

# BENT CRYSTALS in the LHC

a way to improve the collimation efficiency in modern hadron colliders

Walter Scandale *CERN*

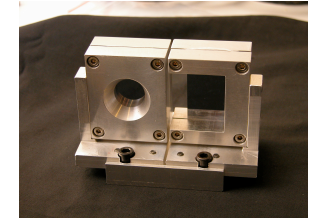
*For the UA9 collaboration*

*Erice*

*October 29 2008*



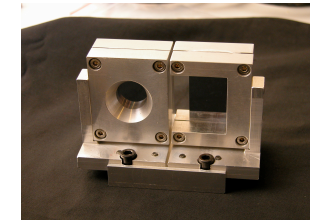
# Outlook



- ◆ Why using crystals in hadron colliders
- ◆ The H8-RD22 experiment at CERN  
(test in a single-pass beam-line)
  - ◆ Experimental layout
  - ◆ Main results
- ◆ The UA9 experiment at the CERN-SPS  
(test in a circular accelerator)
  - ◆ Layout
  - ◆ Expected efficiency
- ◆ Conclusions



# Two stage collimation in a circular collider



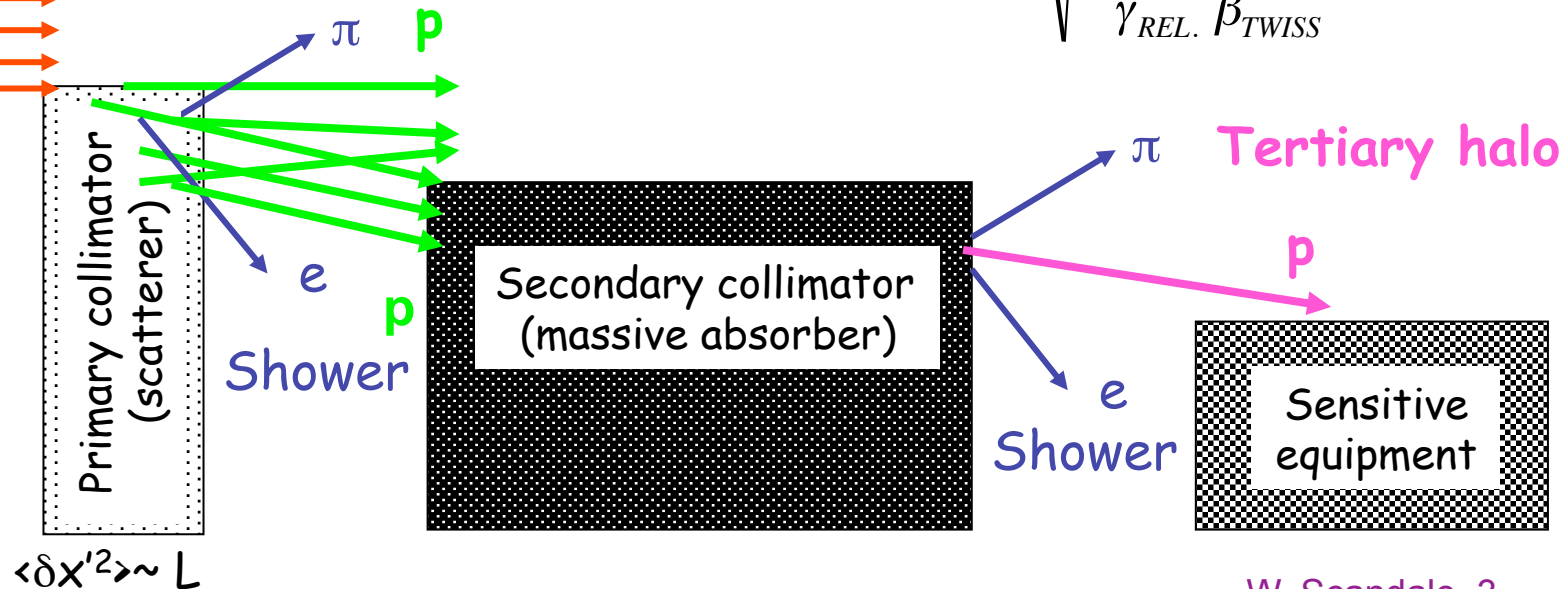
## How it works ?

- ◆ Short **scatterer** deflects the primary halo (ap.  $r_1 = N_1 \sqrt{\beta_{TWISS} \epsilon}$ )
- ◆ Long **collimator** intercepts the secondary halo (ap.  $r_2 = N_2 \sqrt{\beta_{TWISS} \epsilon}$ )
- ◆ halo particles captured through **amplitude increase** via multiple scattering and multi-turn effect.



Secondary halo

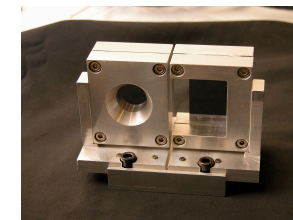
capture condition:  $\delta x' > \sqrt{\frac{(N_2^2 - N_1^2) \epsilon_N}{\gamma_{REL.} \beta_{TWISS}}} \quad \epsilon_N = \epsilon \beta \gamma$





# Requirements for LHC

Nominal beam power: 362 MJ



## Super-Conducting Environment

Proton losses into cold aperture



Local heat deposition



Magnet can quench

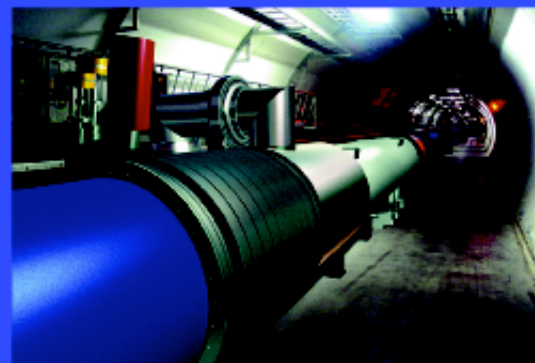


Illustration of LHC dipole in tunnel

Energy [GeV]	Loss rate (10 h lifetime)	Quench limit [p/s/m] ( <b>steady losses</b> )	Cleaning requirement
450	8.4e9 p/s	7.0e8 p/s/m	92.6 %
7000	<b>8.4e9 p/s</b>	<b>7.6e6 p/s/m</b>	<b>99.91 %</b>

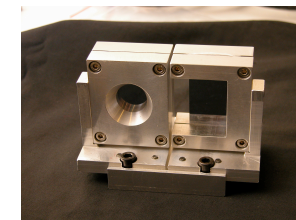
Control **transient losses (10 turns)** to  $\sim 1e-9$  of nominal intensity (top)!

**Capture (clean)** lost protons before they reach cold aperture!

Required efficiency:  $\sim 99.9\%$  (assuming losses distribute over 50 m)



# Ion collimation: why an issue?



Nominal ion beam in LHC has 100 times less beam power than proton beam, but

Physics process	Proton	<sup>208</sup> Pb
$\frac{dE}{Edx}$ due to ionisation	-0.12 %/m -0.0088 %/m	-9.57 %/m -0.73%/m
Mult. Scattering (projected r.m.s. angle)	73.5 $\mu$ rad/m <sup>1/2</sup> 4.72 $\mu$ rad/m <sup>1/2</sup>	73.5 $\mu$ rad/m <sup>1/2</sup> 4.72 $\mu$ rad/m <sup>1/2</sup>
Nucl. Interaction length ≈fragment. length for ions	38.1cm 38.1cm	2.5cm 2.5cm
Electromagnetic dissociation length	-	33cm 19cm

~20 times higher probability of nuclear interactions respect to p

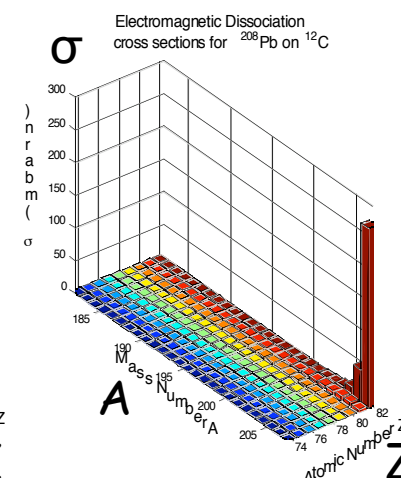
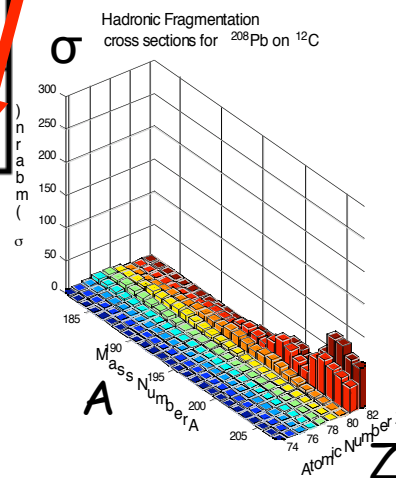
A new disturbance respect to p

