LHC COLLIMATION WITH BENT CRYSTALS:

PROPOSAL FOR AN EXPERIMENT AT LHC

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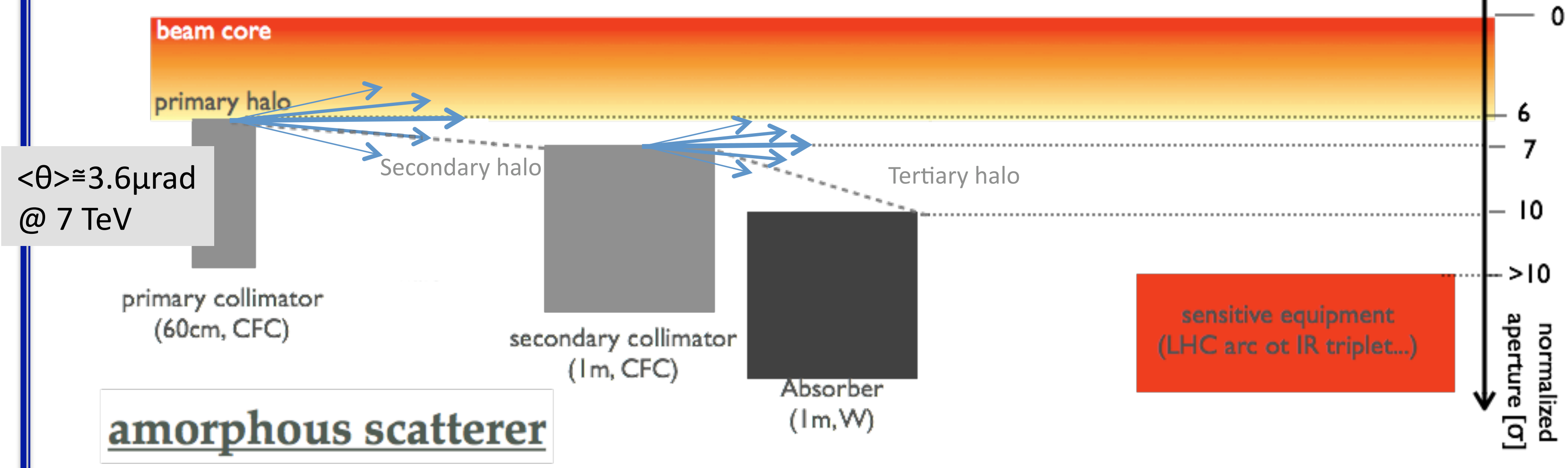
Multi stage collimation in LHC

Multi-stage cleaning based on amorphous collimators.

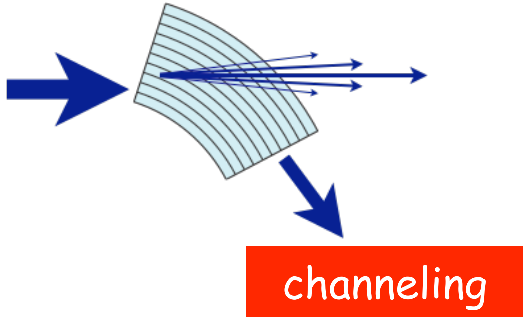
- ❑ The beam tails are removed in three steps:
  1. They first intercept the primary and later the secondary collimators
  2. They are repeatedly deflected by Multiple Coulomb Scattering
  3. They are finally intercepted in the absorber and in the masks protecting the sensitive devices

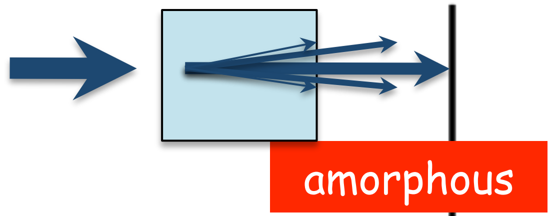


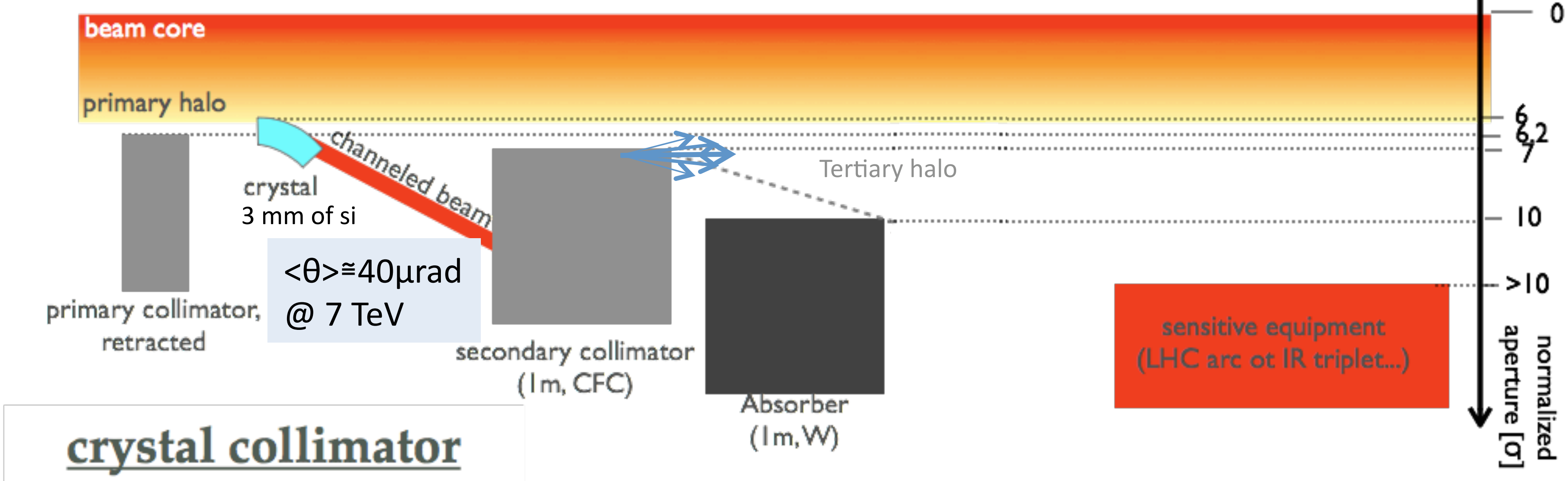
- ❑ Collimation efficiency in LHC > 99.99%
  - ✓ Probably not enough in view of a luminosity upgrade
  - ✓ The basic limitation of the amorphous collimation system
    - ✧ p: single diffractive scattering
    - ✧ ions: fragmentation and EM dissociation

Crystal assisted collimation

- Mechanically bent crystals work as “smart deflectors” and increase the deflection angle
  - ✓ The primary collimator is either fully retracted
  - ✓ Or just retracted by 1-2 σ
- Coherent particle-crystal interactions should minimize the escaping particles and improve the collimation efficiency



