“ New experimental method to measure inelastic nuclear interactions of high energy positive charged particles with bent crystals”

Channeling 2018

Ischia, Italy (23-28 *September 2018*)

Marco Garattini

CERN / Imperial College London

UA9 Collaboration

Outline

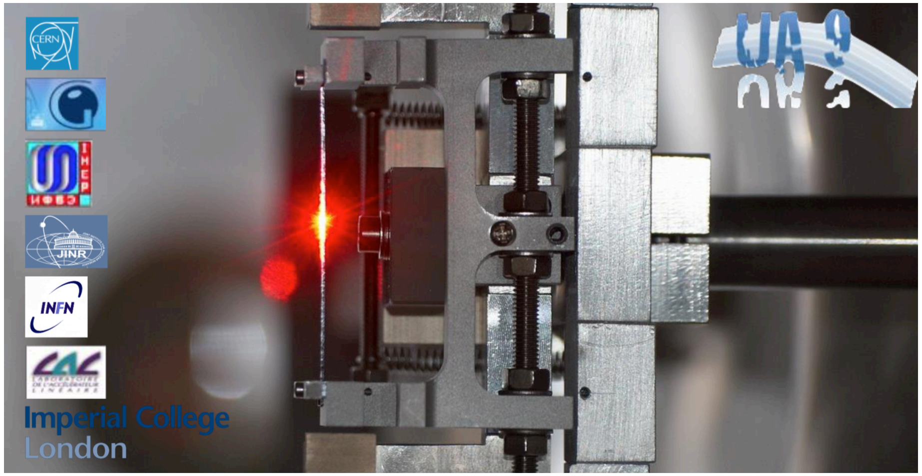
- UA9 experiment at CERN
- I.N.I. studies motivations
- I.N.I. measurements idea & apparatus
- I.N.I. FLUKA simulations
- I.N.I. data analysis and results
- Future applications
- Conclusions

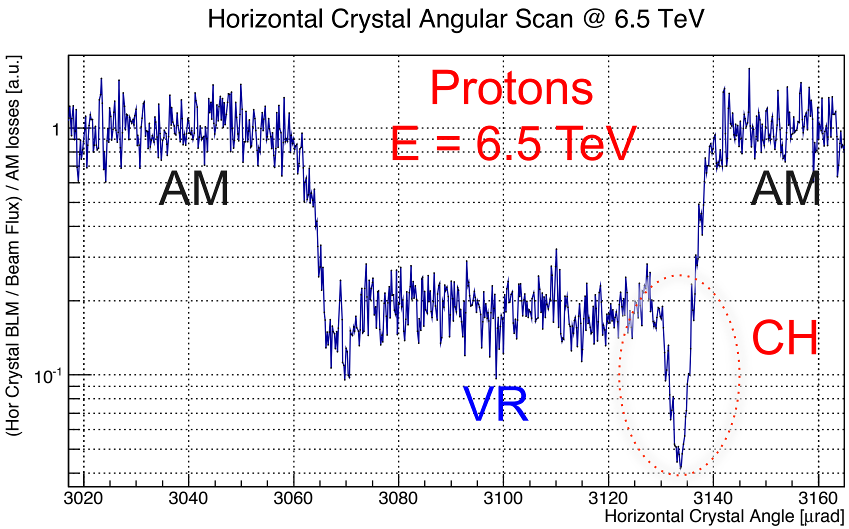
UA9 Collaboration

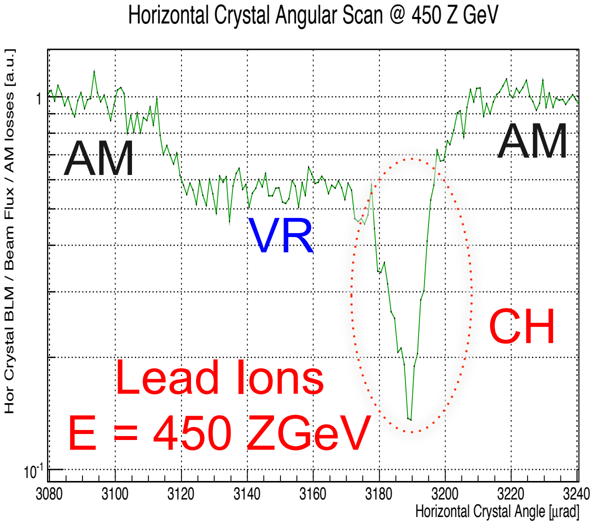
MISSION: assess the possibility to use bent Crystals as primary collimators in hadron accelerators and colliders

GOAL in 2015: Channeling performed in LHC at top energy (6.5 TeV)

2015-2018: further tests and optimization



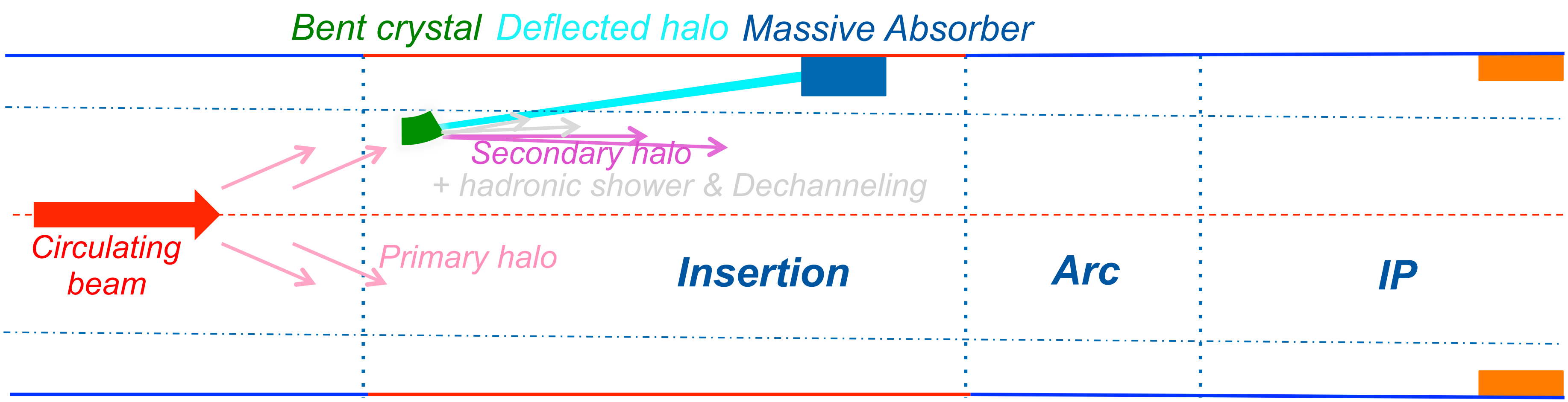




December 2015

*Losses recorded with BLM at goniometer position normalized to beam flux and to loss rate in amorphous.

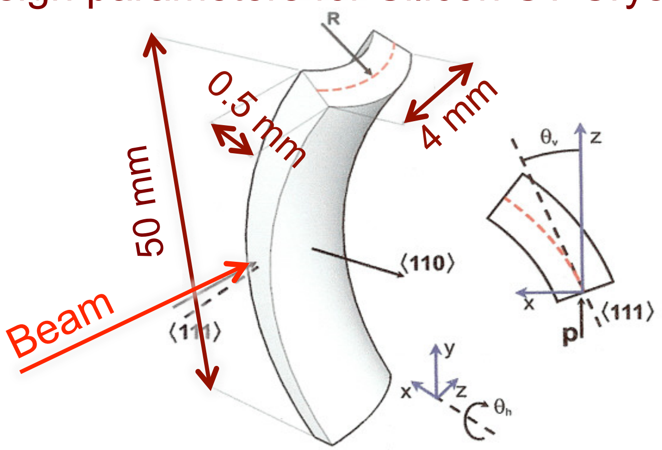
Crystal Collimation for LHC



Main gains:

- ✓ Reduction of **inelastic nuclear interactions**
  - *Reduced off-momentum losses also in DS*
- ✓ **Less collimators** and with larger gaps
  - *Impedance reduction*
- ✓ **Better performances with both p and Pb**
  - *Significant improvement of w.r.t. present*

LHC design parameters for Silicon ST Crystals



Bending 50μrad $B_{eq} \approx 300$ T @ 7 TeV!

