Crystal-Assisted Beam Manipulation at CERN SPS

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on behalf of the UA9 Collaboration

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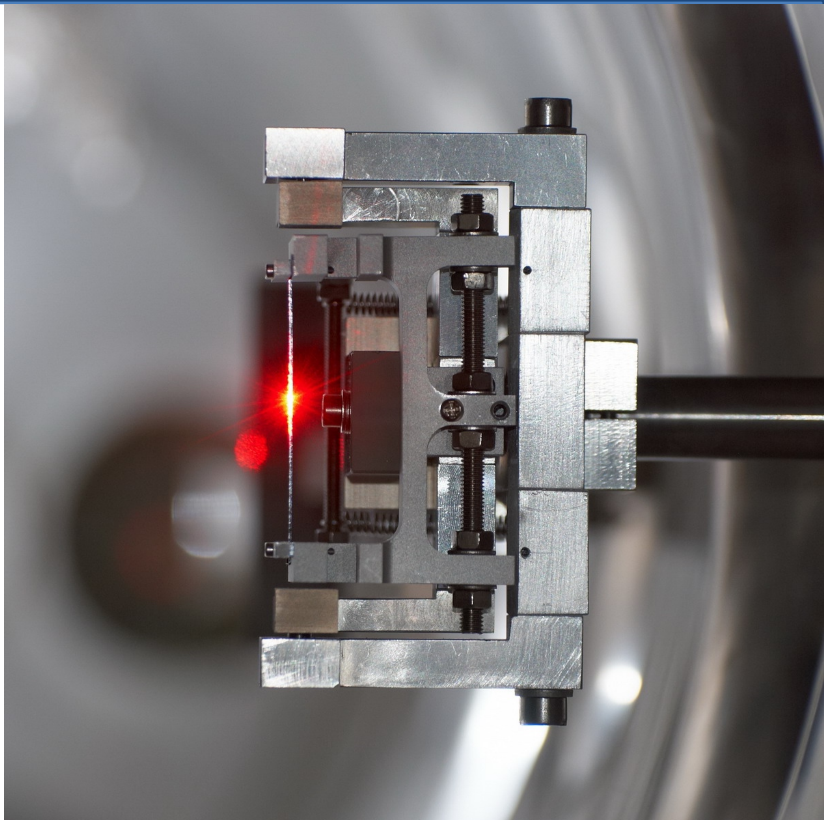


Introduction

The UA9 Experiment at CERN was started in 2009 with the aim of demonstrating the feasibility of crystal-aided beam halo collimation in high energy particle colliders such as the LHC.

This objective has been reached. After a few years of tests in the SPS, the 2 LHC rings have been equipped with 2 goniometers each, and an intensive program of Machine Development is being carried on.
Now crystal-assisted beam collimation is ready to move from experimentation to operation, in particular for the case of ion beams.
Indeed, the decision if crystals should be included in the baseline of the Hi-Lumi collimation layout is expected to be taken before the end of the year.

More recently the scope of the UA9 experiment has been extended to new investigations implying even more challenging methods to manipulate beams by means of bent crystals.
These investigations will be the subjects of this presentation:

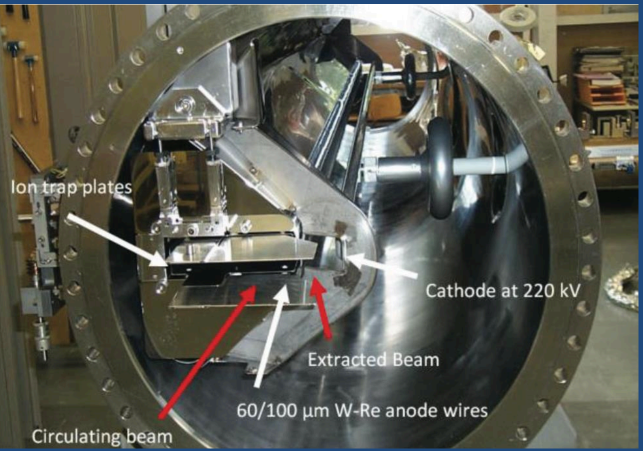
- Crystal-assisted slow extraction has been proposed to mitigate the losses at the conventional electrostatic septum and is being explored at SPS in two different layouts.

- A double-crystal scheme has been proposed in the framework of the “Physics Beyond Colliders” Study Group at CERN, to measure the Electric and Magnetic Dipole Moments of short-lived baryons in the LHC.
  A test layout has been deployed in the SPS with little modification of the UA9 infrastructure.

Motivation for renewed slow extraction studies at CERN SPS

- Future Fixed Target programs at CERN SPS (ex. Beam Dump Facility - SHiP), aim for up to 4 x 10^{19} PoT/year (~4 x as today)

- Conventional slow extraction process is intrinsically affected by local beam losses.



At SPS about 1% of extracted particles hit the Electrostatic Septum (ES) wires
→ show stopper for BDF from machine side

- The irradiated wires tend to spark and may be damaged at the highest beam intensities
- the secondary particle showers strongly activate the area downstream and can also affect the high voltage performance of the ES.

- Slow extraction optimization studies have been revived in order to reduce the losses at the electrostatic septum by a factor 4 at least. Among these:
  - Crystal-assisted slow extraction

Slow extraction in a nutshell

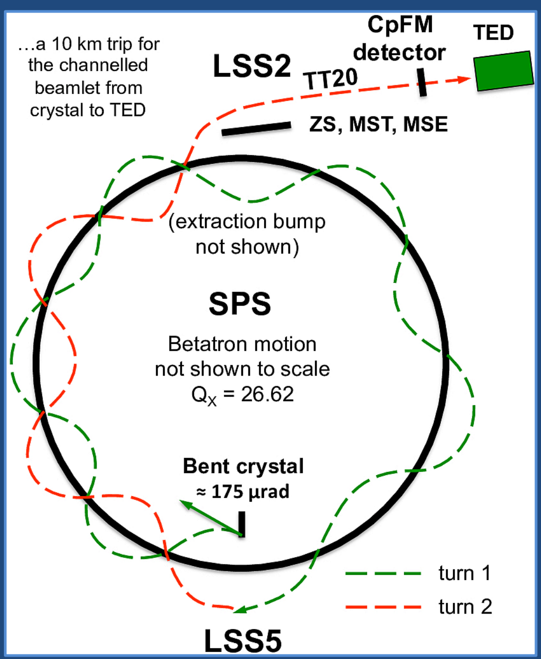
Fixed target experiments normally need an long uniform spill of particles.