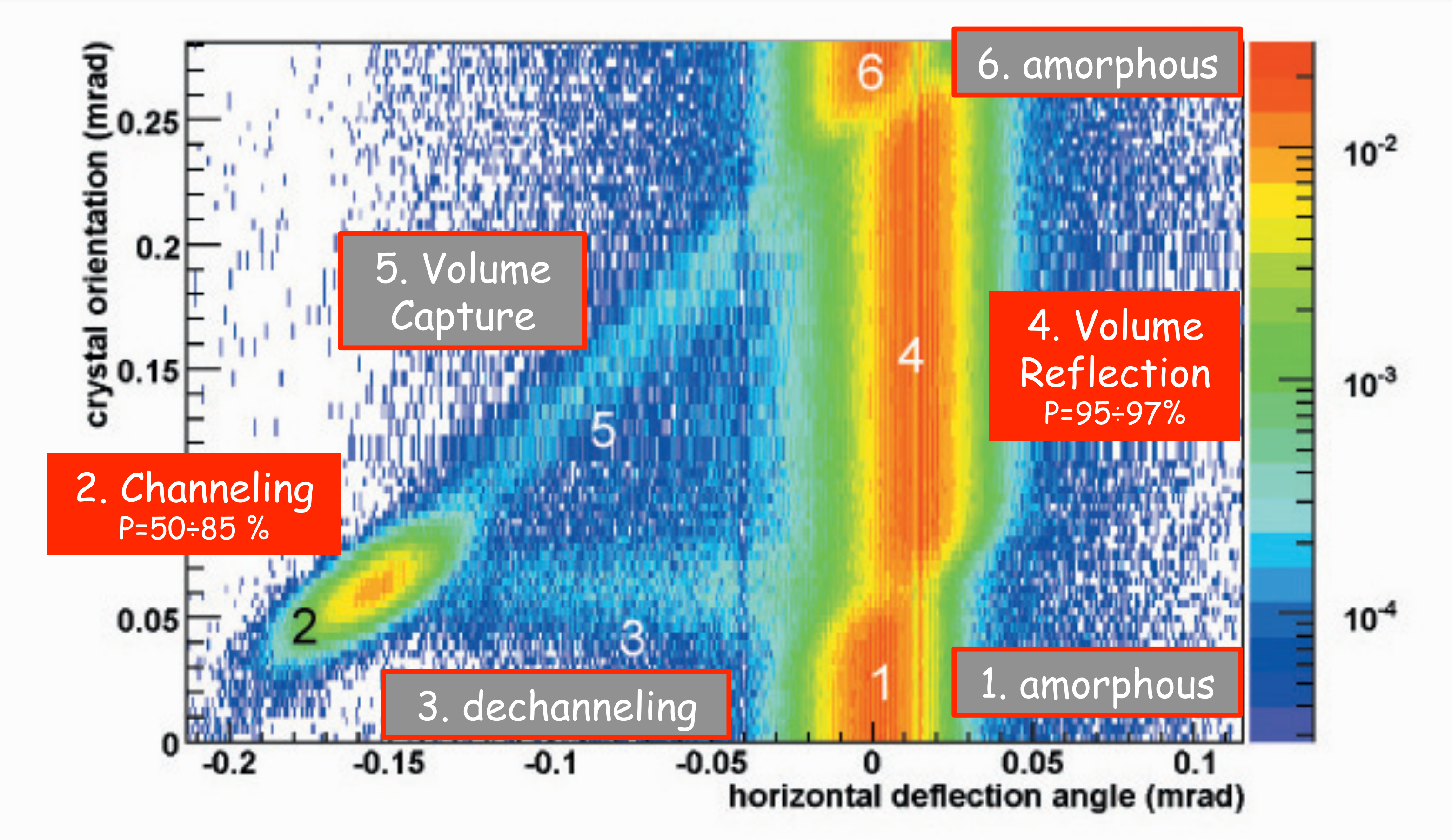




Potential improvements for LHC

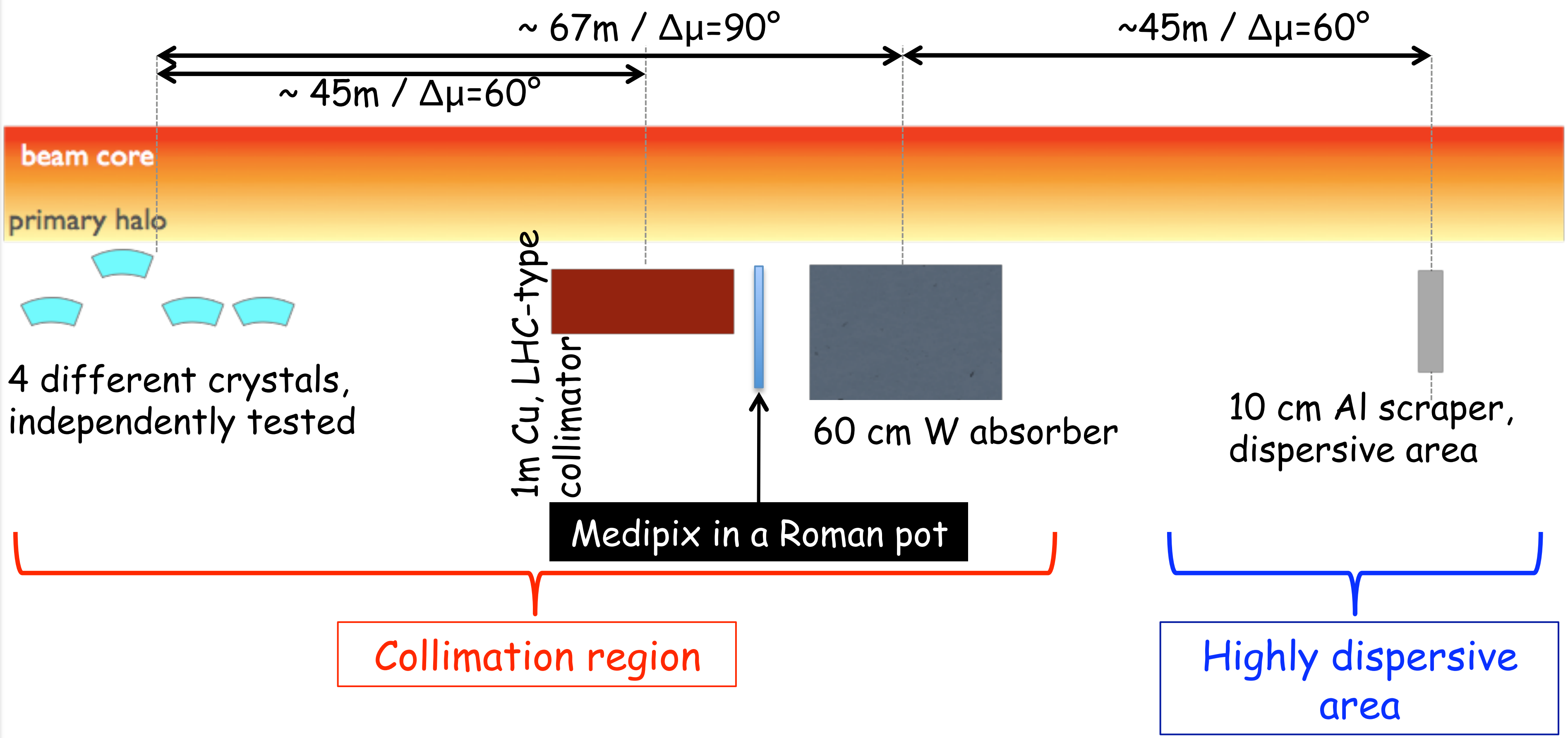
1. Larger impact parameter: crystals deflect the halo particles coherently to a larger angle than the amorphous primary collimator,
   - ✓ better localization of the halo losses ➔ initial evidence from UA9 data in the SPS
   - ✓ reduced collimation inefficiency ➔ $\times 10^{-1}$ expected from simulations
   - ✓ 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 (if primary fully retracted) ➔ 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
   - ✓ × 5÷8 less nuclear events in 120÷250 GeV channeled protons ➔ UA9 data in the SPS ring
   - ✓ × 3÷4 less nuclear events in 120÷250 GeV/u channeled lead ions ➔ UA9 data in the SPS ring

