Status of UA9, the crystal collimation experiment at the CERN-SPS

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CERN – IHEP - Imperial College – INFN – JINR – LAL - PNPI – SLAC

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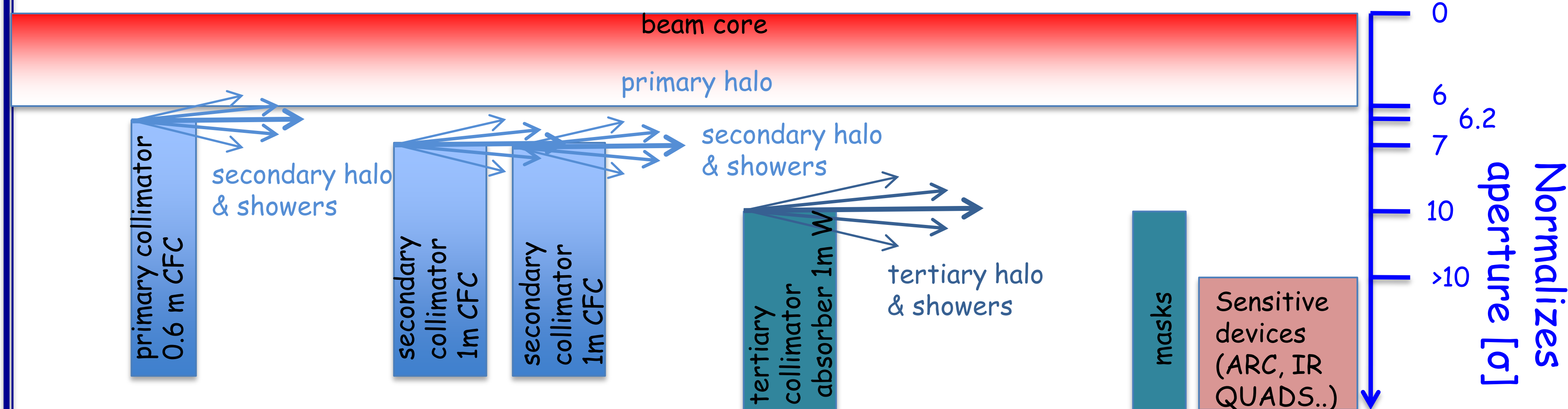
Multi stage collimation as in LHC

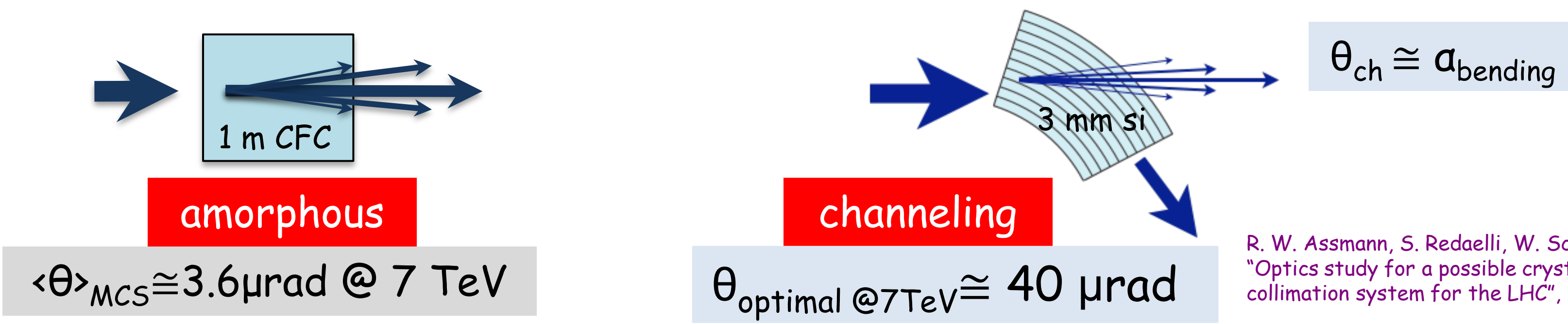
- The halo particles are removed by a cascade of amorphous targets:
  1. Primary and secondary collimators intercept the diffusive primary halo.
  2. Particles are repeatedly deflected by Multiple Coulomb Scattering also producing hadronic showers that is the secondary halo
  3. Particles are finally stopped in the absorber
  4. Masks protect the sensitive devices from tertiary halo



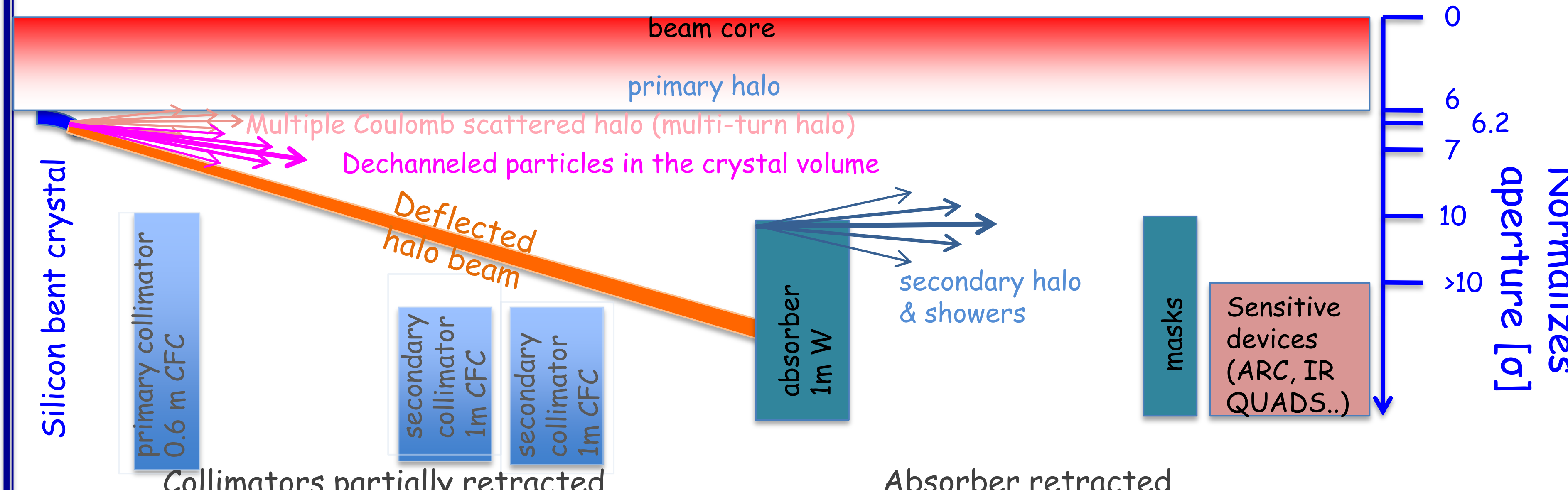
- Collimation efficiency in LHC ≅ 99.98% @ 3.5 TeV
  - ✓ Probably not enough in view of a luminosity upgrade
  - ✓ Basic limitation of the amorphous collimation system
    - p: single diffractive scattering
    - ions: fragmentation and EM dissociation

