Кристаллическая коллимация протонов высокой энергии:от У-70 к LHC

Эксперимент UA9 ПИЯФ-ИФВЭ-ЦЕРН

1997-2001 – высокоэффективный кристаллический вывод и коллимация протонов на У-70 в ИФВЭ

2002-2006 – исследование каналирования и объемного отражения протонов в изогнутых кристаллах на ускорителях ПИЯФ и ИФВЭ

2006-2009 – исследование каналирования и объемного отражения на выведенных пучках в CERN

2009 - 2012 – исследование кристаллической коллимации на циркулирующих пучках ускорителя SPS в CERN

В проекте UA9 было предложено использовать возможность каналирования и объемного отражения протонов высокой энергии в изогнутых кристаллах с целью устранения гало циркулирующих в LHC пучков протонов, что крайне важно для планируемого повышения светимости LHC.

Сотрудничество ИФВЭ-ПИЯФ занимает лидирующие позиции в мире в исследовании и практическом применении кристаллов для управления протонными пучками.

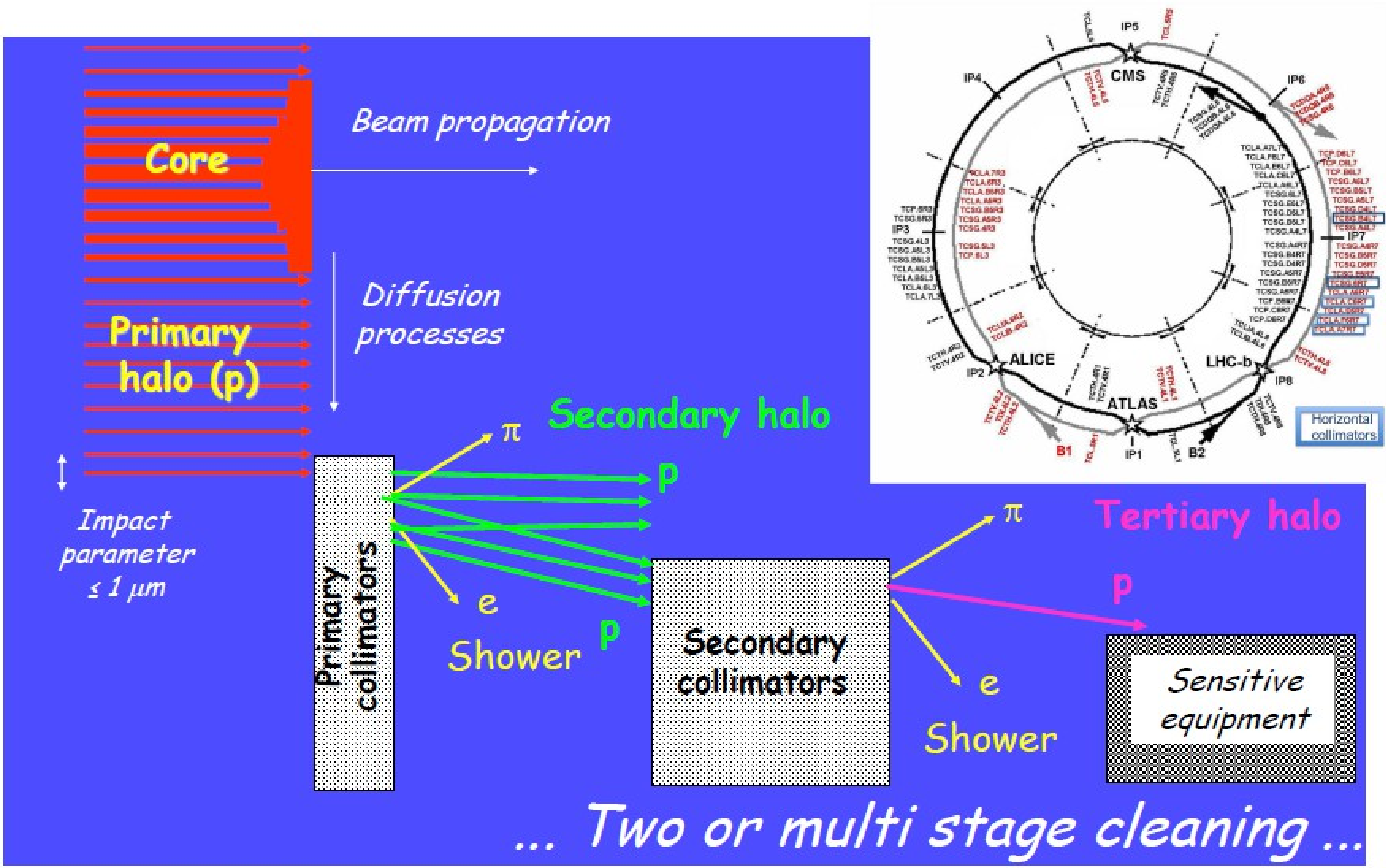
Серия экспериментов, выполненная коллаборацией UA9 в ЦЕРН на выведенных и циркулирующих пучках ускорителя SPS подтвердила перспективность этого метода для коллимации пучков в LHC.

Принято решени об установке в 2013 году пробной системы кристаллической коллимации непосредственно в кольце LHC.