$$L \approx L_{int} = \frac{A_{coll}}{N_A \rho (\sigma_{had} + \sigma_{emd})}$$

High probability of nuclear interactions in the scatterer

→ strong reduction of the 2-stage collimation EFFICIENCY

Courtesy of Bellodi

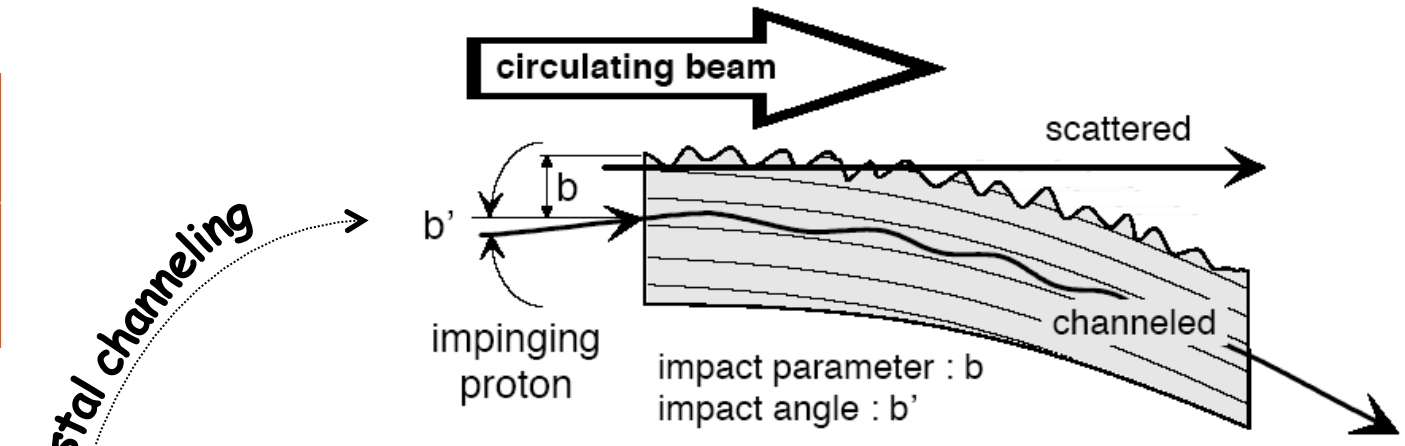
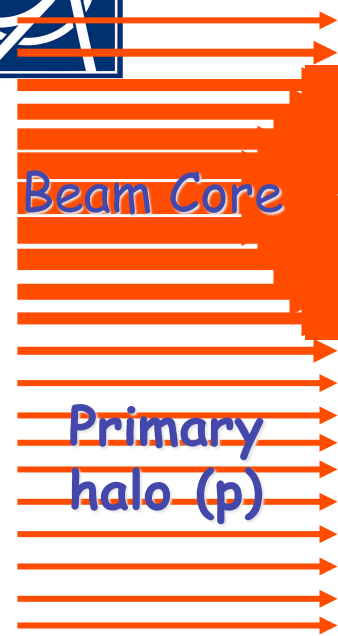
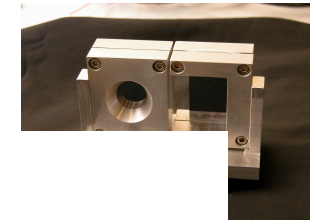


fragmented nuclei,  
Monte Carlo estimate  
of the x-sections

loss 1 n (59%) → <sup>207</sup>Pb  
loss 2 n (11%) → <sup>206</sup>Pb



# Crystal collimation



E. Tsyganov & A. Taratin (1991)

Crystal

p

Shower



$\pi$

e

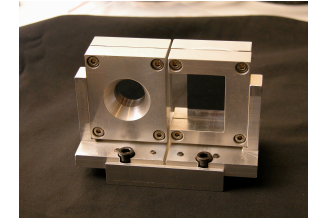


- ◆ Primary halo directly extracted!
- ◆ Much less secondary and tertiary halos!?

*..but no enough data available to substantiate the idea..*

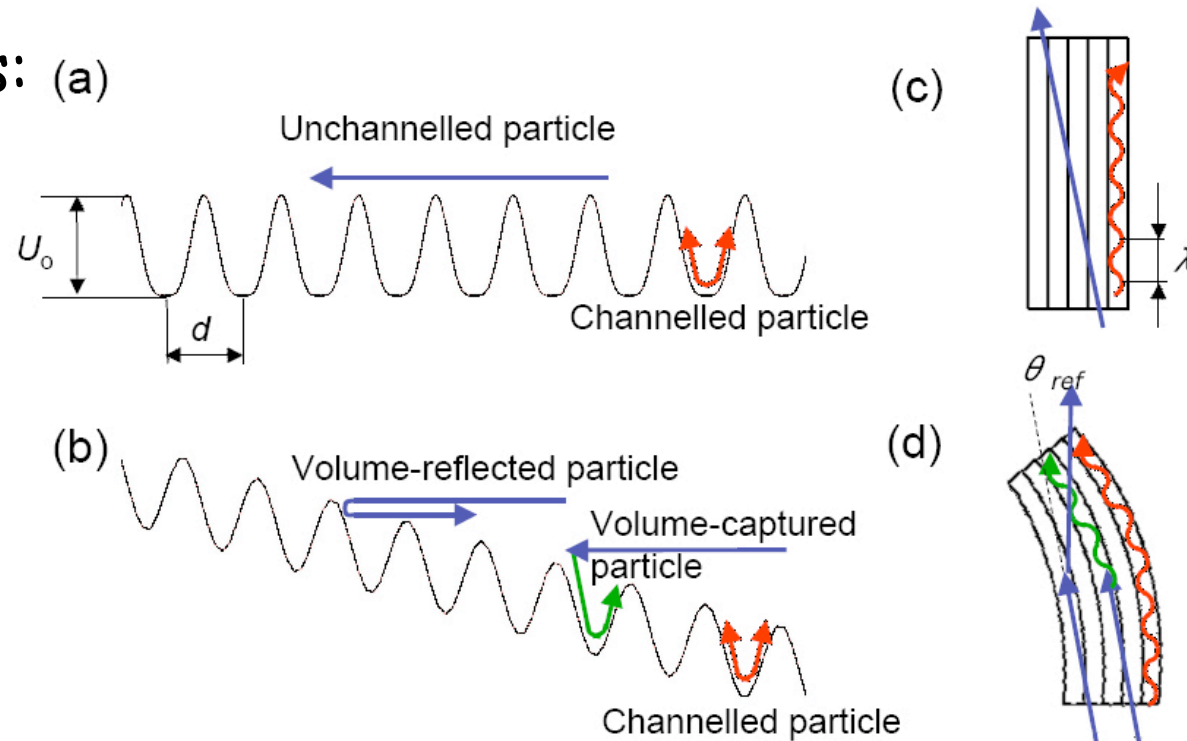


# Particle-crystal interaction



Possible processes:

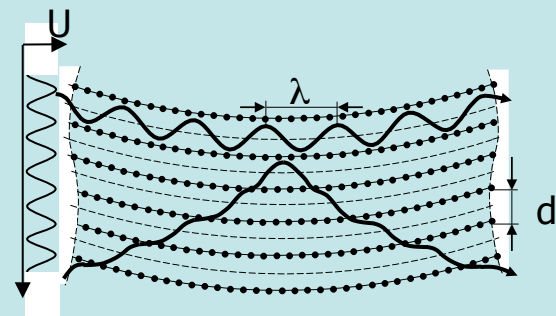
- ◆ multiple scattering
- ◆ channeling
- ◆ volume capture
- ◆ de-channeling
- ◆ volume reflection



## Volume reflection

Prediction in 1985-'87 by  
A.M.Taratin and S.A.Vorobiev,

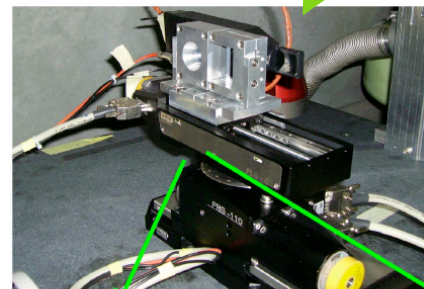
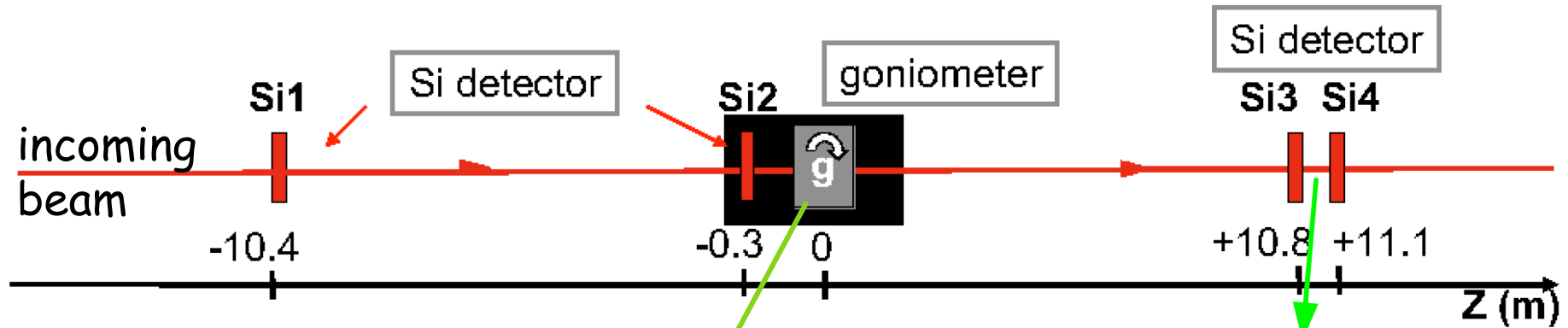
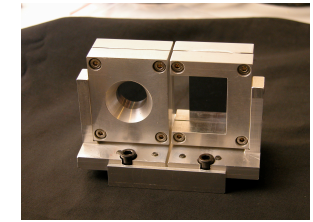
First observation 2006 (IHEP - PNPI - CERN)



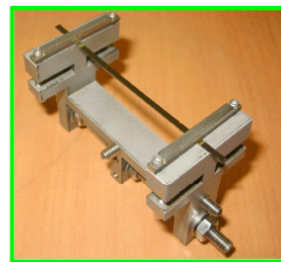
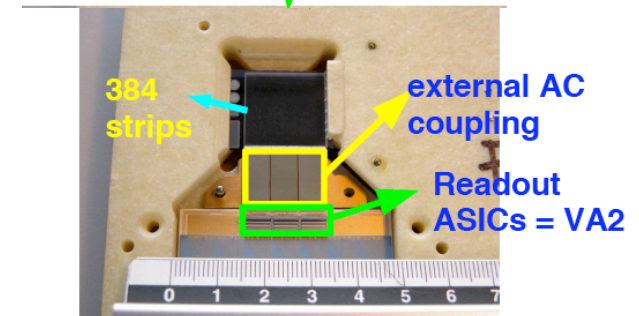


# The H8RD22 apparatus:

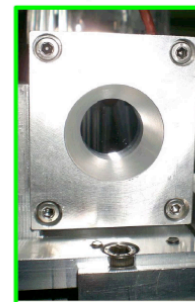
Single pass tests in the SPS-North Area



- 3-stage goniometer (2 lateral + one rotation)
- precision = of the order of  $1\mu\text{rad}$



