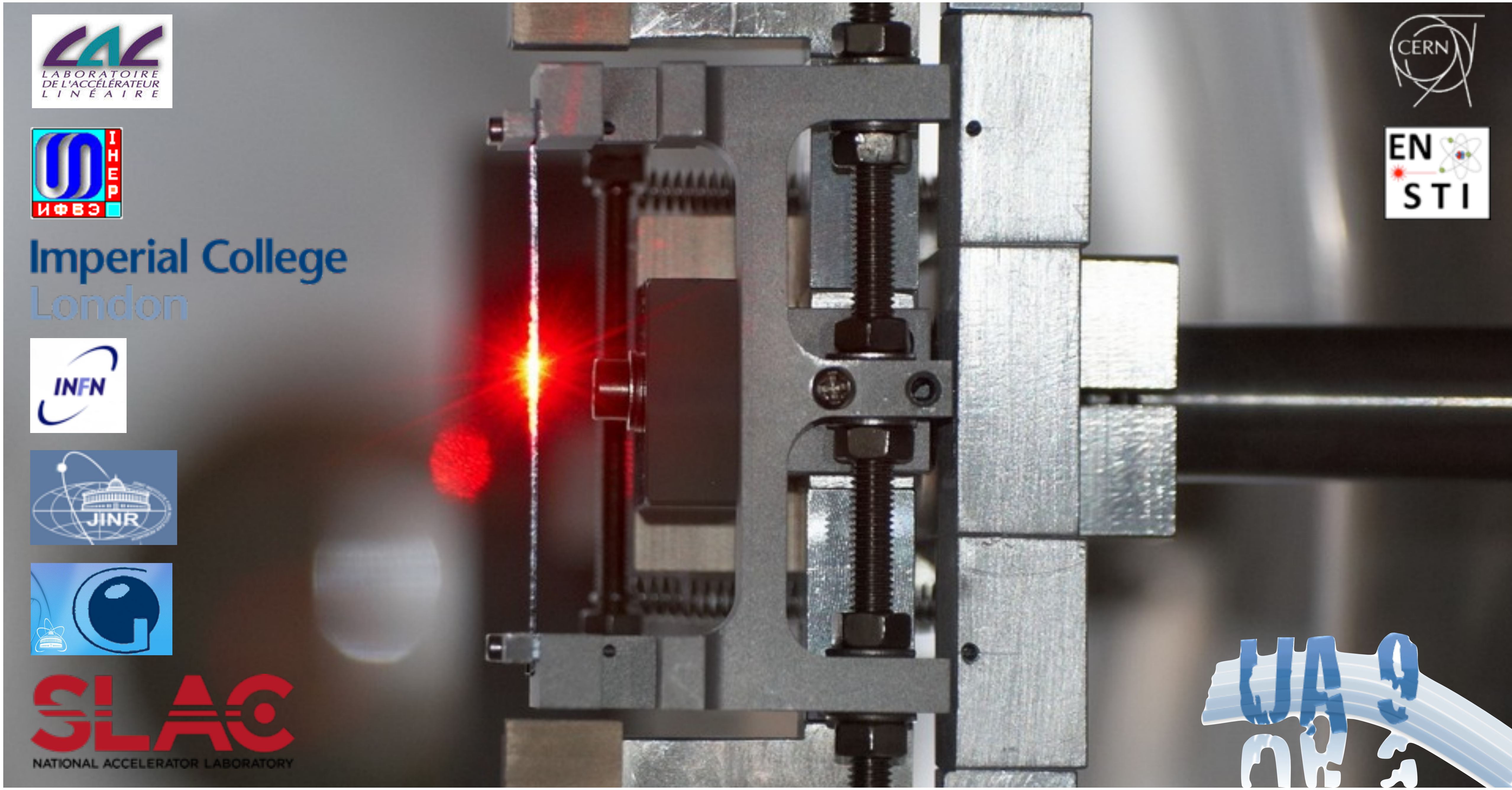


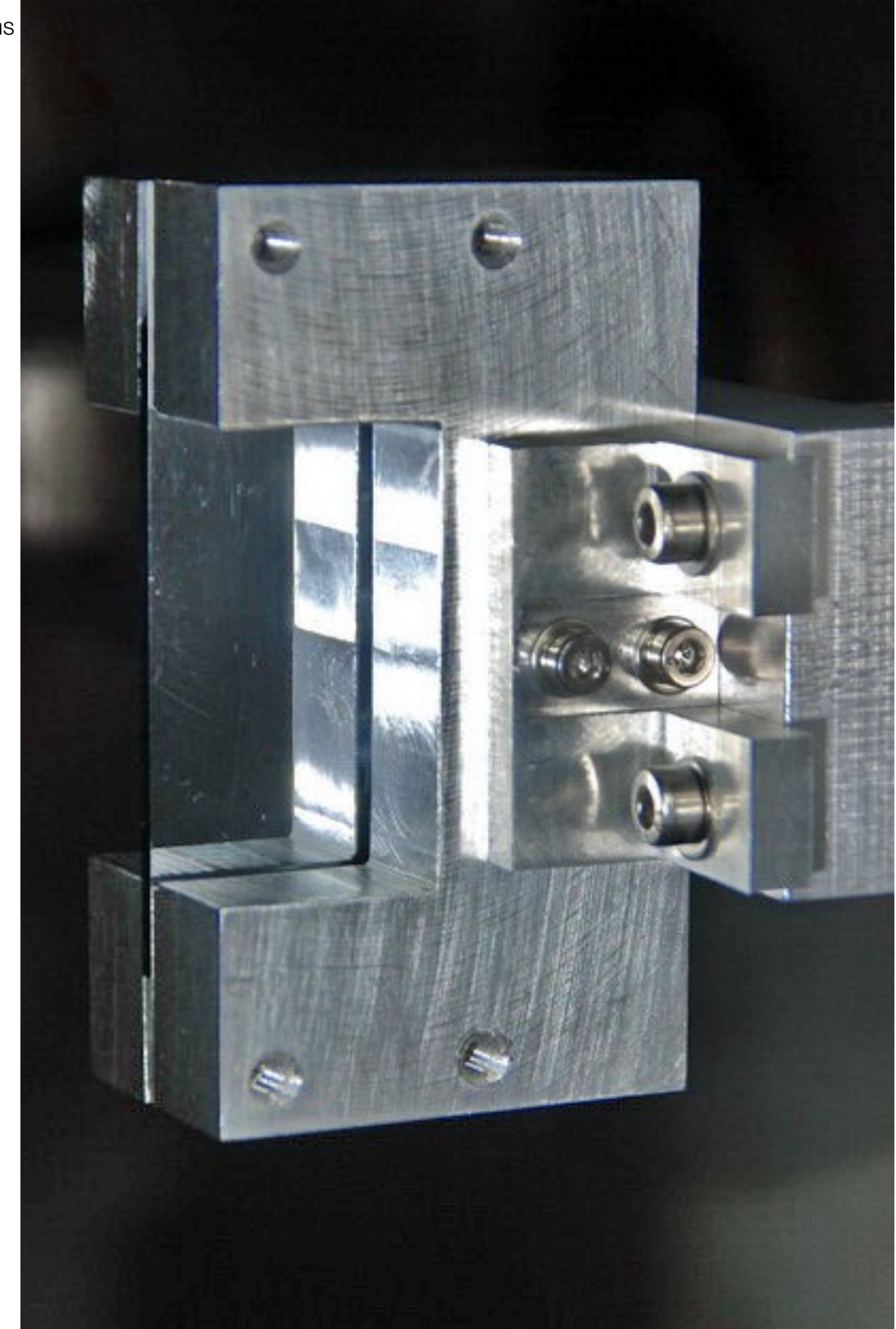
Physics at AFTER using the LHC beams - February 11h, 2013 - ICT* Trento (IT)

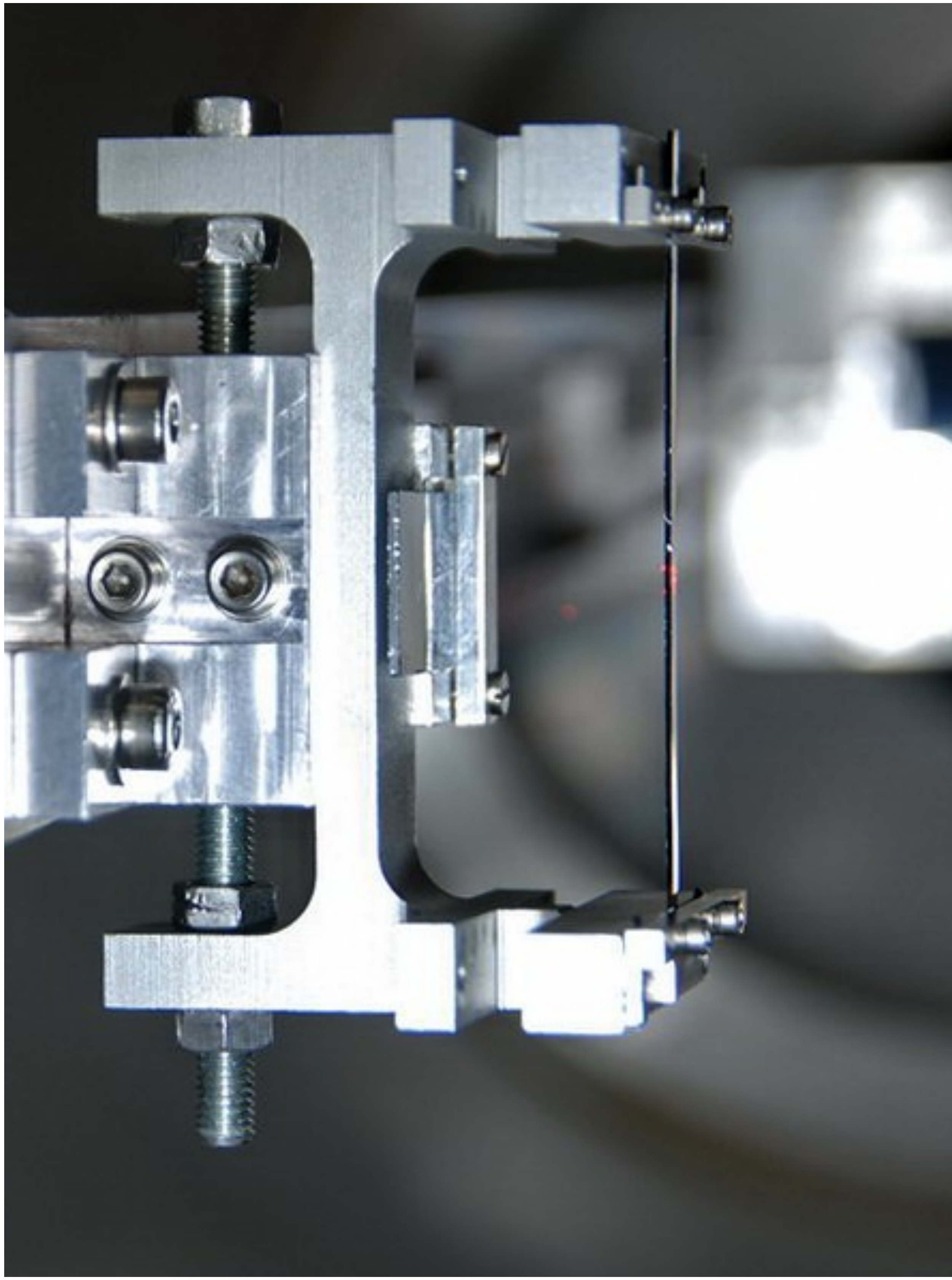
UA9 - Crystal collimation at CERN-SPS

Simone Montesano (CERN - EN/STI)
on behalf of the UA9 collaboration

Outline

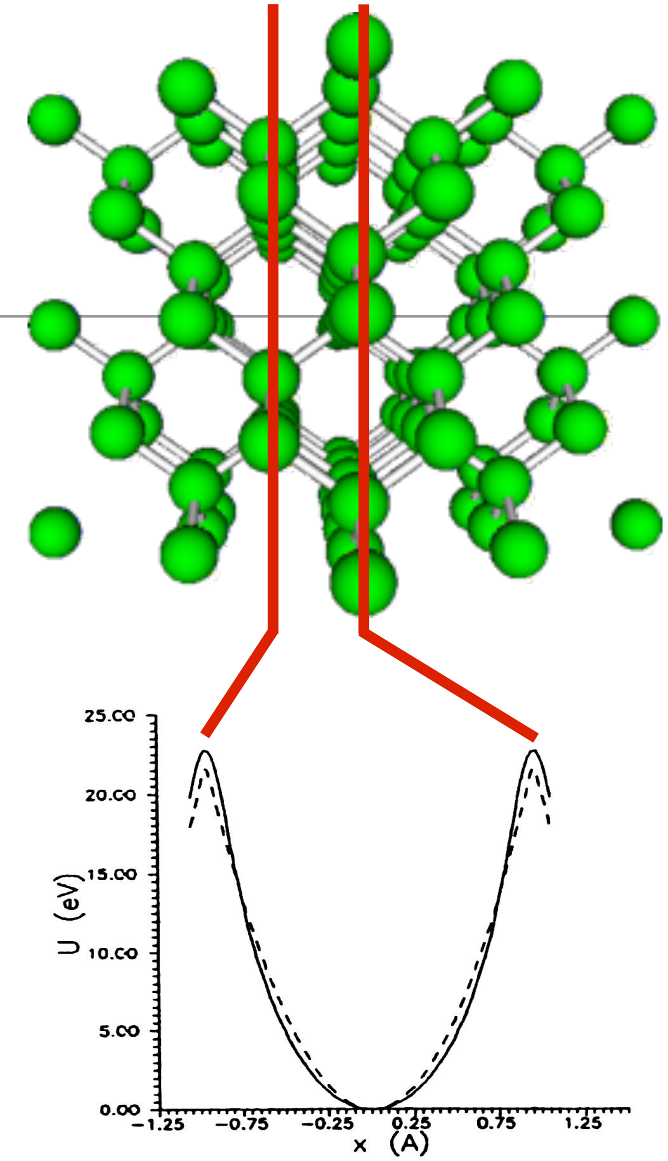
- Introduction:
  - Few words about crystals
  - Few words about beam collimation
- The UA9 experiment at CERN:
  - facilities & installations
  - results
  - future plans



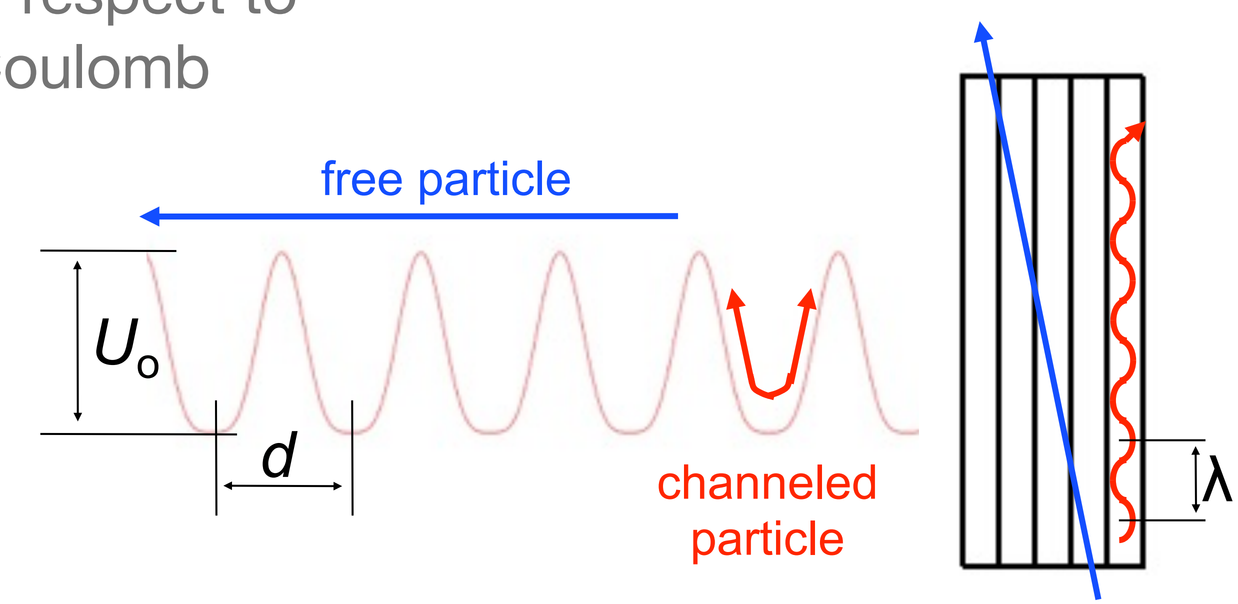


Few words about crystals

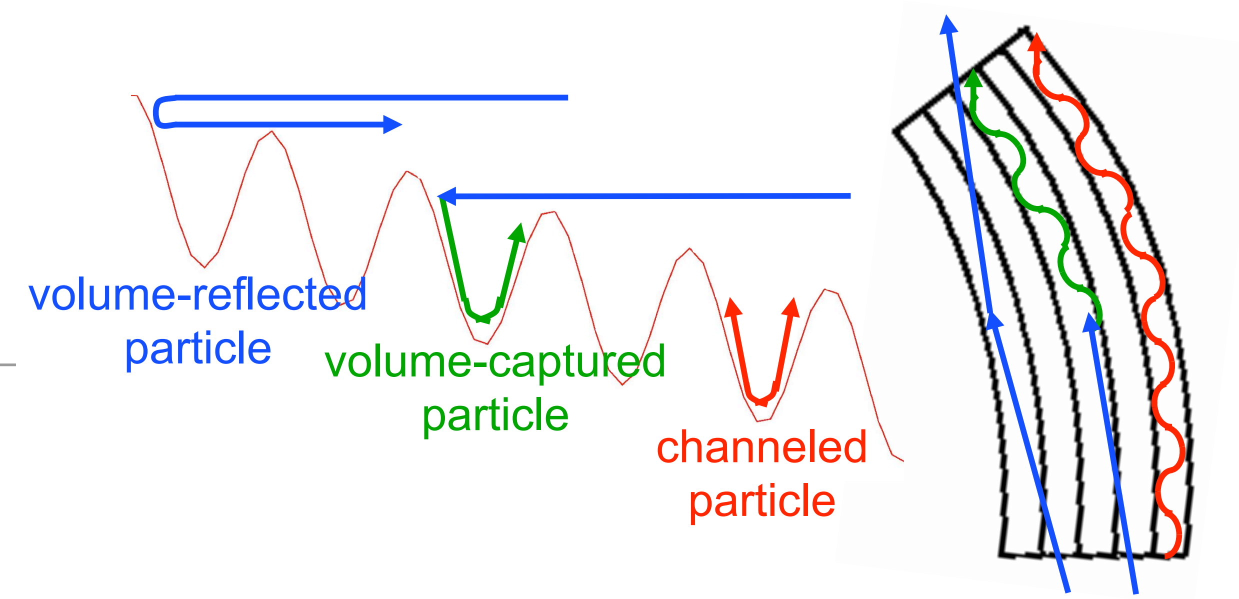
Particle-crystal interactions



- Atoms are distributed according to a **lattice** in crystals
  - Lindhard describes the potential among planes with a continuous function (1965)
- Particles traversing a crystal may undergo **coherent interaction**:
  - **depending on the impinging angle** of the particle with respect to the lattice orientation
  - **interaction cross-sections reduced** with respect to amorphous materials (including multiple Coulomb scattering and nuclear interaction)
  - **reduced energy deposition**
  - particles trapped between crystal planes or along crystal axes (**channeling**)