1. Particles in a synchrotron move slowly towards the beam periphery, being driven by some instability mechanism:
   a. Tune-shift towards betatron resonance by quadrupole excitation (CERN SPS)
   b. Transverse stochastic excitation by some noisy electromagnetic device (IHEP Protvino U-70)

2. Outer particles are trapped in a bending device that deflects them into the extraction line:
   a. Typically an electromagnetic septum
   b. Alternatively: a crystal ...

Constraints:
Use the original UA9 infrastructure without modifying the hardware in the ring, making use of the equipment specific to the UA9 experiment: goniometers with crystals, absorbers, detectors
+ an on purpose Cherenkov detector (CpFM) down the extraction line TT20

Non-local → UA9 Goniometers (LSS5) and Fixed Target Extraction Line are opposite in the SPS ring
Stochastic → particle diffusion from the beam core was enhanced by means of the Transverse Adiabatic Damper (ADT, random transverse kicks) → different ADT excitation = different extraction rate



Beam Parameters:
- Machine tune Qx= 26.62 → appropriate phase advance
- Beam energy = 270 GeV (typical UA9)
- 1 bunch in storage mode as there are not strong enough bumpers in LSS5
- Beam charge = 1.6 x 10^{10} (1 LHC pilot bunch)

Closed orbit bumpers to move channeled beamlet towards electrostatic septum with the right angle to cross the extraction line

Septa ON and in standard place

Absorbers and scrapers to evidence the presence/absence of the beam at certain locations

Detectors:
Beam observation via Timepix and TT20 CpFM

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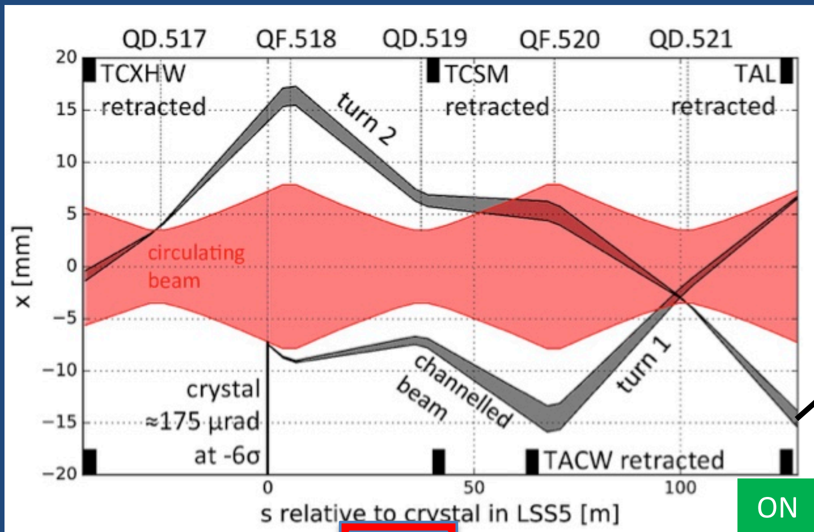
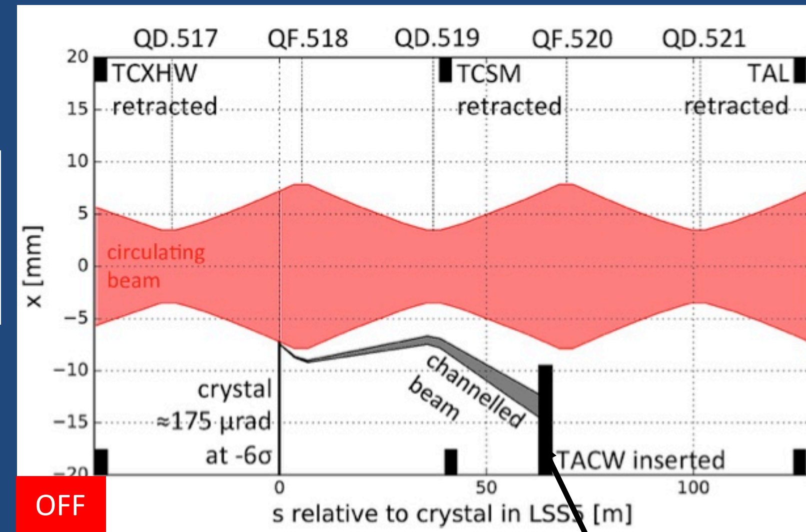
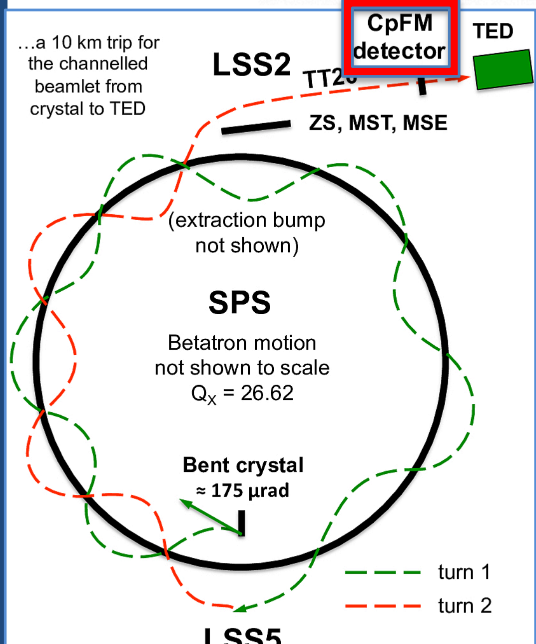
Crystal-aided non-resonant extraction experiment on CpFM

