Crystal collimation of hadron beam at CERN, the UA9 experiment

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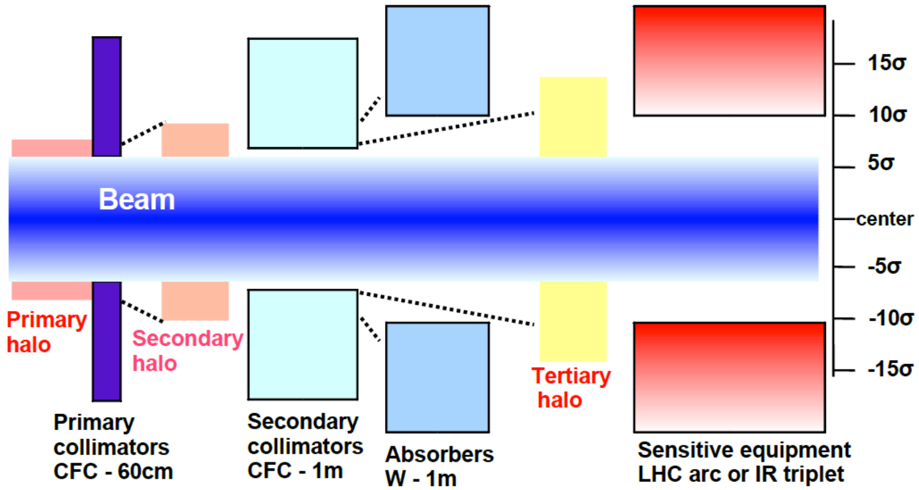
14 giugno 2011

Collimation at colliders

- Passive protection for fast losses
- Cleaning and absorption for slow losses
- Defense against radiation
- Reduction of physics background

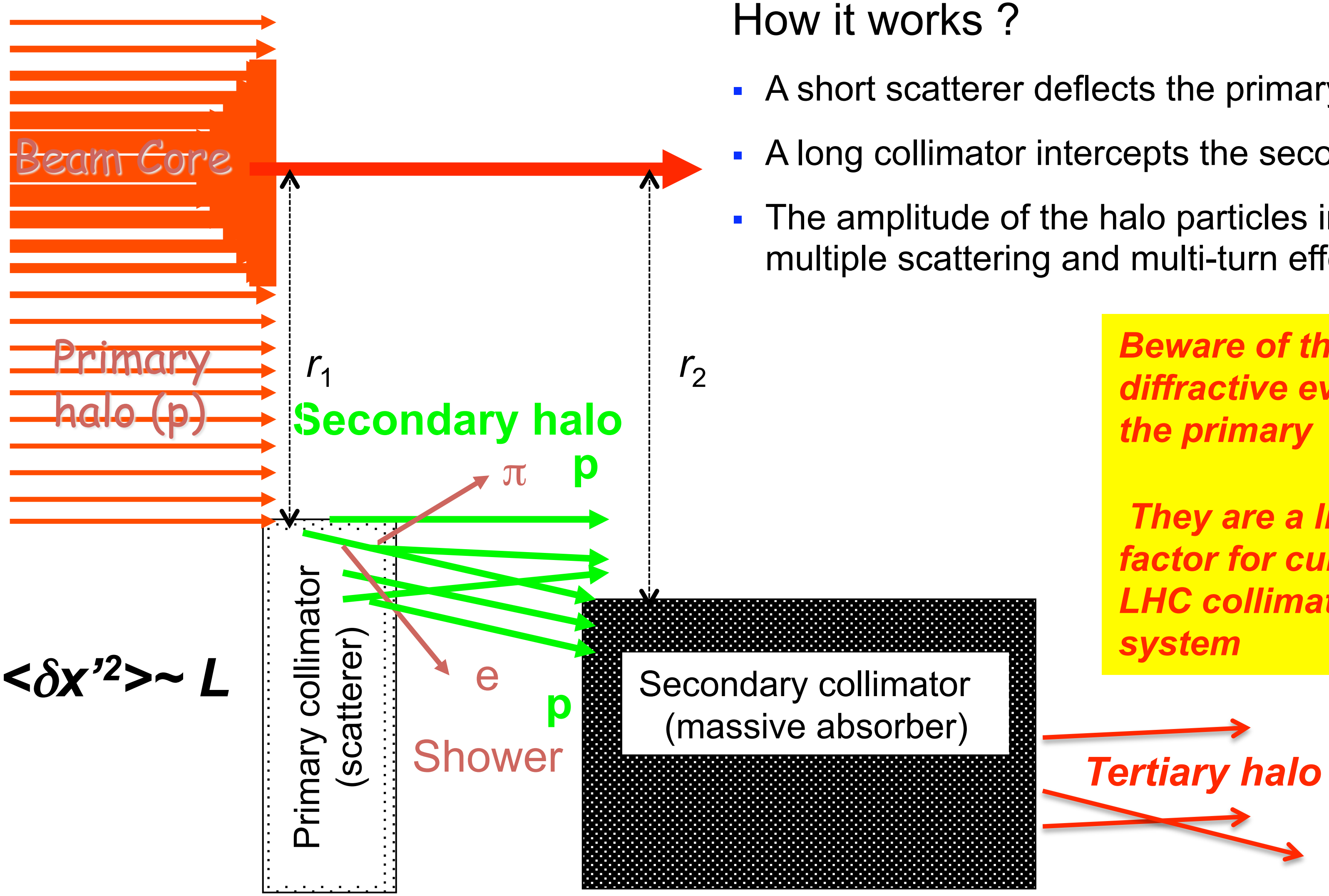


High luminosity requires (eventually) high currents

At 7 TeV 1/50.000 proton lost makes a SC magnet quench!

Cleaning Efficiency

Traditional concept



$<\delta x'^2> \sim L$

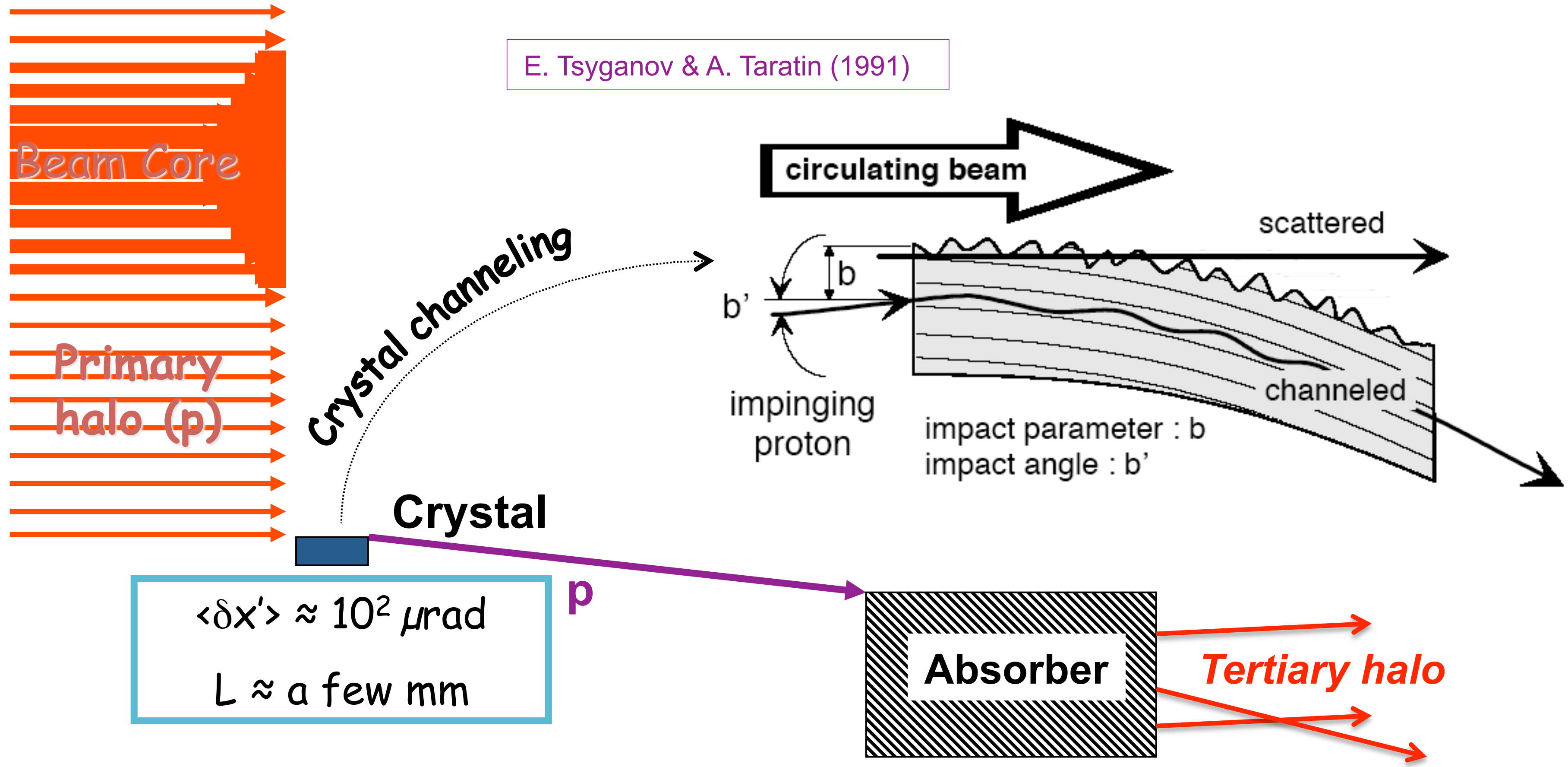
How it works ?

- A short scatterer deflects the primary halo
- A long collimator intercepts the secondary halo
- The amplitude of the halo particles increases via multiple scattering and multi-turn effects.

Beware of the diffractive events in the primary

They are a limiting factor for current LHC collimation system

A new idea!



- **Coherent deviation of the primary halo**
- **Very small probability of inelastic interaction in the crystal**

- ***Larger collimation efficiency***
- ***Less impedance***
- ***Reduced tertiary halo***

Crystal channeling

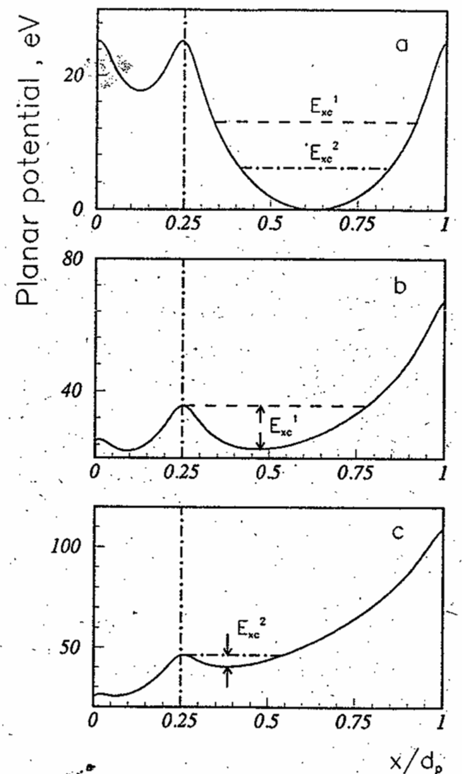


Fig.2. The continuum potential of the (111) silicon channel (a), and the effective planar potential for the crystal bent with the average curvature (b) and with the maximum one (c) at the bending angle of 8.9 mrad. The critical transverse energies of particles E^1_{xc}, E^2_{xc} for the wide channels in the bent crystal are shown by the dashed and dot-dashed lines, accordingly, in fig.2b and fig.2c. The same values of E_{xc} in the straight channel potential are shown in fig.2a.

5

J. Lindhard, Phys. Lett. 12, 126 (1964)
E. Tsyganov , Fermilab, TM-682 (1976)

Charged particle entering crystal with angle wrt lattice place smaller than a critical angle

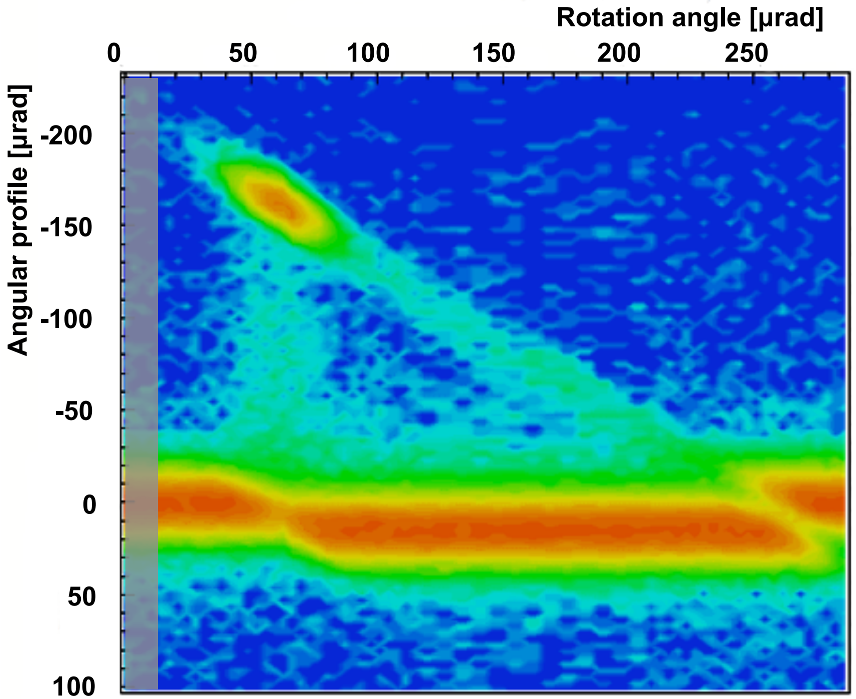
$$\theta_{IN} < \theta_C = \sqrt{\frac{2U}{E}}$$

Oscillation within the lattice planes!
Particles trapped!

If the crystal is BENT, additional centrifugal potential.
Charged particles are deflected!

