓ Volume Reflection (VR) → smaller deflection with larger efficiency
- ❑ SHORT CRYSTALS in channeling mode are preferred W. Scandale et al., Nucl. Inst. and Methods B 268 (2010) 2655-2659.
  - → 5 less inelastic interaction than in VR or in amorphous orientation (single hit of 400 GeV protons)

# Goniometer

The critical angle governs the acceptance for crystal channeling

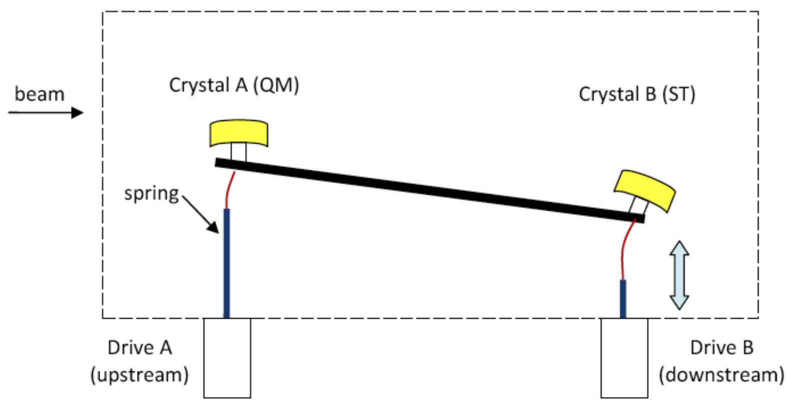
- 120 GeV → $\theta_c$ = 20 μrad
- 450 GeV → $\theta_c$ = 10 μrad
- 7 TeV → $\theta_c$ = 2.5 μrad