Crystal assisted collimation

- **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



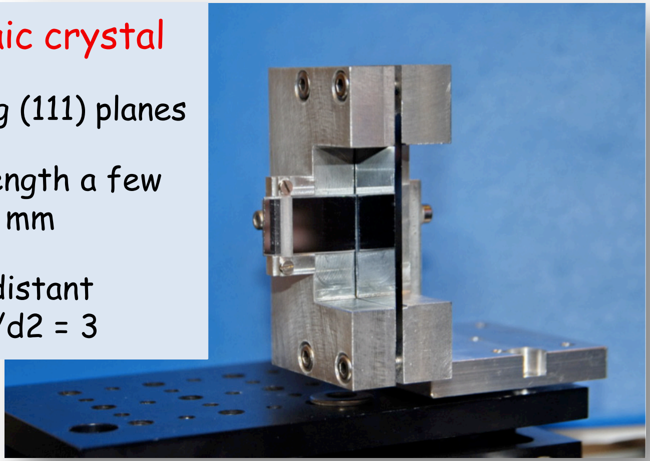
Potential improvements

1. <u>Larger impact parameter:</u> crystals deflect the halo particles coherently to a larger angle than the amorphous primary collimator,
   - ✓ better localization of the halo losses
   - ✓ reduced collimation inefficiency ➔ $\times 10^{-1}$ expected in LHC from simulations
   - ✓ higher beam intensities (if limited by halo density)
2. <u>Less nuclear events:</u> inelastic nuclear interactions with bent crystals strongly suppressed in channeling orientation
   - ✓ reduced loss rate in the vicinity of the crystal
   - ✓ reduced probability of producing diffractive events in proton-crystal interactions
   - ✓ reduced probability of fragmentation and e.m. dissociation in lead ion-crystal interactions
3. <u>Less impedance:</u> reduced amount of material in the beam peripheral
   - ✓ optimal crystals are much shorter than the amorphous primary collimators
   - ✓ primary and secondary collimators are in more retracted positions

Crystals to assist collimation

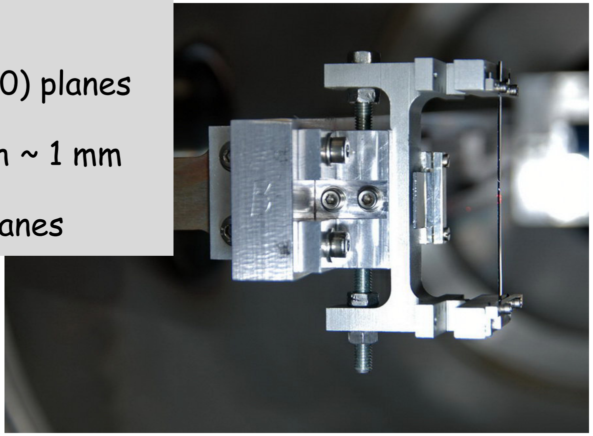
Quasimosaic crystal

- 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

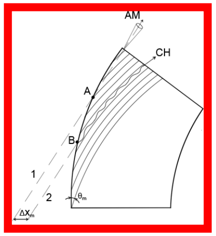


Crystals

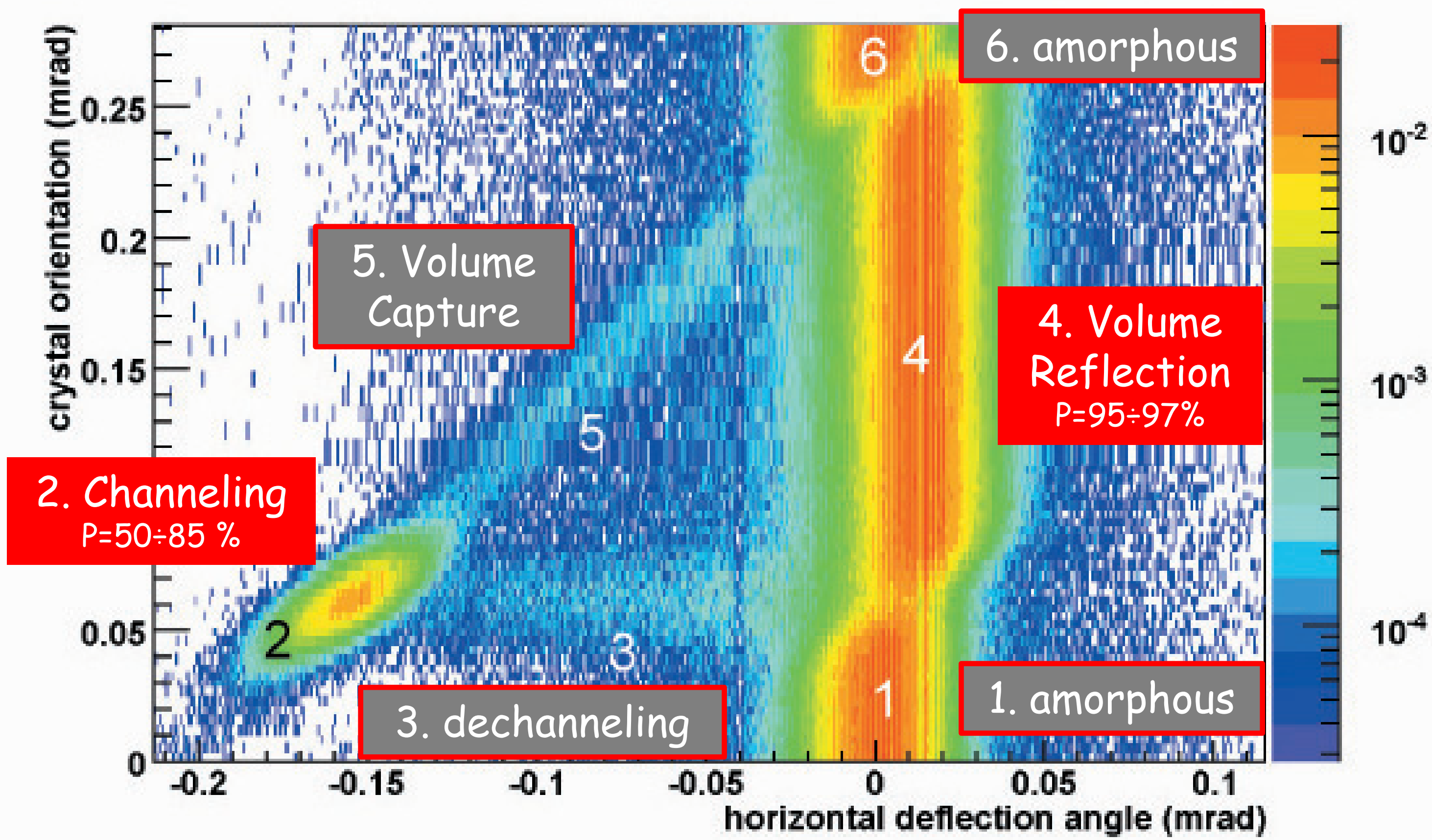
- Dislocation-free silicon crystals plates or strips
- for optimal channeling efficiency
  - ✓ short length (few mm)
  - ✓ moderate bending radius 45 ÷ 70 m

- 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



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)

Goniometer

The critical angle governs the acceptance for crystal channeling

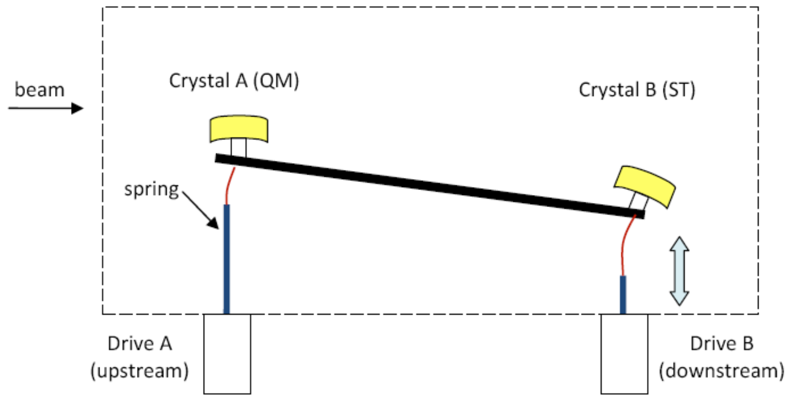
- 120 GeV ➔ θ_c = 20 µrad
- 450 GeV ➔ θ_c = 10 µrad
- 7 TeV ➔ θ_c = 2.5 µrad