In silicon (110) 400 GeV protons
$\theta_c \sim 10\ \mu$rad

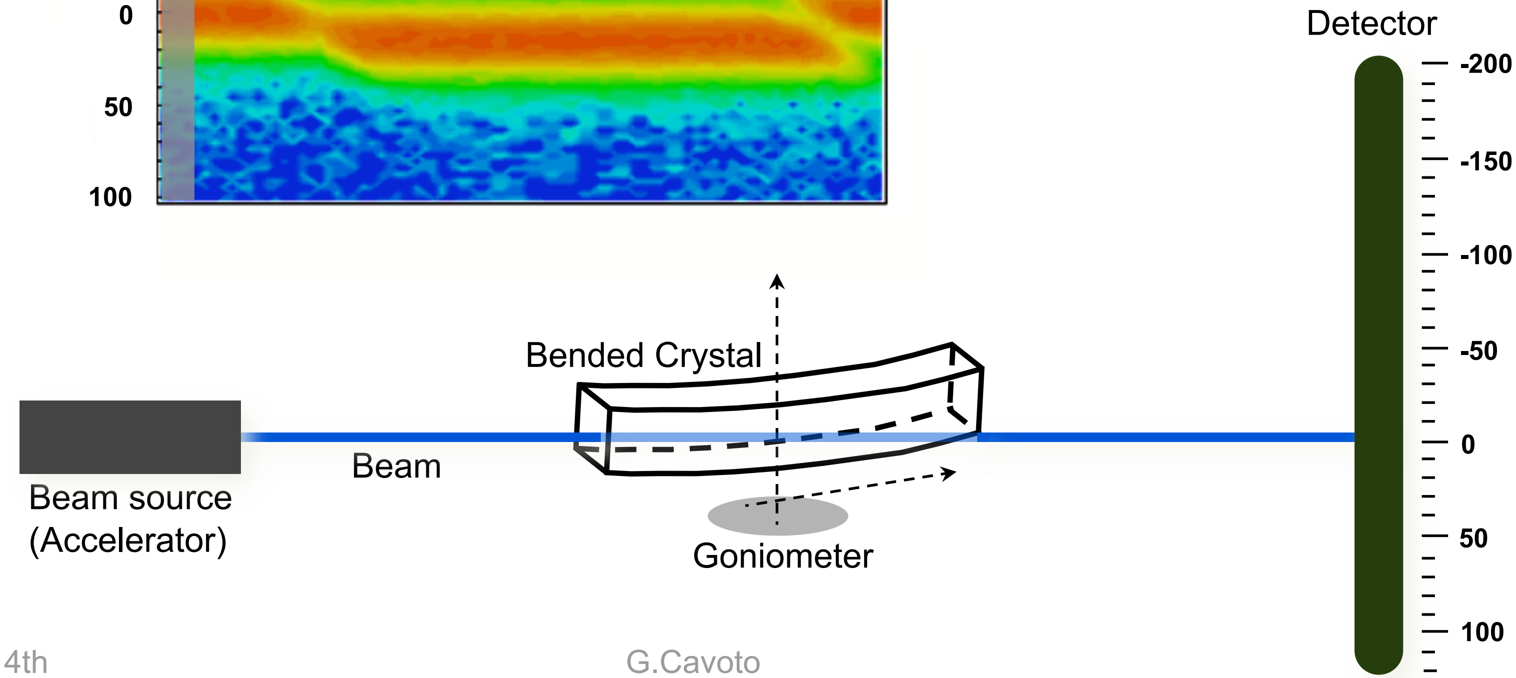
Crystal behaviour



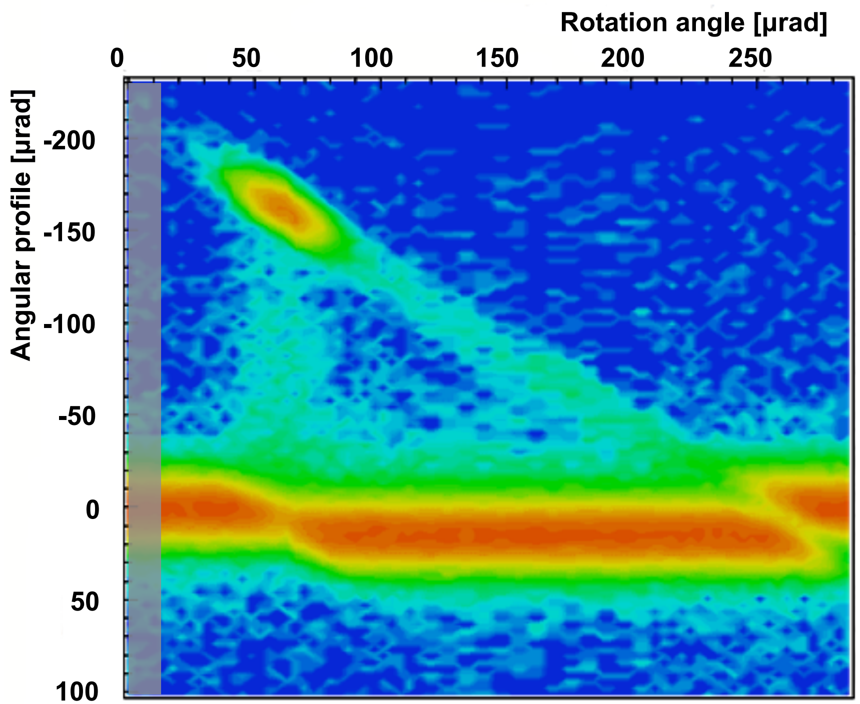
Amorphous behavior

W. Scandale et al. PRL 98, 154801 (2007)

W. Scandale et al. PRST 11, 063501 (2008)



Crystal behaviour



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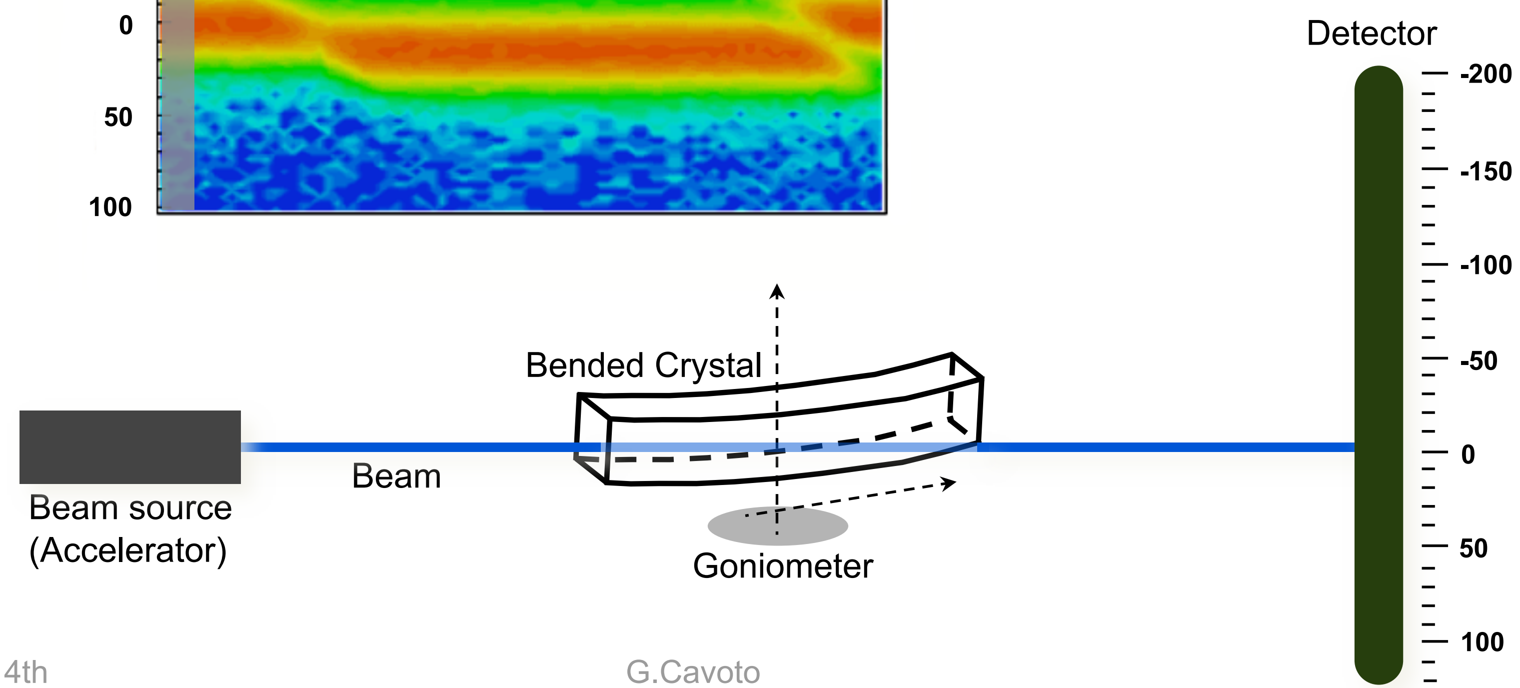
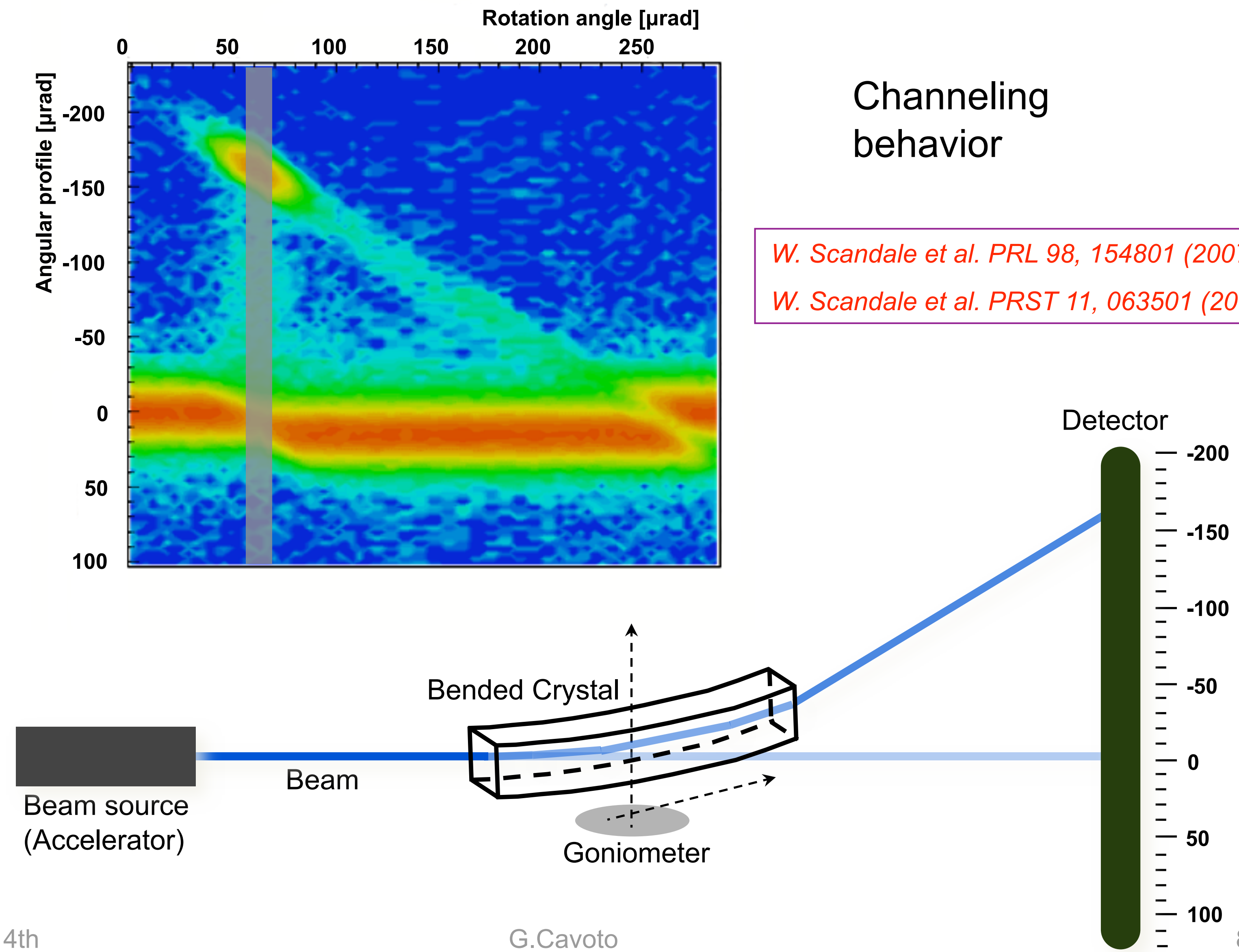


Crystal behaviour

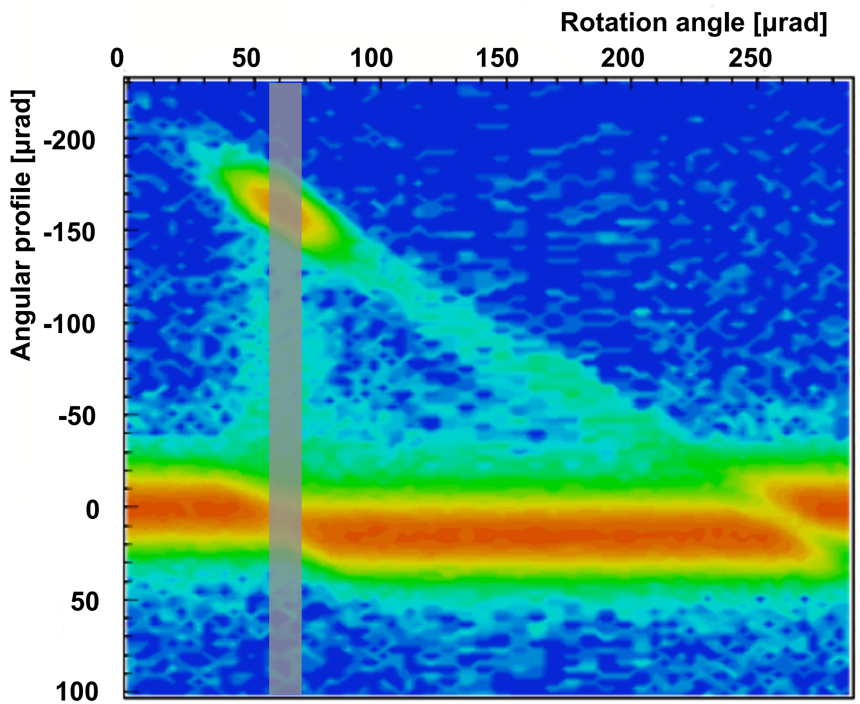


Channeling
behavior

W. Scandale et al. PRL 98, 154801 (2007)

W. Scandale et al. PRST 11, 063501 (2008)

Crystal behaviour



Channeling behavior

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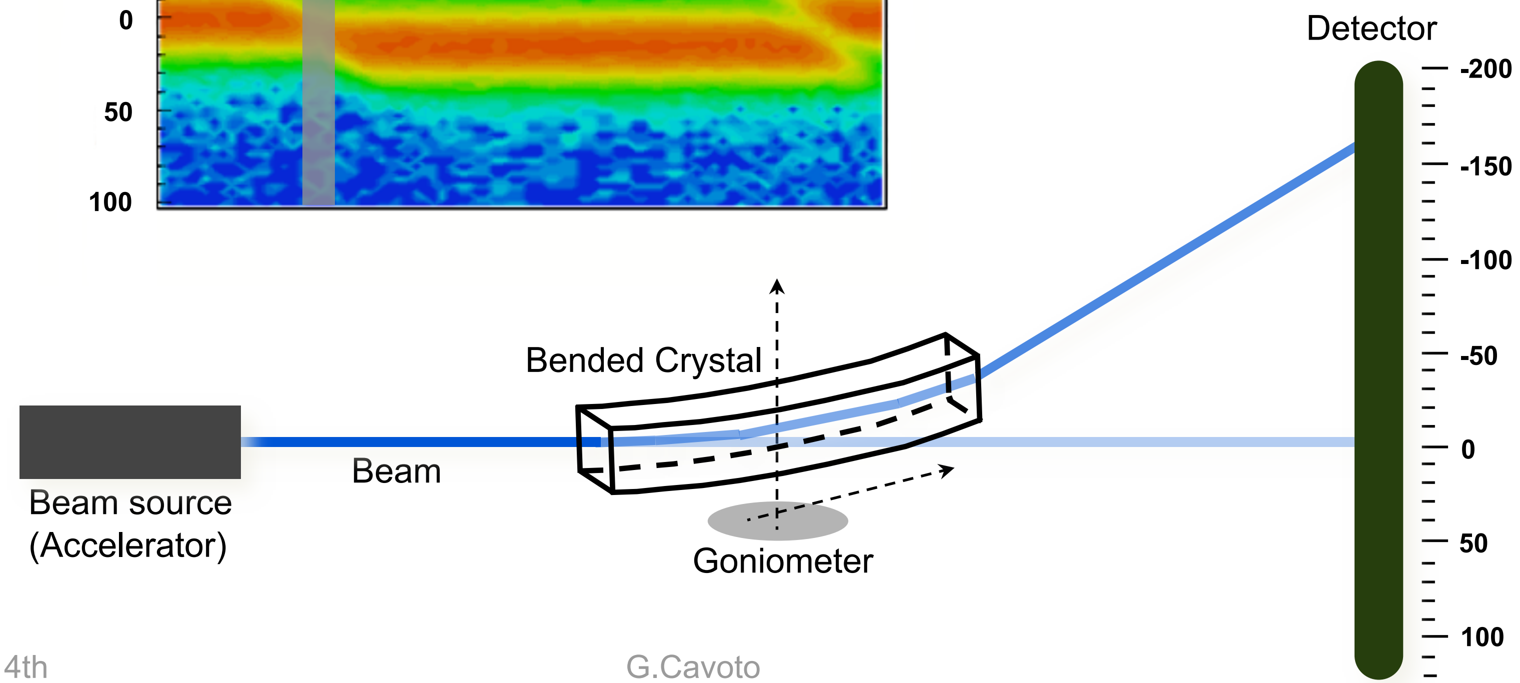
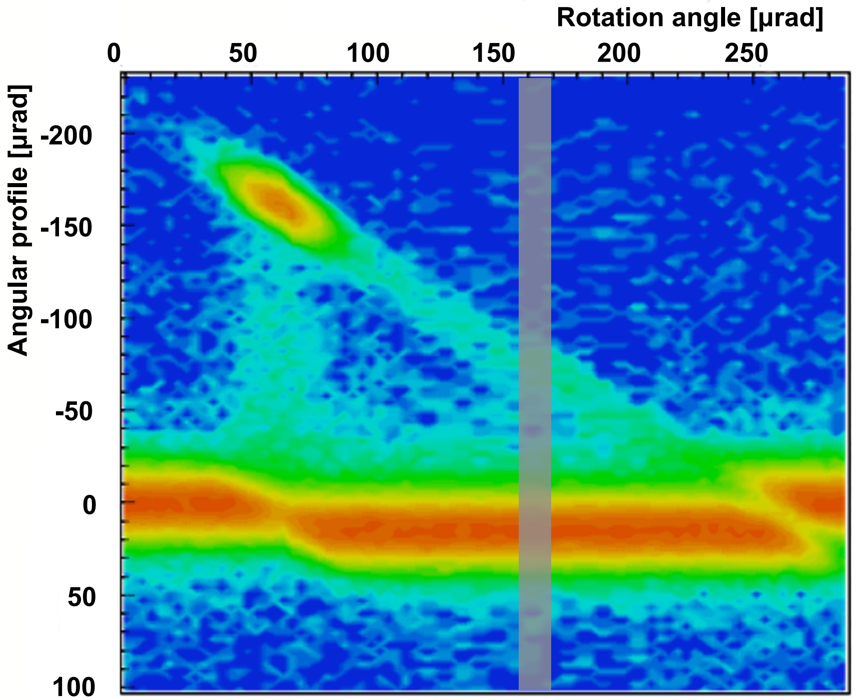


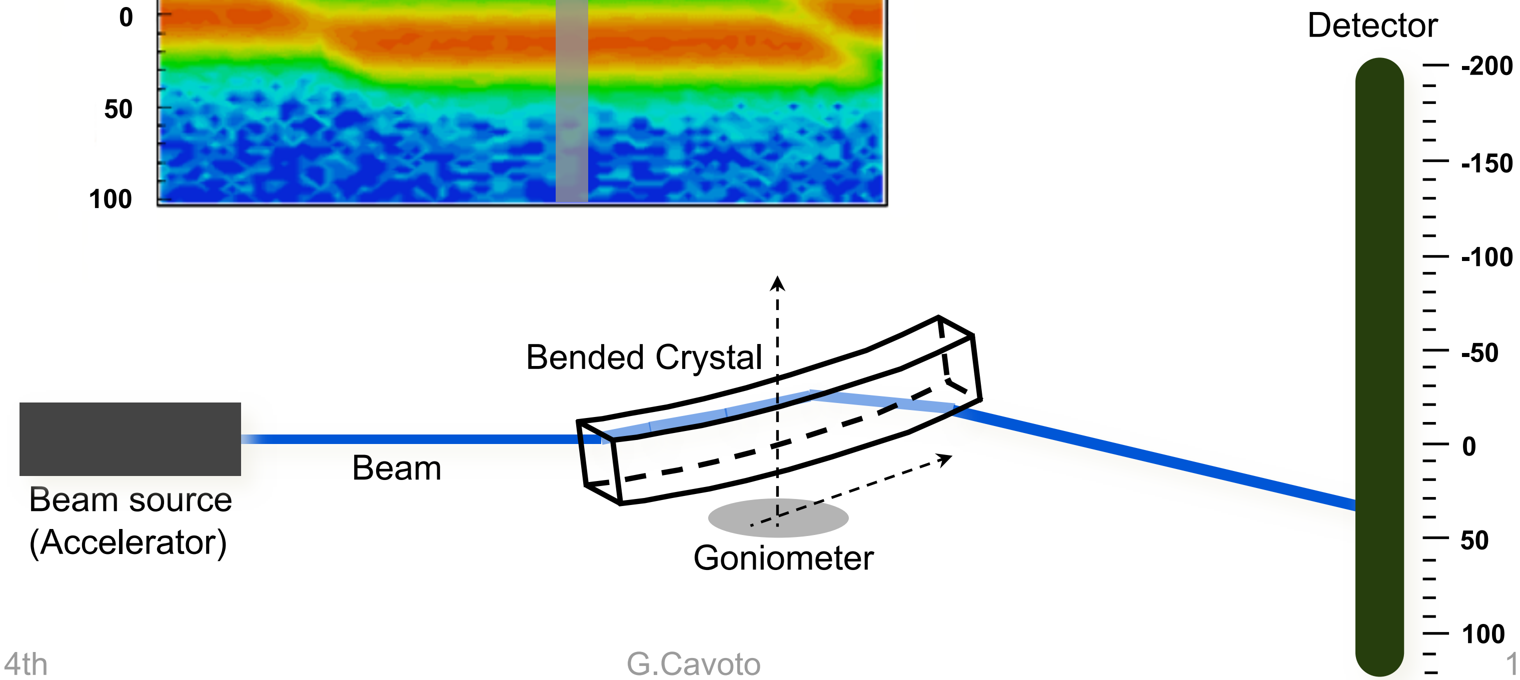
Crystal behaviour



Reflection behavior

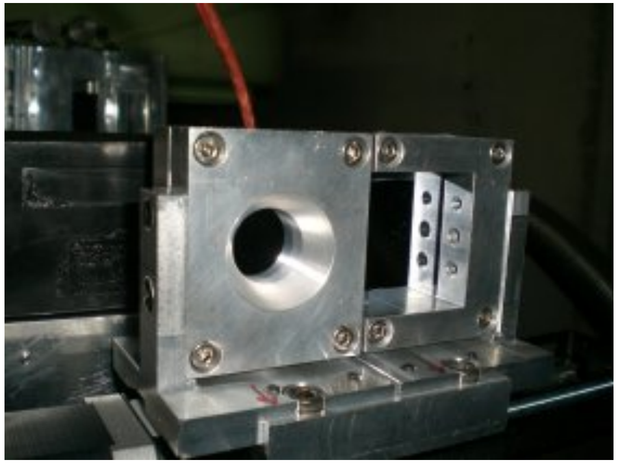
W. Scandale et al. PRL 98, 154801 (2007)

W. Scandale et al. PRST 11, 063501 (2008)

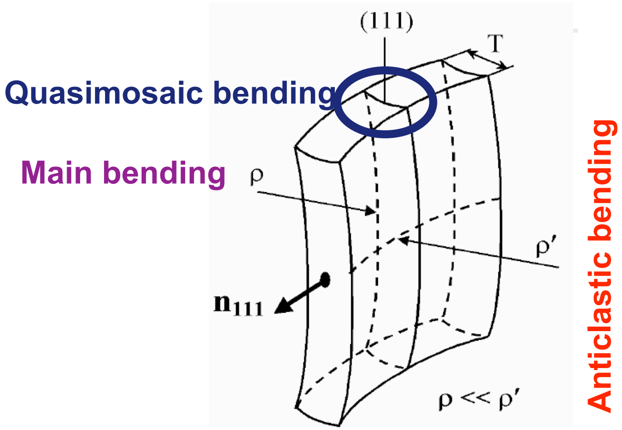


Crystals

Quasimosaic crystals

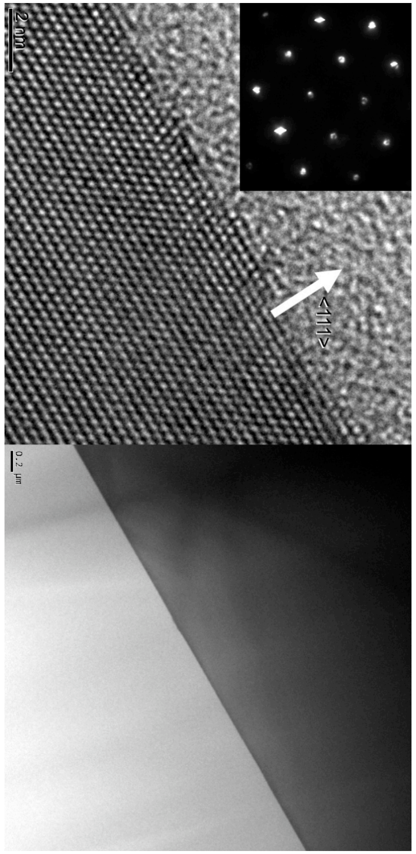


O.I.Sumbaev - PNPI (1957)



