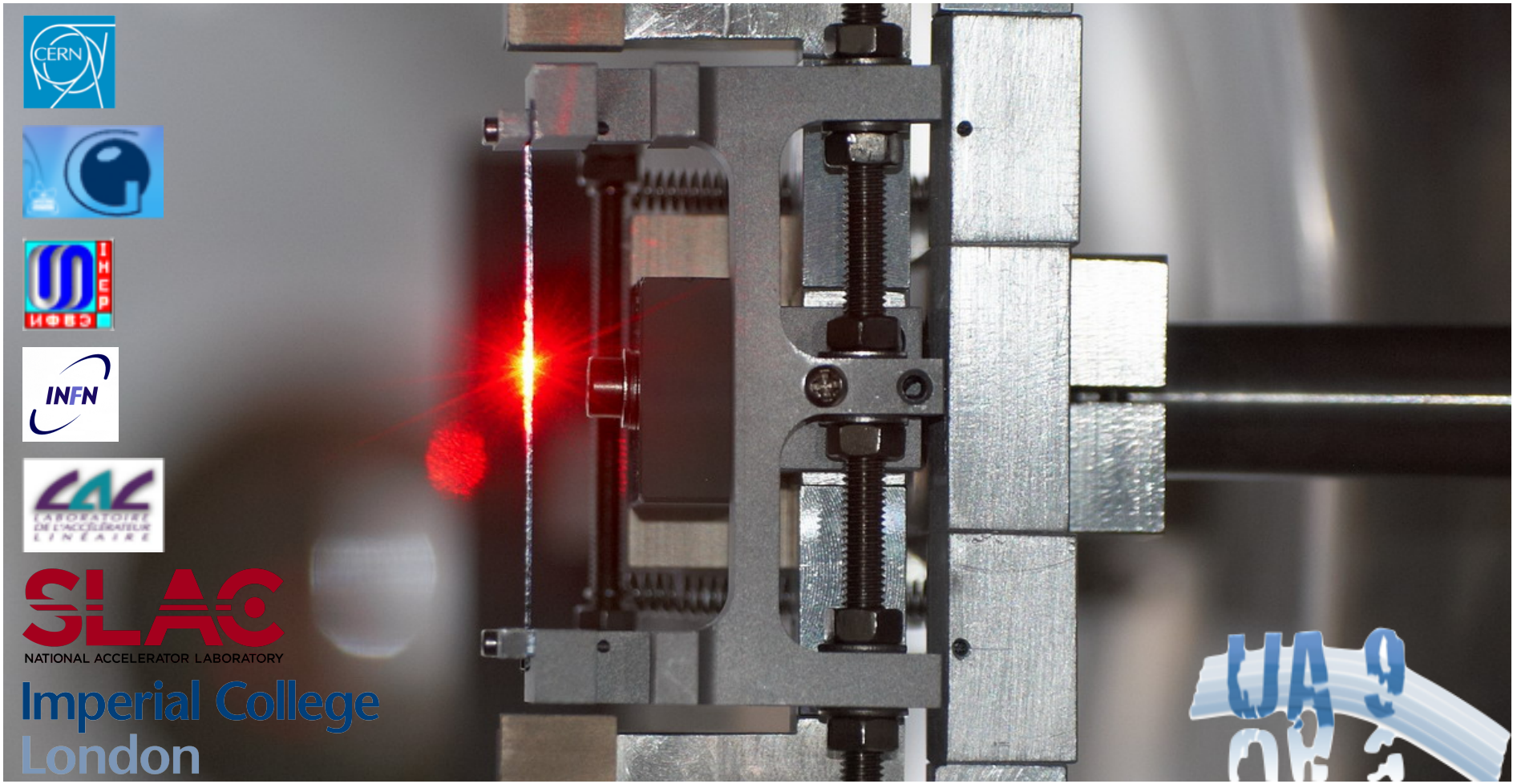


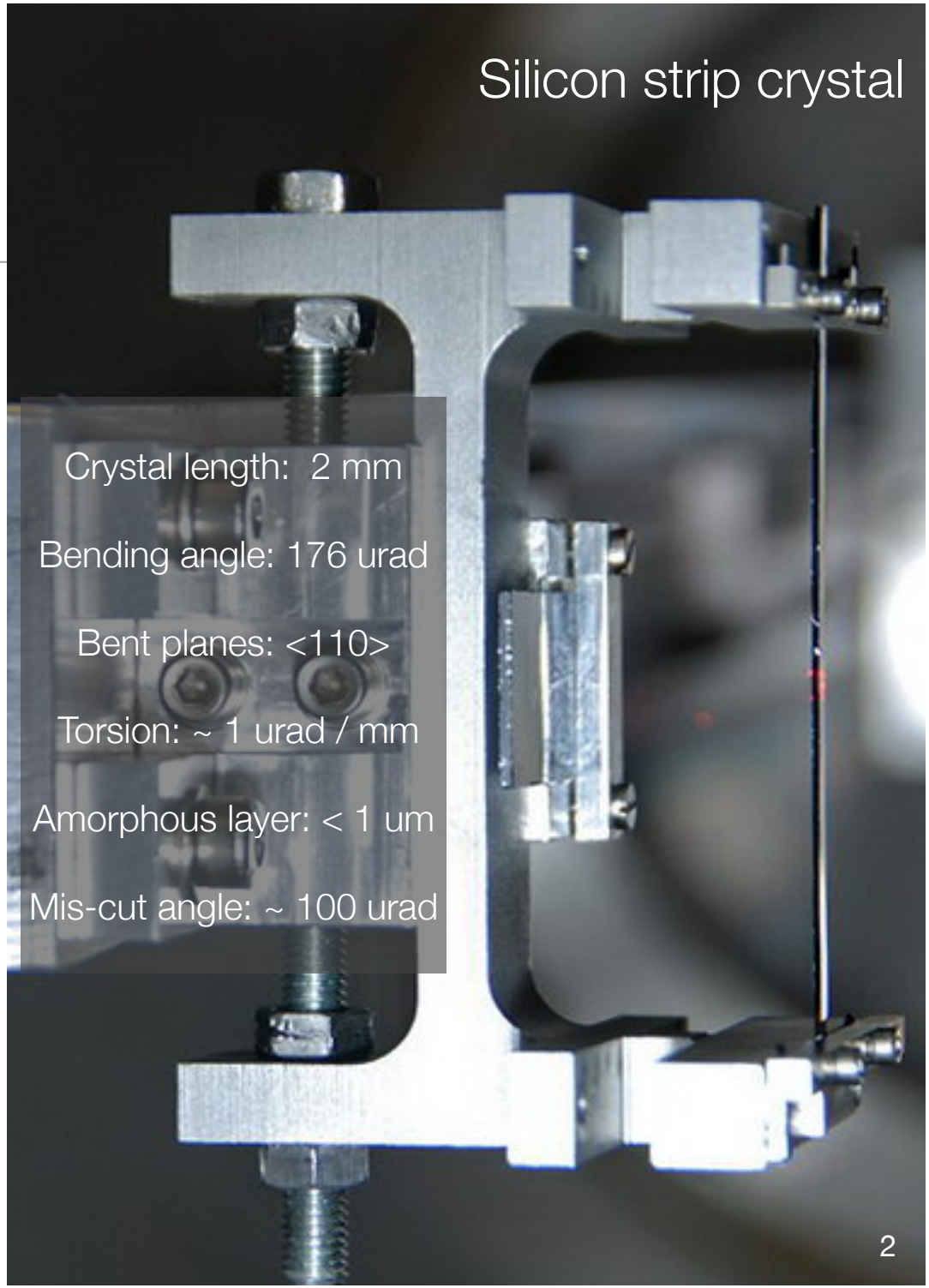
Alghero, Channeling 2012, 23-28 September 2012