I.N.I. Measurements motivations

LHC collimation purposes → study of the LHC losses at the crystal position

- Measure the I.N.I. rate in different crystal orientations:
  - Amorphous (AM)
  - Volume reflection (VR)
  - Planar Channeling (PL-CH)
- Show the I.N.I. reduction in PL-CH w.r.t. AM (or VR)

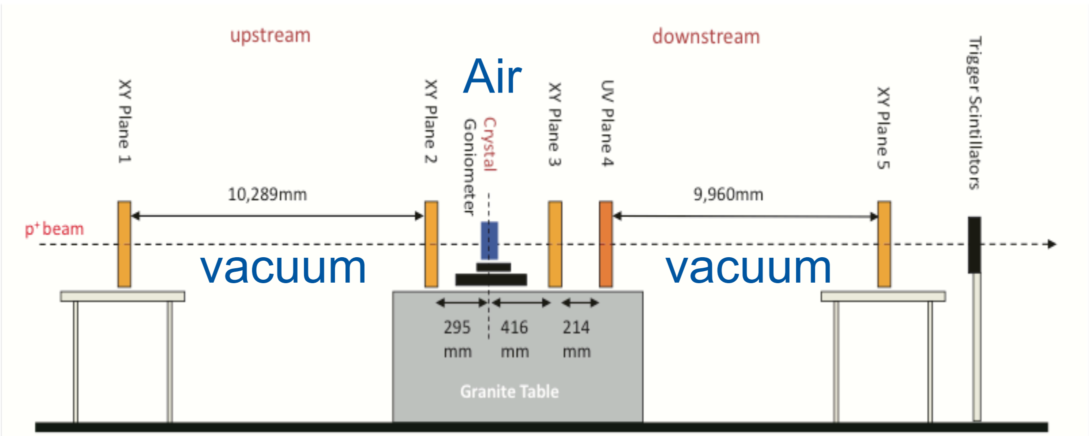
UA9 performed first measurements in 2010

Crystal physics studies (beam steering oriented)

- Show the I.N.I. reduction in Axial Channeling (AX-CH) w.r.t. PL-CH
- Comparison of the I.N.I. rate in AX-CH for different Crystal axis orientations: <111> VS <110>
- I.N.I. PL-CH/AM reduction as a function of crystal curvature
- I.N.I. rate in different crystal orientations w.r.t. to the AX-CH one
- I.N.I. rate in any kind of bent crystal: big angle, focusing, for extraction, …

UA9 Experimental apparatus at the H8 SPS extraction line

High rate and high angular resolution beam telescope based on CMS Tracker HW&SW

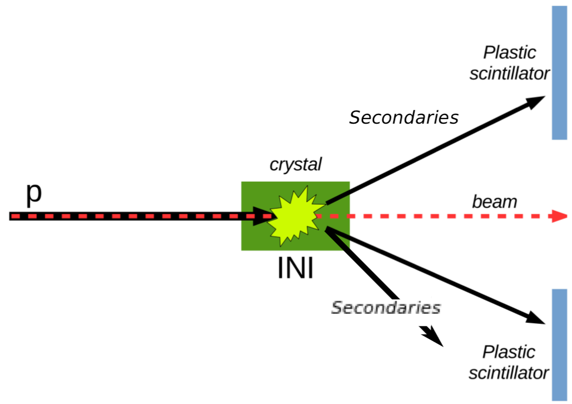


Main steps in the characterisation of bent crystals:

1. **Alignment run:** only the tracking stations are in the beam line (BKG) + I.N.I. BKG
2. **Linear scan:** crystals are placed on the beam line
3. **Detailed angular scan:** ~10^5 events/step are acquired around the channeling orientation
4. **High statistics runs:**
   - the crystal is left in the optimal channeling position for Hi-Stat. of ~10^6 p + I.N.I. in CH
   - the crystal is left in the AM orientation for hi-stat of ~106 p + I.N.I. in AM

I.N.I. H8 apparatus

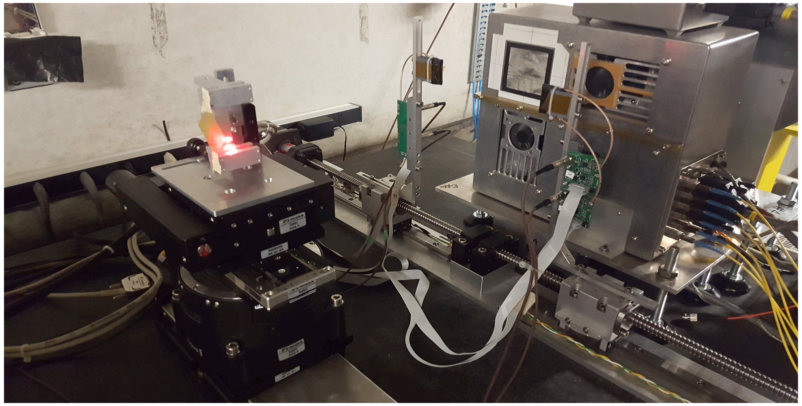
The idea is to perform a coincidence measurement integrated in the Tracker DAQ



Simple idea

↓

Good results



- Two mini scintillators (5x10x25 mm^3): to cut the background stream along the line
- Symmetric position (remote controlled): w.r.t. the beam axis and the crystal position
- Fast coincidence (gate ~ 2 ns): to register “only” I.N.I. correlated with a single track
- Scintillators acquisition is linked to the Tracker acquisition:
  - Selection of events only with single incoming tracks and multiple outgoing tracks
  - Very precise and simple off-line analysis: it is possible to apply geometrical and angular cuts, filtering only the interesting events
- Systematic measurements on any kind of crystal: in parallel with crystal bending angle and efficiency measurements

FLUKA simulations

For I.N.I. data analysis

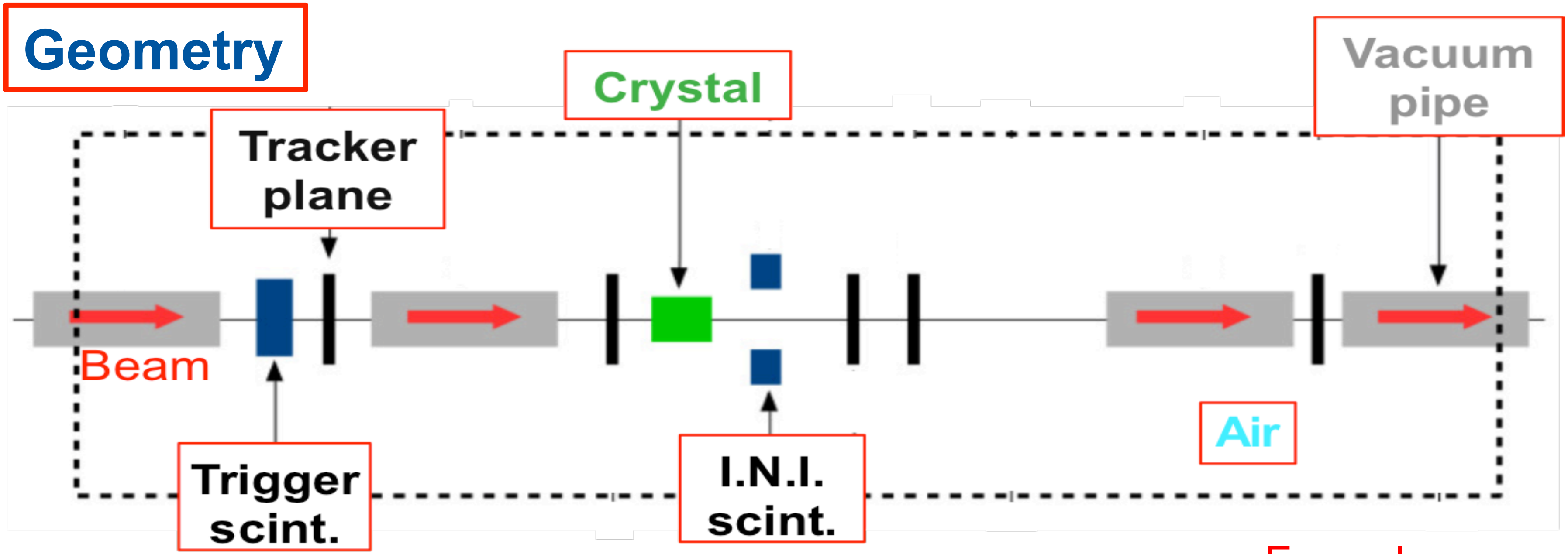
- Estimation of the detection efficiency of the experimental apparatus: physics, geometry, detector behavior