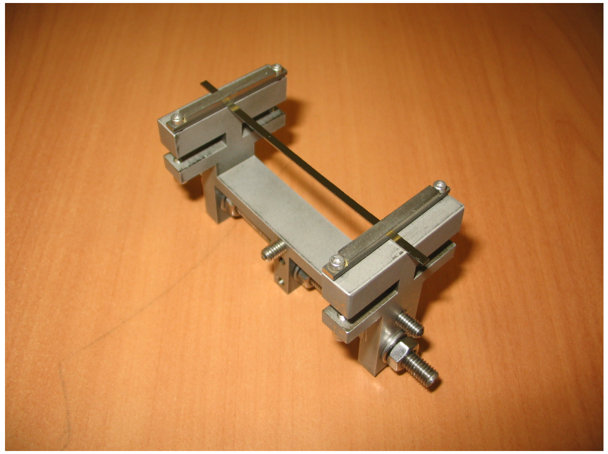
- Bending driven solely by anisotropy

Chemical etching

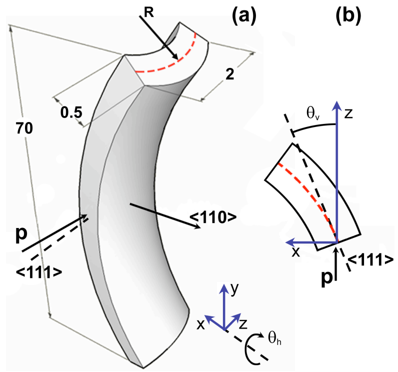


S. Baricordi *et al.*, Appl. Phys. Lett. 91, 061908 (2007)

Strip crystals



A. G. Afonin *et al.*, JETP Lett. 67, 781 (1998)

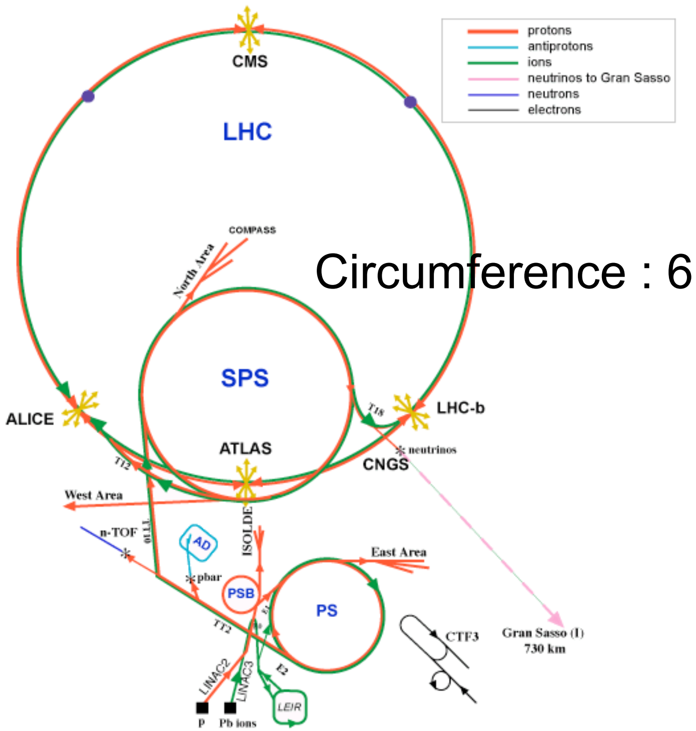


- Bending driven by 2-D elasticity law

UA9 @ SPS

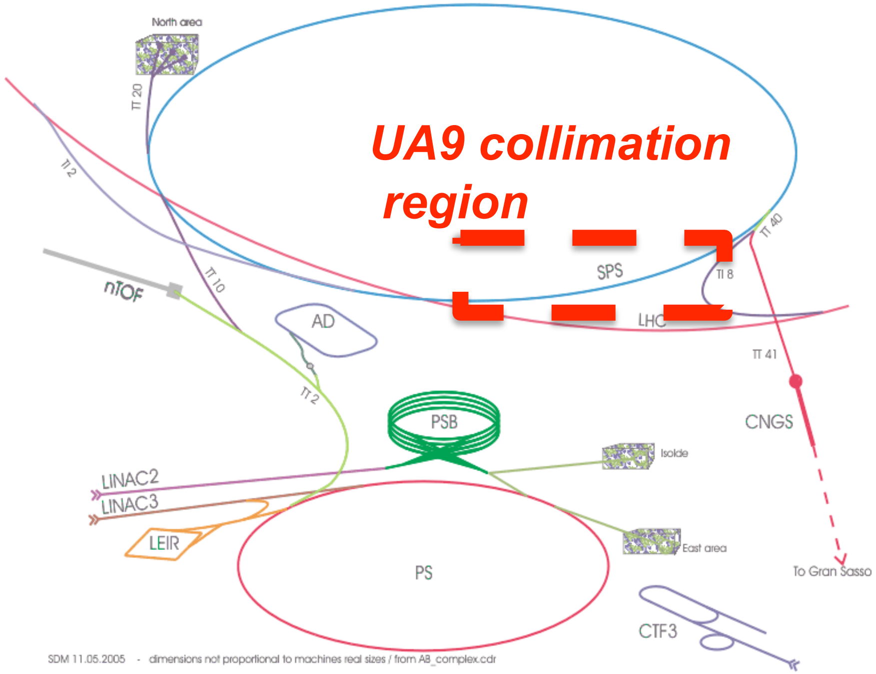
An international collaboration
60 people
CERN, Italy, Russia,UK, US
[INFN FE, LNF,LNL, NA, RM]

CERN Accelerators
(not to scale)



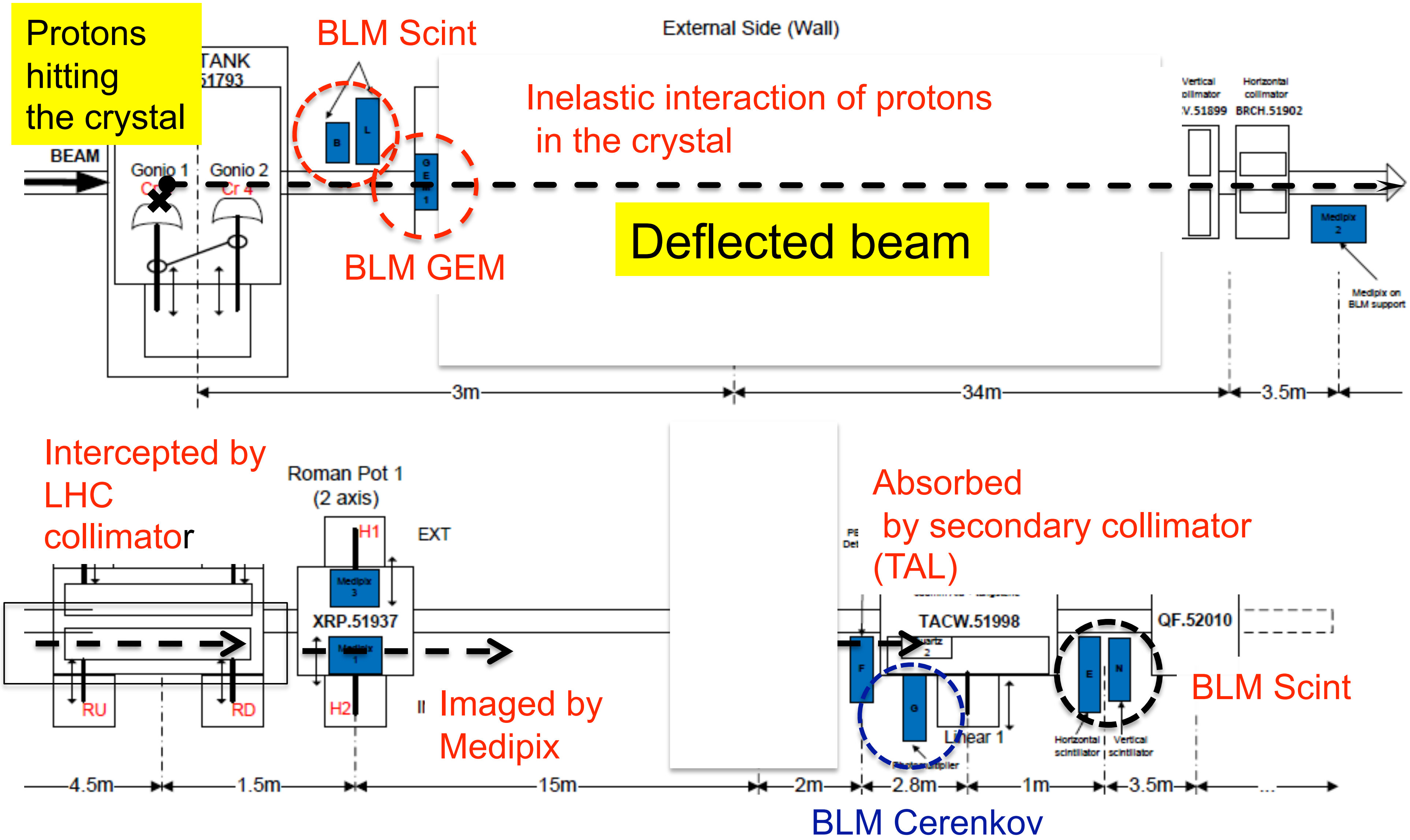
Circumference : 6.9 km

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Seperator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

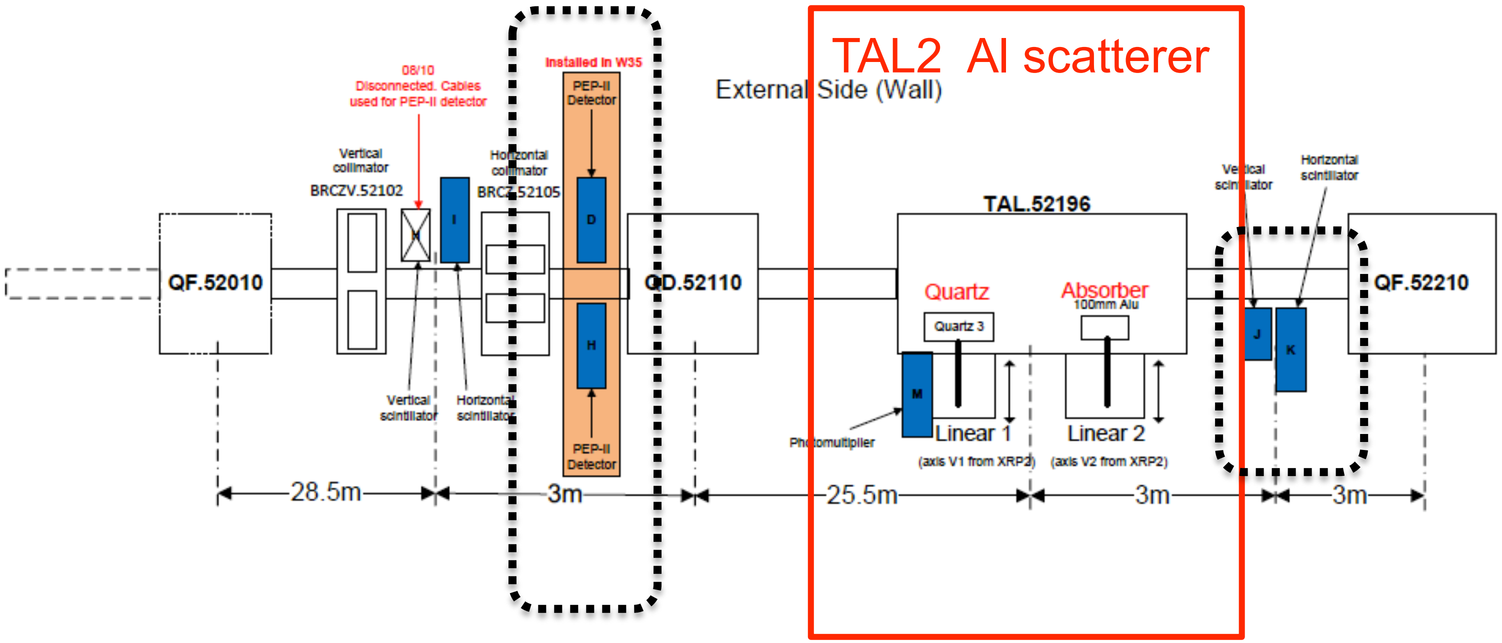


Data-taking during dedicated ***M***achine ***D***evelopment days
with SPS beam in coast mode (~5 in a year, in 2010
4 with protons and 1 with Pb ions
Extracted beam (microbeam at H8) tests.

Collimation region



Out of collimation region



New scatterer + BLM (scint, Cerenkov, ionization ch.)
in highly ***dispersive*** region to detect

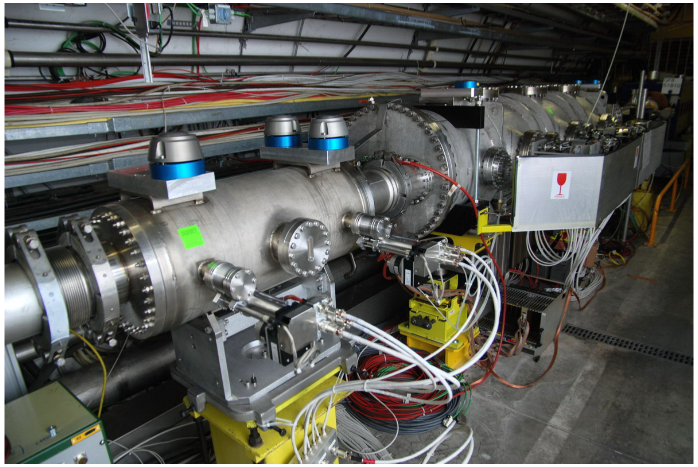
1) **off-momentum particles** (produced in the crystals) which are displaced lateraly
2) any not absorbed secondary halo

Observe the spray rate as a function of scatterer lateral position

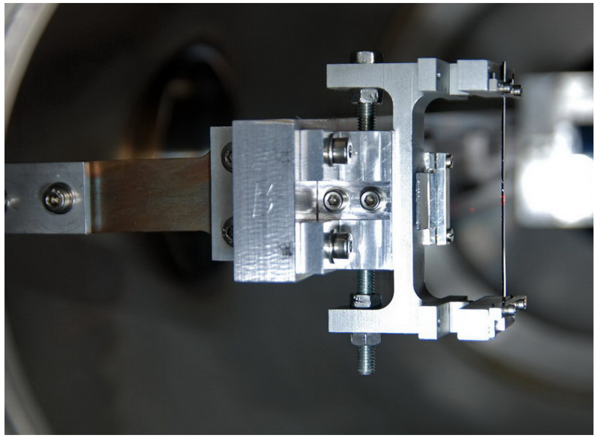
SPS UA9 devices

IHEP tank with goniometers

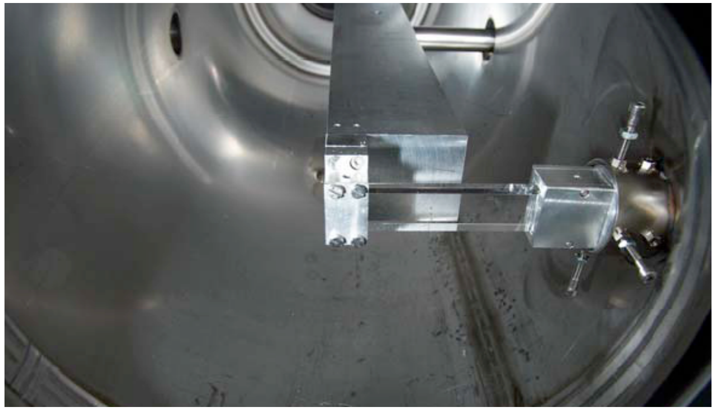
Angular resolution ± 10 μrad



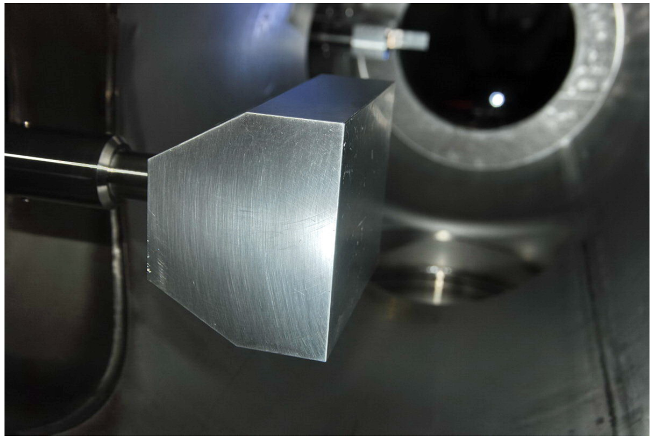
Strip crystal in IHEP tank



TAL absorber & Quartz Cerenkov detector



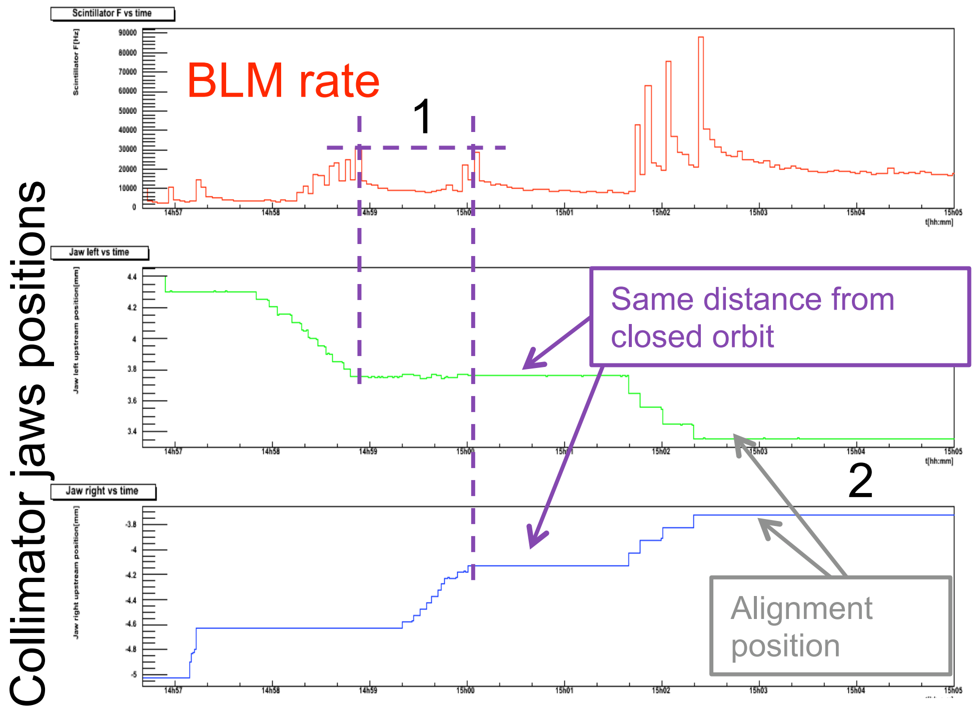
TAL2 Al scatterer



High quality mechanical devices, accurate motion system

Alignment procedure

1) Search of the closed orbit, 2) redefine the beam at how many sigma we want.

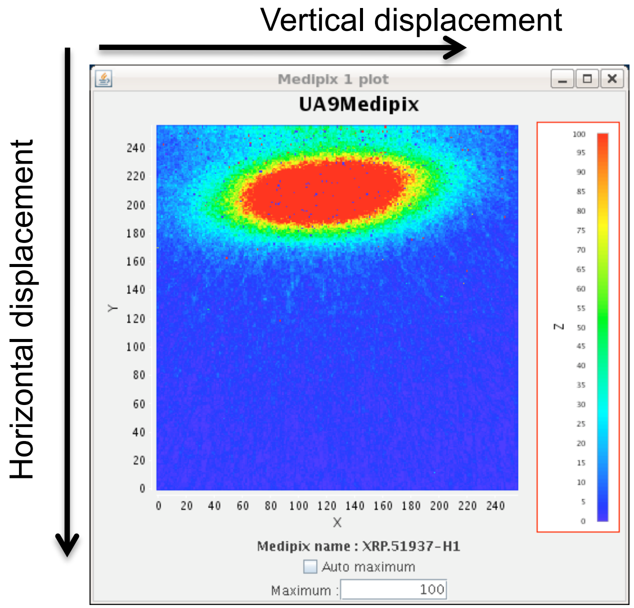


Crystal and all UA9 movable devices are aligned during each fill.

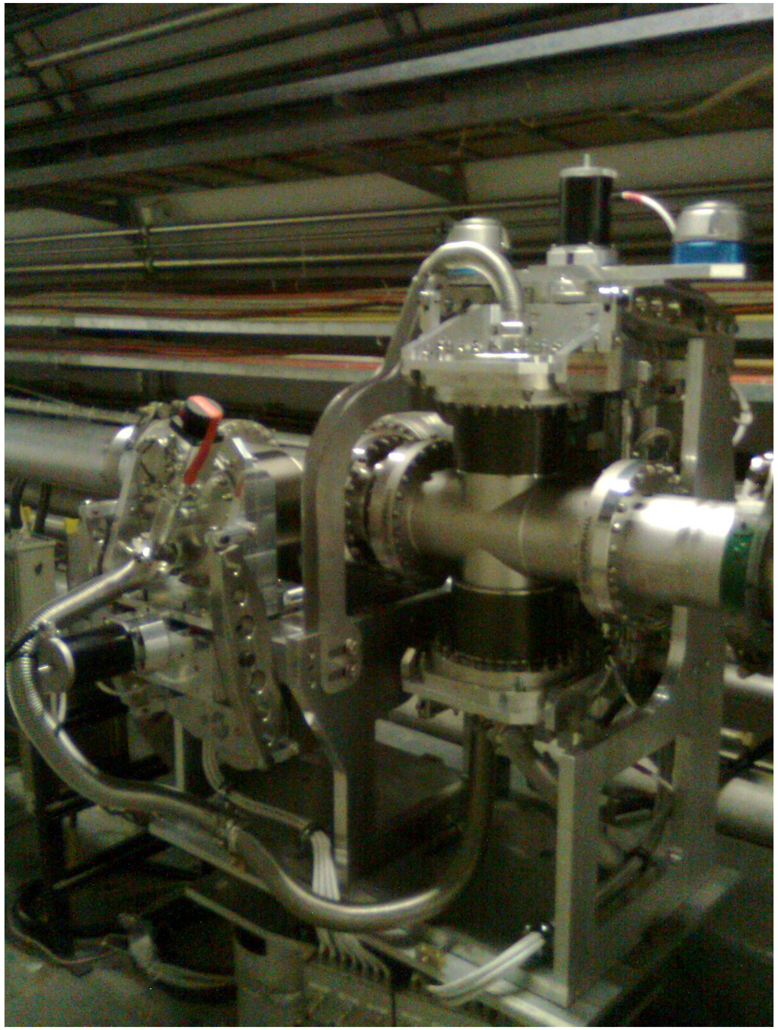
Standard and fast procedure to find channeling configuration and collimation!

