CRYSTAL EXTRACTION

W. Scandale

Spokes person of the UA9 Collaboration

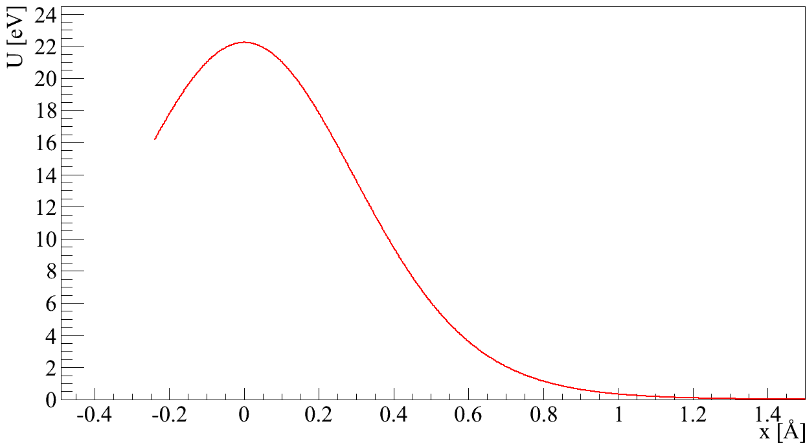
The slow extraction workshop, Darmstadt, 1-3 June 2016

outlook

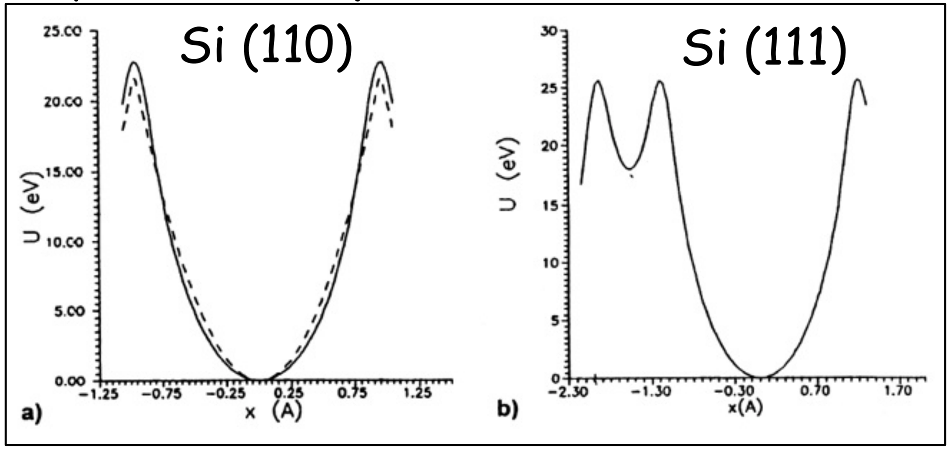
- Crystal-particle interactions
- Non-resonant crystal extraction (1990-'98)
  - RD22 at the CERN-SPS
  - E853 at the FNAL-Tevatron
- Concept of crystal-assisted collimation – halo extraction towards an absorber
- UA9 as a test bed for crystal-assisted collimation
- Test of crystal-assisted collimation in LHC
- Crystal-assisted (resonant and non-resonant) extraction in the SPS

Confinement of particles in a crystal

Potential between a **particle** and an **atom** described by **Thomas-Fermi model:**



Potential between contiguous planes of a **crystalline lattice**



Continuous approximation:

$$U_p(x) = Nd \iint_{-\infty}^{+\infty} V(x,y,z)dydz$$

At the scale of **hundreds of GeV:**

- ✓ Available **energetic levels:**

$$n = \frac{d_p}{\hbar\sqrt{8}}\sqrt{U_{max} m \gamma} \sim 10^{13}$$

- ✓ **de Broglie length:**

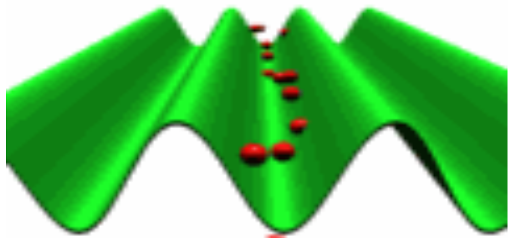
$$\sim 10^{-17} \text{ m} \Leftrightarrow d_p = 1.92 \text{ Å}$$

Classical treatment allowed

*If the protons **have*** $p_T < U_{max}$

$$\Updownarrow$$

$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

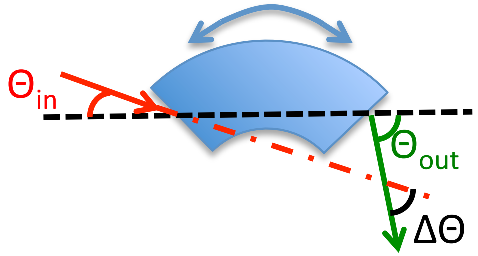


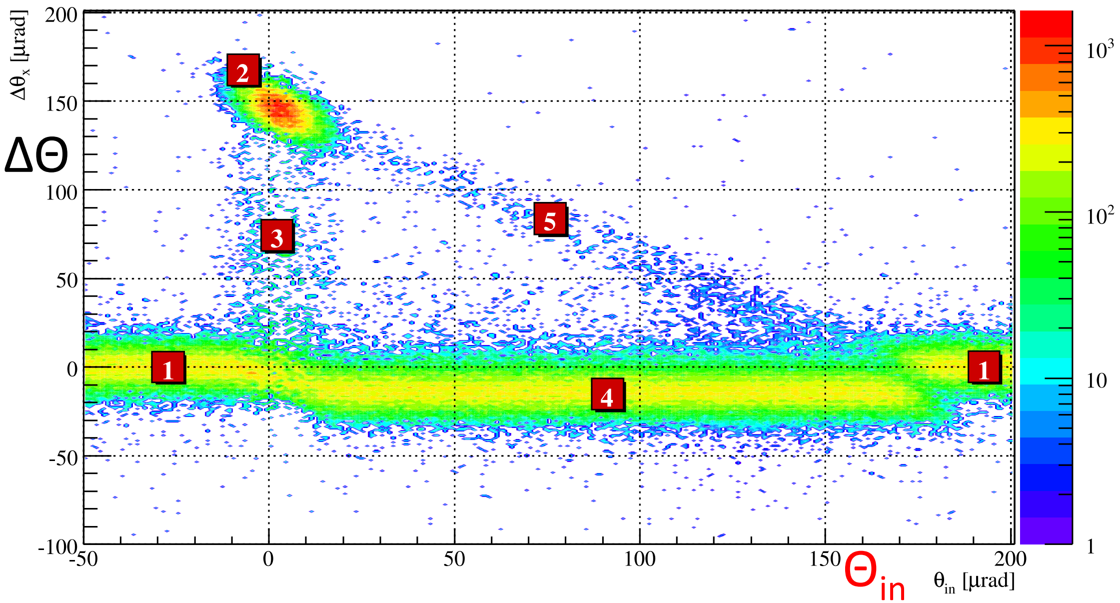
Forced to oscillate in a relatively empty space

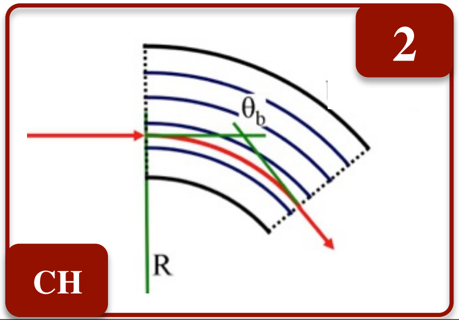
$$x(z) = \frac{d_p}{2}\sqrt{\frac{E_t}{U_{max}}}\sin\left(\frac{2\pi z}{\lambda} + \phi\right)$$

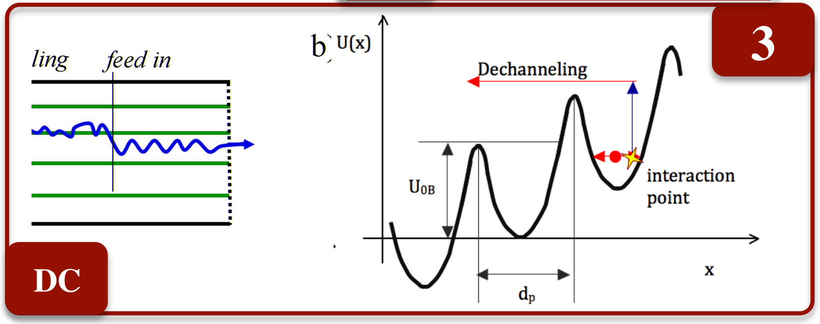
Coherent particle-crystals interactions

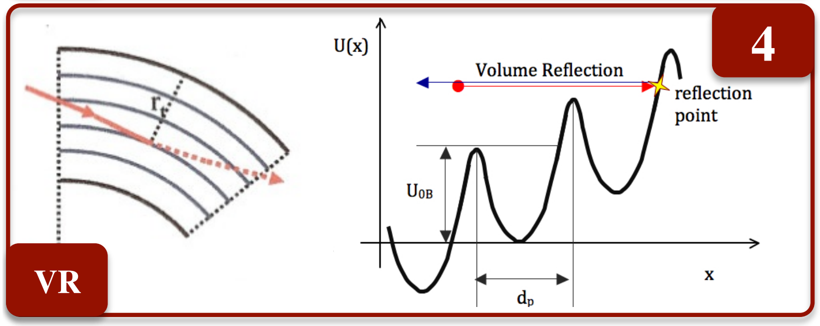
Particles interacting with crystal planes at small angle

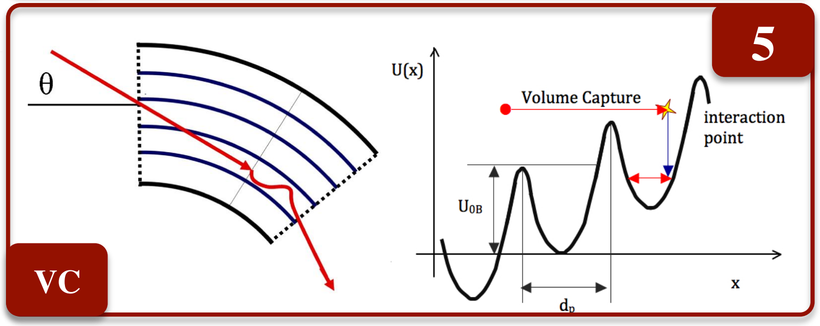












$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Critical angle for channeling

$$\theta_c = \begin{cases} 10\,\mu rad @ 270\text{ GeV} \\ 2\,\mu rad @ 7\text{ TeV} \end{cases}$$

Extraction in LHC for the LHB experiment (1990)

W. Scandale,

Proc. LHC Workshop, eds G. Jarlskog and D. Rein, vol. III p. 760 Aachen 1990.

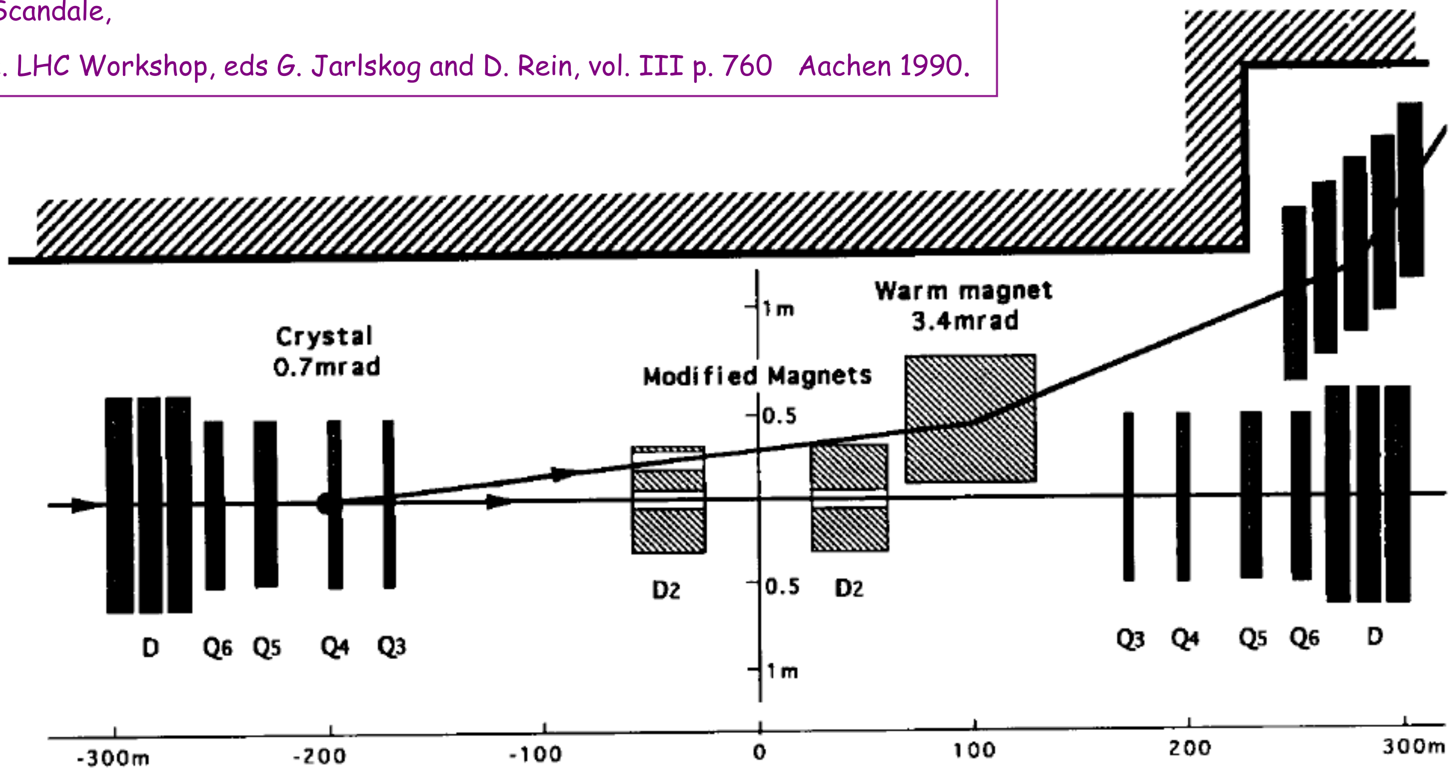
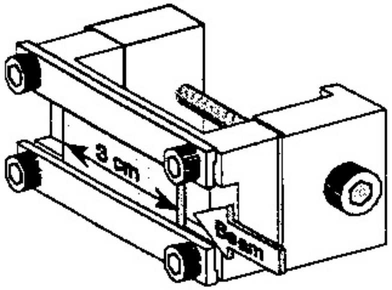


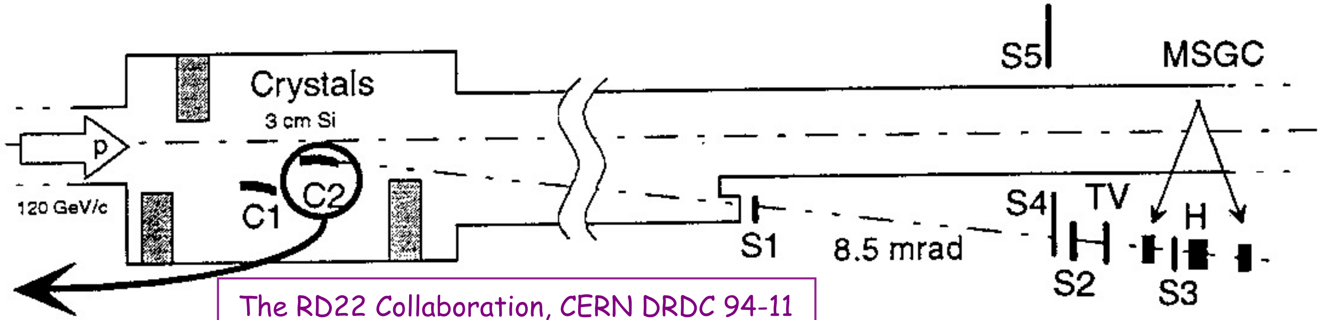
Fig. 2. Schematic layout of vertical halo extraction using channeling in a bent silicon crystal. After the warm septum magnet the extracted beam is bent by a string of five superconducting dipoles of the LHC type [14].