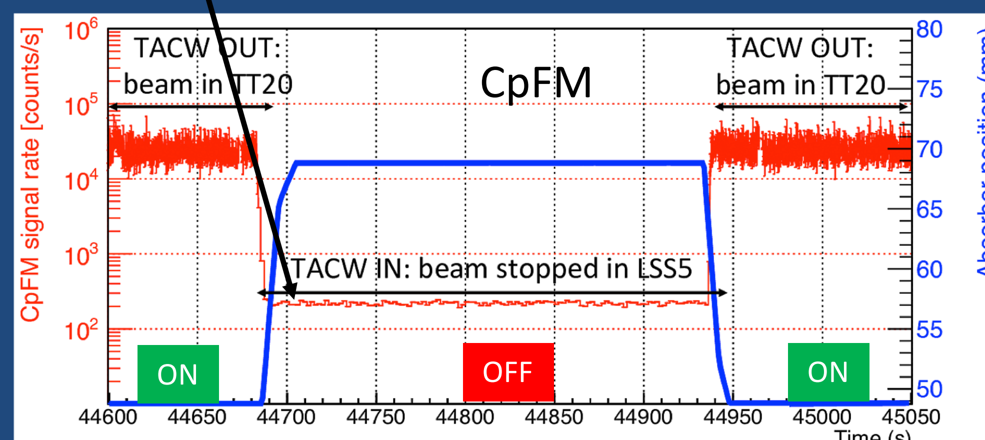


Beam to El. Septum and extraction channel

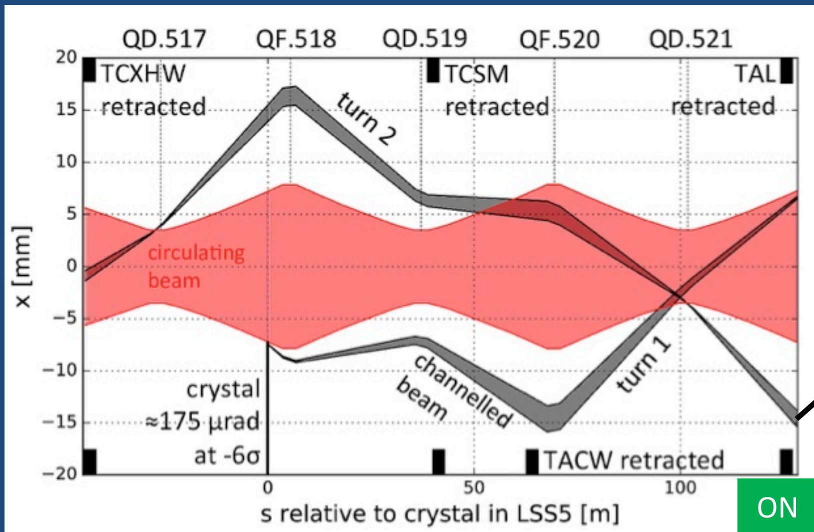




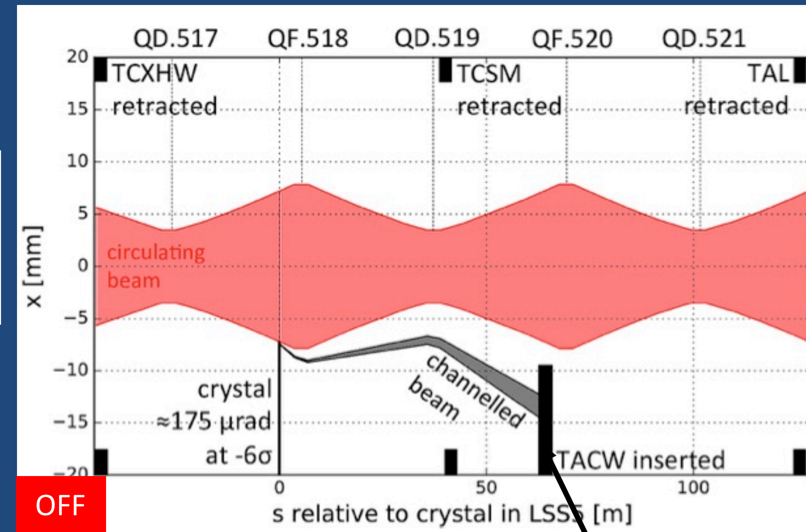
Signal detected by CpFM in the extraction line TT20 disappears when beam is stopped by the TACW absorber



Crystal-aided non-resonant extraction experiment on CpFM



Beam to El. Septum and extraction channel



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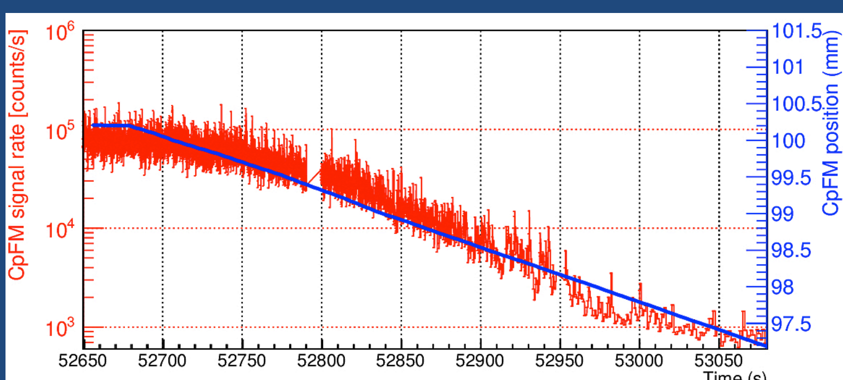
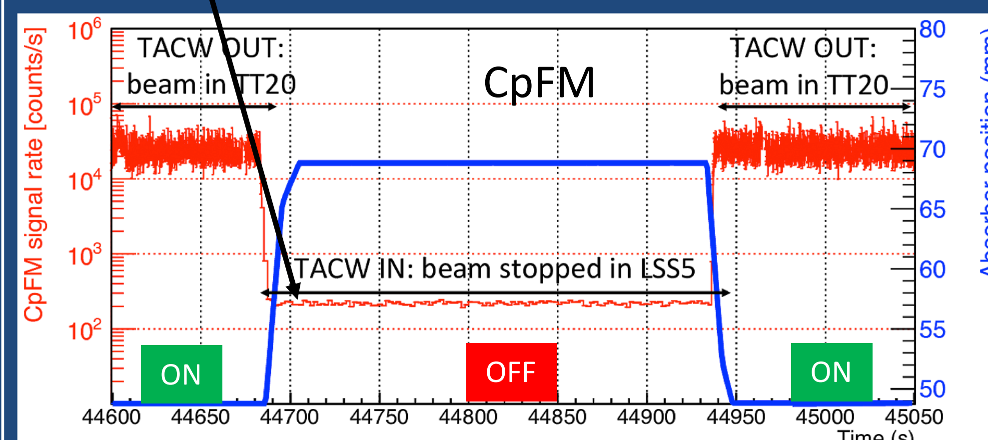
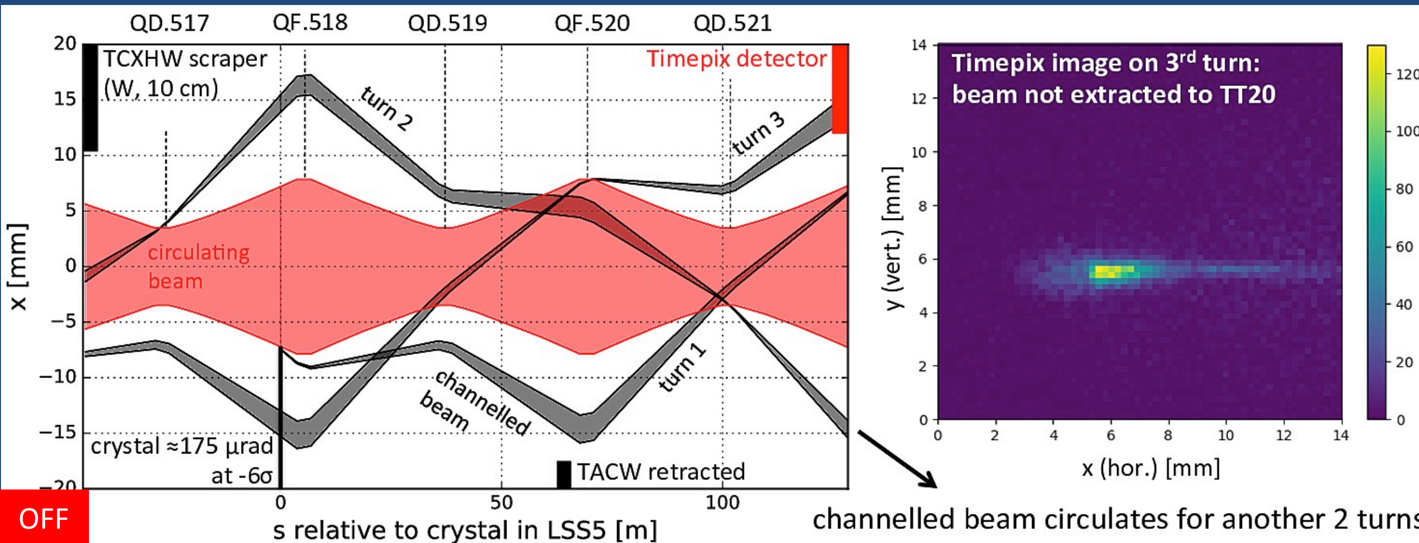