Roman pots

– Movable device housing detectors in secondary vacuum
  » Used to ***acquire images of channeled beam***
  » Relevant to measure channeled beam direction (from centroid) and flux of proton of channeled beam

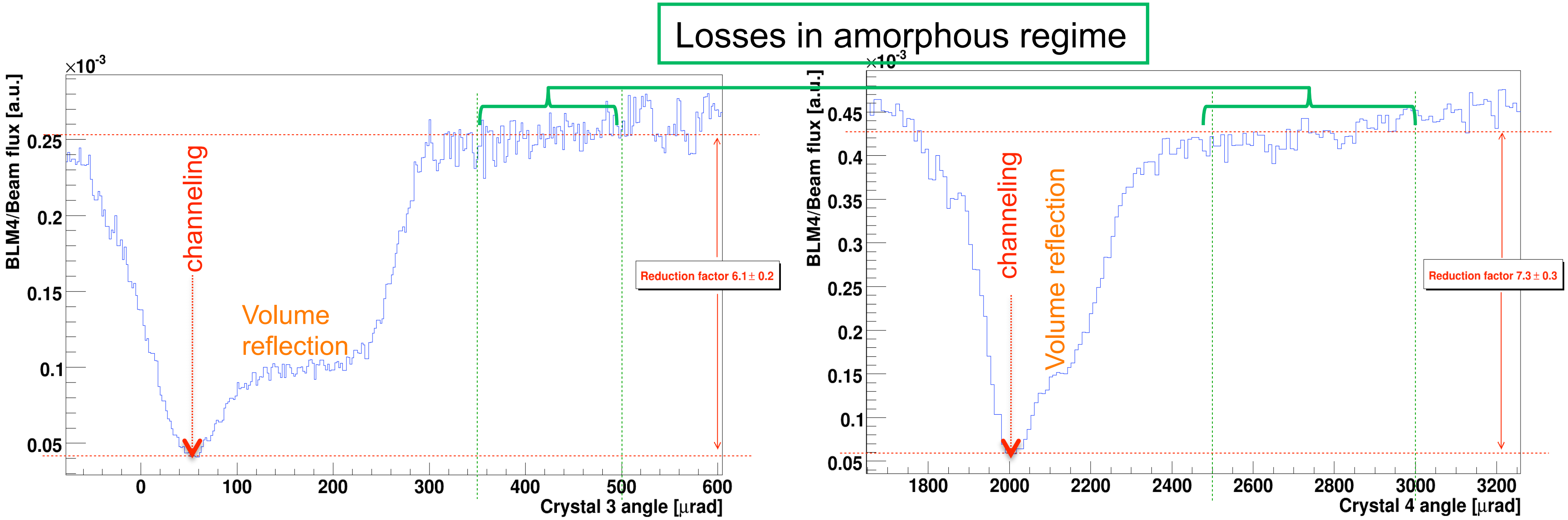


Online picture with Medipix



Angular scans

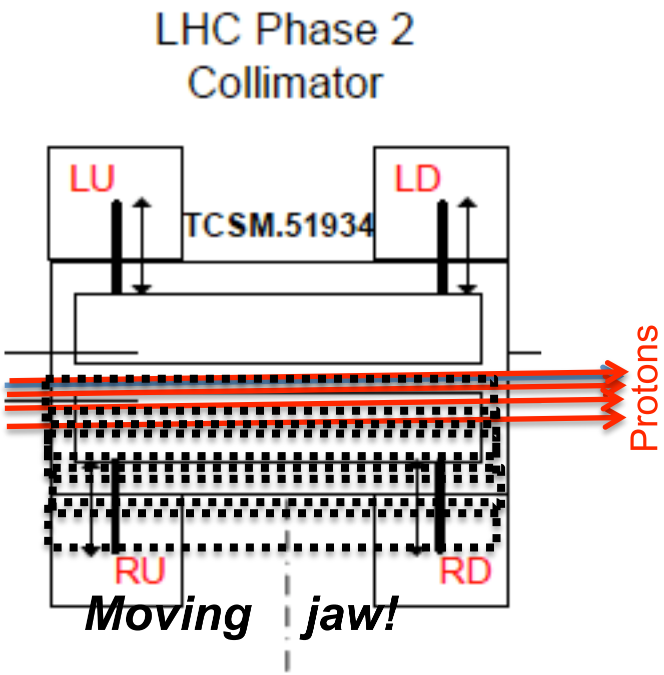
- <u>Reduction factor</u> of the inelastic losses due to inelastic interactions in channeling versus amorphous orientations.
  - Measured with LHC-BLM and GEM detectors
  - Very reproducible in several scans and fills

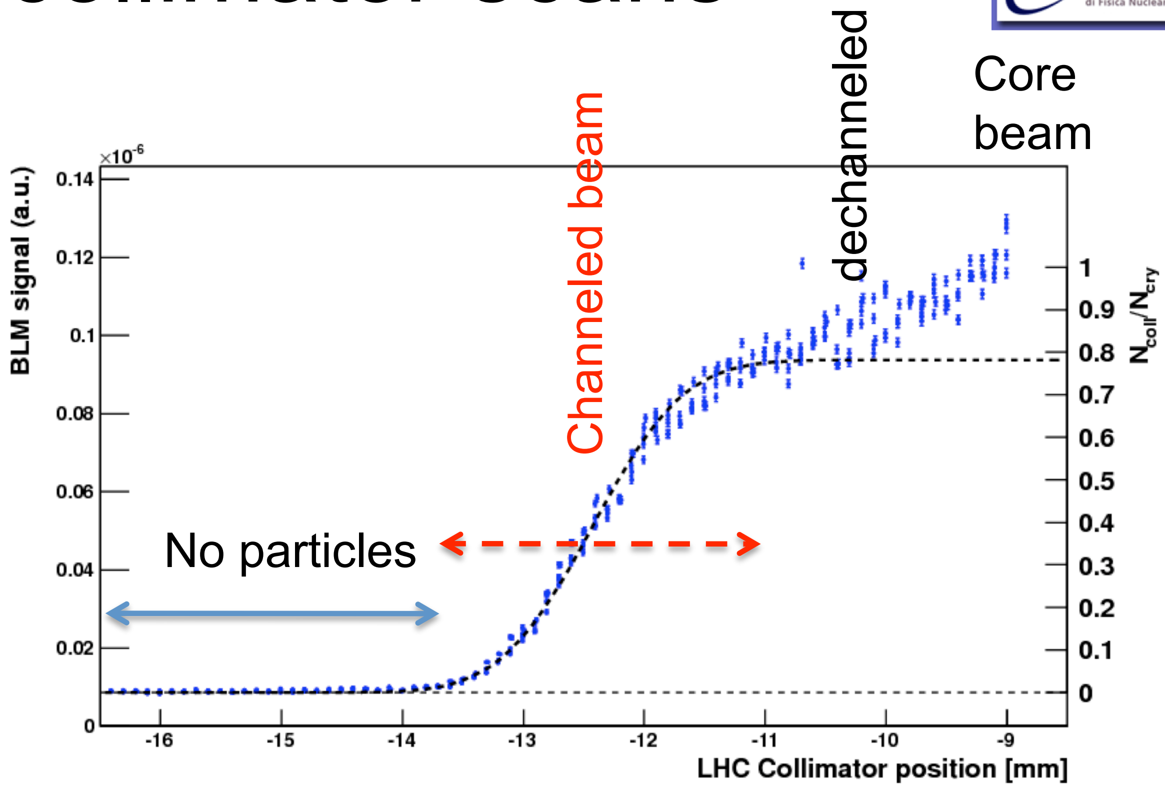


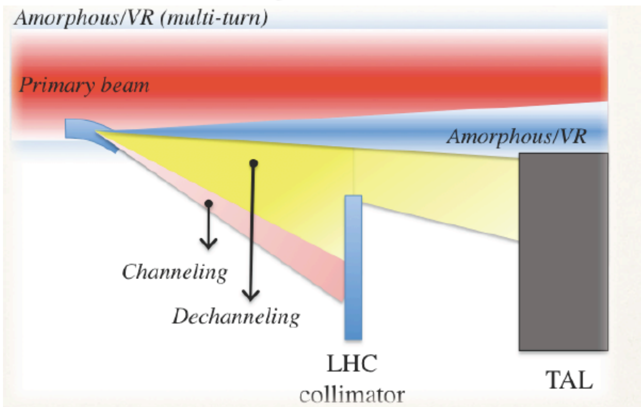
Depending on crystals 5 – 9 reduction factor (protons)
NEW: measurement also with Pb ions: 2-4 factor

Still off with respect to simulation

LHC collimator scans







Measurement of channeled beam position and width

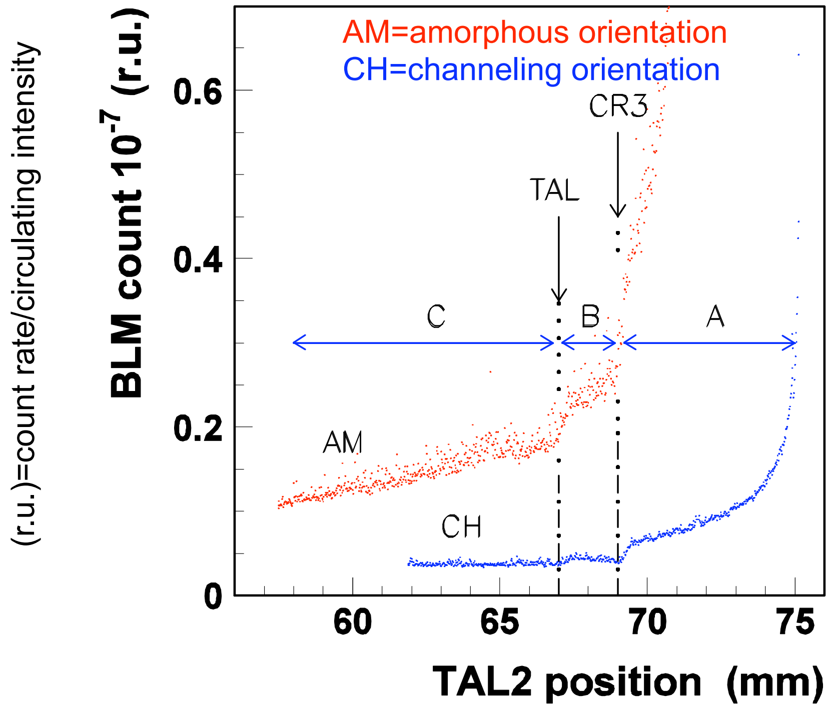
» σ_{beam} **~0.6mm**

Comparison of plateau with core beam

» **Deflection efficiency ~80%,**

Close to expectation (92% and 0.33mm)

Collimation leakage

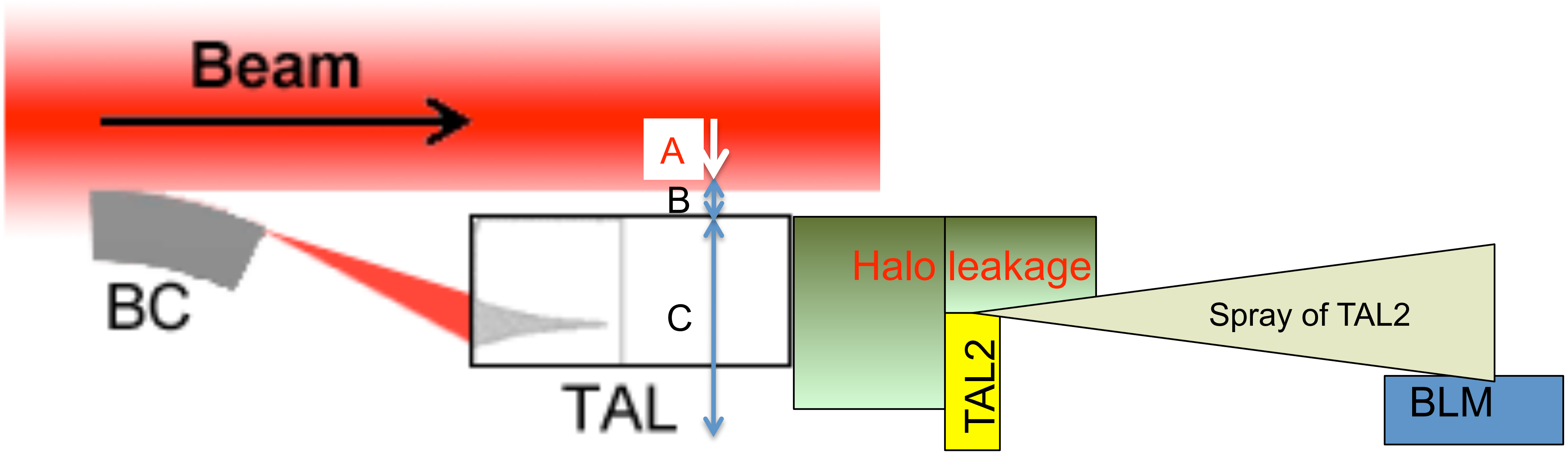


Paper in preparation

A: beam tails (off-momentum and betatronic)

B: multiple Coulomb scattering area

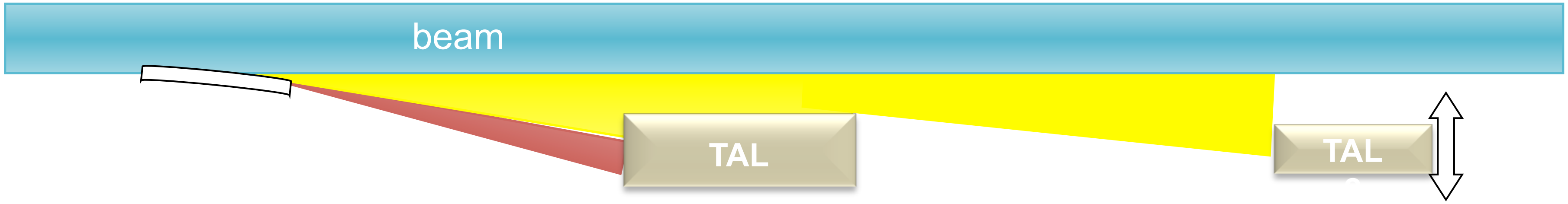
C: shadow of the TAL absorber
Reduction of TERTIARY HALO almost 5 times larger !
Better cleaning efficiency

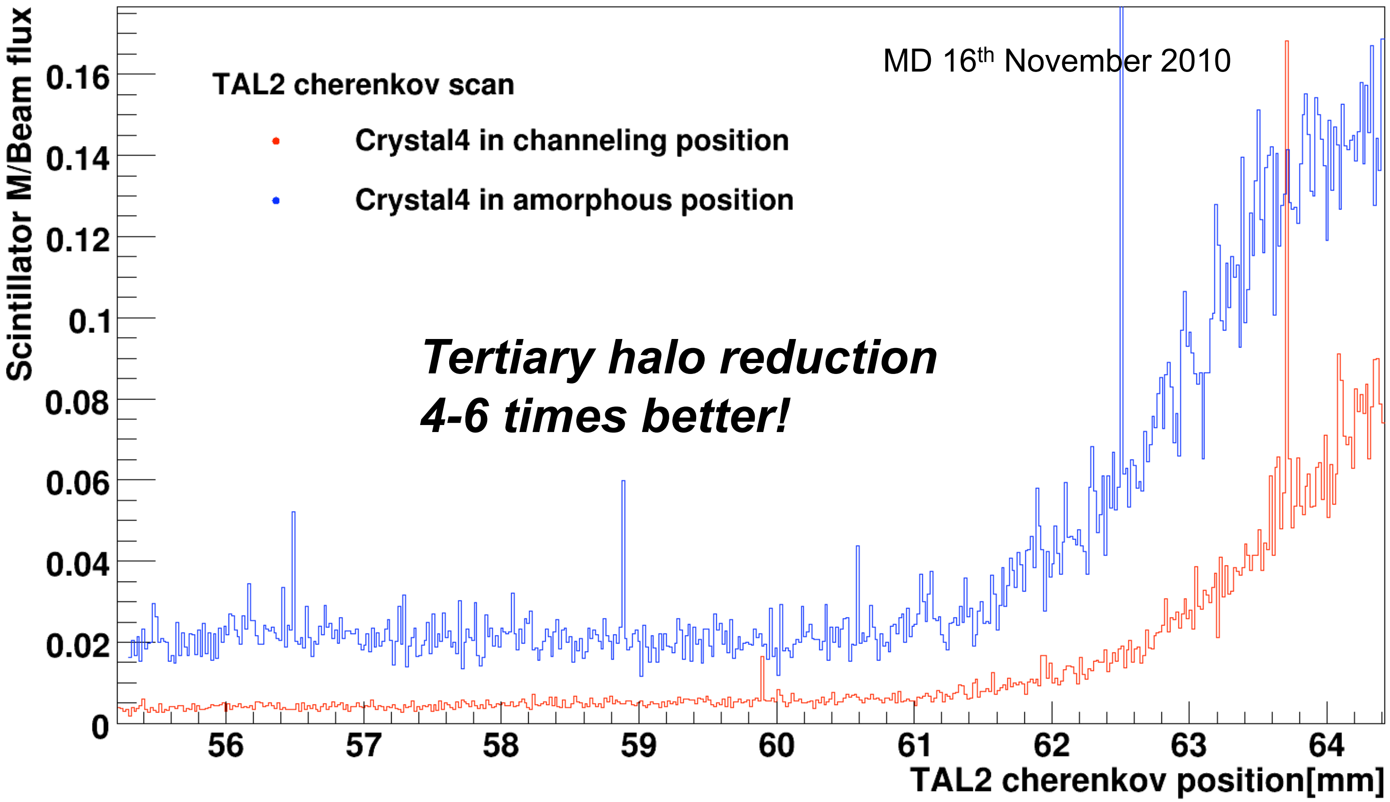


Collimation leakage with ions

Paper in preparation

Only one set of scans made by Cherenkov detector mounted on TAL2.





Summary & Outlook

Summary of 2010 SPS test

Crystal collimation works very well based on *channeling process*

Optimal crystal alignment easily detected and achieved

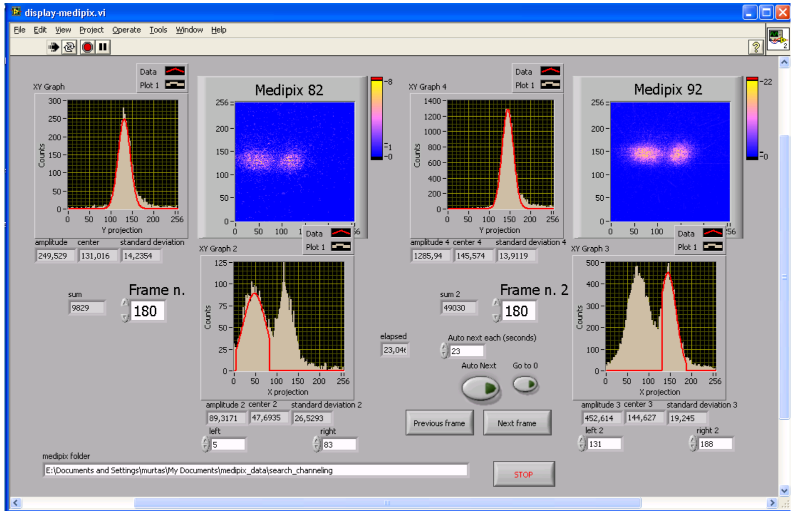
Nuclear loss rate (including **diffractive**) strongly depressed in channeling versus amorphous orientation.
Observed ***for both protons and ions***!