RD22 proposed in the SPS as the demonstrator of crystal-assisted extraction

RD22: extraction of 120 GeV protons (SPS: 1990-95)



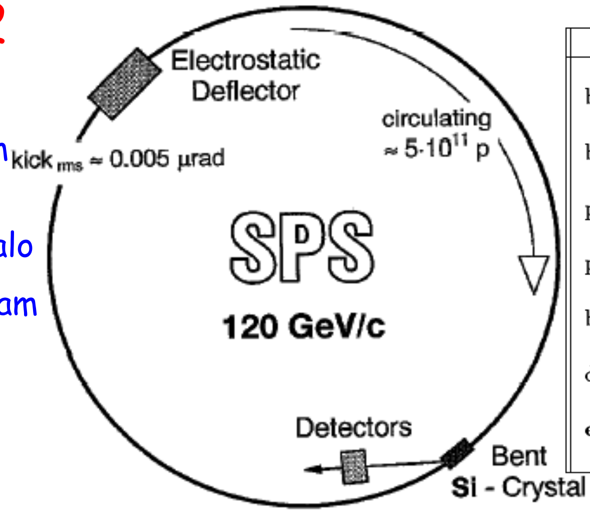
A.A. Asseev et al, Nucl.Inst.Meth. A330 (1993) p39



The RD22 Collaboration, CERN DRDC 94-11

Basic scenario of RD22

- Beam in coasting mode at 120 GeV
- Transverse excitation of the beam core increases halo population
- Bent crystal positioned into the halo
- Extraction channel 13 m downstream of the crystal



Typical data collected in RD22

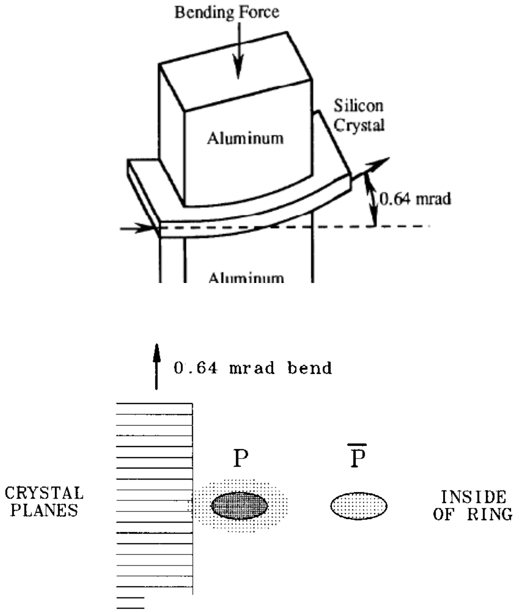
	Crystal 1	Crystal 2
beam intensity (protons)	$(7.0 \pm 0.1) \cdot 10^{11}$	$(3.7 \pm 0.1) \cdot 10^{11}$
beam lifetime (hrs)	20 ± 2	12 ± 1
protons lost per second	$(6.7 \pm 0.6) \cdot 10^{6}$	$(8.9 \pm 0.7) \cdot 10^{6}$
protons detected per second	$5.6 \cdot 10^{5}$	$6.6 \cdot 10^{5}$
background (%)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

Key results

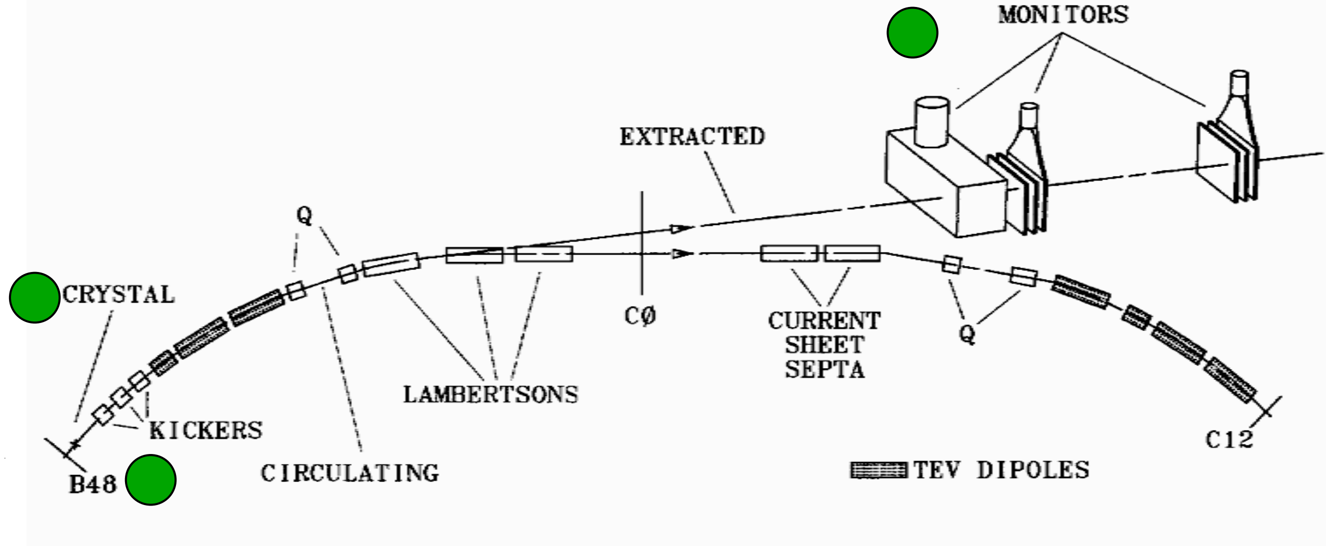
- Large channeling efficiency measured for the first time – also for lead ions
- Consistent with simulation expectation extended to high energy beams
- Experimental proof of multi-turn effect (channeling after multi-traversals)
- Definition of a reliable procedure to measure the channeling efficiency

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

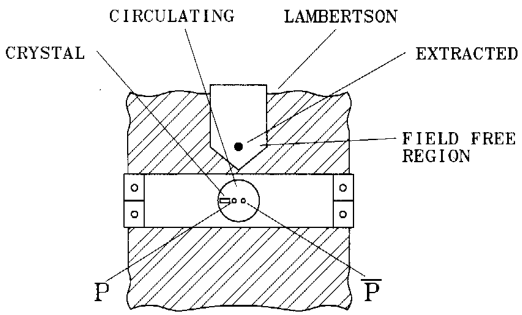
Experiment proposed at FNAL as a test bed for SSC beam extraction



At crystal



R.A. Carrigan jr., et al, Phys.Rev.ST Accel.Beams 5:043501 (2002)

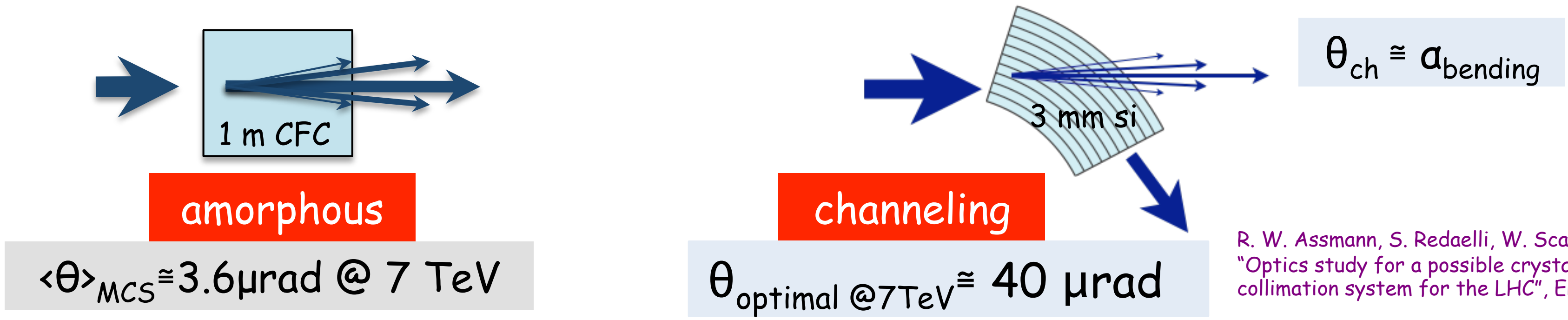


Lambertson, crystal

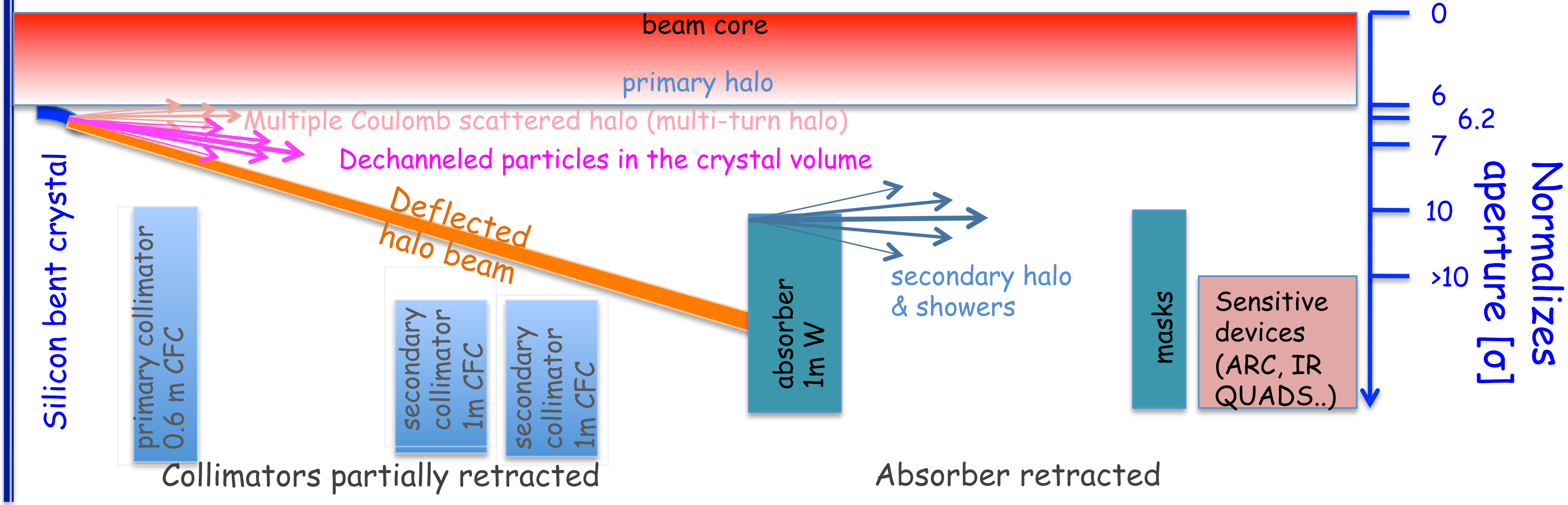
- Extracted significant beams from the Tevatron parasitic, kicked and RF stimulated
- First ever luminosity-driven extraction
- Highest energy channeling ever
- Useful for collimation studies
- Extensive information on time-dependent behavior
- Very robust

Crystal assisted collimation (2006-now)

- 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



Potential improvements for LHC

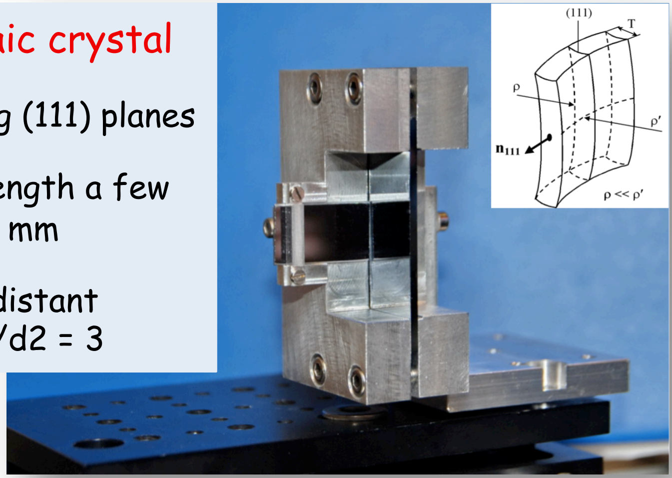
1. Larger impact parameter: crystals deflect the halo particles coherently to a larger angle than the amorphous primary collimator,
   - ✓ better localization of the halo losses ➔ evidence from UA9 data in the SPS
   - ✓ reduced collimation inefficiency ➔ $\times 10^{-1}$ expected from simulations
   - ✓ higher beam intensities (if limited by halo density)
2. Less impedance: Optimal crystals are much shorter than the amorphous primary collimators and produce much less impedance
   - ✓ 20% reduction of the overall impedance (by replacing the primary with a crystal) ➔ from simulations
3. Less nuclear events: inelastic nuclear interactions with bent crystals strongly suppressed in channeling orientation ➔ lower probability of producing proton diffractive events or lead ions fragmentation and dissociation
   - ✓ × 20 less nuclear events in 120÷270 GeV channeled protons ➔ UA9 data in the SPS ring
   - ✓ × 7 less nuclear events in 120÷270 GeV/u channeled lead ions ➔ UA9 data in the SPS ring

