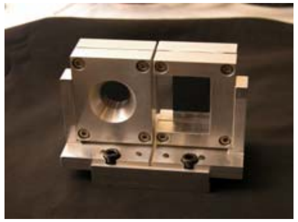


BENT CRYSTALS in the LHC

a way to improve the collimation efficiency in modern hadron colliders

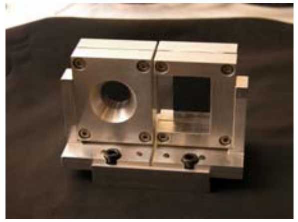
Walter Scandale *CERN*

For the UA9 collaboration

HHH08

November 25th 2008

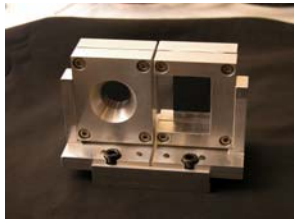
Outlook

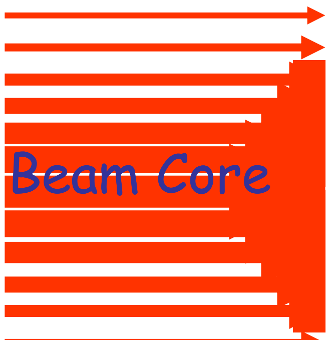


- Why using crystals in hadron colliders
- The H8-RD22 experiment at CERN
  (test in a single-pass beam-line)
  - Experimental layout
  - Main results
- The UA9 experiment at the CERN-SPS
  (test in a circular accelerator)
  - Layout
  - Expected efficiency
- Conclusions

Two stage collimation

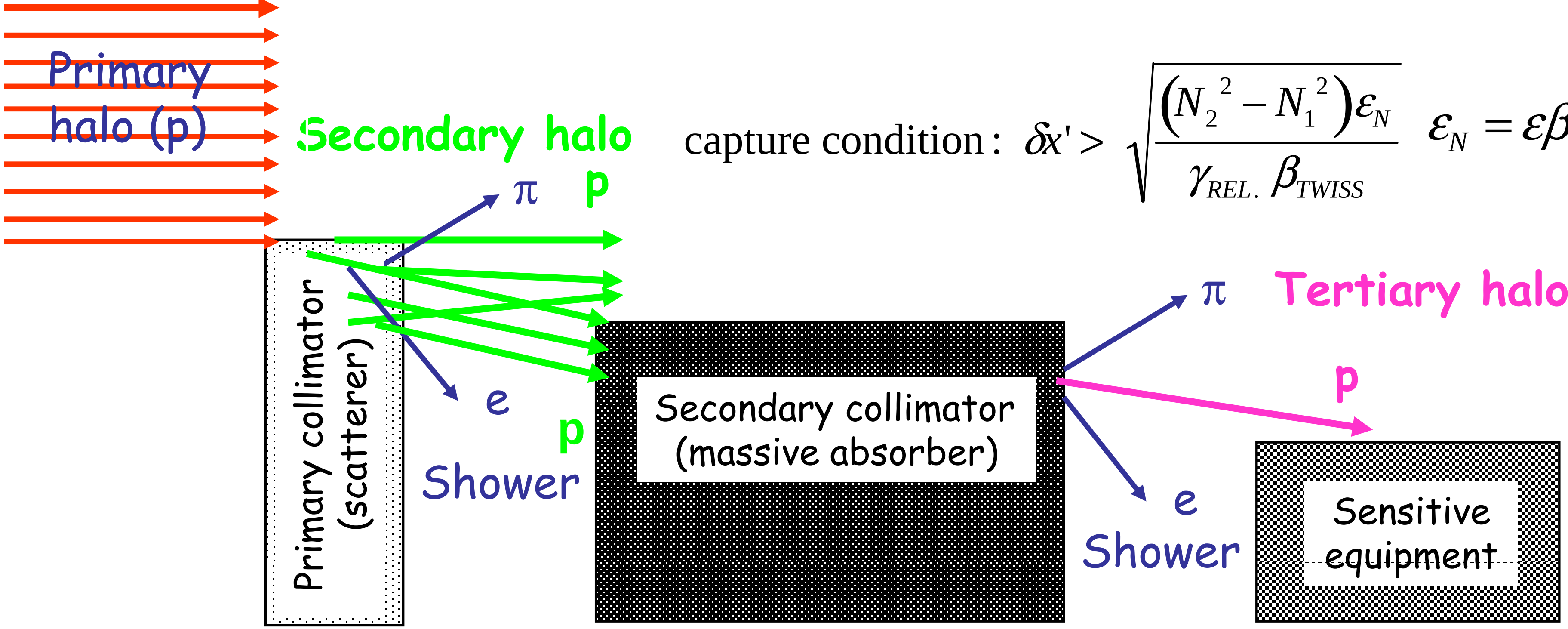
in a circular collider





How it works ?

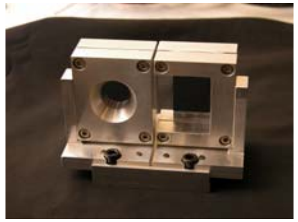
- Short scatterer deflects the primary halo (ap. $r_1=N_1\sqrt{\beta_{TWISS}\varepsilon}$)
- Long collimator intercepts the secondary halo (ap. $r_2=N_2\sqrt{\beta_{TWISS}\varepsilon}$)
- halo particles captured through amplitude increase via multiple scattering and multi-turn effect.



$$\text{capture condition}: \delta x' > \sqrt{\frac{\left(N_2^{\ 2} - N_1^{\ 2}\right)\varepsilon_N}{\gamma_{REL.}\,\beta_{TWISS}}} \qquad \varepsilon_N = \varepsilon\beta\gamma$$

$\langle \delta x'^2 \rangle \sim L$

Requirements for LHC



Nominal beam power: 362 MJ

Super-Conducting Environment

Proton losses into cold aperture

⇩

Local heat deposition

⇩

Magnet can quench

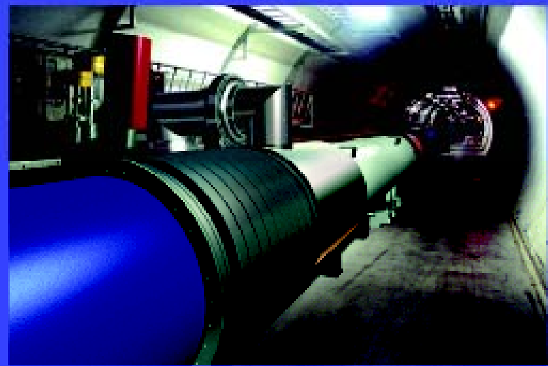


Illustration of LHC dipole in tunnel

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

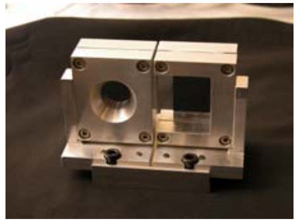
Control **transient losses (10 turns)** to ~1e-9 of nominal intensity (top)!

Capture (clean) lost protons before they reach cold aperture!
Required efficiency: ~ 99.9 % *(assuming losses distribute over 50 m)*

RA LHC MAC 13/3/03

Courtesy of R. Assmann

Ion collimation: why an issue?

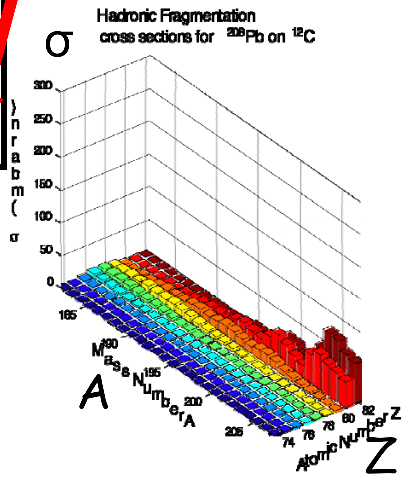


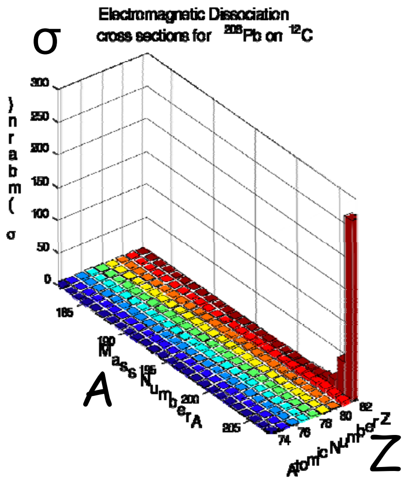
Nominal ion beam in LHC has 100 times less beam power than proton beam, but

Physics process	Proton	^{208}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)	73.5μrad/m^{½} 4.72μrad/m^{½}	73.5μrad/m^{½} 4.72μrad/m^{½}
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





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

High probability of nuclear interactions in the scatterer

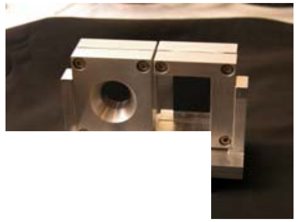
➔ strong reduction of the 2-stage collimation EFFICIENCY