Linear scan of TT20 CpFM through the extracted beam

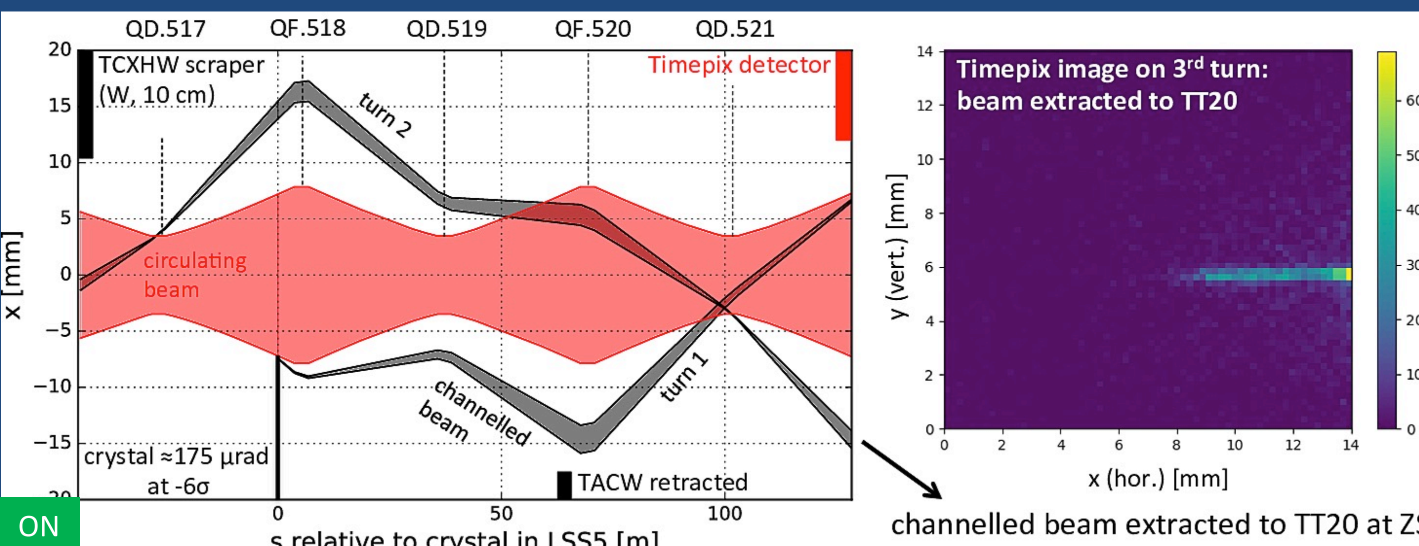


Crystal-aided non-resonant extraction experiment on Timepix



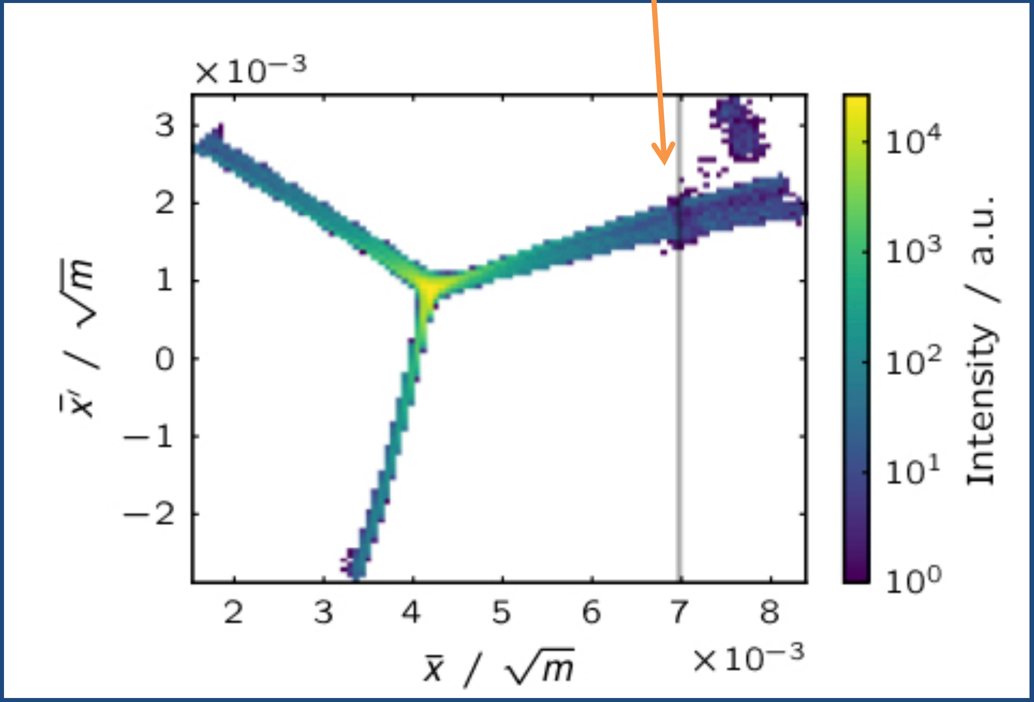
TCXHW inserted to stop the incoming 4th turn

Bump at the electrostatic septum OFF
→ Channeled beam circulates and is detected in the middle of Timepix at the 3rd turn.