W. Scandale et al, Physics Letters B 714 (2012) 231–236

Bent crystals for UA9

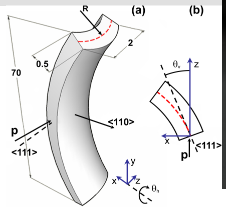
Quasimosaic crystal

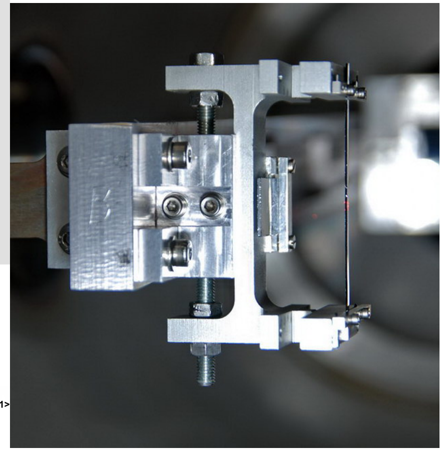
- Bent along (111) planes
- Minimal length a few tenths of mm
- Non-equidistant planes d1/d2 = 3



Strip crystal

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



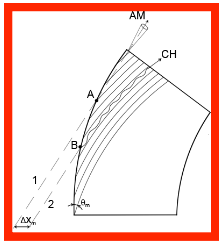


Crystals

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

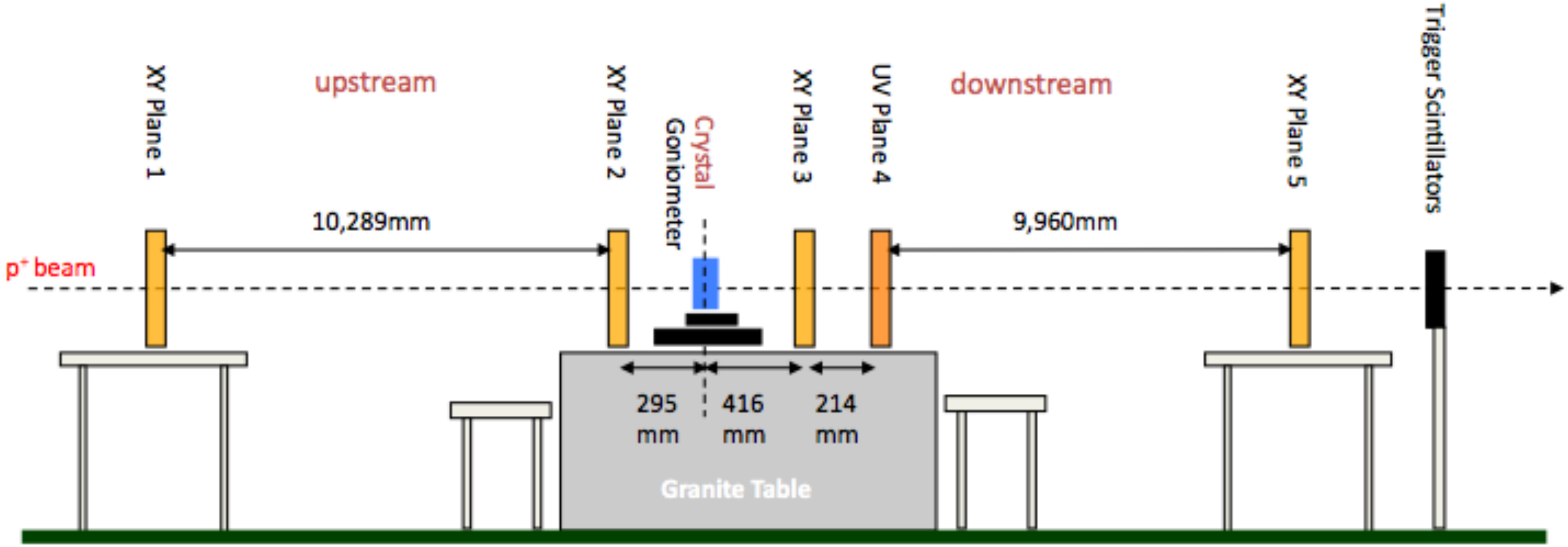
> - SPS at 120÷270 GeV) 1÷2 mm length, 150÷170 μrad angle
> - LHC 3÷5 mm length, 40÷60 μrad angle

- 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



Detectors for UA9 in the North Area

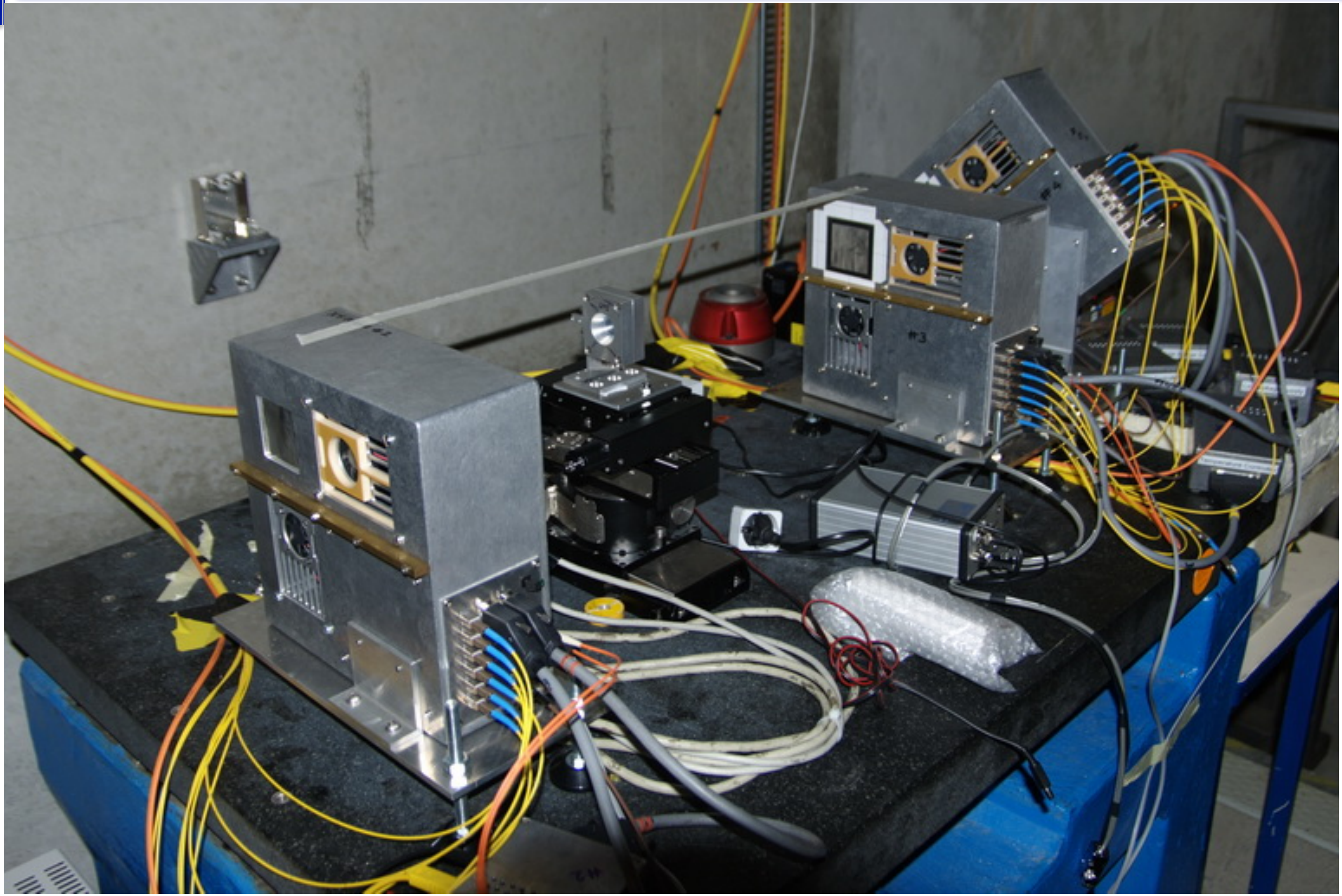
Two measurement arms – 10m length in each



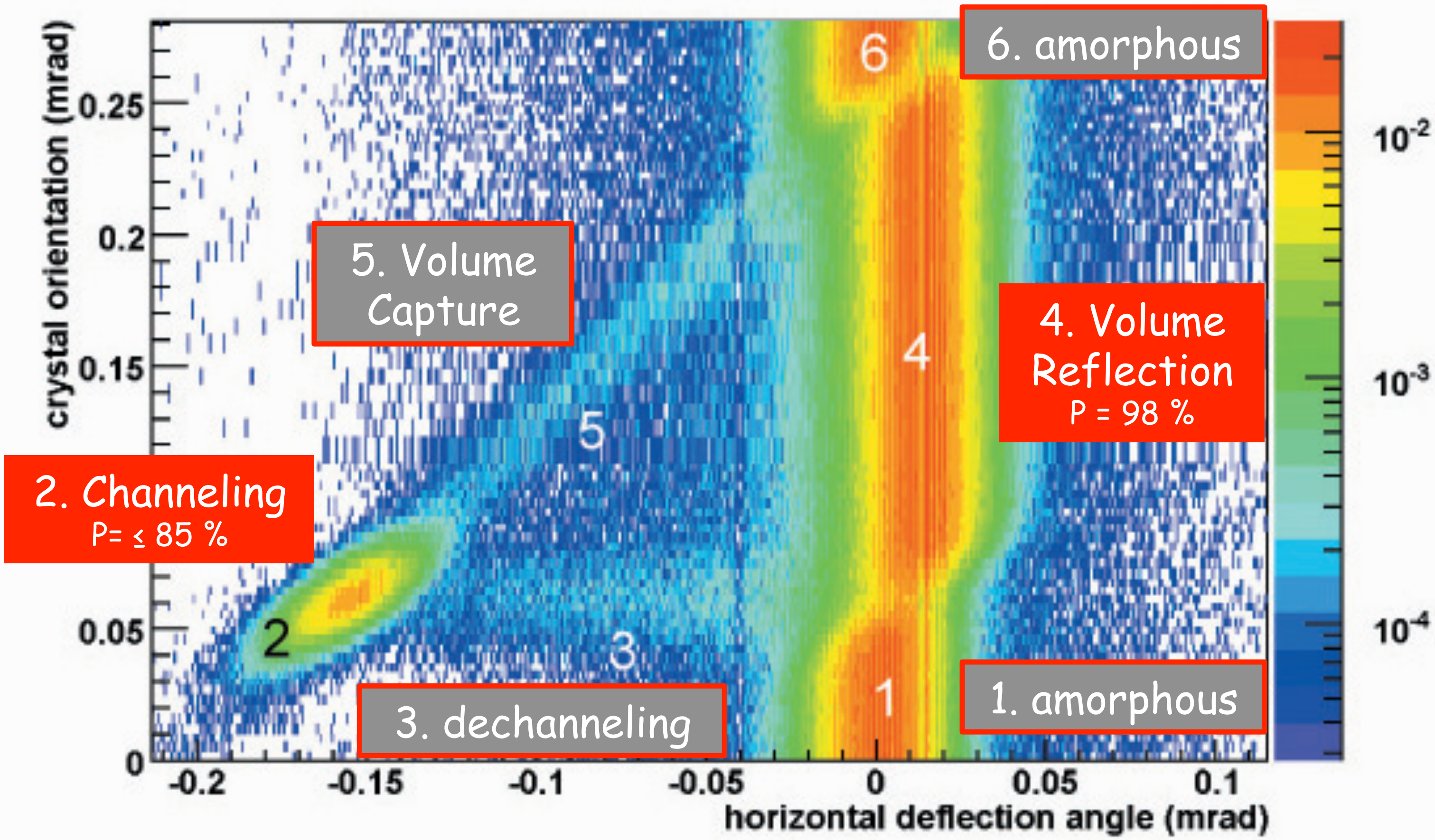
M Pesaresi et al 2011 JINST 6 P04006

- Use a low-divergence incoming beam
- Choose the crystal orientation by acting on the goniometer
- Detect the incoming direction of each particle
- Detect the outgoing direction after the interaction with the crystal
- Detect inelastic events

Detectors for UA9 in the North Area



Coherent interactions in bent crystals

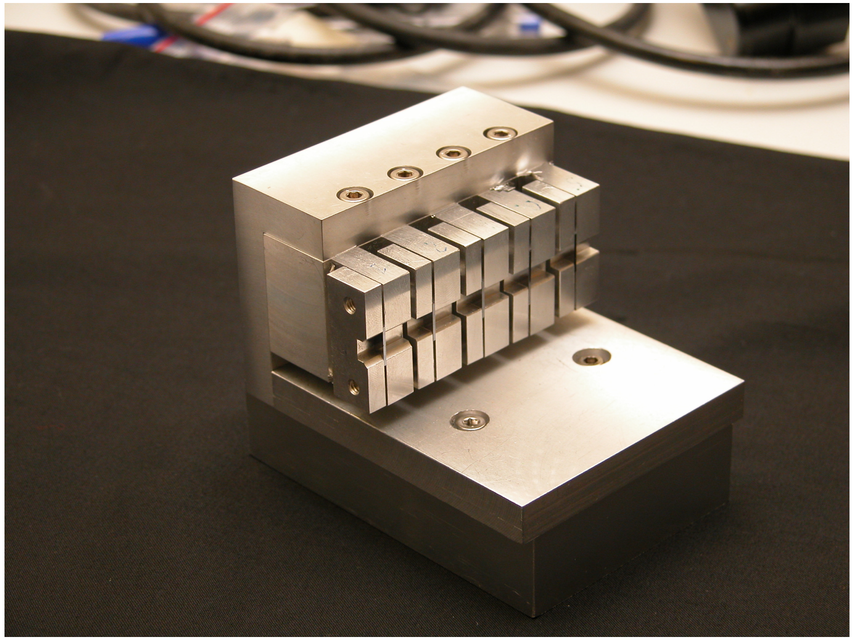


- Two coherent effects could be used for crystal collimation: W. Scandale et al, PRL 98, 154801 (2007)
  - ✓ Channeling → larger deflection with reduced efficiency
  - ✓ Volume Reflection (VR) → smaller deflection with larger efficiency
- SHORT CRYSTALS in channeling mode are preferred W. Scandale et al., Nucl. Inst. and Methods B 268 (2010) 2655-2659.