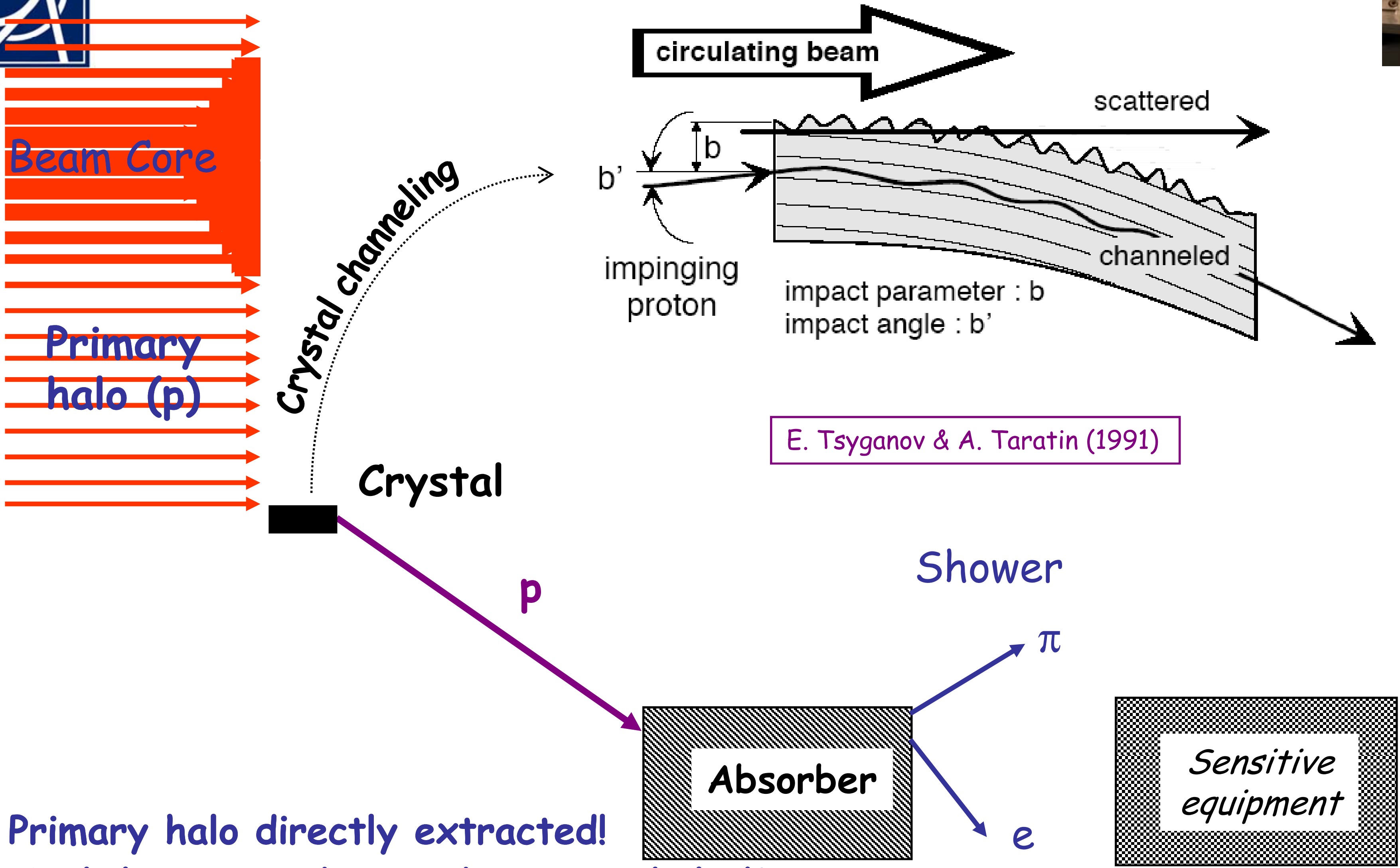
Curtesy of Bellodi

fragmented nuclei, Monte Carlo estimate of the x-sections

loss 1 n (59%) → ^{207}Pb
loss 2 n (11%) → ^{206}Pb

Crystal collimation

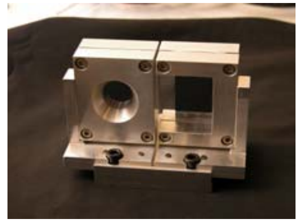




- Primary halo directly extracted!
- Much less secondary and tertiary halos!?

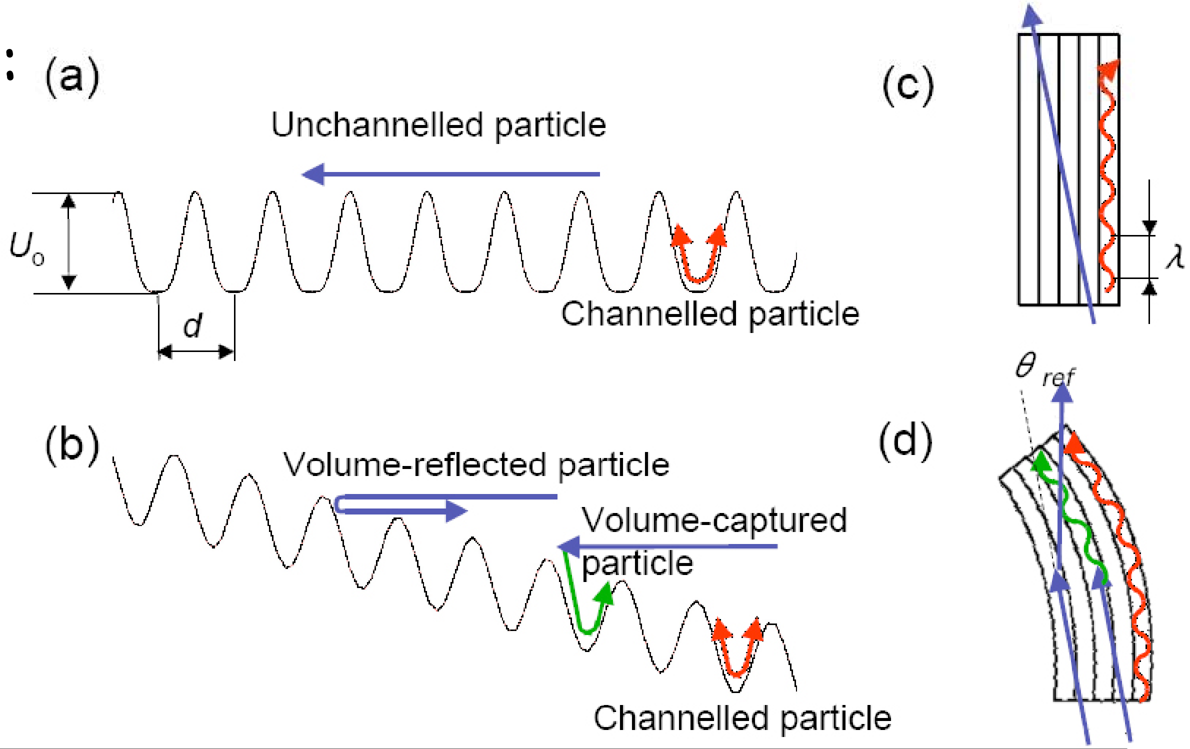
..but no enough data available to substantiate the idea…

Particle-crystal interaction



Possible processes:

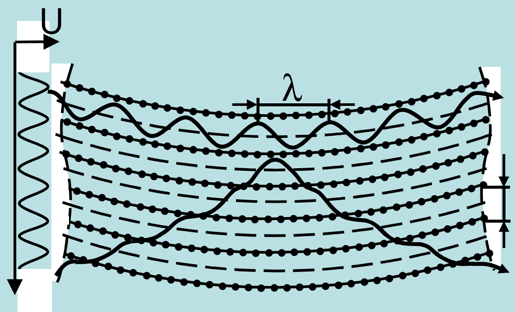
- multiple scattering
- channeling
- volume capture
- de-channeling
- *volume reflection*



Volume reflection

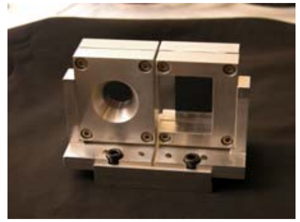
Prediction in 1985-'87 by
A.M.Taratin and S.A.Vorobiev,

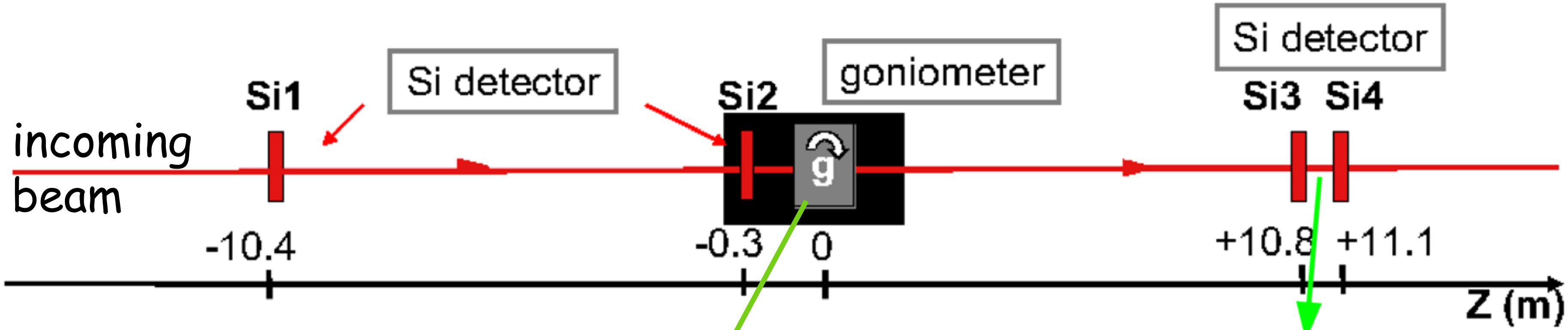
First observation 2006 (IHEP - PNPI - CERN)