Status and Results of the UA9 Crystal Collimation Experiment at the CERN-SPS

Walter Scandale (CERN, LAL, INFN)
for the UA9 collaboration

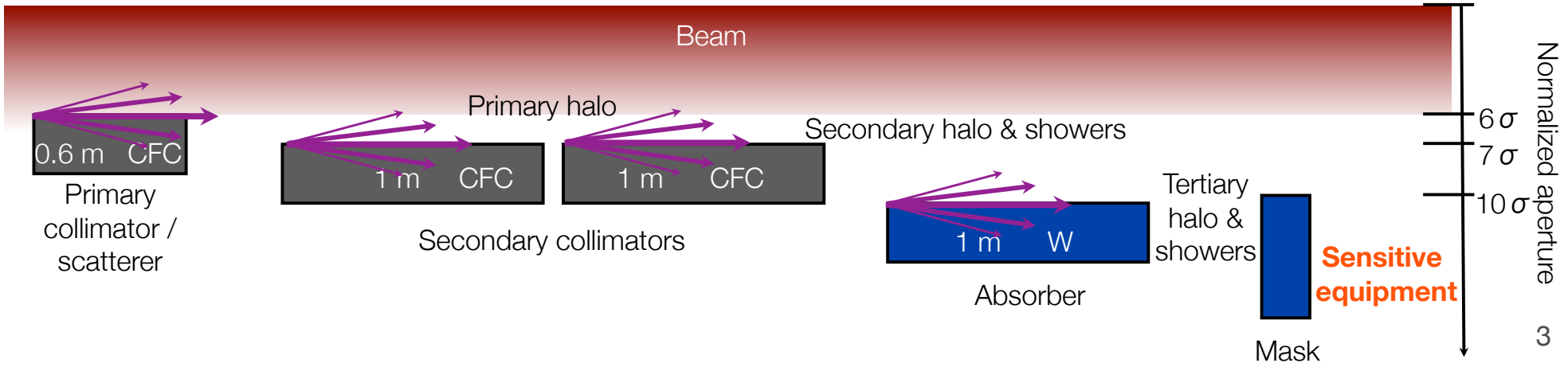
Outline

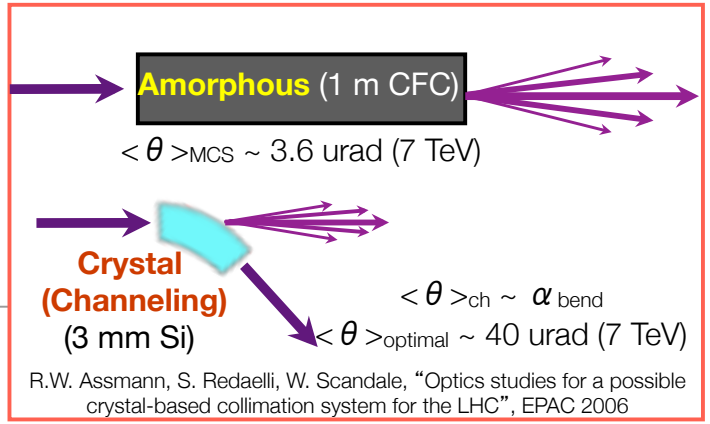
- Crystal collimation and the UA9 experiment
- Results from the UA9 experiment
- On going studies
- Toward the installation of a test system in LHC



Multi-stage collimation system

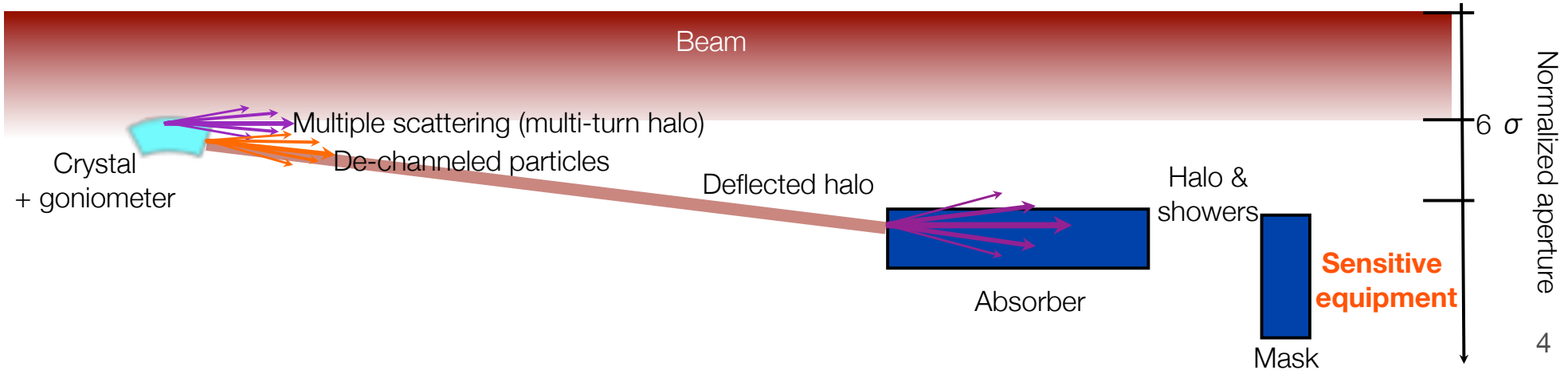
- Diffusive primary halo intercepted by massive amorphous targets:
  - primary particles deflected by Multiple Coulomb Scattering (<θ> ~ 3.6 urad for graphite at 7 TeV), hadronic showers produced by interaction on the target (secondary halo)
  - secondary collimators and absorbers stop deflected particles & showers
  - tertiary collimators protect sensitive equipment from secondary halo
- Optimal performances reached (in LHC: 99.97% collimation efficiency in 2011)
- Limitations: single diffractive scattering, ion fragmentation/dissociation





Crystal collimation system

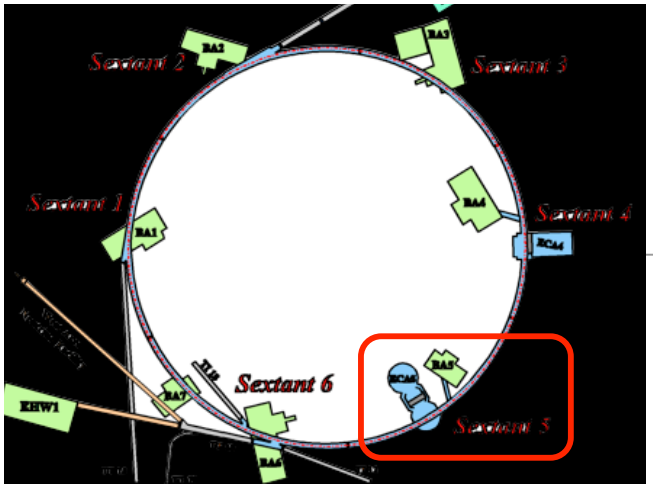
- Mechanically bent crystal as primary deflector.
- If crystalline planes are correctly oriented, particles are subjected to a coherent interaction (channeling):
  - small angular acceptance (19.45 urad for E = 120 GeV, 2.1 urad for E = 7 TeV)
  - localization of the losses on a single absorber, thanks to large deflection angle
  - reduced probability of diffractive events and ion fragmentation/dissociation.
- At present, there is no crystal-collimation system optimized for machine operation.