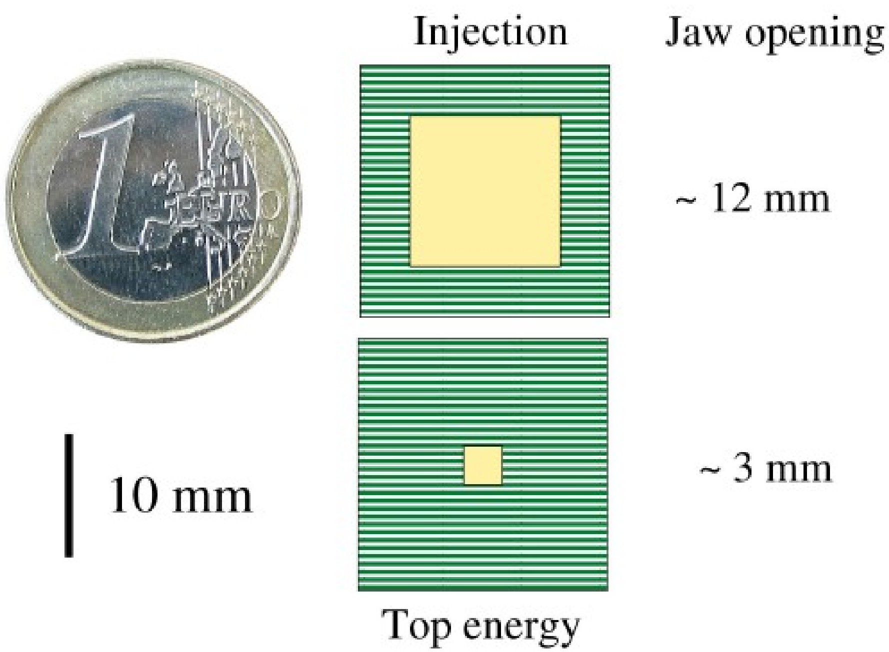
Задачи коллимации

- **Радиационная защита оборудования ускорителя: поглощение потерянных адронов в хорошо определенных местах**
- **Целостность сверхпроводящих магнитов: предотвращение перехода магнитов из сверхпроводящего состояния в нормальное в результате ионизационных потерь потерянных частиц**
- **Оптимальные условия для физических исследований (максимум соотношения сигнал/фон): контроль фона от пучкового гало в экспериментах**

Principle of Beam Collimation



Collimation with small gaps

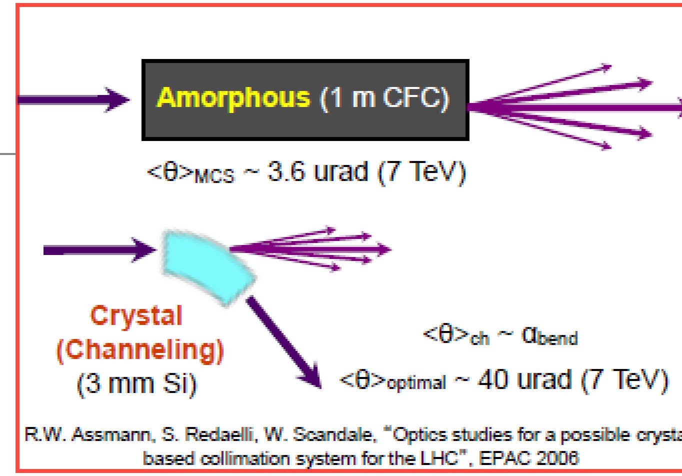


LHC beam will be physically quite close to collimator material and collimators are long (up to 1.2 m)!

- ***Precision positioning***
- ***Risk of damage to collimators!***
- ***Beam electro-magnetic fields interact with the collimator material!***

Machine impedance increases while closing collimators.
*LHC will operate at the **impedance limit** with collimators closed!*

Crystal collimation concept



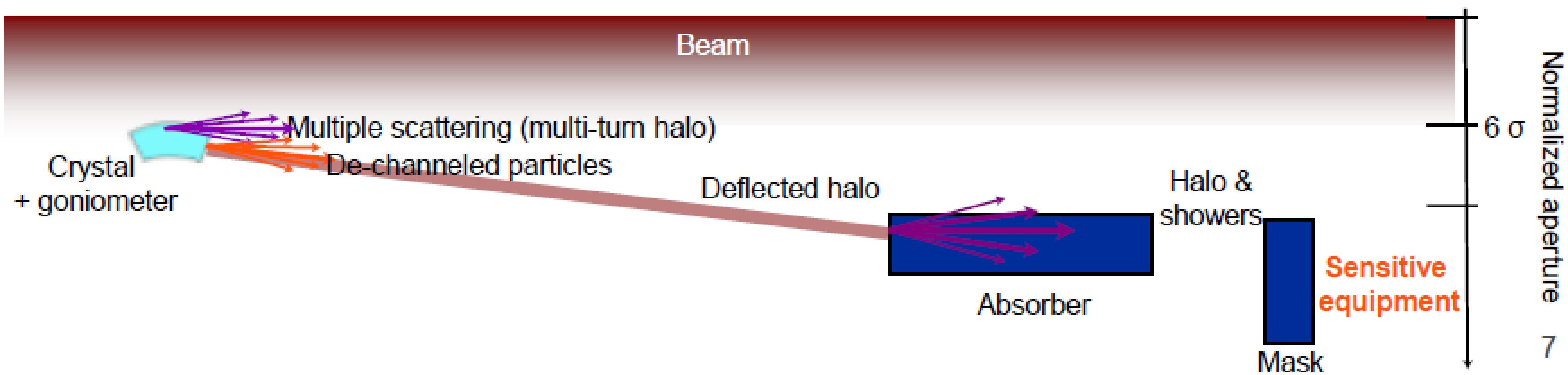
UA9 MISSION: investigate bent crystals as primary collimators in hadron colliders.

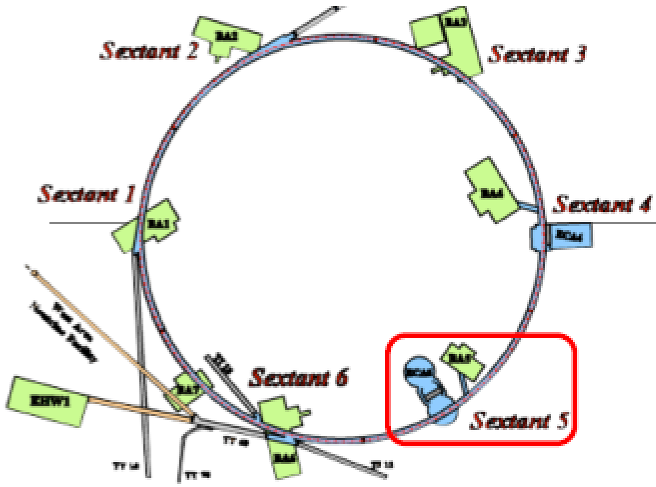
- Mechanically bent crystal instead of amorphous primary deflector.
- Particles are subjected to a coherent interaction (channeling):
  - reduced loss rate close to the crystal
  - reduced probability of diffractive events and ion fragmentation/dissociation