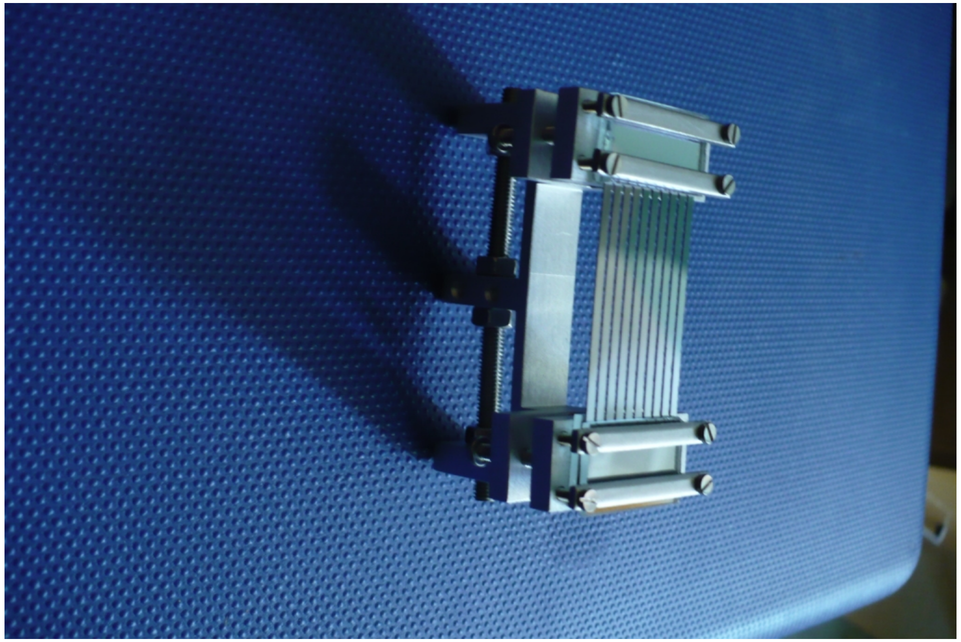
→ ×5 less inelastic interaction than in VR or in amorphous orientation (single hit of 400 GeV protons)

Multi-crystals

multiheads crystal (PNPI)

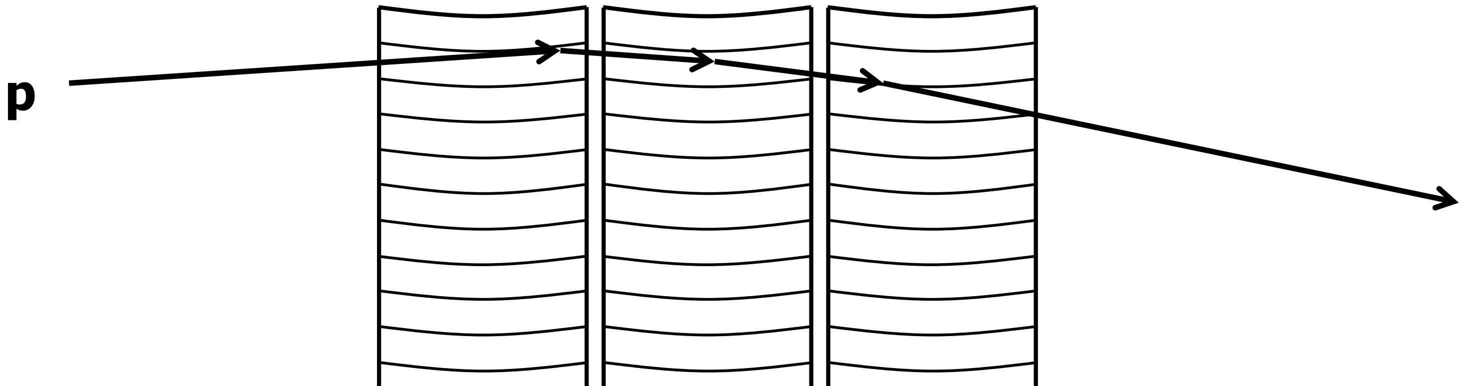


multistrip crystal (IHEP and INFN-Ferrara)