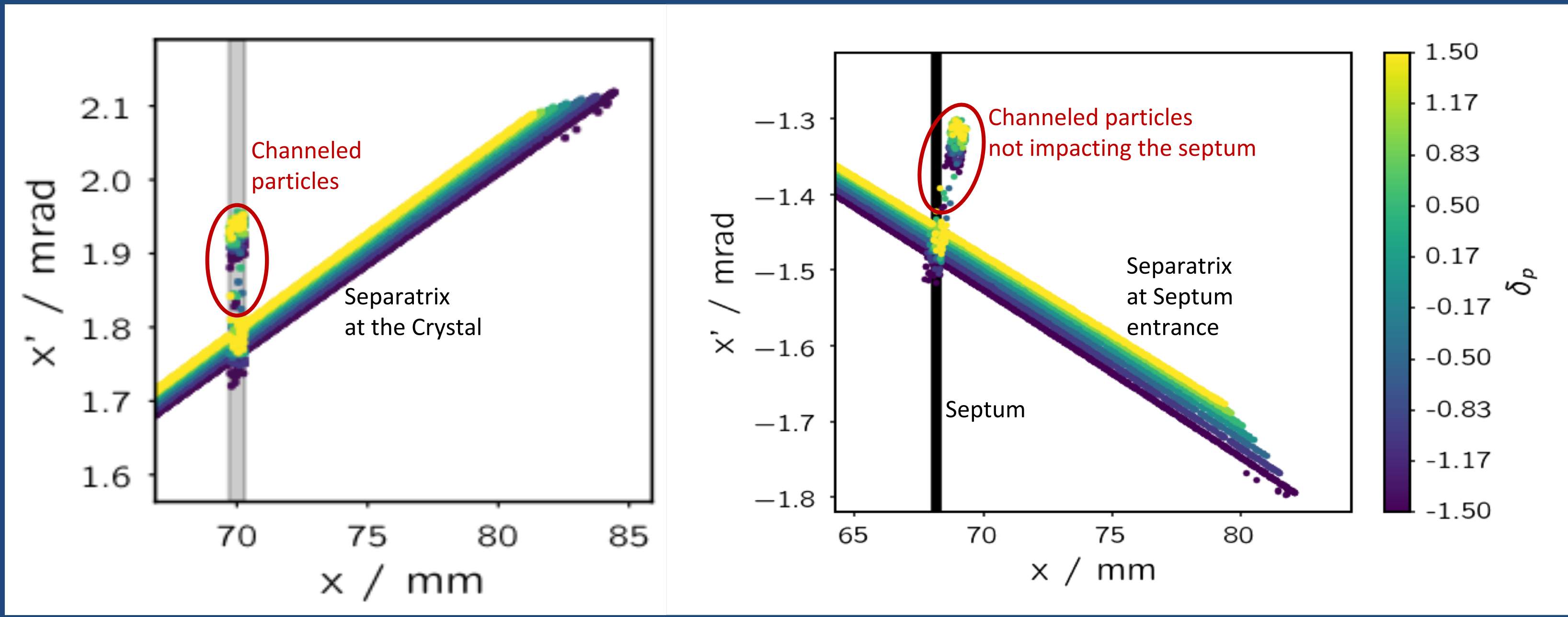
Bump ON
→ EXTRACTION
→ Channeled beamis extracted at turn 1.5 and disappears from Timepix
(plot scales are different!)

In the present SPS slow extraction setup (3rd integer resonance) a bent crystal with the appropriate phase advance from the first septum (i.e. non-local) could shape a gap along the separatrix.



- This would avoid particles in the separatrix hitting the wires of the electrostatic septum (ES) and to shorten its lifetime.
- The local beam loss and the debris produced by ES wires would be reduced, and shifted in a safer area of the accelerator.
- Simulations for an optimized layout account for a factor 4 less particles impinging of the septum. (F. Velotti, PhD Th.)

Experiment of local septum shadowing by a bent crystal at SPS



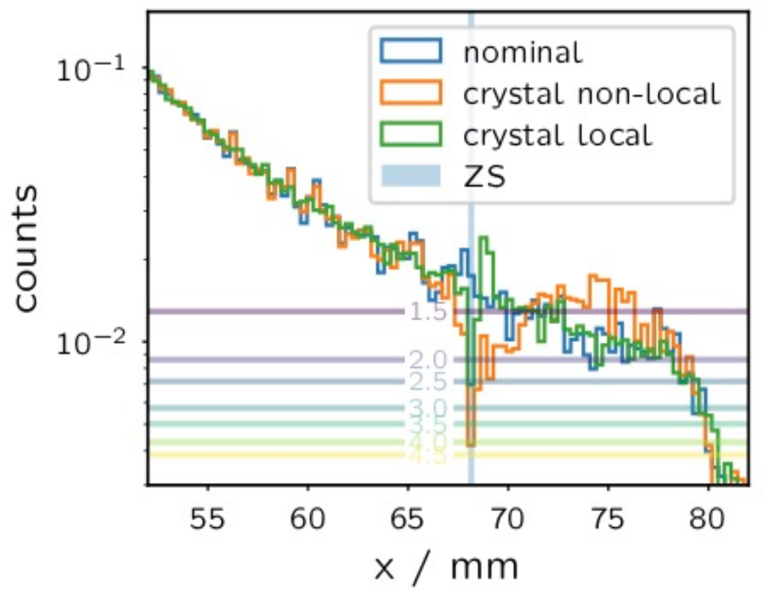
Setup:

- Goniometer installed in front of the first electrostatic septum (local scenario – not optimal, but cheaper)
- 400 GeV proton beam
- 3rd integer resonant extraction cycle, duty cycle as high as possible
- A few 10^{12} particles per spill
- Beam needs to be bumped towards the crystal

- Alignment of the crystal to the wires in cycle mode → big challenge!!

Aim:

- demonstrate the principle of shadowing
- measure loss reduction and compare with simulations
- Understand how the disposal of the channeled particles will need to be addressed for the nominal beam.
- Ultimately → gain experience in view of the installation of an optimized non-local system.



Simulated particle density at the septum

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In optimized non-local position loss reduction ~ 4

In this experiment expected ~ 2.5

First MD session next week

Motivation for a double-crystal proof of principle in the SPS

"Parasitic fixed-target" experiments are proposed (see N. Neri's talk with references) to be located in front of one of the LHC big detectors,

making use of

- 1 bent crystal to separate the periphery of the beam halo from the circulating beam
- 1 target + crystal assembly to generate short living polarized particles like Λ_c and to let their magnetic moment precess in the strong equivalent magnetic field of the bent crystal.