  BUT
  - small angular acceptance $2\times\theta_c$ depending on the beam energy
  - localization of the losses on a single absorber, thanks to large deflection angle

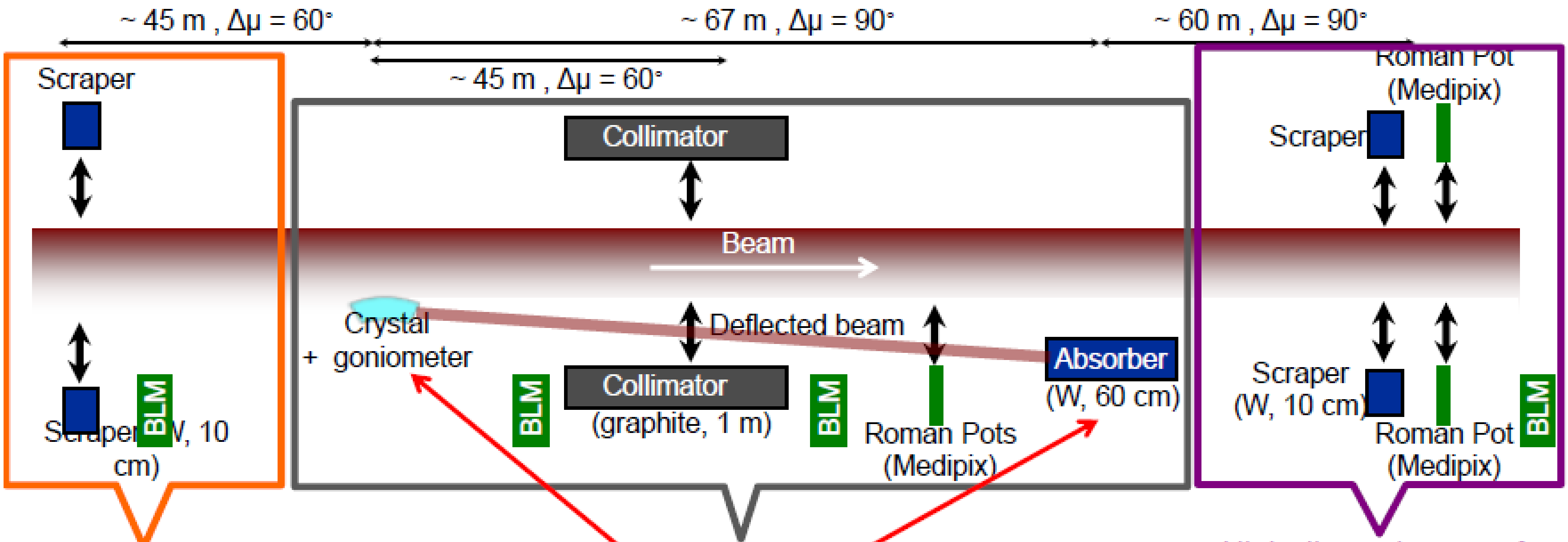
$$\theta_c = \sqrt{\frac{2U_{max}}{E}}$$

Energy	θ_c [µrad]
120 GeV	18.26
270 GeV	7.30
450 GeV	9.42
3.5 TeV	3.38
7 TeV	2.39





UA9 layout in 2012



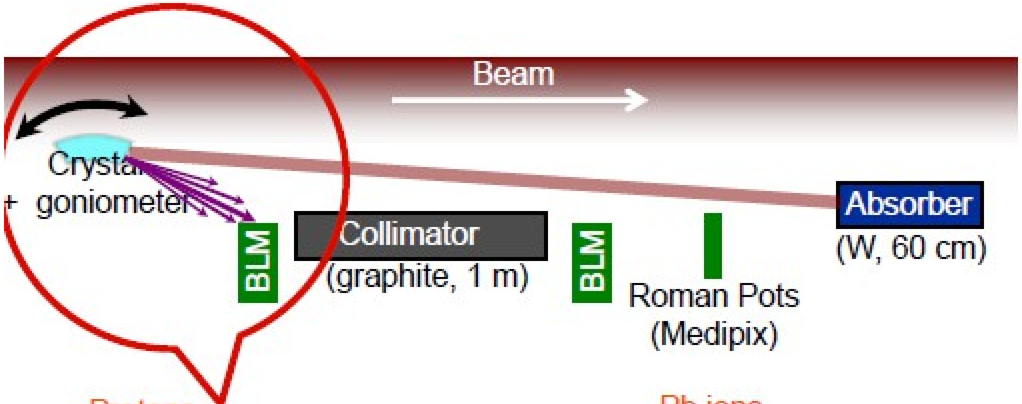
Non-dispersive area for measurements “far” from the collimation system

Crystal collimation system (in two stages)

With instrumentation for loss rate and efficiency measurement

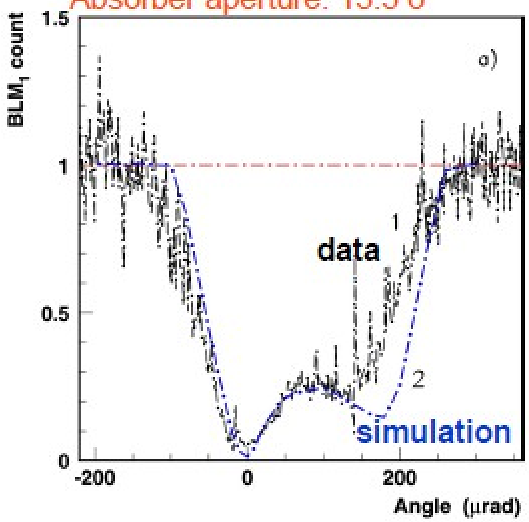
High-dispersion area for measurements on off-momentum halo