Coherent interactions in bent crystals



- Two coherent effects could be used for crystal collimation:
  - ✓ Channeling ➔ larger deflection with reduced efficiency
  - ✓ Volume Reflection (VR) ➔ smaller deflection with larger efficiency
- SHORT CRYSTALS in channeling mode are preferred
  ➔ ×5 less inelastic interaction than in VR or in amorphous orientation (single hit of 400 GeV protons)

Highlights of UA9: layout



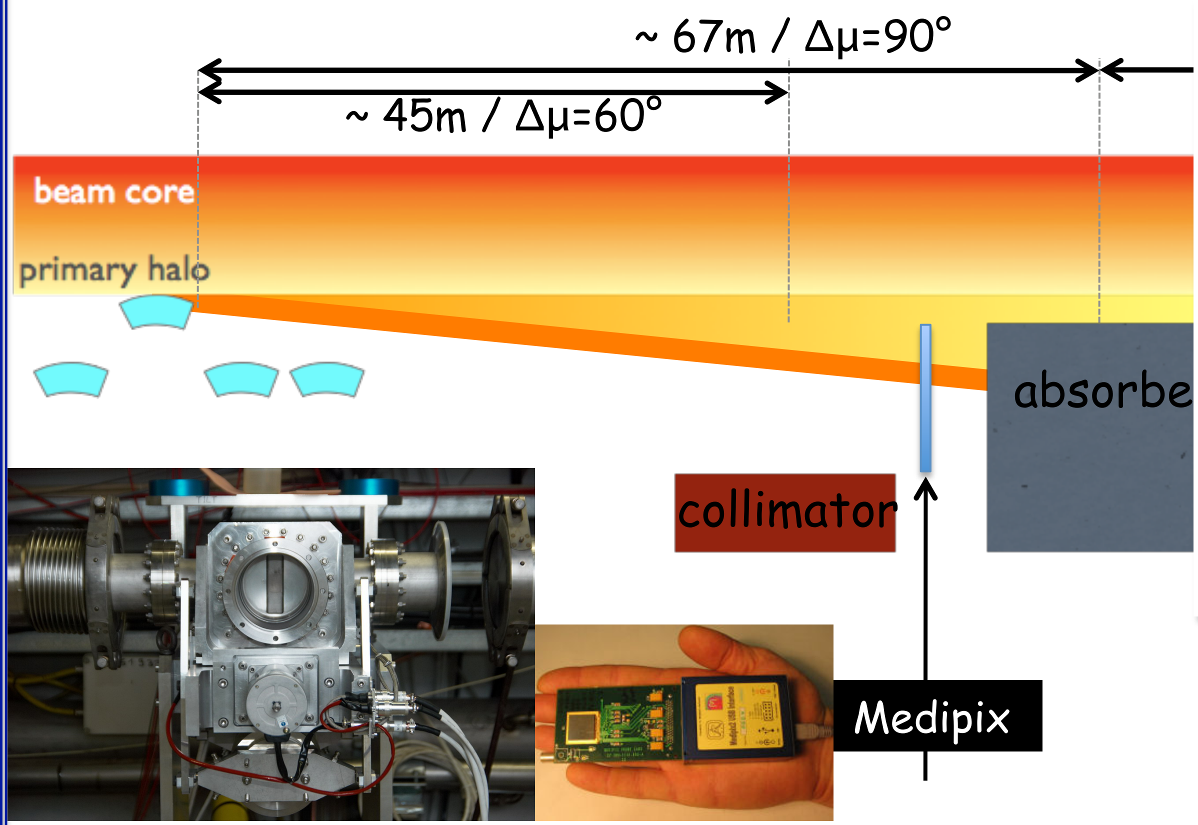
Observables in the collimation area:

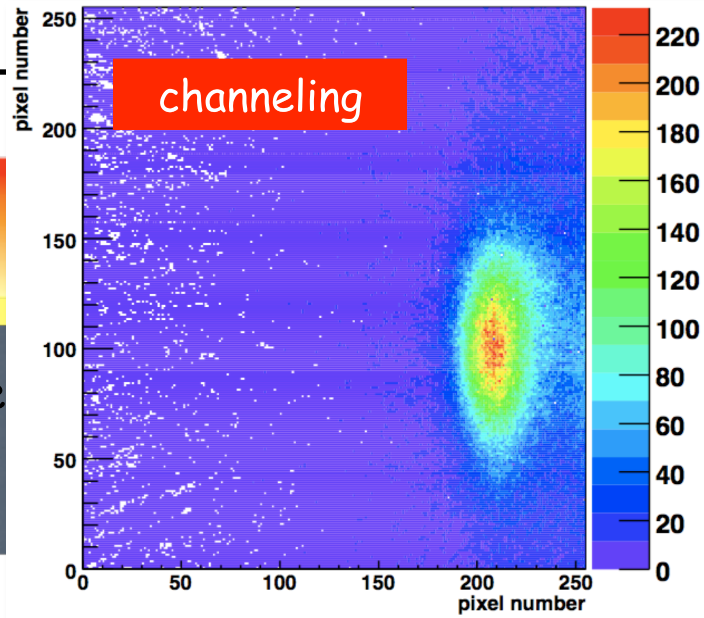
- Intensity, profile and angle of the deflected beam
- Local rate of inelastic interactions
- Efficiency of channeling (with multi-turn effect)

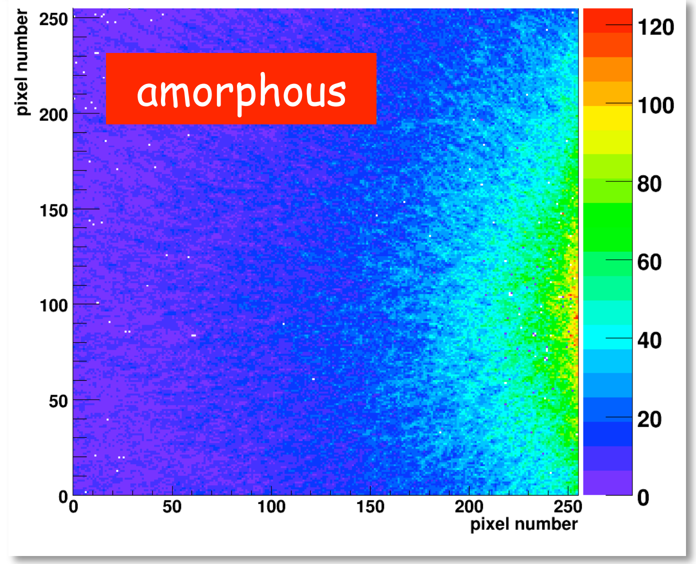
Observables in the high-D area:

- Off-momentum beam tails
- Off-momentum tertiary halo leakage (with multi-turn effect)

Highlights of UA9: channeled beam



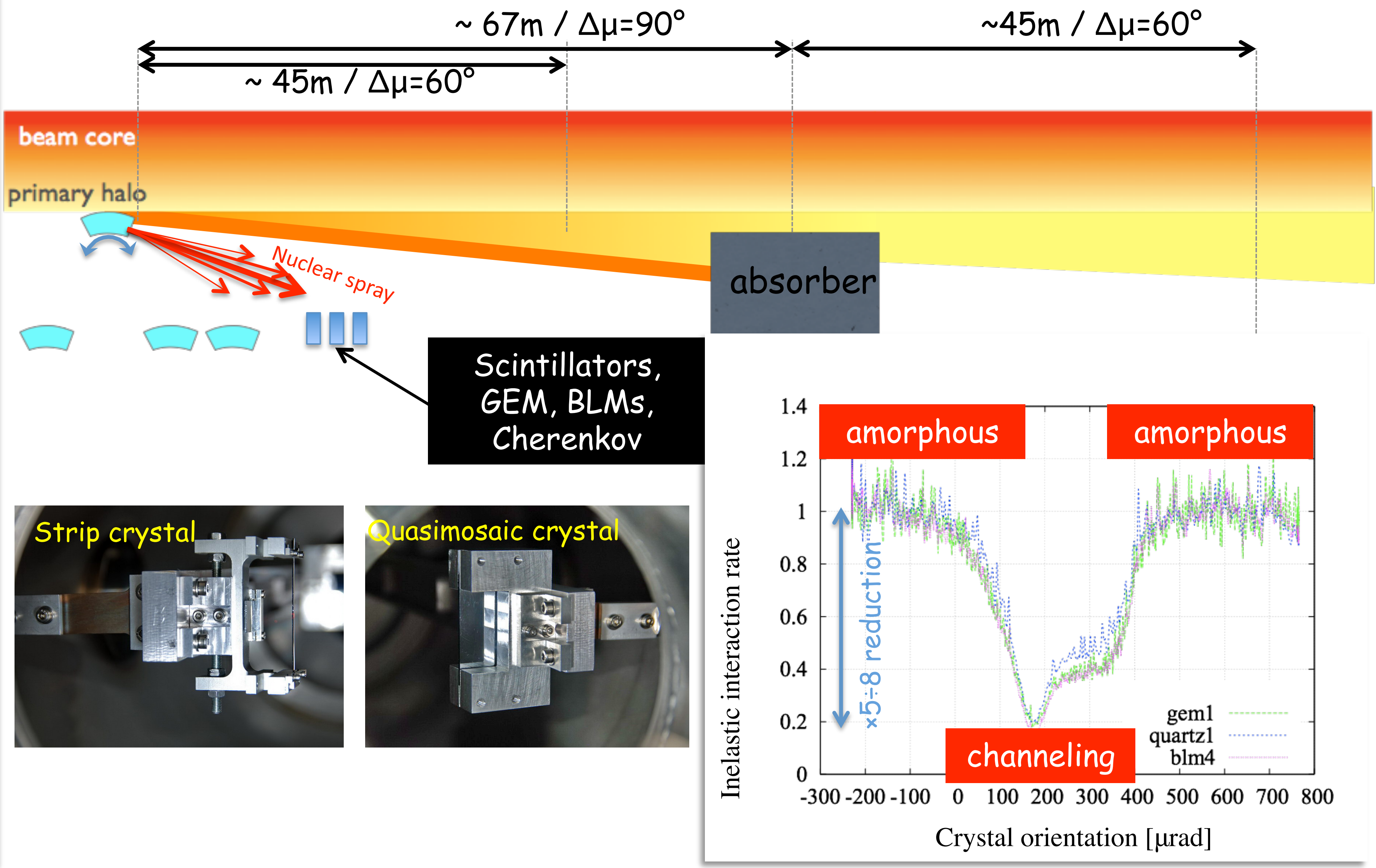




Medipix pixel detector in a Roman pot:

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

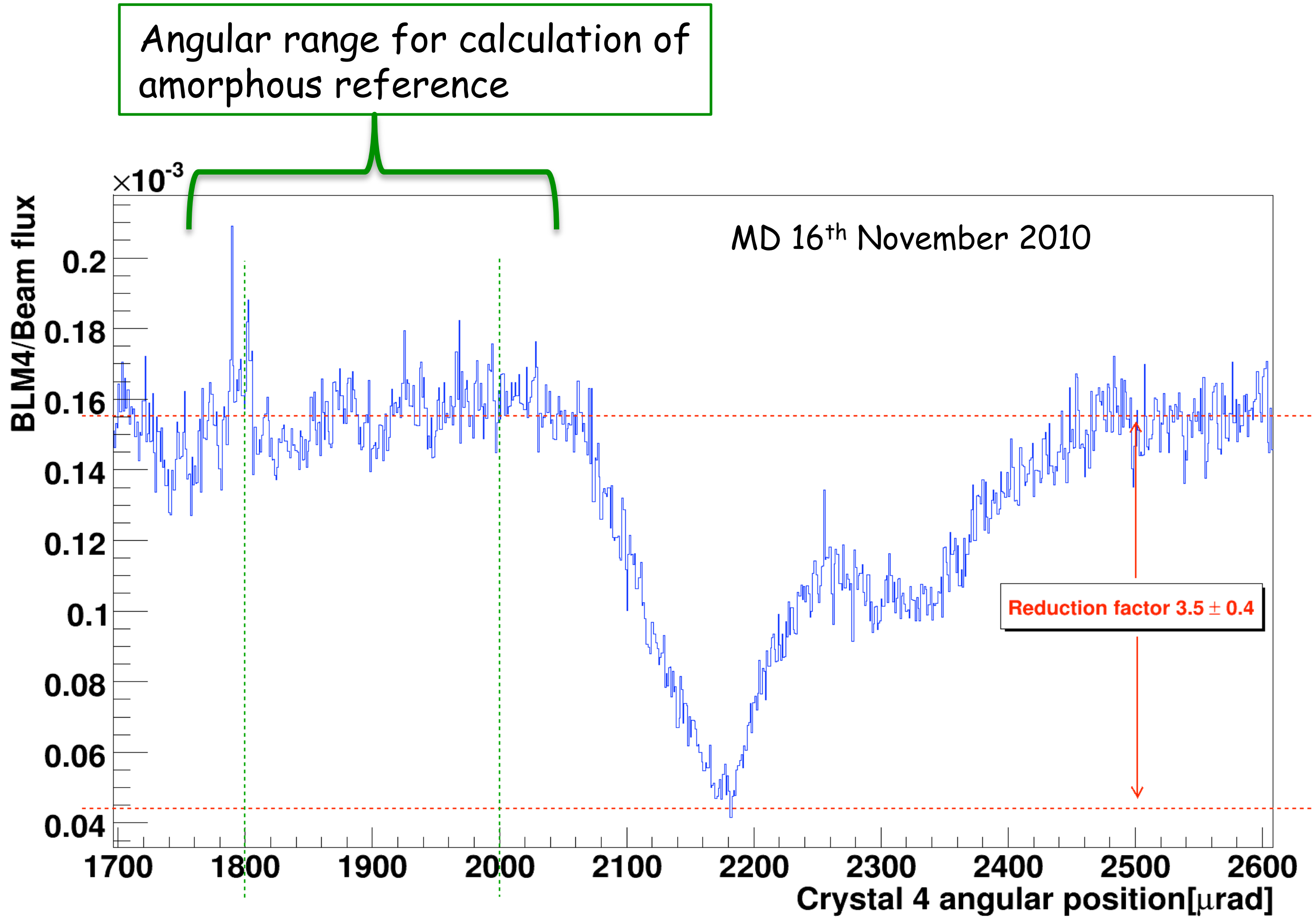
Highlights of UA9: local nuclear loss



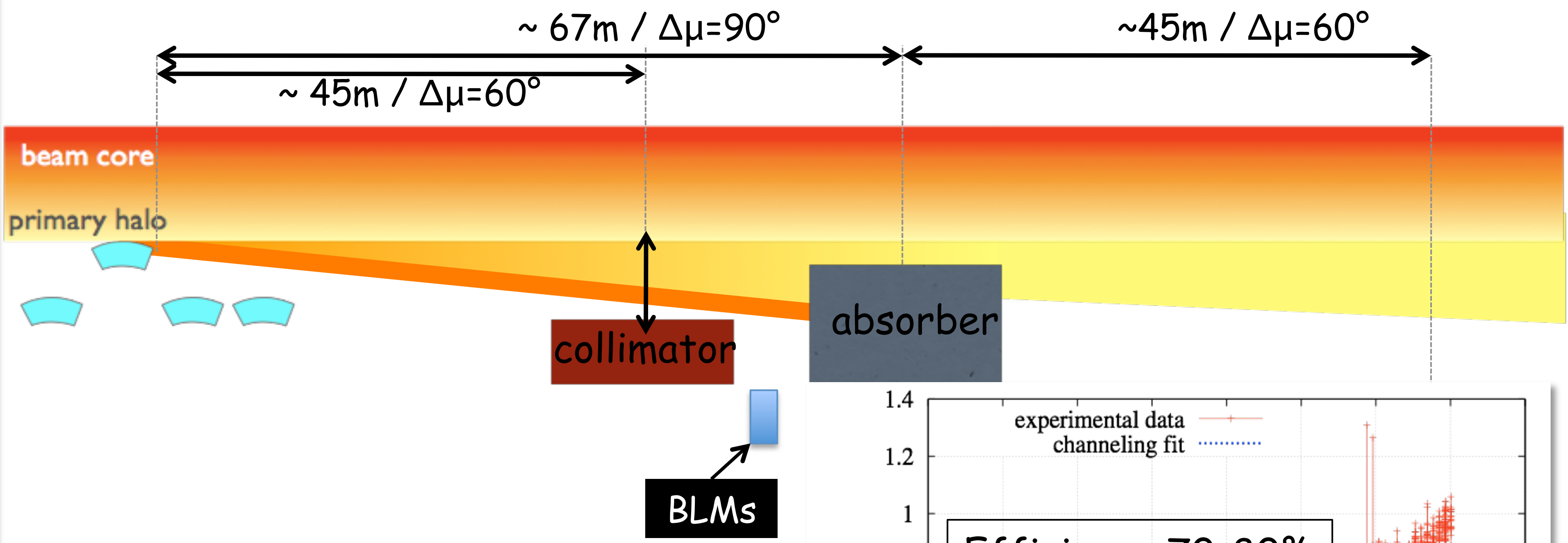
Highlights of UA9: lead ions

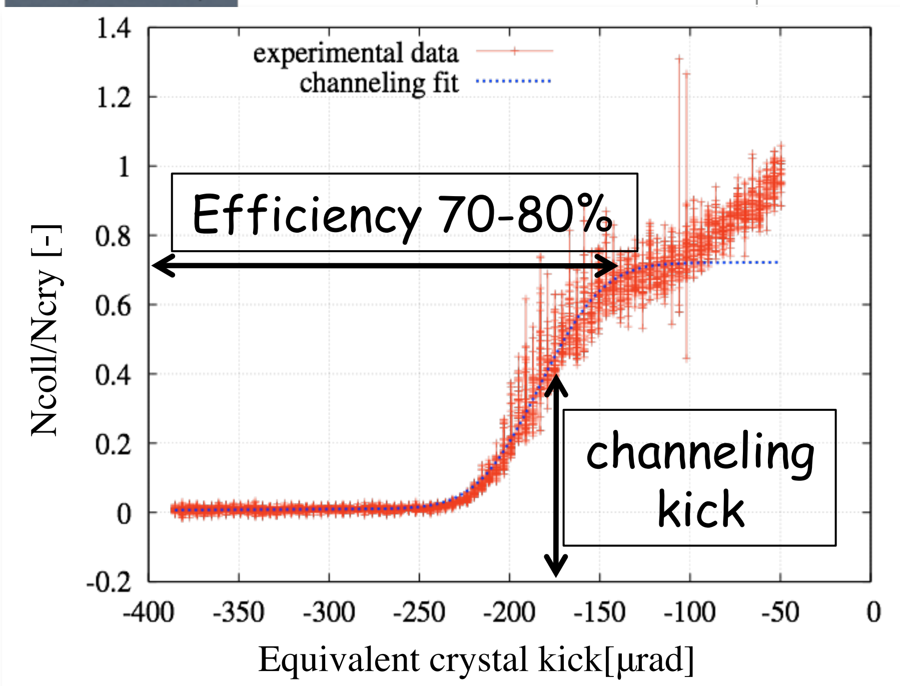
Lead ions

reduction of inelastic interaction rate at the crystal by × **3 ÷ 4**



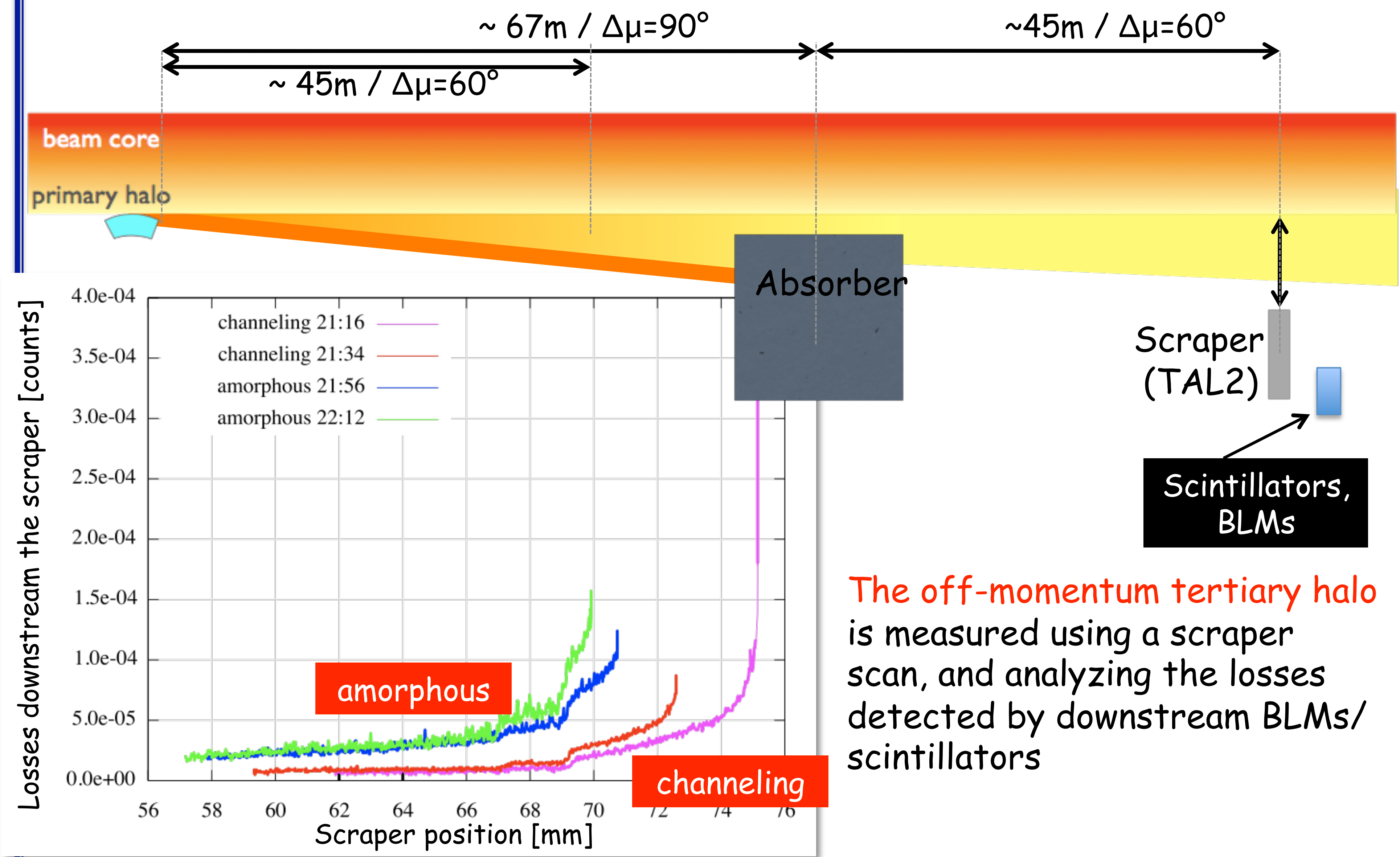
Highlights of UA9:channeling efficiency





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

Highlights of UA9: off-momentum halo

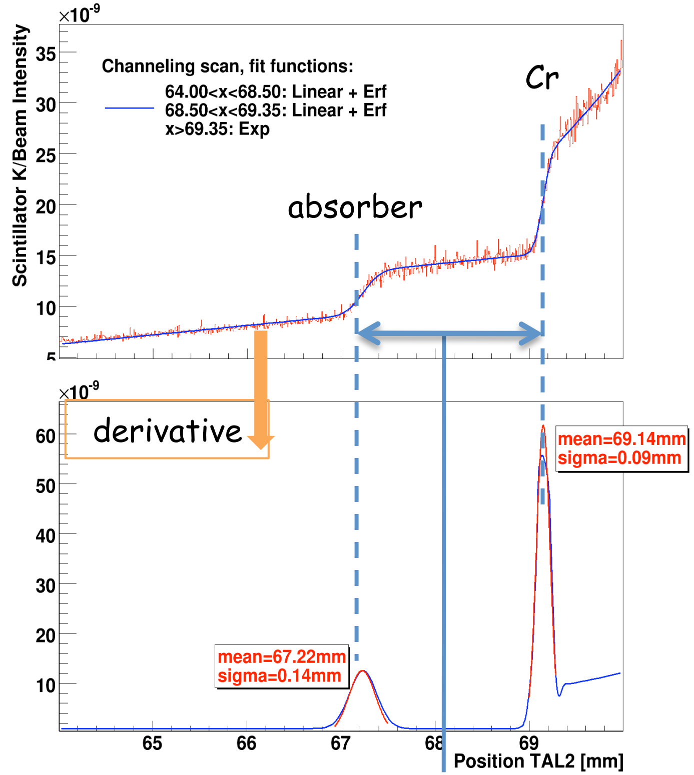