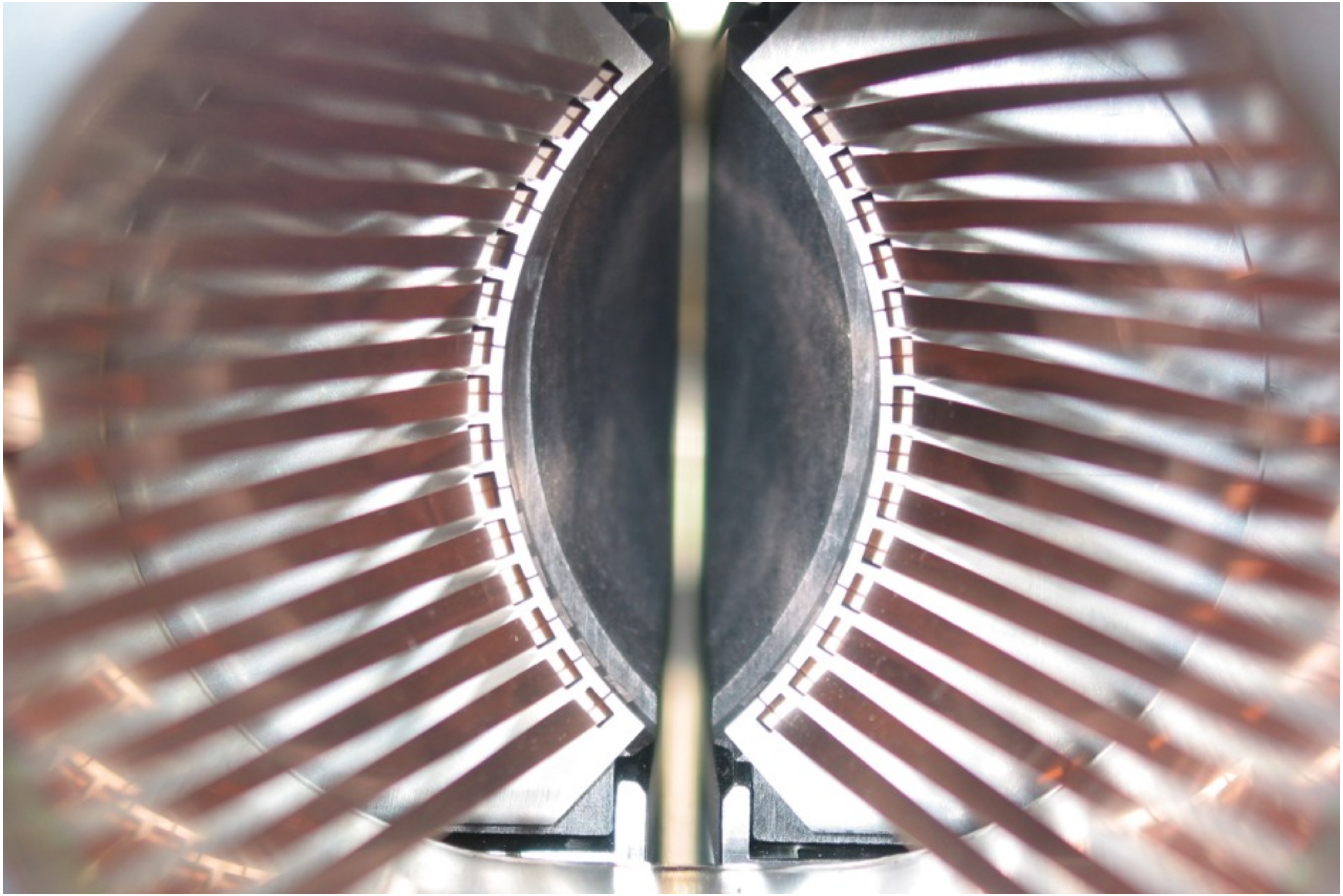


Bent crystals



- For a moderately **bent crystal**:
  - particles still subjected to coherent interaction
  - bent channels can **deflect impinging particles** (**channeling**)
  - particles can be **reflected by crystal planes** as predicted by Taratin and Vorobiov in 1988 (**volume reflection**)
  - interaction with planes can trap particles into channels (**volume capture**)

	Deflection angle	**Angular acceptance**	l = crystal length R = bending radius U_0 = plane potential height E = particle energy $\alpha = l / R$ $\theta_c = \sqrt{(2U_0 / E)}$
Channeling	α	$\pm\ \theta_c$	
Volume reflection	$\sim 1.5\ \theta_c$	α	



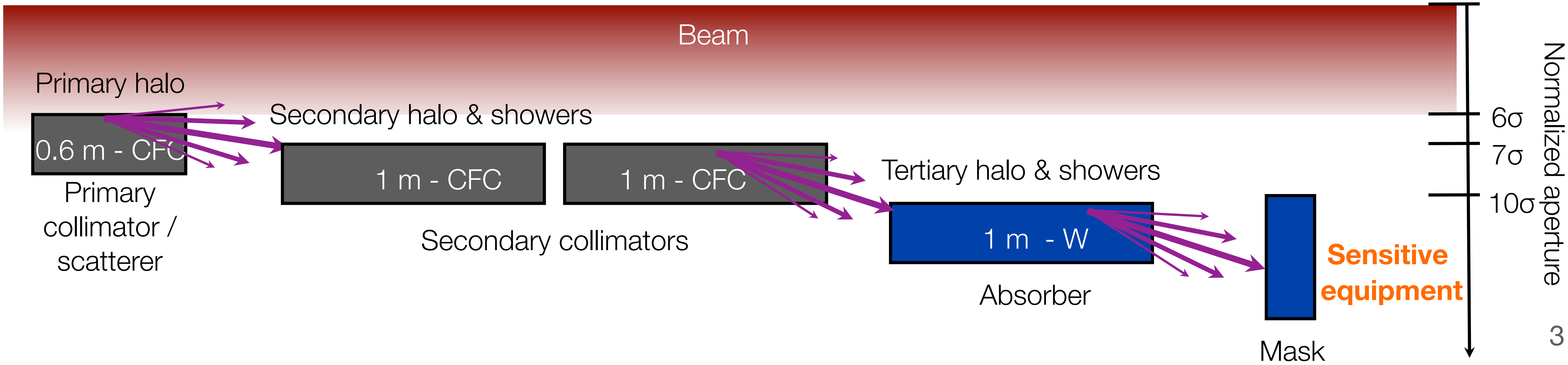
Few words on beam collimation

Beam collimation

- In any accelerator, beam particles are subjected to a **diffusive process** (from the beam core to the **beam halo**):
  - due to scattering on beam pipe residual gas, magnetic field imperfections, intrabeam or beam-beam interaction, ...
  - particles in the **beam halo** are eventually **lost in the machine**
  - beam intensity has a lifetime.
- **Collimators** are use to **intercept particles** that are lost in the machine:
  - **radiation protection**: stop particles at well defined locations (minimal losses and minimal activation at other locations)
  - **superconducting magnet integrity**: prevent beam loss-induced quenches of superconducting magnets.
  - **physics reach**: control background from beam halo in experiments
  - **hardware integrity**: passive machine protection (beam lost first at collimators).

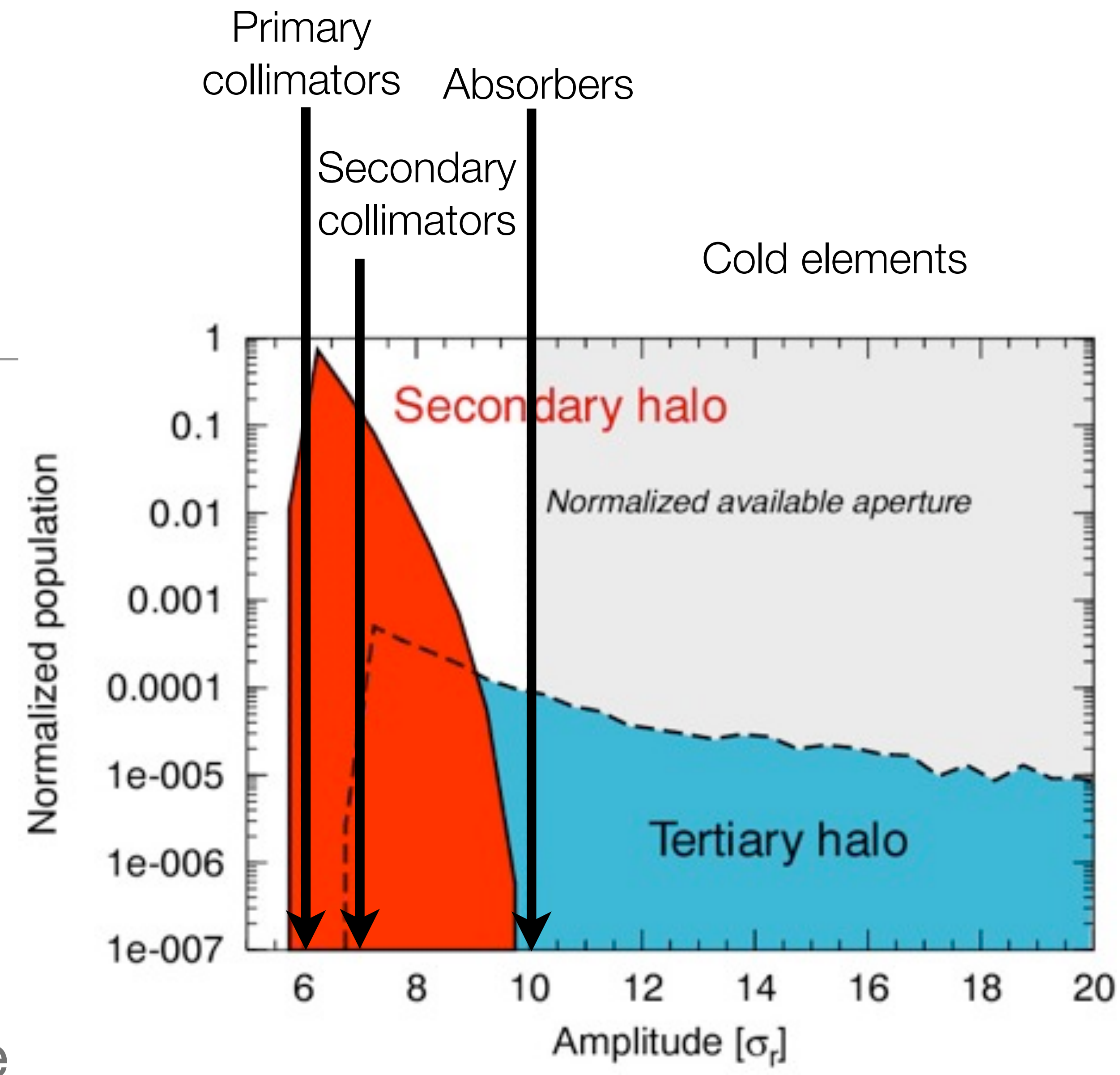
Multi-stage collimation system

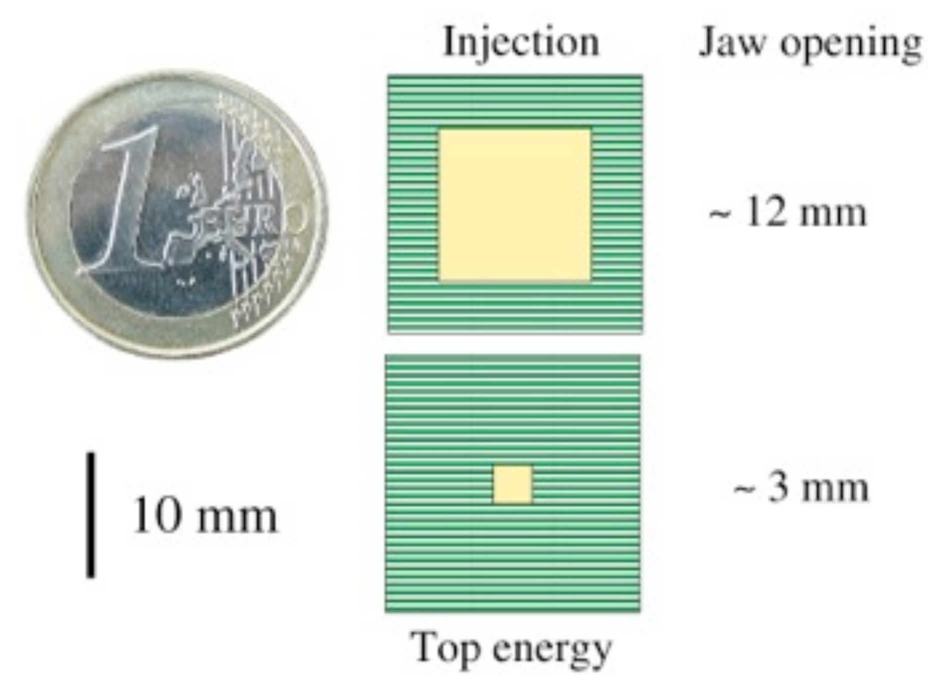
- Diffusive primary halo intercepted by massive targets (**primary collimators**):
  - **primary particles deflected** by Multiple Coulomb Scattering (<θ> ~ 3.6 urad for graphite at 7 TeV),
  - **hadronic showers produced** by interaction on the target
- **Secondary collimators** and absorbers stop deflected particles & showers
- **Tertiary collimators** and masks protect sensitive equipment from secondary halo.