Magnetic moment of channeled particles should precess in a bent crystal

$$\vartheta_{spin} = \frac{g-2}{2}\gamma\vartheta_{crystal}$$

See V.G. Baryshevskii, Pis'ma Zh. Tekh. Fiz.5, 182 (1979) and PLB 757 (2016) 426-9.

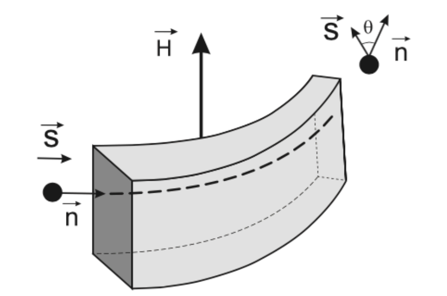


Figure 1. Spin rotation in a bent crystal

Superconducting environment in LHC is extremely challenging:

- careful beam manipulation
  - control of double channeling
  - Intercept not channeled particles impinging on crystal (scattered, dechanneled, ...)
- total control of the beam-induced background for machine protection

Minimal changes in the SPS UA9 layout provided a valuable test bench for the double-crystal scenario in LHC.

Key parameters:

Efficiency of double channeling, with and without target

Background estimate

First observed double channeling with a thin second crystal

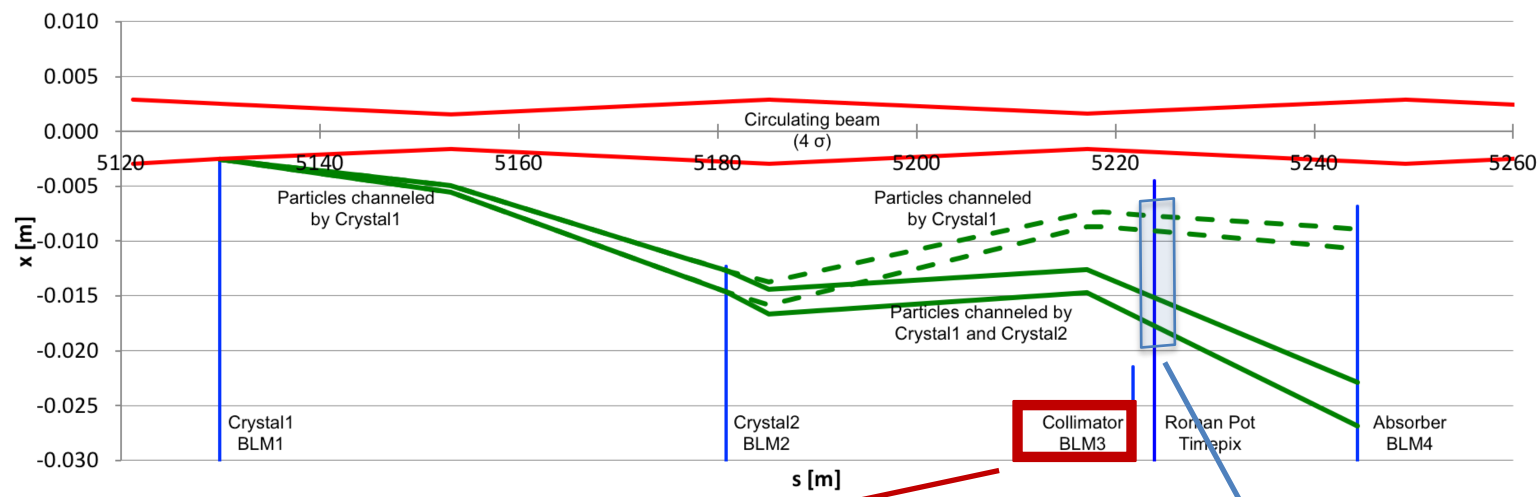


Figure 1: Horizontal beam envelope and position of the main devices in the UA9 Experiment installation.

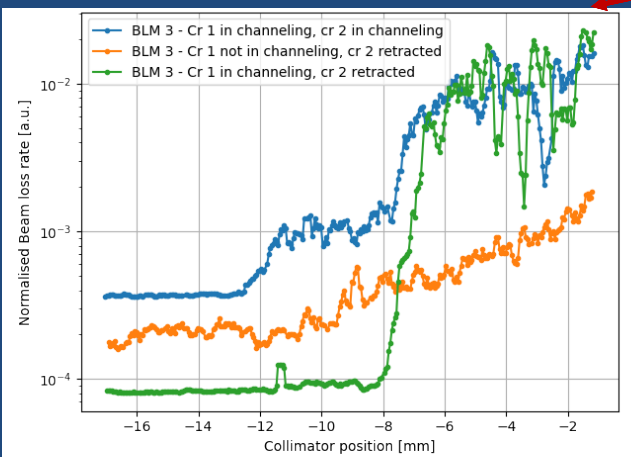


Figure 4: Beam loss rate as a function of the position of the collimator for different configurations of the crystals.

Only a small fraction of the first channeled beam could be channeled a second time