Estimate of cleaning efficiency of collimation region

Leakage is a factor 5 better in aligned orientation versus amorphous

Next for 2001:
Better goniometer accuracy
Thinner Cerenkov detector to resolve proton pile-up
More accurate analysis of tertiary halo [new Medipix]
disentagling betatron from synchrotron tertiary halo

Crystal test station at SPS H8



Silicon strip telescope and gas chamber
to characterize new crystals

Si, (110 plane), miscut: 22 μrad
Deflection angle: 100 μrad
size: 55x5x2 mm^3
Torsion : holder can regulate torsion within 0.2 μrad/mm

Study more exotic crystals
for different collimation scheme

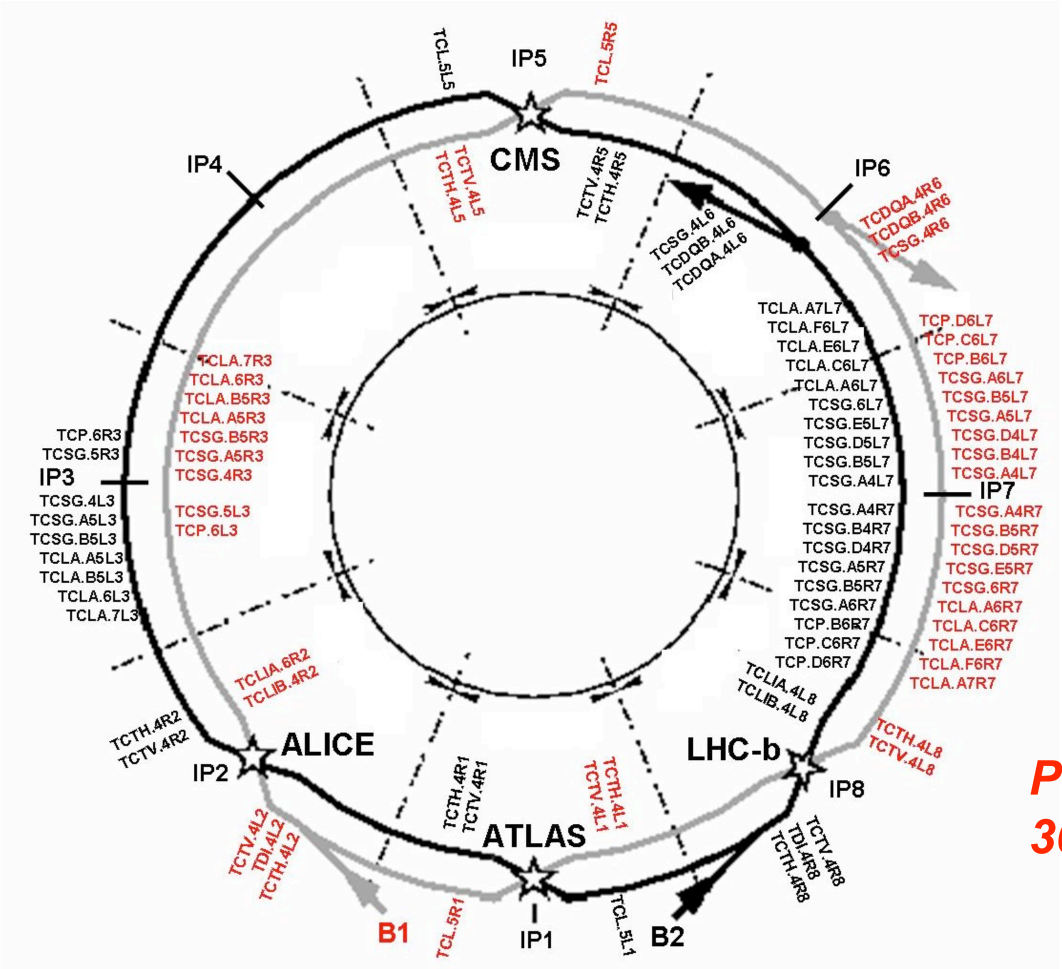
Thin Crystals

Study new particle coherent interaction effects

PXR

Study ion Pb_{82} channeling

LHC Phase 2 collimation



Overall ~150 collimator locations in LHC and transfer lines

Two warm insertions dedicated to collimation:

- IR3 **momentum cleaning**
- IR7 **betatron cleaning**

Layout has been optimized for phase 1

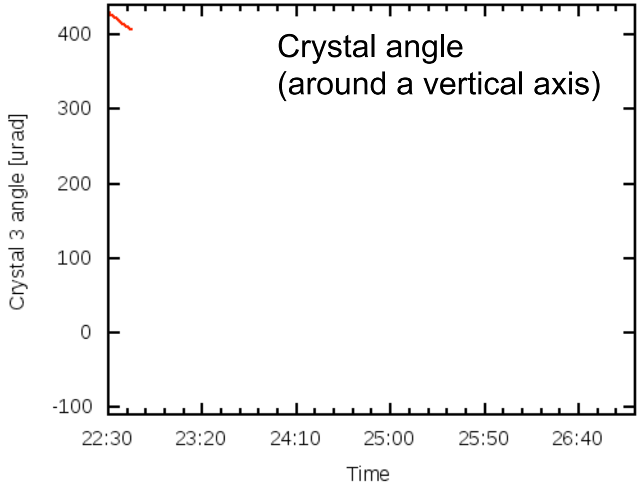
Phase 1 means 30-40% of nominal beam intensity

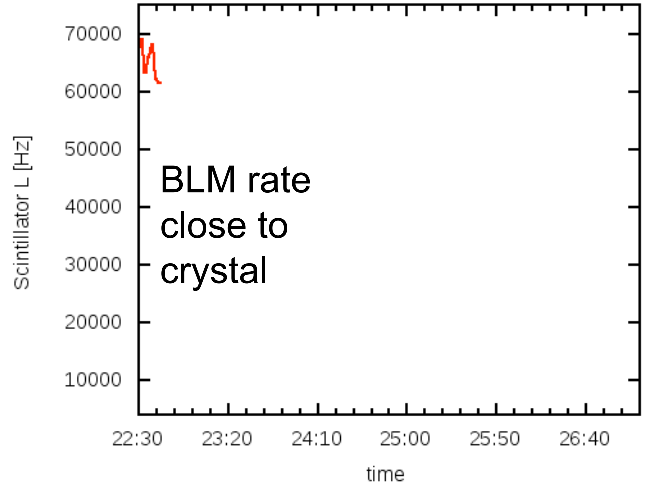
Assman. R. et al, “The final collimation system for the LHC”, EPAC 2006

Letter of Intent for LHCC in preparation

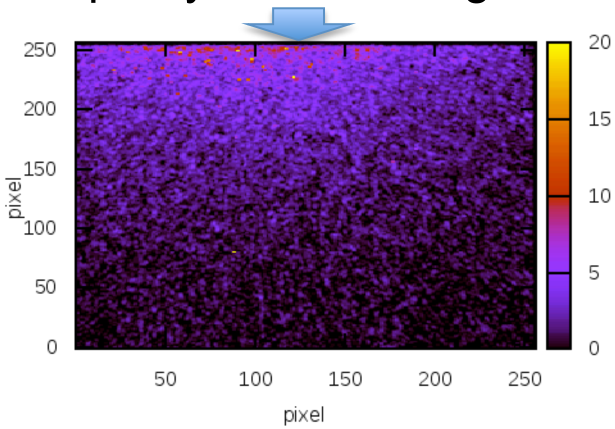
Plan is to install a crystal collimation region on LHC in 2012

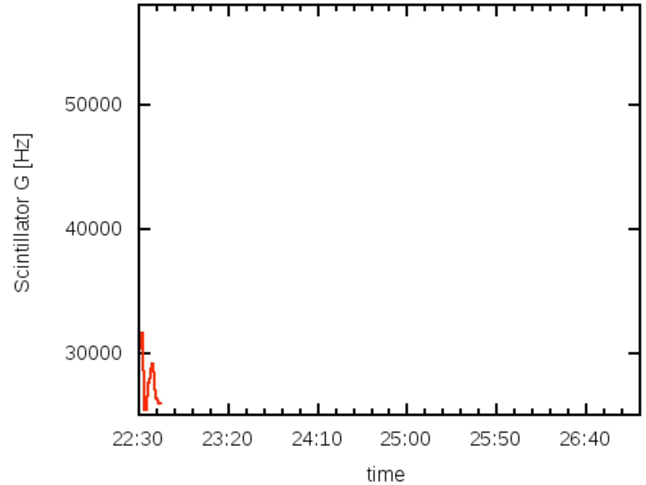
Rotating crystal in the beam





Periphery of circulating beam





Appearance of 120 GeV/c proton beam deflected by crystal channeling

Road-map for a test in LHC

Parameters	Obtained in 2009	Obtained in 2010	Required for LHC	
Channeling efficiency	75	80	90÷95	★★
Nuclear loss reduction	5	5-10	20÷30	★★
Goniometer: angular accuracy [μrad]	30÷40	10	1÷2	★
Crystal bend [μrad]	140÷150	150÷170	50÷100	★★★
Crystal torsion [μrad]	20÷30	0.1÷1 (*)	0.1÷1	★★★
Amorphous layer on crystal	About zero	About zero	About zero	★★
Collimation leakage reduction	-	5	Should be analyzed	★★

(*) On external beam test

Backup

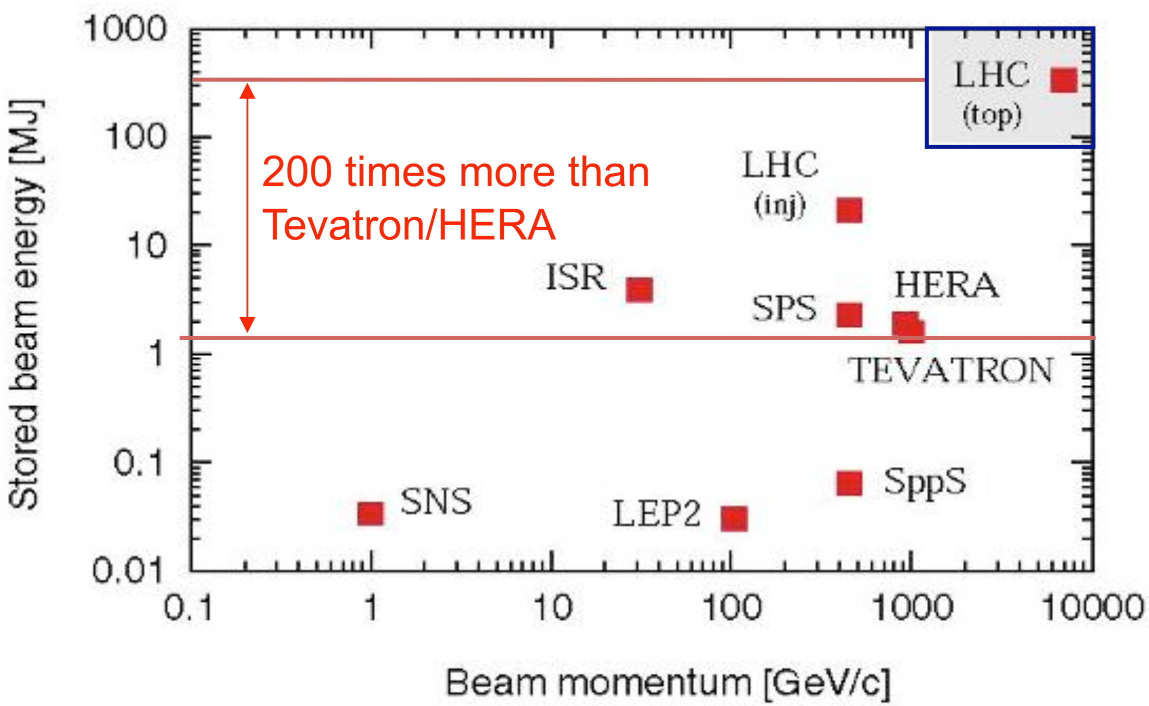
Collimation at LHC

A very energetic beam in a superconducting environment!

Stored beam energy : **360 MJ**
Quench limit for LHC magnets: **10 mJ** over **1 cm^3**

Equivalent to
90 Kg of TNT

Robustness

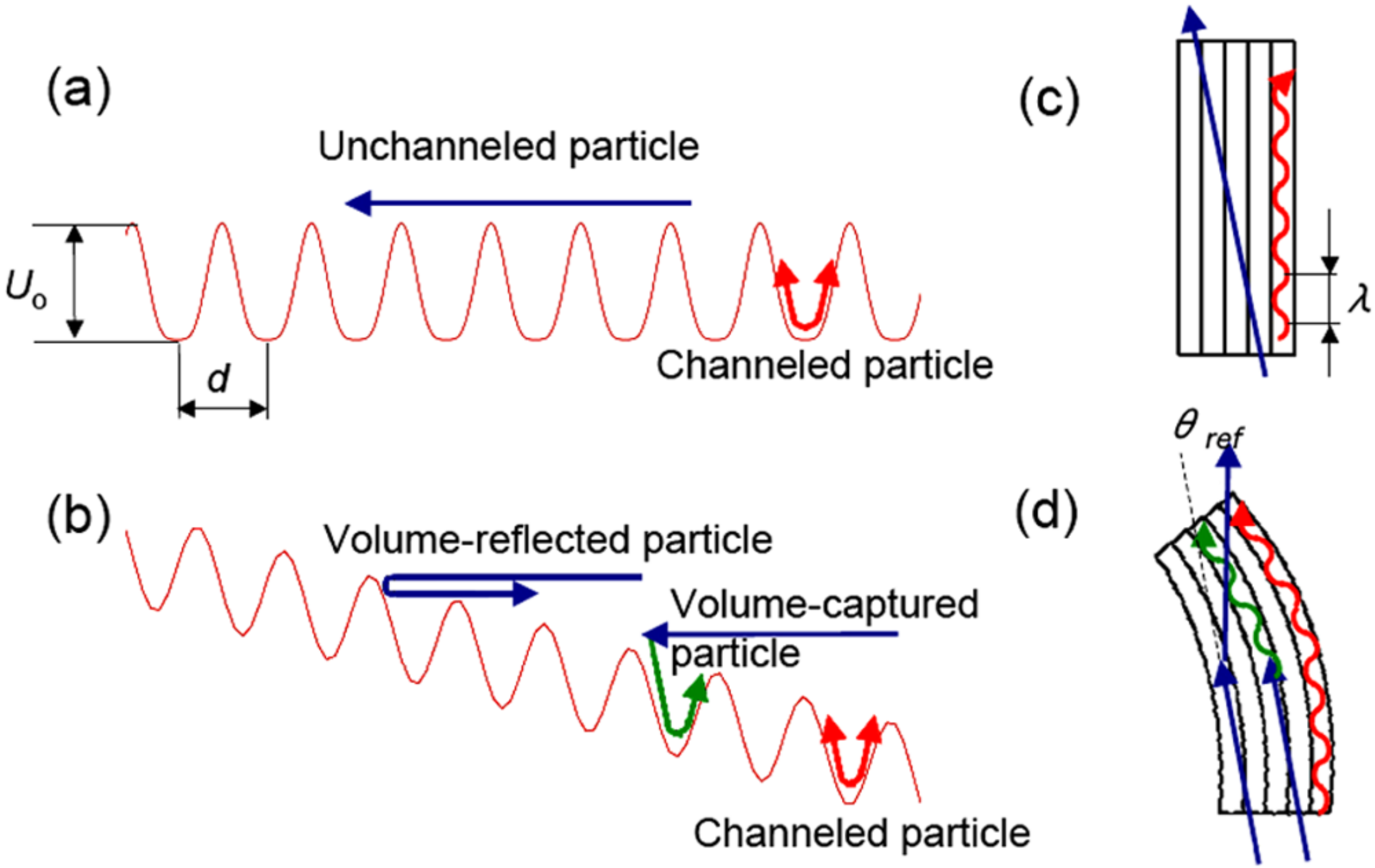


Courtesy of R. Assmann

At 7 TeV 1/50.000 proton lost makes a SC magnet quench!

Cleaning Efficiency

Other coherent interactions!

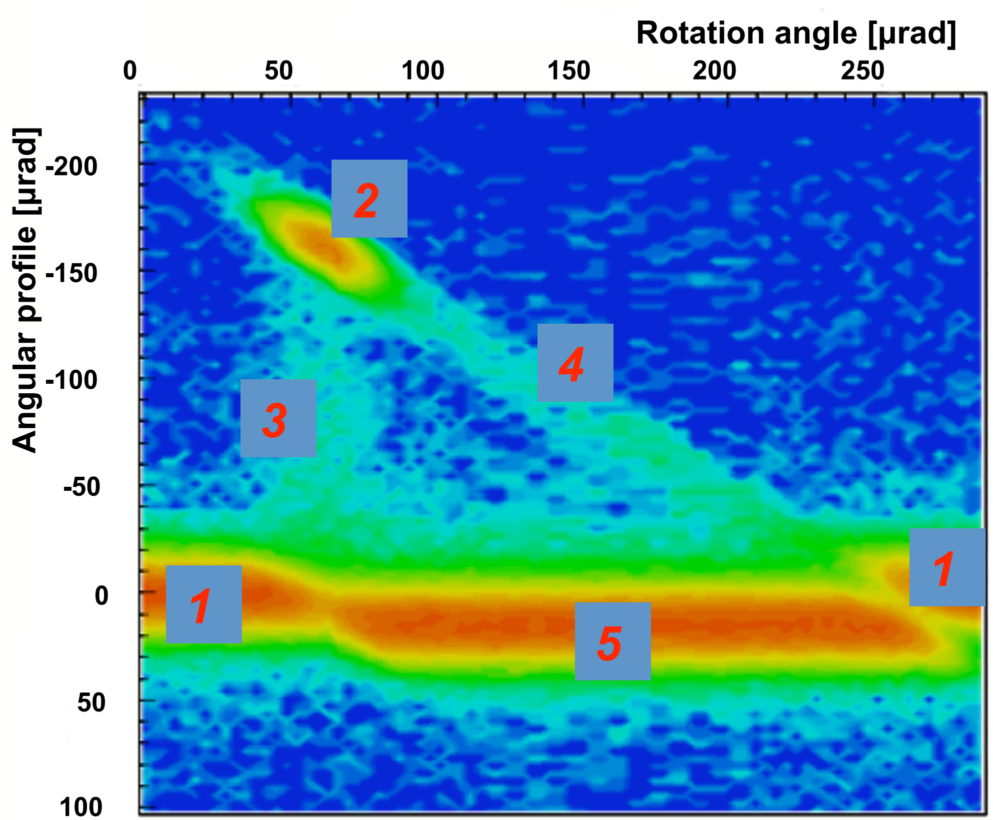


Proton coherent interactions

W. Scandale et al. PRL 98, 154801 (2007)

W. Scandale et al. PRST 11, 063501 (2008)

9mm long Si-crystal deflecting 400GeV protons



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

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

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

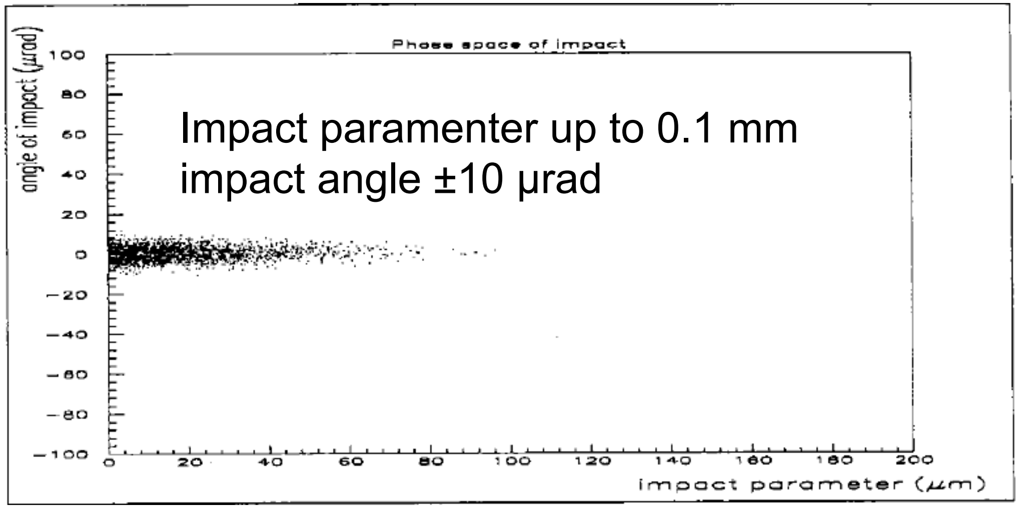
		(peak efficiency)
1 -	*"amorphous" orientation*	
2 -	*channeling*	(50 %)
3 -	*de-channeling*	(1 %)
4 -	*volume capture*	(2 %)
5 -	*volume reflection*	(98 %)

New thinner (2mm) crystal tested : channeling eff up to 80%(theoretical limit!)