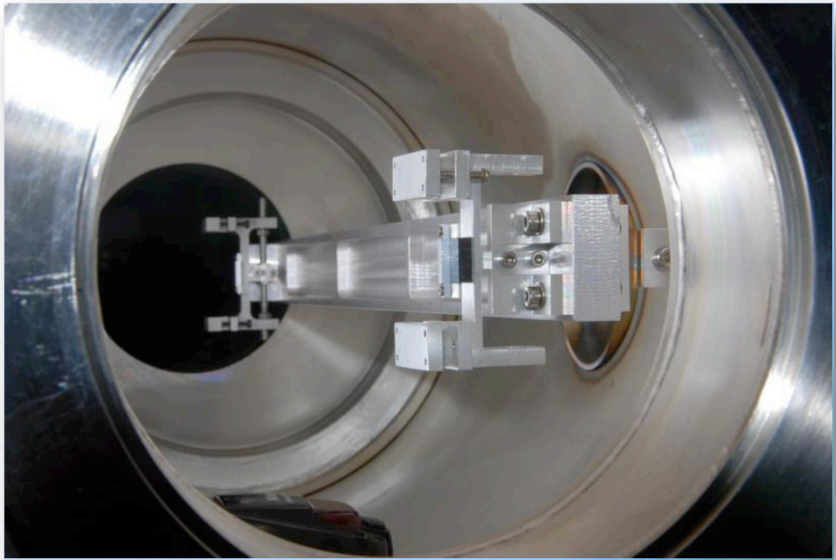
$$\theta_c = \sqrt{\frac{2U_0}{E}}$$

Required goniometer accuracy

- $\delta\theta$ = 10 µrad for E ≤ 450 GeV
- $\delta\theta$ = 1÷2 µrad at LHC collision

IHEP goniometer providing $\delta\theta$ = 10 µrad

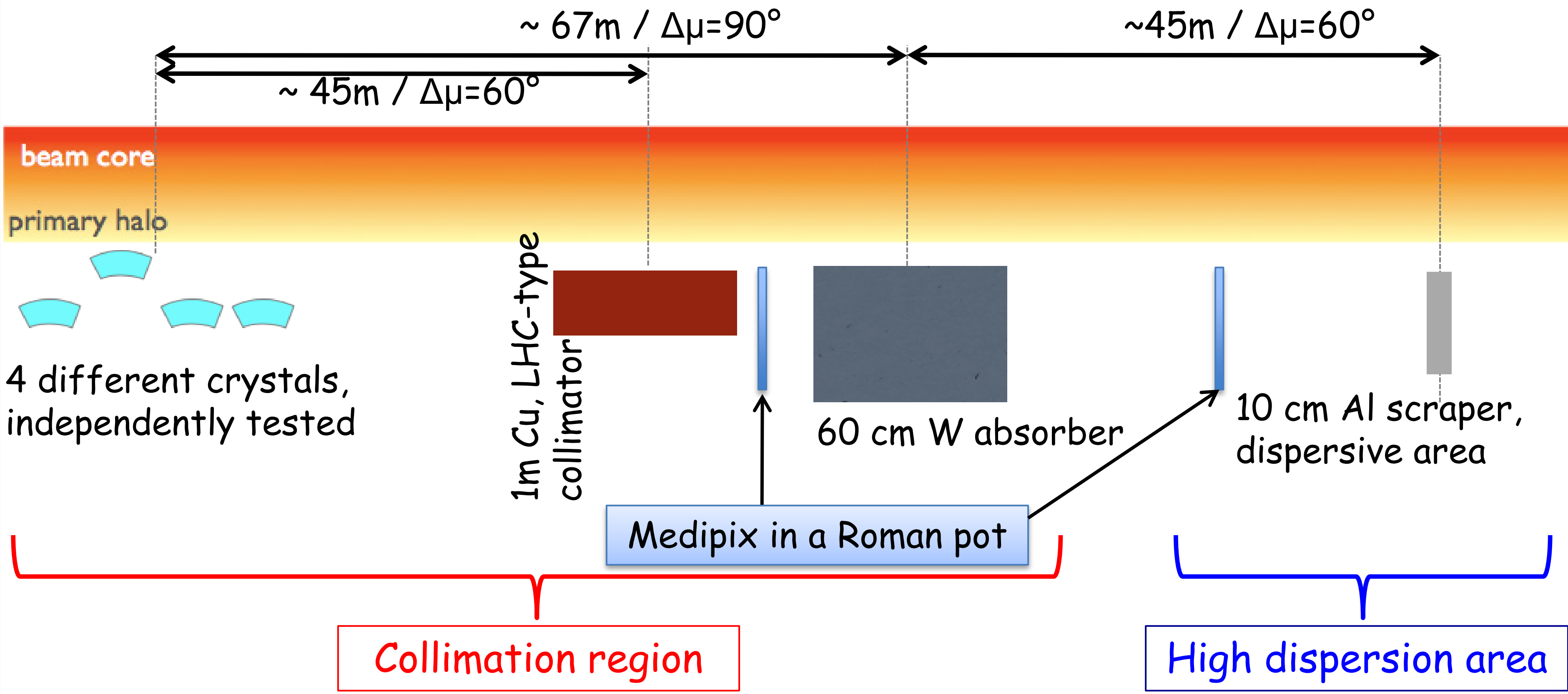




Upgrade of the goniometer launched in view of application to LHC

UA9 basic layout in the SPS

W. Scandale, M. Prest, SPSC-P-335 (2008).
W. Scandale et al, "The UA9 experimental layout", submitted to JINST, Geneva (2011).