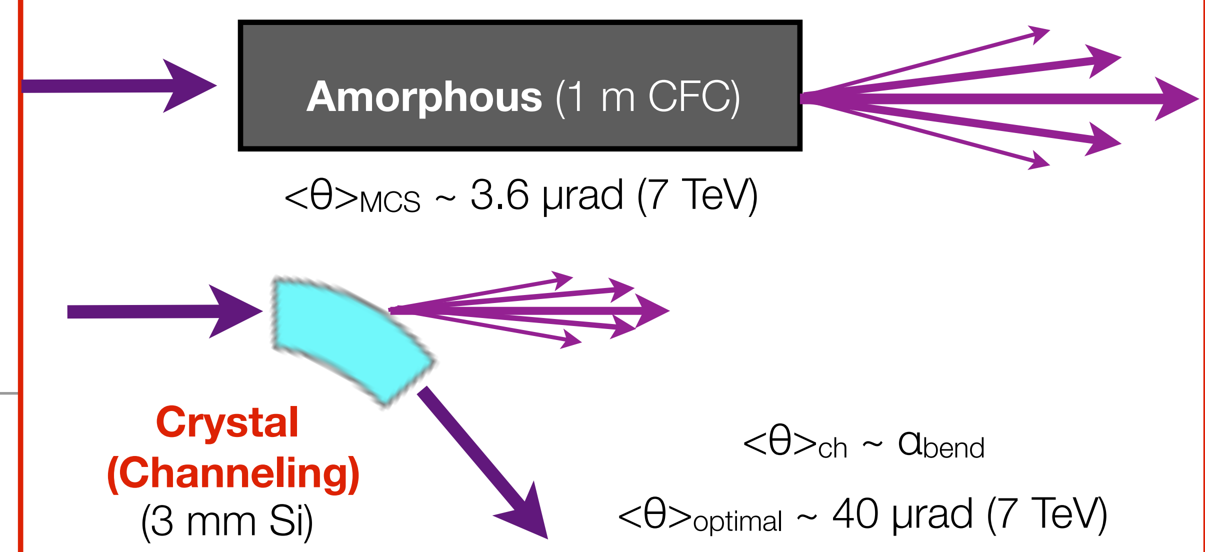


Collimation in LHC

- Three stages of collimation system:
  - **Optimal performances reached** (99.97% collimation efficiency in 2011)
- Limitations:
  - **single diffractive scattering**
    - **particles** back-scattered towards the machine aperture, eventually **lost in high dispersion areas**
  - **ion fragmentation and dissociation**
  - **high impedance** of the collimators (1 m long CFC jaws at few mm from the beam center)







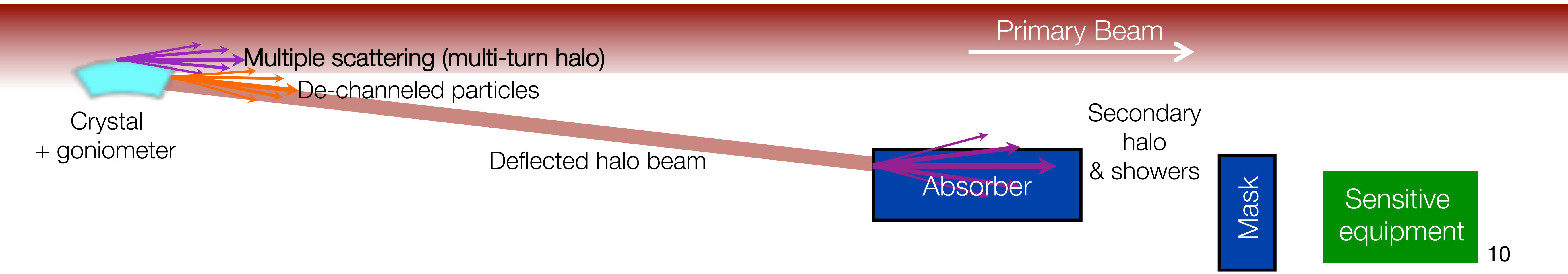
R.W. Assmann, S. Redaelli, W. Scandale, "Optics studies for a possible crystal-based collimation system for the LHC", EPAC 2006

Crystal collimation

- Bent crystals as primary collimators:
  - **coherent interaction** (channeling) of particles impinging on the crystal:
    - ✓ **reduce probability of diffractive events** and **ion fragmentation and dissociation**
    - ✓ **reduce loss rate close to the crystal**
  - **localization of the losses** on a single absorber, at larger distance from the beam (thanks to large deflection angle)
  - **small angular acceptance** ($2 \times \theta_c$)

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

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



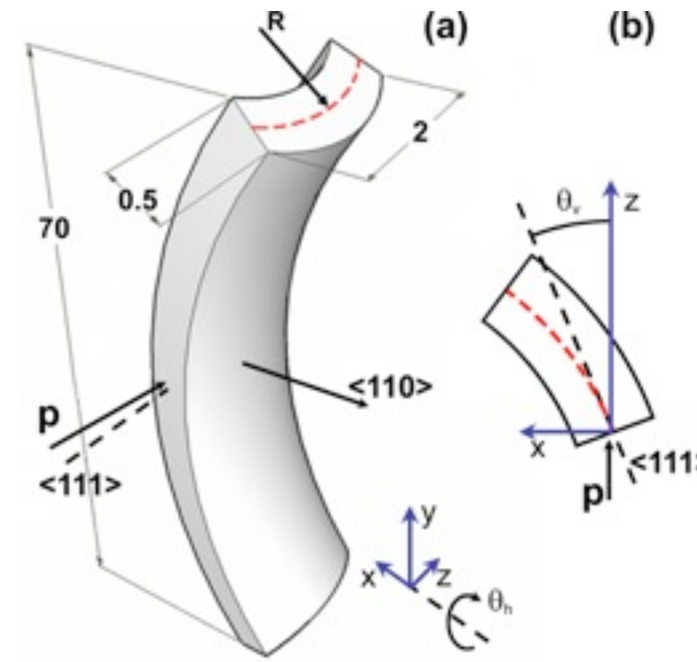
The UA9 experiment

The UA9 experiment

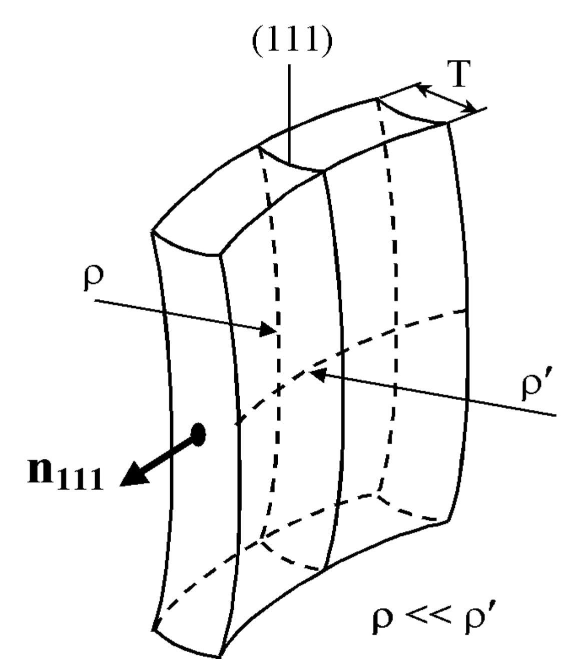
MISSION: Assess the possibility to **use bent crystals as primary collimators** in hadronic accelerators and colliders.

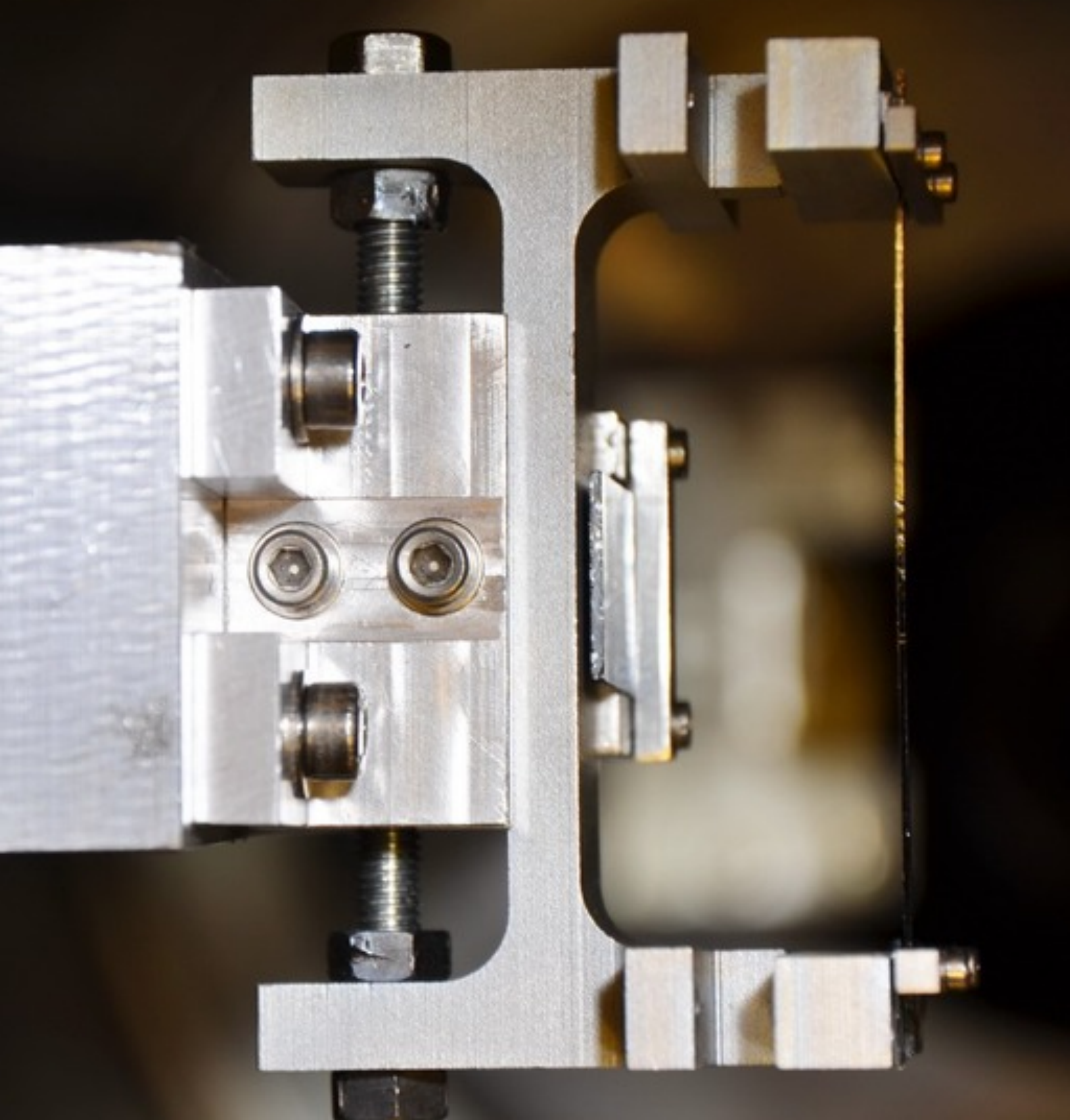
- **Test beams at CERN North Area**
  (400 GeV/c/n protons or Pb ions, 3--5 weeks per year):
  - Study of crystal – beam interactions.
  - Measurement of crystal properties before installation in CERN-SPS.
- **Prototype crystal collimation system installed in CERN-SPS**
  (120 or 270 GeV/c/n protons or Pb ions in COAST, ~ 5 days per year):
  - Test crystals and instrumentation suitable for an operational system.
  - Study the properties of a crystal collimation system.
- **Working for future installation of a prototype system in LHC**.

Production of bent crystals



- **Strip crystals** (INFN Ferrara and IHEP):
  - the applied vertical bending induces an **anti-clastic deformation** (radius R)
    - minimal crystal length ~ 1 mm
  - particles interact with **crystallographic planes <110>**
    - planes are equidistant
- **Quasi-mosaic crystals** (PNPI):
  - the initial bending (radius ρ) induces a **deformation -due to anisotropy-** along the “T” direction
    - minimal crystal length is few tenths of mm
    - the anti-clastic deformation (radius ρ’) is parasitic in this case
  - particle interact with the **crystallographic plane (111)**
    - Non-equidistant planes d1/d2 = 3



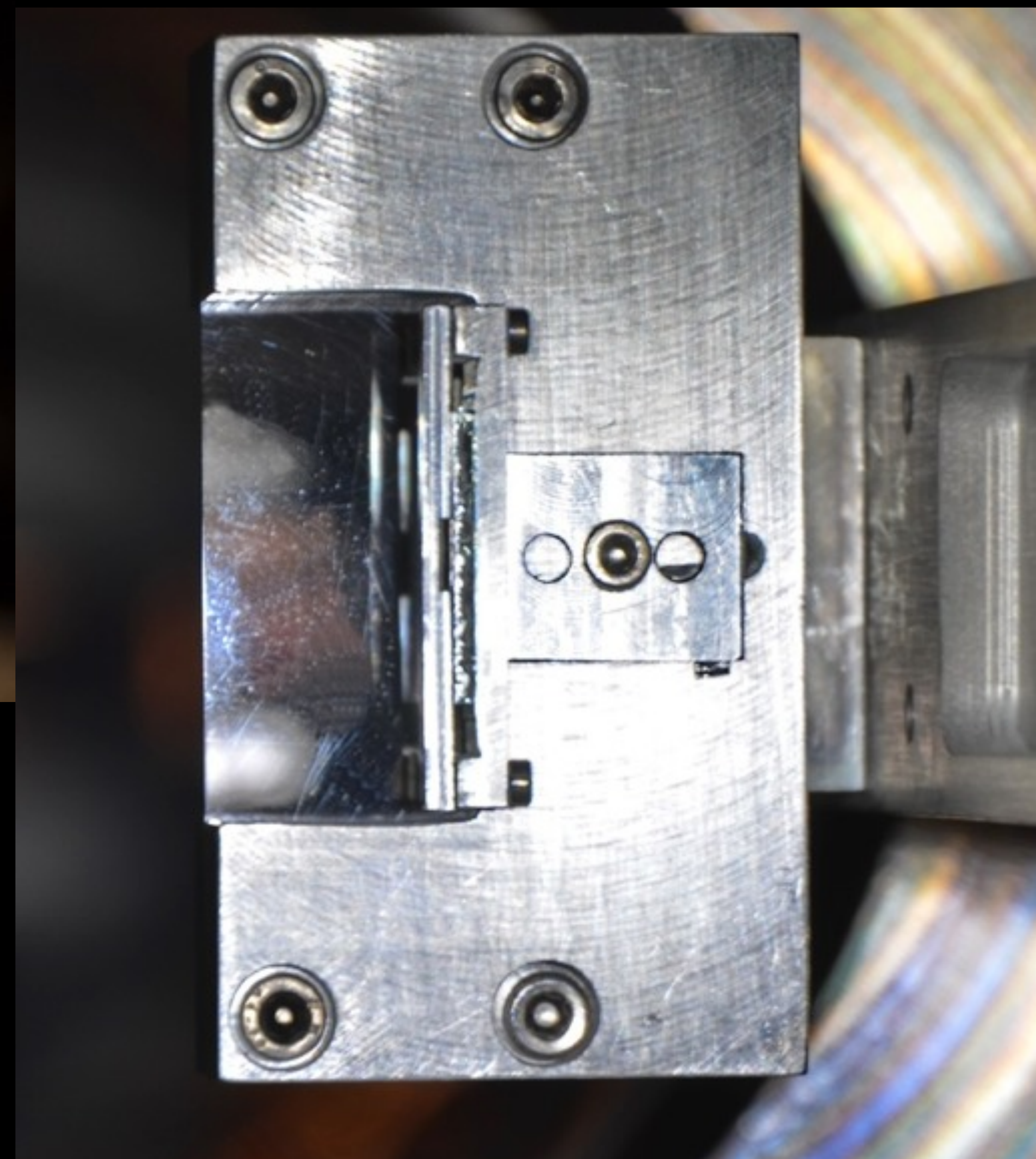


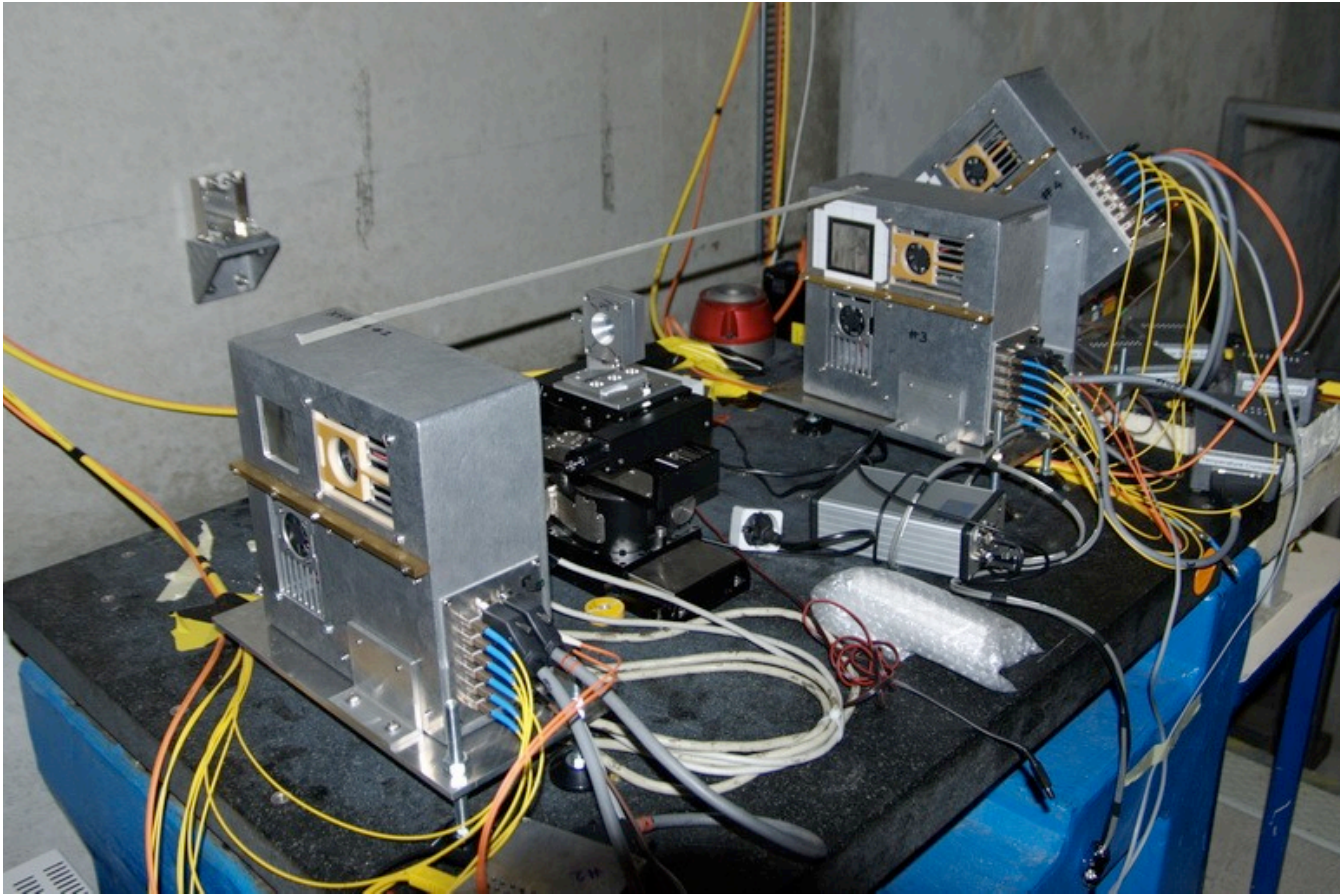
STF49 (strip crystal)

length: 0.8 mm
bending angle: 246 μrad
bent planes: <110>
torsion < 10 μrad / mm
amorphous layer < 100 μm
mis-cut angle < 170 μrad