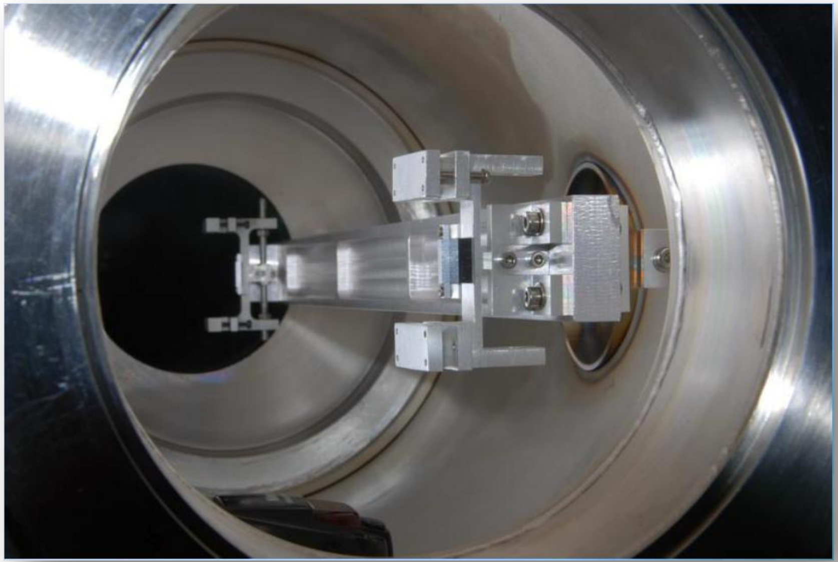
$$q_c = \sqrt{\frac{2U_0}{E}}$$

Required goniometer accuracy

- δθ = 10 μrad for E ≤ 450 GeV
- δθ = 1÷2 μrad at LHC collision

IHEP goniometer providing δθ = 10 μrad

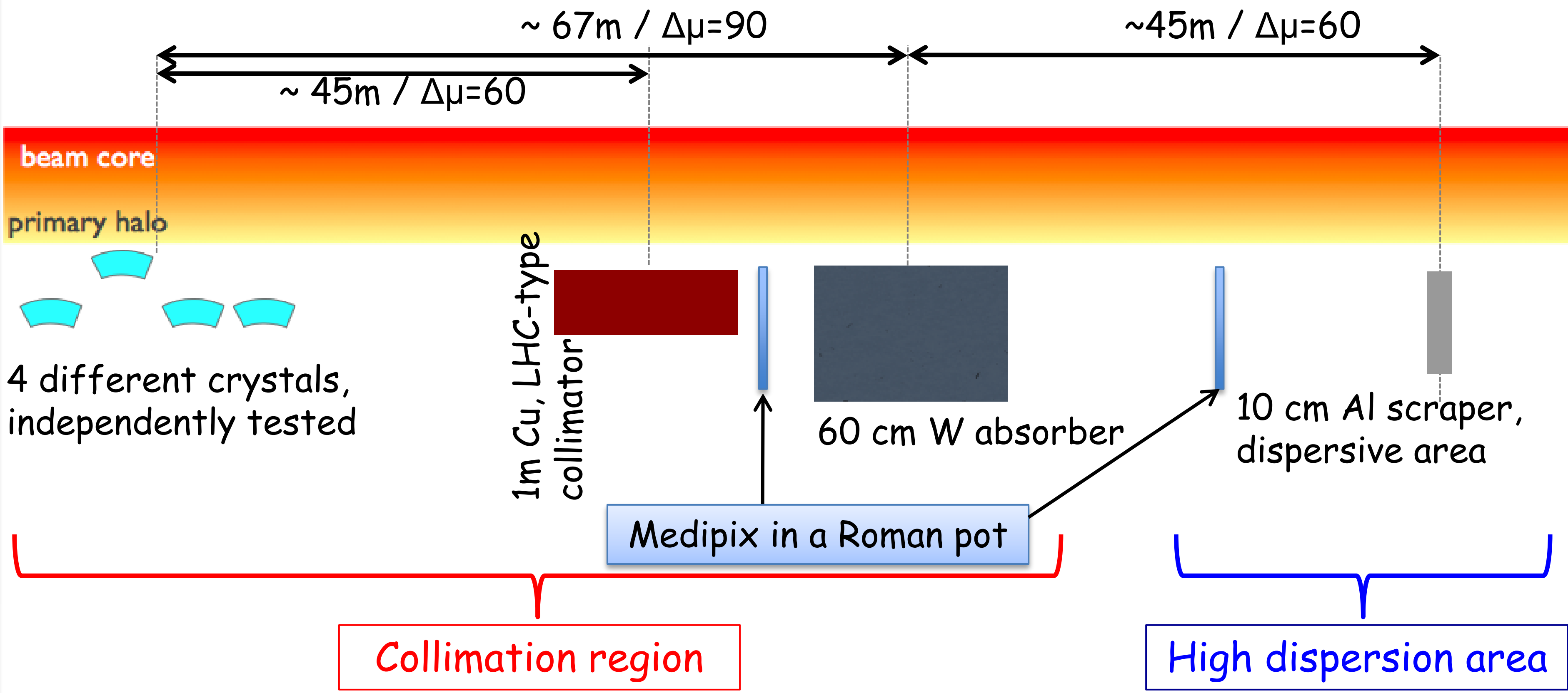


Upgrade of the goniometer launched in view of application to LHC

# UA9 basic layout in the SPS

W. Scandale, M. Prest, SPSC-P-335 (2008).
W. Scandale et al, "The UA9 experimental layout", submitted to JINST, Geneva (2011).