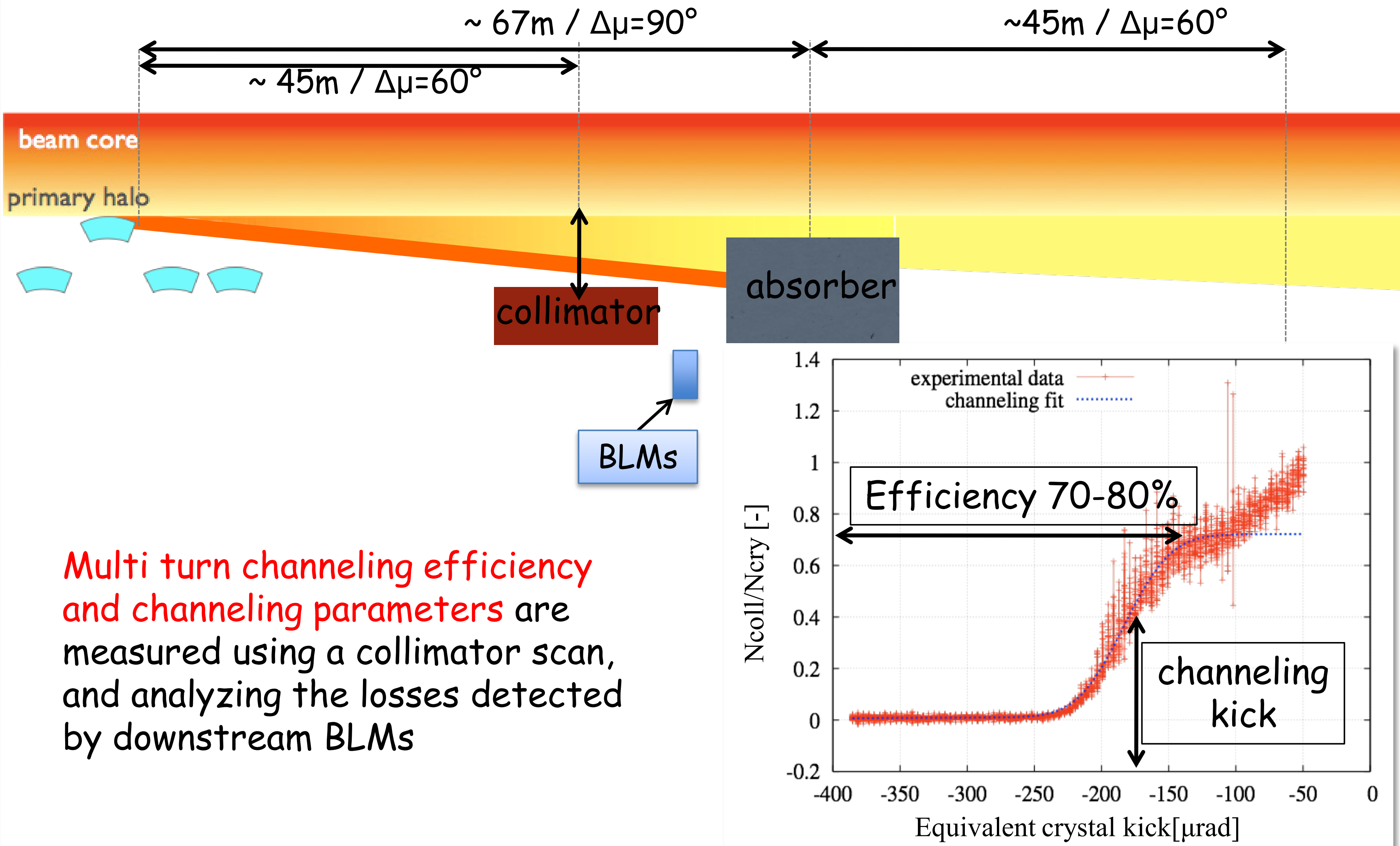
Observables in the collimation area:

- 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:

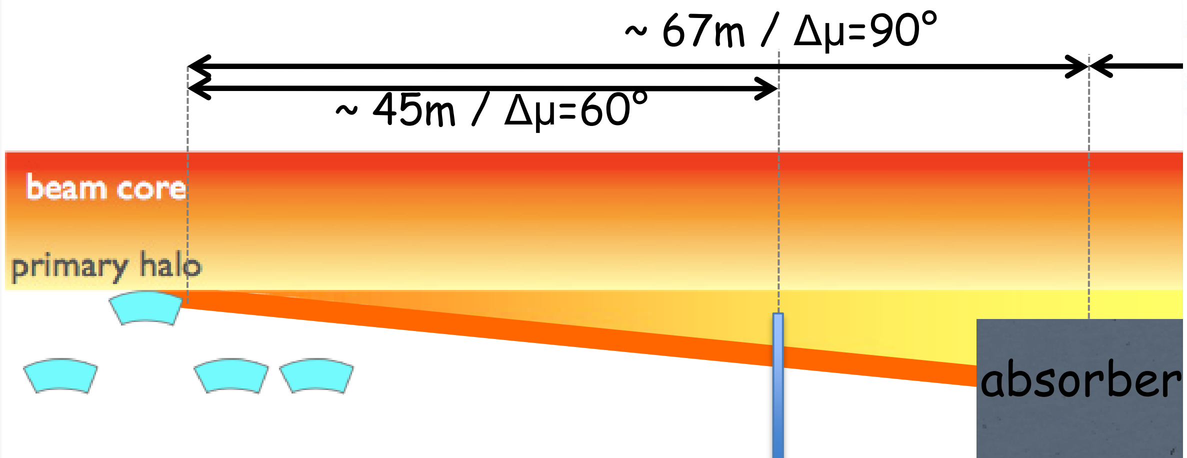
- Off-momentum halo population escaping from collimation (with multi-turn effect)
- Off-momentum beam tails

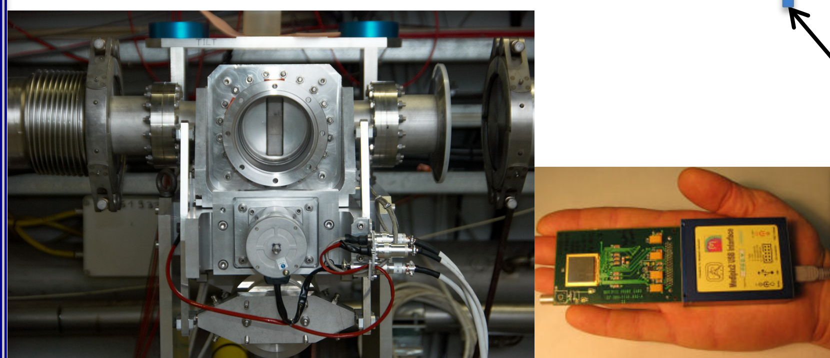
Channeling efficiency by coll. scans

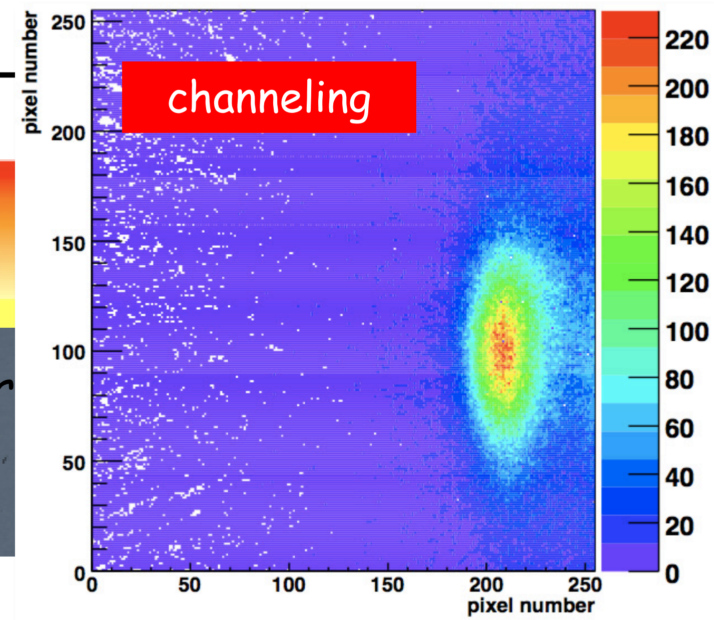


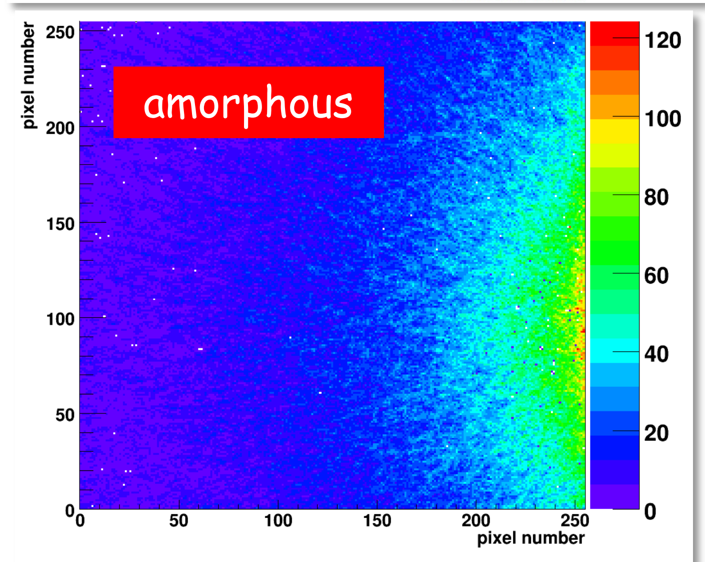
Multi turn channeling efficiency and channeling parameters are measured using a collimator scan, and analyzing the losses detected by downstream BLMs