QMP32 (quasi-mosaic crystal)

length: 1 mm
bending angle: 175 μrad
bent planes: <111>
amorphous layer < 100 μm
mis-cut angle < 50 μrad

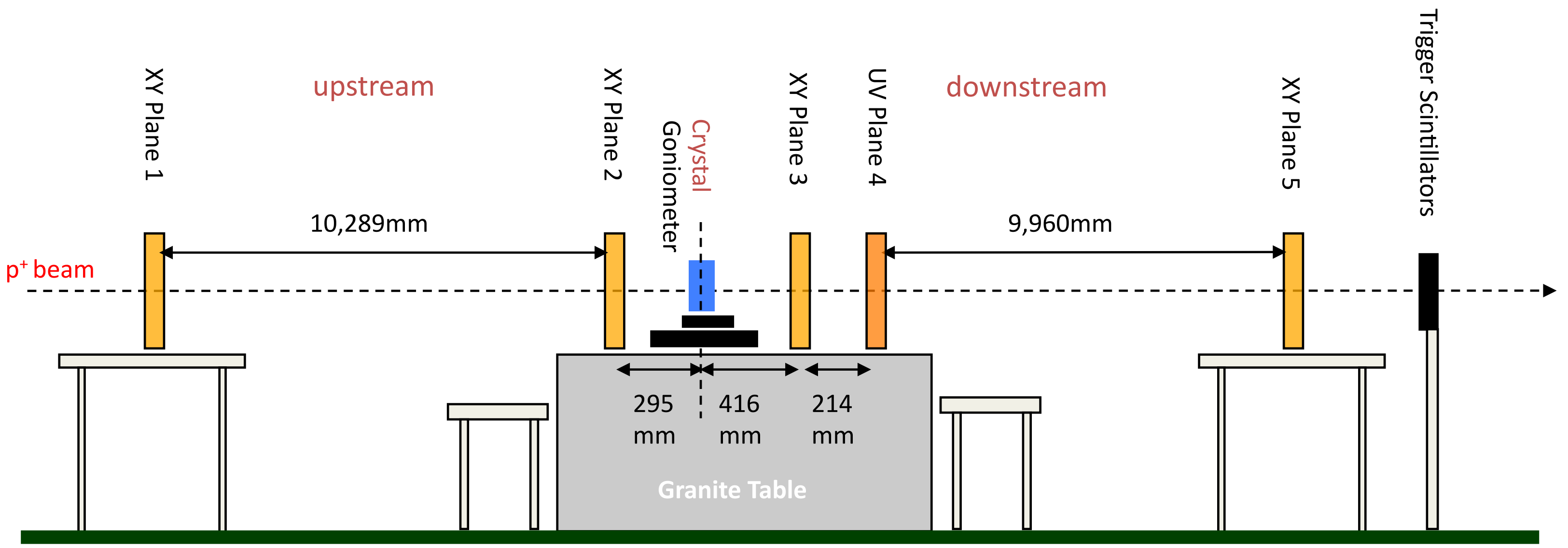




UA9-H8 test beam facility

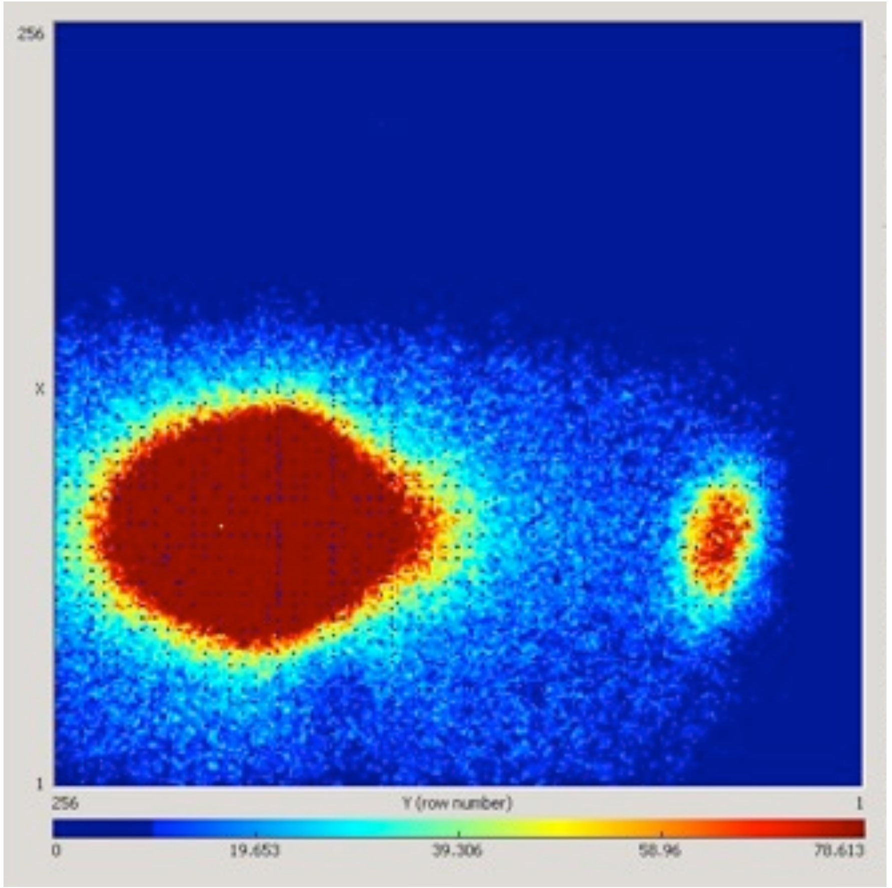
Test beam facility in SPS North Area

- **Semi-permanent installation**:
  - tracking detectors
  - 4-axis goniometer
  - GEM and Medipix detectors for imaging



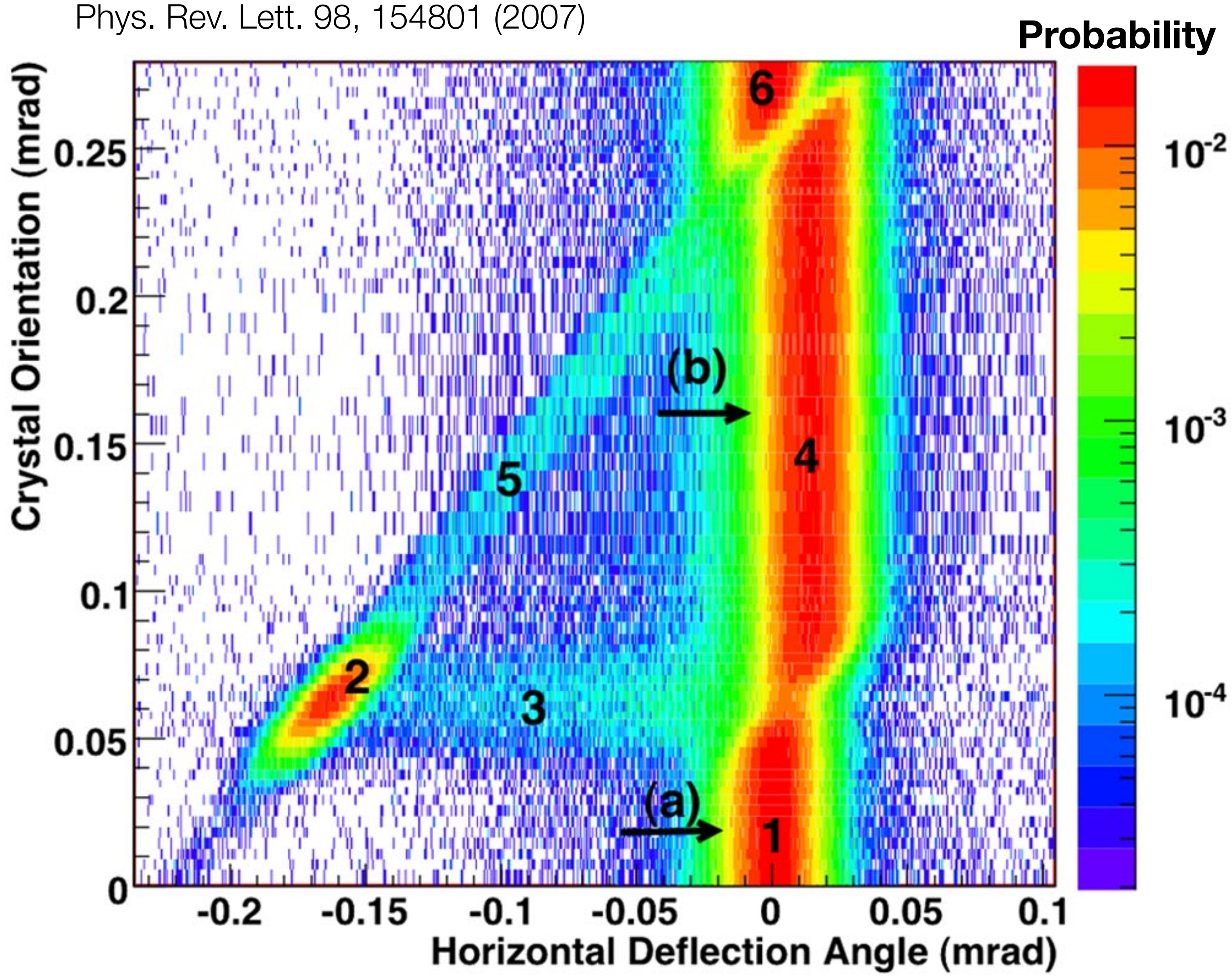
M Pesaresi et al 2011 JINST 6 P04006

- **Crystal tested with a primary beam** (400 GeV/c/n protons or Pb ions):
  - **crystal optimized for SPS or LHC** (constant technological improvements)
  - **"exotic" crystals** (multi-crystals, crystals with variable curvature, ...)
  - **new physics** (radiation production, interaction rates, ultra-thin crystals, ...)



Proton beam impinging on a bent crystal target

W. Scandale *et al*. (H8RD22 Collaboration)
Phys. Rev. Lett. 98, 154801 (2007)



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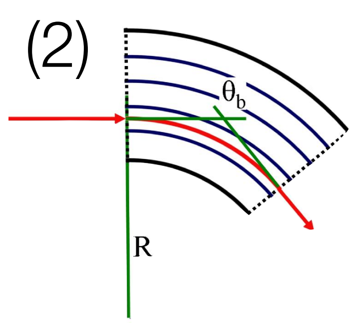

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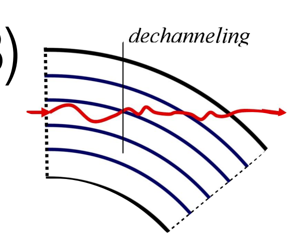
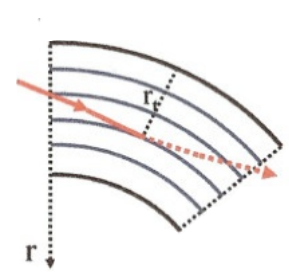


(4)



(1) particles on average not deflected, undergoing multiple Coulomb scattering (**amorphous** regime)

(2) particles deflected by **channeling** interaction

(3) particles escaping from channeling interaction (**dechanneled** particles)

(4) particles deflected by reflection on atomic planes (**volume reflection** regime)

(5) particles starting channeling interaction inside the crystal (**volume capture**)

(6) particles on average not deflected, undergoing multiple Coulomb scattering (**amorphous** regime)

Recent results (UA9 test beam)

- W. Scandale et al., Deflection of high-energy negative particles in a bent crystal through axial channeling and multiple volume reflection stimulated by doughnut scattering. Phys. Lett. B 693 (2010) 545–550.

- W.Scandale et al., Probability of Inelastic Nuclear Interactions of High-Energy Protons in a Bent Crystal. Nucl. Instr. Meth. B, 268 (2010) 2655.

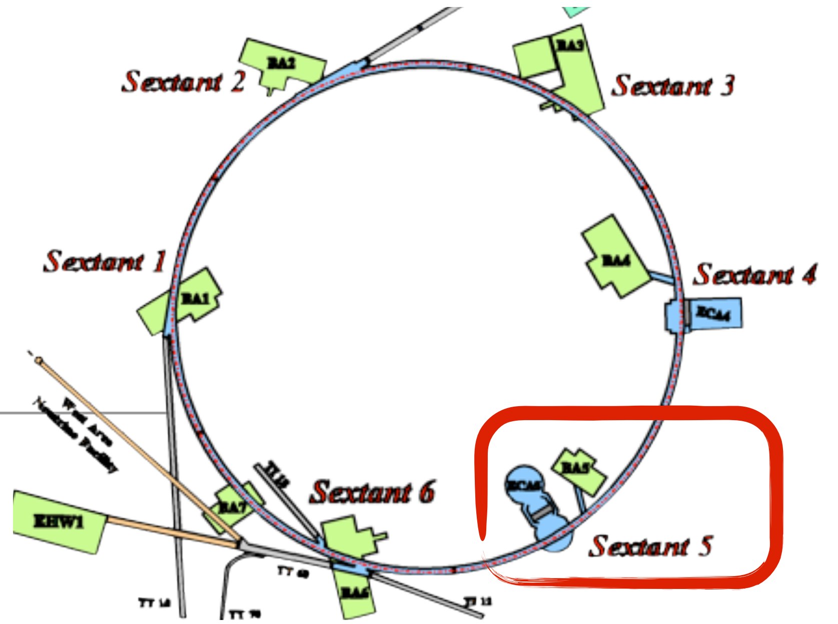
- W.Scandale et al., Multiple volume reflections of high-energy protons in a sequence of bent silicon crystals assisted by volume capture. Phys. Lett. B, 688 (2010) 284.

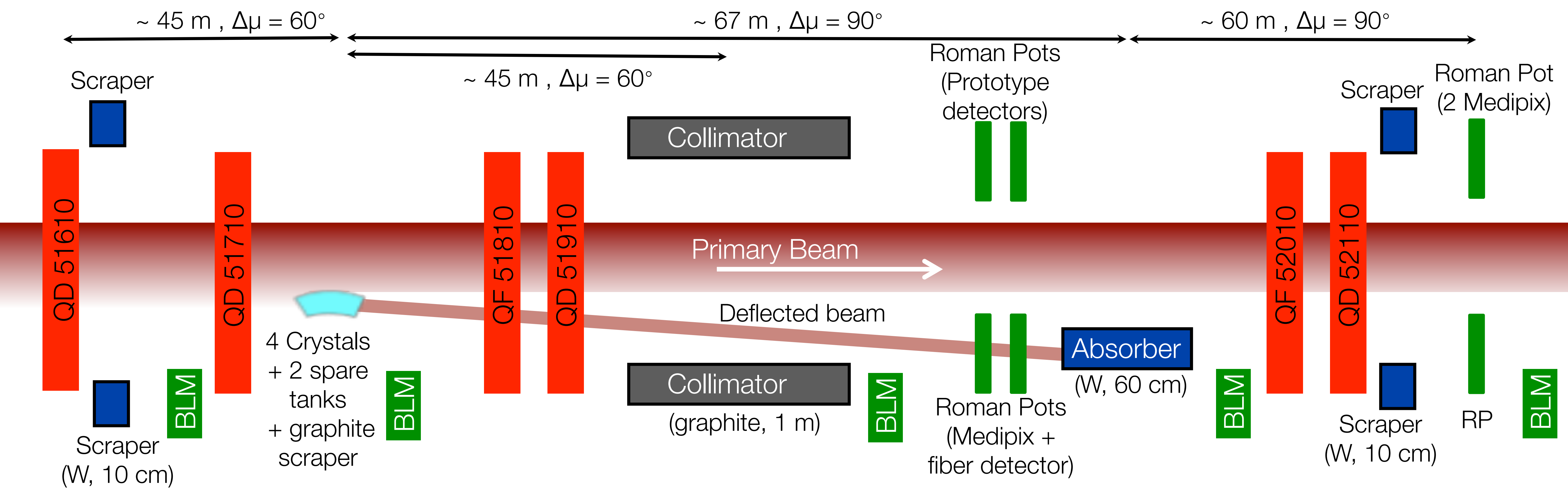
- W.Scandale et al., Observation of Multiple Volume Reflection by Different Planes in One Silicon Crystal for High-Energy Negative Particles. EPL 93 (2011) 56002.