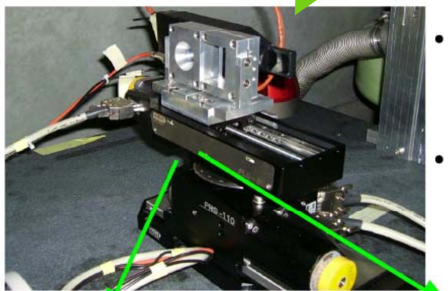


The H8RD22 apparatus:

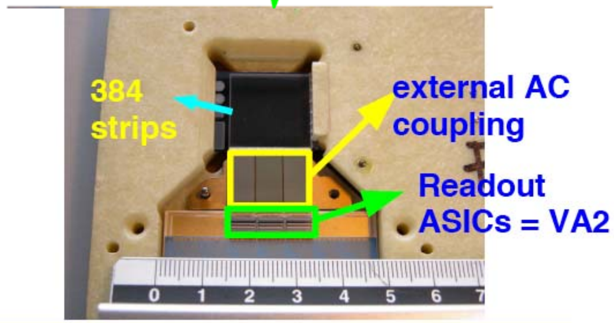
Single pass tests in the SPS-North Area







- 3-stage goniometer (2 lateral + one rotation)
- precision = of the order of 1μrad



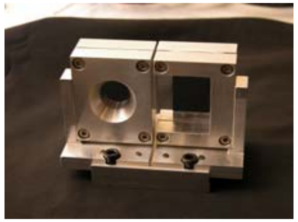
Strip crystal **(limited but regular surface)**

Quasimosaic crystal **(big surface)**

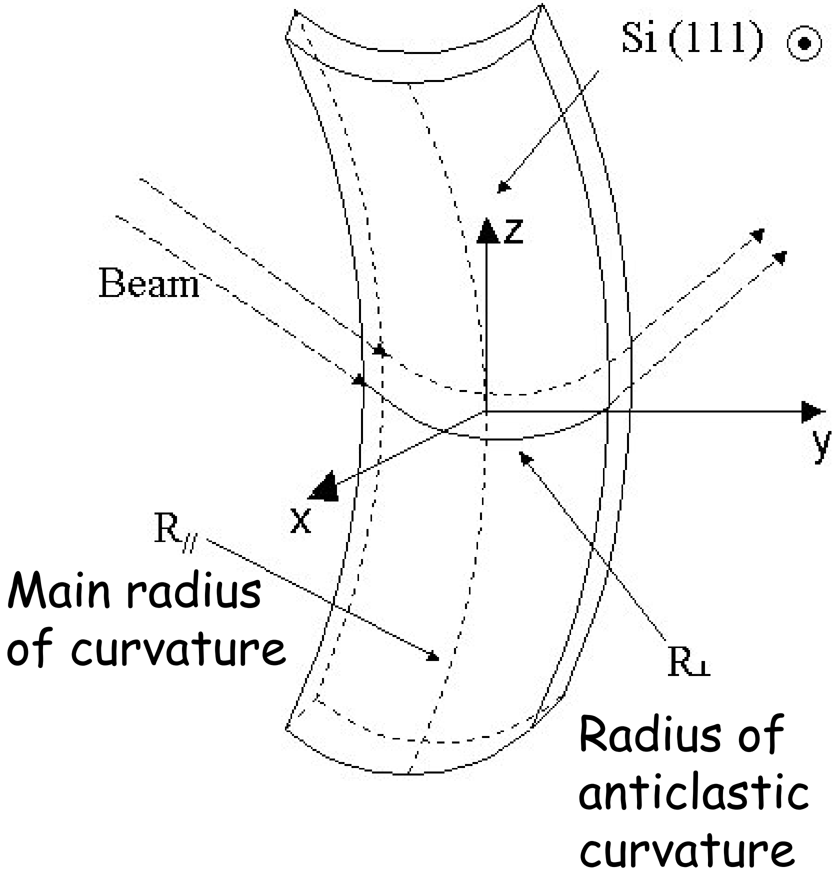
- **double sided silicon strip detector with 50μm pitch**
- **dimensions = 1.92x1.92 cm²**
- **SNR = 80:1 with a 5 MHz readout clock and 25m cables**
- **Residual = better than 5 μm**
- **DAQ rate = 2.1kHz → 10k events per spill**

Strip crystals

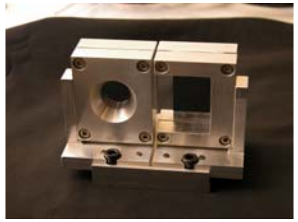
Built at INFN – Ferrara in collaboration with IHEP - Protvino



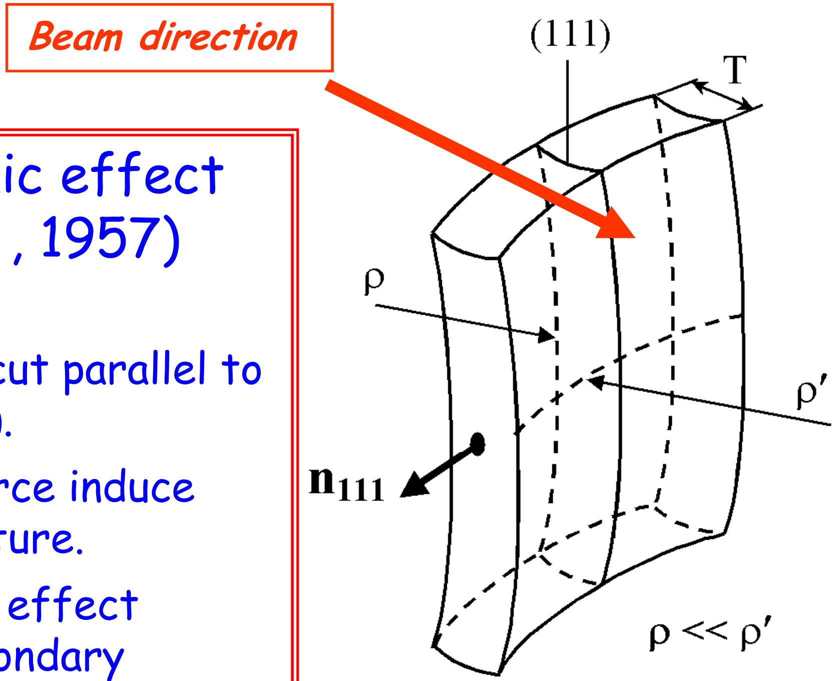
The main curvature due to external forces induces the anticlastic curvature seen by the beam



Quasimosaic crystals

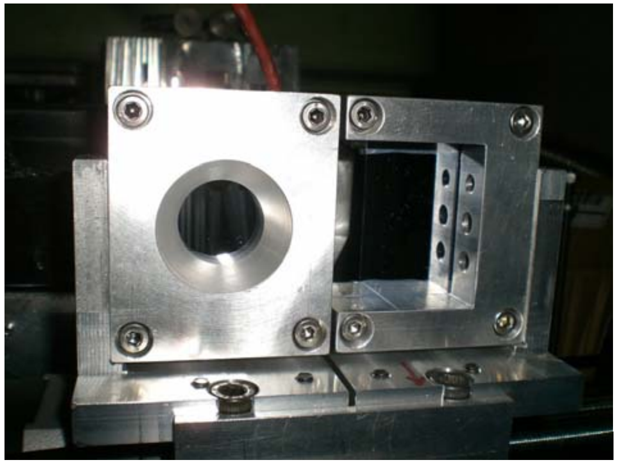


Built at PNPI - Gatchina



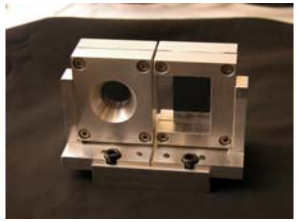
Quasi-Mosaic effect (Sumbaev , 1957)

- 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.