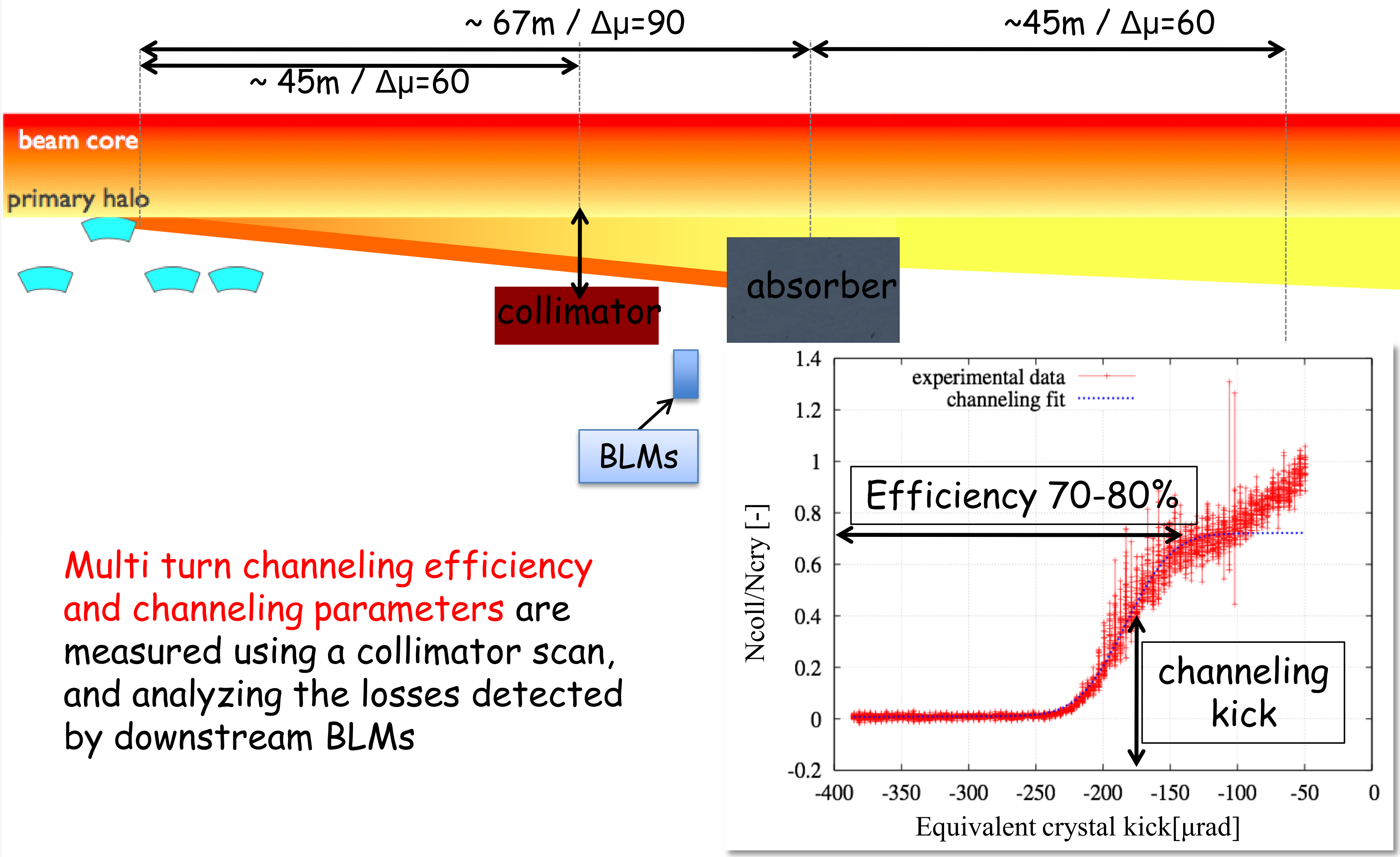

## Observables in the collimation area:

- Intensity, profile and angle of the deflected beam
- Local rate of inelastic interactions
- Channeling efficiency (with multi-turn effect)

## Observables in the high-D area:

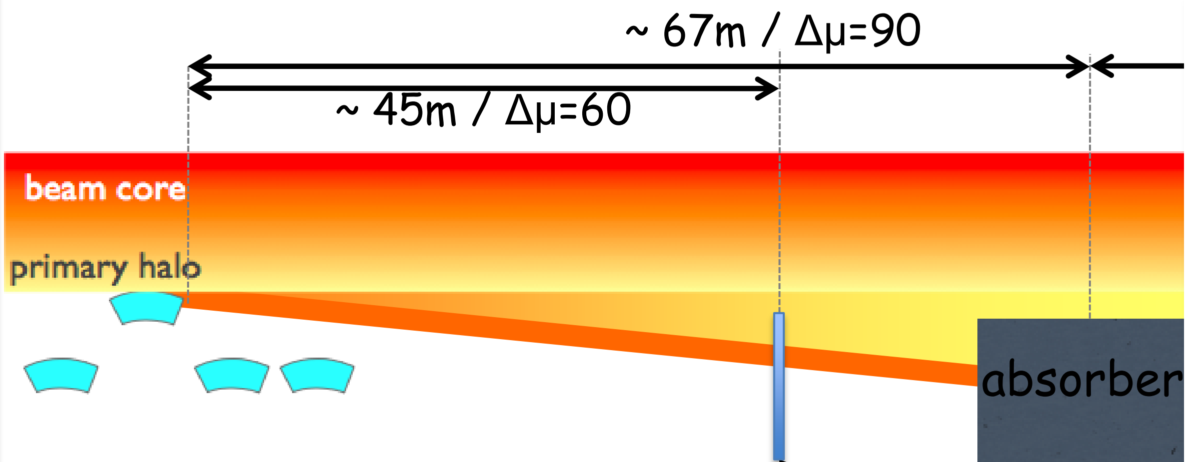
- Off-momentum halo population escaping from collimation (with multi-turn effect)
- Off-momentum beam tails