Strip crystal (limited but regular surface)



Quasimosaic crystal (big surface)

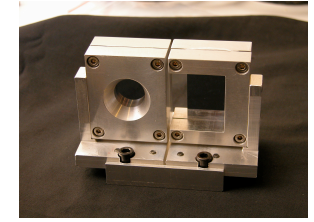
- double sided silicon strip detector with  $50\mu\text{m}$  pitch
- dimensions =  $1.92 \times 1.92 \text{ cm}^2$
- SNR = 80:1 with a 5 MHz readout clock and 25m cables
- Residual = better than  $5 \mu\text{m}$
- DAQ rate = 2.1kHz  $\rightarrow$  10k events per spill



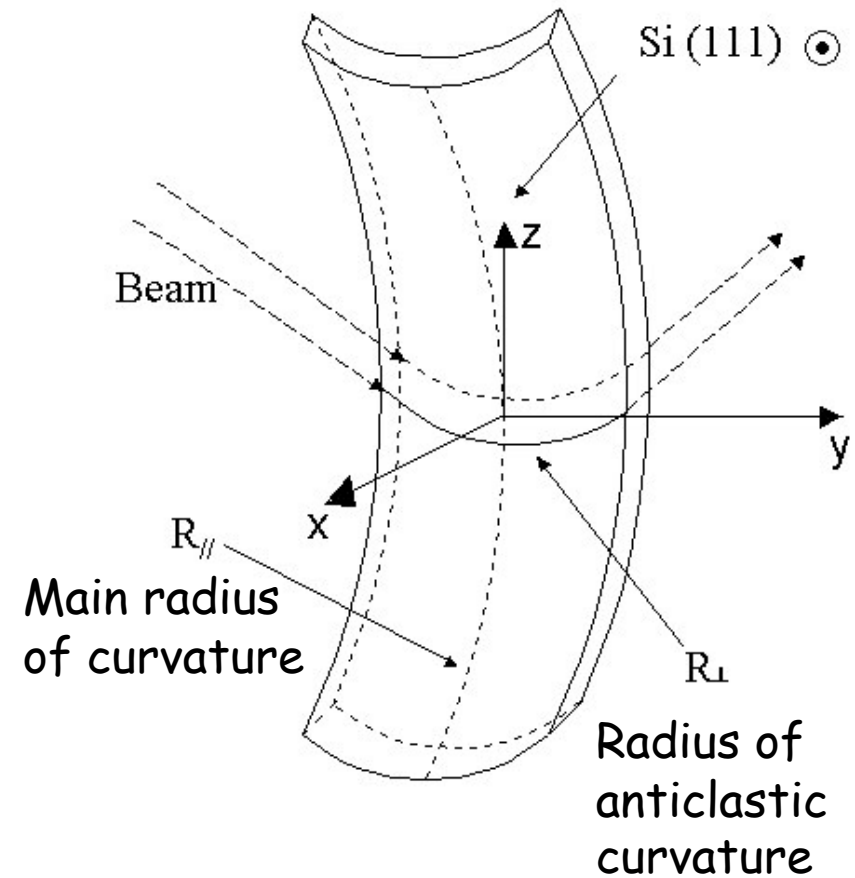


# Strip crystals

Built at INFN - Ferrara in collaboration with IHEP - Protvino



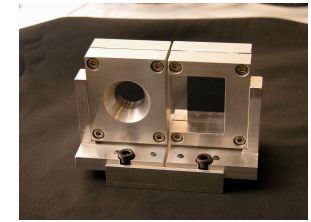
The main curvature due to external forces induces the anticlastic curvature seen by the beam





# Quasimosaic crystals

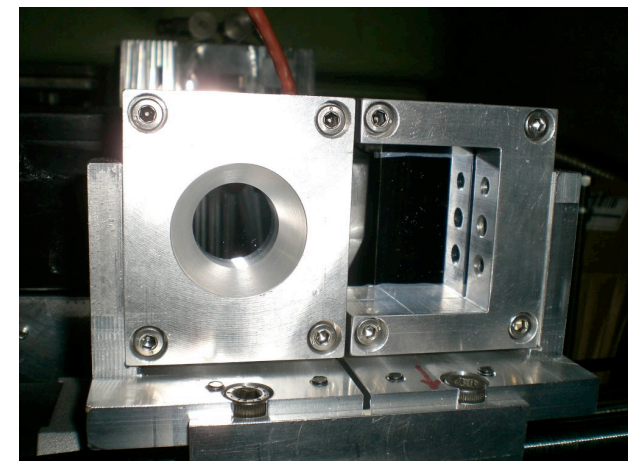
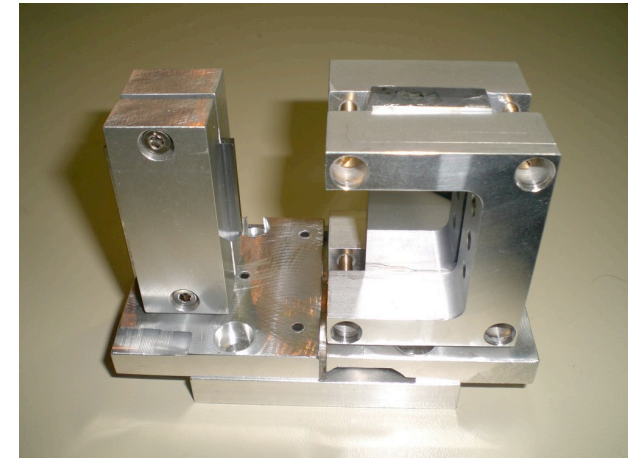
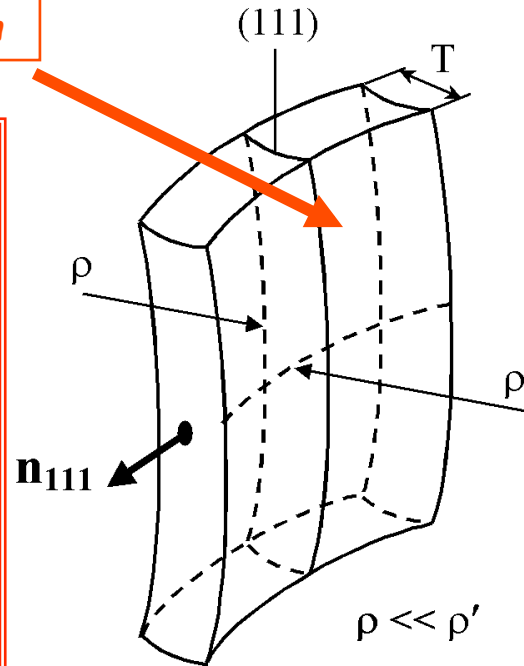
Built at PNPI - Gatchina



Beam direction

## Quasi-Mosaic effect (Sumbaev, 1957)

- The crystal is cut parallel to the planes (111).
- An external force induce the main curvature.
- The anticlastic effect produces a secondary curvature
- The anisotropy of the elastic tensor induces a curvature of the crystal planes parallel to the small face.

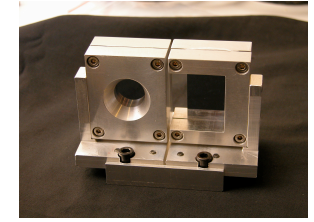


Crystal size: 0.7 x 30 x 30 mm<sup>3</sup>

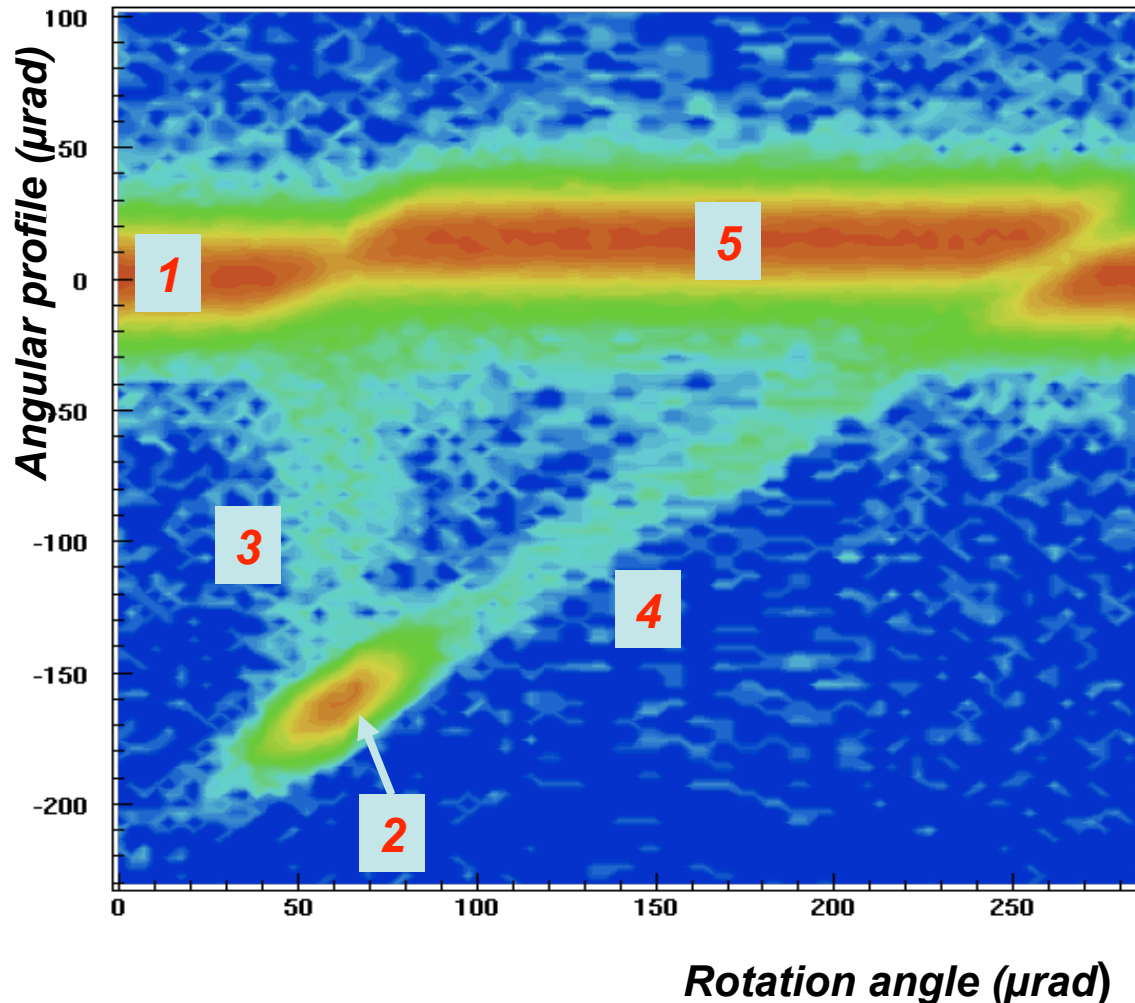
W. Scandale 10



# Angular beam profile as a function of the crystal orientation



9mm long Si-crystal deflecting 400GeV protons



The **angular profile** is the change of beam direction induced by the crystal

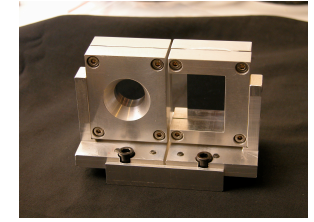
The **rotation angle** is angle of the crystal respect to beam direction