- Estimation I.N.I. absolute probability from I.N.I. frequency

To design the most efficient experimental apparatus

- i.e.: signal/BKG optimization for measurements of heavy ions beam I.N.I. in bent crystals

FLUKA simulations to estimate the I.N.I. apparatus efficiency



Efficiency factor

$F_{12} = N_{(coinc.)} / N_{(I.N.I.)}$

Prob.= Freq. / F_{12}

F_{12} was computed simulating the local experimental setup around the crystal and the scintillators

Example:

Framework	F_{12} (protons)
GEANT4	0.3301
FLUKA	0.3510

Background estimation

We are looking for very tiny effects (<1‰):
the BKG control is crucial !!!

The BKG is reduced "a priori":

- studying I.N.I. track by track
- using I.N.I. scintillators with only few ns of time coincidence gate
- using small I.N.I. scintillators

Anyway, some BKG sources are not erasable:

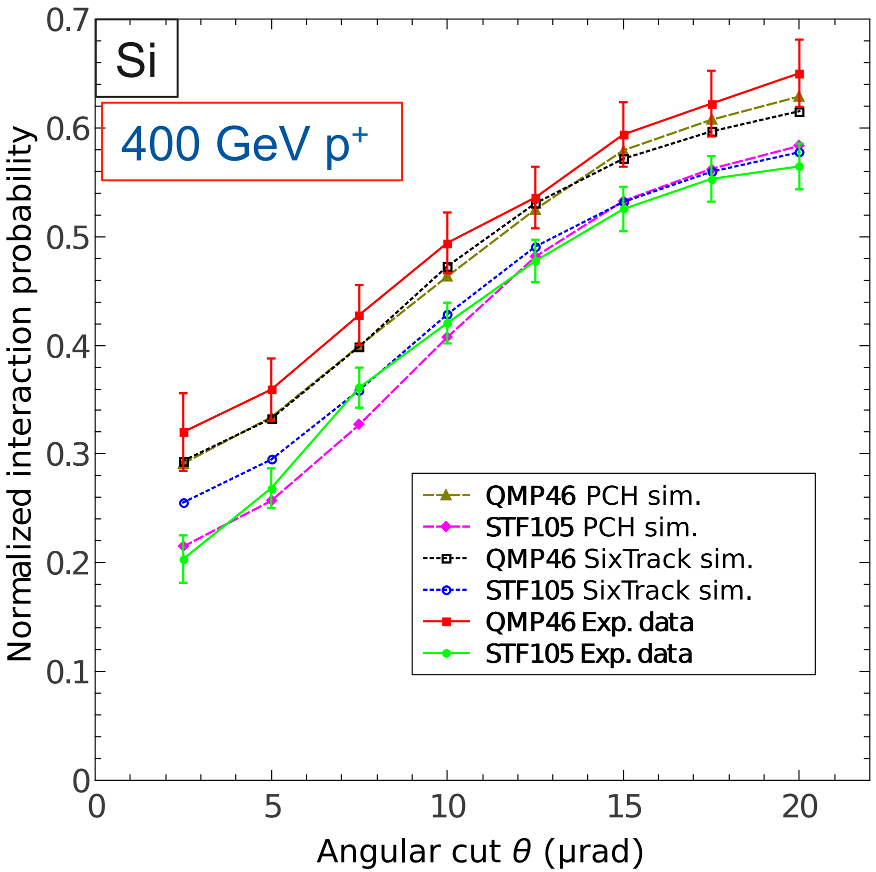
- An high "cosmological" BKG is present along the H8 beam line, due to the interaction of the beam with the line components
- I.N.I. interactions with the "no-crystal" matter between the 2nd and the I.N.I. detectors positions (silicon strips, air, etc…)

Solution: a hi-stat BKG run is acquired removing only the crystal from the beam line, and then subtracting "a posteriori" this signal during the data analysis. This BKG component is ~25% w.r.t. the I.N.I. signal in CH, an half of what the UA9 experiment had in 2010

Main results (1/4)

I.N.I. studies for LHC collimation purposes:

comparison between the two kinds of crystals successfully tested in LHC:
for CH strip crystals use (110) planes, instead quasi-mosaic uses (111) ones



I.N.I. reduction factor in CH w.r.t. AM orientation (within $\Theta_c/2$ = 5 μrad):

Strip: ~3.7

Quasi-mosaic: ~2.8

This difference is due to the different average planes distance

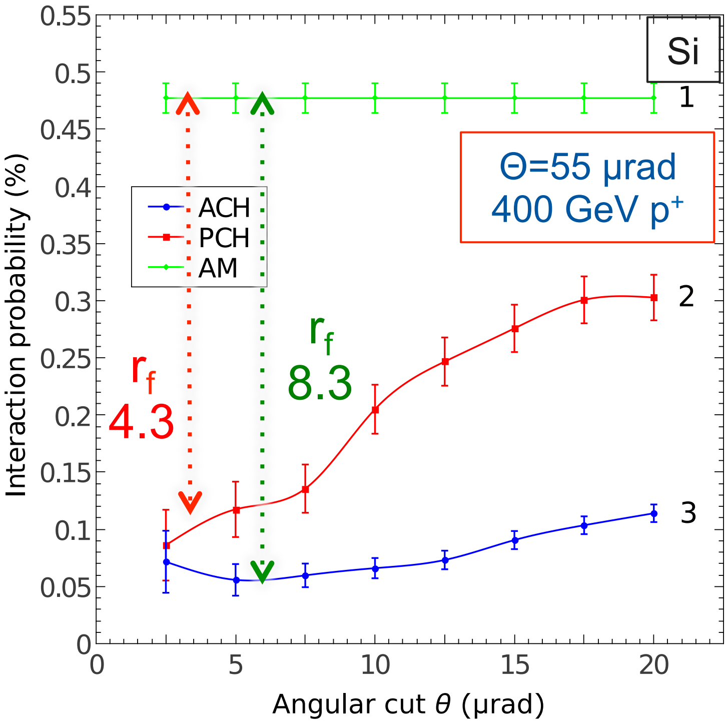
Strip→ 1.92 Å
Quasi-mosaic → 1.57 Å

Very good agreement both with Planar Channeling full analytical and SixTrack Monte Carlo simulations