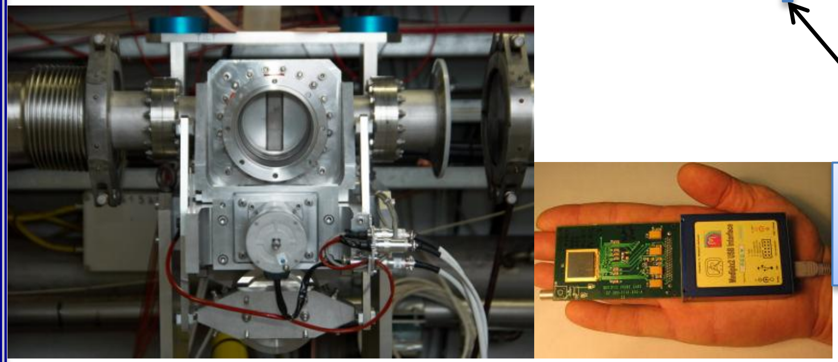
# Channeling efficiency by coll. scans

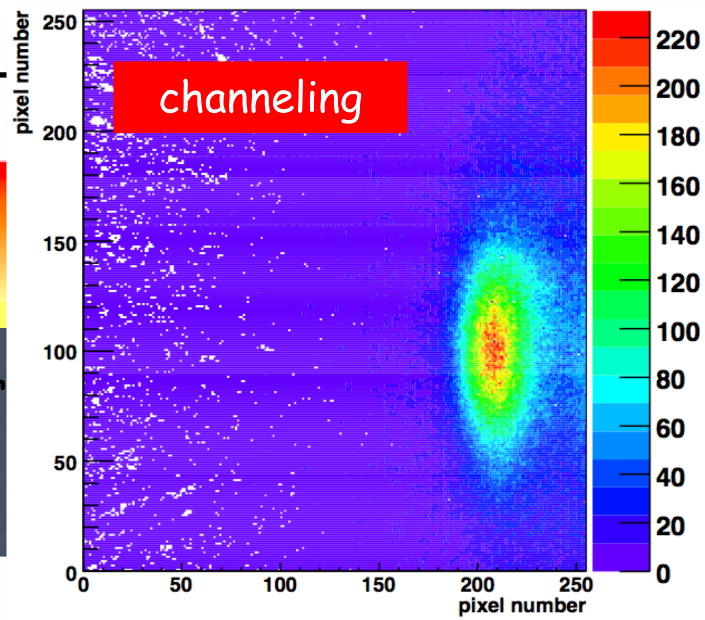


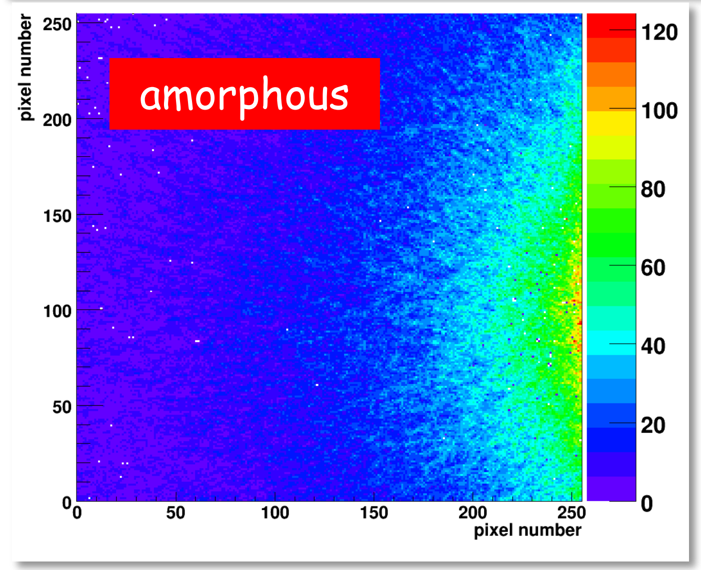

Multi turn channeling efficiency and channeling parameters are measured using a collimator scan, and analyzing the losses detected by downstream BLMs