The off-momentum tertiary halo is measured using a scraper scan, and analyzing the losses detected by downstream BLMs/ scintillators

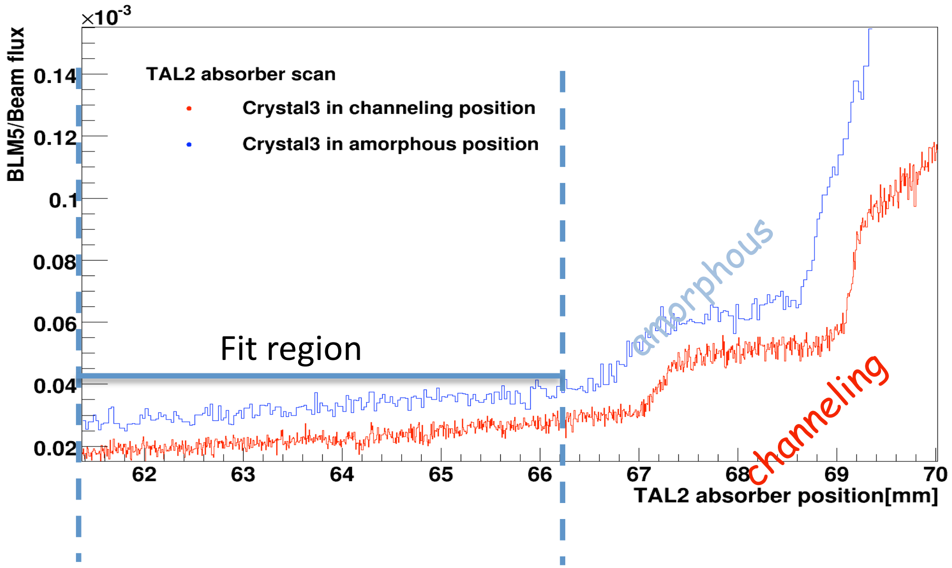
Highlights of UA9: off-momentum halo

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 off-momentum tertiary halo escaping from the collimation area is smaller in channeling mode than in amorphous orientation



Expected distance = 2.13mm
Measured=1.92±0.25mm



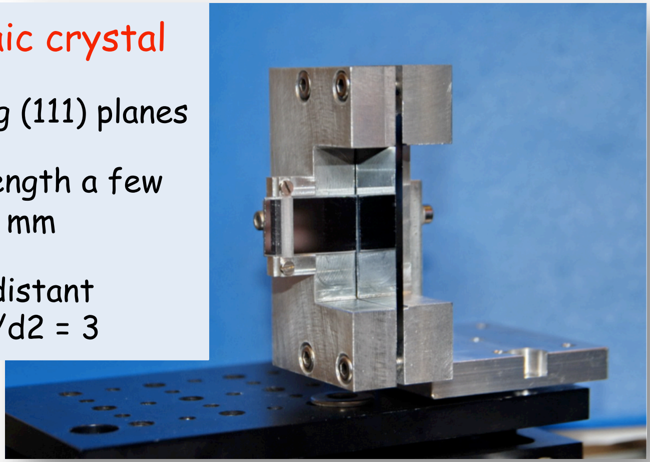
The reduction factor of the tertiary halo