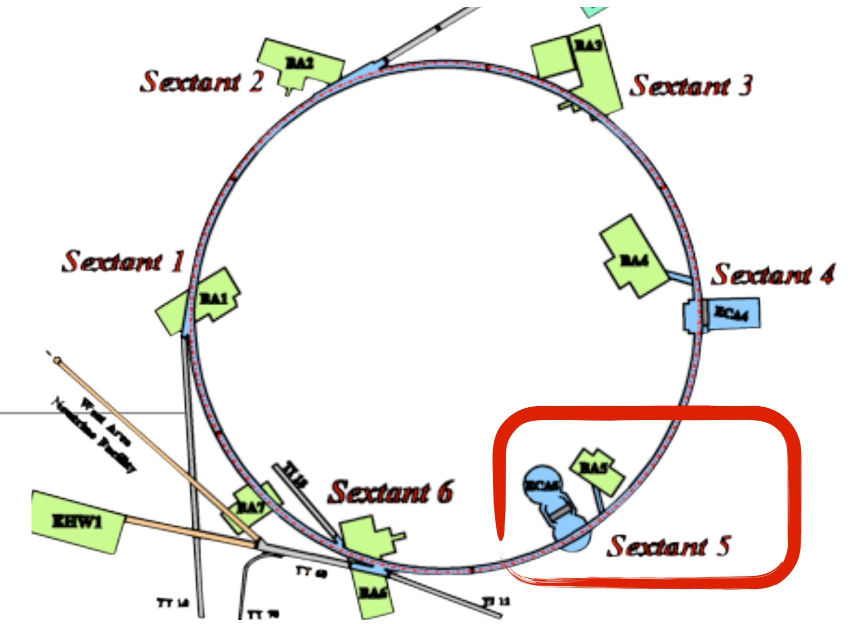
- W, Scandale et al., Observation of parametric X-rays produced by 400 GeV/c protons in bent crystals. Phys. Lett. B 701 (2011) 180–185.

UA9 installation in the SPS

Layout of the installation in SPS

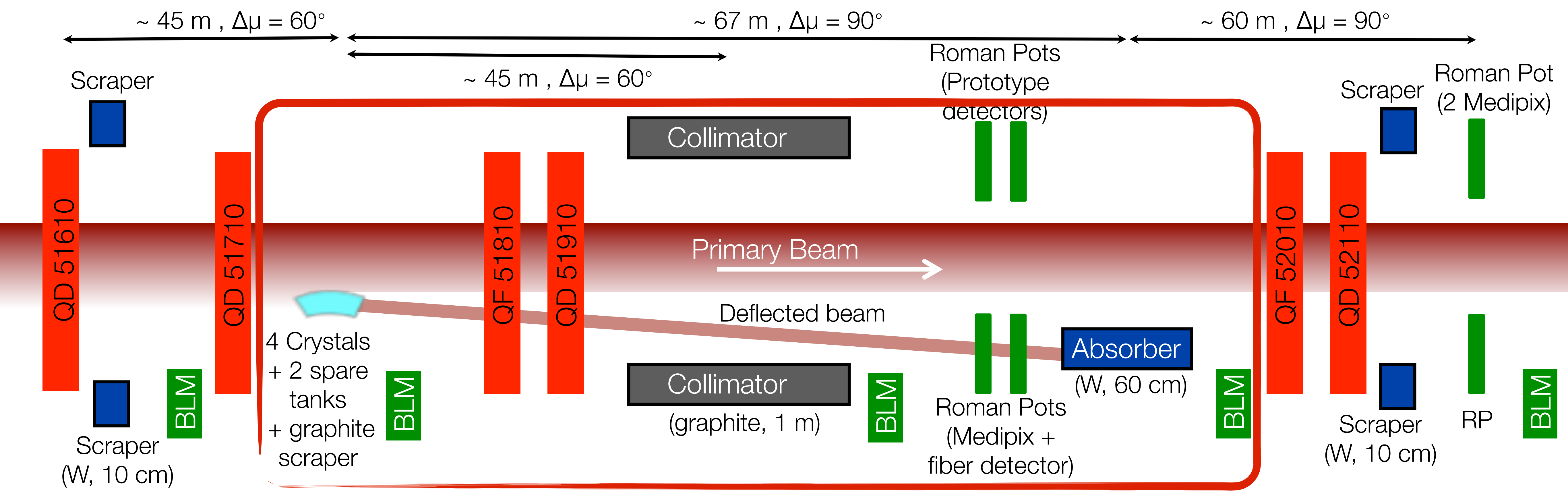


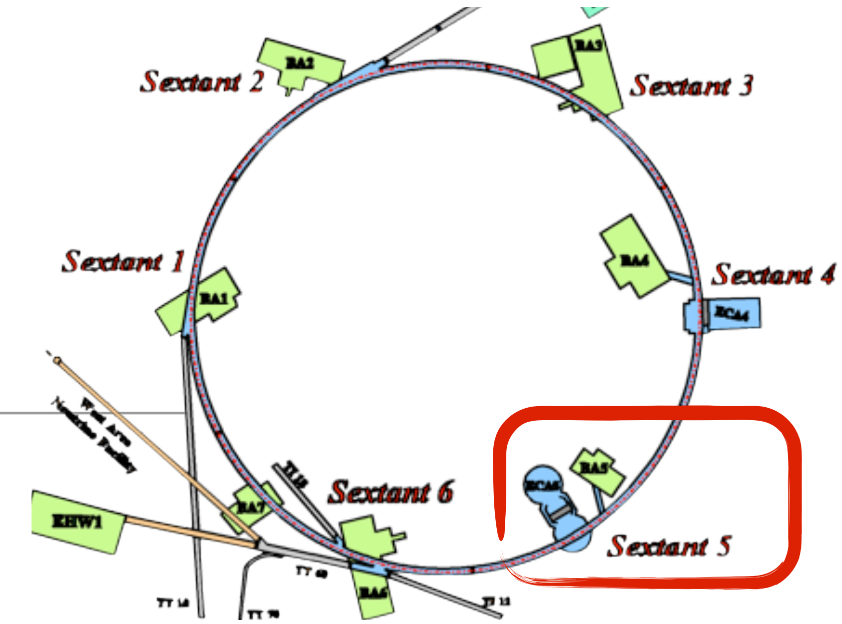




Layout of the installation in SPS

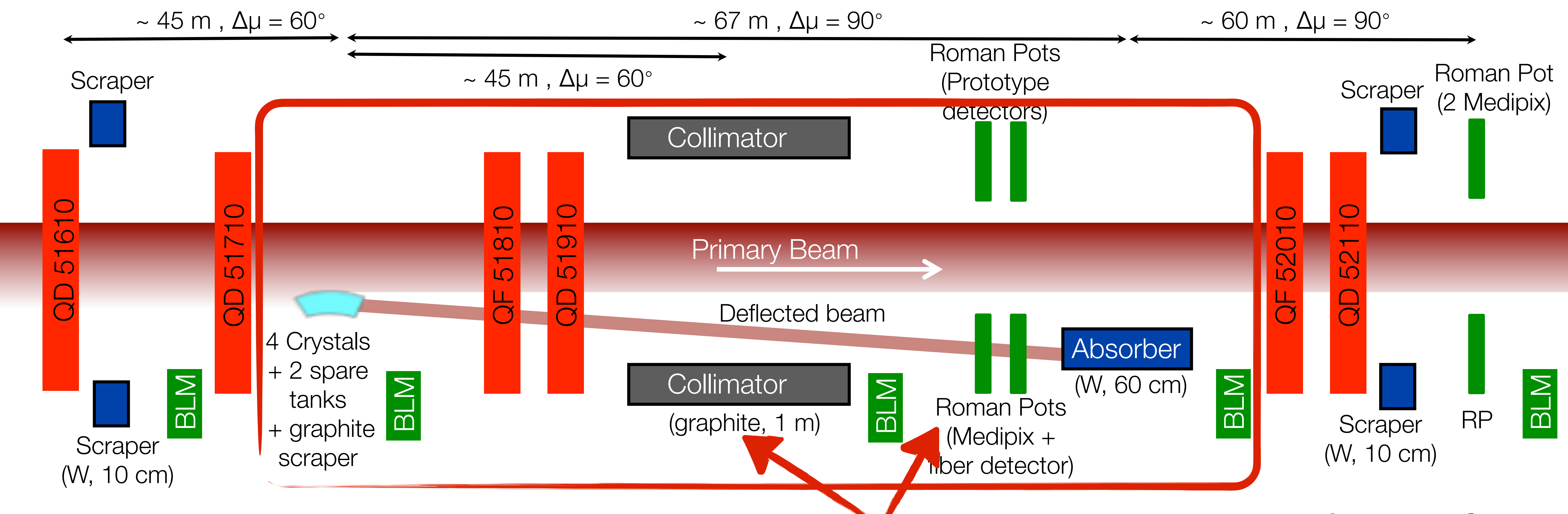
prototype collimation system (crystal + absorber)





Layout of the installation in SPS

prototype collimation system (crystal + absorber)



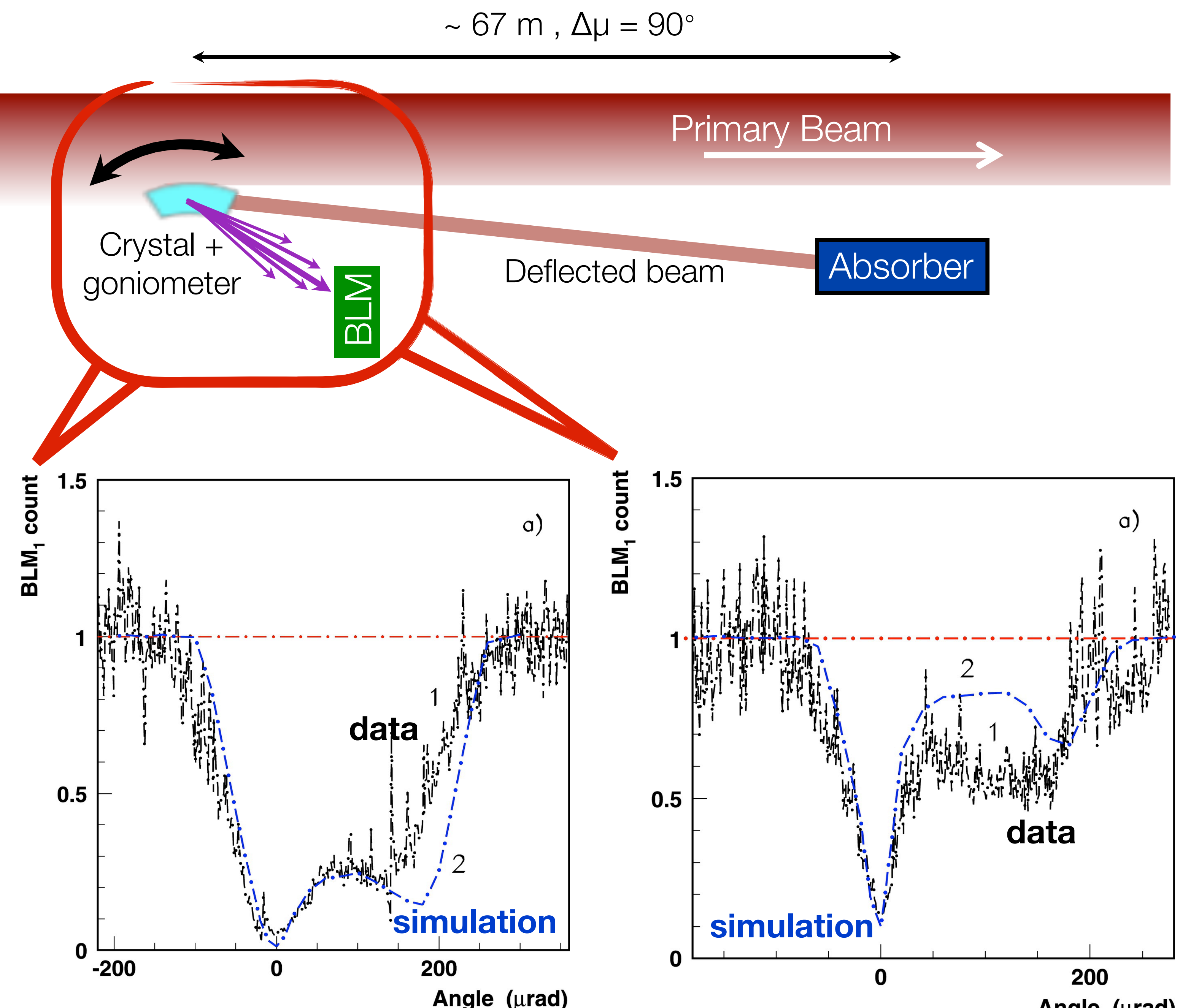
equipment for the measurements of the multi-turn halo (**upstream the crystal**)

several Cherenkov, scintillator, PEPII **detectors**

equipment for **efficiency measurement in the collimation area**

equipment for **high dispersion area** halo measurement

Local beam loss reduction

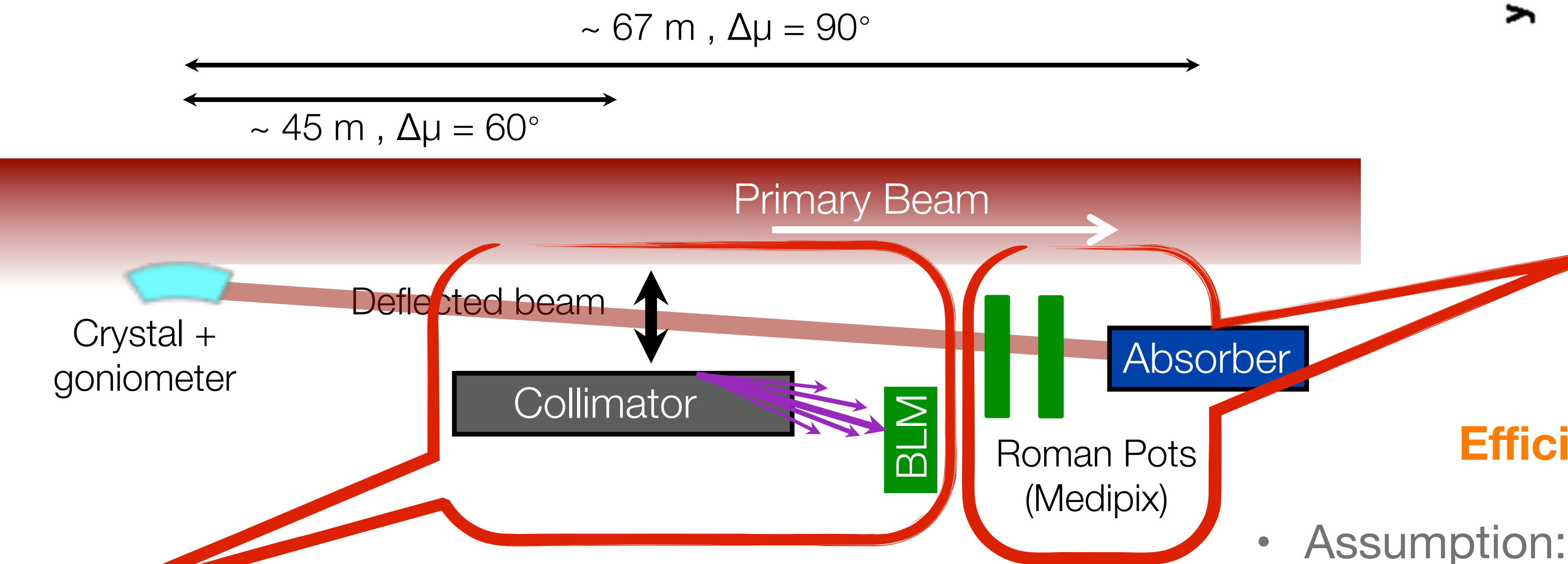


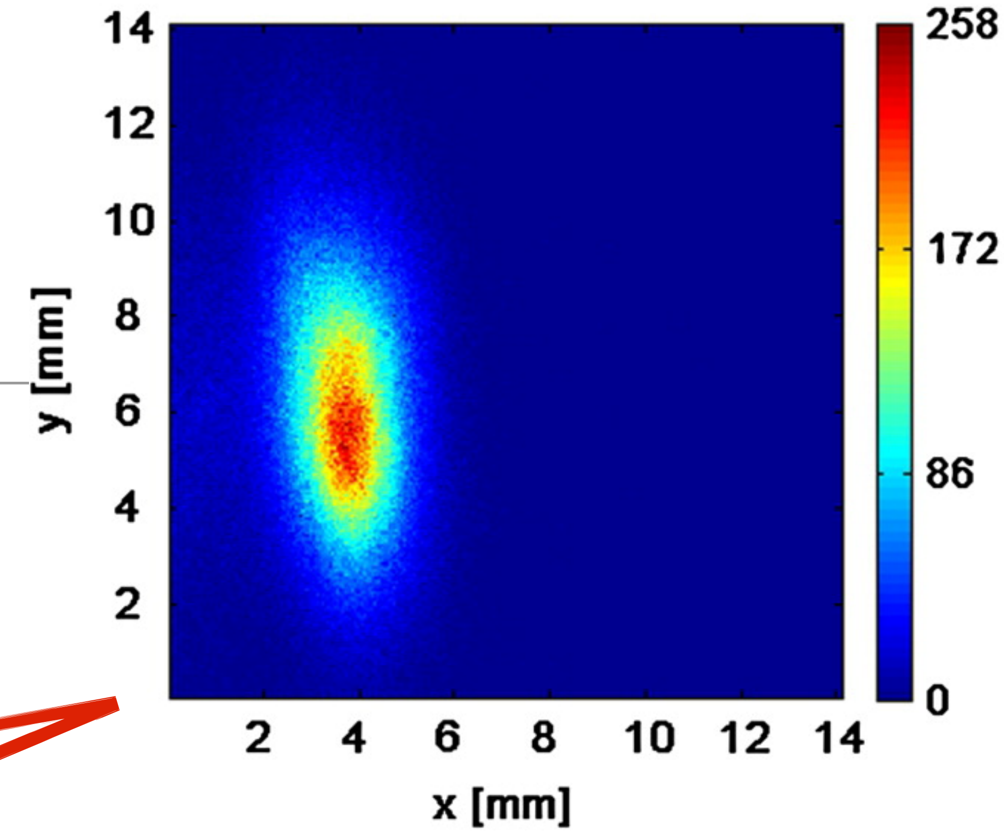
Protons, 270 GeV
Crystal aperture: 9 σ
Absorber aperture: 13.5 σ