Direct view of channeled beam





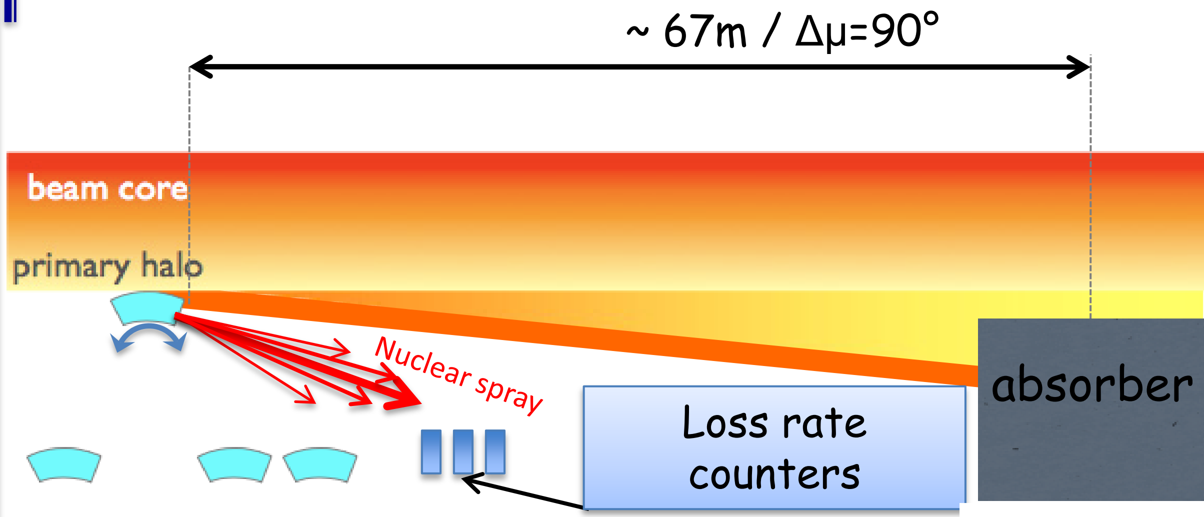




Medipix pixel detector in a Roman pot:

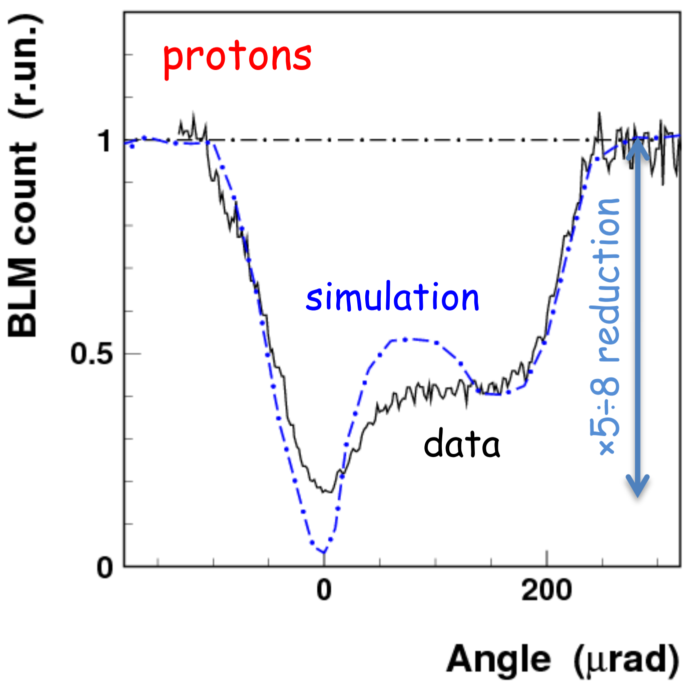
- Intensity, profile and angle of the deflected beam
- Efficiency of channeling (with multi-turn effect) (needs information on circulating beam current)

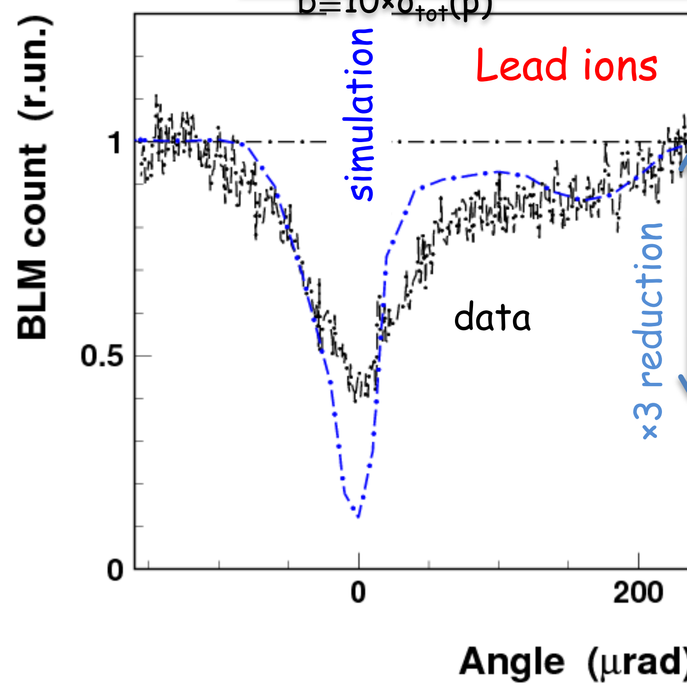
Loss rate reduction at the crystal



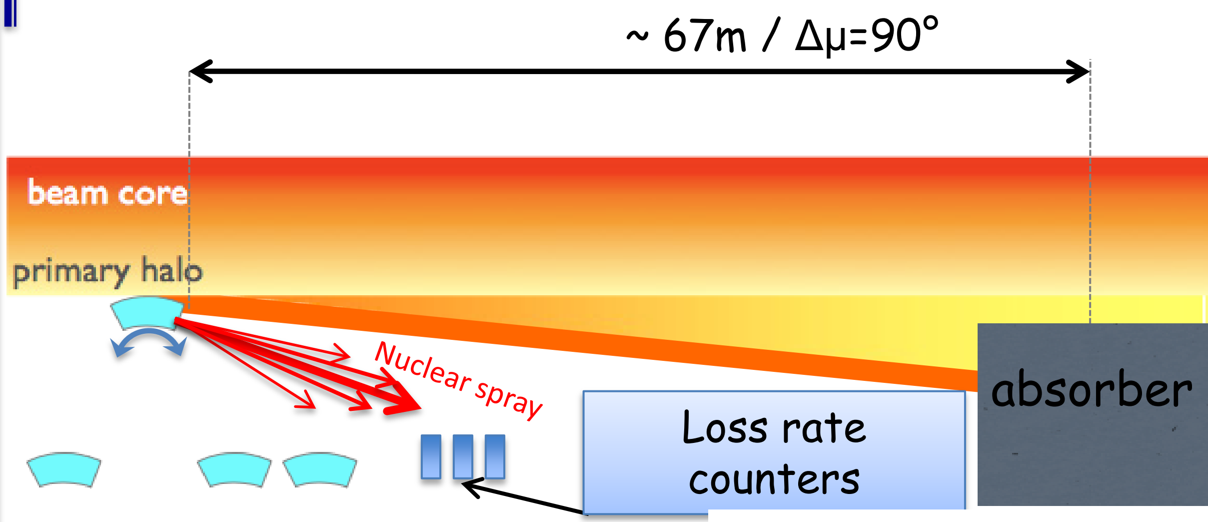
Loss rate reduction factor

- for protons 5÷8
- for lead ions ≈ 3
- σ_{tot}(lead ions)=σ_h+σ_{ed}=5.5 b≅10×σ_{tot}(p)