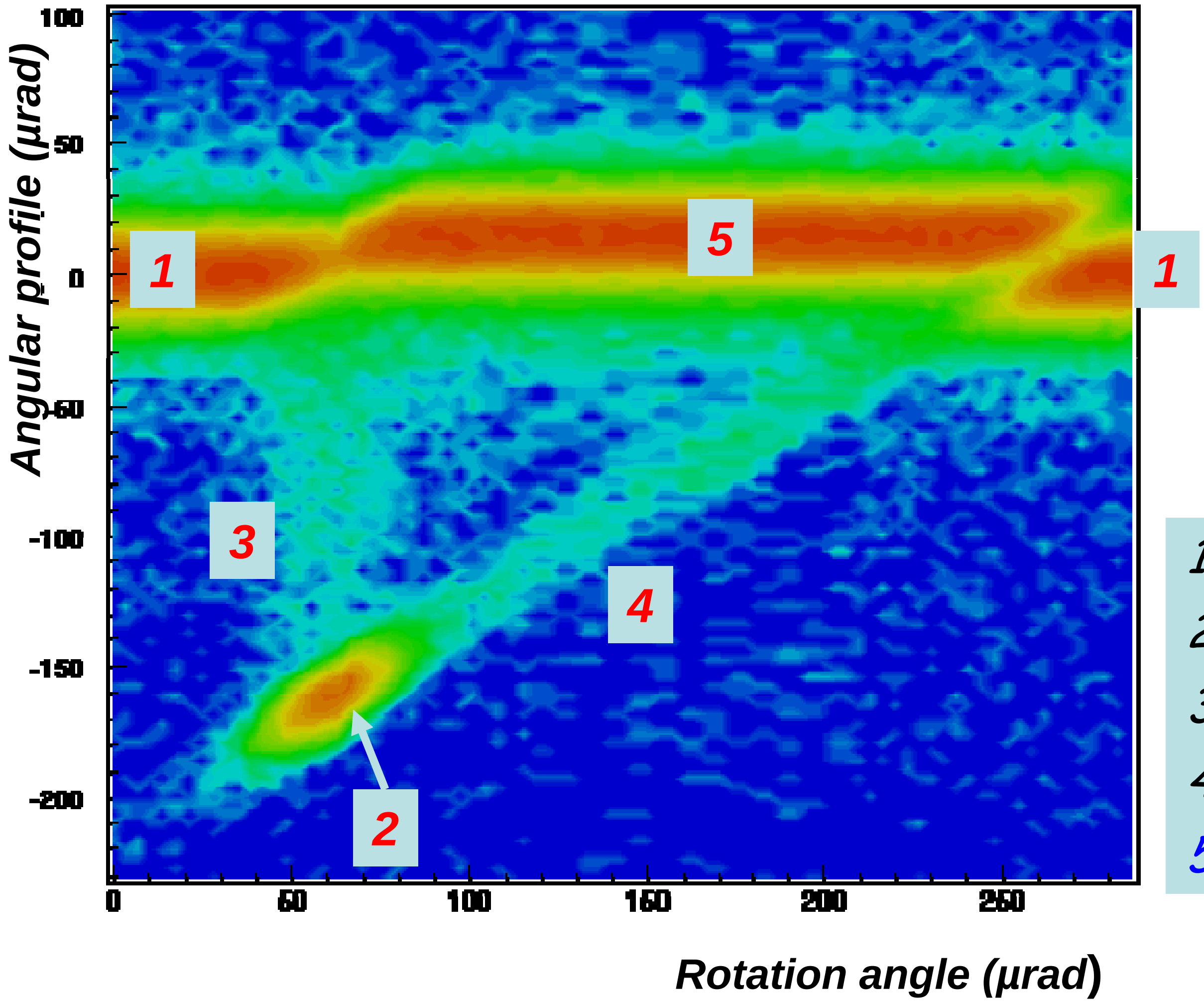


Crystal size: 0.7 x 30 x 30 mm^3

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

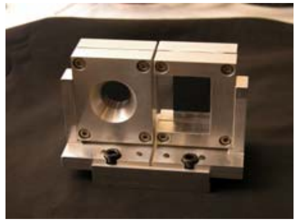
2 - channeling (50 %)

3 - de-channeling (1 %)

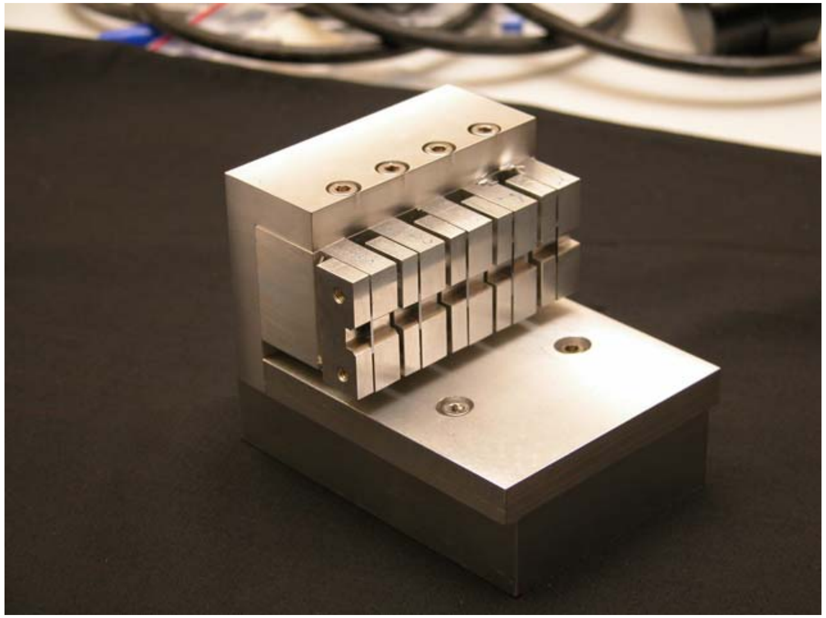
4 - volume capture (2 %)

5 - volume reflection (98 %)

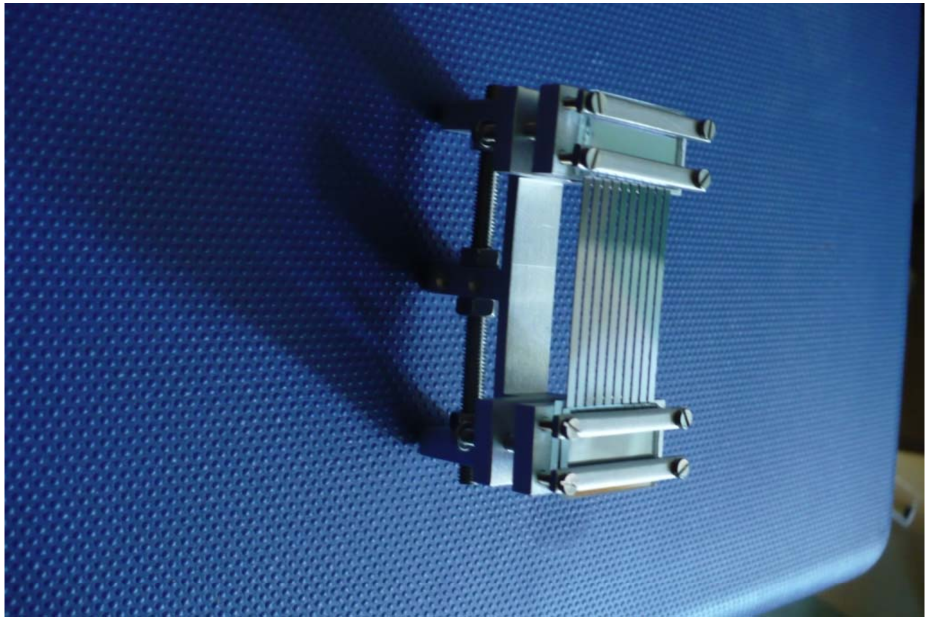
Multi-crystals



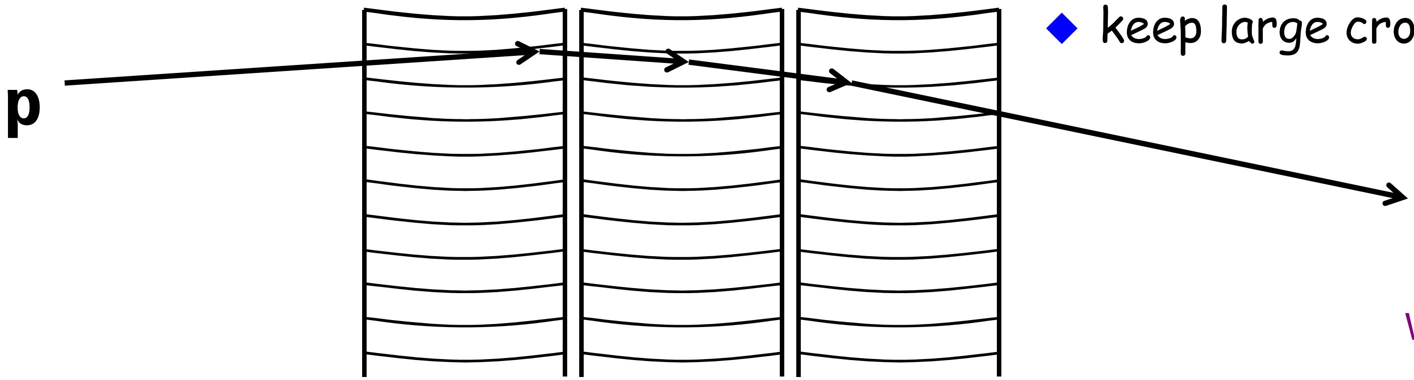
multiheads crystal (PNPI)



multistrip crystal (IHEP and INFN-Ferrara)