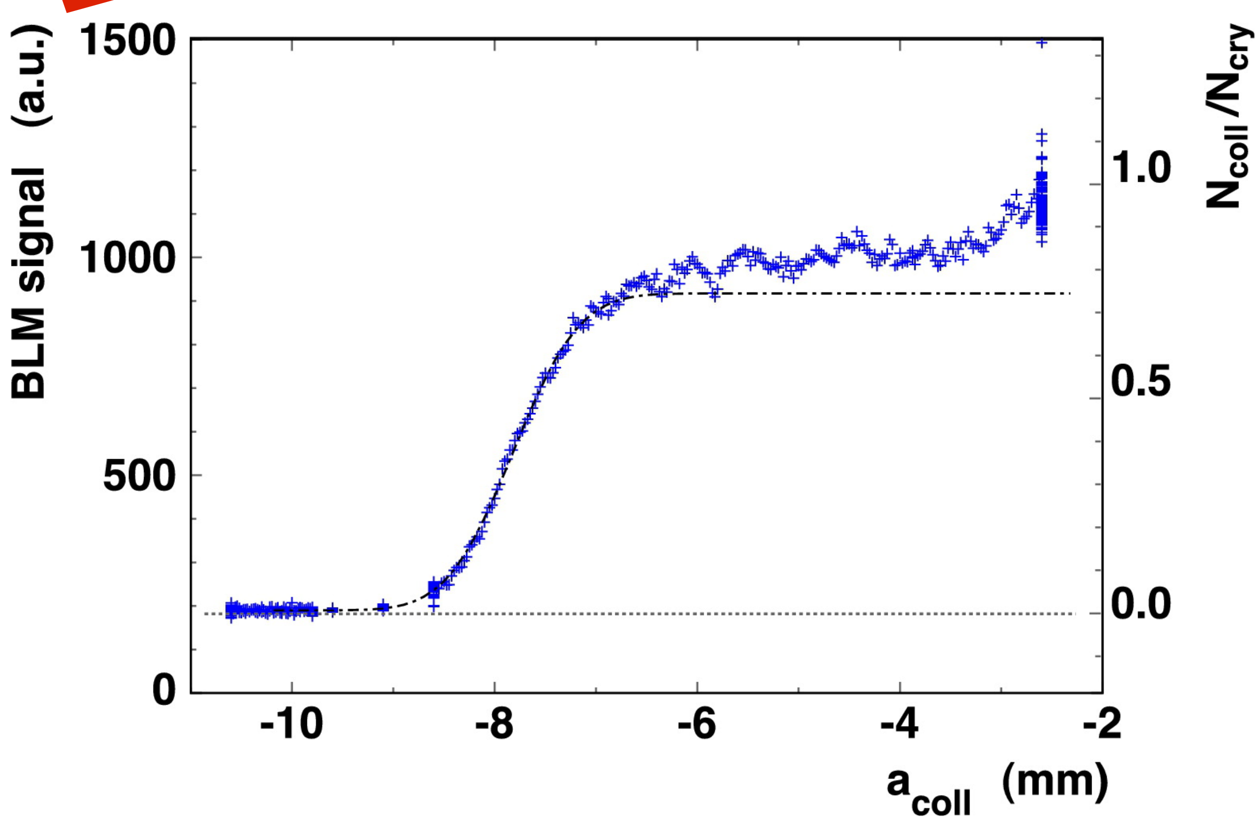
Pb ions, 270 GeV/n
Crystal aperture: 3.5 σ
Absorber aperture: 7 σ

- When the crystal is oriented in **channeling** (angle = 0 μrad) or in volume reflection mode (50 μrad < angle < 200 μrad), the **loss rate is reduced**:
  - the “angular scan” is **routinely used to identify channeling** orientation
  - loss **reduction depends on crystal imperfections** (amorphous layer, torsion, mis-cut angle, ...) and length:
    - **5÷20x reduction for protons**
    - **3÷7x reduction for Pb ions**
  - simulation can reproduce data with few minor discrepancies

Halo extraction efficiency



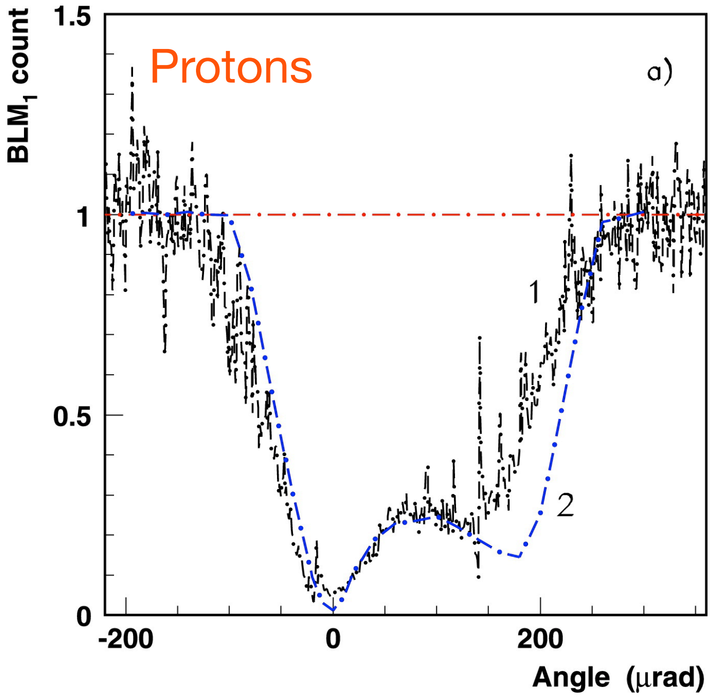


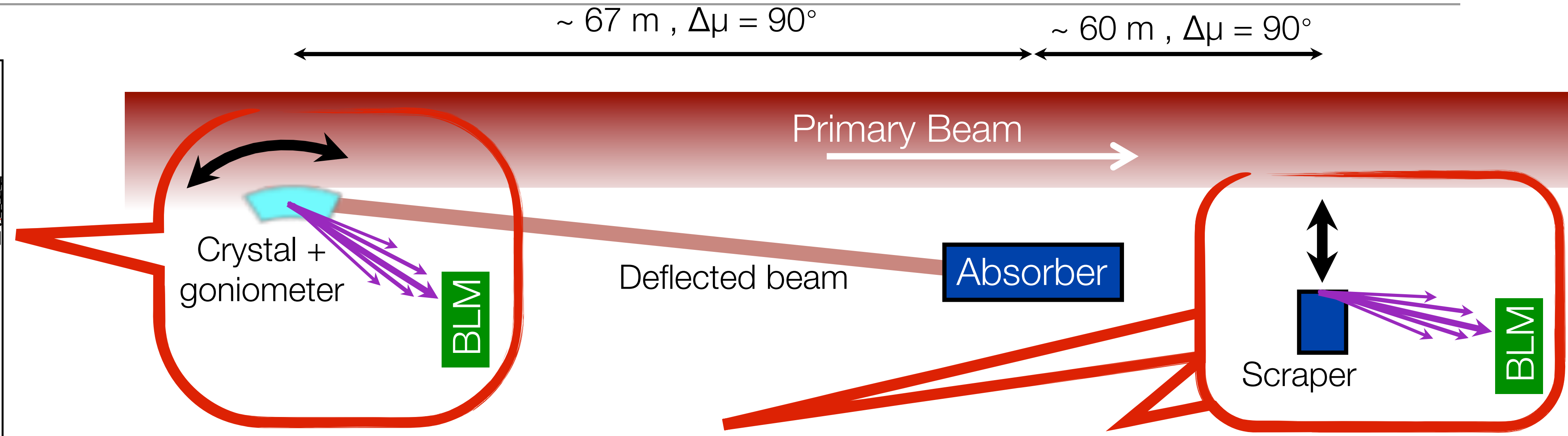


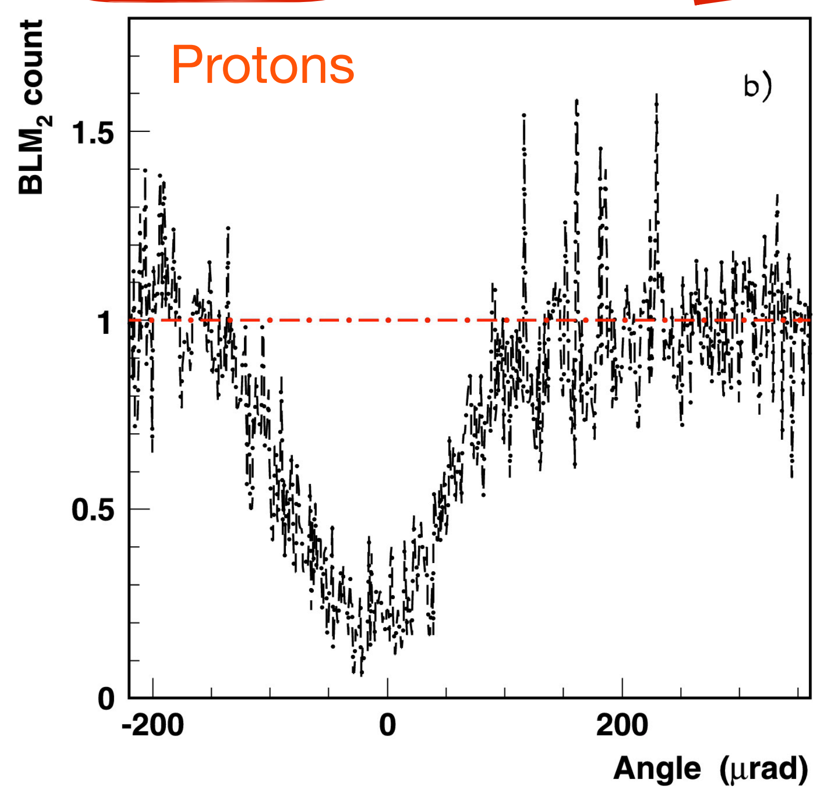
Efficiency = $N_{deflected}$ / $N_{crystal}$

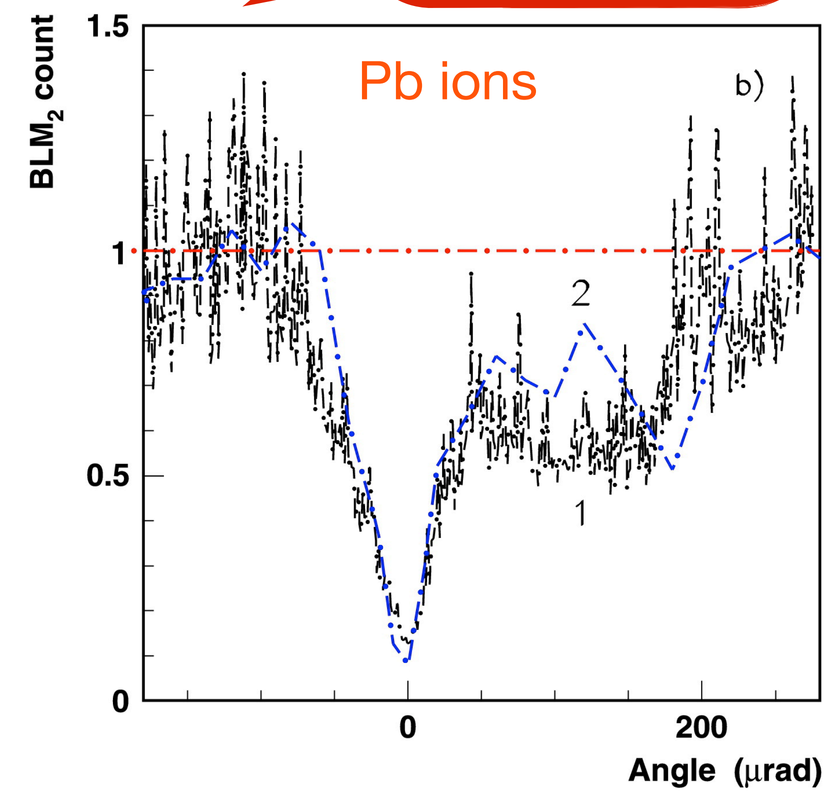
- Assumption: the number of particles intercepted by a moving object is proportional to the loss rate downstream the object
- Moving the collimator to intercept the deflected halo:
  - $N_{deflected}$ is proportional to the losses when intercepting the whole deflected beam
  - $N_{crystal}$ is proportional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

Beam loss reduction in the high dispersion area





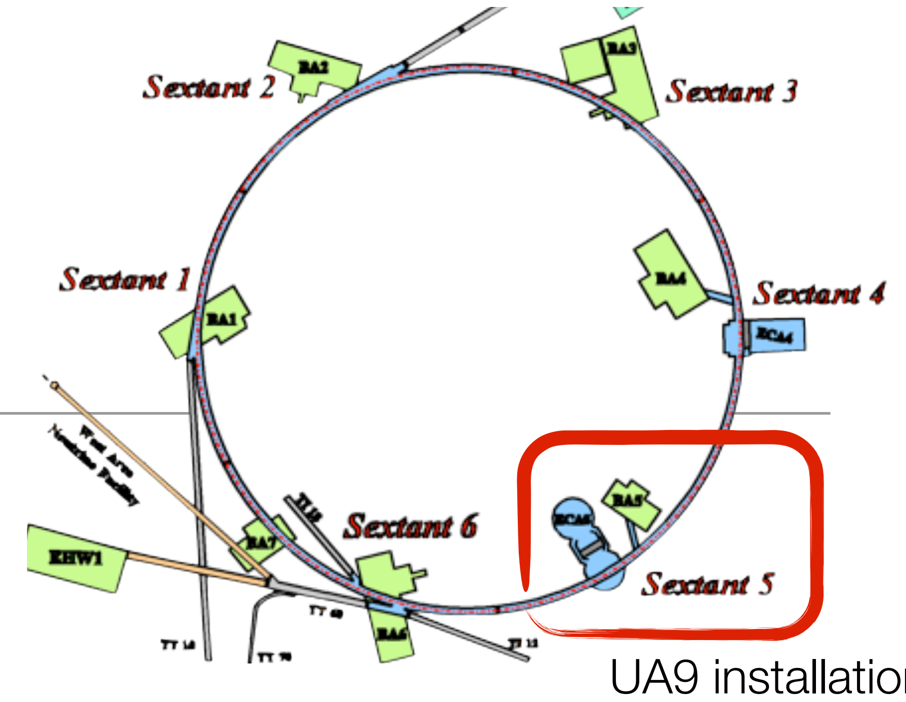




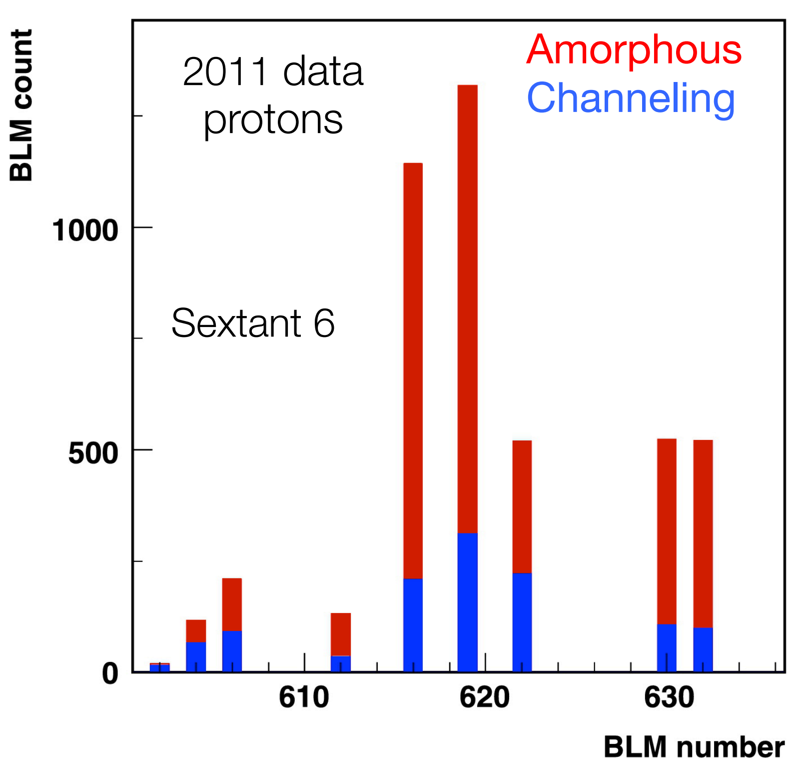
- The **beam loss rate in the high dispersion area** can be enhanced using by restricting the aperture with the installed scraper (~ 30 σ):
  - beam loss rate determined by crystal orientation
  - good correlation with beam losses at the crystal location