Loss rate reduction in the crystal area

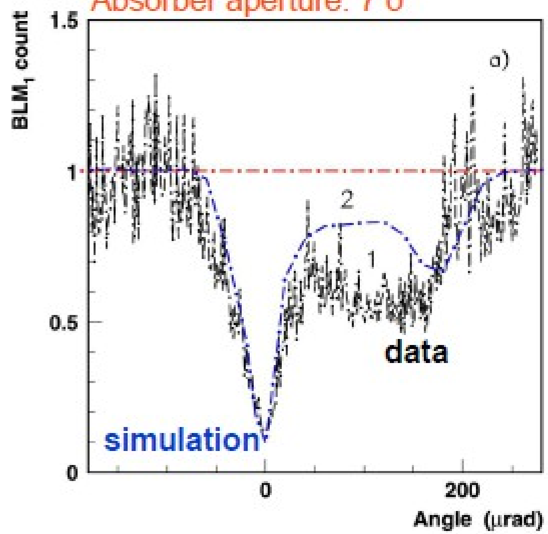


- Large loss reduction factor from "amorphous" to "channeling" orientation
  - 5÷20x reduction for protons
    3÷7x reduction for Pb ions
  - Best performance using a 1 mm long crystal
- Small discrepancy data/simulation
  - Mis-cut crystal modeled in simulation