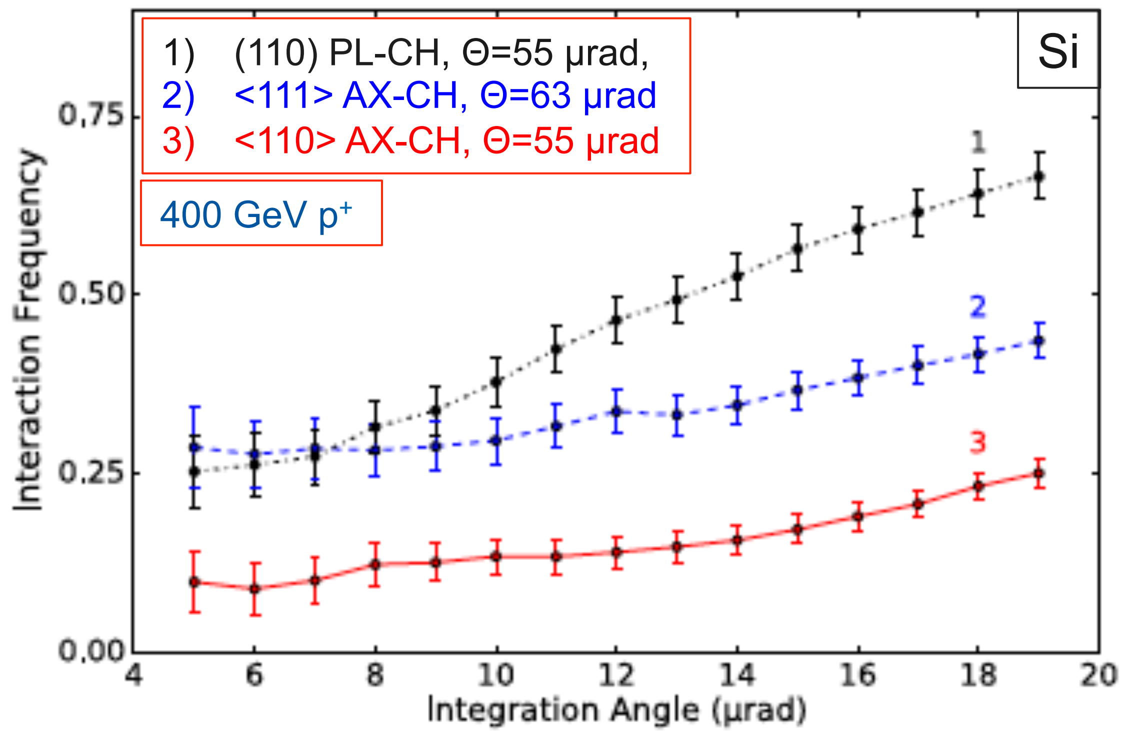
Main results (2/4)

Studies of I.N.I. probability in Axial Channeling:

Very first estimation of I.N.I. absolute probability in AX-CH



Comparison of I.N.I. probability (AM normalized) between <110> and <111> axis orientation

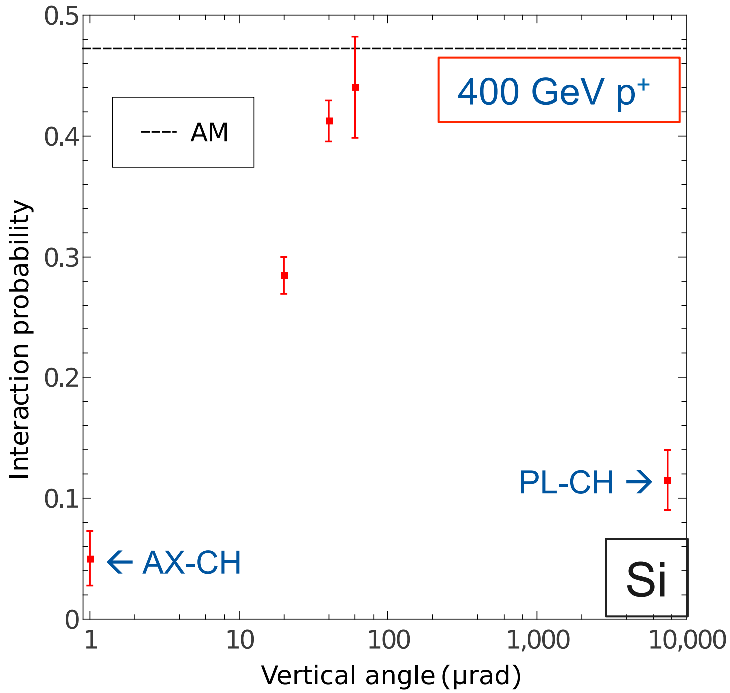


Crystals thickness along the beam direction: ~ 2mm

Main results (3/4)

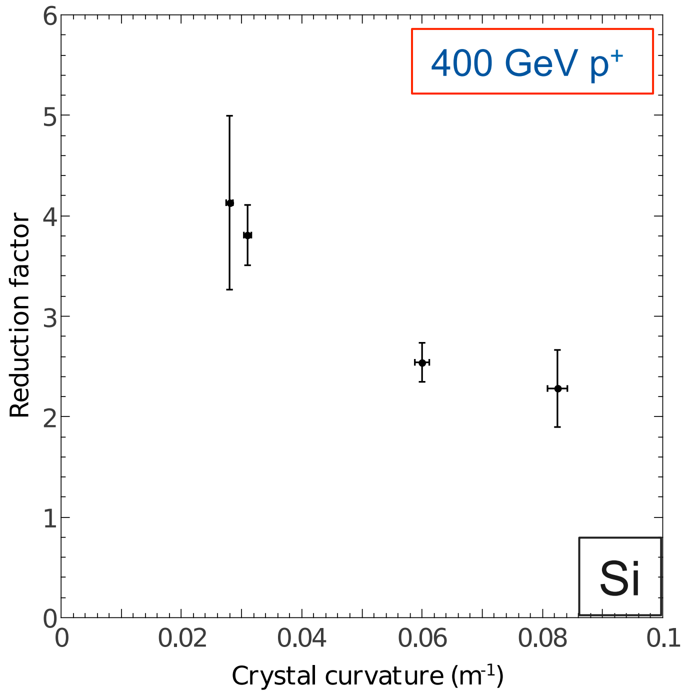
Further I.N.I. probability studies:

I.N.I. absolute probability as a function of vertical misalignment w.r.t. the AX-CH orientation



Crystal bending angle Θ=55 μrad
Crystal thickness along the beam: 2 mm

PL-CH I.N.I. reduction factor w.r.t. the crystal curvature



Crystals thickness
along the beam: 2 mm

Main results (4/4)

Two publications produced:

Physics Letter B, 2016

Physics Letters B 760 (2016) 826–831

Contents lists available at ScienceDirect

Physics Letters B

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High-efficiency deflection of high energy protons due to channeling along the ⟨110⟩ axis of a bent silicon crystal

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ABSTRACT

A deflection efficiency of about 61% was observed for 400 GeV/c protons due to channeling, most strongly along the ⟨110⟩ axis of a bent silicon crystal. It is comparable with the deflection efficiency in planar channeling and considerably larger than in the case of the ⟨111⟩ axis. The measured probability of inelastic nuclear interactions of protons in channeling along the ⟨110⟩ axis is only about 10% of its amorphous level whereas in channeling along the (110) planes it is about 25%. High efficiency deflection and small beam losses make this axial orientation of a silicon crystal a useful tool for the beam steering of high energy charged particles.

1. Introduction

In the last twenty years, channeling has been exploited for steering [1], collimation [2–4] and extraction [2,5–7] of relativistic beams in circular accelerators, as well as splitting and focusing of extracted beams [8]. In the last decade, a significant boost to the research on particle-crystal interactions was provided by the fabrication of uniformly bent crystals with thickness along the beam direction suitable for experiments at high-energy. The novel generation of crystals has demonstrated the capability of efficiently steering positively charged [9,10] particle beams and to observe the deflection of negatively charged particle beams [11,12]. As well as efficient deflection, channeling has been shown to modify the probability of incoherent interactions with atomic nuclei with respect to an amorphous material of the same length [13]. In particular, the use of bent crystals as a primary collimator has been demonstrated to reduce the beam losses in the SPS proton synchrotron at CERN [14–16], leading to the installation of two bent crystals in the LHC collider [17]. The crystals installed in the LHC were successfully tested and shown to reduce the beam losses in the LHC ring with 6.5 TeV/c protons [18].