The **particle density** decreases from **red** to **blue**

- 1 - "amorphous" orientation
- 2 - channeling (50 %)
- 3 - de-channeling (1 %)
- 4 - volume capture (2 %)
- 5 - volume reflection (98 %)

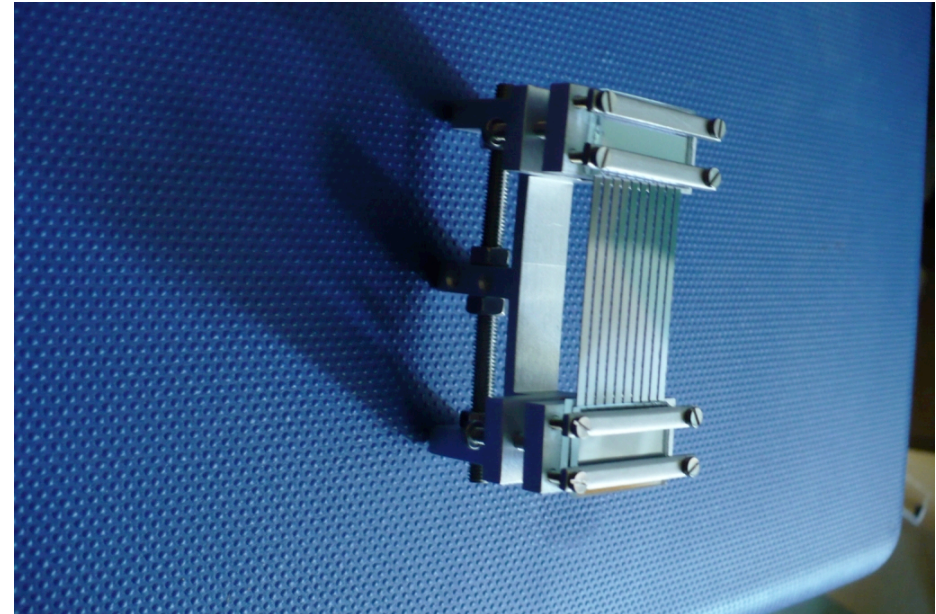
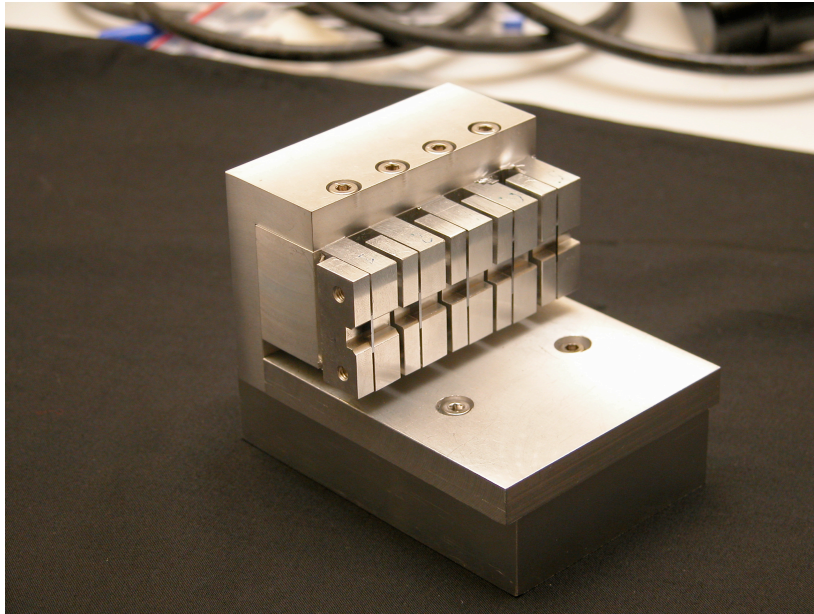


# Multi-crystals

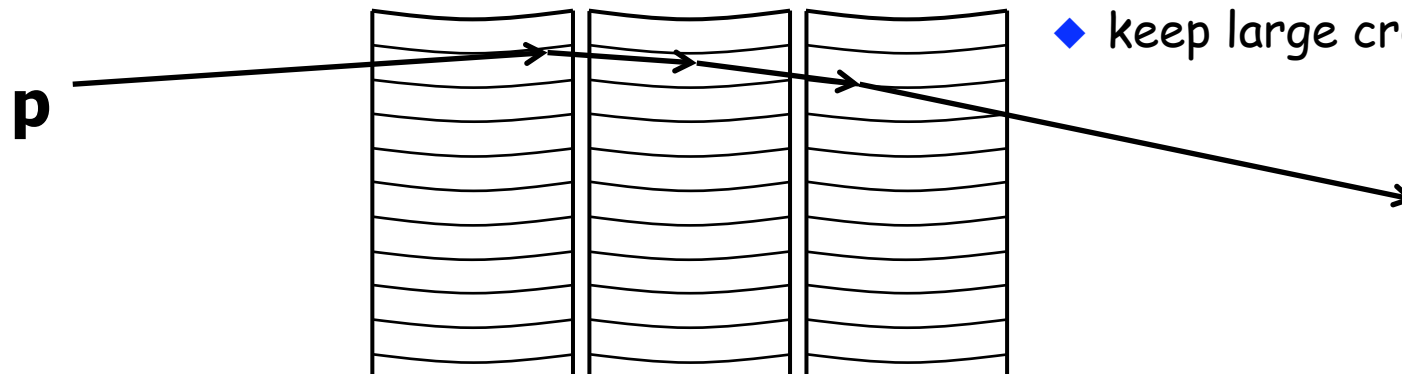


multiheads crystal (PNPI)

multistrip crystal (IHEP and INFN-Ferrara)



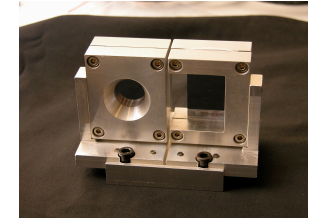
Several consecutive reflections



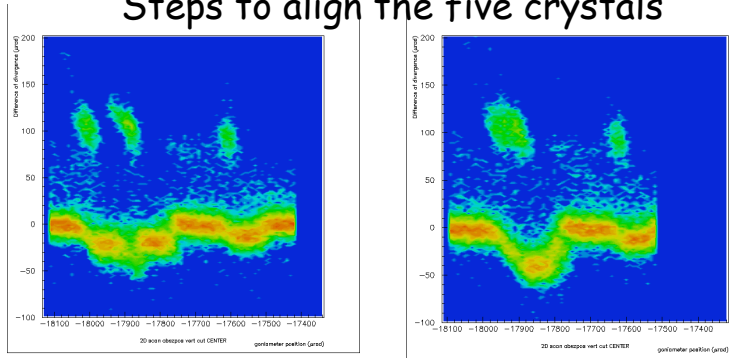
- ◆ enhance the deflection angle
- ◆ keep large cross section