The UA9 experiment

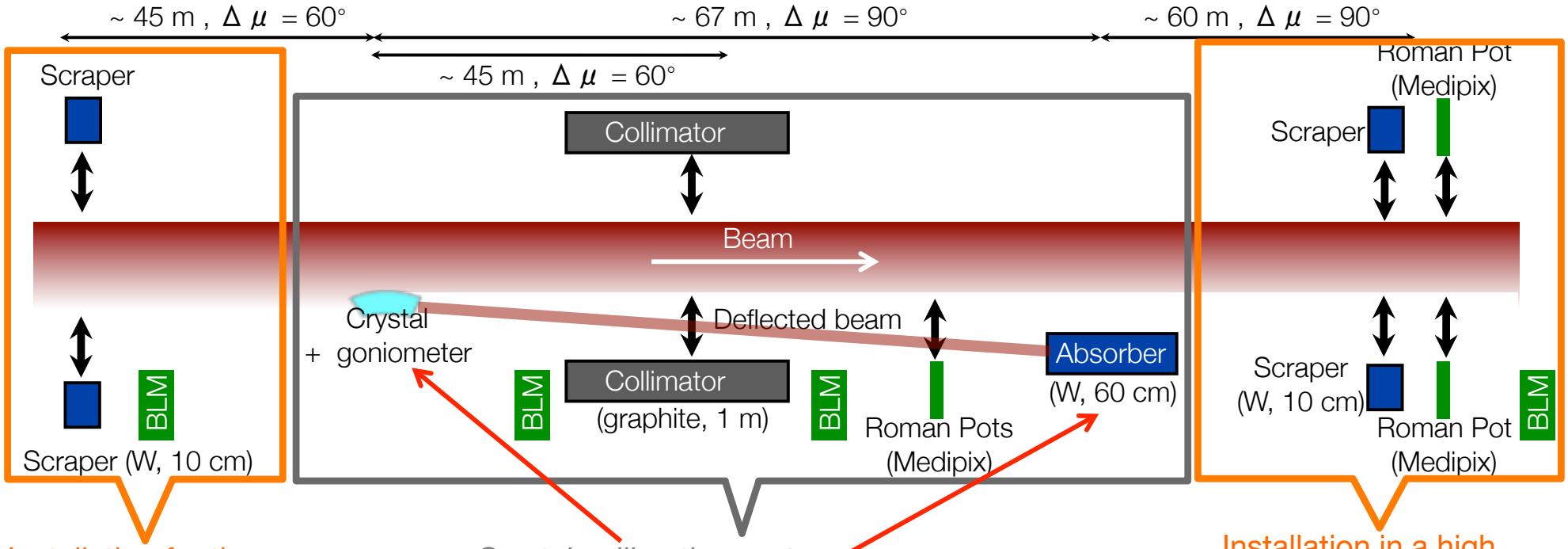
MISSION: Assess the possibility to use bent crystals as primary collimators in hadronic accelerators and colliders.

- Test with extracted beams at CERN North Area (~ 3 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 (~ 5 days per year):
  - 2009 → First results on the SPS beam collimation with bent crystals (Physics Letters B, vol. 692, no. 2, pp. 78–82).
  - 2010 → Comparative results on collimation of the SPS beam of protons and Pb ions with bent crystals (Physics Letters B, vol. 703, no. 5, pp. 547–551).
  - 2011→ Direct measurement of a strong reduction of the off-momentum halo in crystal assisted collimation of the SPS beam (Physics Letters B, 714(2-5), 231–236)
  - 2012 → Direct observation of the halo population reduction far from the crystal, SPS loss maps, optimized apertures for collimation system elements, … (data taking still on-going)
- Working for future installation of a prototype system in LHC



SPS prototype system

- Test crystals and instrumentation suitable for an operational system.
- Study the properties of a crystal collimation system (beam in coast, E = 270 GeV/n)

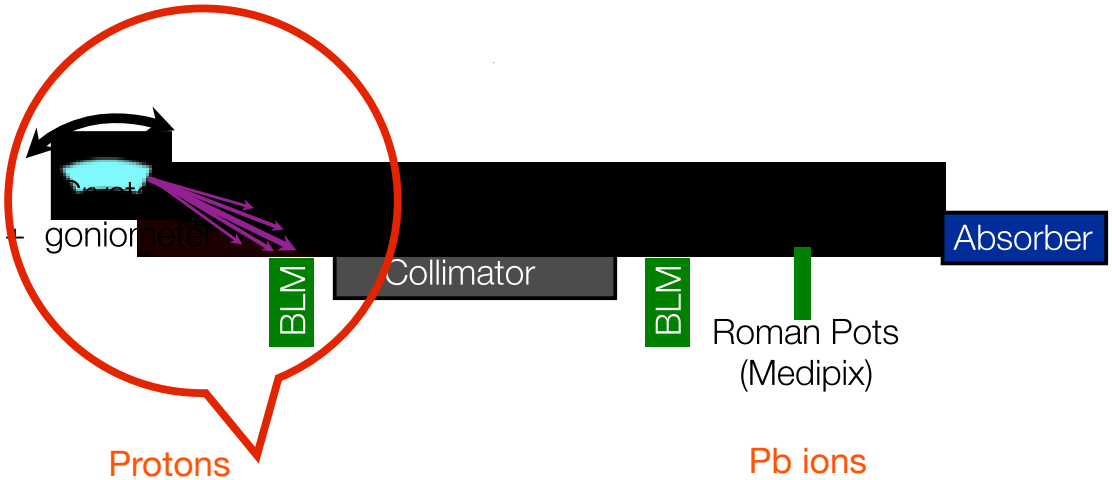


Installation for the measurements “far” from the collimation system

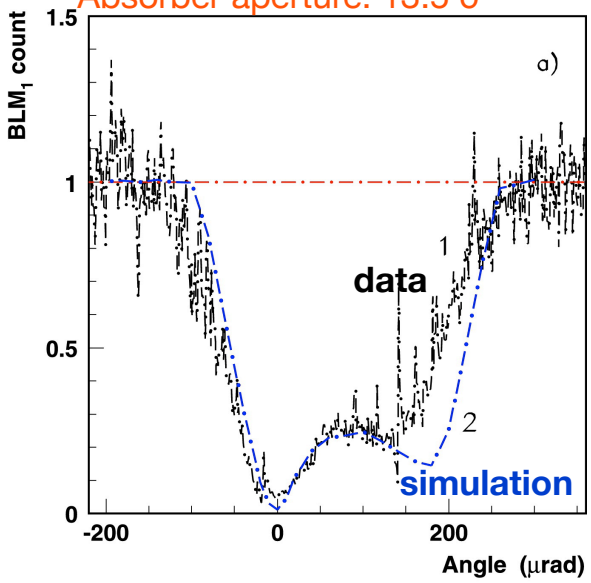
- Crystal collimation system
- Instrumentation for efficiency measurement