because

Crystal2 thickness = 0.5 mm

i.e. ~ ¼ expected beam spot

→ A WIDER crystal is needed

Beam loss monitor

Pixel detector

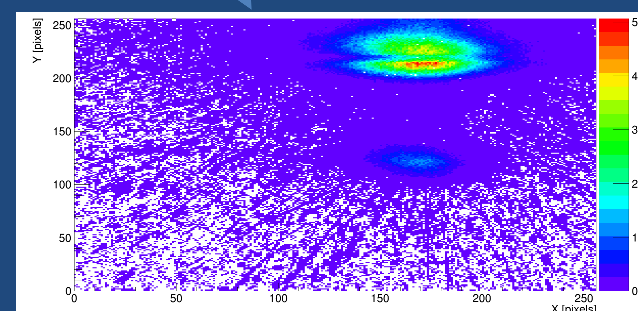
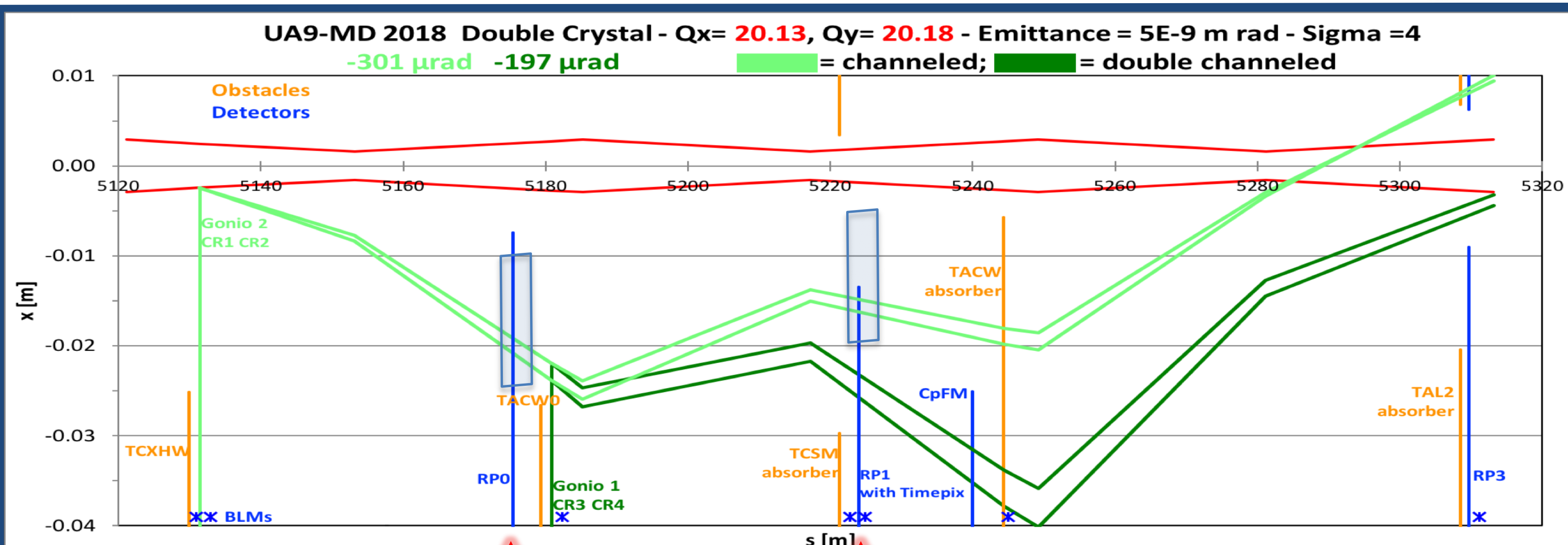


Figure 5: Image of the single-channeled (top) and double-channeled (middle) beams on the Timepix detector. The image should be rotated by 90°counter-clockwise in order to reproduce the real spatial position of the beams. The color scale represents the average number of counts per second per pixel.

S. Montesano, IPAC2018, TUPAF043

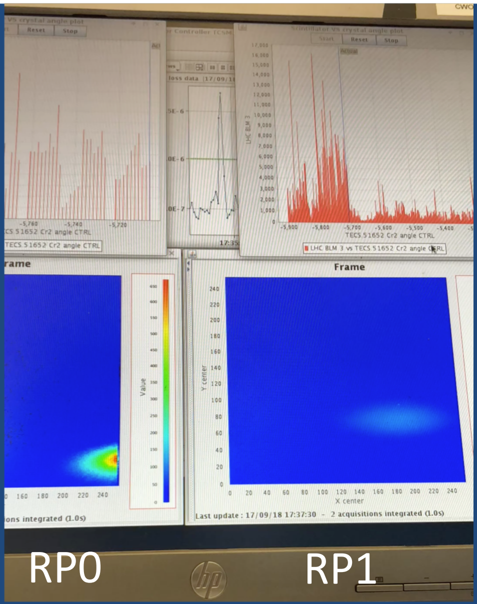
Layout upgrade and latest observation of SINGLE channeling



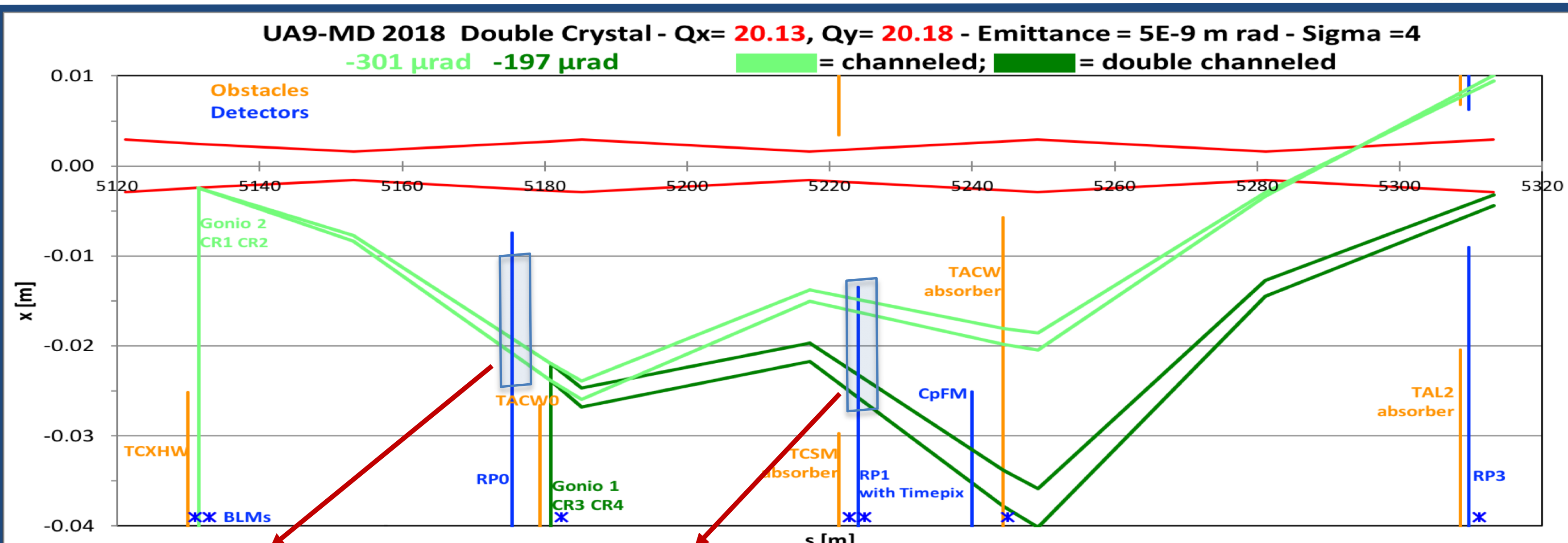
Added:

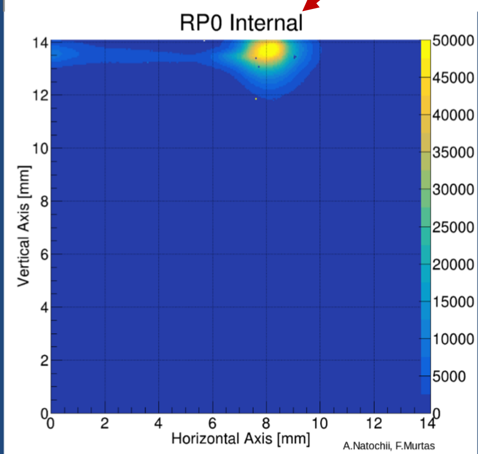
- A 4 mm wide crystal installed in downstream Gonio
- A new Roman Pot (RP0) equipped with Timepix2
- A new Tungsten Absorber