# 5 heads multi-crystals

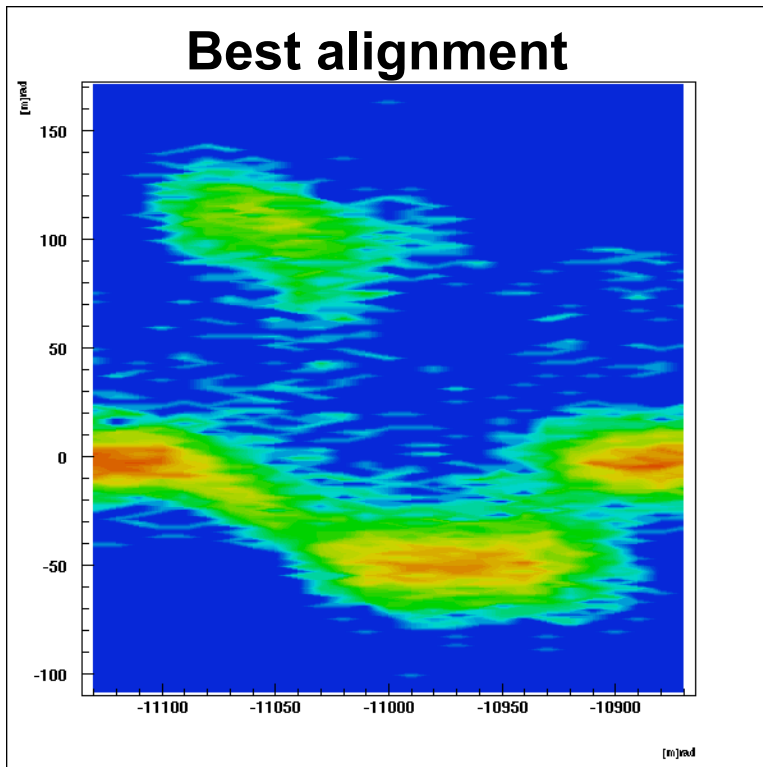


Steps to align the five crystals

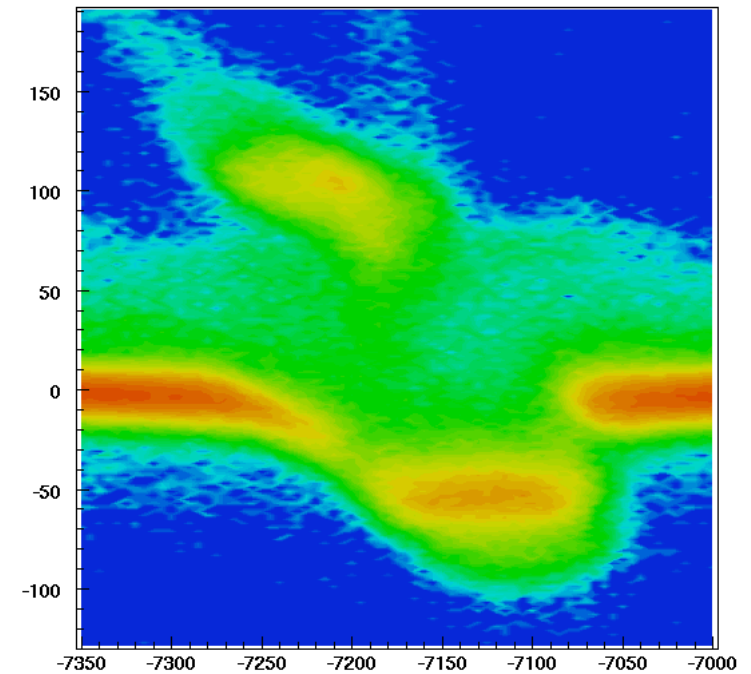


- ◆ Volume reflection angle  $53 \mu\text{rad}$
- ◆ Efficiency  $\geq 90 \%$

Best alignment



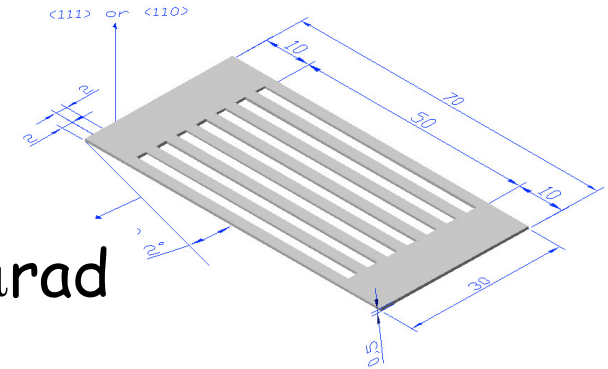
High statistics





# Multi-strips

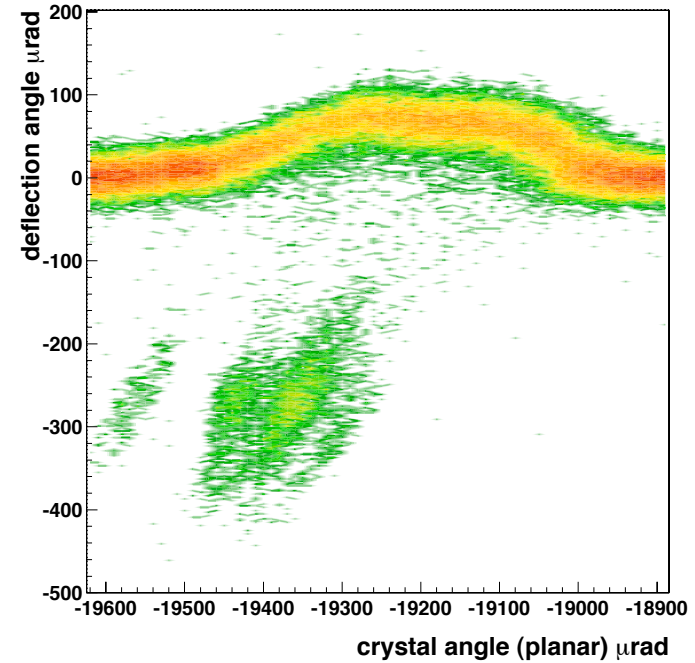
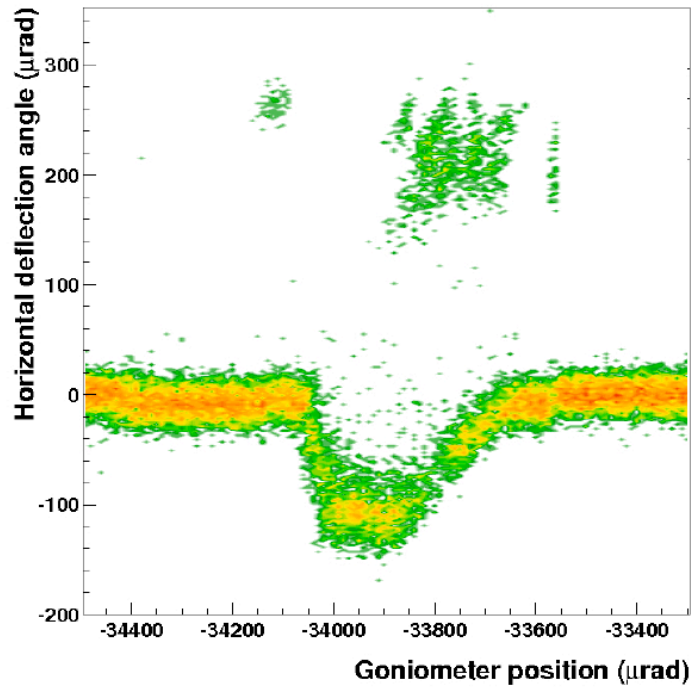
- ◆ Volume reflection angle  $\sim 100 \mu\text{rad}$
- ◆ Efficiency  $\sim 90 \%$



MST 14 – 400 Gev – R=4.61m

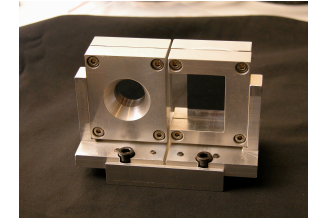
INFN-Ferrara

IHEP





# Other results of H8RD22



## PROTON BEAM (400GeV/c),

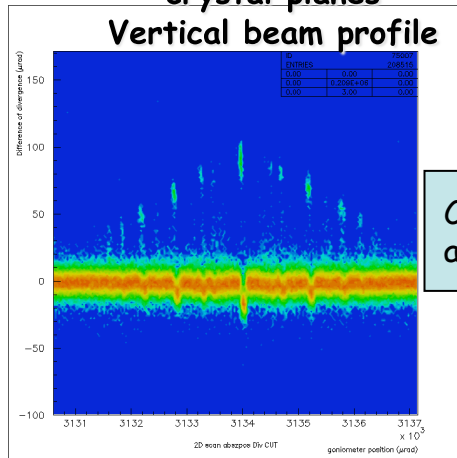
- ◆ Volume reflection dependence from the curvature of the crystal
- ◆ Axial channeling

## ELECTRON/POSITRON BEAM (180GeV/c),

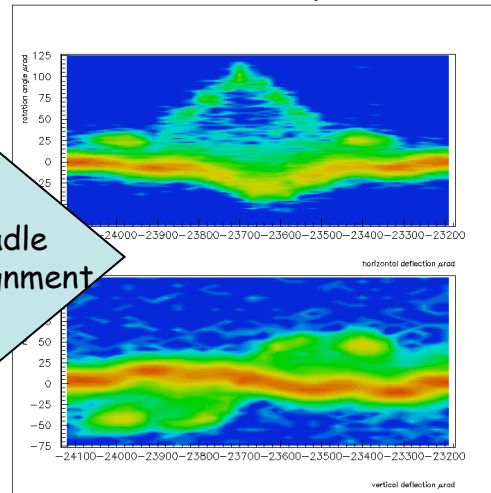
- ◆ Volume reflection with electrons and positrons
- ◆ Radiation emission with e<sup>+</sup>/e<sup>-</sup> beams in channeling condition

Channeling from secondary crystal planes

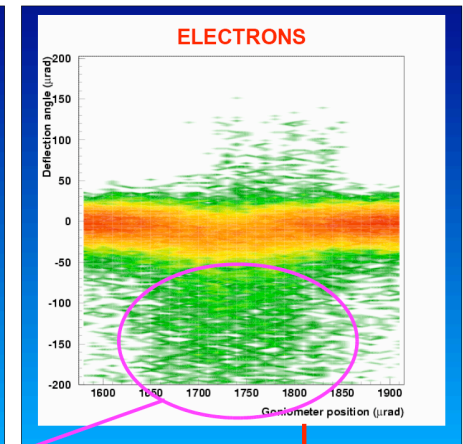
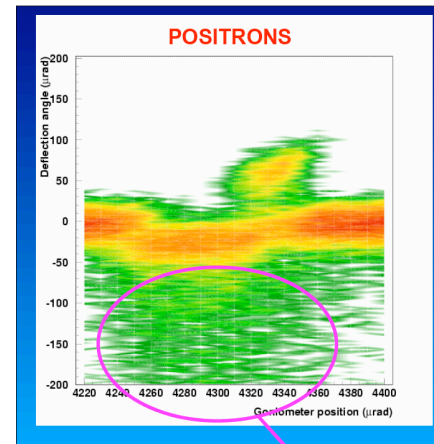
Vertical beam profile



Modulated VR & y scan



Cradle alignment



e<sup>+</sup>/ e<sup>-</sup> having lost energy via radiation emission

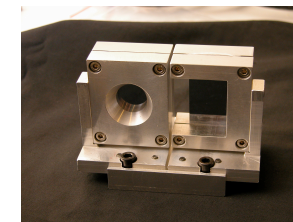
The crystal is not ideal but it's there!!!!!!