Installation in a high dispersion area for measurements on off-momentum halo

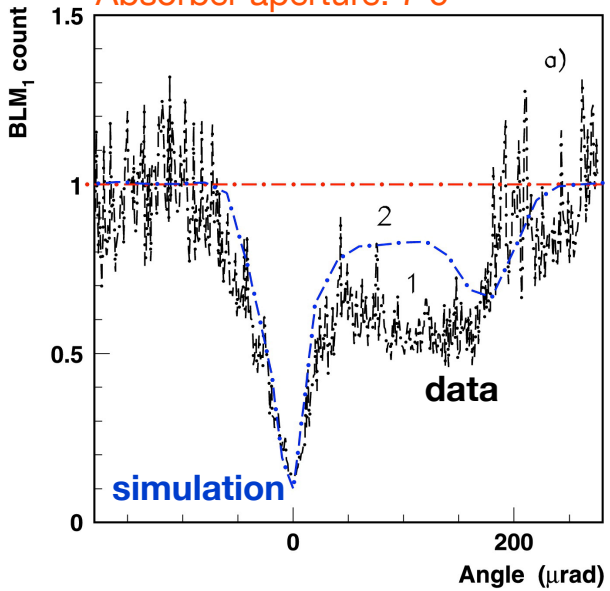
Results: local loss rate reduction



Protons
Crystal aperture: 9 σ
Absorber aperture: 13.5 σ

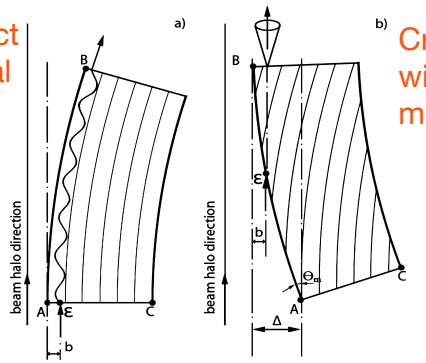


Pb ions
Crystal aperture: 3.5 σ
Absorber aperture: 7 σ



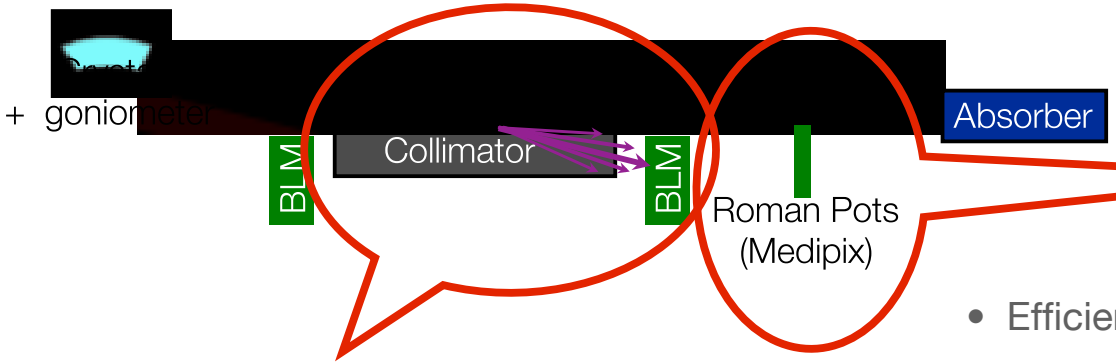
- Reduction of losses observed rotating crystal from "amorphous" to "channeling" orientation
  - very good reproducibility of loss rate profile and channeling angle
  - 5÷20x reduction for protons
    3÷7x reduction for Pb ions
- Small discrepancy between simulation and data
  - crystal imperfections (mis-cut angle) just implemented