# Direct view of channeled beam



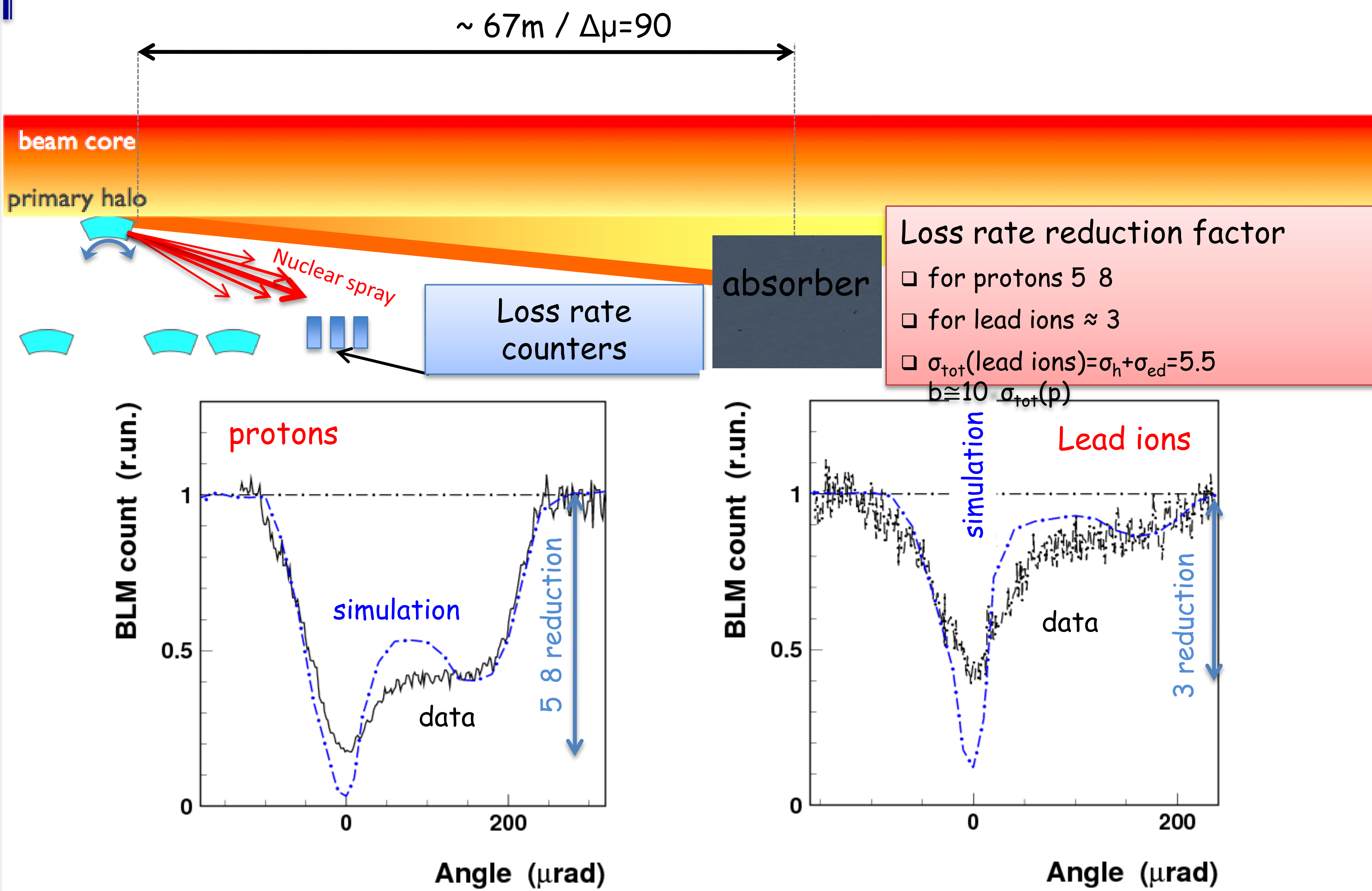



## Medipix pixel detector in a Roman pot:

- Intensity, profile and angle of the deflected beam
- Efficiency of channeling (with multi-turn effect) (needs information on circulating beam current)

# Loss rate reduction at the crystal

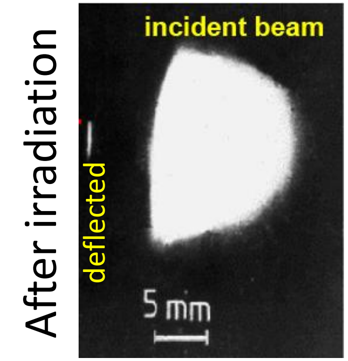


# Radiation hardness

## Test of power deposit at IHEP U-70 (Biryukov et al, NIMB 234, 23-30)

- 70 GeV protons hitting a 5 mm long si-crystal for several minutes
- Hit rate: $10^{14}$ protons in 50 ms, every 9.6 s
- The channeling efficiency was unchanged

**Equivalent in LHC to the instant dump of 2 nominal bunches per turn for 500 turns every ~ 10 s.**




## Test of radiation damages at NA48 (Biino et al, CERN-SL-96-30-EA)

- 450 GeV protons hitting a 10x50x0.9 $mm^3$ si-crystal for one year
- Hit rate: 5 $10^{12}$ protons over 2.4 s every 14.4 s
- Total flux: 2.4 $10^{20}$ $p/cm^2$ over an area of 0.8 x 0.3 $mm^2$
- The channeling efficiency over the irradiate area was reduced by ~30%

**LHC loss density 0.5 $10^{20}$ $p/cm^2$ per year**

- 3 $10^{14}$ stored protons per fill and per ring