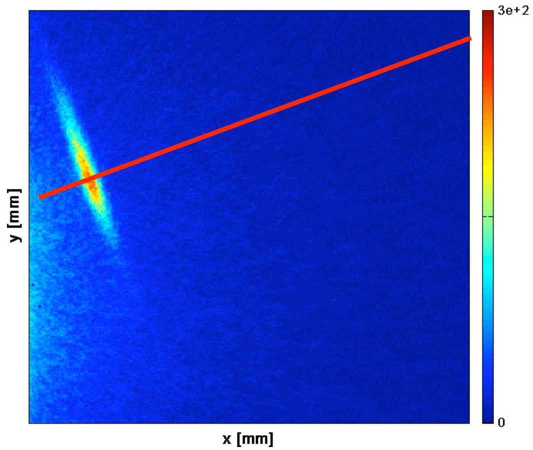
Our SPS beam

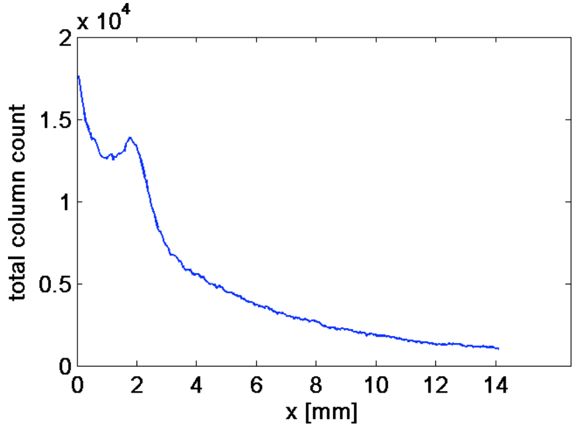
	bunched
RF Voltage [MV]	1.5
Momentum P [GeV/c]	120
Tune Qx	26.13
Tune Qy	26.18
Tune Qs	0.004
normalized emittance (at 1 σ) [mm mrad]	1.5
transverse radius (RMS) [mm]	1
momentum spread (RMS) $\Delta p/p$	4×10^{-4}
Longitudinal emittance [eV-s]	0.4

- Intensity a few 10^{10} up to a few 10^{12} circulating particles in a single bunch.
- Initial beam lifetime larger than 80 h, determined by the SPS vacuum.
- A halo flux of a few 10 to a few 10^3 particles per turn



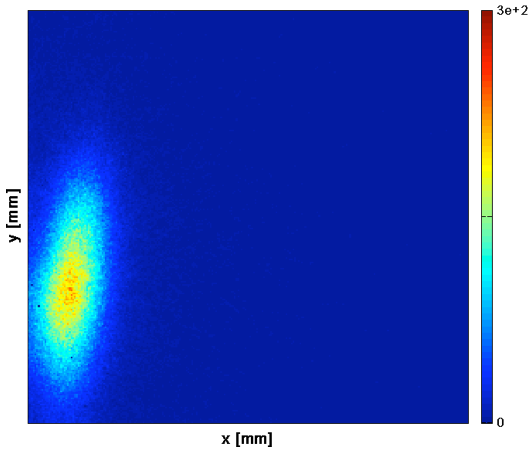
Channeled beam profiles

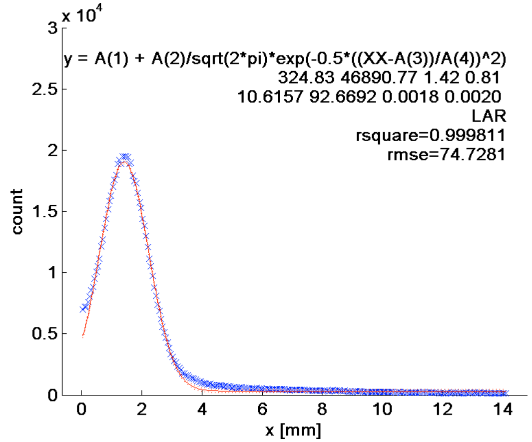




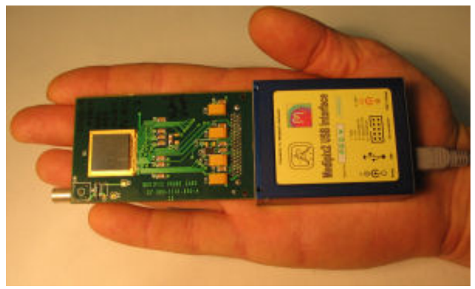
Crystal 1

The skew inclination of the extracted beam is due to the combined effect of the strip crystal residual torsion and to its quasi-axial orientation that inducing channeling by the skew crystal planes.





Crystal 2

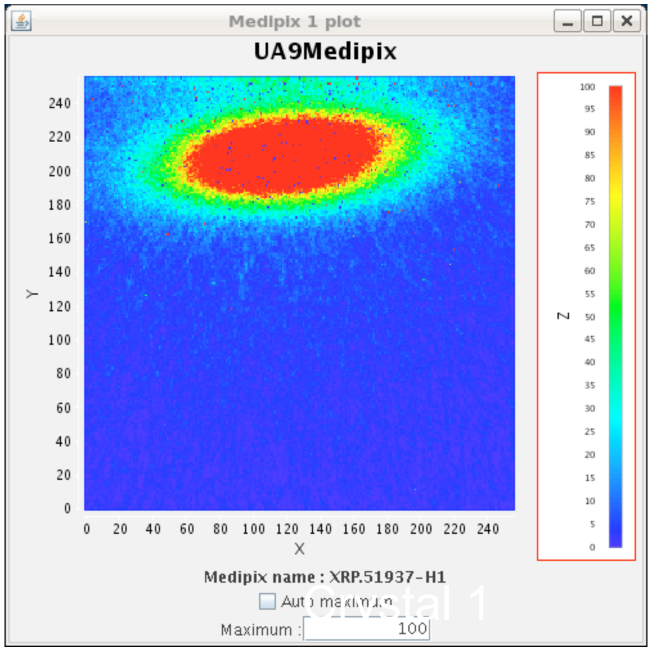


An example of Medipix detector

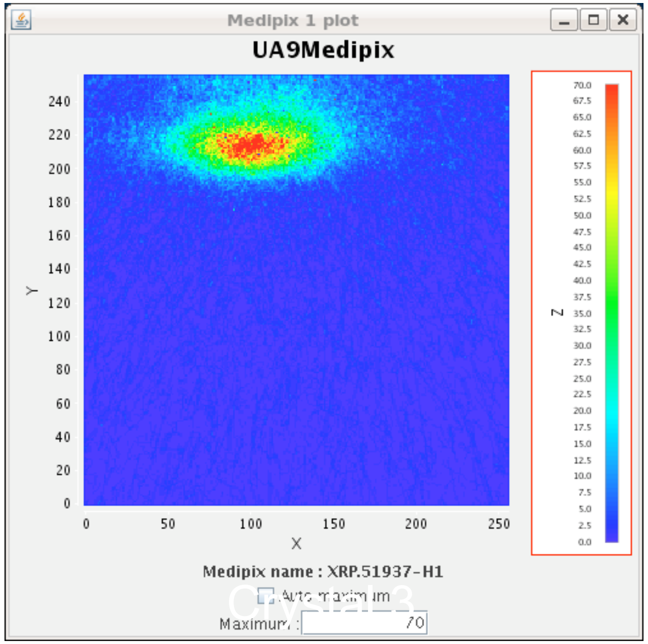
MD in SPS 2010

5 MD with protons and Pb ions

2 quasi-mosaic and 2 strip crystals being tested

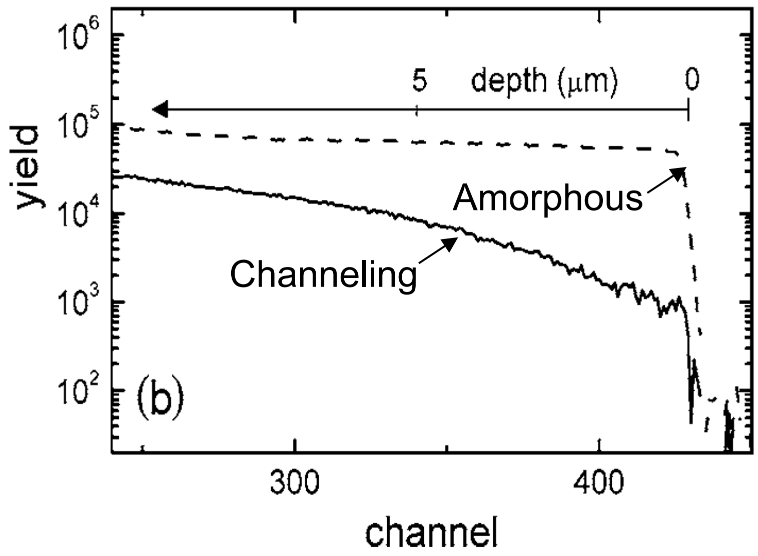


Online pictures!



Crystal characterization

Proton backscattering yield as a function of depth.



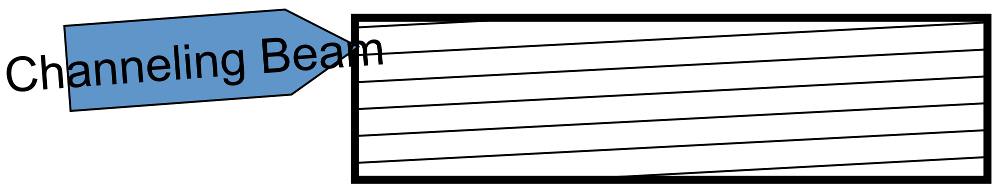
INFN LNL

Backscattered protons are proportional to non-channeled particles.

Inefficiency (χ) can be measured as a function of depth.

At low energy, inefficiency is very sensitive to nuclear scattering and defects.

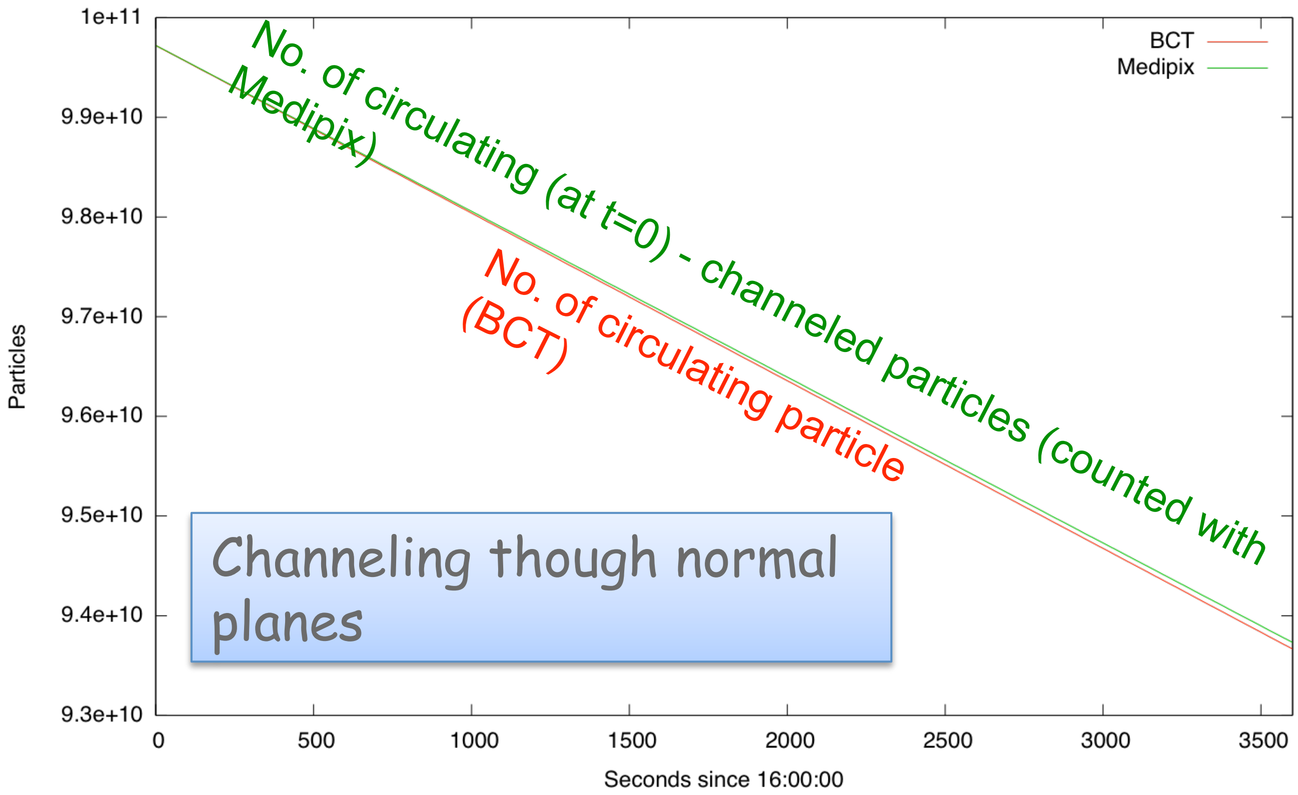
Miscut angle measured at 30 μrad



High Resolution scan around X-Ray Bragg Diffraction of crystalline planes.

Find lattice defects: plane deformation on crystal surface

Collimation efficiency with beam profiles



Multi-pass channeling efficiency very large -> compatible with 100%

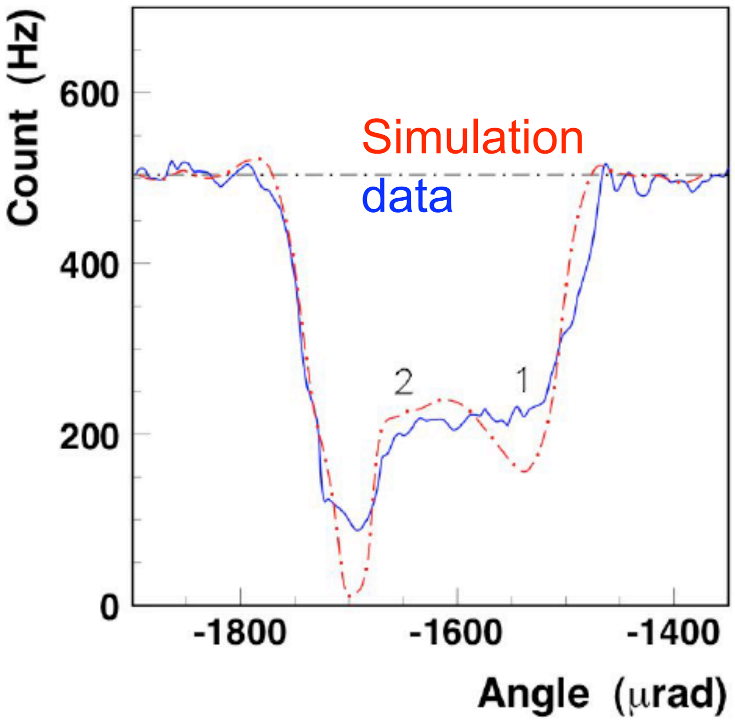
Measured efficiency ≥ 86 %

20 % uncertainty due to BCT and MEDIPIX calibration

large ClosedOrbit glitches ≥ 200 mm every a few tenth of seconds during the data taking

SPS 2009 results

W. Scandale et al. / Physics Letters B 692 (2010) 78–82)



Inelastic interaction rate close to crystal (strip, #1)

Depression in channeling mode not completely described by MC (x5 vs. x50)

Crystal vertical torsion not compensated

RD22 goniometer unstable

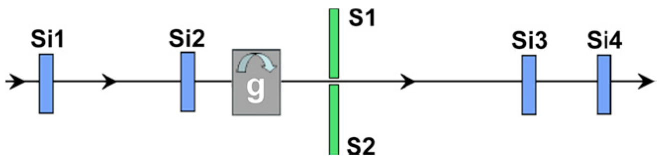
Deflection efficiency for crys 1 and 2 : (75±4)% and (85±5)%

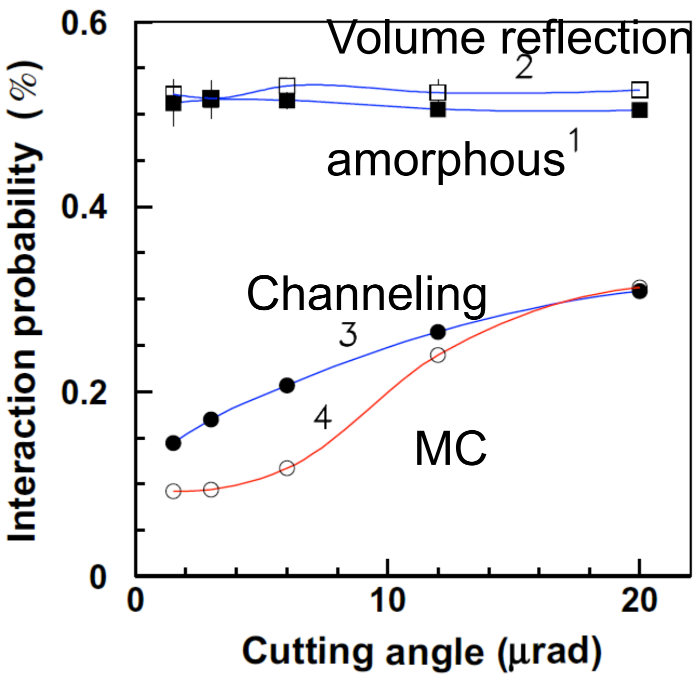
But large variation in different scan [alignment errors]

Inelastic rate in channeling mode: H8 beam results

W.Scandale, et al., NIMB 268 (2010) 2655–2659

Experimental set-up



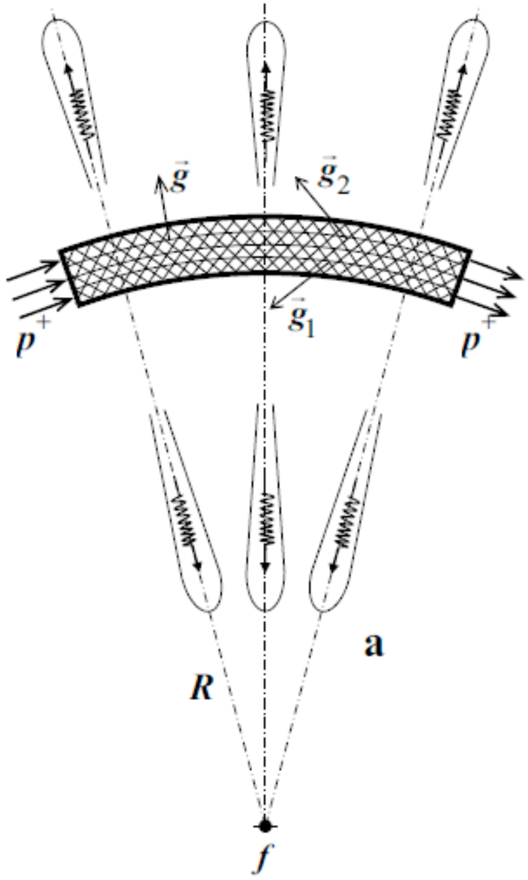


Select event with incident angle smaller than a given ***cutting angle.***

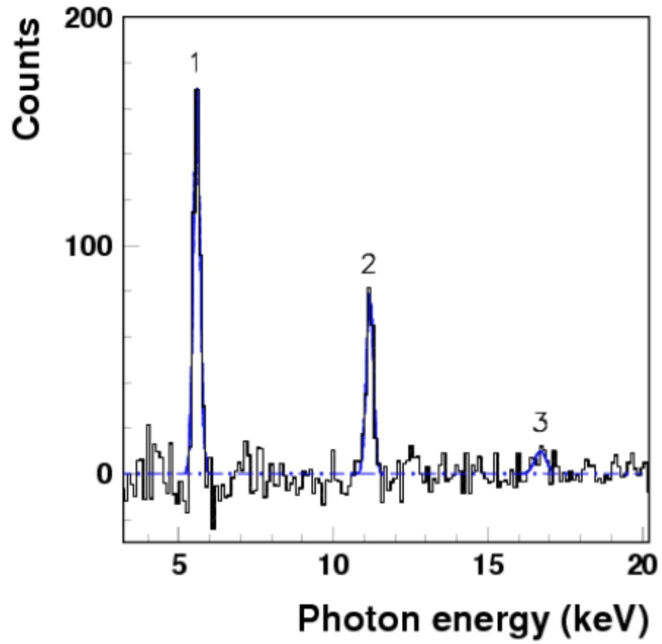
Count events with hit on S1 & S2

Probability of inelastic interaction in channeling vs amorphous is 3-4 times smaller!