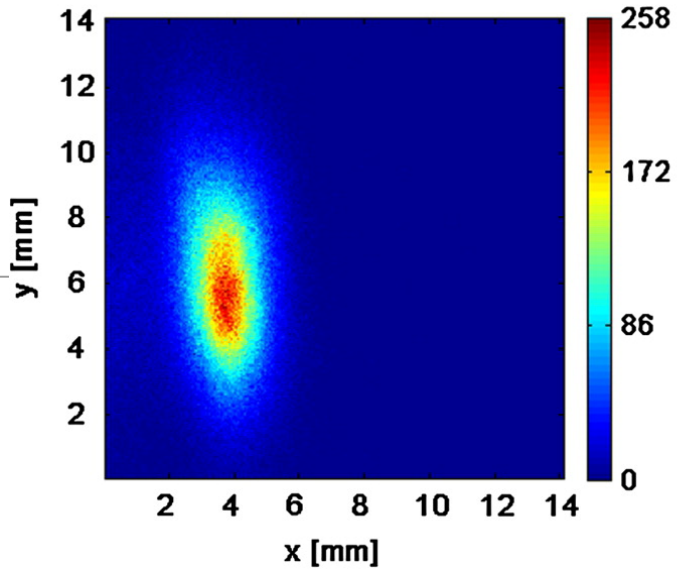
Perfect crystal



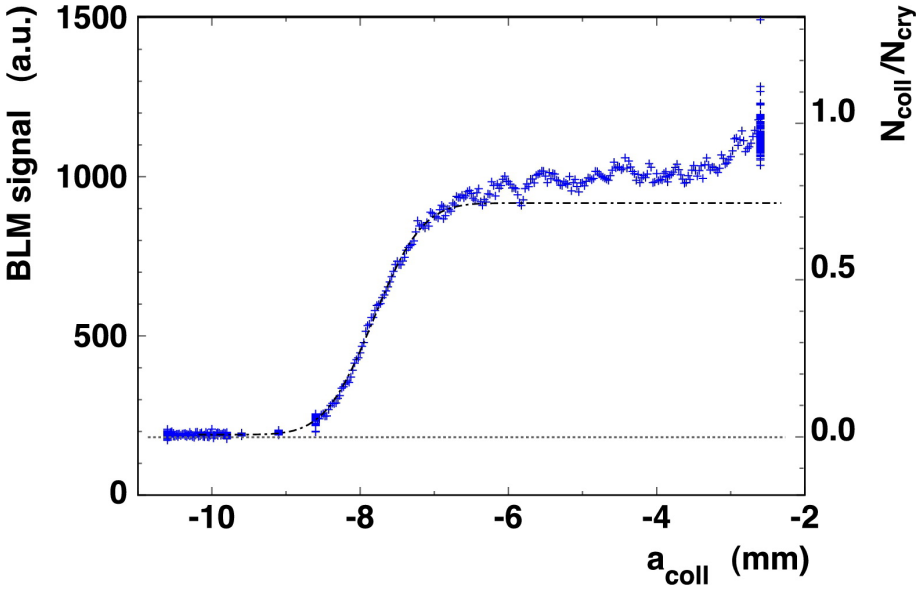
Crystal with mis-cut

Results: extraction efficiency



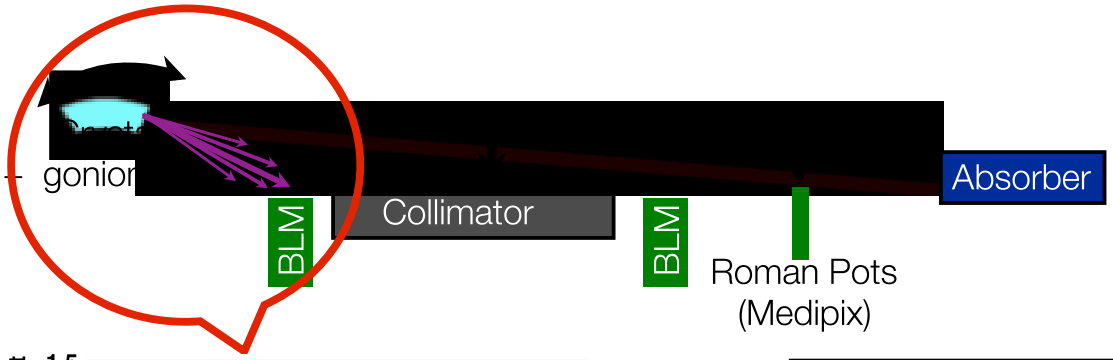


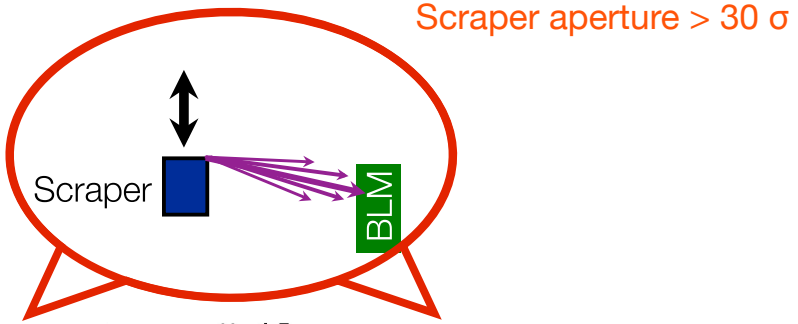
Extracted beam observed with the Medipix

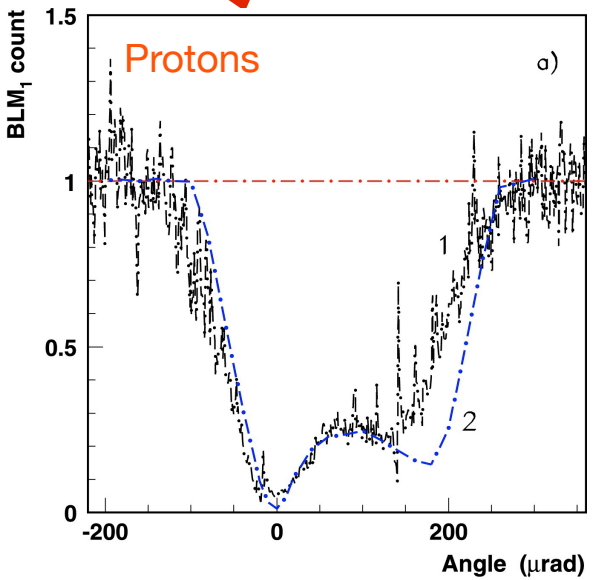


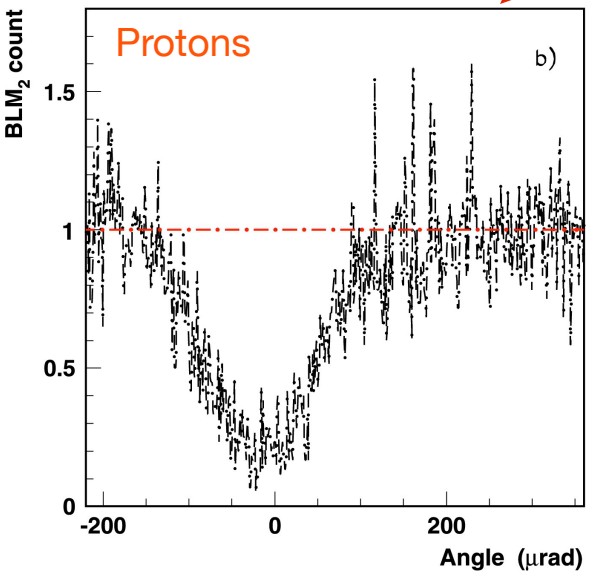
- Efficiency = $N_{deflected}$ / $N_{crystal}$
- Assumption:
  the number of particles intercepted by a moving object is proportional to the loss rate downstream the object
- Moving the collimator to intercept the deflected halo:
- $N_{deflected}$ is proportional to the losses when intercepting the whole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

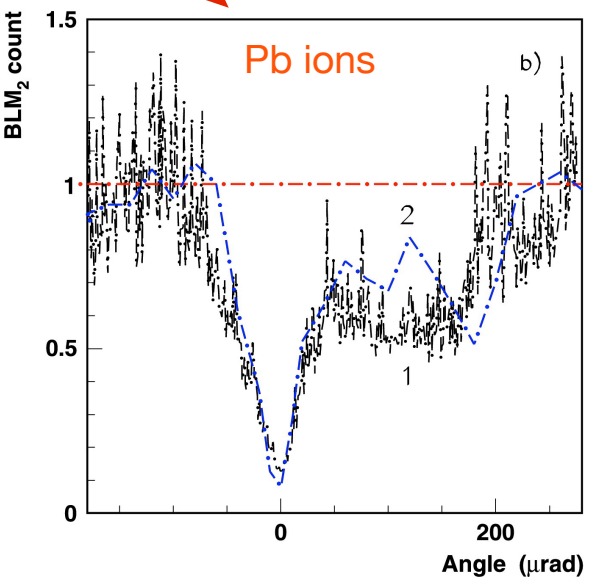
Results: off-momentum halo population reduction





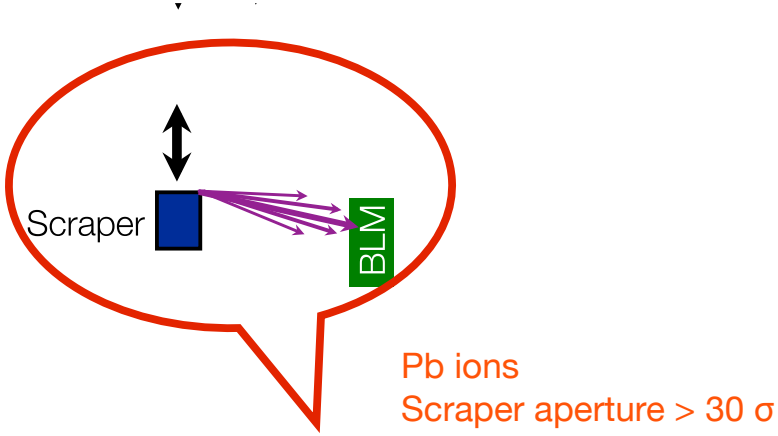




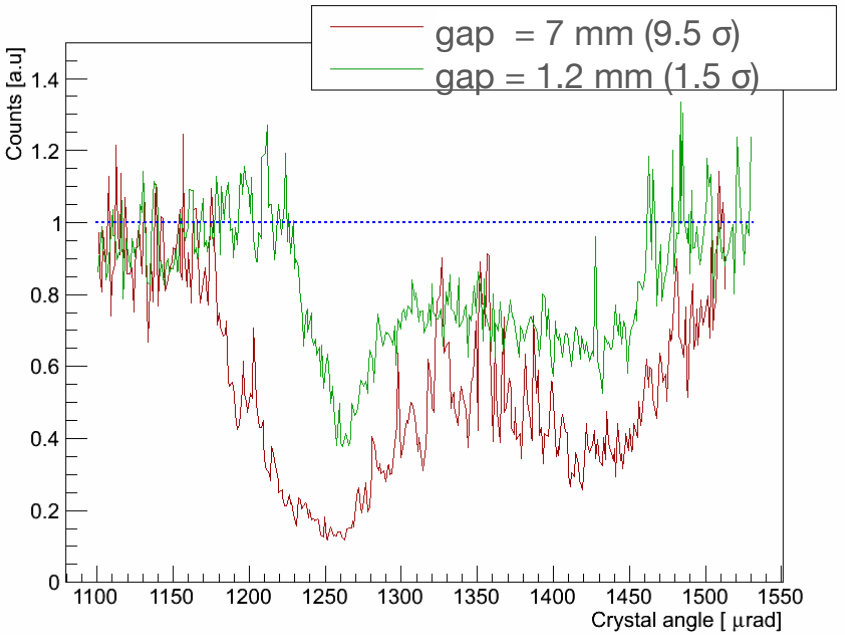


- Reduction of losses in the high dispersion area:
  - good correlation with the losses observed close to the crystal
- 2÷6x reduction for protons (less than in crystal region)
- 3÷7x reduction for Pb ions (equal to crystal region reduction)