W. SCARF 10

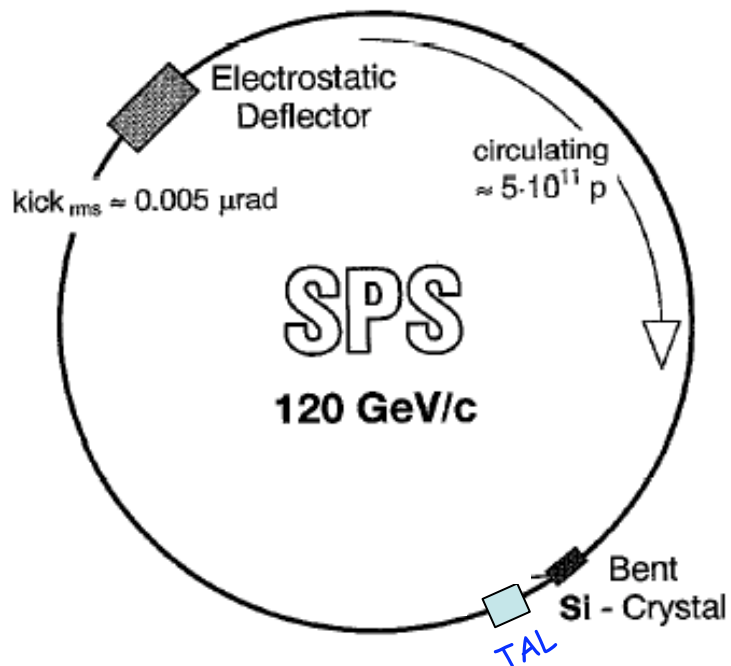


# UA9

## The underground experiment in the SPS



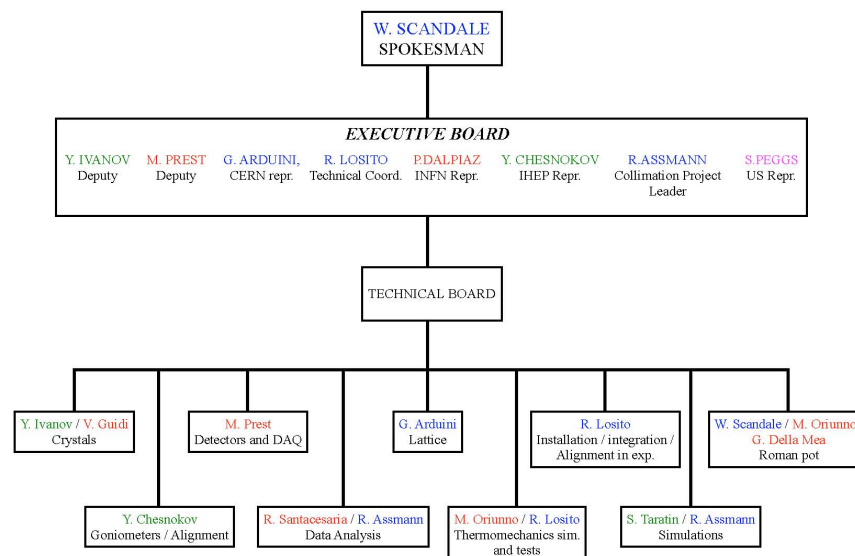
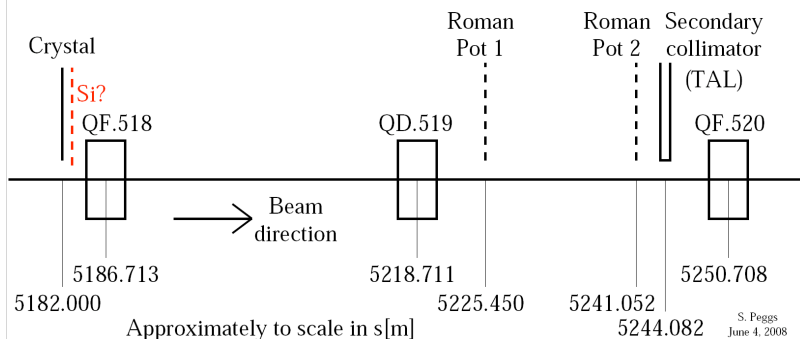
Approved by the CERN Research Board of the 3 Sept 2008



### Goals:

- ◆ Demonstrate high efficiency collimation assisted by bent crystals (loss localization)
- ◆ Follow single particle dynamics in crystal-collimation system

### CRYSTAL experiment layout



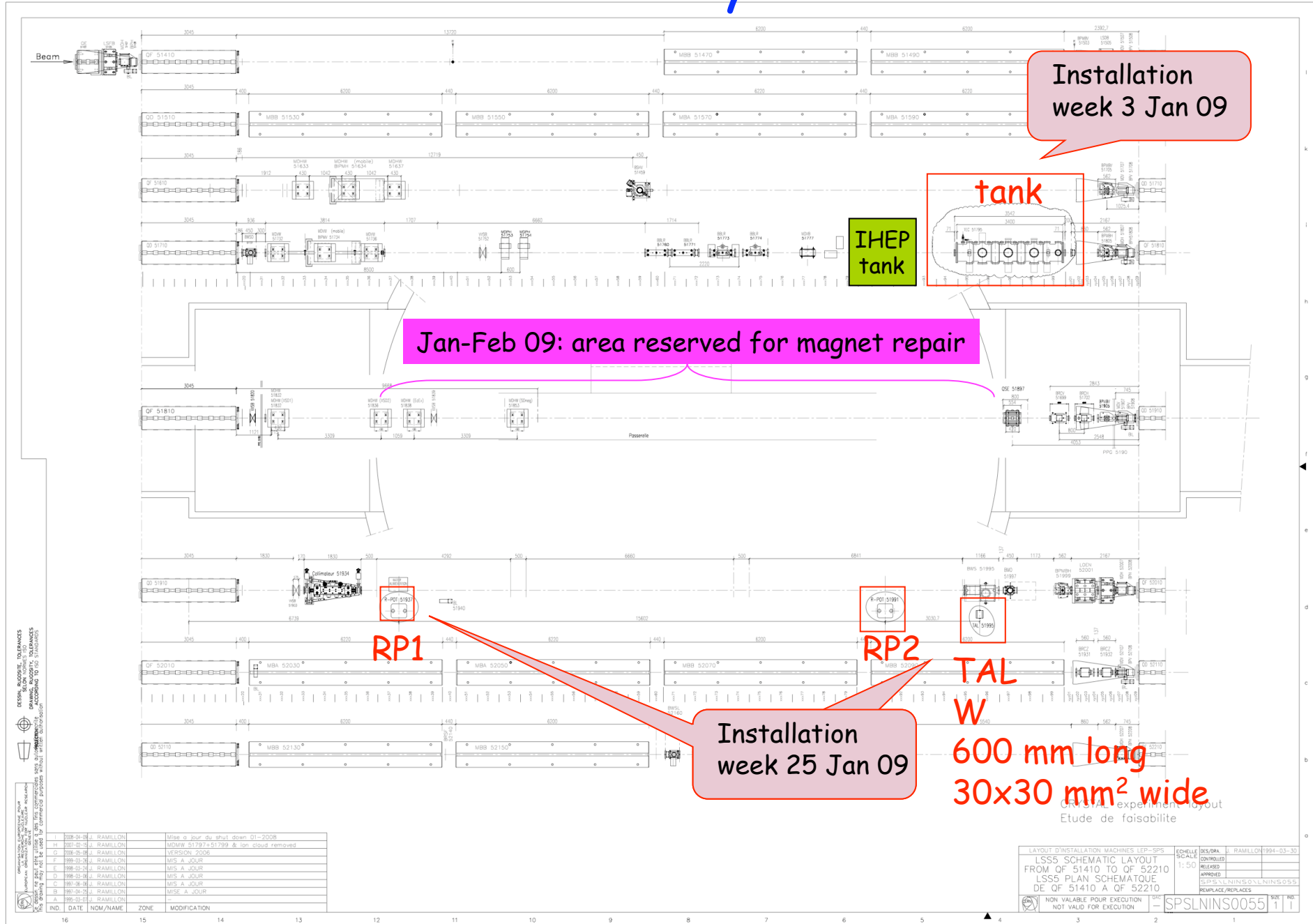
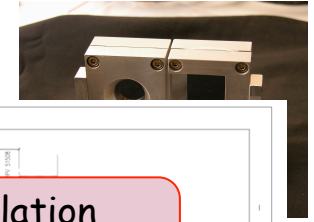
CRYSTAL organization chart; colors refer to different agencies: blue for CERN, green for Russian Institutions, red for INFN and violet for USA Institutions.