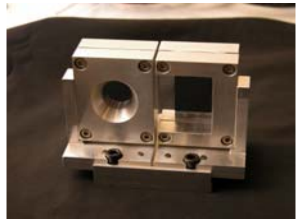


Several consecutive reflections

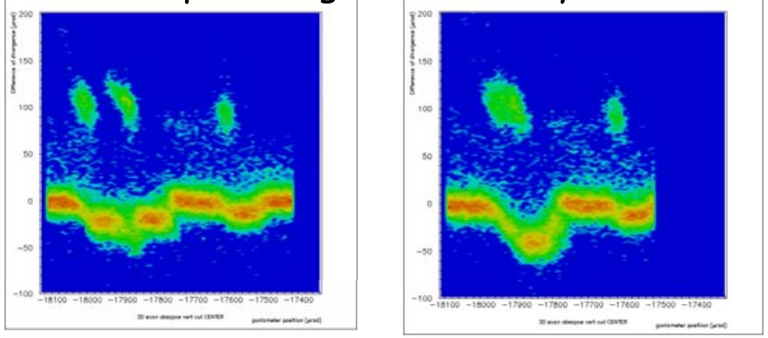


- enhance the deflection angle
- keep large cross section

5 heads multi-crystals

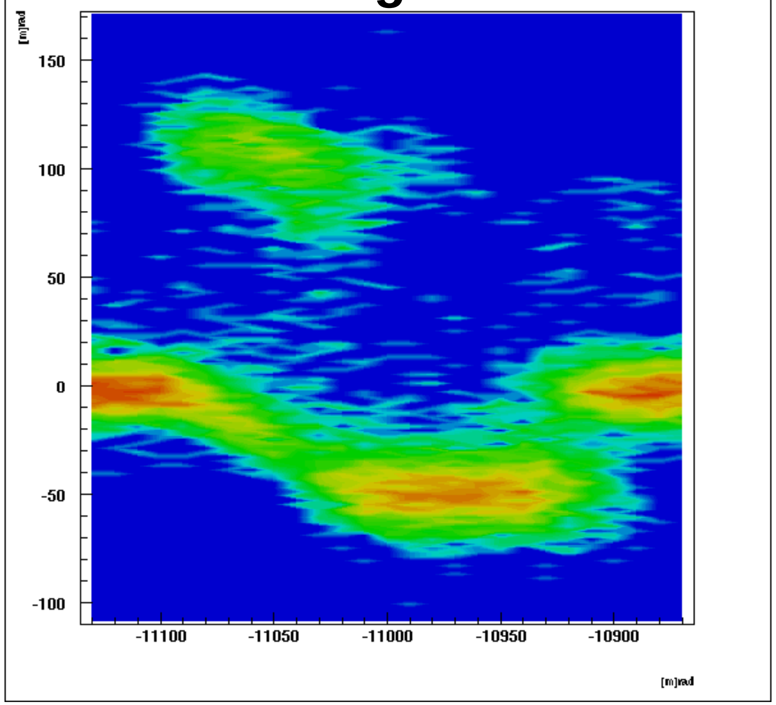


Steps to align the five crystals

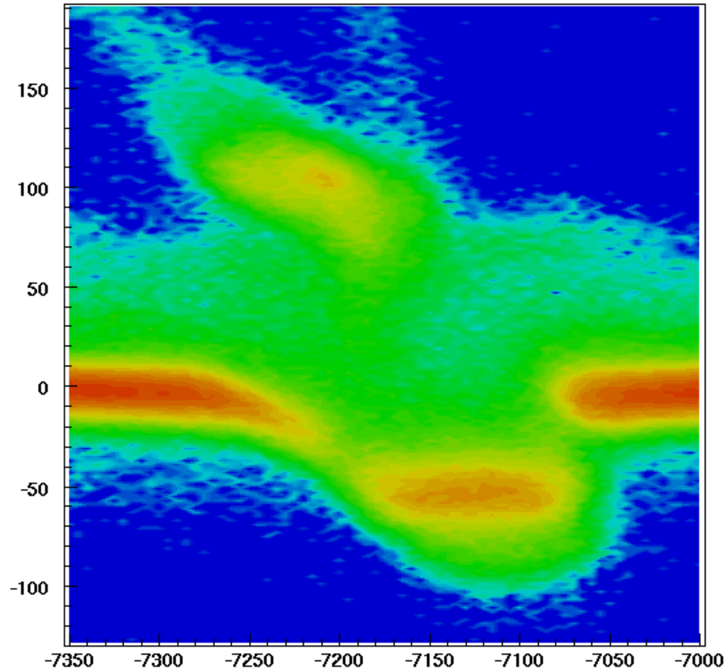


- Volume reflection angle 53 μrad
- Efficiency ≥ 90 %

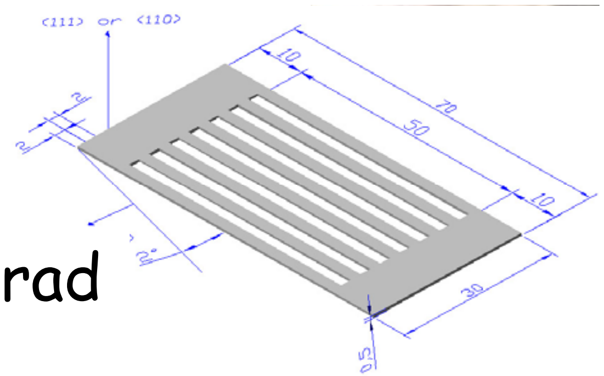
Best alignment



High statistics



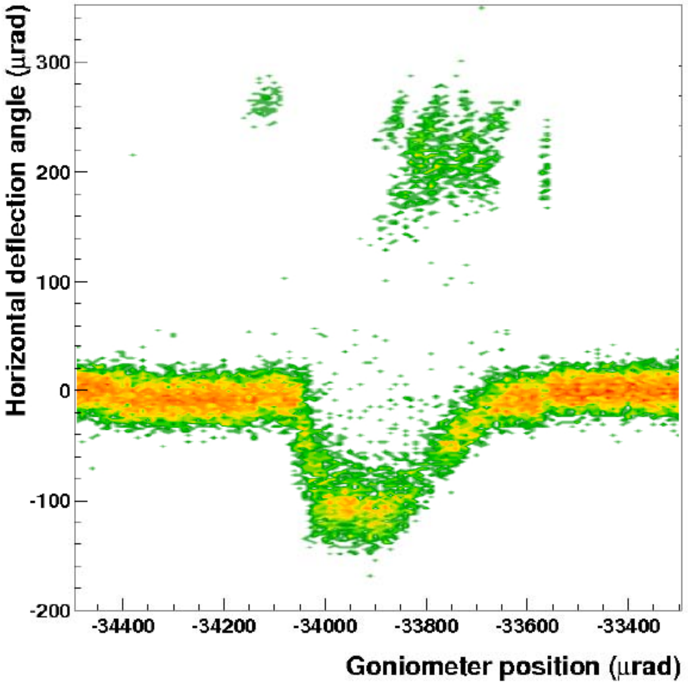
Multi-strips



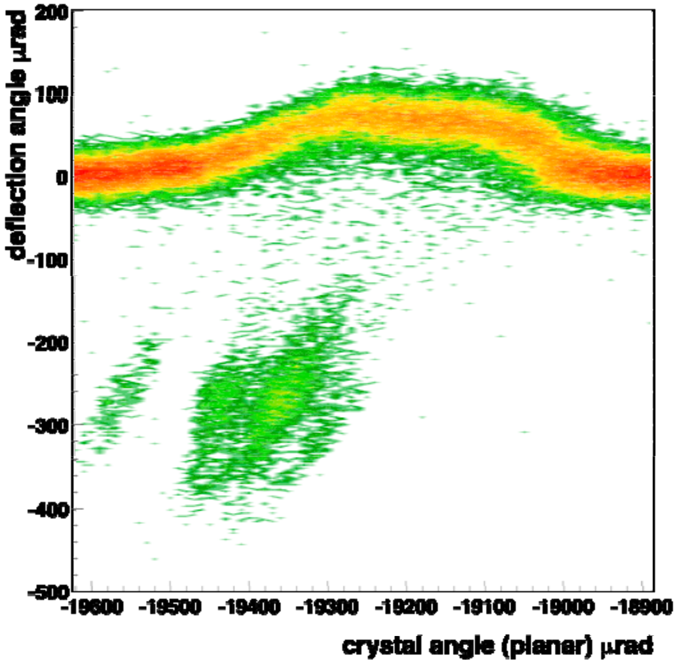
- Volume reflection angle ~100 μrad
- Efficiency ~ 90 %

MST 14 – 400 Gev – R=4.61m

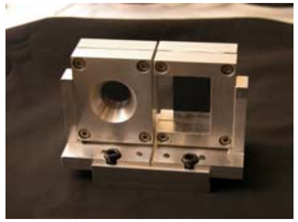
INFN-Ferrara



IHEP



Other results of H8RD22



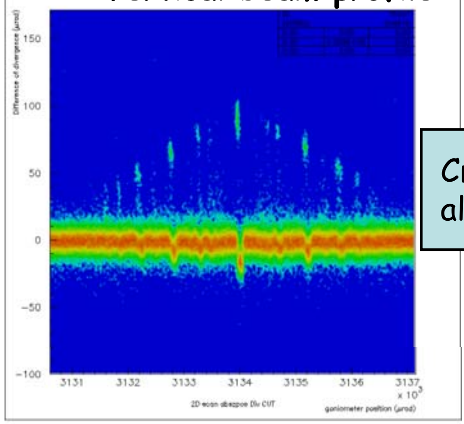
PROTON BEAM (400GeV/c),

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

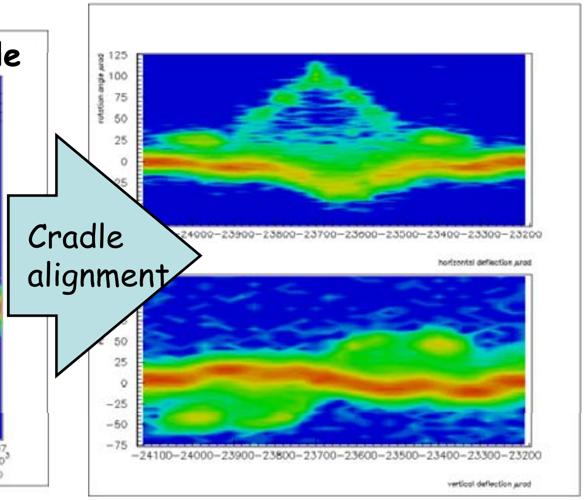
ELECTRON/POSITRON BEAM (180GeV/c),

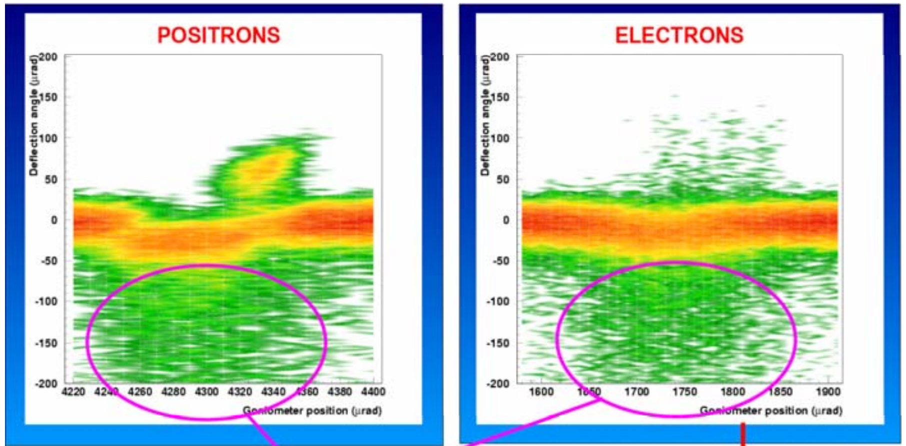
- Volume reflection with electrons and positrons
- Radiation emission with e+/e- beams in channeling condition