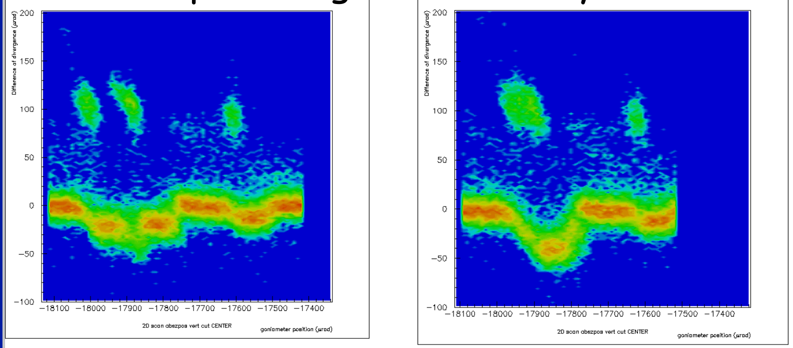
Several consecutive reflections

- enhance the deflection angle
- enhance the angular acceptance



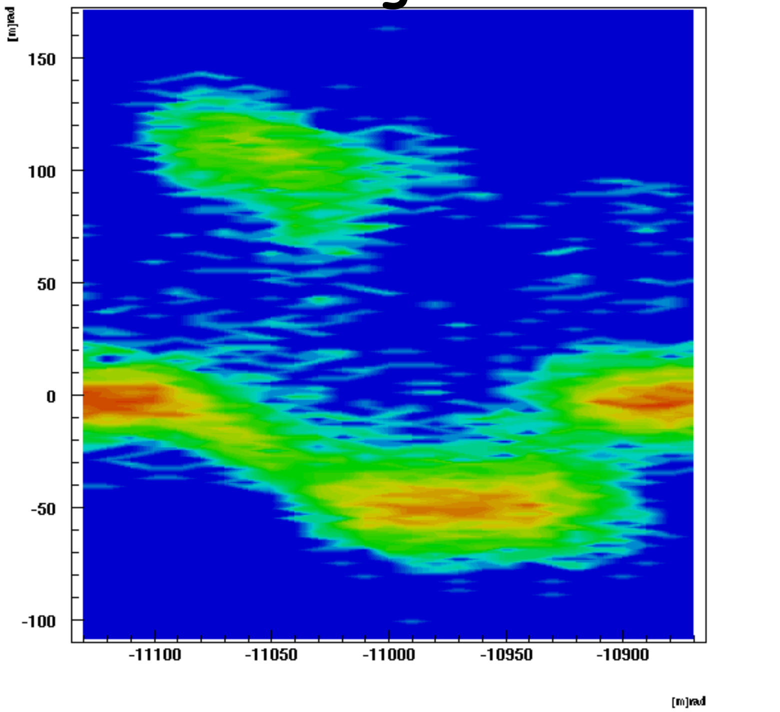
5-heads multi-crystals

Steps to align the five crystals

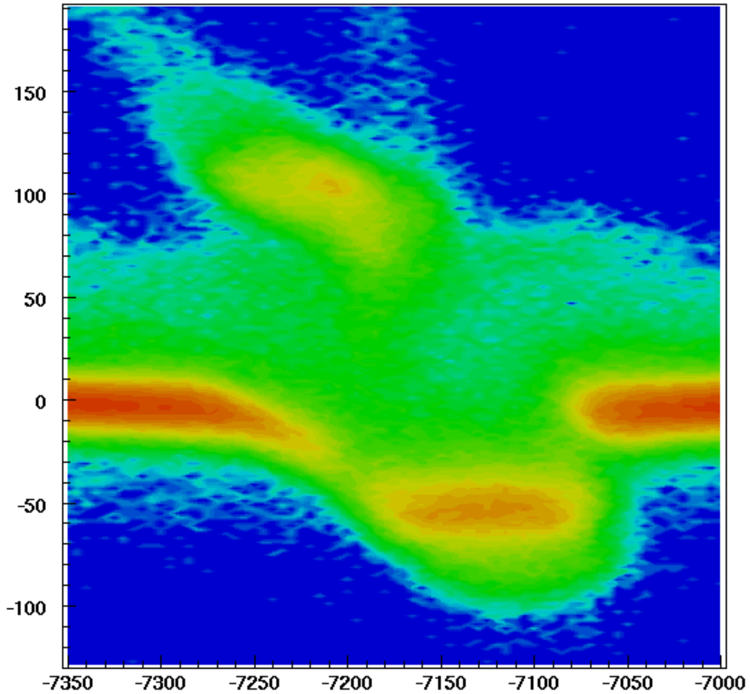


- Volume reflection angle 53 μrad
- Efficiency ≥ 90 %

Best alignment

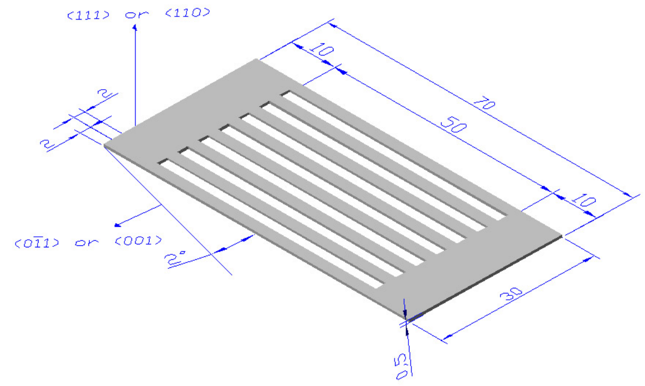


High statistics

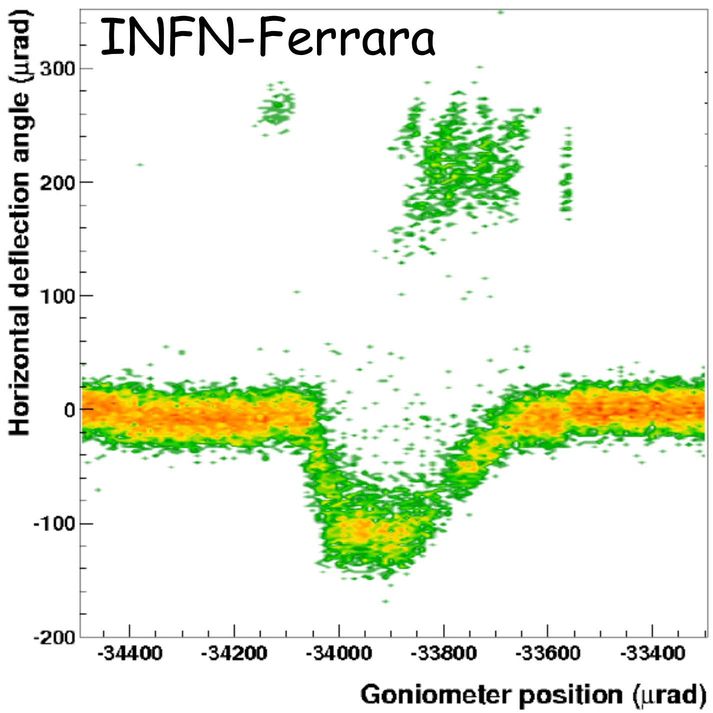


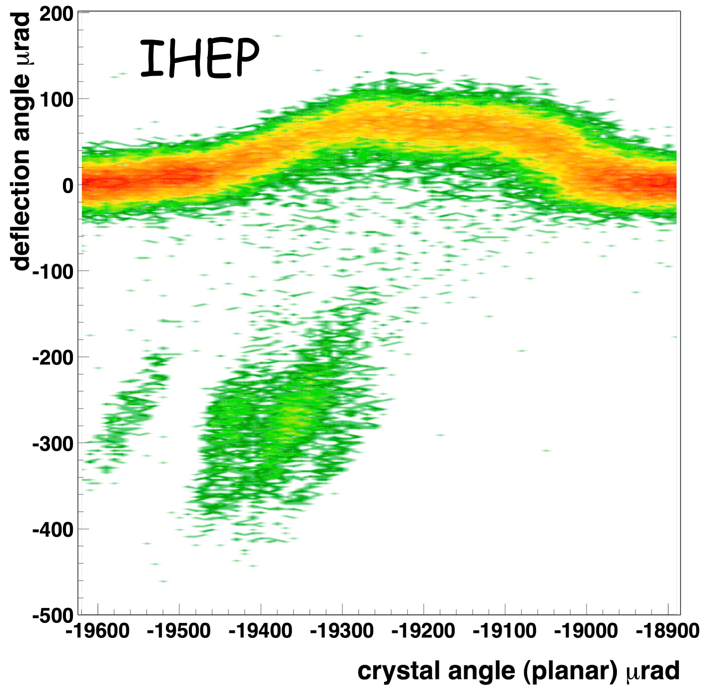
MULTISTRIP

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



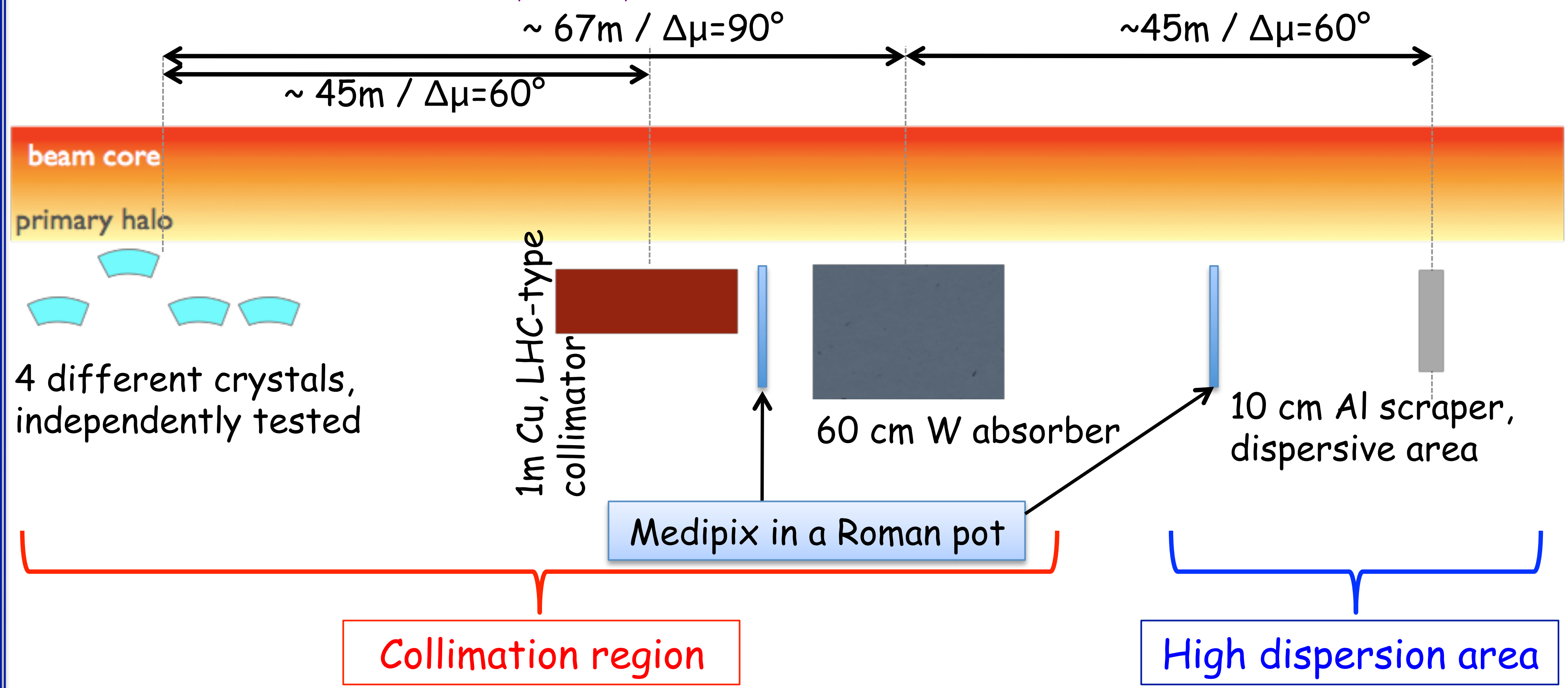
MST 14 – 400 Gev – R=4.61m





UA9 basic layout in the SPS (2008-now)

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:

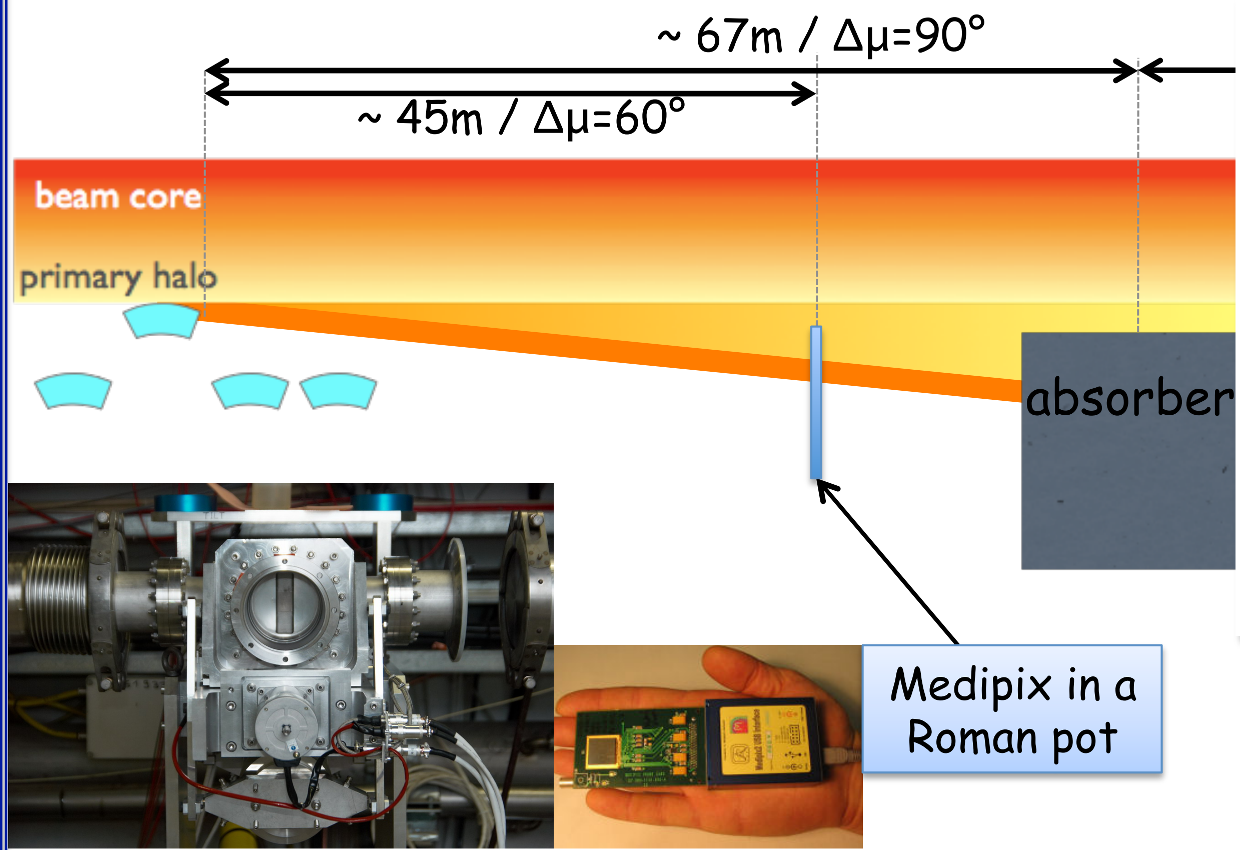
- Intensity, profile and angle of the deflected beam
- Local rate of inelastic interactions
- Channeling efficiency (with multi-turn effect)

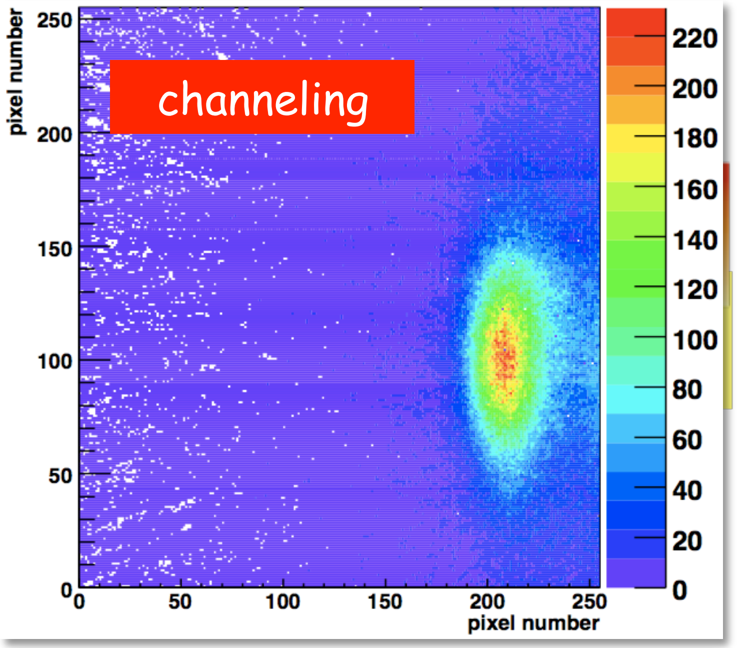
Observables in the high-D area:

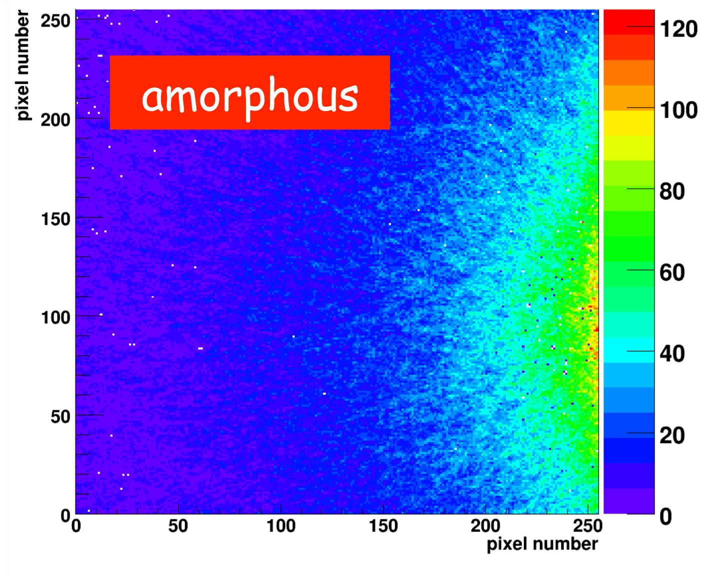
- Off-momentum halo population escaping from collimation (with multi-turn effect)
- Off-momentum beam tails

Some UA9 devices in the SPS

Direct view of channeled beam







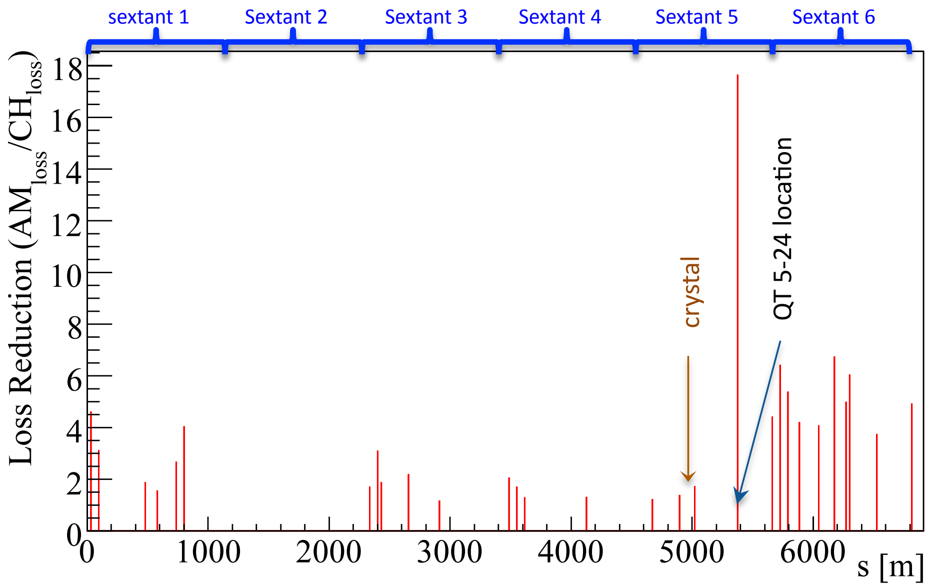
Medipix pixel detector in a Roman pot:

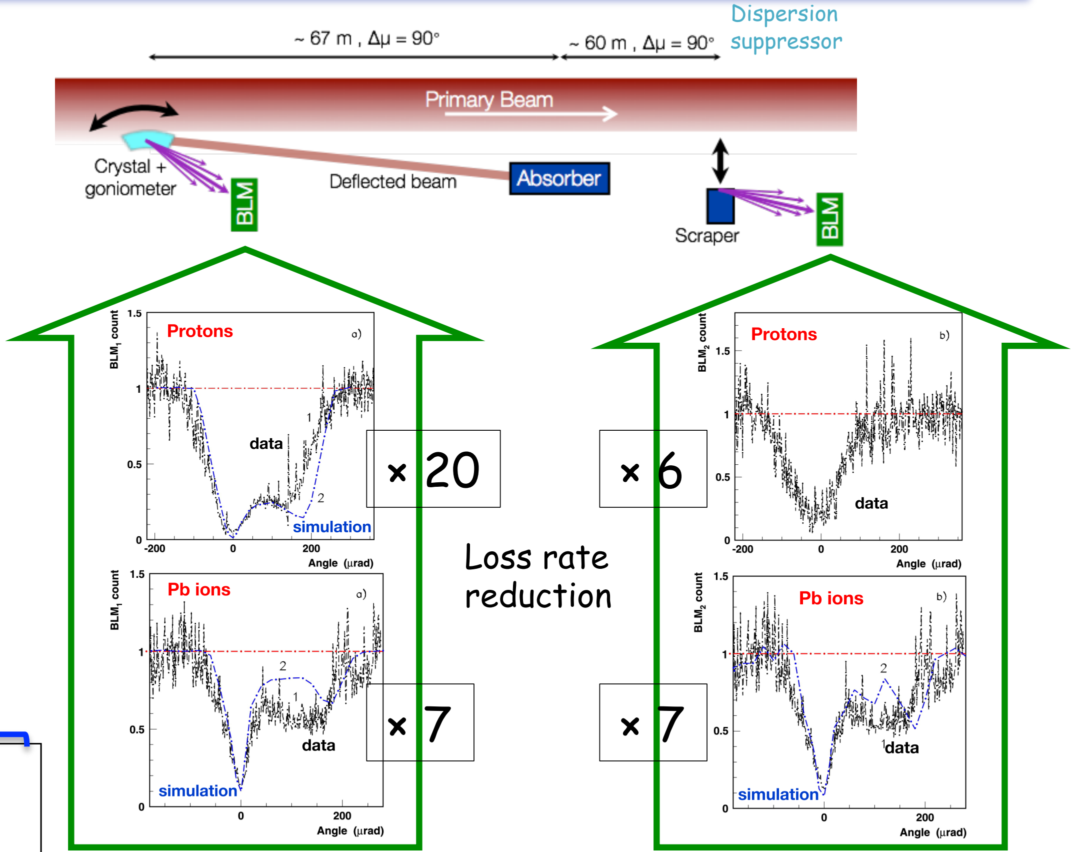
- Intensity, profile and angle of the deflected beam
- Efficiency of channeling (with multi-turn effect) (needs information on circulating beam current)