Parametric X Radiation

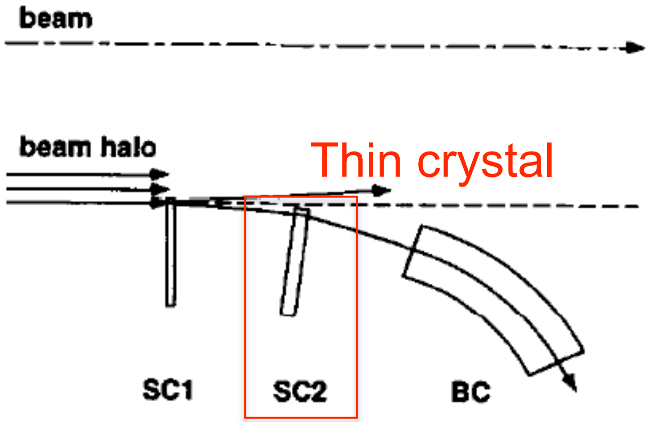


- Bragg diffraction of virtual photon of charged particles on lattice planes

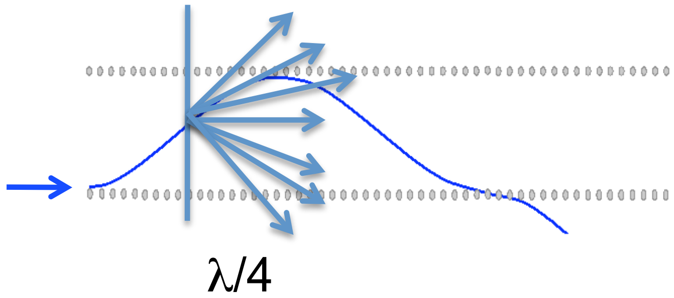


- Observed at H8 (paper sub to PLB)
- Can be used to monitor
  the curvature of the crystal

Thin crystals



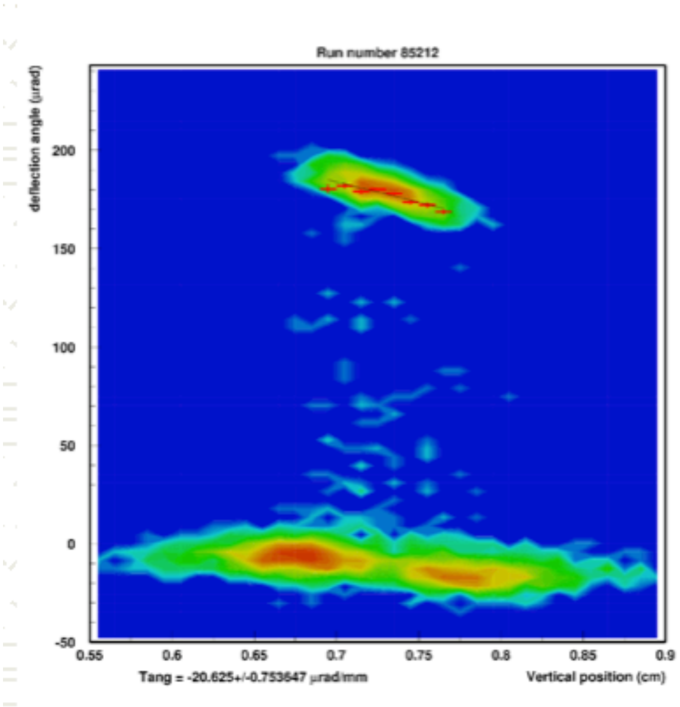
E. Tsyganov , A. Taratin,
NIMA 363, (1995)
511-519

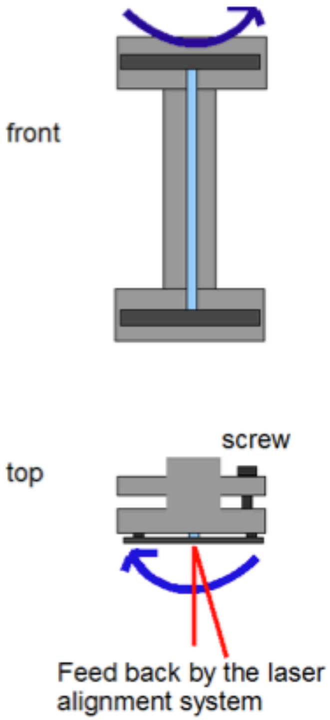


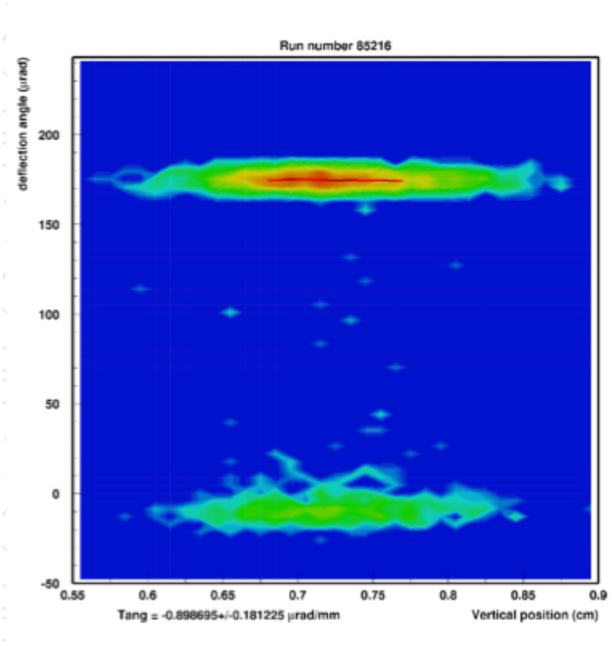
– Special 10-30μm thin crystal (λ/2 or λ/4): they act as ***scatterer*** or mirror

- improve problem of imperfect surface layer of bent crystal (BC)

Torsion removal







Critical to reach good uniformity along the crystal height

2010 ang. scan results

Protons Crystal	Apertures		Reduction factor			
	Cr[σ]	TAL[σ]	Sci L	Cerenkov A	GEM 1	BLM 4
3	5.7	7.2	5.8±0.6	3.3±0.3	4.1±1.0	4.5±0.3
4	7.1	8.6	8.2±0.8	2.8±0.1	6.9±0.3	7.3±0.3
3	6.2	5.9	5.5±0.8	4.3±0.4	3.9±0.2	5.8±0.8
3	6.2	5.9	7.4±1.7	5.7±0.4	5.1±0.3	8.1±0.9

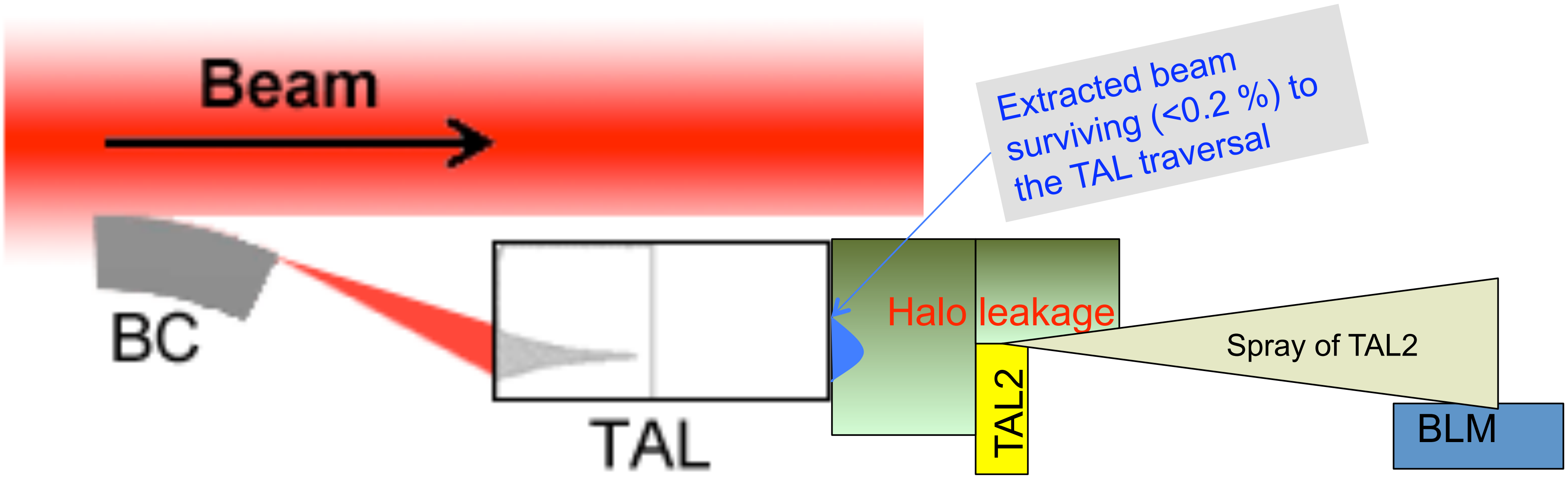
Ions Crystal	Apertures		Reduction factor BLM4
	Cr[σ]	TAL[σ]	
3	5.7	8.4	1.9 ± 0.2
3	5.7	9.3	1.9 ± 0.2
4	4.0	5.7	3.5 ± 0.4
4	5.2	7.4	3.7 ± 0.6

LHC collimator scans

protons Crystal	Deflection angle [μrad]	Sigma [μrad]	Channeling efficiency
3	178	29	69 %
3	186	25	67 %

ions Crystal	Deflection angle [μrad]	Sigma [μrad]	Channeling efficiency
3	199	24	74 %
3	199	26	68 %
3	226	33	69 %
3	198	24	53 %
3	146	41	45 %

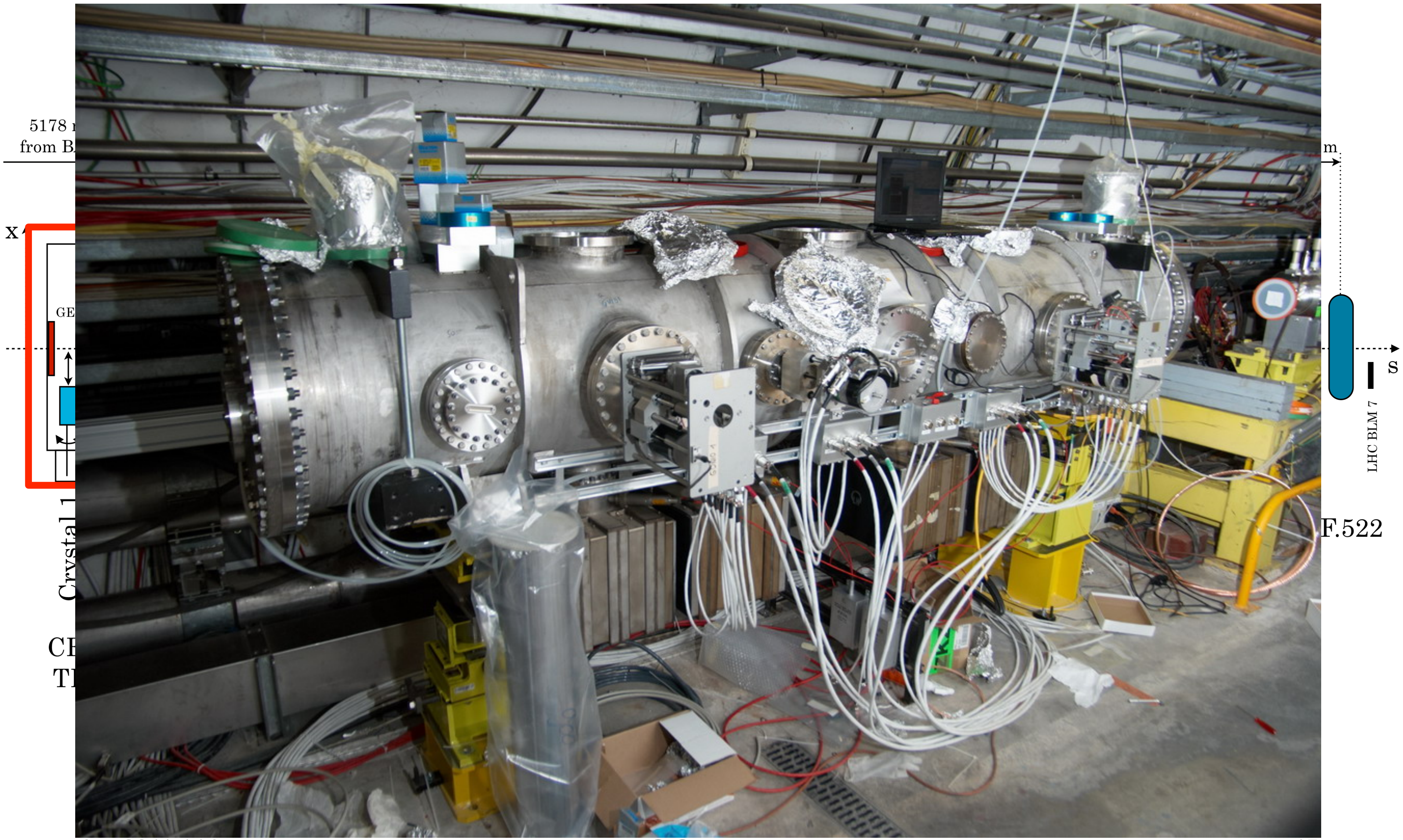
A model for the leakage



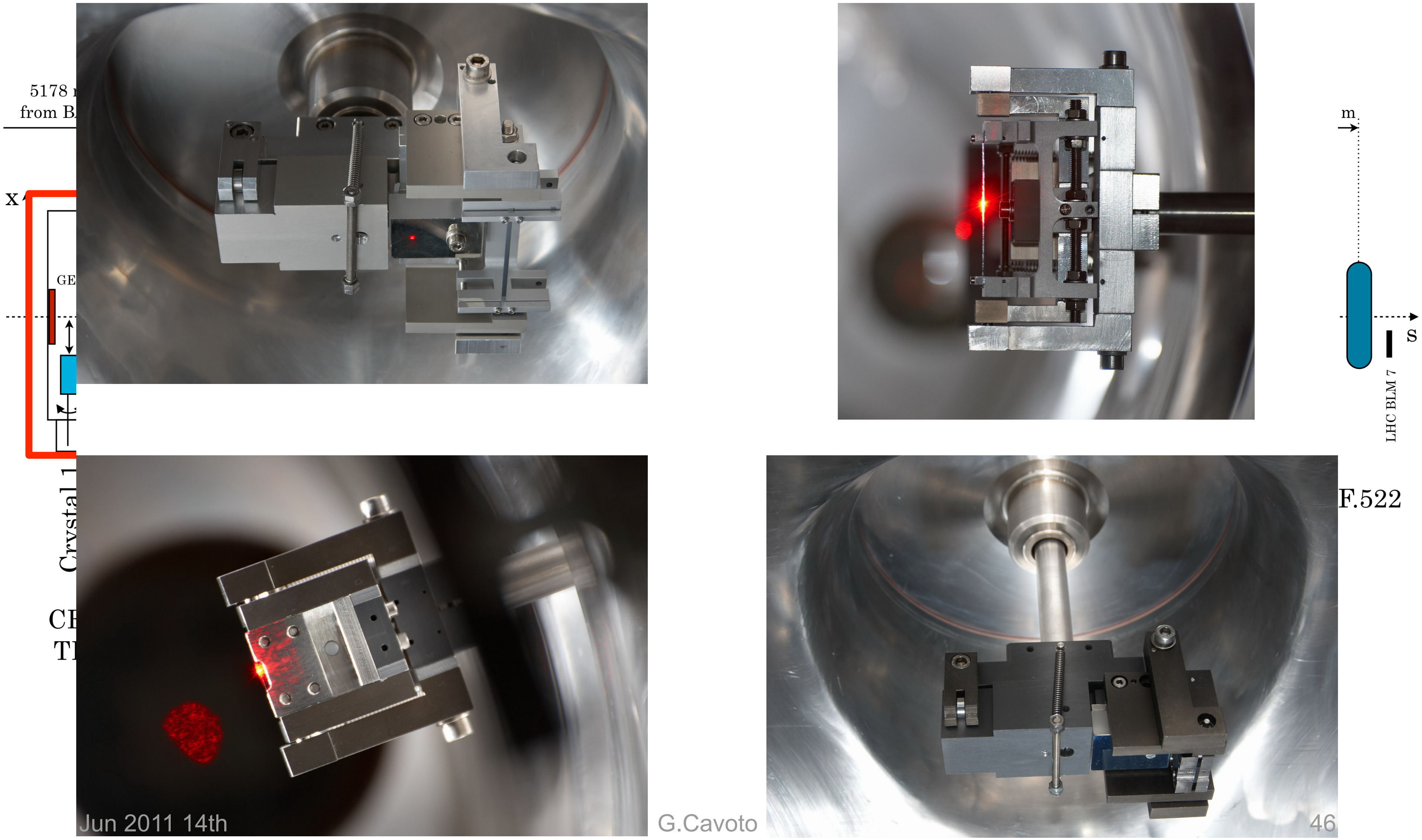
Need a more detailed simulation to compare with data