Channeling from secondary crystal planes
Vertical beam profile



Modulated VR & y scan



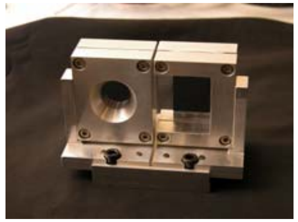


e+/ e- having lost energy via radiation emission

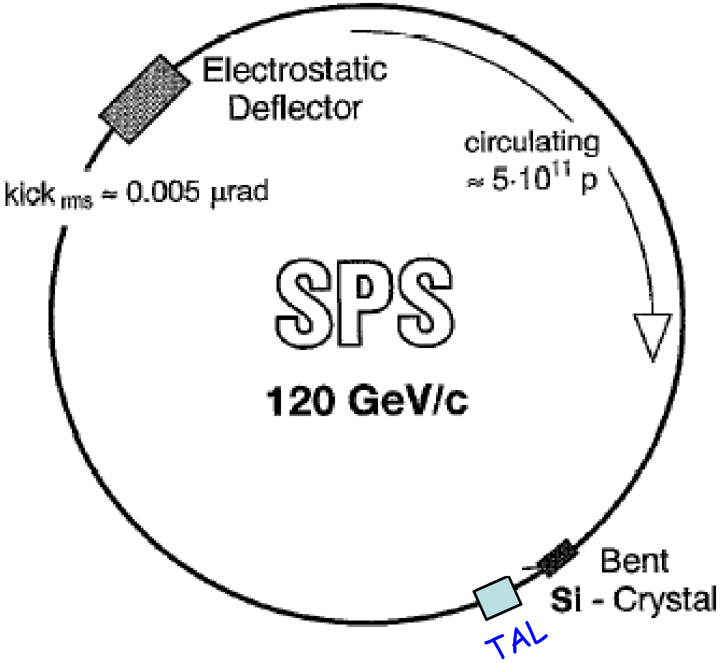
The crystal is not ideal but it's there!!!!!!

UA9

The underground experiment in the SPS

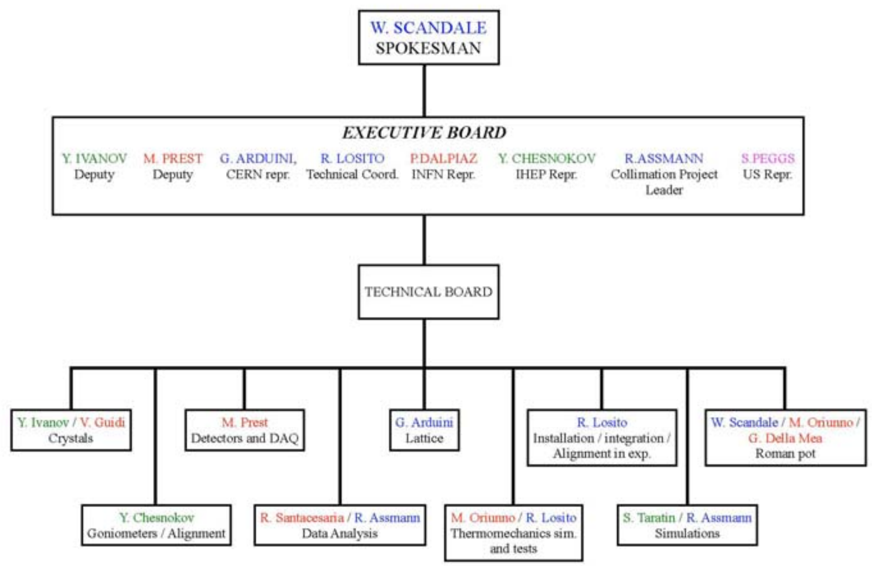


Approved by the CERN Research Board of the 3 Sept 2008



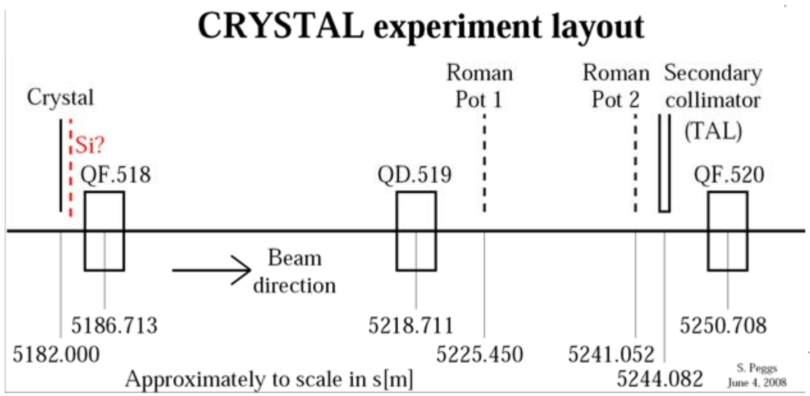
Goals:

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

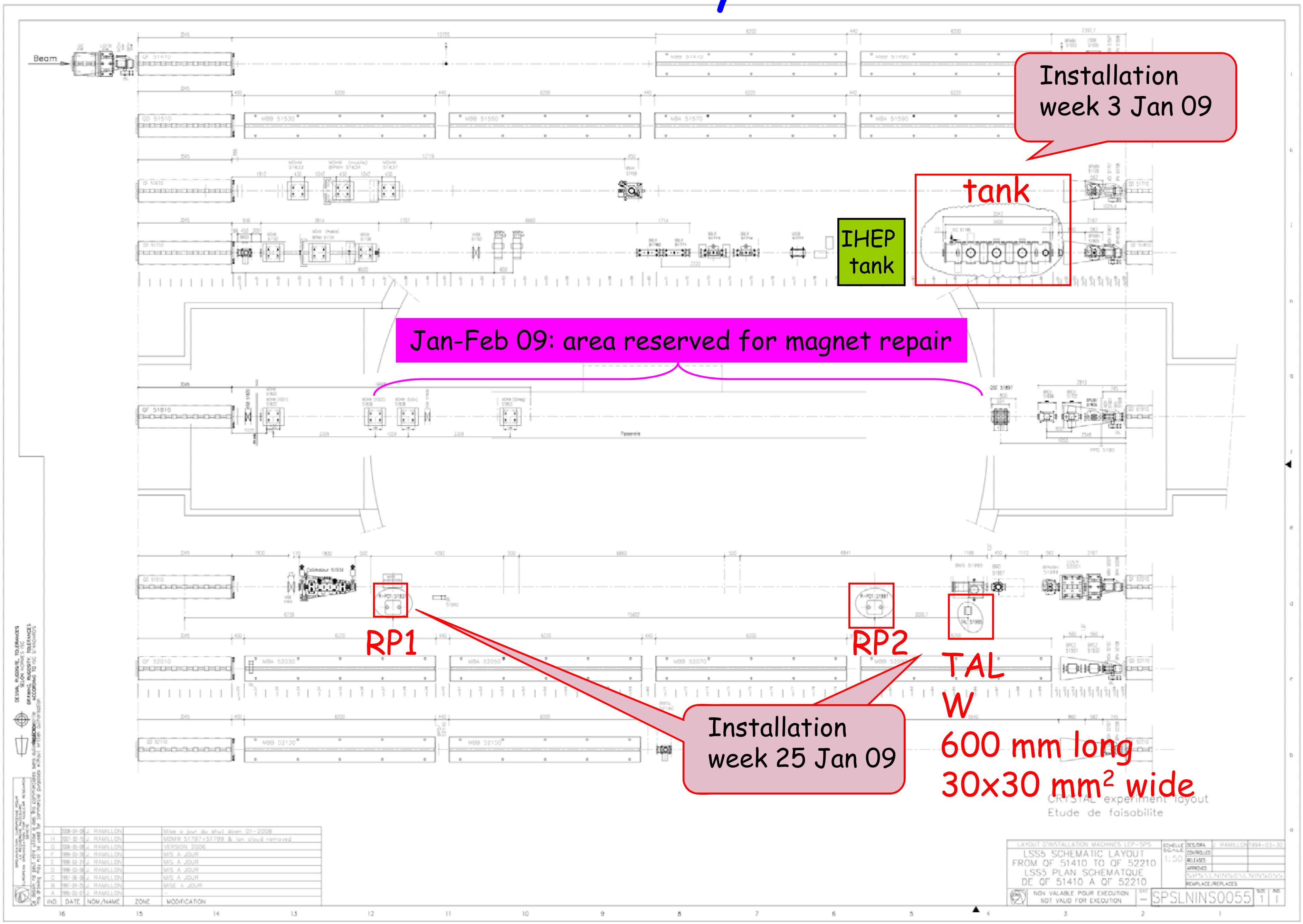


CRYSTAL organization chart; colors refer to different agencies: blue for CERN, green for Russian Institutions, red for INFN and violet for USA Institutions.