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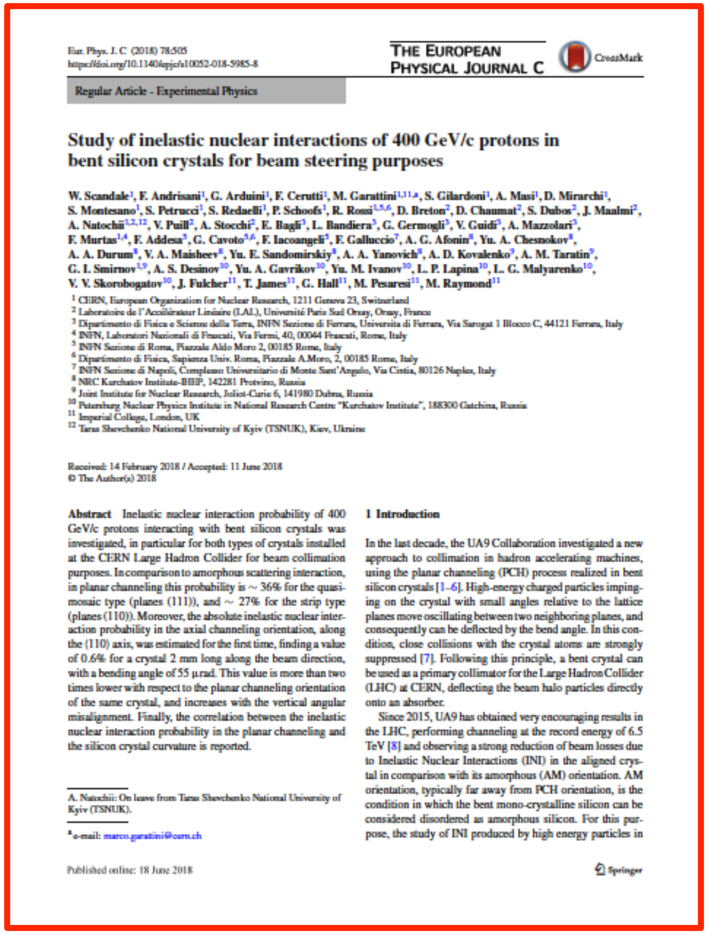

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Study of inelastic nuclear interactions of 400 GeV/c protons in bent silicon crystals for beam steering purposes

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Abstract Inelastic nuclear interaction probability of 400 GeV/c protons interacting with bent silicon crystals was investigated, in particular for both types of crystals installed at the CERN Large Hadron Collider for beam collimation purposes. In comparison to amorphous scattering interaction, in planar channeling this probability is ∼ 36% for the quasi-mosaic type (planes (111)), and ∼ 27% for the strip type (planes (110)). Moreover, the absolute inelastic nuclear interaction probability in the axial channeling orientation, along the ⟨110⟩ axis, was estimated for the first time, finding a value of 0.6% for a crystal 2 mm long along the beam direction, with a bending angle of 55 μrad. This value is more than two times lower with respect to the planar channeling orientation of the same crystal, and increases with the vertical angular misalignment. Finally, the correlation between the inelastic nuclear interaction probability in the planar channeling and the silicon crystal curvature is reported.

1 Introduction

In the last decade, the UA9 Collaboration investigated a new approach to collimation in hadron accelerating machines, using the planar channeling (PCH) process realized in bent silicon crystals [1–6]. High-energy charged particles impinging on the crystal with small angles relative to the lattice planes move oscillating between two neighboring planes, and consequently can be deflected by the bend angle. In this condition, close collisions with the crystal atoms are strongly suppressed [7]. Following this principle, a bent crystal can be used as a primary collimator for the Large Hadron Collider (LHC) at CERN, deflecting the beam halo particles directly onto an absorber.

Since 2015, UA9 has obtained very encouraging results in the LHC, performing channeling at the record energy of 6.5 TeV [8] and observing a strong reduction of beam losses due to Inelastic Nuclear Interactions (INI) in the aligned crystal in comparison with its amorphous (AM) orientation. AM orientation, typically far away from PCH orientation, is the condition in which the bent mono-crystalline silicon can be considered disordered as amorphous silicon. For this purpose, the study of INI produced by high energy particles in

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Future applications

- I.N.I. measurements of heavy ions in bent crystals for LHC
- I.N.I. measurements of heavy ions and 180 GeV pions in bent crystals for beam steering in general
  - Collimation
  - Focusing
  - Extraction
  - Splitting
- I.N.I. measurements on hi-dose irradiated crystals
- In the last two years UA9 collected new interesting data and the analysis is on going

Conclusions

- Studies of I.N.I. interactions in bent crystals are essential for a better understanding of their behavior as LHC collimators, but also to investigate their physical features for different beam steering applications.
- A very effective method and experimental setup to measure the INI frequencies in bent crystals, and a reliable analysis and simulation tool to estimate the related INI absolute probability, have been implemented.
- A study of I.N.I. of high-energy protons with LHC bent crystals was performed, estimating the reduction factor in CH orientation w.r.t. AM one.
- A very first estimation of I.N.I. absolute probability in <110> AX-CH orientation and its reduction factor w.r.t. PL-CH was obtained for <111> & <110> axis
- I.N.I. measurements of high-energy protons in bent crystals with different shapes and different orientation was obtained
- Using FLUKA a new setup for I.N.I. studies of high-energy heavy ions and 180 GeV pions in bent crystals has been realized
- New interesting results are expected form the data recently collected

Thank you for your attention !

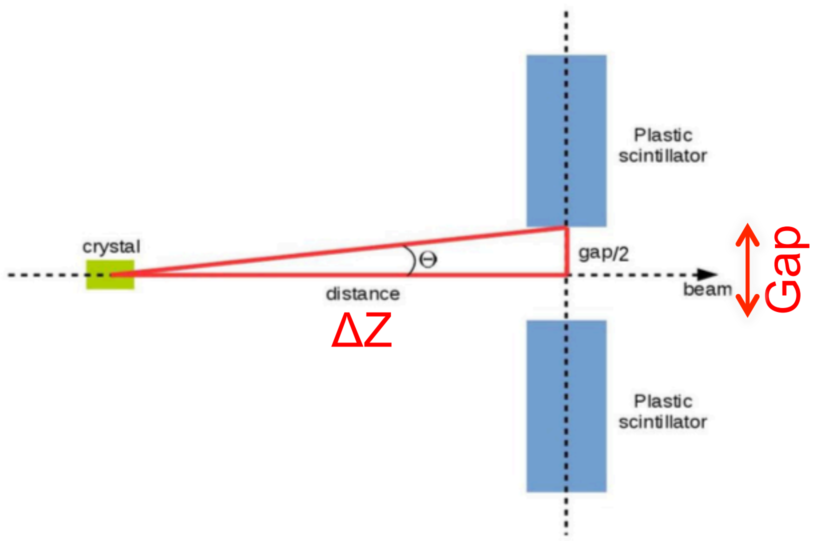
SPARES SLIDES

Future studies for Pb Ions beam I.N.I. in the Crystal

November 2016

Some fixed parameters for practical reasons:

1) The gap between the two scintillators has to be larger w.r.t. the Pb Ions beam size: Gap ≥ 1 cm
2) Due to space limitations in UA9 setup, the distance (ΔZ) between the Crystal and the scintillators has to be: 15 cm < ΔZ < 25 cm



Pb Ions 30 AGeV produce an
huge background
along the line, that cover the I.N.I. signal.