Need more data with larger range scan

UA9 layout

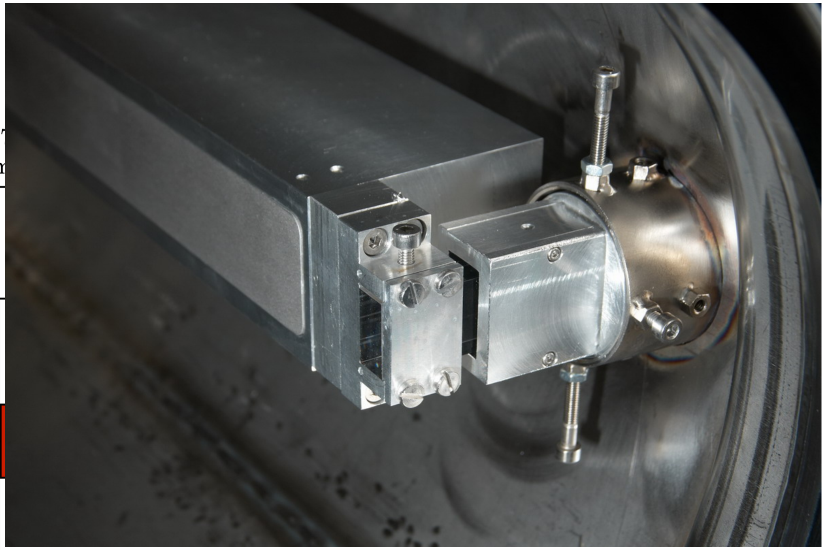


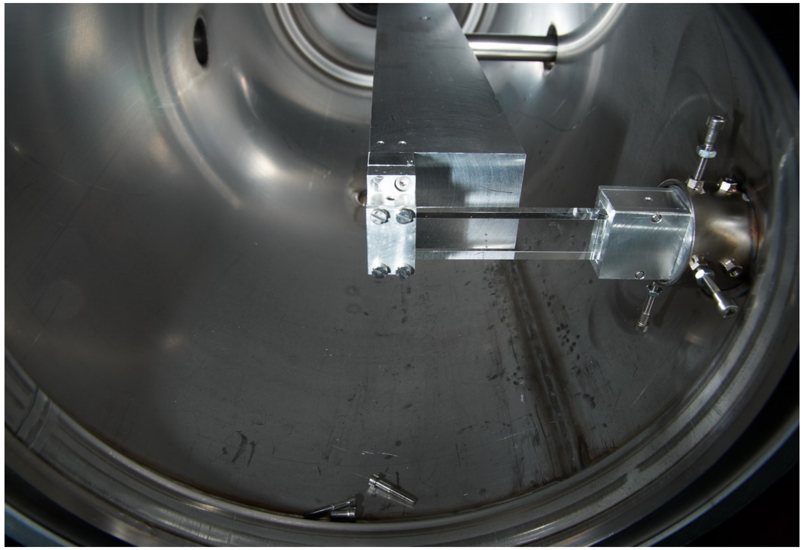
UA9 layout



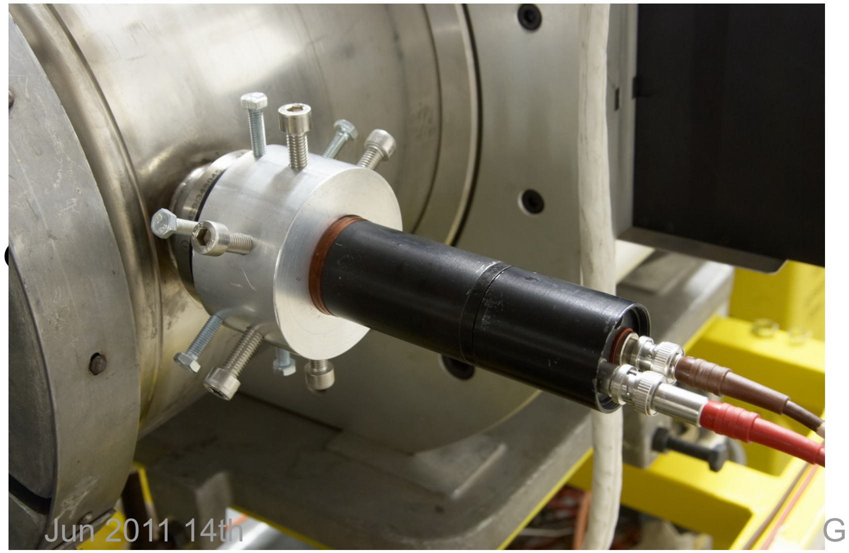
UA9 layout

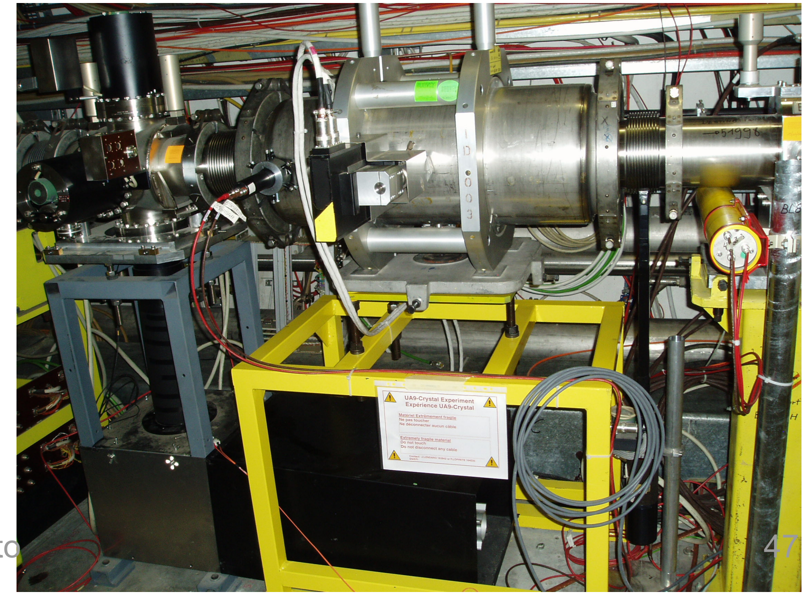
51
from
x



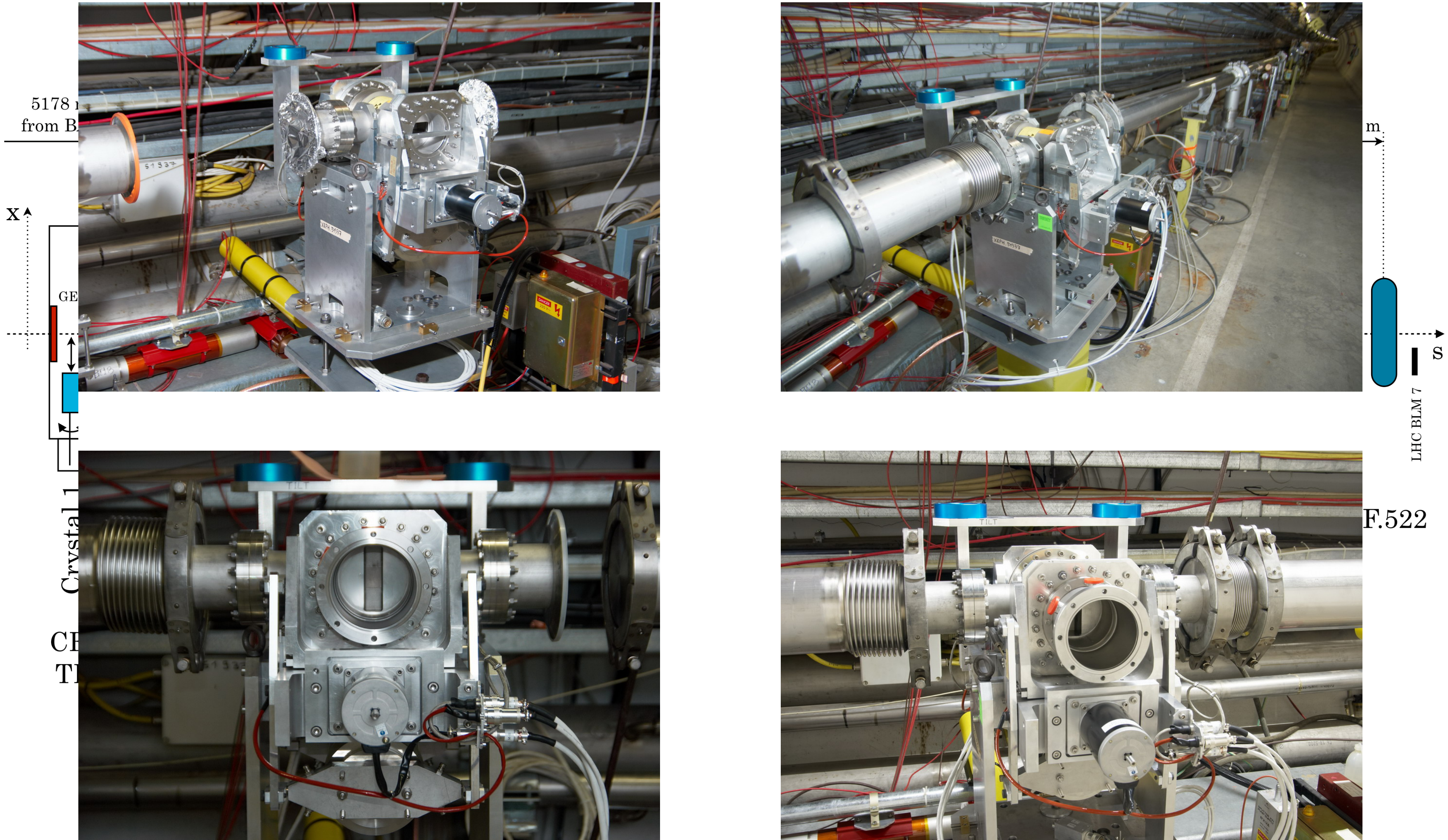


s
LHC BLM 7
.522

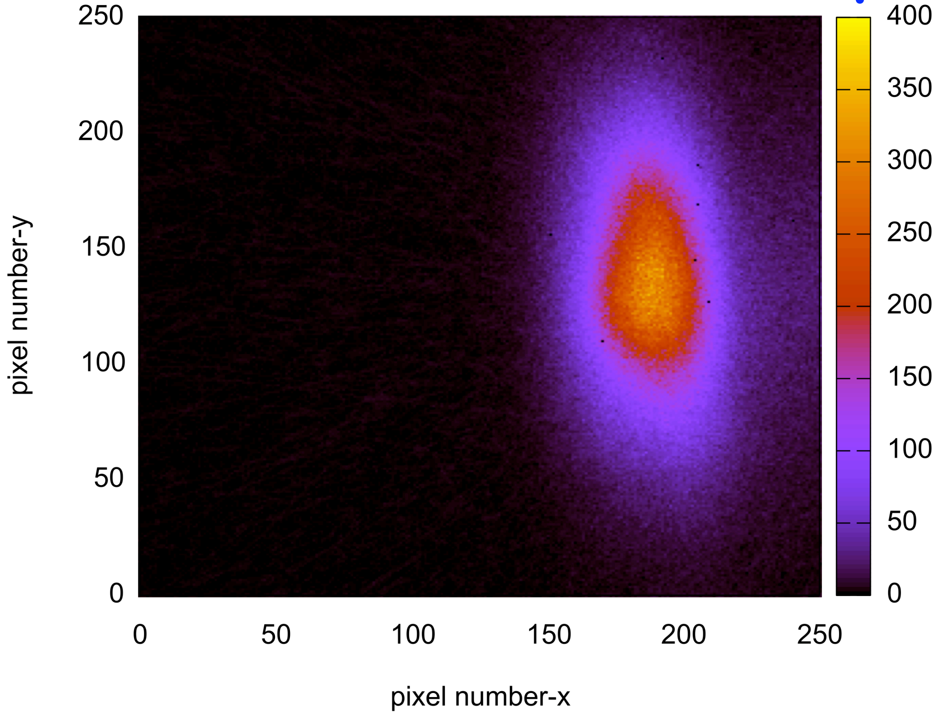


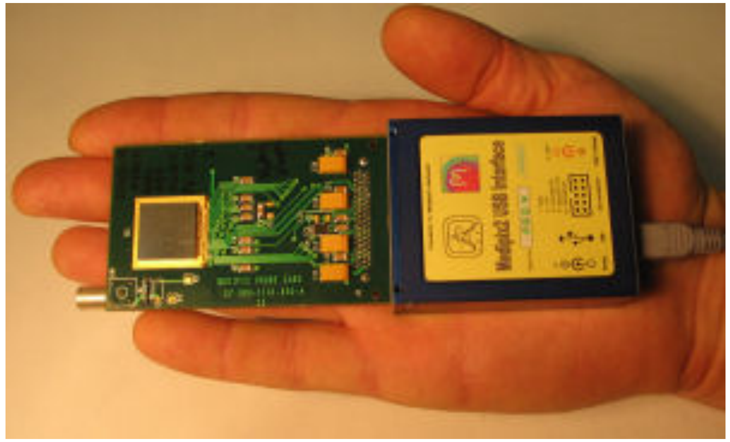


UA9 layout



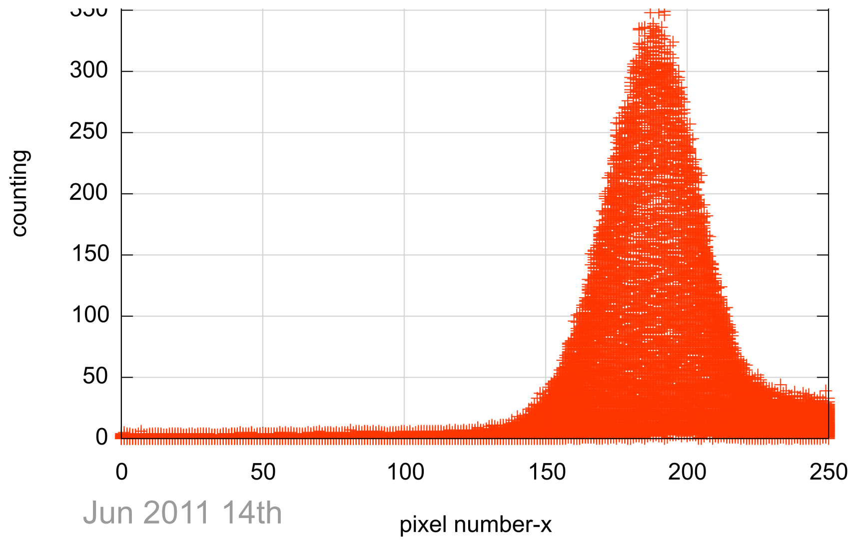
Deflected beam profile with medipix





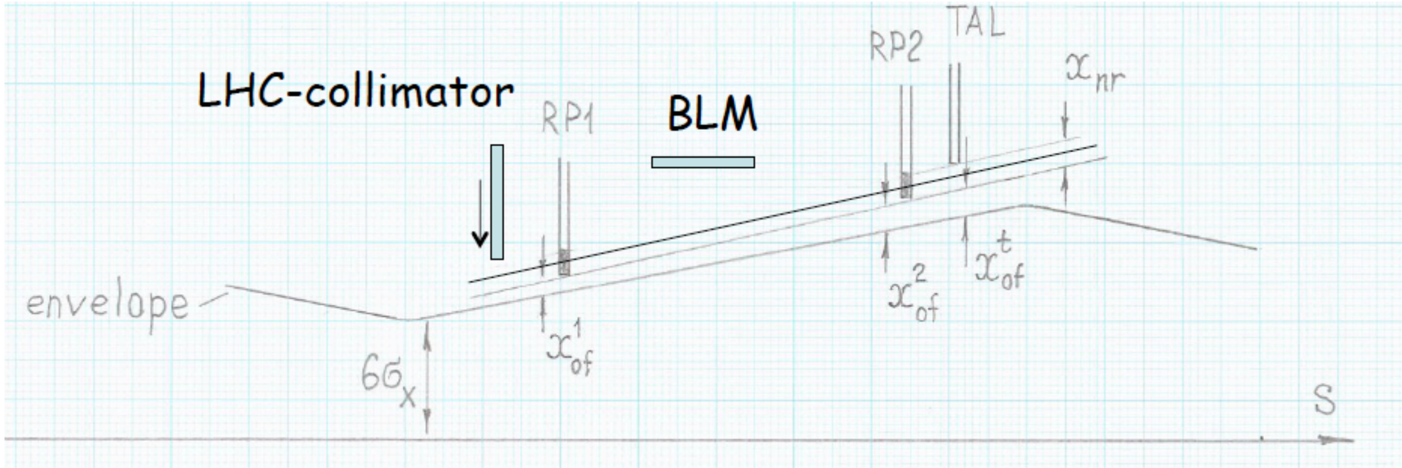
Medipix sensor of the type inserted in the UA9 roman pot,
provided by L. Tlustos (PH/ESE)

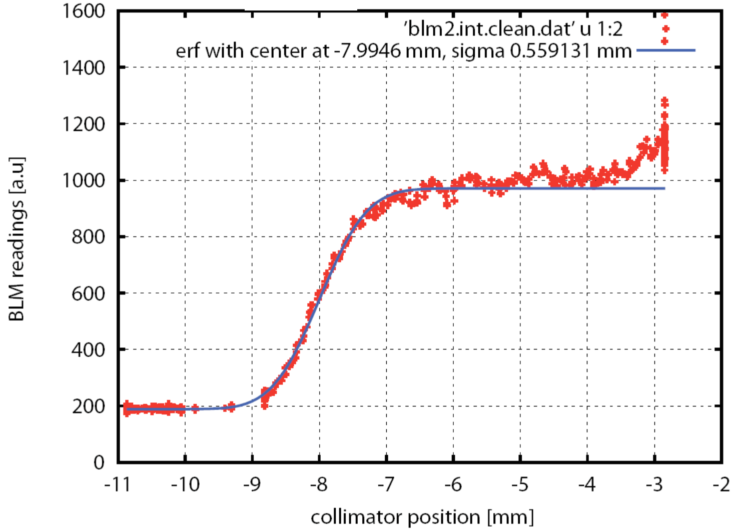
- 256×256 square pixels
- 1 pixel size = 55 μm
- 1 frame integration time 1 s

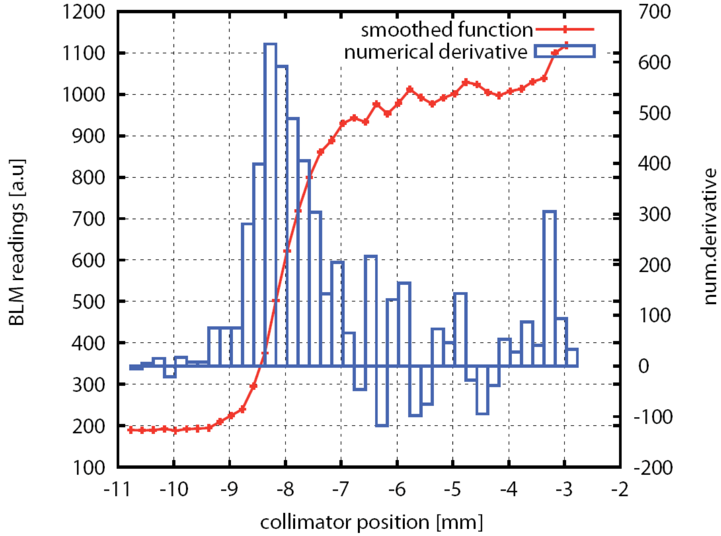


- Pick/valley density ratio = 10
- We observed a ratio of 30 (recording lost for a computer crash)

crystal collimation efficiency using the LHC-collimator

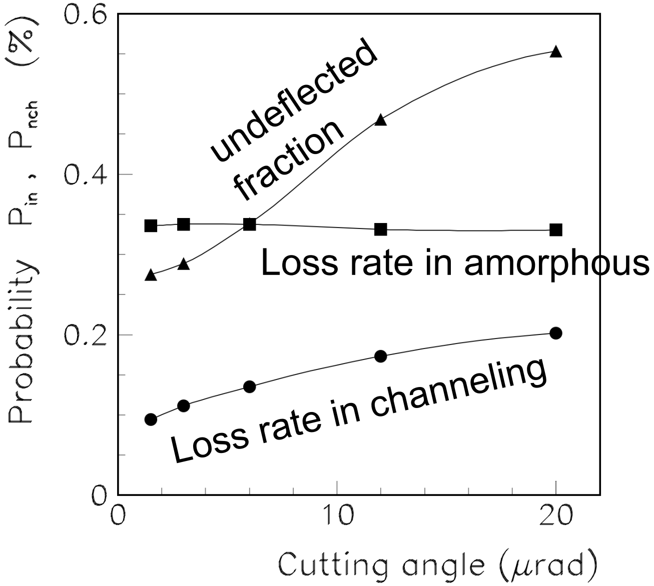


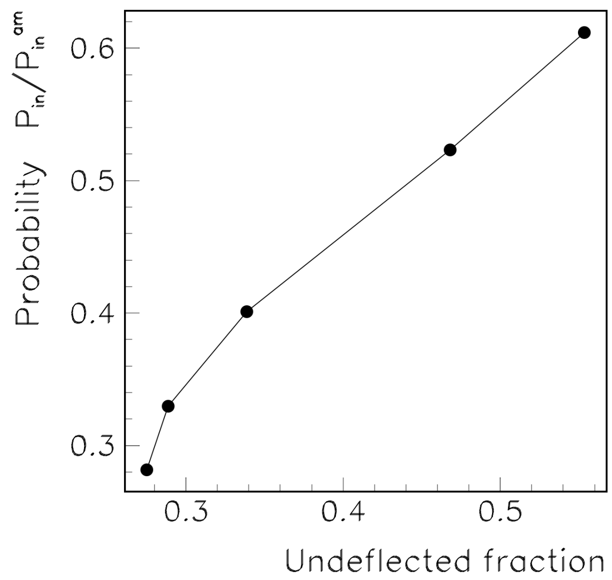


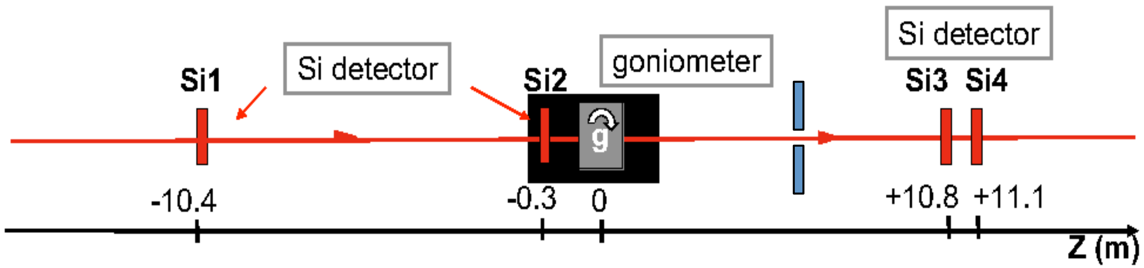


nuclear rate in H8

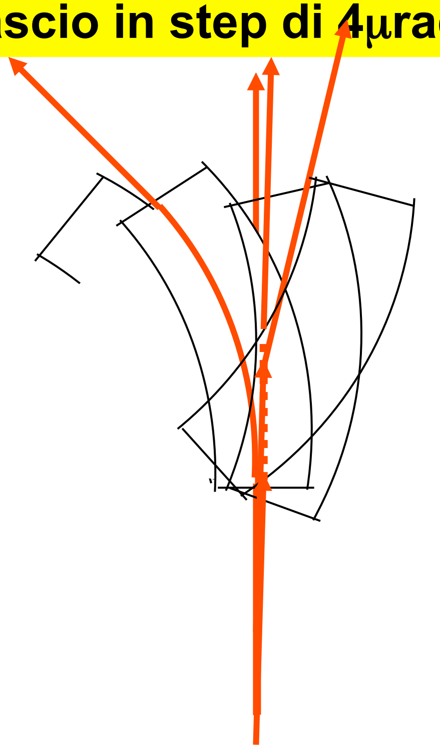
- *Nuclear loss rate* (including diffractive) strongly depressed
  - In channeling versus amorphous mode : × 5 in multi-turn (SPS) and × 3 in single-pass (NA)

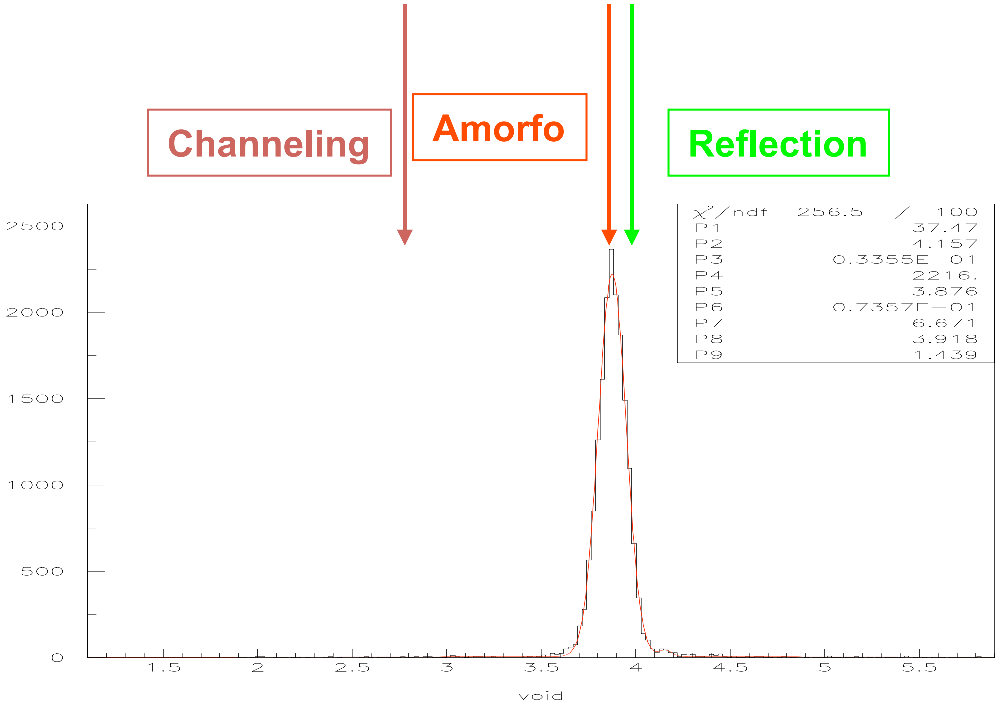






Profilo orizzontale del fascio osservato a circa 70m dal goniometro variando l'orientazione del cristallo rispetto al fascio in step di 4μrad





cm

INTENSE PRODUCTION OF e+e- PAIRS WITH RADIATION FROM CRYSTALS

- **SUMMARY & CONCLUSIONS**
- *** The hybrid source using the intense radiation from an axially oriented crystal to create a large number of e+e- pairs in an amorphous converter placed at some distance is very promising for the yield, the phase space and above all for the reduced PEDD.**
- *** Such a system has been chosen as the baseline for CLIC**
- *** Further studies of the hybrid source may concern the thermal behavior, particularly for the fast energy deposition**
- *** Systematic tests are being operated at KEK; results on the e+ yield and enhancement are already available. Thermal observations are under development.**