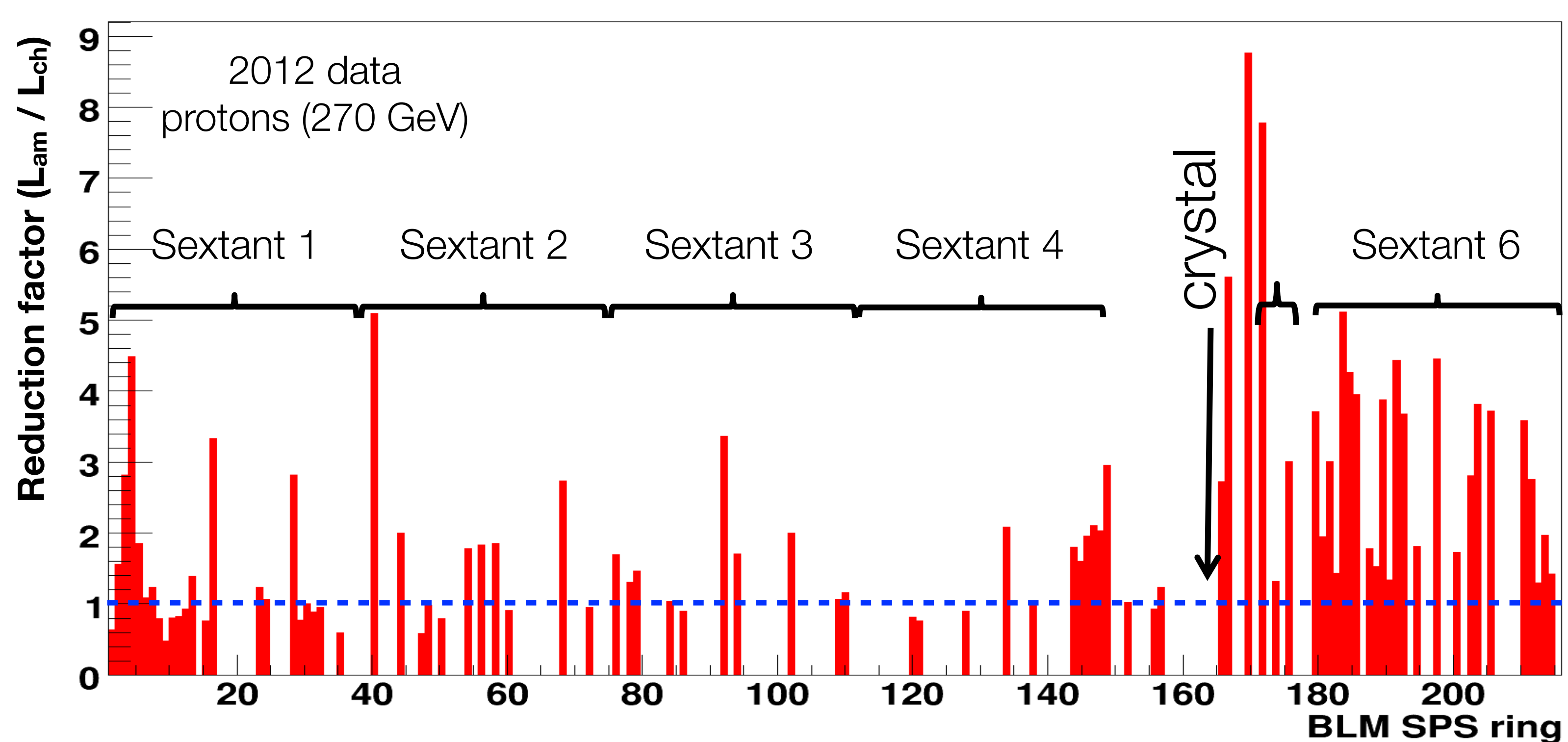
- **2÷6x reduction for protons (less than in the crystal region)**
- **3÷7x reduction for Pb ions (equal to the crystal region)**

Beam loss maps



- Beam loss monitor rates along the accelerator ("loss maps") are the natural validation for collimation systems.
- **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 signal below the BLM threshold).
- **Loss map measurement in 2011**:
  - intensity increased from 1 bunch ($I = 1.15 \times 10^{11}$ p) to 48 bunches,
  - clear **reduction of the losses seen in Sextant 6**.
- **Loss map measurement in 2012**:
  - maximum possible intensity: 3.3×10^{13} protons (4 x 72 bunches with 25 ns spacing),
  - **average loss reduction in the entire ring**!





Recent results (UA9 SPS installation)

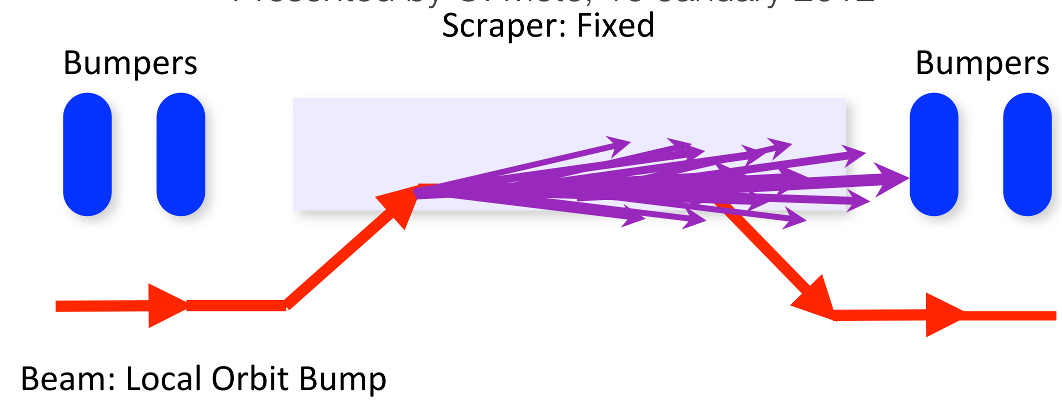
- W. Scandale et al., First Results on the SPS Collimation with Bent Crystals. Phys. Lett. B 692 (2010) 78–82.
- W. Scandale et al, The UA9 experimental layout. JINST 6 T10002 (2011).
- W. Scandale et al., Comparative results on collimation of the SPS beam of protons and Pb ions with bent crystals. Phys. Lett. B 703 (2011) 547–551.
- 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.
- Last data taking session ended in November 2012: Beam loss reduction in the whole SPS using crystal assisted collimation.

Following these results the UA9 collaboration has proposed to install a prototype system in the LHC.

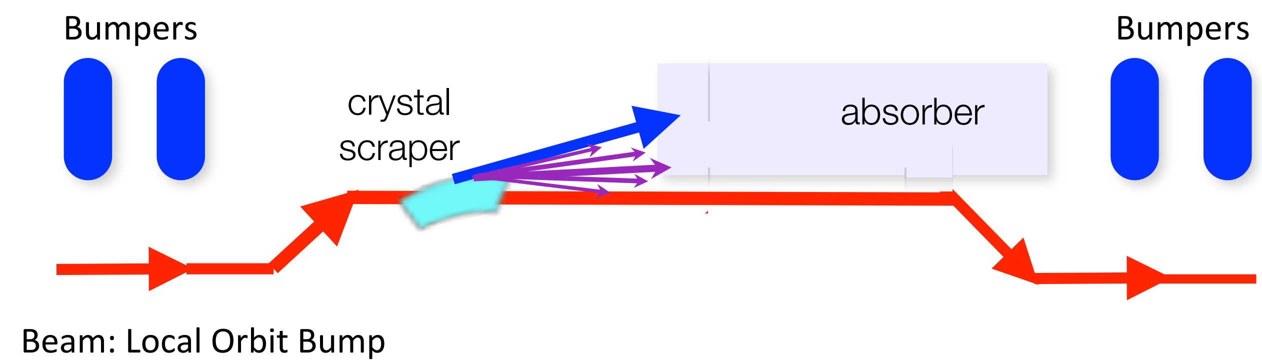
Beam scraping with a crystal

- **Beam scraping** in the SPS:
  - reduce beam tails before injection in the LHC (**reduce losses at injections**)
  - current system relies on the fast movement of a graphite foil across the beam periphery
  - possible **upgrade with a local orbit bump** that deflects the beam towards a **fixed scraper**.
- A **crystal** could be used to **localize all the losses in the absorber**:
  - **particles** intercepted by the crystal are **extracted** (by volume reflection) rather than absorbed:
    - **absorber not subjected to multi-turn** passage of particles (heating reduced)
    - **impact parameter** on the absorber defined by crystal deflection angle (i.e. **possibly one or more mm**)
  - **reduced probability of diffractive events** (and fragmentation and dissociation, if used with ions).

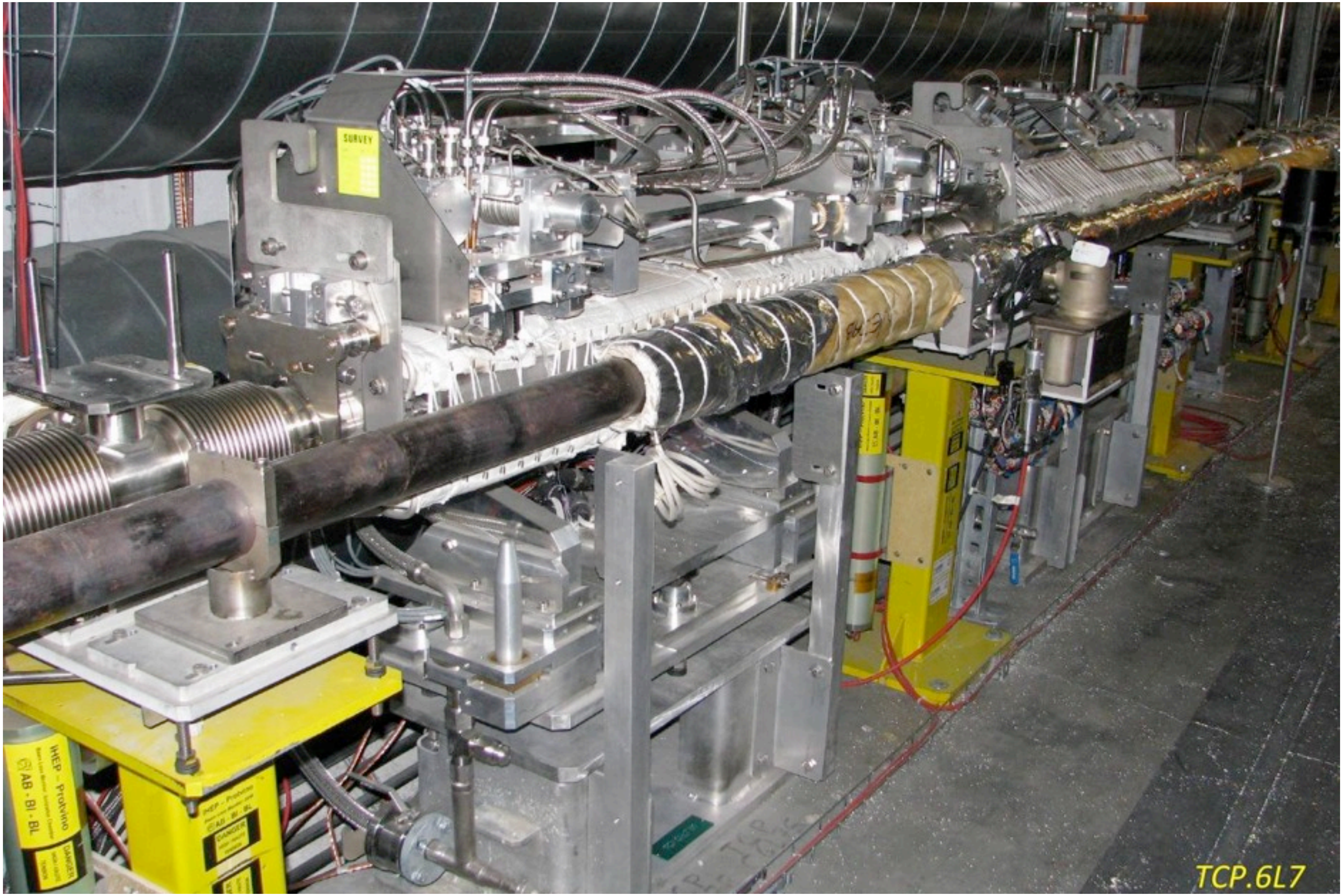
LIU-SPS Beam Scraper
Tail cleaning system with a magnetic bump.
Presented by O. Mete, 15 January 2012



Possible crystal-based beam scraper system
with a magnetic bump.

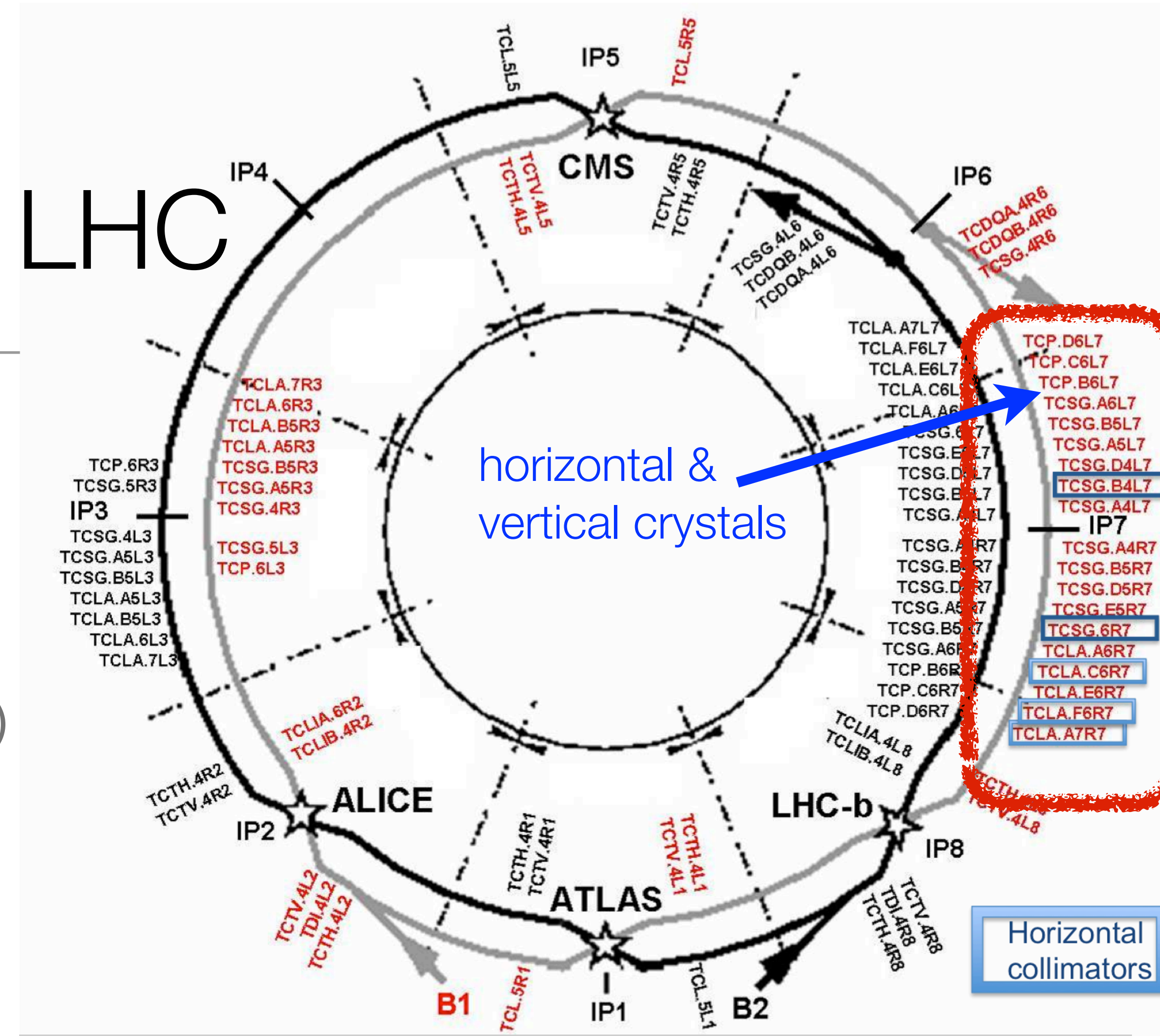


- **tests performed** in November 2012 (at low energy)
- results presented in January 2013:
  - **investigation will continue** after the CERN long shutdown