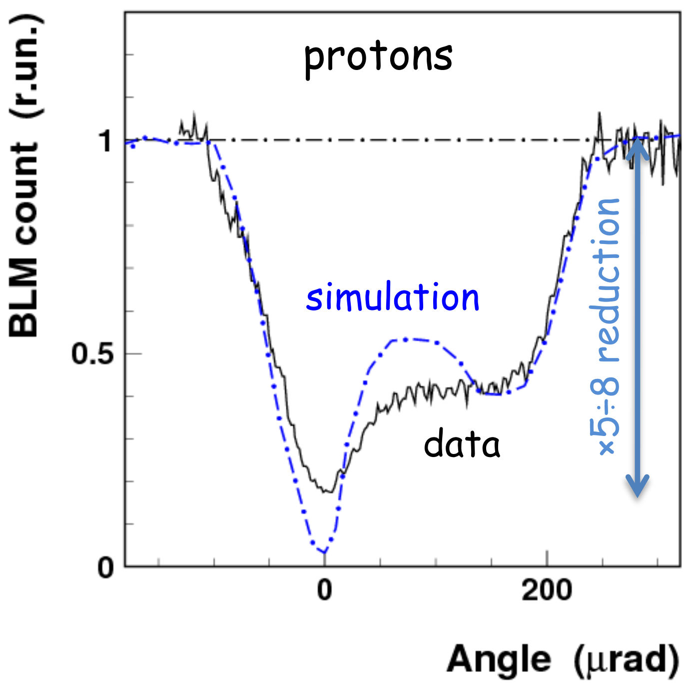


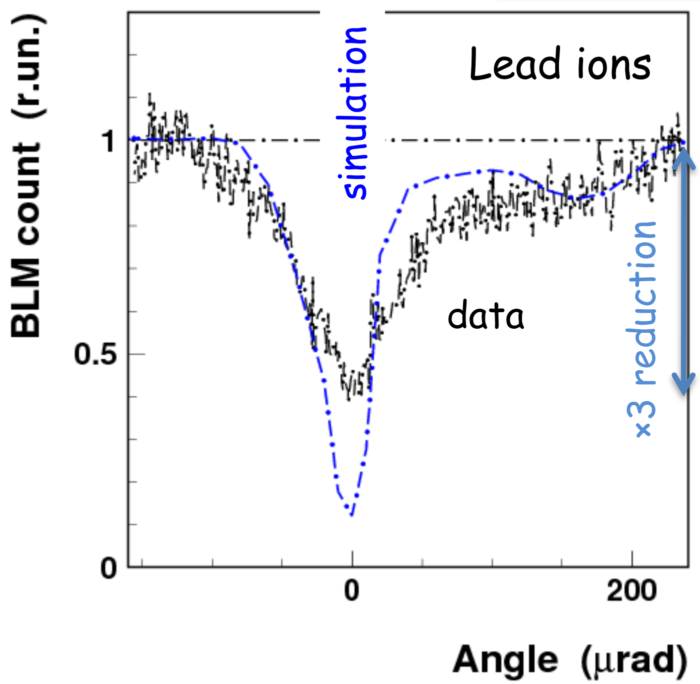
Loss rate reduction at the crystal

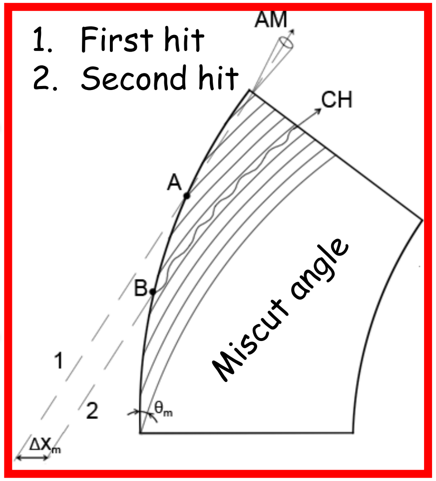


Discrepancy between data and simulation:

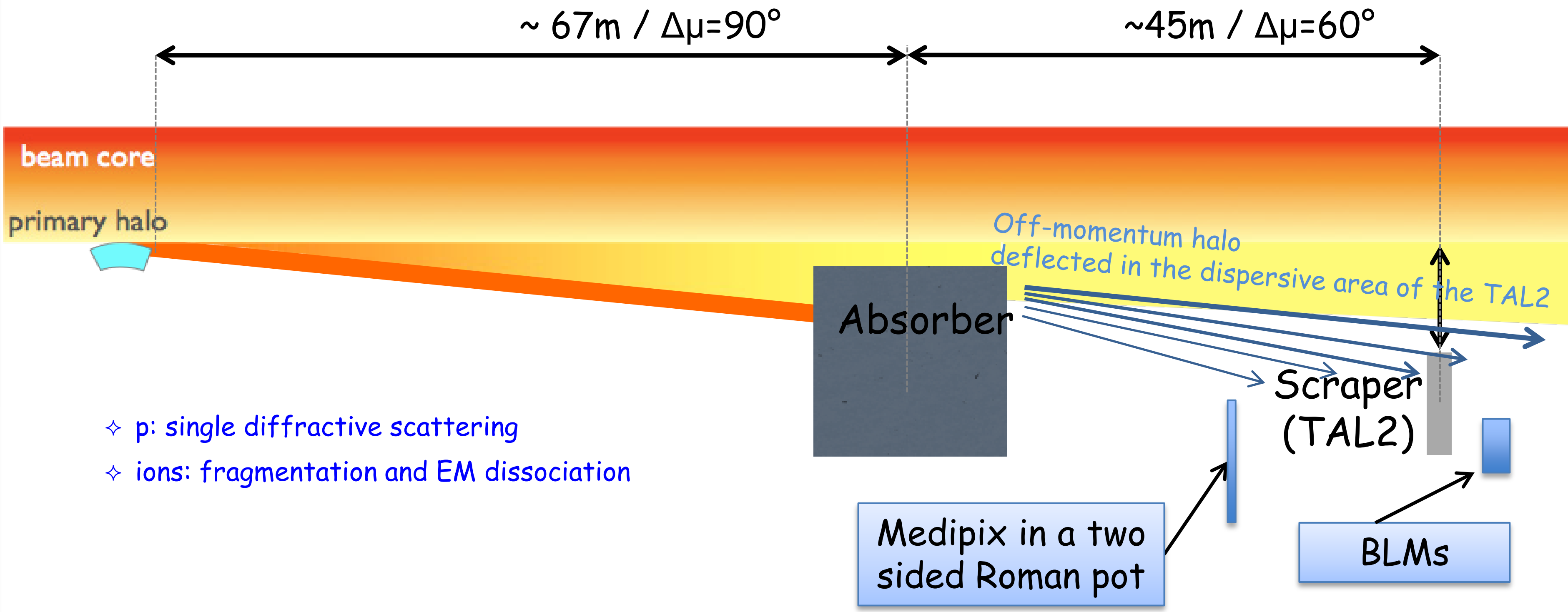
- crystal torsion
- crystal surface imperfections
- miscut angle