CERN  
INFN  
PNPI  
IHEP  
JINR  
SLAC  
FNAL  
LBNL





# UA9 layout



Installation week 3 Jan 09

tank

IHEP tank

Jan-Feb 09: area reserved for magnet repair

RP1

RP2

TAL

Installation week 25 Jan 09

W  
600 mm long  
30x30 mm<sup>2</sup> wide

Etude de faisabilité

DESIGN, MANUFACTURE, TOLERANCES  
DRAWINGS SHOULD BE TO STANDARDS  
UNLESS SPECIFIED OTHERWISE

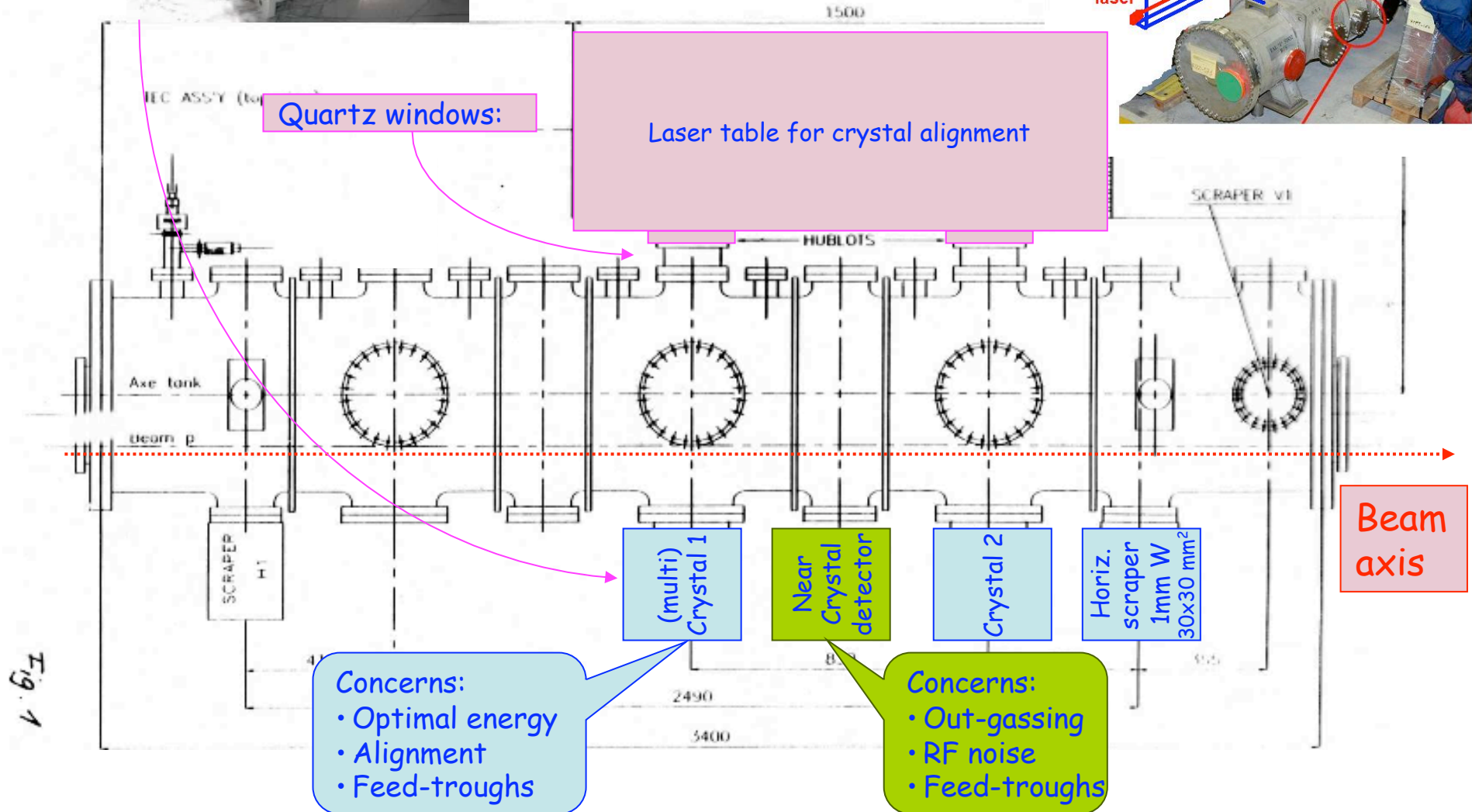
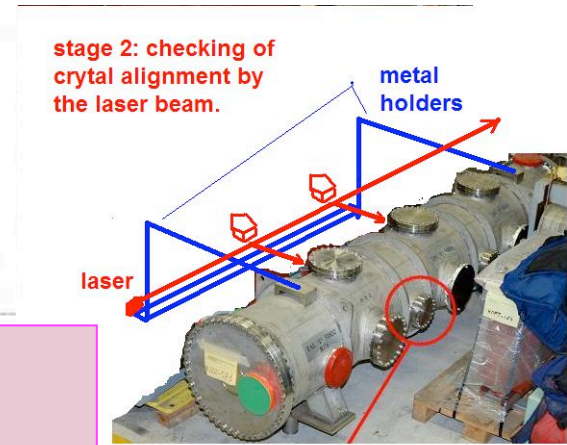
IND.	DATE	NOM/NAME	ZONE	MODIFICATION
H	2008-01-01	J. RAMILLON		Mise a jour du shut down 01-2008
H	2007-05-14	J. RAMILLON		M0MW 51797+51799 & lon_cloud removed
C	2008-05-01	J. RAMILLON		VERSION 2008
F	1998-03-26	J. RAMILLON		MIS A JOUR
E	1998-03-26	J. RAMILLON		MIS A JOUR
D	1998-03-01	J. RAMILLON		MIS A JOUR
C	1997-08-01	J. RAMILLON		MIS A JOUR
B	1997-08-21	J. RAMILLON		MISE A JOUR
A	1995-01-01	J. RAMILLON		-

LAYOUT D'INSTALLATION MACHINES LEP-SPS	SCALE	DESIGNER	RAMILLON1994-03-30
LSS5 SCHEMATIC LAYOUT FROM QF 51410 TO QF 52210	1:50	CONTROLLED	
LSS5 PLAN SCHEMATIC DE OF 51410 A QF 52210		RELEASED	
		APPROVED	
		REPLACE/REPLACES	SPSLNINS055

NON VALABLE POUR EXECUTION  
NOT VALID FOR EXECUTION

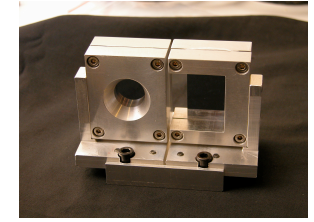
SPSLNINS0055

# RD22 tank





# The SPS beam



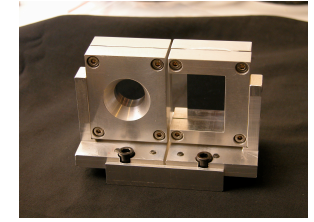
- Possible energy range from 70 to 270 GeV.
- We selected two energies of interest:
  - 120 GeV, as for the RD22 experiments (reference data in the literature);
  - 270 GeV, as for other planned experiment in the SPS (faster setting-up)

	High energy	unbunched	bunched
RF Voltage [MV]	1.5	0	1.5
Momentum P [GeV/c]	270	120	120
Tune Q <sub>x</sub>	26.13	26.13	26.13
Tune Q <sub>y</sub>	26.18	26.18	26.18
Tune Q <sub>s</sub>	0.0021	0	0.004
normalized emittance (at 1 $\sigma$ ) [mm mrad]	1.5	1.5	1.5
transverse radius (RMS) [mm]	0.67	1	1
momentum spread (RMS) $\Delta p/p$	2 to $3 \times 10^{-4}$	2 to $3 \times 10^{-4}$	$4 \times 10^{-4}$
Longitudinal emittance [eV-s]	0.4	$\leq 0.4$	0.4

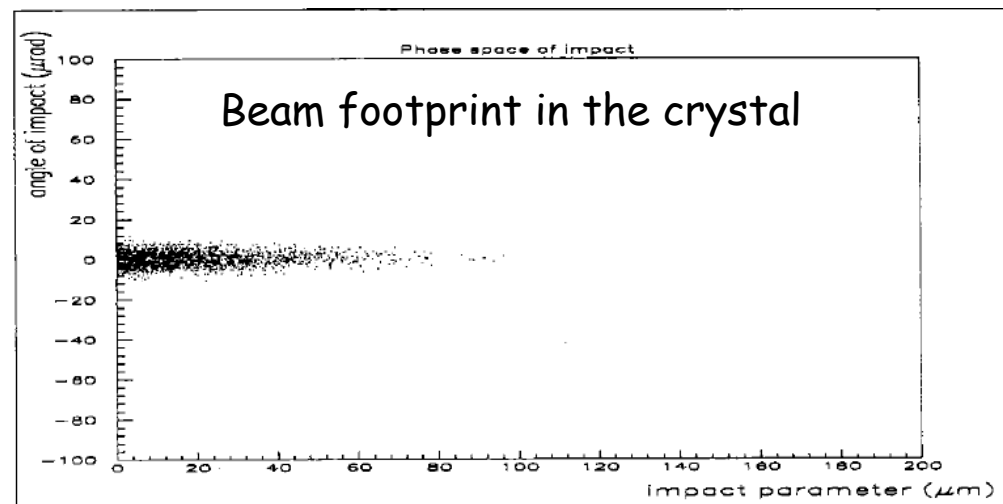
alternative tunes are those selected in RD22 (Q<sub>x</sub>=26.62, Q<sub>y</sub>=26.58).



# The SPS beam

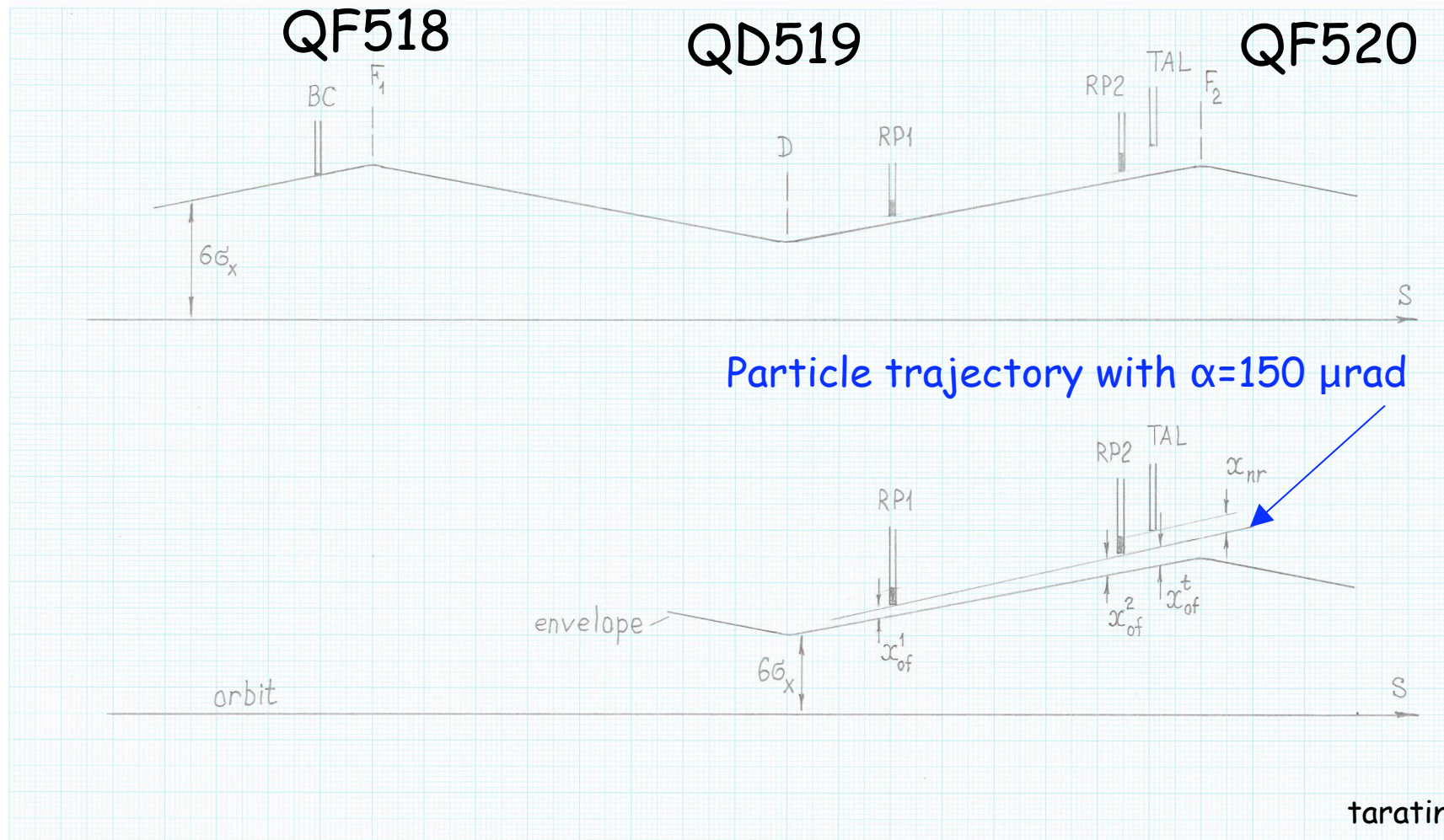
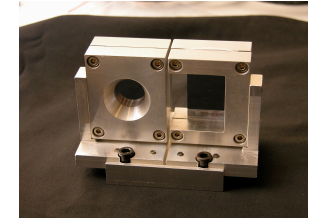