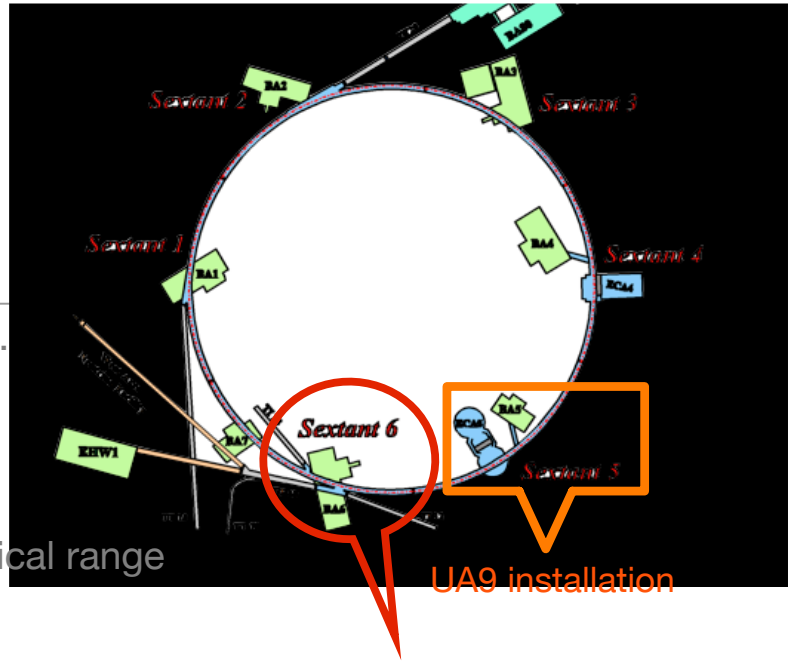
Studies: optimal aperture of the absorber



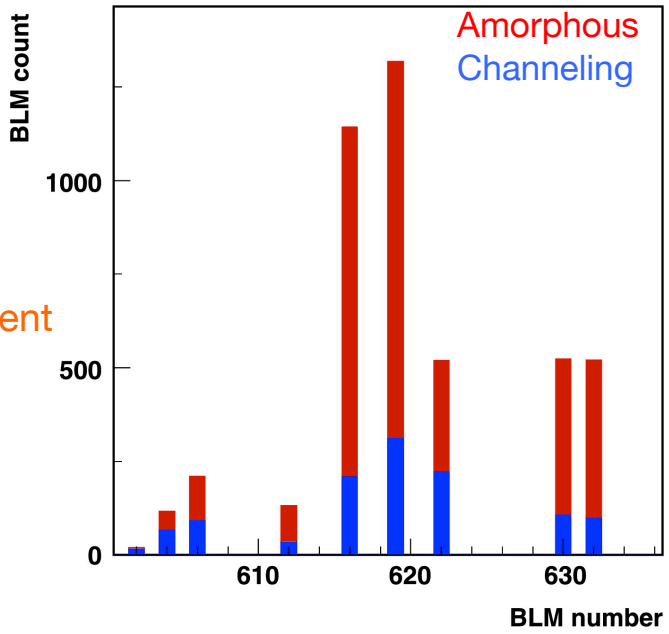
- According to simulation, the main contribution to losses in dispersive area is due particles back-scattered by the absorber:
- Loss reduction in the dispersive area strongly dependent on the absorber aperture
- Identify the difference in aperture between crystal and absorber (= gap) that minimize the losses:
- Preliminary results for ions:
  optimal gap is ~ 7 mm
- Measurements for protons on going