- (assume 200 fills per year and ⅓ of the current lost in 4 collimators)
- 0.25 $10^{14}$ protons lost per crystal
- Area of the irradiated crystal 1mm 10μm

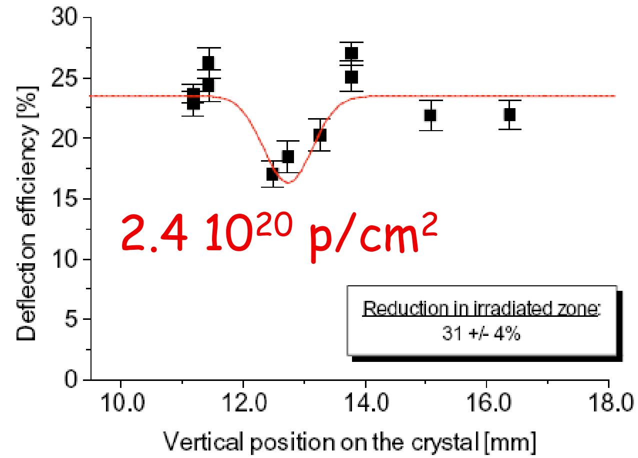



Figure 5 *A fit using the inverted irradiation profile to the measured points at expected optimum alignment*

# Summary

The SPS tests on crystal assisted collimation at have shown that

- The procedure for crystal channeling is robust, fast and well reproducible
  - ✓ The crystal and the absorber are positioned at the beam peripheral
  - ✓ The absorber is retracted by 2  $3\sigma$ to allow multi-turn extraction of the halo
  - ✓ The crystal is very precisely oriented in channeling mode using BLM signals
- In channeling states the benefits are threefold
  - ✓ Most of the halo population is promptly deflected towards the absorber
  - ✓ The rate of the nuclear interaction at the crystal is strongly reduced
  - ✓ The population of the self-generated off-momentum halo decreases
- The crystal technology is fully mature to meet requirements of larger hadron colliders such as the LHC

UA9 is being extended in LHC