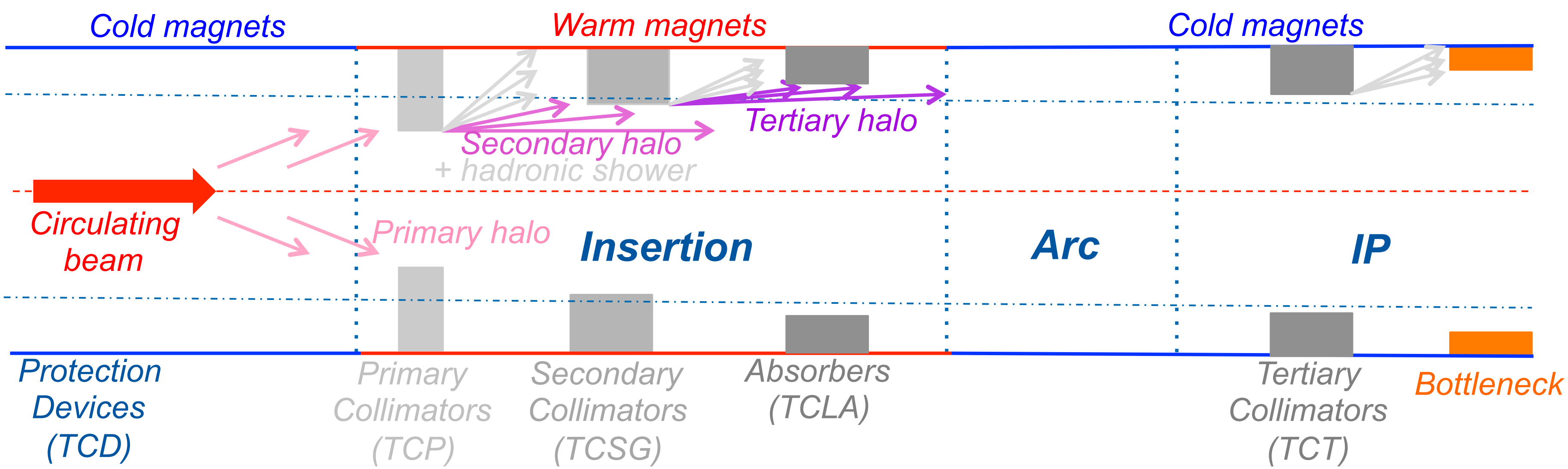
↓

It's important to reduce the size and the coincidence time gate as much as possible

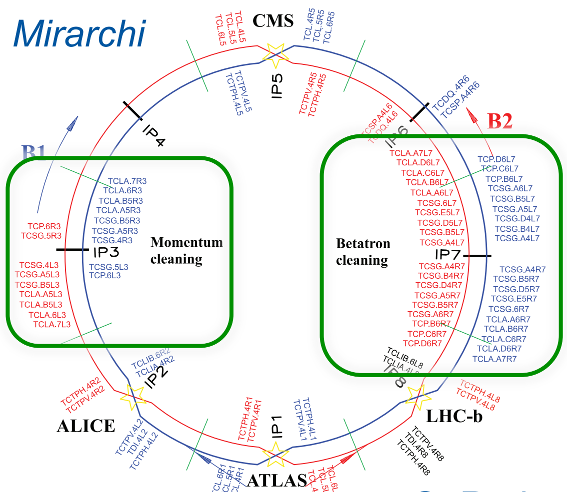
↓

With FLUKA simulation is possible to choose the best experimental layout to have **the best possible SIG/BKG ratio**

Present LHC collimation system



D. Mirarchi



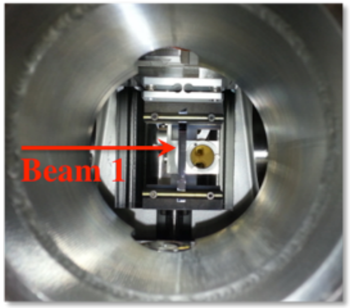
S. Redaelli

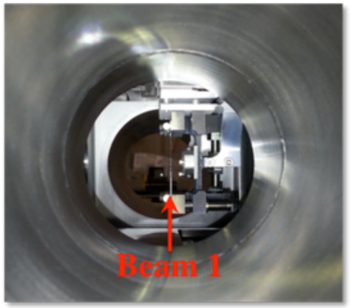
Multi-stage cleaning with about 50 collimators per beam, two dedicated insertions

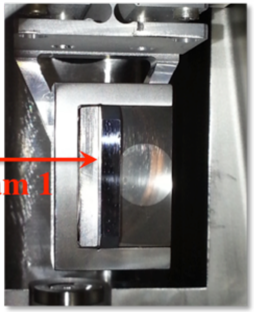
Hardware installed in the LHC

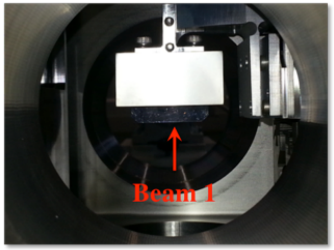
Two crystals** installed in the **IR7 (Beam1)** during **April 2014: (developed in the UA9 framework)

Silicon Strip crystal in the horizontal plane









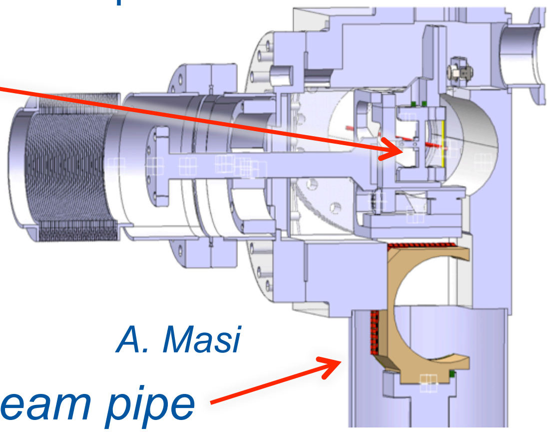
Quasi-mosaic crystal in the vertical plane

And two goniometers: (UA9 framework)

- ✓ Piezo actuator in closed loop (angular stage)
- ✓ Transparent during normal operation