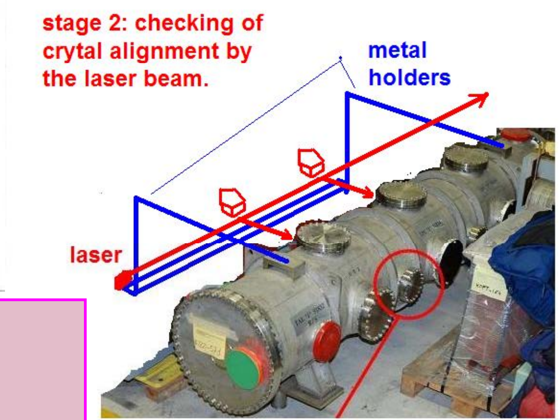
CERN
INFN
PNPI
IHEP
JINR
SLAC
FNAL
LBNL



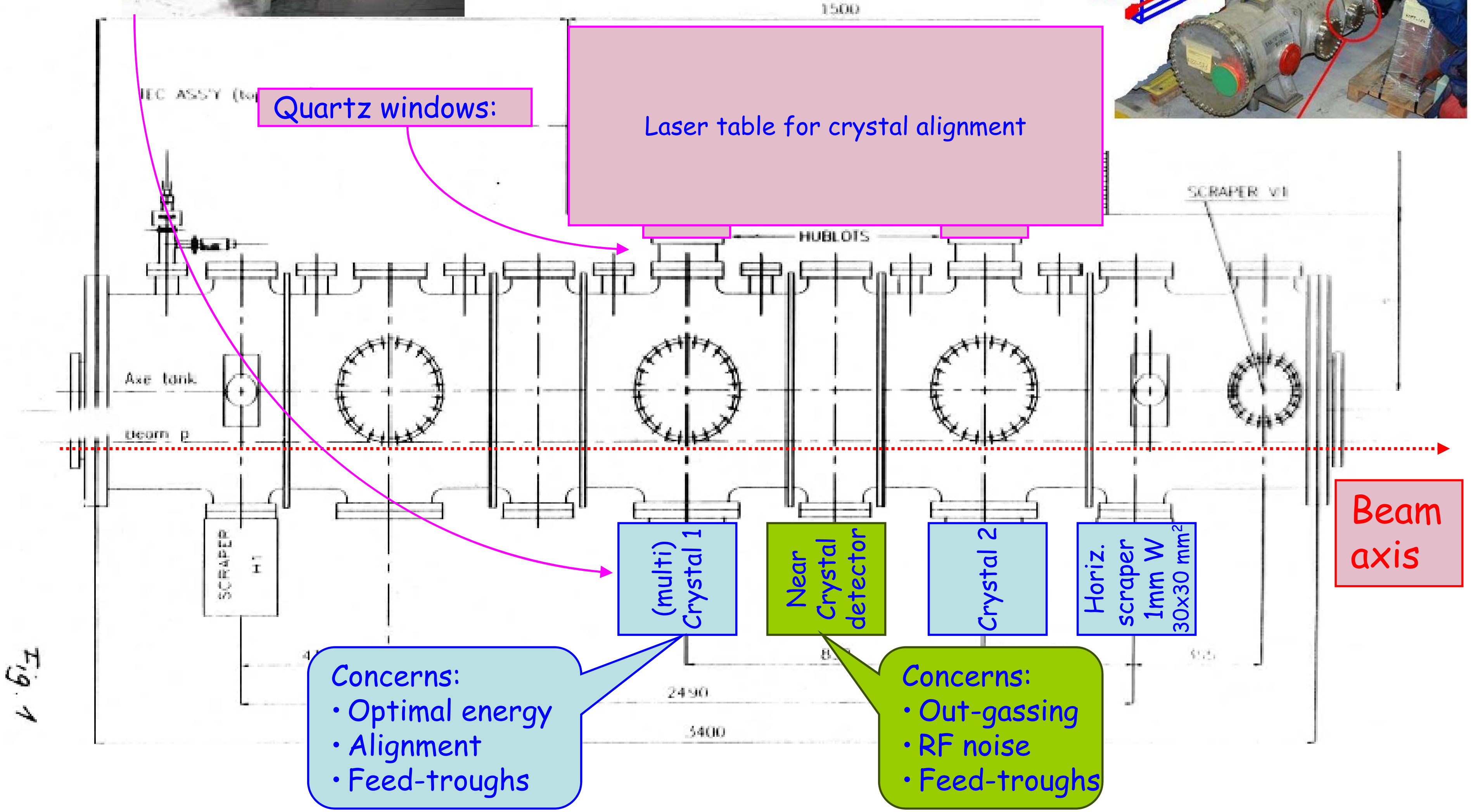
UA9 layout


Beam
Installation
week 3 Jan 09
tank
IHEP
tank
Jan-Feb 09: area reserved for magnet repair
RP1
RP2
TAL
W
600 mm long
30x30 mm² wide
Installation
week 25 Jan 09
CRYSTAL experiment layout
Etude de faisabilite
LSS5 SCHEMATIC LAYOUT
FROM QF 51410 TO QF 52210
LSS5 PLAN SCHEMATIQUE
DE QF 51410 A QF 52210
SPSLNINS0055

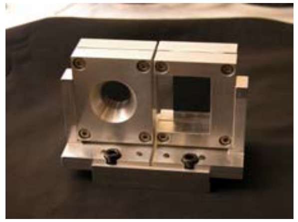
RD22 tank



stage 2: checking of crytal alignment by the laser beam.
metal holders
laser



1500
Quartz windows:
Laser table for crystal alignment
HUBLOTS
SCRAPER V1
Axe tank
SCRAPER H1
(multi) Crystal 1
Near Crystal detector
Crystal 2
Horiz. scraper 1mm W 30x30 mm²
Beam axis
2490
3400
Fig. 1
Concerns:
• Optimal energy
• Alignment
• Feed-troughs
Concerns:
• Out-gassing
• RF noise
• Feed-troughs



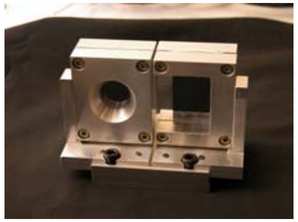
The SPS beam

- 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)

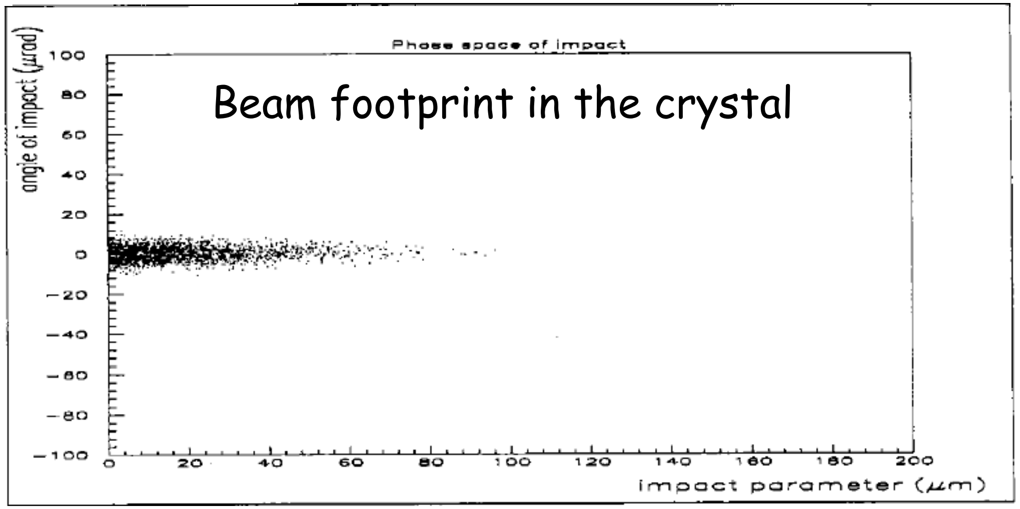
	High energy	unbunched	bunched
RF Voltage [MV]	1.5	0	1.5
Momentum P [GeV/c]	270	120	120
Tune Qx	26.13	26.13	26.13
Tune Qy	26.18	26.18	26.18
Tune Qs	0.0021	0	0.004
normalized emittance (at 1 σ) [mm mrad]	1.5	1.5	1.5
transverse radius (RMS) [mm]	0.67	1	1
momentum spread (RMS) $\Delta p/p$	2 to 3×10^{-4}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

alternative tunes are those selected in RD22 (Qx=26.62, Qy=26.58).