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

Crystal station

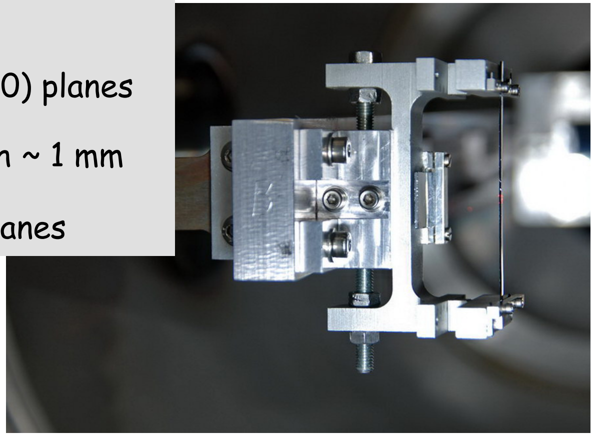
Quasimosaic crystal

- 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 is the optimal choice ➔ fully confirmed by UA9 experience
- Short sample (few mm) for optimal channeling efficiency ➔ UA9 data in the SPS North Area
- Bending radius = 45 ÷ 70 m for optimal channeling at 7 TeV ➔ UA9 data and simulations
- 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: cannot completely be avoided, but negligible effect if good orientation is applied ➔ experience from T980
  - ✓ Torsion: can reduced down to 1 μrad/mm ➔ experience from UA9 in the SPS North Area

Goniometer

The critical angle governs the acceptance for crystal channeling

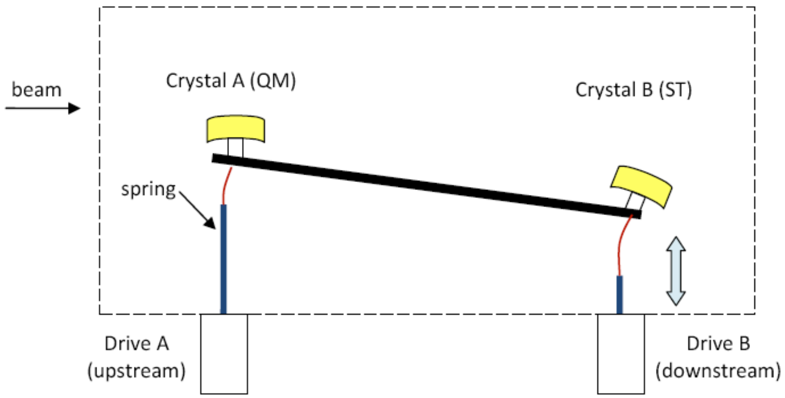
- 450 GeV protons θ_c = 10 μrad
- 7 TeV protons θ_c = 2.5 μrad

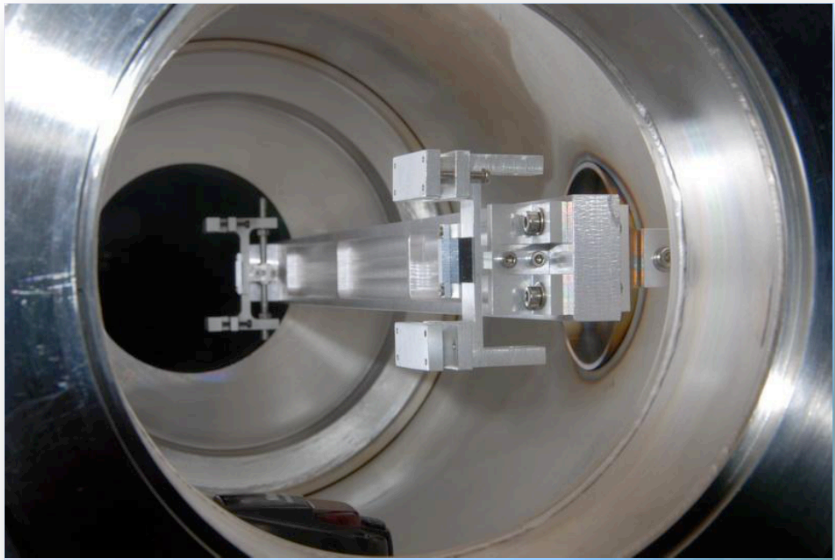
$$\theta_c = \sqrt{\frac{2U_0}{E}}$$

Required goniometer accuracy

- δθ = 5÷10 μrad at LHC injection
- δθ = 1÷2 μrad at LHC collision

IHEP goniometer providing δθ = 10 μrad





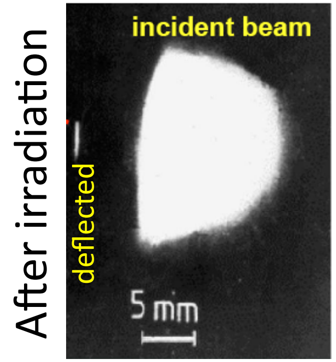
Three developments launched by UA9 Collaboration, one in IHEP and two with industrial partners CINEL (I) and ATTOCUBE (D)

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.



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

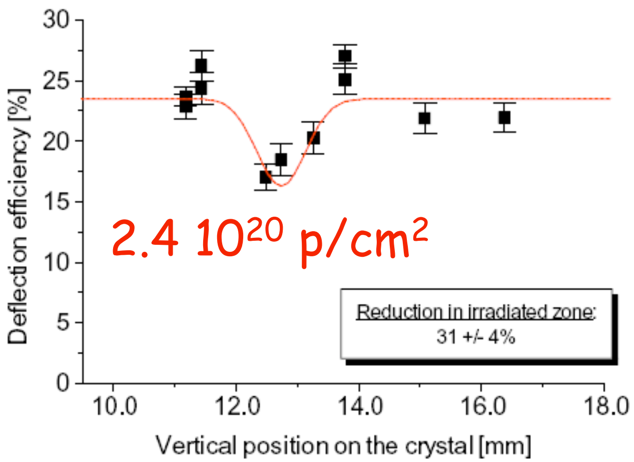


Figure 5 *A fit using the inverted irradiation profile to the measured points at expected optimum alignment*

From UA9 to LUA9: open issues

1. Orientating the crystal optimally for channeling requires alignment mechanisms with an accuracy *beyond* the state-of-the-art
   ➔ three developments launched, two of which with industrial partners
2. Deflected halo trajectories should comply with the reduced size of LHC beam pipe ➔ preliminary solution already available
3. When using bent crystals for collimation, the entire halo particle power is deposited in a small spot of the collimator-absorber
   ➔ circulating intensity limited by the robustness of the existing absorbers
4. Demonstration of crystal-assisted collimation in the four-stage collimation system of the LHC with an already achieved cleaning efficiency of >99.99%. The benefits of bent crystals in such a multi-stage system can only be demonstrated in the LHC
   ➔ waiting for the LHCC approval
5. Thermal and geometrical stability of the bent crystals for high power halo extraction of up to 1 MW, including questions of heat load, trapped modes and cooling ➔ simulations in preparation

Goals of LUA9

1. Investigate appropriate solutions for the optimal crystals and their optimal integration in the existing layout of the LHC collimation system