Loss rate reduction

Crystal collimation has been extensively tested in SPS

- ✓ Alignment (linear and angular) of the crystal is fast and well reproducible.
- ✓ Consistent reduction of the losses when comparing the crystal in channeling and in amorphous orientation:

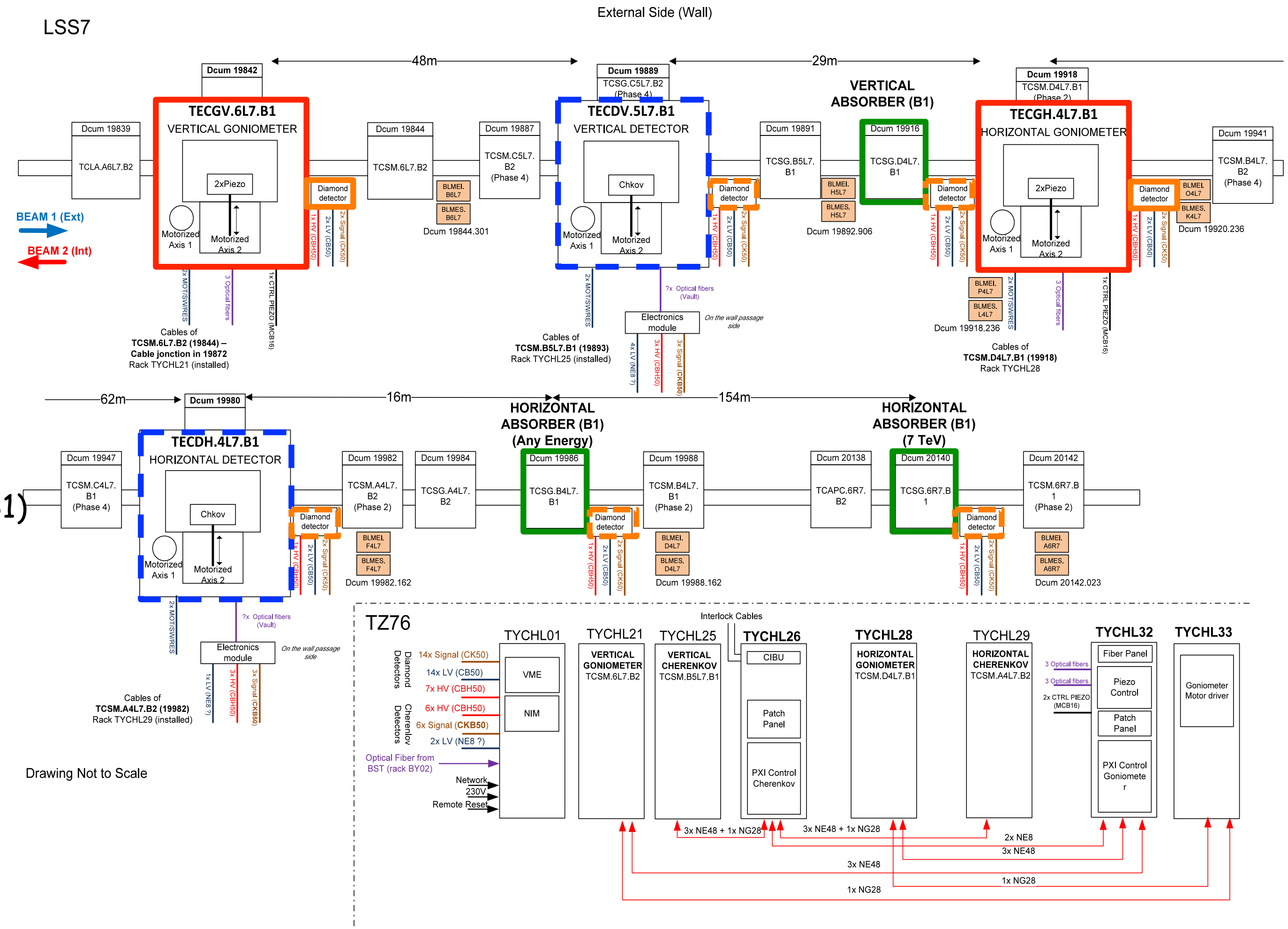




- ❑ Loss rate reduction at the crystal up to 20x for protons, 7x for ions.
- ❑ Loss rate reduction in the dispersion suppressor up to 6x for protons, 7x for ions.
- ❑ Losses all around the accelerator ring consistently reduced.

Layout in LHC

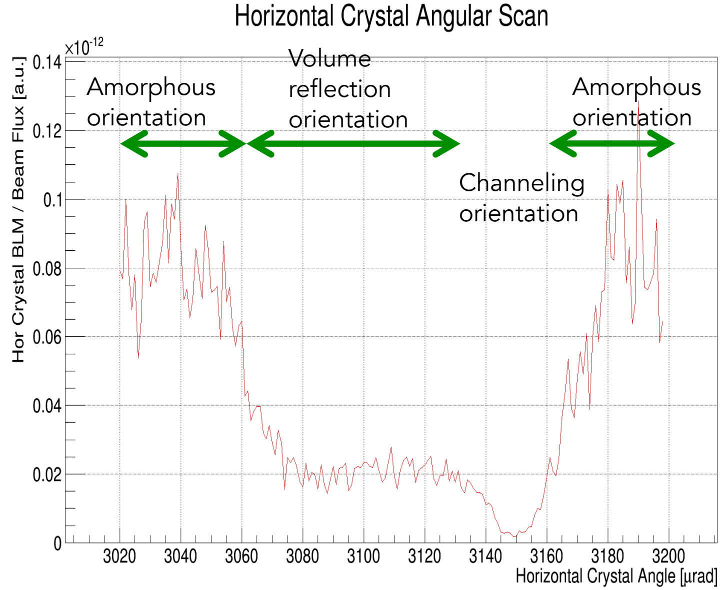
- 2 goniometers with crystals
  - ✓ Cables from phase-2 collimators + new optical fibers
  - ✓ 1 new support, 1 support from phase-2 collimator
- 3 absorbers
  (TCSGs – already installed)
- 2 Cherenkov detectors
  (not for installation during LS1)
  - ✓ 2 new supports
  - ✓ New signal and HV cables
  - ✓ New vacuum system cables
- 7 diamond BLMs
  (2 for installation during LS1)
  - ✓ New cables
- Control electronics to be installed in TZ76

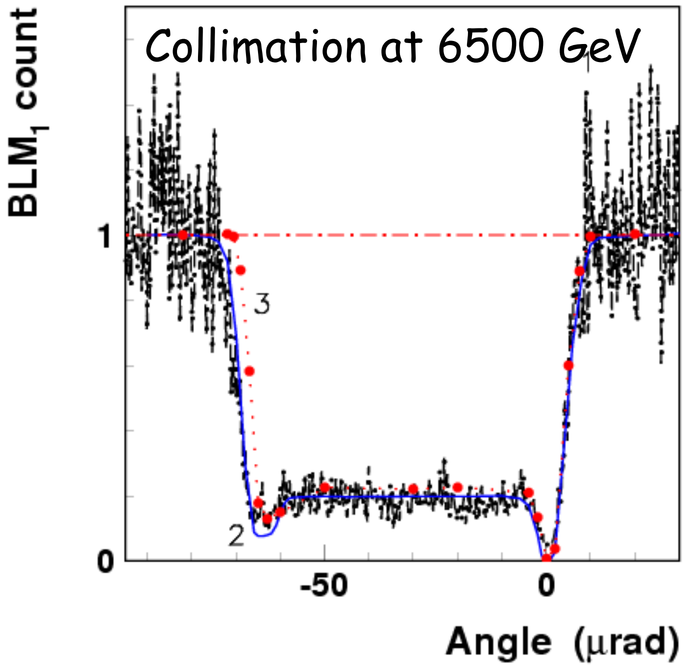


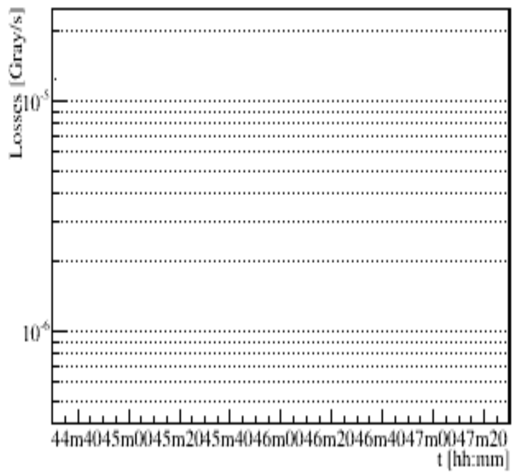
LHC Collimation data

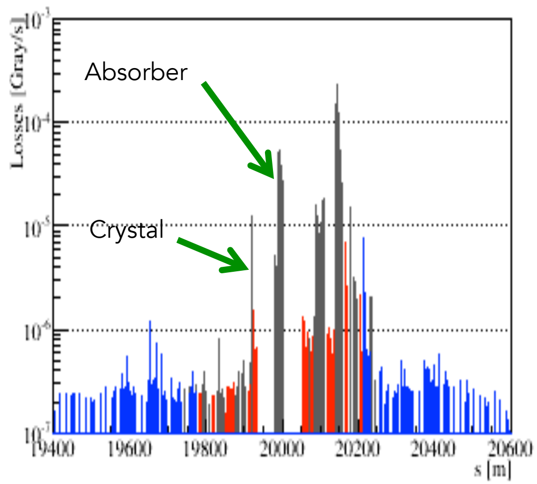
- Crystal collimation setup:
  - Crystal at ~ 5.6 σ (1 σ = 1.53 mm)
  - Collimators upstream the crystal are retracted
  - TCSGs at 7 σ, TCLAs at 10 σ (nominal position)
- Repeated angular scans:
  - Loss reduction factor in channeling w.r.t. amorphous orientation: ~ 39.
  - Redistribution of the losses from the crystal to the absorber
- Scan with TCSG:
  - Deflection angle: ~ 60 μrad
  - Extracted beam size: RMS = 436 μm

Collimation at 400 GeV







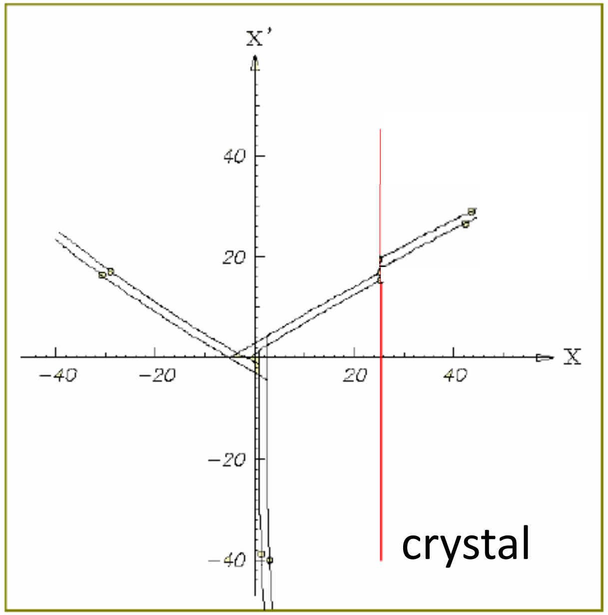


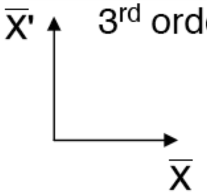
Crystal-aided slow-extraction in the SPS

Four possible scenarios of crystal-assisted extraction in the SPS

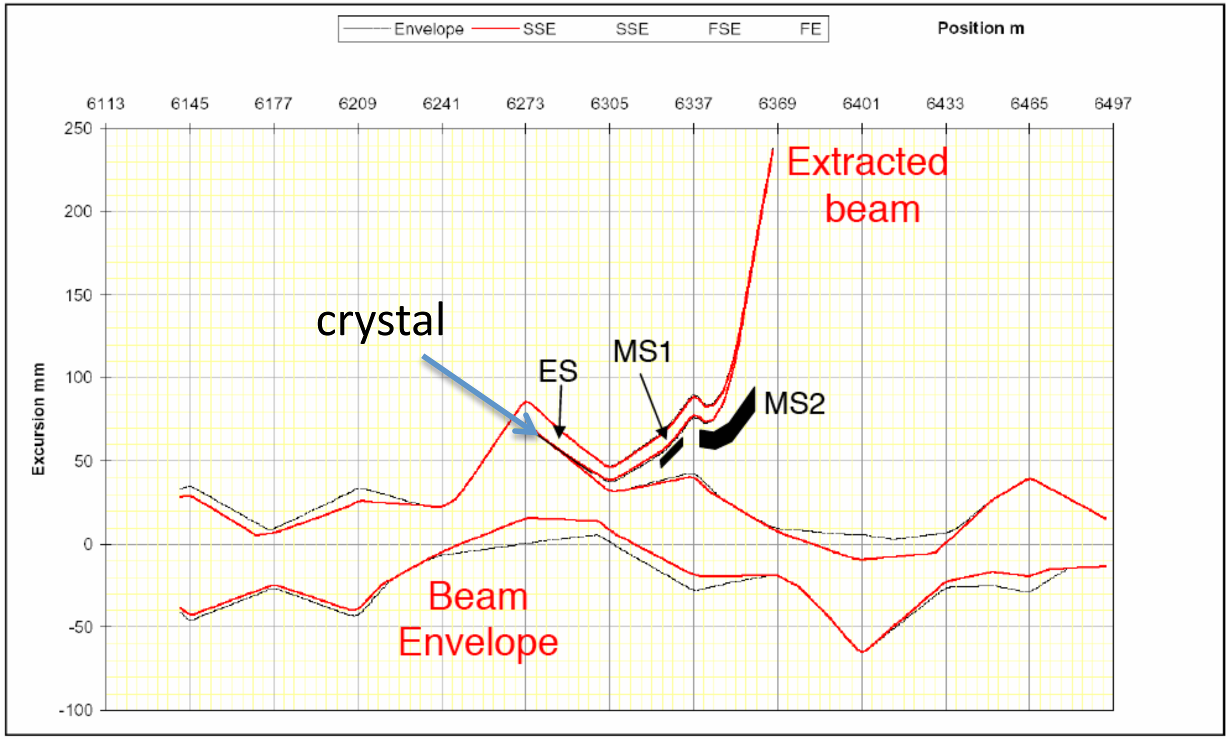
- Non-resonant extraction (a la RD22) based on crystal-channeling
- Non-resonant extraction (a la RD22) based on multi-volume-reflection
- Resonant extraction with a single thin crystal shadowing the electrostatic wires
- Resonant extraction with crystals replacing the electrostatic septum

… from a seminar of W. Scandale on October 26th, 2014





3rd order resonant extraction



Role of the UA9 Collaboration

CERN

Edms No. 1509966
7 May 2015

MEMORANDUM

To : Walter Scandale, Chairperson of the UA9 Collaboration

From : Frédérick Bordry, Director for Accelerators and Technology

c.c.: Paul Collier, Head of the Beams Department
José Miguel Jiménez, Head of the Technology Department
Roberto Saban, Head of the Engineering Department
Brennan Goddard, TE-ABT Group Leader

Subject : Slow extraction assisted by bent crystals in the SPS

Following the interest generated by the *Proposal for Investigating Slow Extraction Assisted by Bent Crystals in the SPS,* I would like to ask the support of the UA9 collaboration both for the studies and for the developments of hardware and software which these might entail.