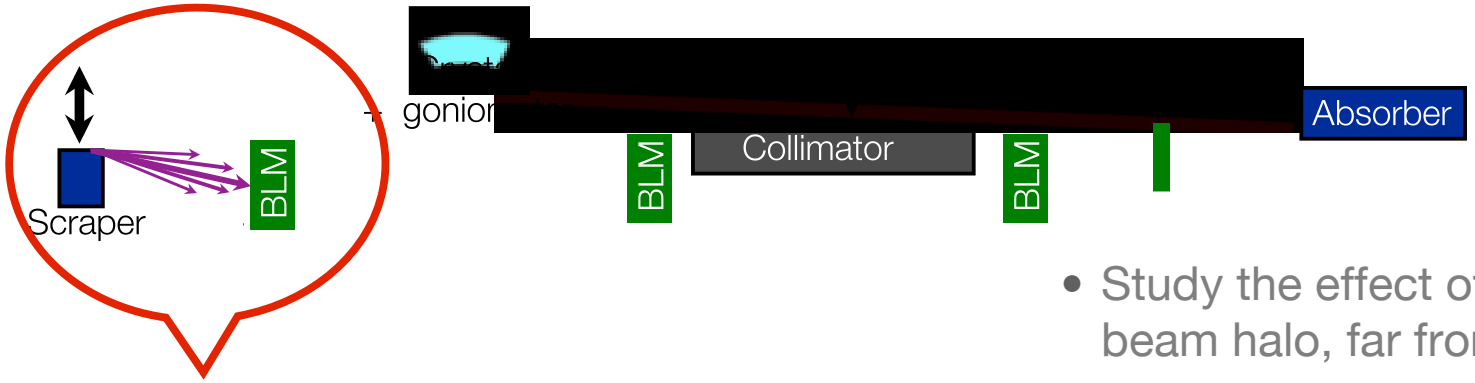
Studies: SPS ring loss maps

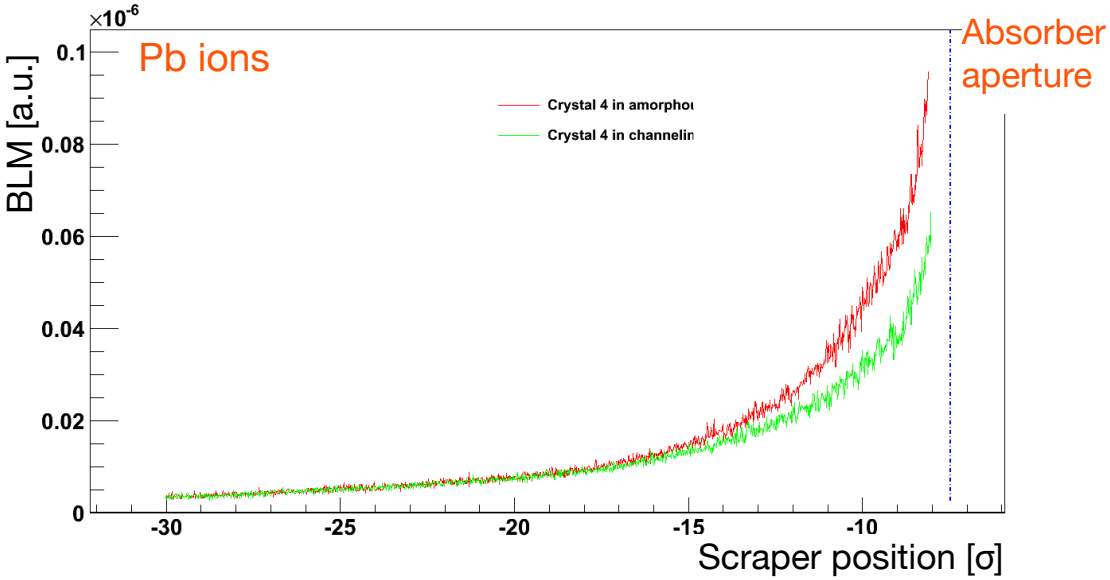


- "Loss maps" are the natural validation for collimation systems.
- Loss map measurement with the crystal collimation prototype is not trivial:
  - the SPS BLM system is not optimized to have high dynamical range
  - SPS losses are low and concentrated in very few regions (injection, extraction)
- Loss map measurement in 2011:
  - intensity increased from 1 bunch (I = 1.15 x 10^{11}) to 48 bunches, beam loss rate artificially increased
  - Clear reduction of the losses in the sextant closer to the experiment
- Measurement tried in 2012:
  - total intensity: 3.3 x 10^{13}, 4 x 72 bunches with 25 ns spacing
  - unexpected loss increase for every small movement of devices (electron cloud?)
  - installation of a solenoid may allow for future measurement



Studies: halo profile “far from the crystal”

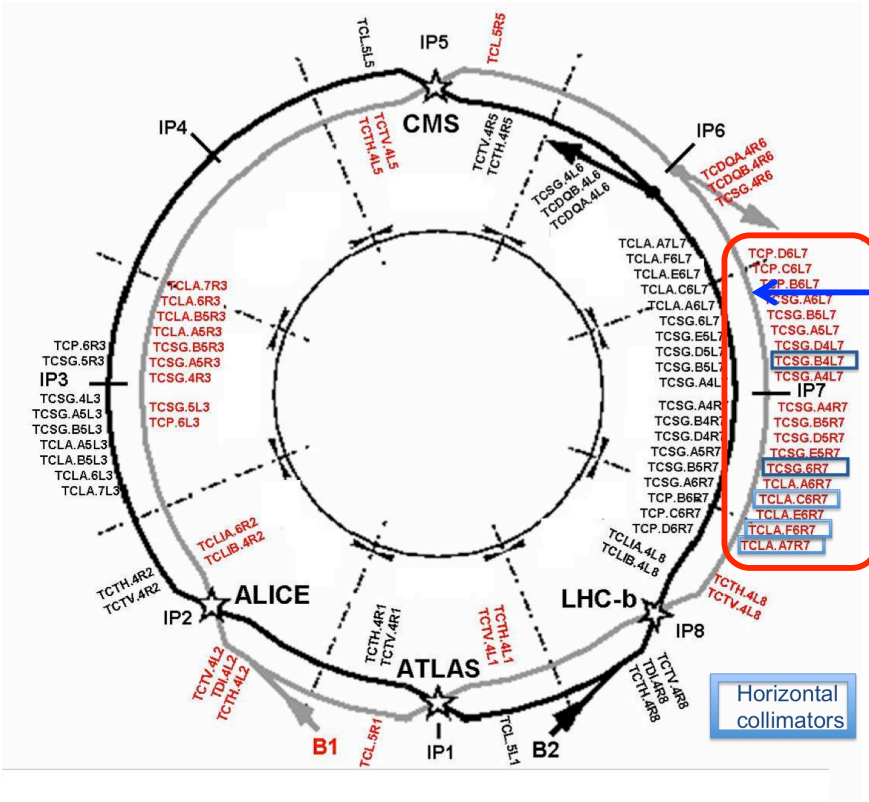


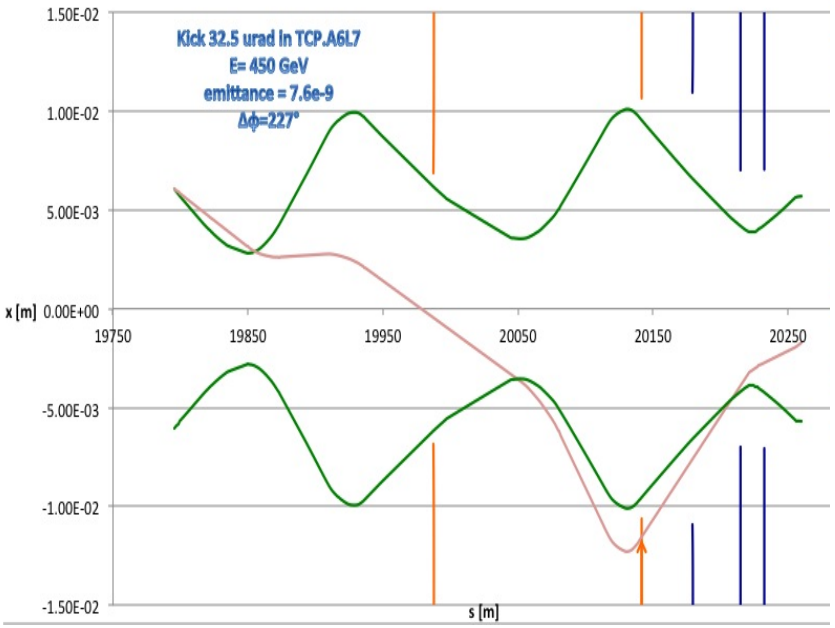


- Study the effect of crystal collimation on beam halo, far from the collimation region:
  - new scraper recently installed upstream the crystal
  - compare linear scans with crystal in channeling and amorphous position
  - Pb ions beam: small reduction of halo population for channeling orientation (signal close to detector baseline)
  - measurements for protons on-going

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
  - the next steps:
    - prepare the installation of at least one crystal
    - demonstrate the extraction of the beam halo in the LHC
    - measure the possible improvements with respect to standard collimation