2. Provide a unique test-bed to assess the beneficial effects of crystal-assisted collimation on operational efficiency and off-momentum halo reduction in the LHC

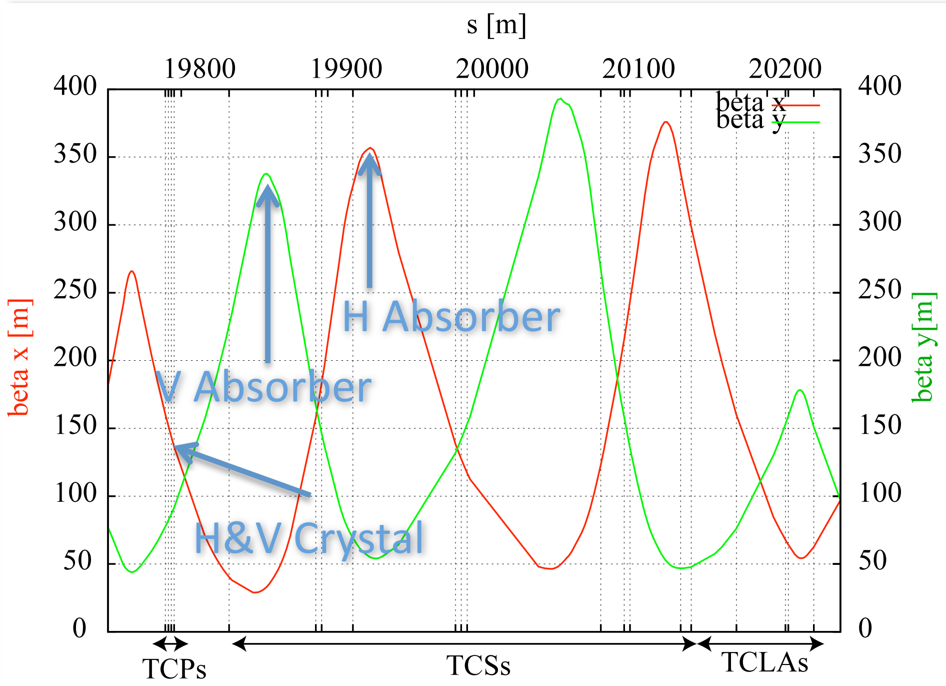
3. Confirm the operational robustness of crystal-assisted collimation demonstrated in the SPS

4. Demonstrate an improved cleaning efficiency with bent crystals in the four-stage collimation system of the LHC

5. Confirm geometrical and thermal stability of bent crystals with high power halo losses (up to 1 MW)

Possible LUA9 layout

- The bent crystal should be installed close to the existing LHC primary collimators in IP7
- Three planes of cleaning enhanced with crystal channeling should be utilized: horizontal, vertical and skew
- Available crystal locations have β' ≠ 0 ➔ crystal assisted collimation to be made at fixed energy
- In a preliminary layout the optimal channeling angle for LHC was estimated to be 40-50μrad



Additional detectors:

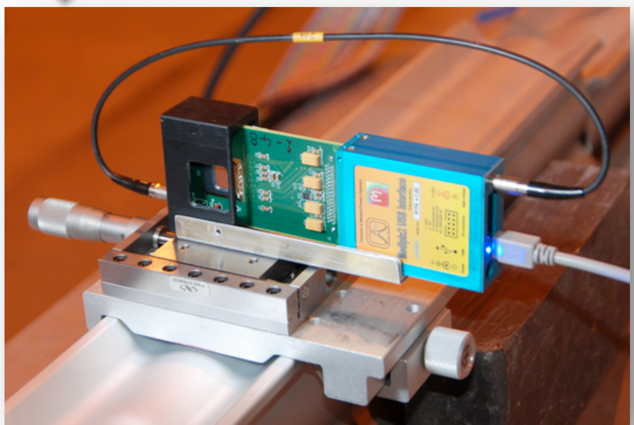
- In-vacuum detectors in a Roman Pot located in the beamline between the crystal and absorber
- In-vacuum quartz Cerenkov counters just in front of the crystals and absorber
- Additional out-of-vacuum loss counters based on scintillator counters and GEMs for reliable detection of the loss maps close to the crystal and the absorber and in the large dispersion areas downstream

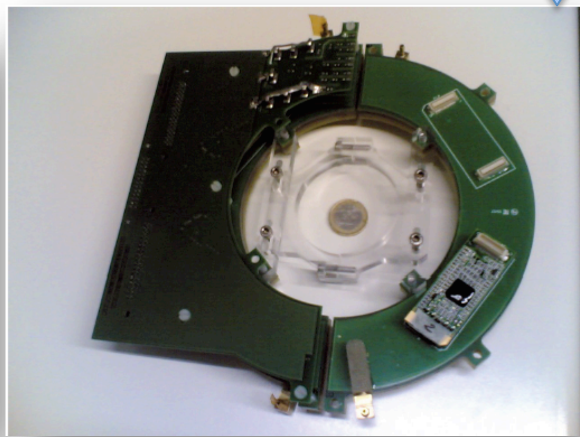
LUA9 additional detectors

LHC BLMs for losses pattern over the full ring

Additional detectors for local losses, high radiation hardness required :

- ❑ Out vacuum, to measure inelastic interaction rate at the crystal
  - ✓ Plastic scintillators
  - ✓ GEM (less saturation problems, already used in LHCb)
- ❑ In vacuum, to measure population and shape of the channeled beam
  - ✓ Medipix, good shape measurement, difficult evaluation of the population
  - ✓ Thin scintillating fibers (less accuracy in shape measurement, but more precise counting
  - ✓ Micro-capillaries filled with scintillating liquid





timetable

- **June 2011:** launch simulation studies for the optimal crystal collimation scenario in one LHC ring relying on three crystal/goniometer setups and three Roman Pots
- **Nov 2011:** fix the locations of the three crystals and Roman Pots for insertion 7 of the LHC

→ TDR ←

- **Winter shutdown 2011/12:** install the basic infrastructure (additional cables, segmented pipes with vacuum valves) where the installation of crystals and Roman Pots can be made in a short time with minimal impact on vacuum
- **2011/2012:** produce three crystal/goniometer setups based in the IHEP/PNPI technology and three mini Roman Pots based on CERN technology
- **Winter shutdown 2012/13:** install at least one but possibly three full crystal/goniometer plus mini Roman Pot setups
- **Jan/Mar 2013:** crystal collimation tests with beam

Beam request to the LHCC: 15 shifts per calendar year.

Cost and manpower

Basic hardware

- Three devices to clean the beam halo in the horizontal, vertical and skew transverse planes in only one LHC ring
- A goniometer with two crystals, one specialized for the injection and the other for collision energy, per collimation channel
- A Roman Pot with highly segmented pixel detectors, two in-vacuum Cerenkov plates and a scintillator telescope of two counters and a highly segmented GEM, out of vacuum

Cost

- 1.3 MCHF for the infrastructure (cables, vacuum pipes, electronic drivers for motors, the counting room and software drivers)
- 400 kCHF per extraction channel (200 kCHF for the crystal- goniometer and 200 kCHF for detectors, power supplies and the controllers)

The total cost of the investment is 2.5 MCHF

The manpower come from the UA9 Collaboration (30 FTE per year) and from the Collimation Project (2 FTE per year)