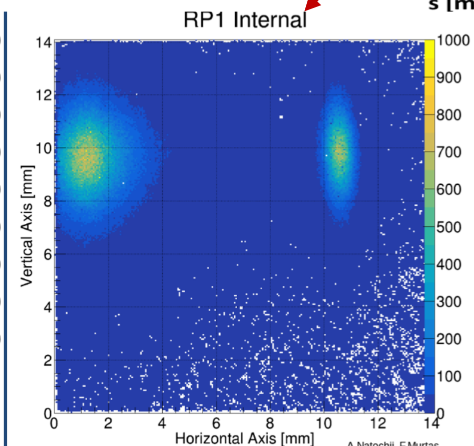
Single crystal angular scan:
Online observation
from channeling to volume capture
θ_{Cr2} = 300 µrad
(Axes continuously self adjusting !!!!)

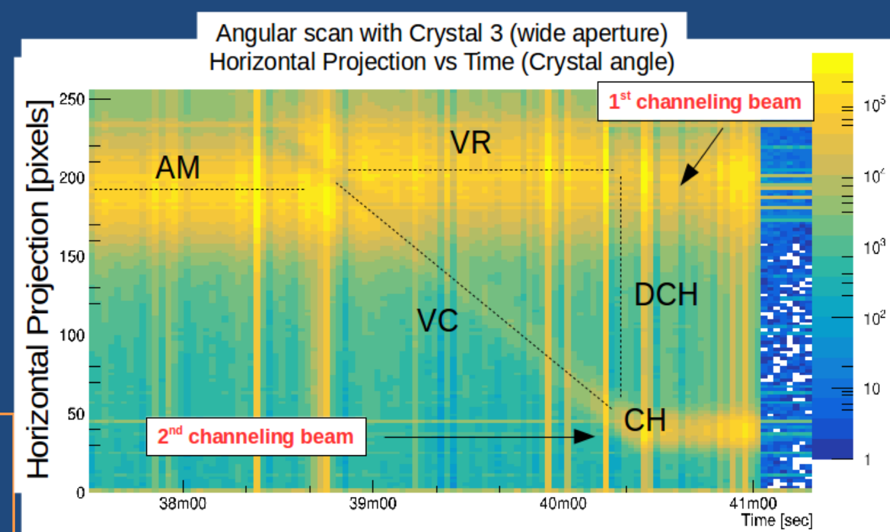


Latest observation of DOUBLE channeling





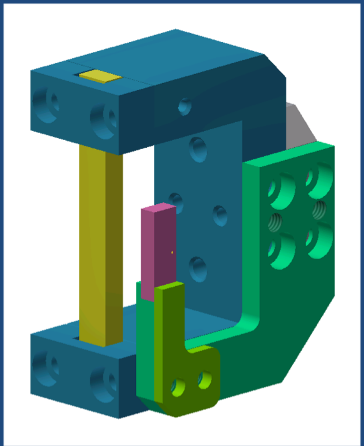




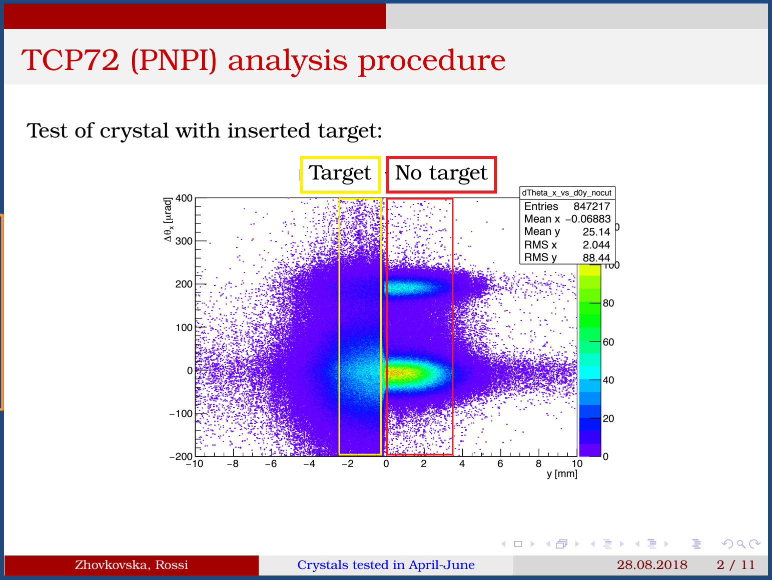
The availability of our in-vacuum detectors, Timepixes and CpFM (not shown here), was crucial to find the proper alignment and the correct orientation of the second crystal, in particular for the wide one.

Next step: double channeling with a target

- Target installation was delayed due to higher priority machine activities during SPS 1st Technical Stop
- Finally a W target was installed in front (total shadow) of the second crystal in TS2.
- Reference data have been taken in double channeling without the target, and analysis is in progress.
- We need now to complete the data set with same data with target in order to evaluate the process efficiency and the relative background.
- Extra run in October requested



A similar crystal half covered by a Tungsten target, as measured at our H8 test-beam, and bending in the vertical direction



Conclusion

The UA9 collaboration has gained considerable experience in the manipulation of beams by means of bent crystals.

- After the LHC collimation
- The proof of principle of extracting the beam from SPS by means of a crystal assisted non-local non-resonant mechanism was very successful.
  Although several systems need to be upgraded in the machine itself before the non-resonant extraction procedure could become operational, like for instance:
  - More local setup → shorted distance crystal to septum
  - Strong bumpers at the crystal to allow running in cycled mode
  - Diagnostics, …

  this remains extremely promising because of the possibility of suppressing the ES septum in the extraction channel. If validated, on the long term this setup may drastically reduce the complexity and cost of the extraction systems, resulting in much easier integration scenarios for beam extraction at very high energy, for example for the multi-TeV fixed-target beams in the FCC era.
- The shadowing test in preparation is quite challenging. If successful, it may bring immediate benefits for the daily SPS operation and ensure a safe extraction scenario for the high intensities required by the Beam Dump Facility.
- Finally the double-channeling experiment in the SPS can help giving some insight about the challenges to be faced for a full scale experiment in the LHC.

The extraction activities were performed in collaboration with the CERN TE/ABT group

THANK YOU

FOR

YOUR ATTENTION