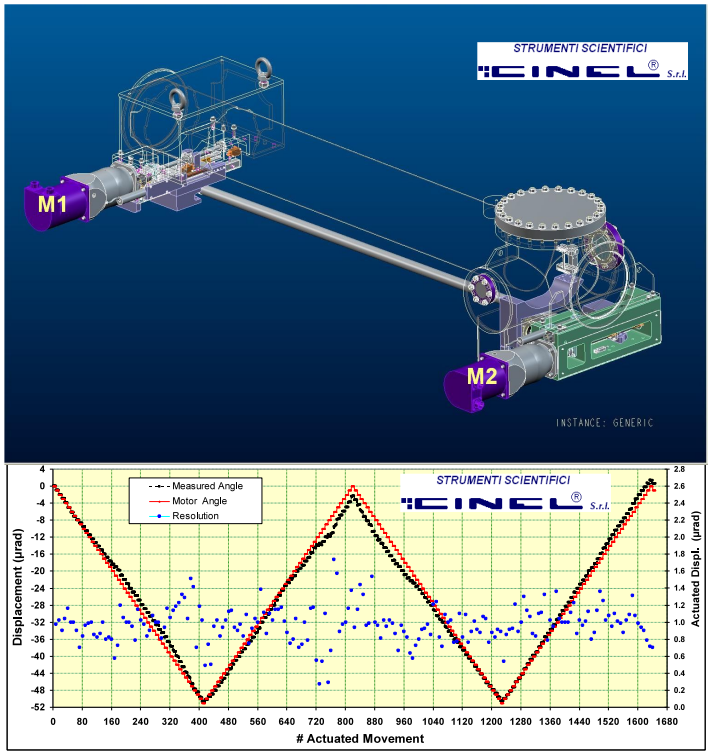


Toward LHC: layout

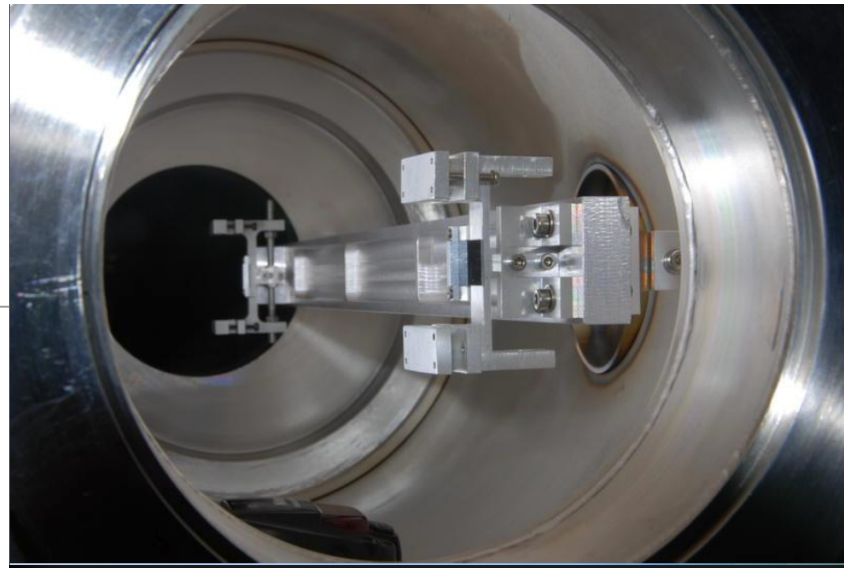
- Initial studies for the layout of the LUA9 experiment have considered:
  - only one beam (beam 1)
  - only one crystal (horizontal)
  - injection energy (450 GeV)
  - all standard collimation system in place
- Natural position for the crystal is close to the primary collimators (see arrow):
  - extracted beam absorbed by a secondary collimator with ~ 1 mm impact parameter
  - highest radiation area, tight space allowance
  - alternative possibilities are being studied

Toward LHC: R&D for a goniometer

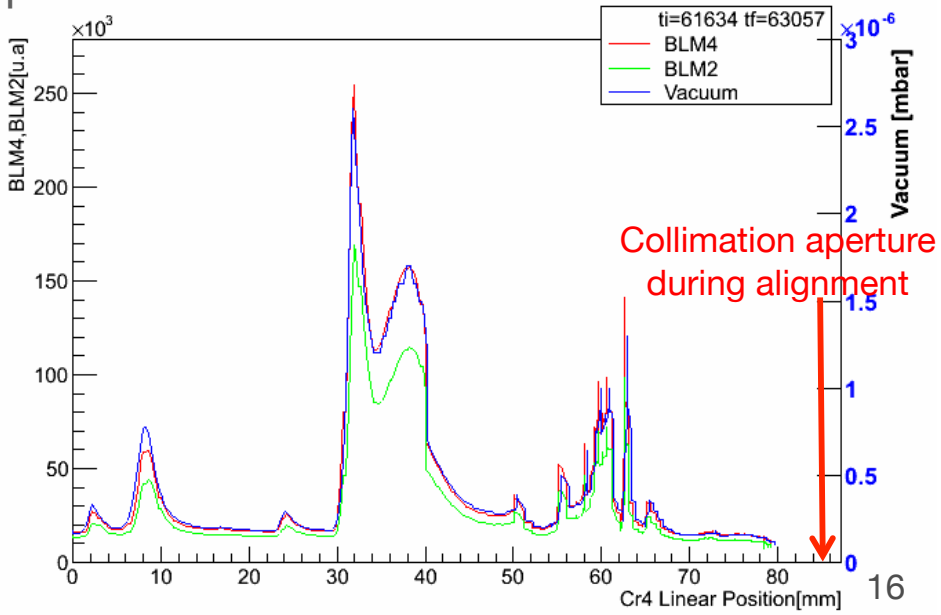
- Acceptance for channeling defined by the critical angle $\theta_c = \sqrt{2U_0/E}$:
  - θ_c = 19.45 urad for E = 120 GeV
    θ_c = 10 urad for E = 400 GeV
    θ_c = 2.1 urad for E = 7 TeV
- Goniometer accuracy must be smaller than angular acceptance (i.e. < 2 urad):
  - SPS mechanical goniometer (IHEP, Russia) has resolution < 10 urad, an improved version has been built
  - mechanical device developed by industrial partner CINEL: static resolution meets expectations, test on going to assess accuracy in dynamic regime
  - piezoelectric device under development in collaboration with industrial partner ATTOCUBE.



Electron cloud?



- In order to register loss maps:
  - total intensity: 3.3 x 10^{13}, 4 x 72 bunches with 25 ns spacing
- During the initial alignment of the crystals with the beam, strange local loss patterns observed, most probably due to electron cloud formation:
  - losses well correlated with crystal transversal position
  - losses extremely correlated with vacuum pressure
  - 50 cm aluminum bar in the goniometer
- Measurement with high intensity beam postponed
  - solenoid installed around goniometer tank, could mitigate the effect, if due to electron cloud
  - tests on going…



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.

Publications & Acknowledgments

1. W. Scandale et al., First Results on the SPS Collimation with Bent Crystals. Phys. Lett. B 692 (2010) 78–82.
2. 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.
3. W.Scandale et al., Probability of Inelastic Nuclear Interactions of High-Energy Protons in a Bent Crystal. Nucl. Instr. Meth. B, 268 (2010) 2655.
4. 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.
5. 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.
6. W. Scandale et al, The UA9 experimental layout. JINST, 1748-0221_6_10_T10002, Geneva (2011).
7. 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.
8. 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.
9. 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.

The EN/STI group at CERN is providing extraordinary support to UA9.
The BE/OP-BI-RF groups carefully prepare the SPS to allow for our measurements.

We specially thank our funding agencies, reference Committees and Referees.

Crystal damage

- Radiation resistance:
  - IHEP U-70 (Biryukov et al, NIMB 234, 23-30): 70 GeV protons, 50 ms bunch of 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 x 10^{12} p every 14.4 s, one year irradiation, channeling efficiency reduced by 30%
  - LHC: 7 TeV protons, 3 x 10^{14} p per fill
  - Possible future test at HiRadMat:
    - 440 GeV protons, max 288 bunches, 1.7 x 10^{11} protons per bunch
    - intensity comparable with worst accident scenario in LHC (asynchronous beam dump)
    - from very quick computation (only beam energy and silicon heat capacity): ΔT = 5 K per bunch, $T_{melting}$ after ~ 280 bunches