Needless to say, the beam time required for the validation of the concept will be taken from SPS Machine Development time and appropriate funding will be supplied by the EN Department for the developments of hardware and software components.

If you agree, I would like to launch the study with the group composition included in the proposal attached.

Non-resonant extraction based on UA9 crystals

Simplified scenario for a test in the SPS

- Stored beam at 270 GeV with Q26 optics.
- UA9 crystals in LSS5 should deflect the beam halo into TT20.
- Push the particles into the crystal either the CO dipoles (fast swipe of the beam, ~6 mm, into the crystal) or by the beam damper (slow swipe).

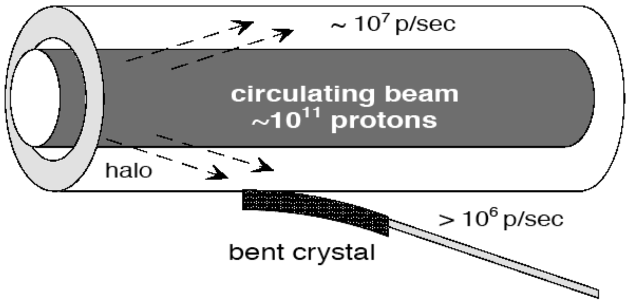
Required hardware

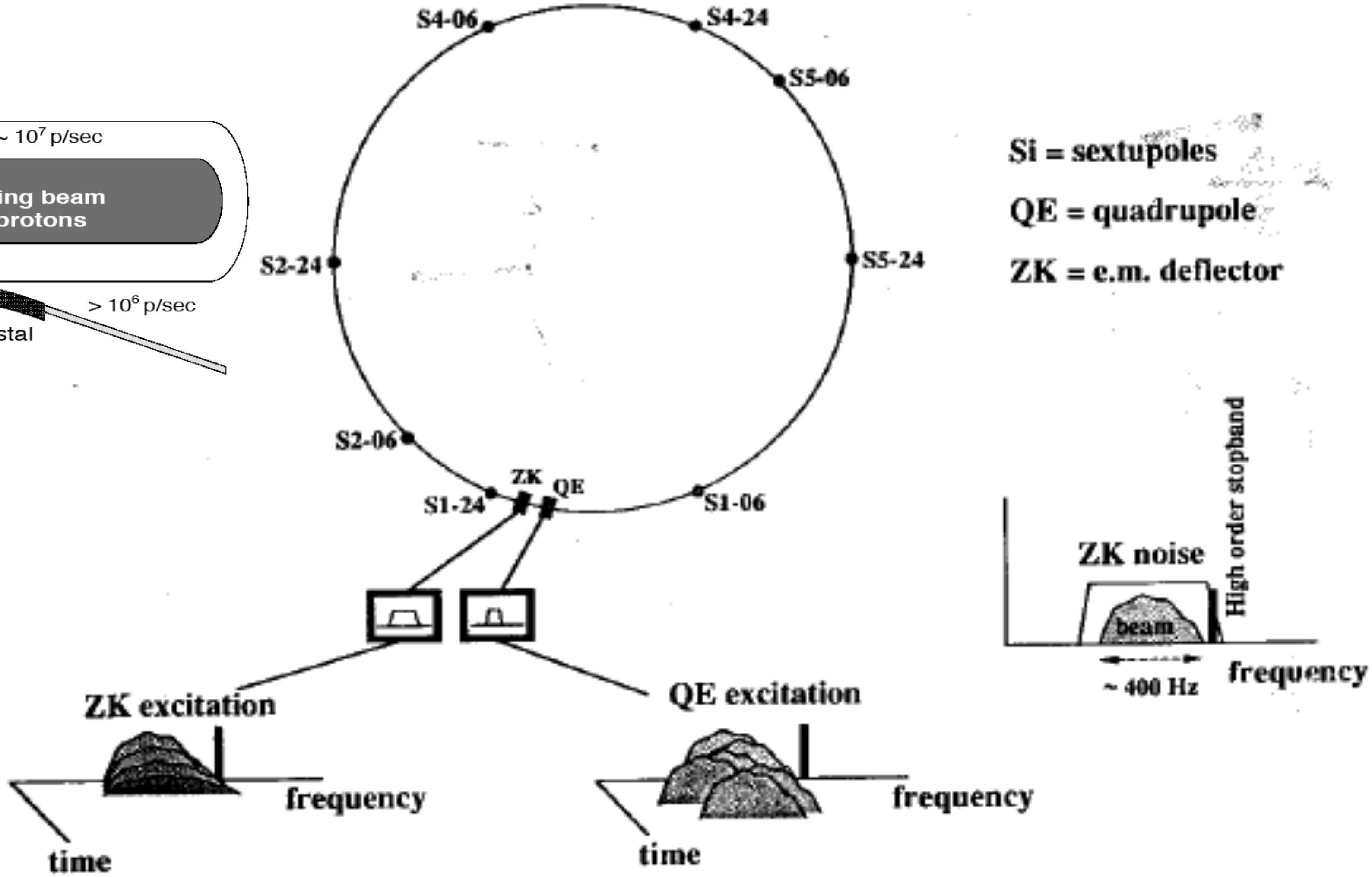
1. The phase advance between the UA9 crystal in LSS5 and the electrostatic septum in LLS2 should be a odd multiple of 90°. -> Use Q26 optics.
2. A Cherenkov detector should be installed in TT20 in order to investigate the spill quality and if possible the extraction efficiency (eff ≈ rate in TT20/beam lifetime) (we need a reference for the extraction efficiency).
3. The extraction mini-scanner.

Status

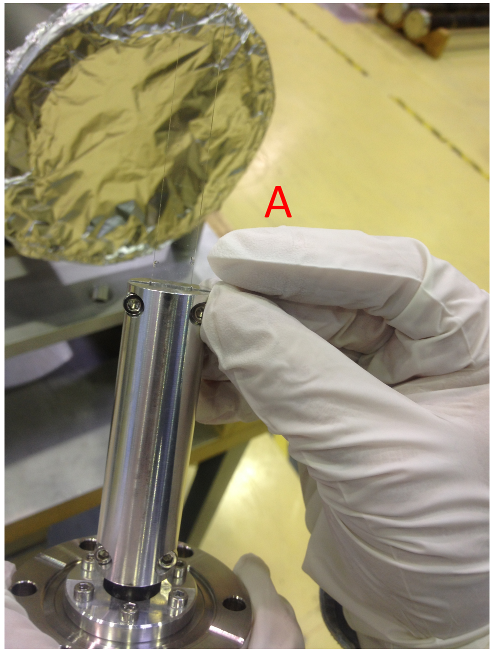
1. Q26 optics was tested in 2015
2. Cherenkov detector: the tank was installed in TT20; radiator and front-end electronics provided by LAL, available at CERN, tested in H8 in 2015/'16.
3. Test with beam in the second half of 2016.

Non-resonant extraction

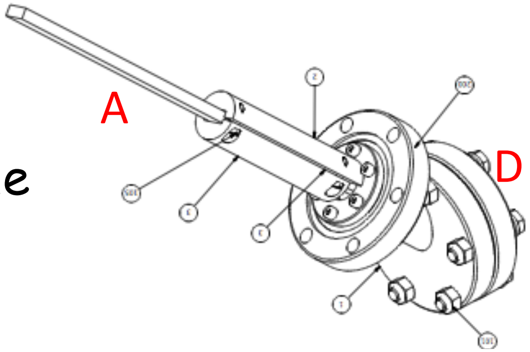


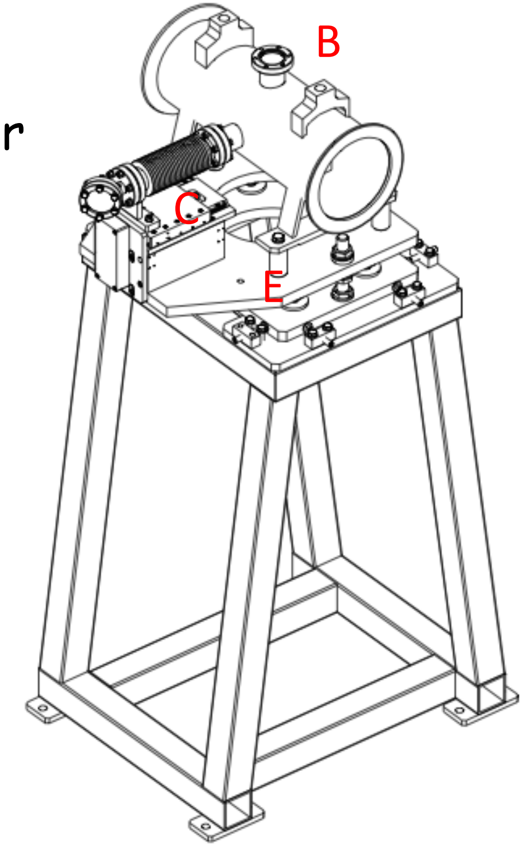


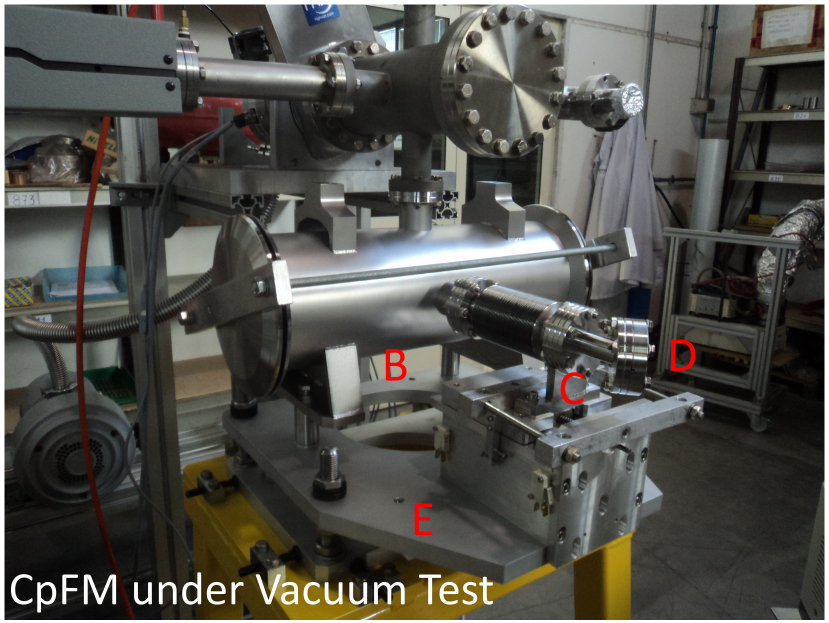
Basic detector in TT20



A. Fused silica bar
B. Tank
C. Motorized extension with bellow to move the detector bar towards the beam and out
D. Optical quartz window to be coupled to the PMT
E. Mechanical support for alignment and leveling







CpFM under Vacuum Test

Non-resonant extraction based on multi-crystals producing multi-reflection

Simplified scenario for a test in the SPS

- Same scenario as for the UA9 crystals
- Expected to enhance the angular acceptance.

Required hardware

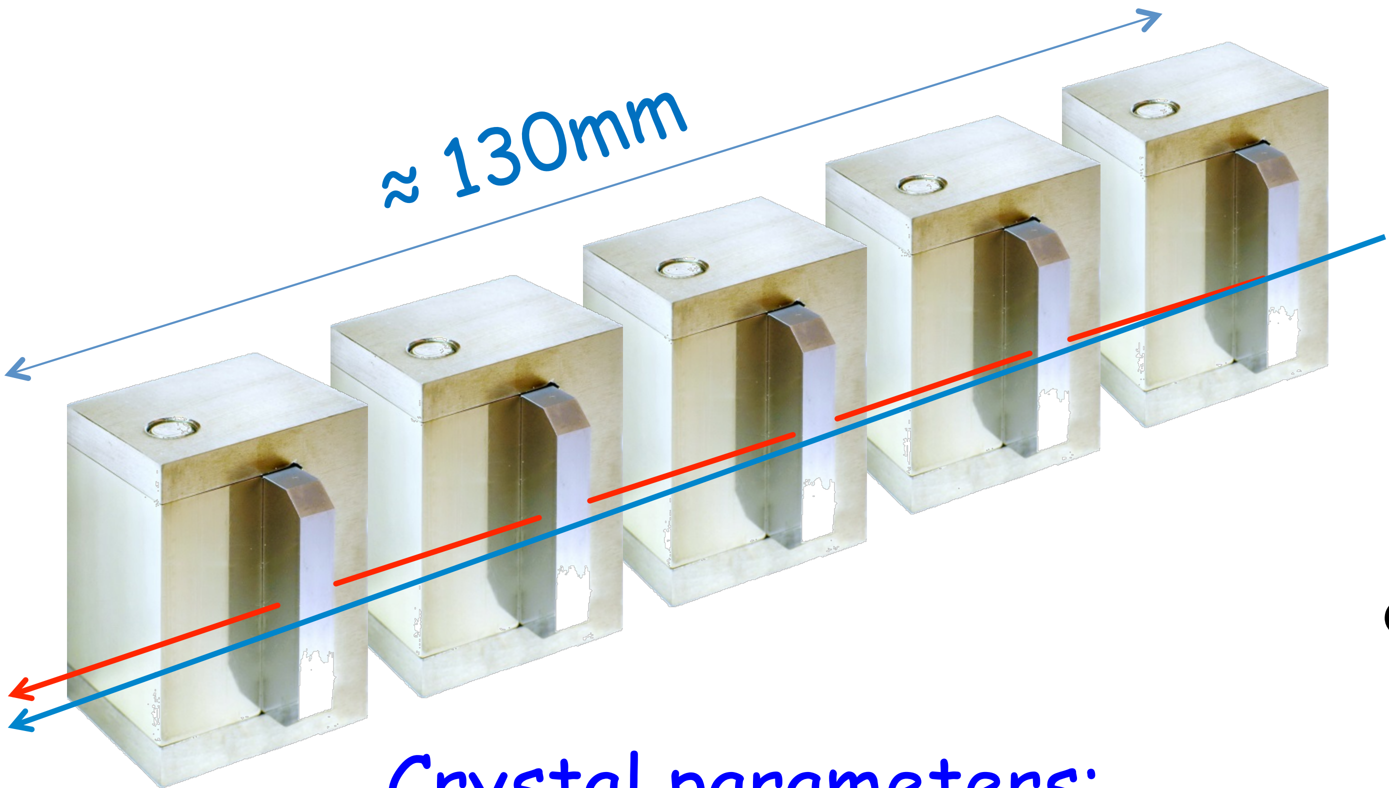
1. Multi-crystals made of 5 stages producing ~ 60 μrad deflection.
2. Cherenkov detector in TT20 (eventually already tested in 2016).
3. Extraction mini-scanner