Protons
Crystal aperture: 9 σ
Absorber aperture: 13.5 σ

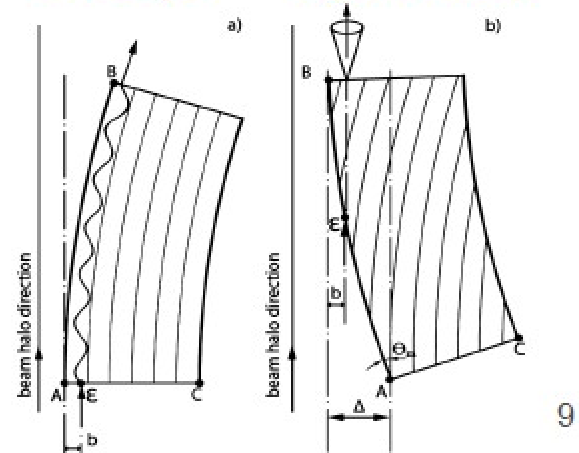


Pb ions
Crystal aperture: 3.5 σ
Absorber aperture: 7 σ

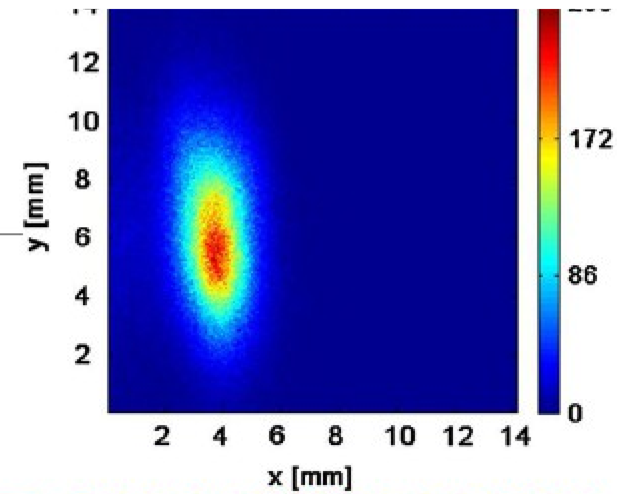


Perfect crystal

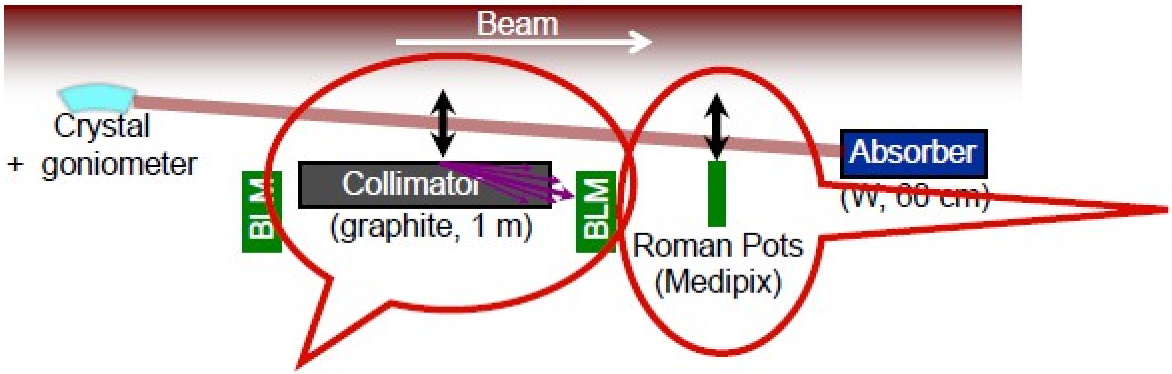
Crystal with mis-cut

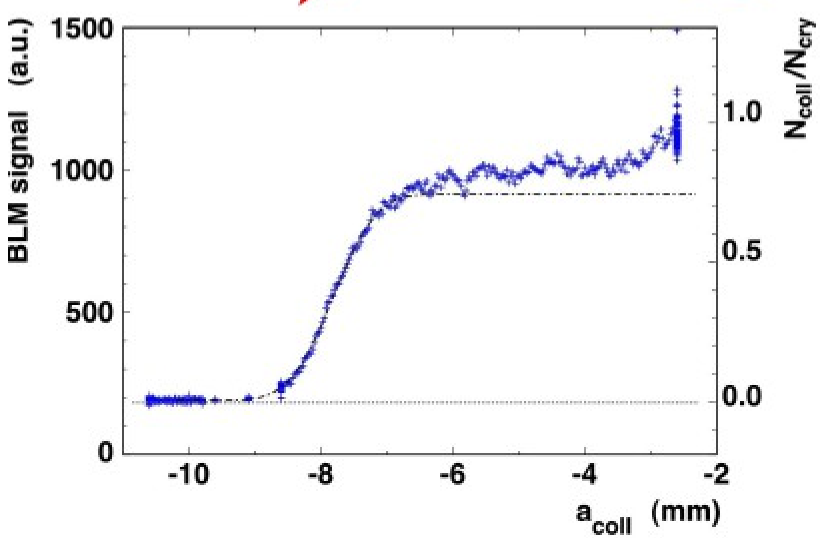


Extraction efficiency



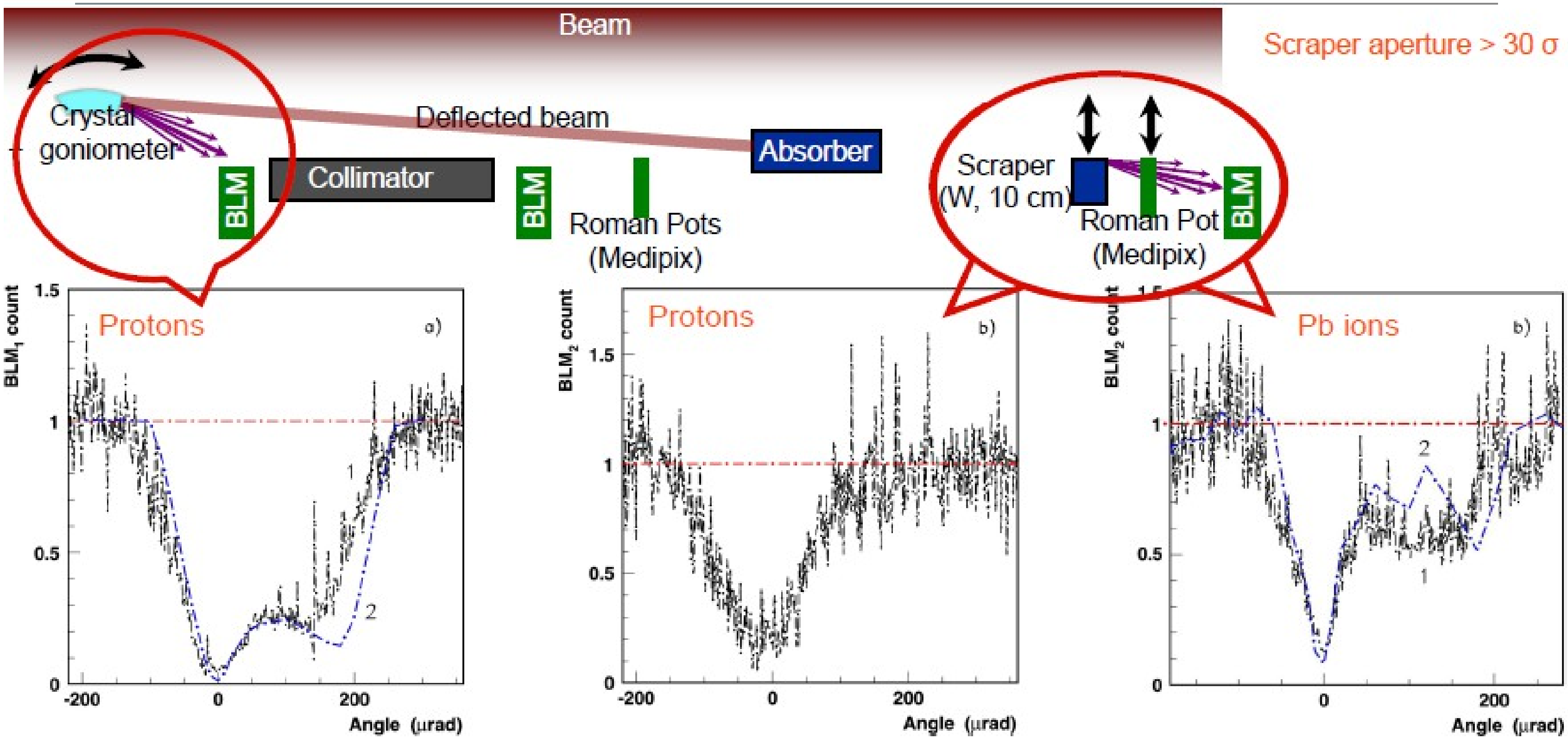
Extracted beam observed with the Medipix





- Efficiency = $N_{deflected}$ / $N_{crystal}$
- Assumptions:
  - the number of particles intercepted by a moving object is proportional to the loss rate downstream the object
    - $N_{deflected}$ is proportional to the losses when intercepting the whole deflected beam
    - $N_{crystal}$ is proportional to the losses when the collimator is the primary aperture
- efficiency for protons: 70÷80%
- efficiency for Pb ions: 50÷70%

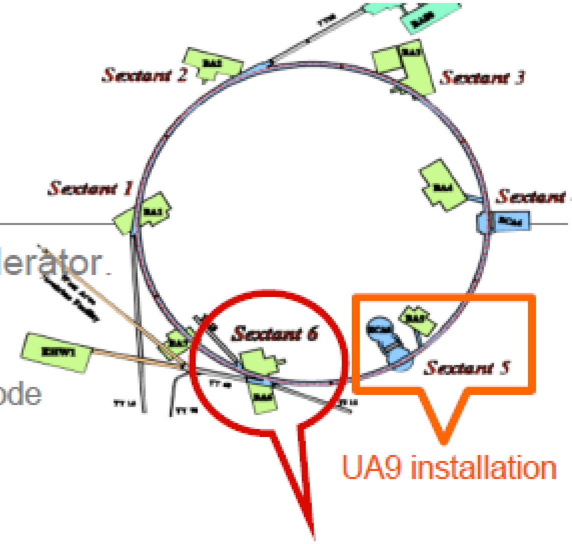
Reduction of the off-momentum halo population



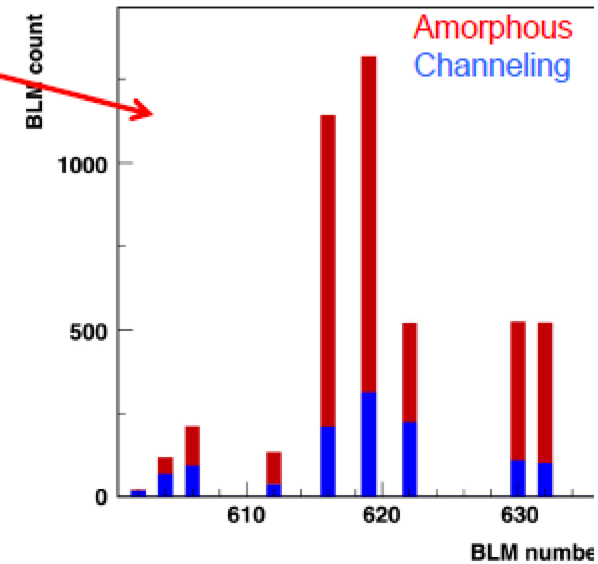
- ❑ excellent correlation with the losses observed at high-dispersion and at the crystal
- ❑ 2÷6x reduction for protons (less than in crystal region)
- ❑ 3÷10x reduction for Pb ions (equal to crystal region reduction)