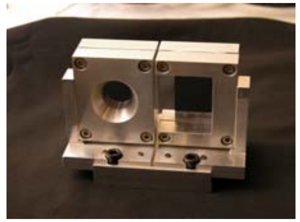
The SPS beam

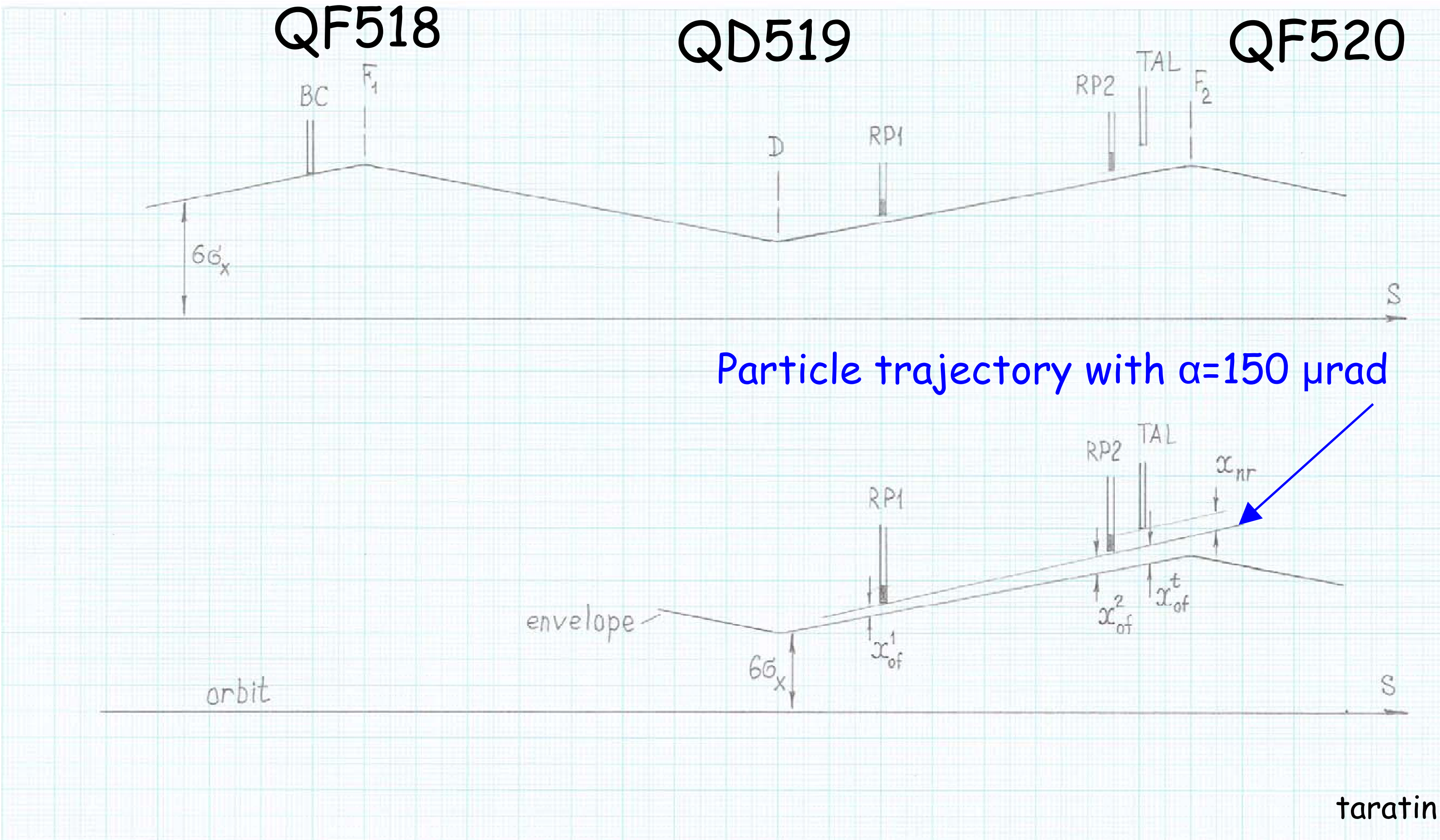


- Intensity a few 10^{11} up to a few 10^{12} circulating particles.
- Beam either unbunched or bunched in a few tens of bunches.
- Beam lifetime larger than 80 h, determined by the SPS vacuum.
- A halo flux of a few 10^2 to a few 10^4 particles per turn, which can be investigated with the detectors 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.



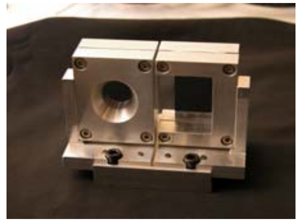
Deflected beam

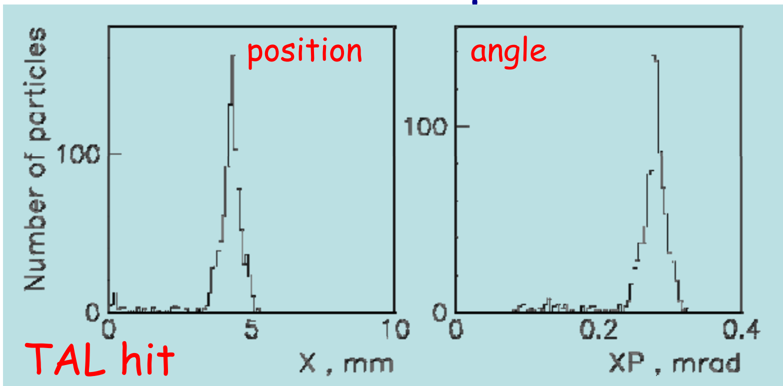


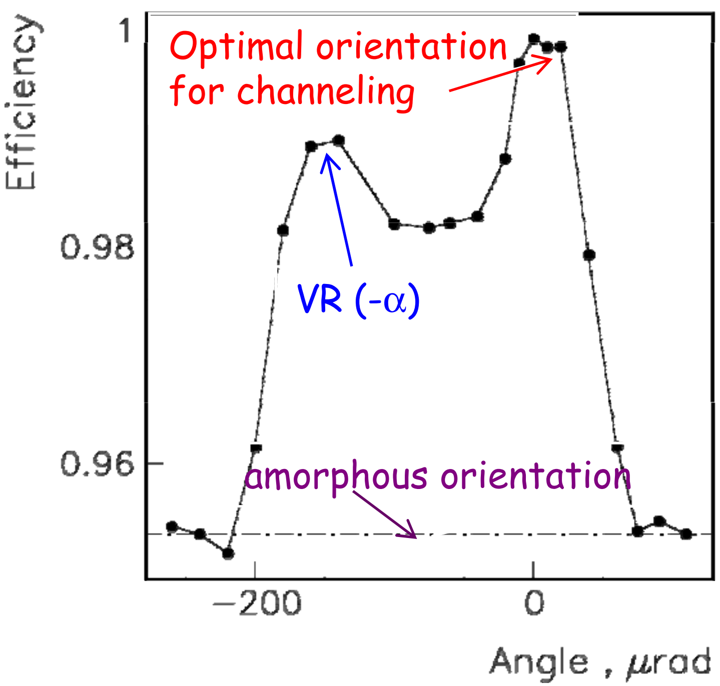


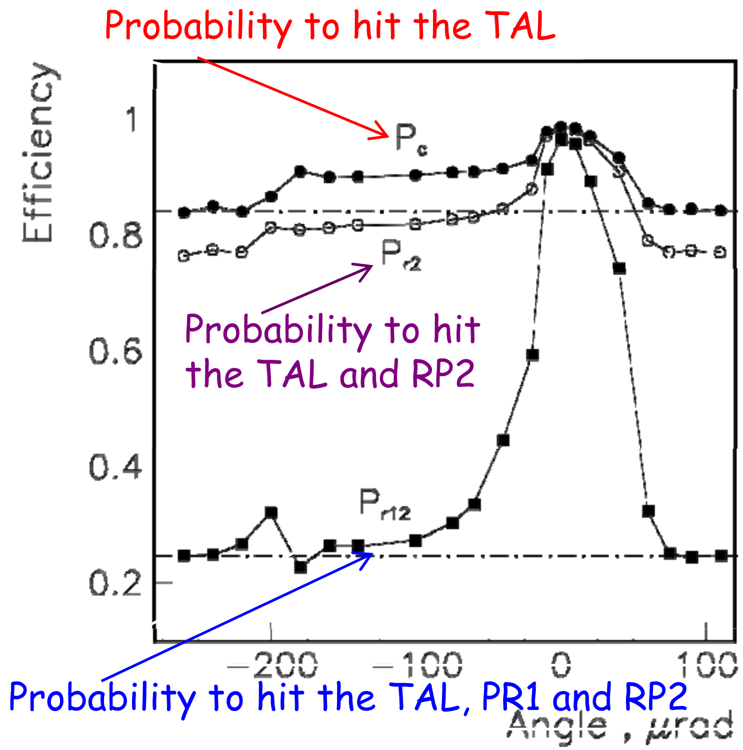
Expected efficiency

for α=150 μrad

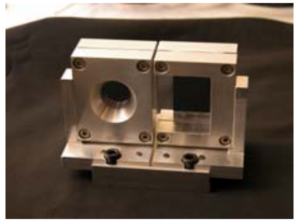








Plans for 2009



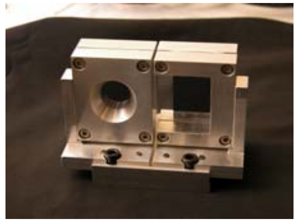
UA9

- 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

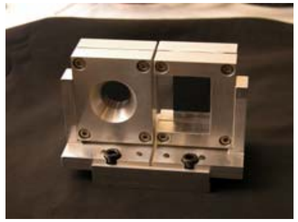
Conclusion



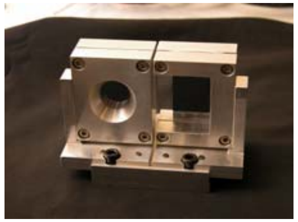
- High efficient reflection (and channeling) observed in single pass interaction of high-energy protons with bent crystals (0.5 to 10 mm long)
- Single reflection on a Si bent crystal deflects > 98 % of the incoming beam by an angle 12÷14 μrad
- Very promising for application in crystal collimation
- 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**



Acknowledgments

We acknowledge partial support by

- The European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” program (CARE, contract number RII3-CT-2003-506395),
- the INTAS program
- The MIUR 2006028442 project,
- The Russian Foundation for Basic Research grant 06-02-16912,
- The Council of the President of the Russian Federation grant NSh-3057.2006.2,
- The Program "Physics of Elementary Particles and Fundamental Nuclear Physics" of Russian Academy of Sciences.
- INFN: NTA programme