off-momentum halo population



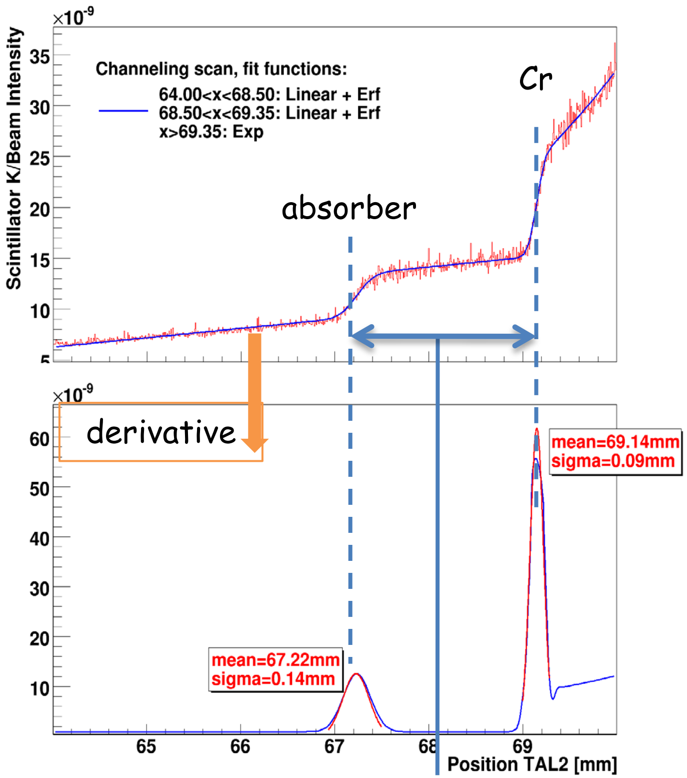
Off-momentum halo population

1. Linear scan made by the TAL2 (or Medipix) with the crystal in fixed orientation
2. angular scan of the crystal with the TAL2 (or the Medipix) in fixed position in the shadow of the absorber

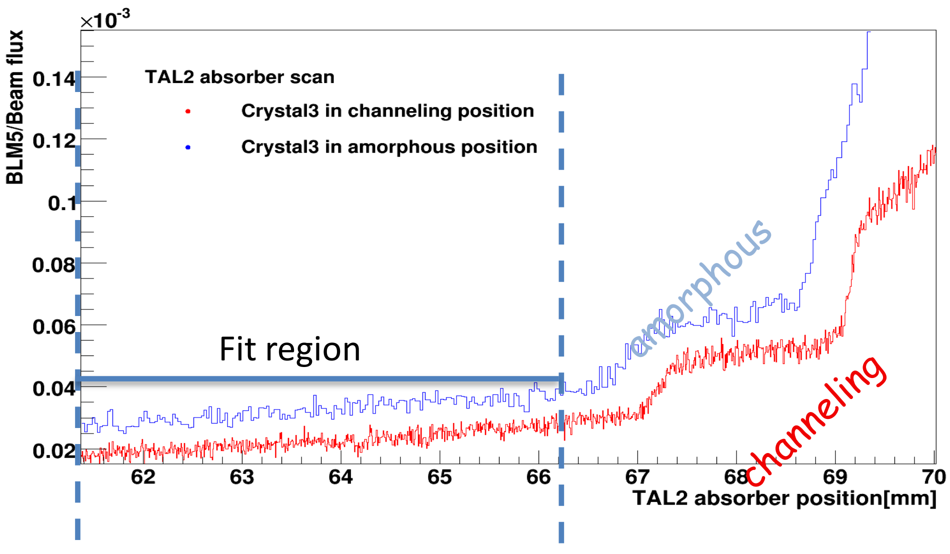
Scan of the off-momentum halo (1)

Loss rate as a function of the scraper position

- The two kinks are the shadows of the crystal and of the absorber edges
- The off-momentum tertiary halo escaping from the collimation area is estimated by fitting the loss rate behind the absorber
- The population of the off-momentum tertiary halo is smaller in channeling mode than in amorphous orientation



Expected distance = 2.13mm
Measured=1.92±0.25mm



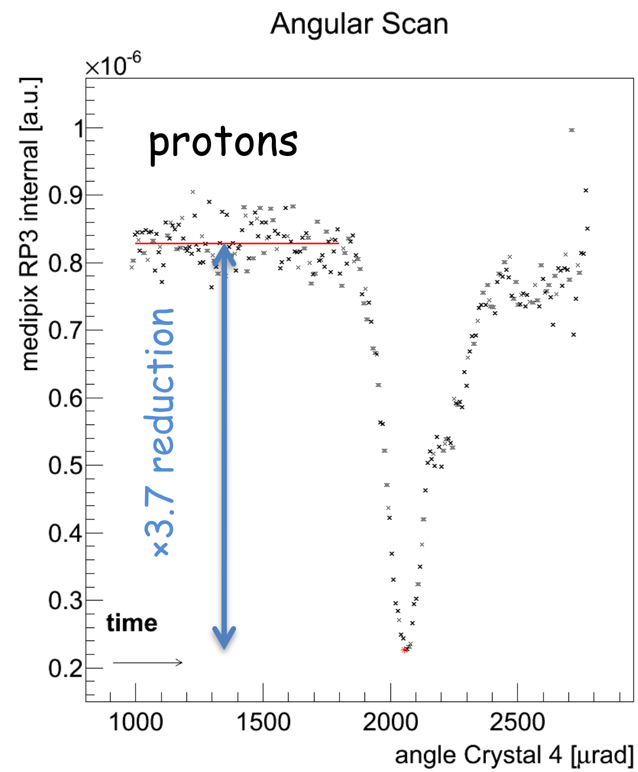
The reduction factor of the tertiary halo

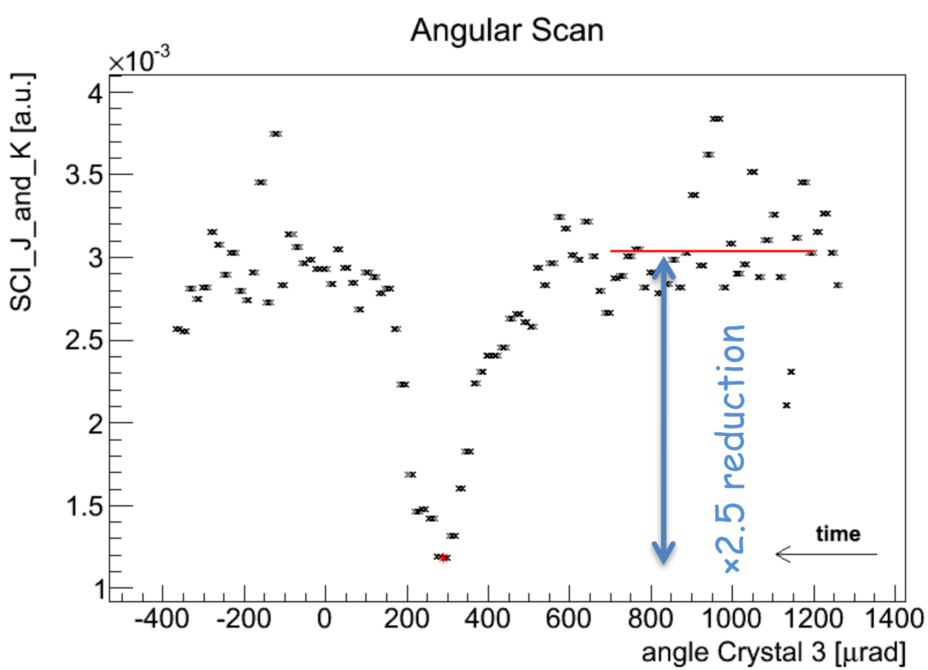
- for protons **1.4÷5.2**
- for lead ions **3.9÷5.9**