Loss maps

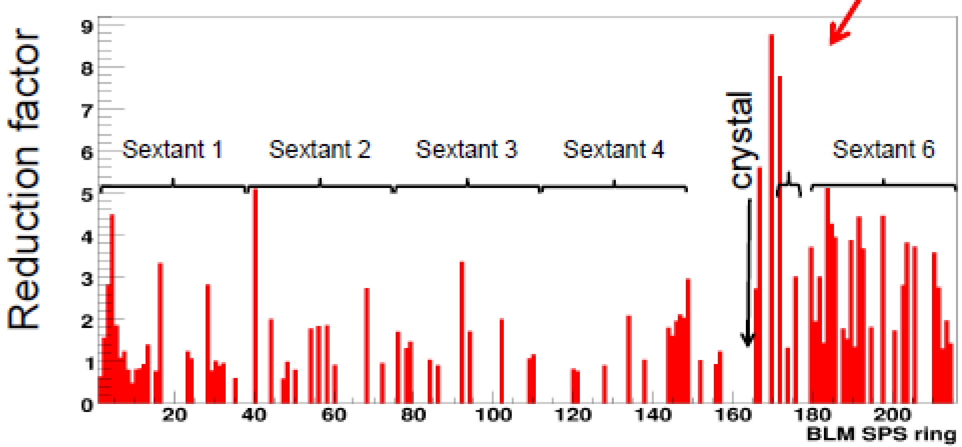
Loss maps are beam loss monitor rates registered along the accelerator.



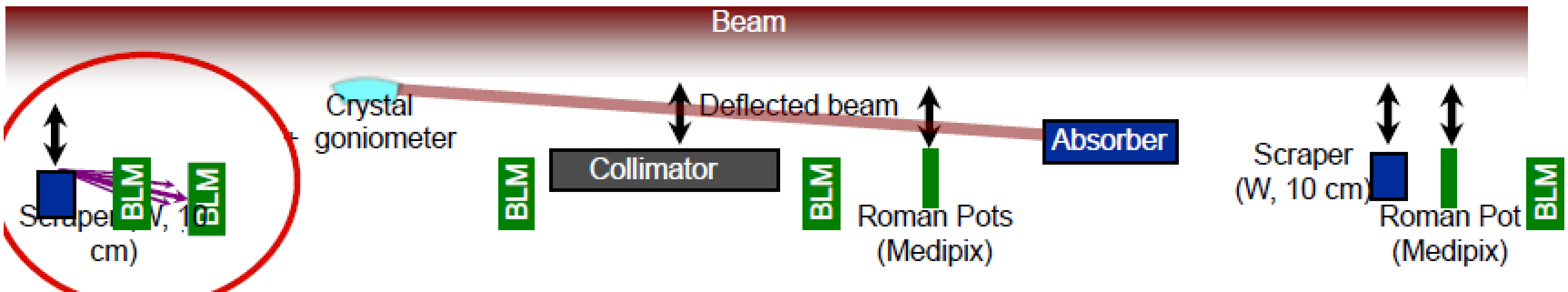
- Loss map measurement is not trivial in UA9:
  - the SPS BLM system is optimized for high-intensity operation in pulsed mode
  - UA9 operates at low intensity and low loss rate.
- Loss map measurement in 2011:
  - intensity increased from 1 bunch (I = 1.15 x 10^{11}) to 48 bunches,
  - Clear reduction of the losses in the Sextant 6 next to the experiment

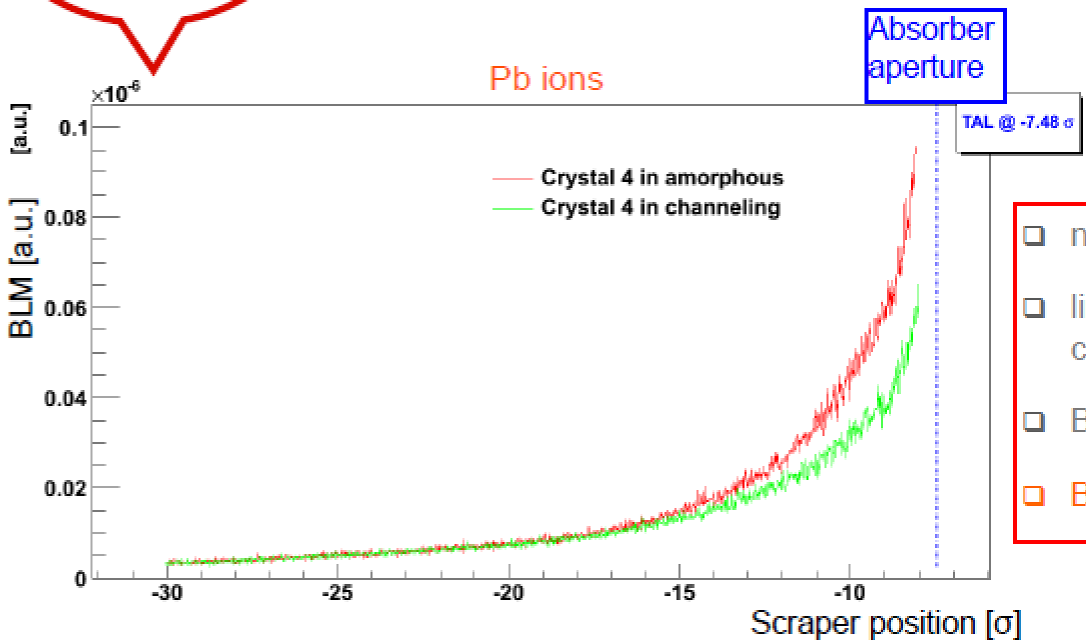


- Loss map measurement in 2012:
  - total intensity: 3.3 x 10^{13}, 4 x 72 bunches with 25 ns spacing
  - Loss reduction in the entire ring (in the reliable BLMs)