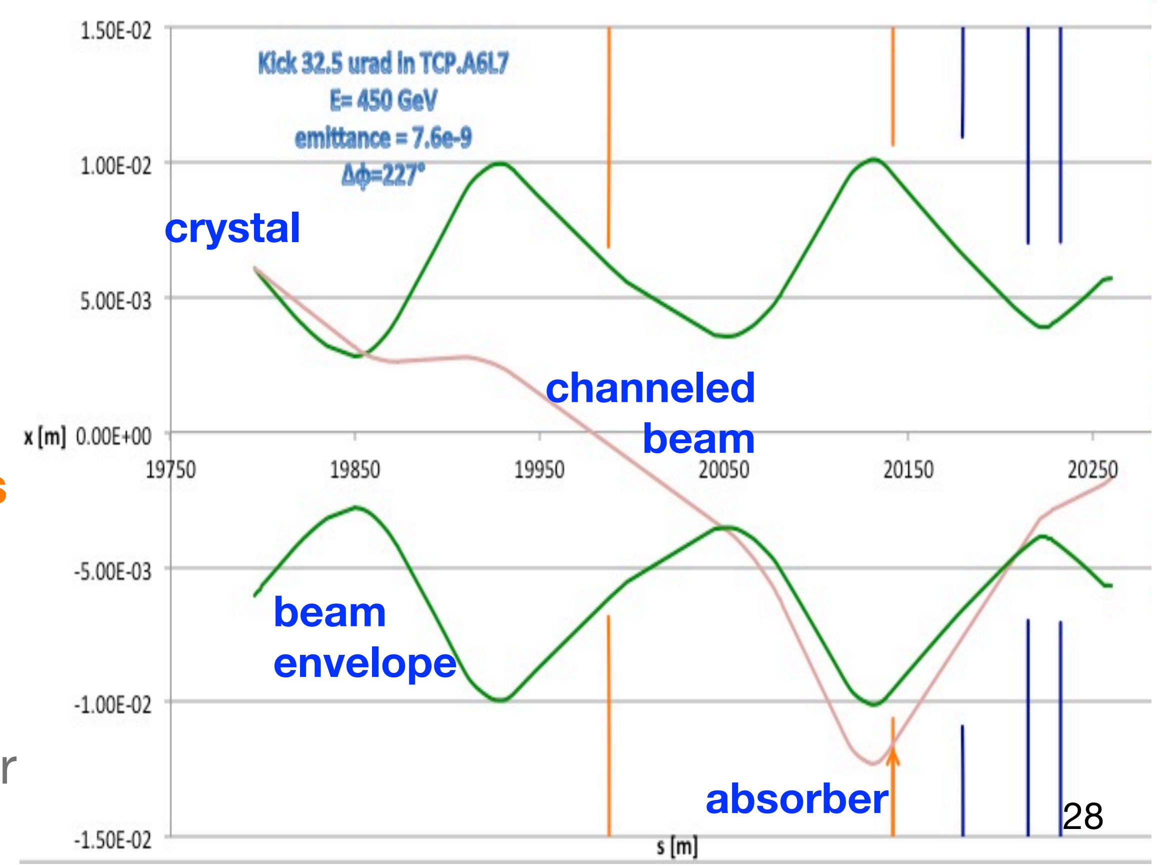
LUA9 future installation in LHC

Towards an installation in the LHC



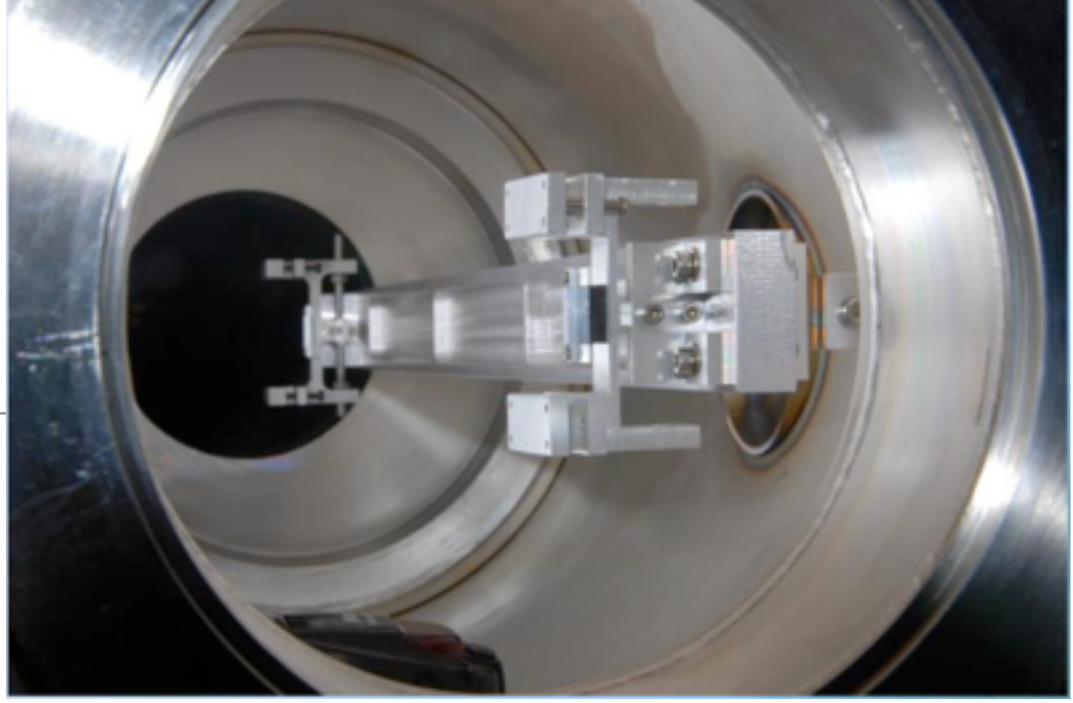
Crystal installation in LHC recommended by the LHCC.

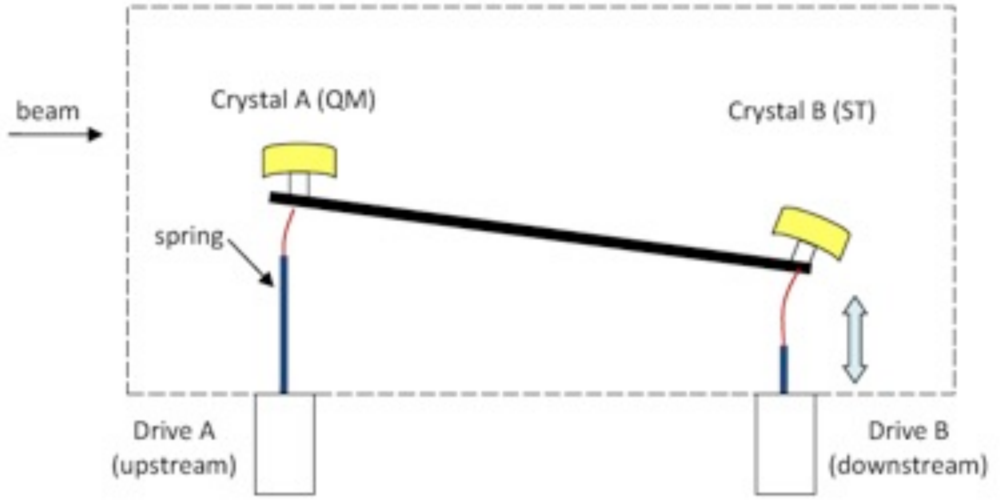
- Roadmap for the experiment in LHC:
  - **propose** and **install** a minimal number of devices in the LHC (possibly **during the shutdown in 2013-2015**)
  - **demonstrate** the **extraction of the beam halo** in the LHC with low intensity
  - assess the theoretical improvements with respect to standard collimation
- Possible experimental layout under investigation:
  - **only one beam** (beam 1), **two crystals** (horizontal & vertical) close to the primary collimators
    - highest radiation area, tight space allowance
  - **extracted beam absorbed by secondary collimators**
    - simulation work ongoing to assess the optimal collimation system setup during the tests
  - Cherenkov detector (in vacuum) in front of the absorber



Crystal alignment in LHC

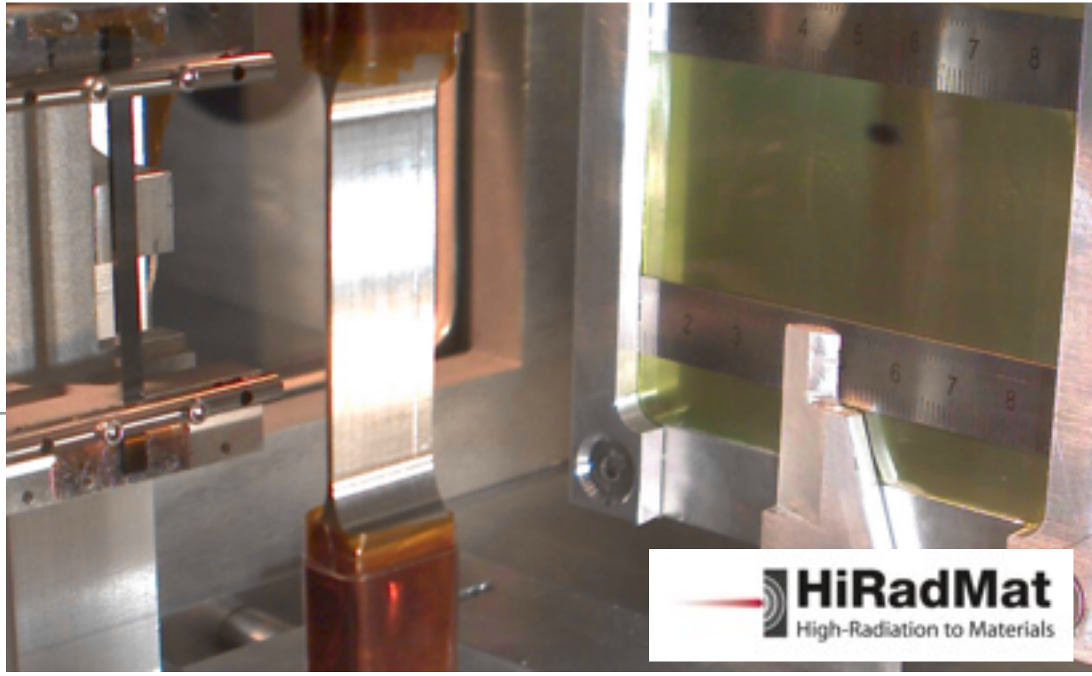
- **Angular acceptance** for channeling interaction is defined by the **critical angle** (θ_c = 2.39 μrad at 7 TeV)
- Goniometer accuracy must be smaller than channeling angular acceptance:
  - **Mechanical goniometer** (in-kind contribution) installed in 2012 **in SPS** (see pictures) has resolution < 10 μrad.
  - New **mechanical device** developed in 2012 by **industrial partner CINEL** for tests in the SPS:
    - static resolution ok, dynamic behavior and impedance to be improved.
  - **Piezoelectric device** under design in collaboration with **industrial partners ATTOCUBE** and **CEDRAT/MECARTEX/CINEL**
    - all requirements theoretically met, very compact design





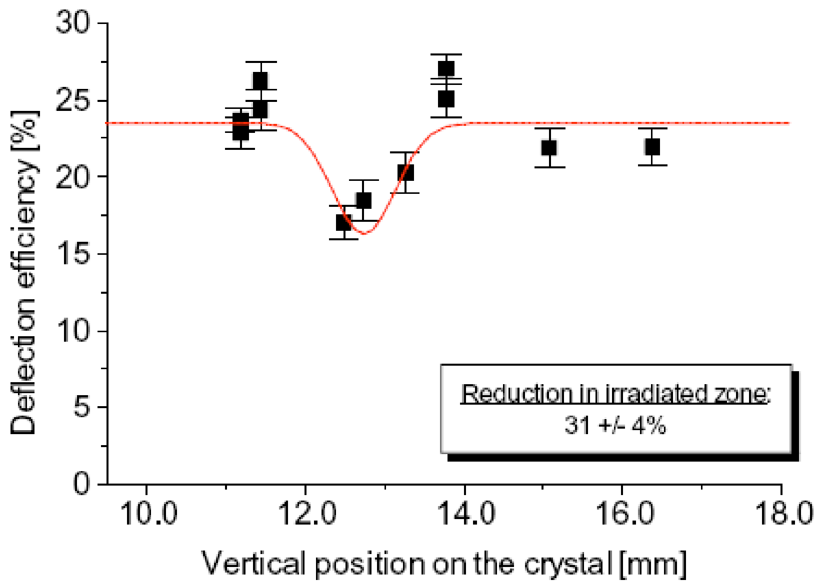
- Linear stroke: 70 mm
- Linear resolution: 1 μm
- Angular range: ±10 mrad
- Angular resolution: 0.1 μrad
- Angular overshoot: 10%
- Angular accuracy (70 mm travel): ±1 μrad
- Angle settling time: 20 ms
- Max angular speed in scan mode: 50 steps/s (1 μrad step)

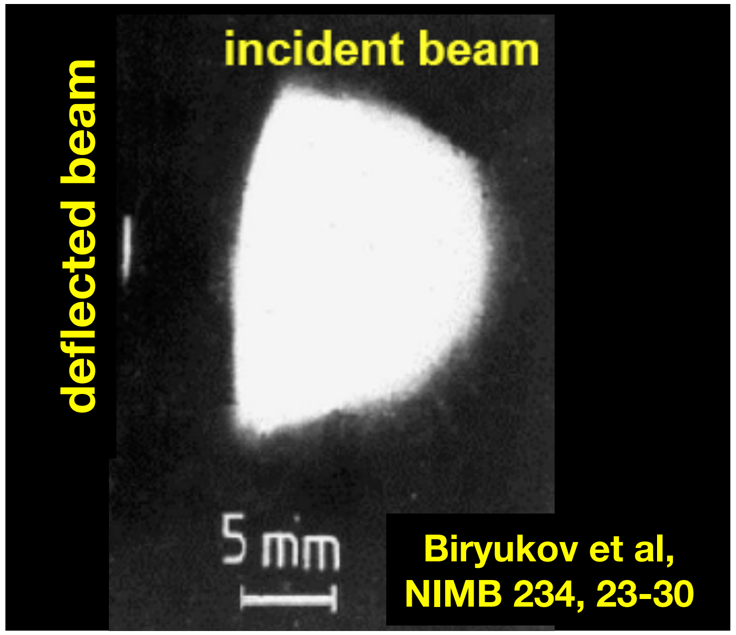
Crystal resistance to irradiation



- **IHEP U-70** (Biryukov et al, NIMB 234, 23-30):
  - 70 GeV protons, 50 ms spills of **10^{14} protons every 9.6 s**, several minutes irradiation
  - equivalent to 2 nominal LHC bunches for 500 turns every 10 s
  - 5 mm silicon crystal, **channeling efficiency unchanged**
- **SPS North Area - NA48** (Biino et al, CERN-SL-96-30-EA):
  - 450 GeV protons, 2.4 s spill of 5 x 10^{12} protons every 14.4 s, one year irradiation, **2.4 x 10^{20} protons/cm^2** in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - 10 x 50 x 0.9 mm^3 silicon crystal, 0.8 x 0.3 mm^2 area irradiated, **channeling efficiency reduced by 30%**.
- **HRMT16-UA9CRY** (HiRadMat facility, November 2012):
  - 440 GeV protons, up to 288 bunches **in 7.2 μs**, 1.1 x 10^{11} protons per bunch (**3 x 10^{13} protons** in total)
  - energy deposition comparable to an asynchronous beam dump in LHC
  - 3 mm long silicon crystal, **no damage to the crystal after accurate visual inspection**, more tests planned to assess possible crystal lattice damage
    - **accurate FLUKA simulation of energy deposition** and residual dose

NA48 - Biino et al, CERN-SL-96-30-EA





Biryukov et al, NIMB 234, 23-30

Conclusion

- The **UA9 experiment** is investigating the possibility to use **crystals** as primary obstacles in **collimation systems**:
  - **Test beam facility** at the SPS North Area.
  - **Prototype collimation system** in the SPS.
  - Future installation of a **prototype system in LHC**.
- **Future plans** of the UA9 collaboration:
  - look forward for the experiment **installation in LHC**, followed by exciting results,
  - **study the optimization** of the prototype crystal collimation system **in SPS**,
  - study **new crystal physics** and **technological improvements** with the test beam facility at the **SPS North Area**,
  - **offer expertise** to possible projects involving crystals as beam deflecting devices
    - **beam scraping in SPS** as an example
    - **AFTER@LHC ?**

Acknowledgments

The UA9 experiment would not be possible without:

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- all the institutions supporting the experiment
  (CERN, LAL, IHEP, Imperial College London, INFN, JINR, PNPI, SLAC)
- the funding agencies
- the Reference Committees and Referees that follow the experiment
- many people at CERN and in particular:
  - the EN/STI group that provides extraordinary support to the experiment
  - the BE/OP-BI-RF groups that carefully prepare the SPS to allow for the UA9 measurements
  - the EN/MEF group that takes care of the facilities used for the UA9 experimental activities

Thank you for your attention!