Scan of the off-momentum halo (2)

Loss rate as a function of the crystal orientation

- The scraper is in a fixed position in the shadow of the absorber
- The off-momentum tertiary halo is estimated by fitting the loss rate behind the absorber as a function of the crystal angle
- The population of the off-momentum tertiary halo is smaller in channeling mode than in amorphous orientation





Summary

The SPS tests on crystal assisted collimation at have shown that

- The procedure for crystal channeling is robust, fast and well reproducible
  - ✓ The crystal and the absorber are positioned at the beam peripheral
  - ✓ The absorber is retracted by 2÷3σ to allow multi-turn extraction of the halo
  - ✓ The crystal is very precisely oriented in channeling mode using BLM signals
- In channeling states the benefits are threefold
  - ✓ Most of the halo population is promptly deflected towards the absorber
  - ✓ The rate of the nuclear interaction at the crystal is strongly reduced
  - ✓ The population of the self-generated off-momentum halo decreases
- The crystal technology is fully mature to meet requirements of larger hadron colliders such as the LHC

UA9 is ready to propose a crystal test in LHC

Why a test in LHC

1. Investigate appropriate solutions for the optimal integration bent crystals in the existing layout of the LHC collimation system
2. Provide a unique test-bed to assess the operational merits of crystal-assisted collimation and to demonstrate the off-momentum halo reduction in the LHC
3. Confirm the operational robustness of crystal-assisted collimation demonstrated in the SPS
4. Demonstrate an improved cleaning efficiency with bent crystals in the four-stage collimation system of the LHC
5. Demonstrate geometrical and thermal stability of bent crystals and absorbers with high power halo losses (up to 1 MW)

Acknowledgement

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- BE/OP-BI-RF and PH/ESE groups carefully prepared the SPS for our needs

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- the INTAS program
- The MIUR 2006028442 project,
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- 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

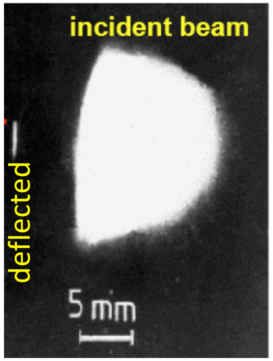
Radiation hardness

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

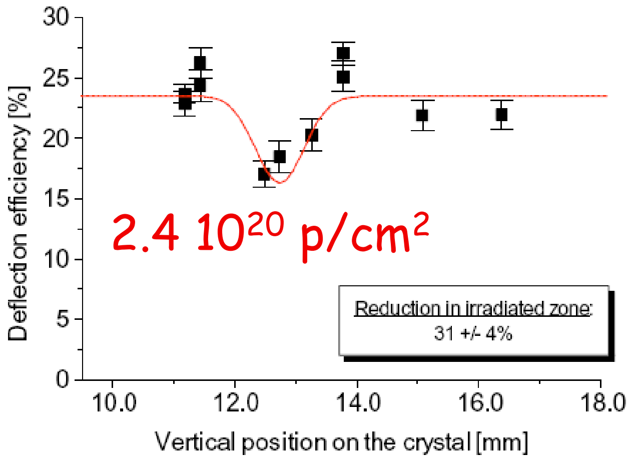
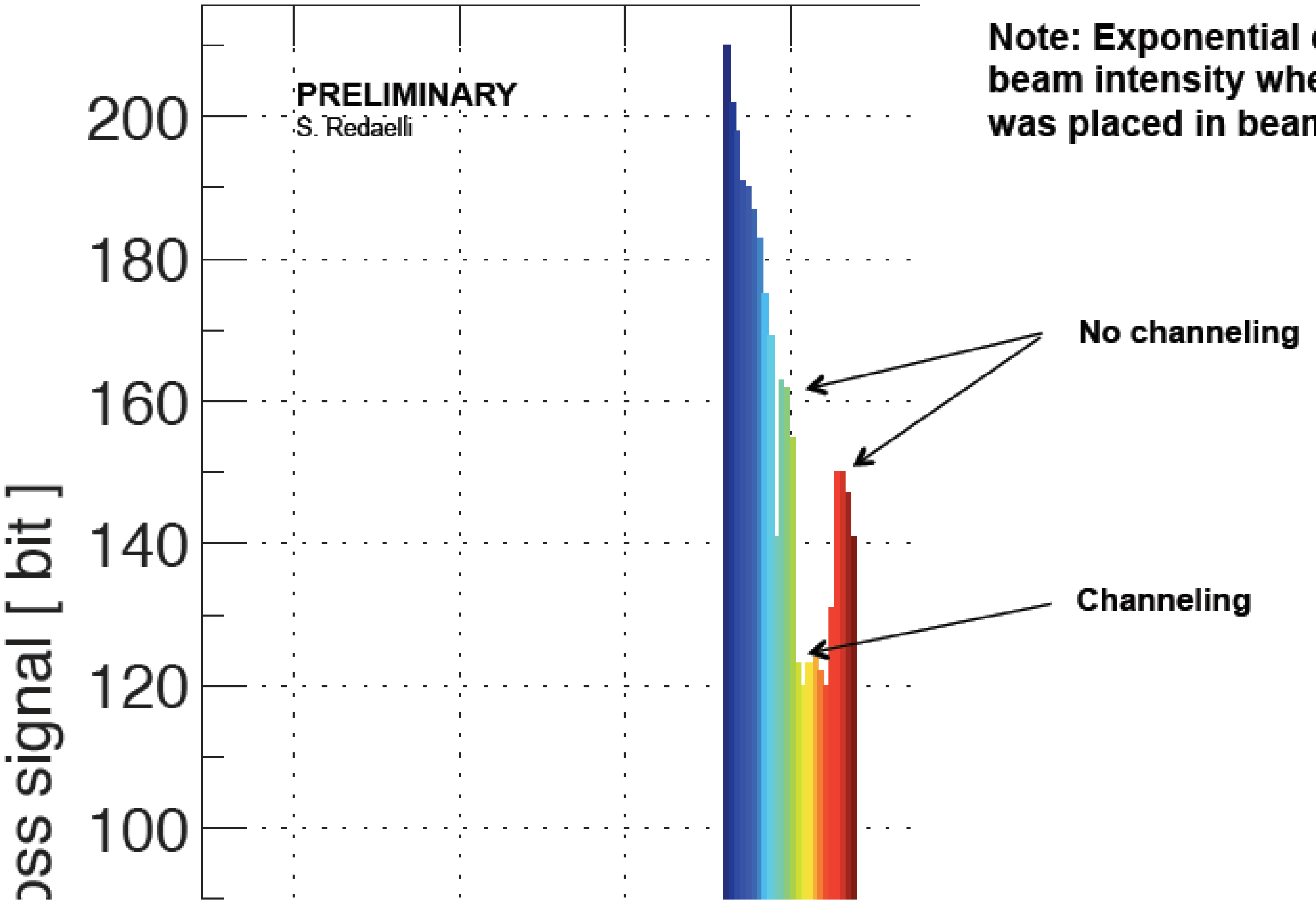


Figure 5 *A fit using the inverted irradiation profile to the measured points at expected optimum alignment*

Halo detection in LSS6 BLM



Note: Exponential decay of beam intensity when crystal was placed in beam core.