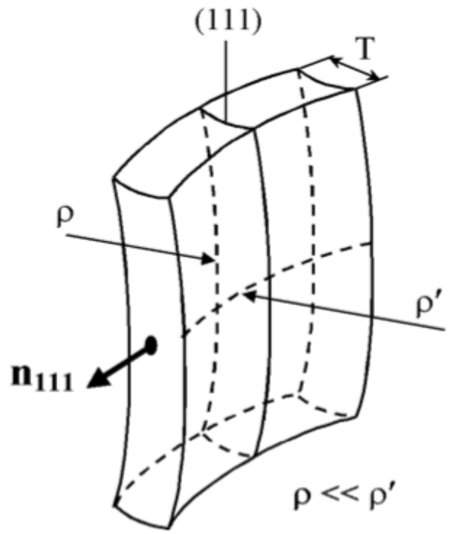
Status

1. One stage of the multi-crystal was tested in H8 in 2015.
2. Five stages multi-crystal under production at PNPI.
3. Test of the multi-crystal pack in H8 planned in second half of 2016.
4. Installation in the SPS planned in the YETS16
5. Simulation to be made in 2016/17.
6. Test to be scheduled in 2017.

Simulation requires multidisciplinary approach.

Crystals in an array for VR





Quasimosaic bending

Crystal parameters:

- thickness 1-4 mm
- CH deflection angle 60-150 μrad
- MVR deflection angle ≈ 60 μrad
- open area ≤ 5 x 20 mm²

Resonant extraction

Scenario for a test in the SPS

- Test in pulsed mode.
- A crystal should be located in the SPS in a region where a CO bump is possible, the phase advance from the ZS in LSS2 is a odd multiple of 90°.
- The crystal should be a multi-crystal to enhance the angular acceptance.
- A new goniometer should be used to orient and position the crystals.
- High-sensitivity BLM are required in the location downstream of the crystal.

Required hardware

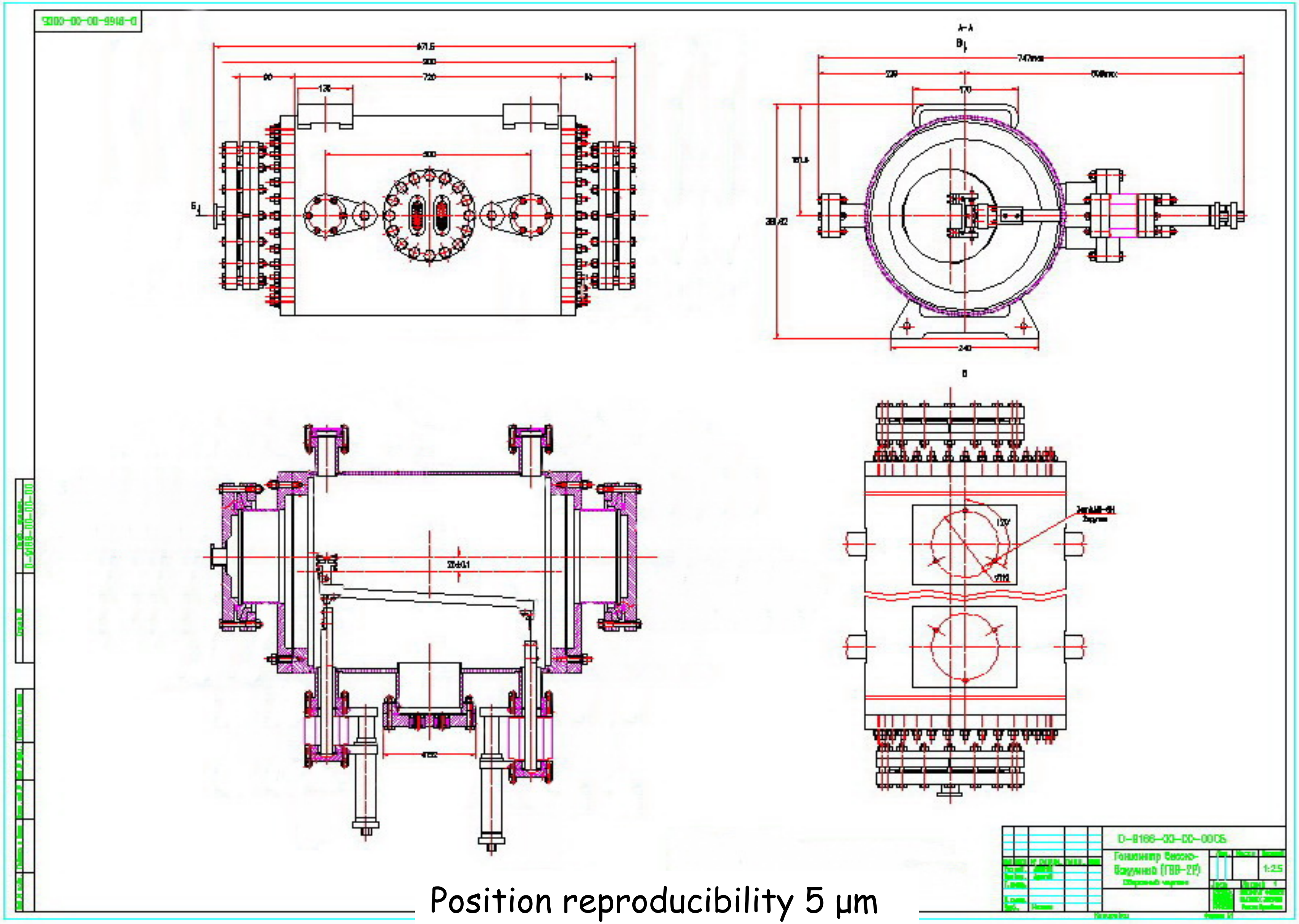
1. A multi-crystal pack
2. A goniometer

Status

1. The goniometer should be built and tested
2. The multi-crystal pack is being built and will be tested in H8 in 2016 and in the SPS in 2017.
3. Simulations should be made to evaluate the expected efficiency of the process, including the crystal one (plans to launch this study have been discussed with S. Redaelli).

Our aim is to test resonant extraction early in 2018.

IHEP Goniometer (fits in a SSS)



Position reproducibility 5 μm
Angular reproducibility 1 μrad

Resonant extraction in shadow mode

Scenario for a test in the SPS

- Test in pulsed mode.
- A crystal should be located in the SPS in a region where a CO bump is possible, the phase advance from the ZS in LSS2 is a odd multiple of 90°.
- The crystal should be a very thin with a large the angular acceptance.
- A new goniometer should be used to orient and position the crystal.
- High-sensitivity BLM are required in the location downstream of the crystal.

Required hardware

1. A thin-crystal
2. A goniometer

Status

1. The UA9 Collaboration had to delay the effort to conceive, produce and test the crystal with the right characteristics due to the load of the ongoing activity.

Our aim is to start this effort early in 2017.

Resonant extraction in shadow mode

Why the scenario is so difficult

- We need a crystal very thin in the transverse dimension (not yet available)
- trade-off of crystal robustness, low-angle and large angular acceptance in reflection mode, large angle and small angular acceptance in channeling mode.
- Simulation to evaluate the trajectory of the deflected slice.
- Simulation to evaluate the efficiency of the deflected slice
- Instrumentation for the crystal alignment to the wires.
- Instrumentation to evaluate the loss reduction at the wires.
- Motivation for UA9 versus other tasks (collimation, standard extraction…)

Conclusive remarks

- Extraction assisted by crystal is feasible
- Long way for an optimal performance
  - Crystal acceptance
  - Channeling efficiency
  - Nuclear loss
  - Compatibility with machine protection
- Non-resonant extraction
  - Optimal for extraction in colliders with small mechanical acceptance
- Resonant extraction assisted by bent crystals
  - should provide reduced loss at the electrostatic septum
  - shadowing method very attractive
  - still to be demonstrated: test in SPS will start soon

Thanks for your attention

Reserve slides

RD22: some literature

- W. Scandale, Proc. LHC Workshop, eds G. Jarlskog and D. Rein, Aachen, 1990, vol. III p. 760.
- The RD22 Collaboration, CERN DRDC 91-25
- The RD22 Collaboration, CERN DRDC 92-51
- The RD22 Collaboration, Phys. Lett. B 313 (1993) 491-491
- A.A. Asseev et al, Nucl.Inst.Meth. A330 (1993) p39
- The RD22 Collaboration, CERN DRDC 94-11
- F. Ferroni for the RD22 Collaboration, Nuclear Instruments and Methods in Physics Research A 351 (1994) 183-187
- The RD22 Collaboration, CERN SL-95-088
- The RD22 Collaboration, Phys. Lett. B 357 (1995) 671-677
- G. Arduini et al., CERN SL 97-031 and SL 97-055
- G. Arduini et al., CERN SL 97-036 and SL 97-043

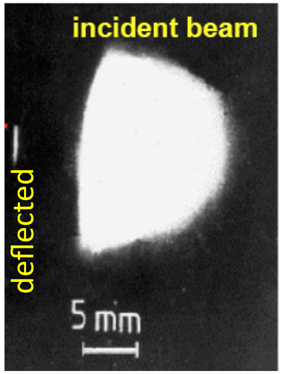
Radiation hardness

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.

After irradiation



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*

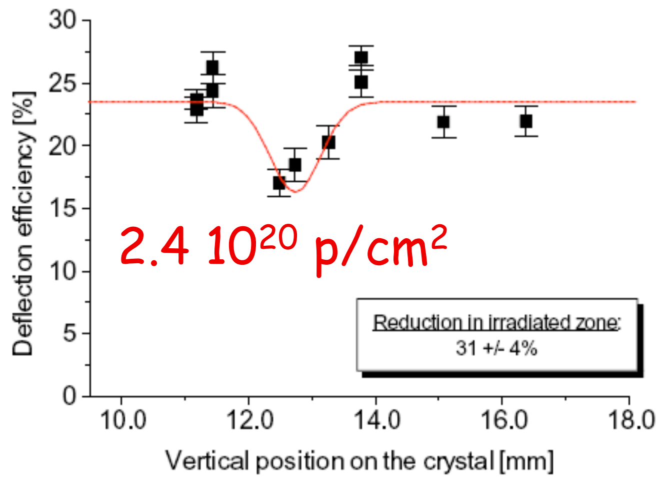
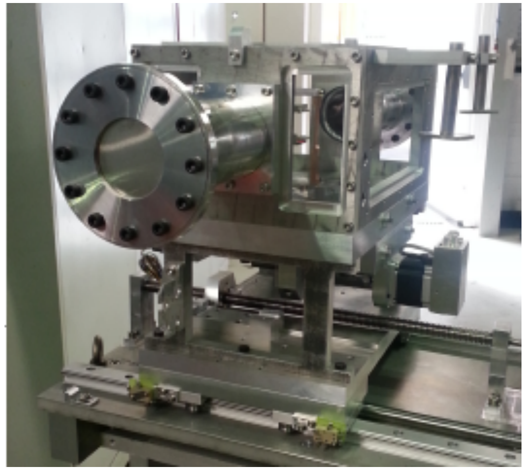


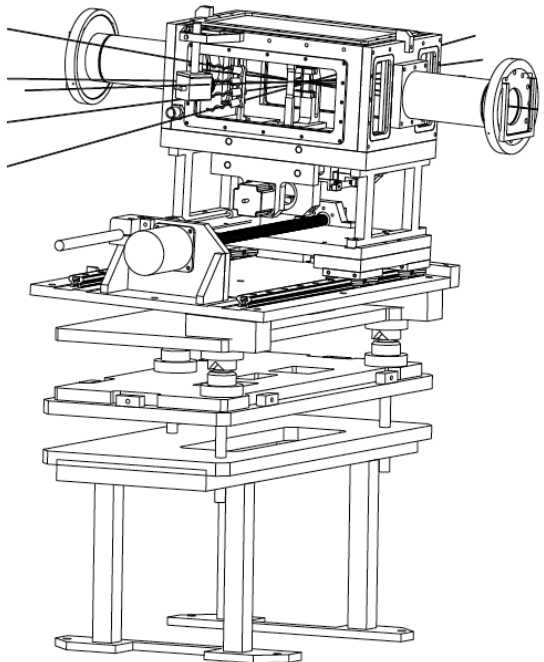
Figure 5 *A fit using the inverted irradiation profile to the measured points at expected optimum alignment*

Radiation hardness

test HRMT16-UA9CRY performed at HiRadMat facility:

- 440 GeV protons, max 288 bunches, 1.7 x 10^{11} protons per bunch
- intensity comparable with worst accident scenario in LHC (asynchronous beam dump)
- Simulation with only beam energy and silicon heat capacity): $\Delta T = 5$ K per bunch, $T_{melting}$ after ~ 280 bunches





Courtesy of Frederic Loprete

- The experiment performed in 2012
- No sign of damage in the irradiated crystal
- Crystal broken for a bad manipulation in INFN-LNL