- Intensity a few  $10^{11}$  up to a few  $10^{12}$  circulating particles.
- Beam either unbunched or bunched in a few tens of bunches.
- Beam lifetime larger than 80 h, determined by the SPS vacuum.
- A halo flux of a few  $10^2$  to a few  $10^4$  particles per turn, which can be investigated with the detectors in the roman pots
  - evenly distributed along the revolution period (unbunched beam);
  - or synchronous to the bunch structure (bunched beam).
- Larger fluxes up to a few  $10^5$  particles per turn, which should be studied using only the beam loss monitors.





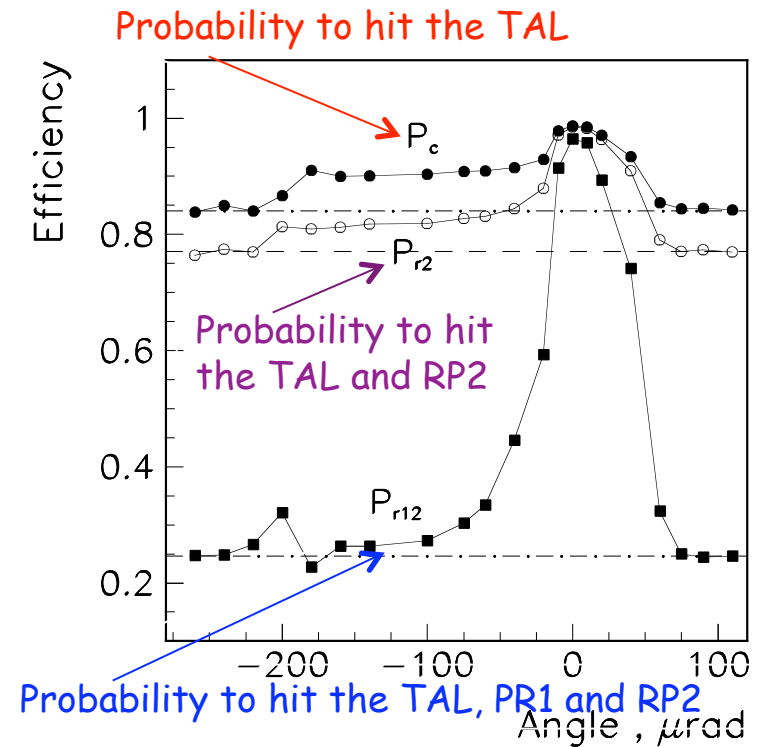
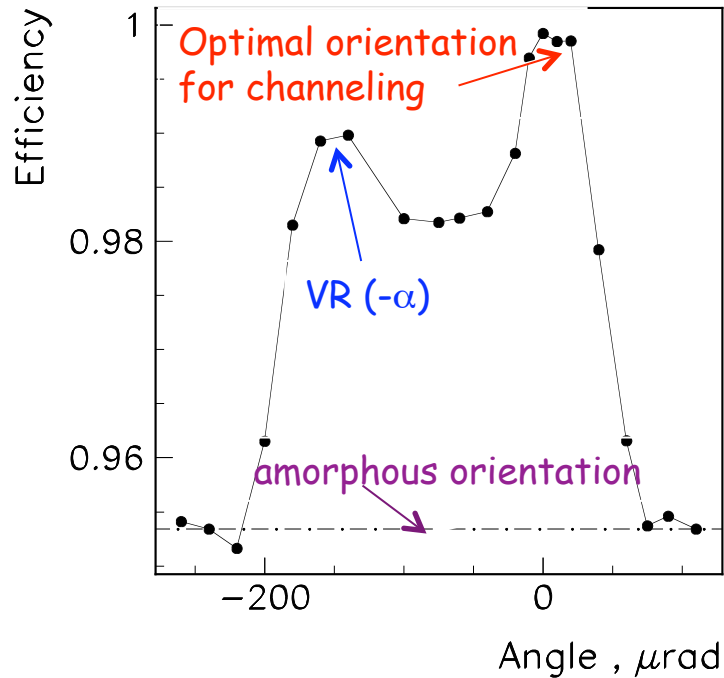
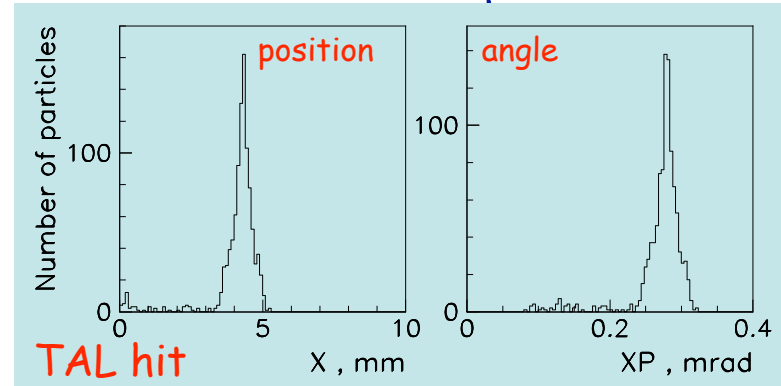
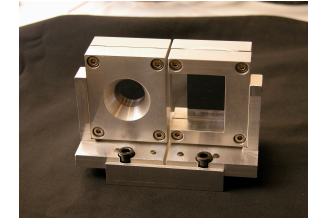
# Deflected beam





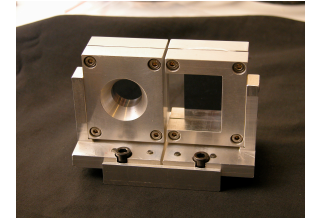
# Expected efficiency

for  $\alpha=150 \mu\text{rad}$





# Plans for 2009



## UA9

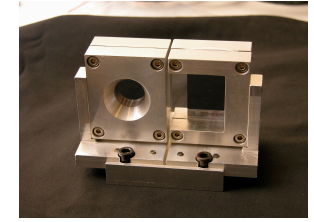
- Installation in the SPS tunnel: Feb 09
- First run: June 09
- Loss localization experiment: Sept 09
- Observation of single particles and efficiency measurement: Nov 09

## H8RD22

- 400GeV proton microbeam: Oct 09
- 150GeV electro/positron muon beam: Nov 09



# Conclusion



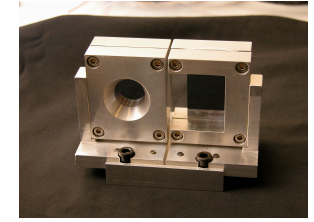
- ◆ High efficient reflection (and channeling) observed in single pass interaction of high-energy protons with bent crystals (0.5 to 10 mm long)
- ◆ Single reflection on a Si bent crystal deflects  $> 98\%$  of the incoming beam by an angle  $12\div 14\ \mu\text{rad}$
- ◆ Very promising for application in crystal collimation
- ◆ Multi-reflections on a sequence of aligned crystals to enhance the reflection angle successfully tested in the 2007 and 2008 runs. Efficiency  $> 90\%$ .
- ◆ Axial channeling also observed (scattering enhancement ?)

In 2009 the UA9 test planned in the SPS will provide us with the final word on crystal collimation for future hadron colliders





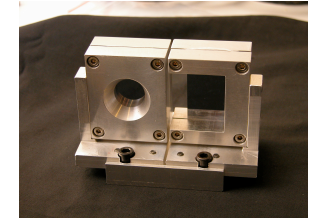
# Recent Publications



- ◆ 2006-PhysRevLett\_97\_144801 **Volume Reflection of a Proton Beam in a Bent Crystal**
- ◆ 2007-NIMB54908 **Volume reflection of high-energy protons in short bent crystals**
- ◆ 2007-PRL98 **High-Efficiency Volume Reflection of an Ultrarelativistic Proton Beam with a Bent Silicon Crystal**
- ◆ 2008-NIMB55427 **Efficiency increase of volume reflection of high-energy protons in a bent crystal with increasing curvature**
- ◆ 2008-PHYSICAL REVIEW SPECIAL TOPICS – ACCELERATORS AND BEAMS 11, 063501 (2008) **Deflection of 400 GeV/c proton beam with bent silicon crystals at the CERN Super Proton Synchrotron**
- ◆ 2008-PLB 658 **Double volume reflection of a proton beam by a sequence of two bent crystals**
- ◆ 2008-PRL 101, 164801 (2008) **High-Efficiency Deflection of High-Energy Protons through Axial Channeling in a Bent Crystal**
- ◆ 2008-RSI 79 **Apparatus to study crystal channeling and volume reflection phenomena at the SPS H8 beamline**
- ◆ 2008-SPSC-P-335 **PROPOSAL OF THE CRYSTAL EXPERIMENT**



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