Halo profile "far from the crystal"



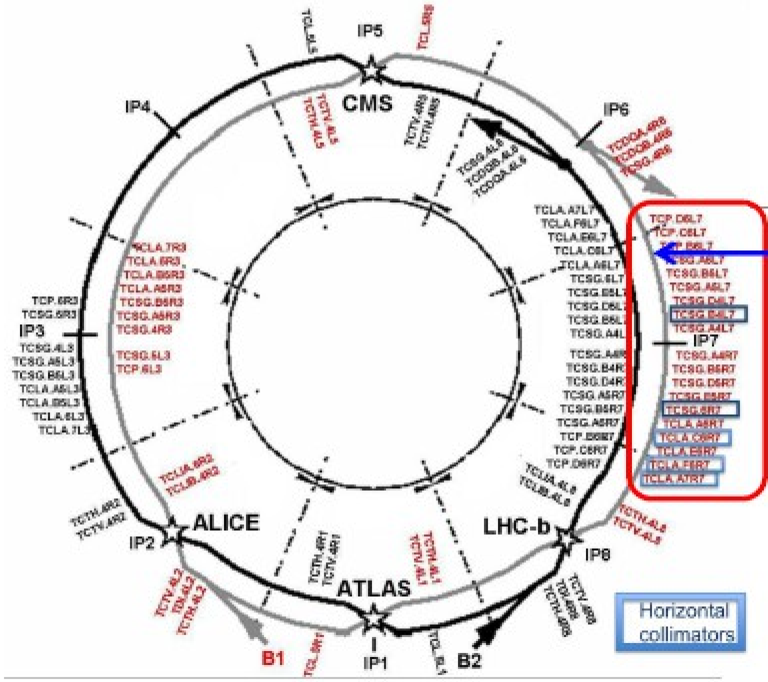


- new scraper upstream the crystal
- linear scans of the scraper with crystal in channeling and amorphous position
- BLM signal close to detector baseline
- BLM rate reduced with Pb-ions

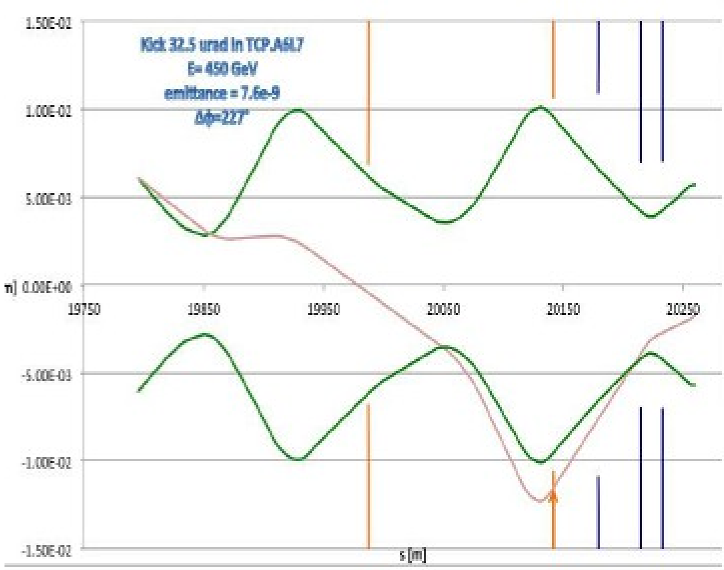
Toward installation in LHC

- In September 2011, a letter of intents was presented to the LHCC, asking to extend UA9 to the LHC:
  - new experiment (LUA9) recommended by the LHCC and accepted by the accelerator directorate
  - goals:
    - demonstrate the extraction of the beam halo in the LHC
    - measure the possible improvements with respect to standard collimation
  - the UA9 Collaboration together with the LHC collimation team (leader S. Redaelli) will conduct the test.

Toward LHC: layout



H & V crystals



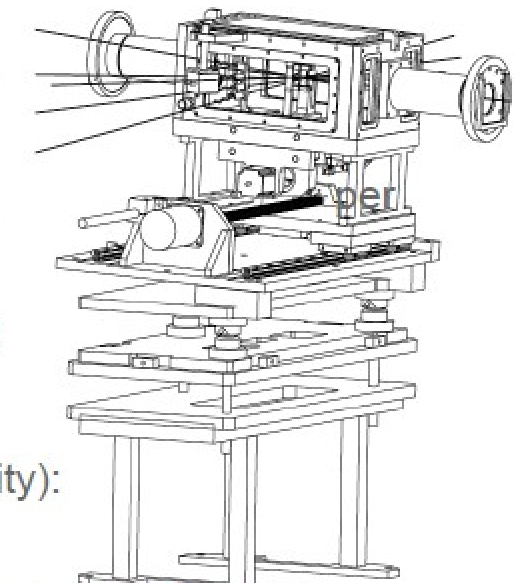
- Layout of the LUA9 experiment
  - only one beam (beam 1)
  - two crystal (horizontal and vertical)
  - two detector stations (horizontal and vertical)
    - Mini-Roman pot with a segmented detector
    - Cherencov detector in vacuum
  - initially/later:
    - test at steady/ramping energy
    - standard collimation system in-place/retracted
- Crystal located close to the primary collimators (see arrow):
  - extracted beam absorbed by a secondary collimator
  - highest radiation area, tight space allowance

Toward LHC: R&D for a goniometer

- Acceptance for channeling defined by the critical angle $\theta_c = \sqrt{2U_0/E} = 2.4\ \mu rad$ (7TeV)
- Goniometer accuracy must be smaller than angular acceptance:
  - Total angular range : >10 mrad
  - "Resolution": <0.1 μrad
  - "Accuracy": < 1 μrad
    - Maximum tilt inaccuracy: < 1 μrad
    - Linear resolution: 5 μm
  - Total linear range: 40 mm
- Possible solutions
  - mechanical goniometer à la "SPS (IHEP, Russia)" has resolution < 10 urad
  - mechanical device developed by industrial partner CINEL for the SPS:
    - static resolution and accuracy meet the LHC specifications
    - test on going to assess accuracy in dynamic regime
  - piezoelectric device under development in collaboration with industrial partner ATTOCUBE.