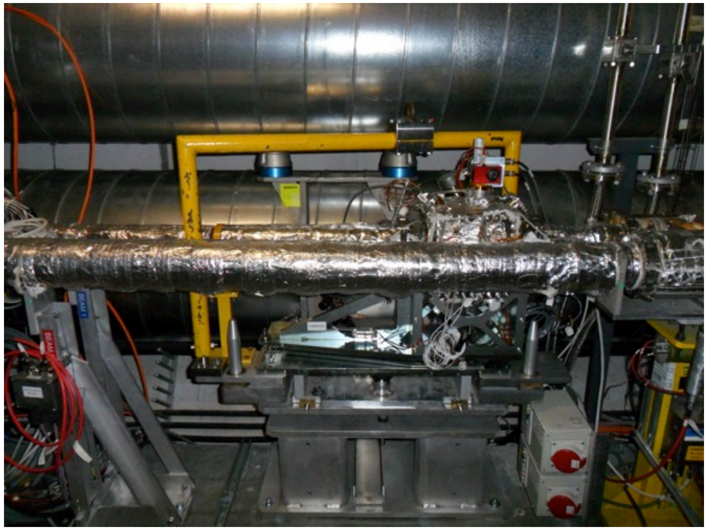
Crystal

Able to align the Crystal with an accuracy **~ 0.1 μrad**



A. Masi

Movable segment of beam pipe

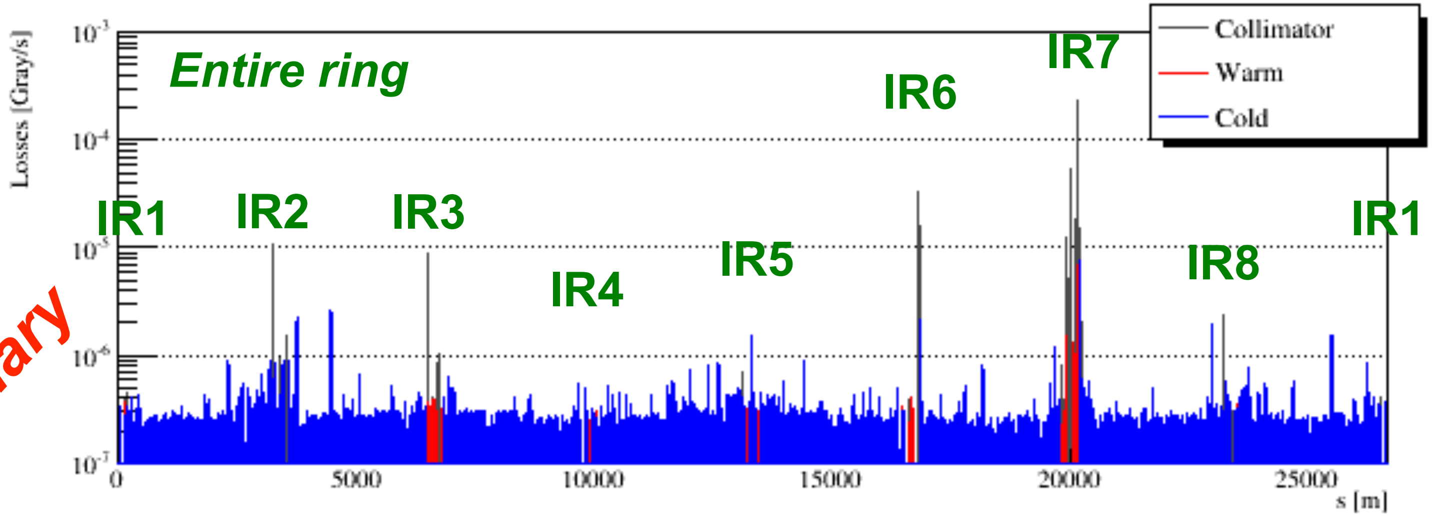


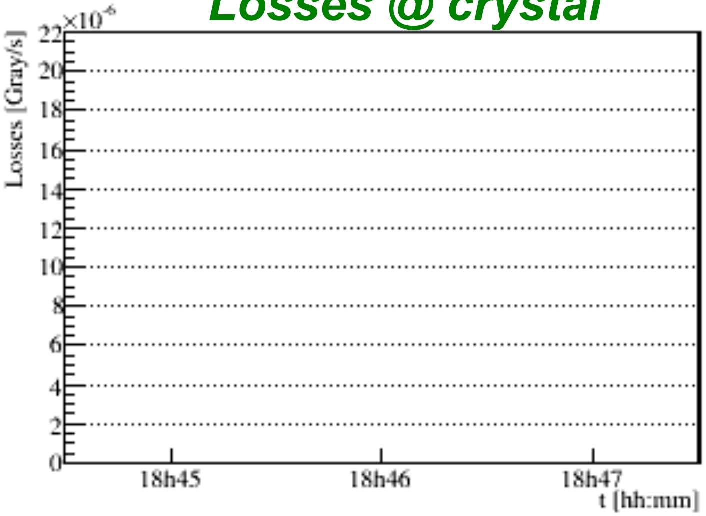
Beam loss pattern during angular scan

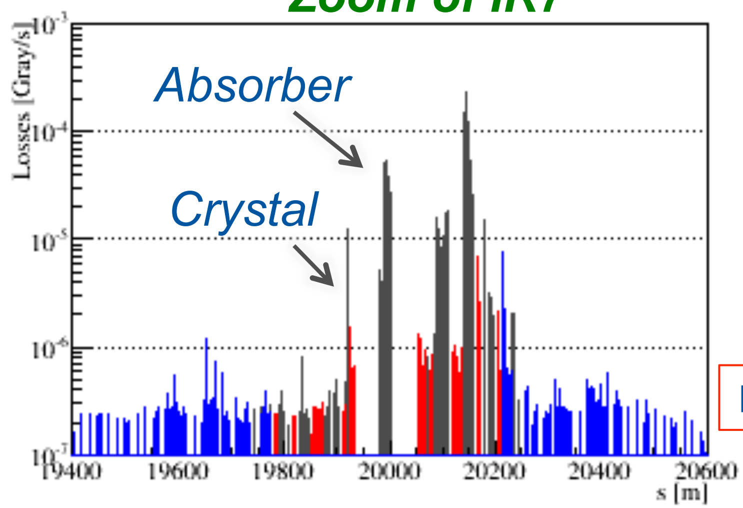
***2015: On-line observation** of the **crystal channeling** in the LHC! (**E = 450 GeV**)*

Preliminary

Raw data



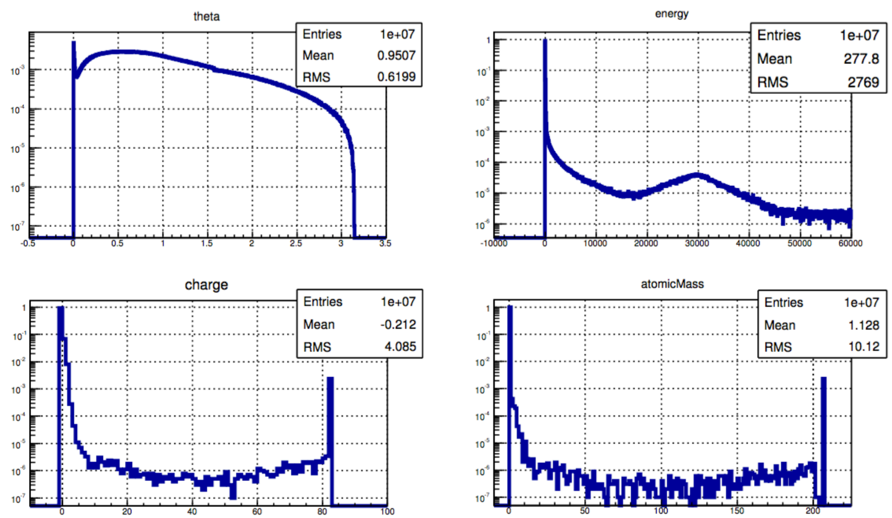


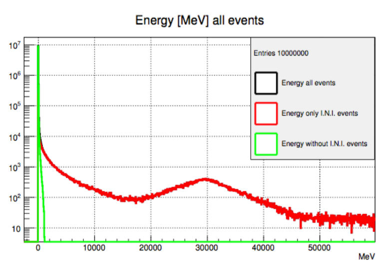


D. Mirarchi

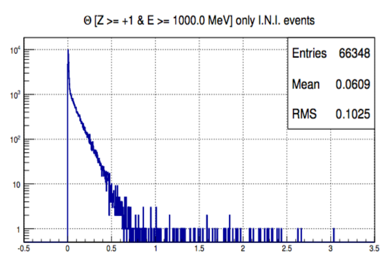
Study of the I.N.I. products in the Crystal

- Pb Ions beam: E = 30 AGeV
- Silicon Crystal: ΔX=1 mm, ΔY=55 mm, ΔZ=2mm (Strip Crystals)





(a) Energy distribution.



(b) Angular distribution for INI secondaries.

Only Crystal + Pb beam simulation:

products are emitted mainly at very small angles, so we have to choose:

1. The minimum possible gap: 1 cm
2. The maximum possible distance: 25 cm

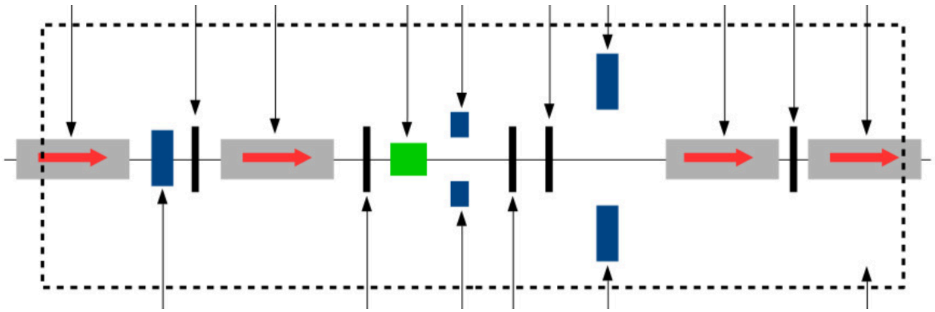
I.N.I. main products features:

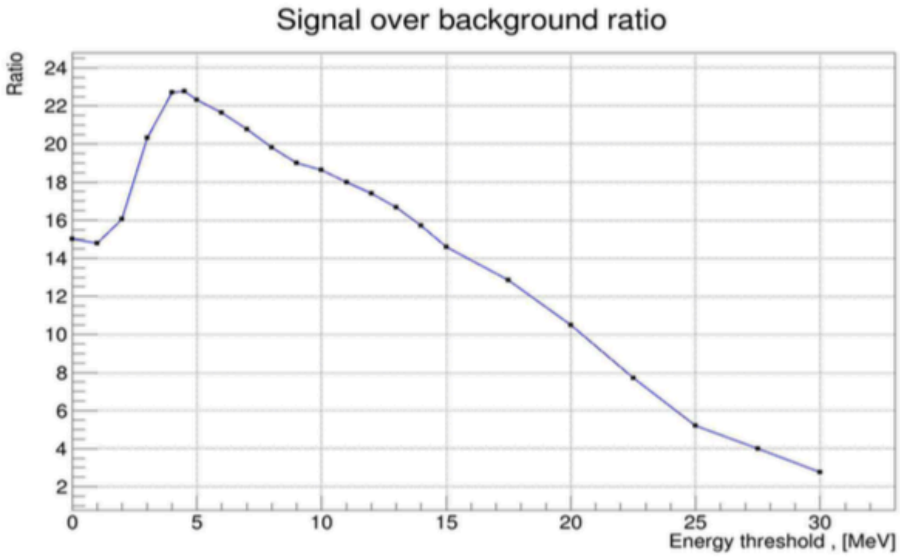
E > 1 GeV

Z ≥ 1 (and neutrons)

Scintillators energy thresholds

Full geometry simulation





For:

Gap = 10 mm

Scintillators size:
ΔX=10 mm, ΔY=25 mm, ΔZ=5mm

Distance from the crystal: ΔZ=25 cm

Scintillators thresholds = ~ 4 MeV

SIG/BKG ~ 23

This was repeated for each possible layout, and this is **the best result**

I.N.I. user routine

Modified mgdraw.f file

```
*                                                                      *
      ENTRY ENDRAW ( ICODE, MREG, RULL, XSCO, YSCO, ZSCO )
      RETURN
*
*======================================================================*
*                                                                      *
*     SOurce particle DRAWing:                                         *
*                                                                      *
*======================================================================*
*
      ENTRY SODRAW
      RETURN
*
*======================================================================*
*                                                                      *
*     USer dependent DRAWing:                                          *
*                                                                      *
*     Icode = 10x: call from Kaskad                                    *
*             100: elastic   interaction secondaries                   *
*             101: inelastic interaction secondaries                   *
*             102: particle decay  secondaries                         *
*             103: delta ray  generation secondaries                   *
*             104: pair production secondaries                         *
*             105: bremsstrahlung  secondaries                         *
*             110: decay products                                      *
*     Icode = 20x: call from Emfsco                                    *
*             208: bremsstrahlung secondaries                          *
*             210: Moller secondaries                                  *
*             212: Bhabha secondaries                                  *
*             214: in-flight annihilation secondaries                  *
*             215: annihilation at rest   secondaries                  *
*             217: pair production        secondaries                  *
*             219: Compton scattering     secondaries                  *
*             221: photoelectric          secondaries                  *
*             225: Rayleigh scattering    secondaries                  *
*             237: mu pair     production secondaries                  *
*     Icode = 30x: call from Kasneu                                    *
*             300: interaction secondaries                             *
*     Icode = 40x: call from Kashea                                    *
*             400: delta ray  generation secondaries                   *
*  For all interactions secondaries are put on GENSTK common (kp=1,np) *
*  but for KASHEA delta ray generation where only the secondary elec-  *
*  tron is present and stacked on FLKSTK common for kp=npflka          *
*                                                                      *
*======================================================================*
*
      ENTRY USDRAW ( ICODE, MREG, XSCO, YSCO, ZSCO )
* No output by default:
      IF(ICODE.EQ.101) THEN
         WRITE(99,*) NCASE, MREG
      END IF
      RETURN
```

Code "101" indicates the I.N.I. processes


```
*
      ENTRY USDRAW ( ICODE, MREG, XSCO, YSCO, ZSCO )
* No output by default:
      IF(ICODE.EQ.101) THEN
         WRITE(99,*) NCASE, MREG
      END IF
      RETURN
```


If there occurs an I.N.I. process → Write the corresponding event ♯ and the region ♯ (*_fort.99)

Output files

Ask to FLUKA to read and consider "my" mgdraw.f modified file

USERDUMP — Type: Dump; What: Complete; Unit: 22; Score: No Source, Traj, Losses; File: test; Dump: User Defined

EVENTBIN — Type: Region; Part: ENERGY; Print: Non-Zero Cells; Unit: 23 ASC; R1from: ScorR; R1to: ScorL; R2from: ; R2to: ; R3from: ; R3to: ; Name: ScorLR; Step1: 1.0; Step2: ; Step3:

Event by event energy deposition

STF100LR25x10mm24cm001_fort.99

63	3
70	9
70	5
70	5
70	9
145	4
145	5
145	5
145	5
145	5
145	5
145	5
145	5
145	5
328	2
477	4
527	9
555	2
732	2
739	4
739	5

Primary ♯ 63 has produced I.N.I. only in the region 3

Primary ♯ 70 has produced I.N.I. in the regions: 9, 5, 5, 9

For example primaries ♯ 1…57…77…340…999...etc... haven't produced I.N.I.

STF100LR25x10mm24cm001_fort.23

```
*****                                                                                   *****

         DATE:  7/17/15,  TIME: 17:25:44

        Total number of particles to be followed        10000000, event by event

1
   Region    binning n.   1  "ScorLR    " , generalized particle n.  208
         2 bins corresponding to the region sets:
      from region      7 to region     8 in step of     1 regions, or
      from region      0 to region     0 in step of     1 regions, or
      from region      0 to region     0 in step of     1 regions
      Data follow in an array A(ir), format (1(5x,1p,10(1x,e11.4)))

      accurate deposition along the tracks requested
      only non-zero cells will be printed

   Binning n:    1, "ScorLR    ",  Event #:            1, Primary(s) weight  1.0000E+00
   Number of hit cells:           0
```

No energy deposition in any scintillators

```
   Binning n:    1, "ScorLR    ",  Event #:            2, Primary(s) weight  1.0000E+00
   Number of hit cells:           0

   Binning n:    1, "ScorLR    ",  Event #:         1886, Primary(s) weight  1.0000E+00
   Number of hit cells:           1
      2  1.071974285878241E-03
```

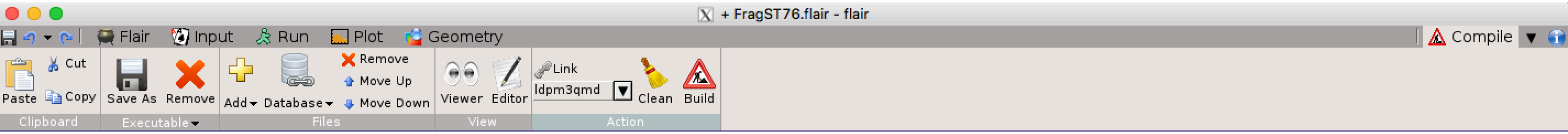
Energy deposition only in the left scintillators

```
   Binning n:    1, "ScorLR    ",  Event #:         2326, Primary(s) weight  1.0000E+00
   Number of hit cells:           2
      1  2.455924404785037E-03        2  8.104706066660583E-04
```

Energy deposition in both scintillators: **coincidence !!!** → **I.N.I. !!!**

Pb Ions simulations

Executable (ldpm3qmd)



Beam parameters

BEAM Beam: Energy ▾ E: 30.0 Part: HEAVYION ▾
Δp: Flat ▾ Δp: 0.0 Δϕ: Gauss ▾ Δϕ: 0.017
Shape(X): Rectangular ▾ Δx: 0.5 Shape(Y): Rectangular ▾ Δy: 1.0

HI-PROPE Z: 82.0 A: 207.0 Isom:

Transport

explicetly request transport of ALL ions
IONTRANS Transport: HEAVYION ▾

Physics

PHYSICS Type: COALESCE ▾ Activate: 12001.0
Model 1: 1.0 Model 2: 1.0 Model 3: Model 4:

PHYSICS Type: EVAPORAT ▾ Model: New Evap with heavy frag ▾

PHYSICS Type: EM-DISSO ▾ EM Disso: Proj&Target EM-Disso ▾