Crystal damage

- Radiation resistance:
  - IHEP U-70 (Biryukov et al, NIMB 234, 23-30): 70 GeV protons,
    10^{14} p every 9.6 s, several minutes irradiation, channeling efficiency unchanged
  - NA48 (Biino et al, CERN-SL-96-30-EA): 450 GeV protons, 2.4 s spill of 5×10^{12} p every 14.4 s, one year irradiation, channeling efficiency reduced by 30%
  - LHC: 7 TeV protons, 3×10^{14} p per fill
  - test HRMT16-UA9CRY under approval at HiRadMat facility:
    - 440 GeV protons, max 288 bunches, 1.7×10^{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

experiment has been performed and no sign of damage were observed in the irradiated crystal

Conclusion

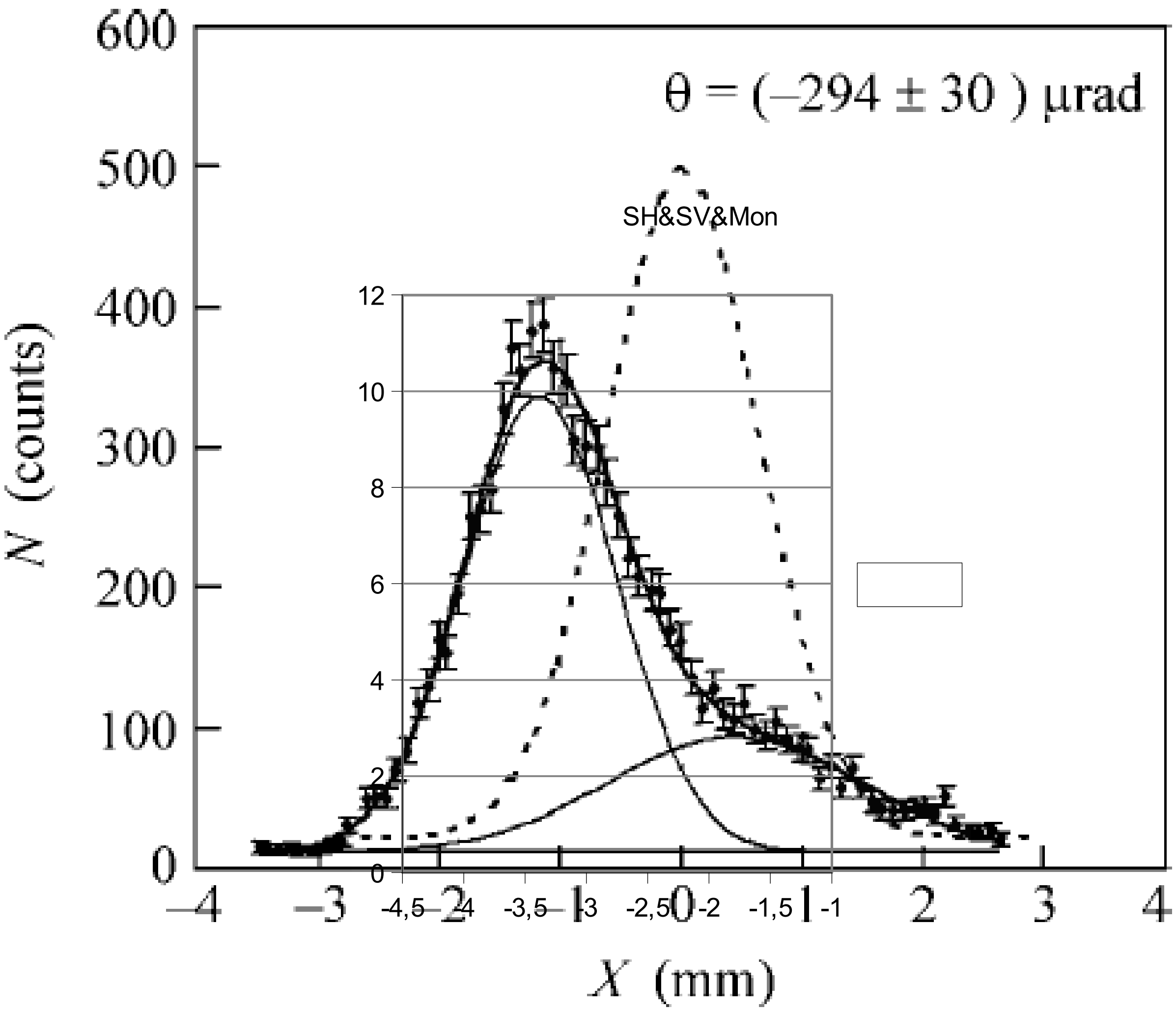
- The UA9 experiment is studying the possibility to use crystals as primary obstacle in collimation systems.
  - Test beam measurements demonstrate the possibility to efficiently deflect particles at high angles using bent crystals.
  - Using a prototype crystal collimation system in the CERN-SPS:
    - collimation of the beam reliably obtained for proton and lead ion beams
    - losses in the collimation system and in the closest high dispersion area reduced when using a crystal target instead of an amorphous one
    - new measurements to estimate loss reduction in the whole accelerator ring and to optimize the parameters of the system
  - The team is preparing the installation of a minimal crystal collimation system in the LHC.

Публикации 2012

- W. Scandale et al., Strong reduction of the off-momentum halo in crystal assisted collimation of the SPS beam. Phys. Lett. B, 714 (2012), 231–236.

Измерения в ПИЯФ

Микро-пучок 1 ГэВ протонов



Интенсивность:

I ~ 102 – 103 p/сек

Размер на мишени:

σ ~ 10 мкм

Расходимость:

σ ~ 20 мкрад

Размер в 5 м от мишени:

σ ~ 100 мкм

Холодная зима 2012