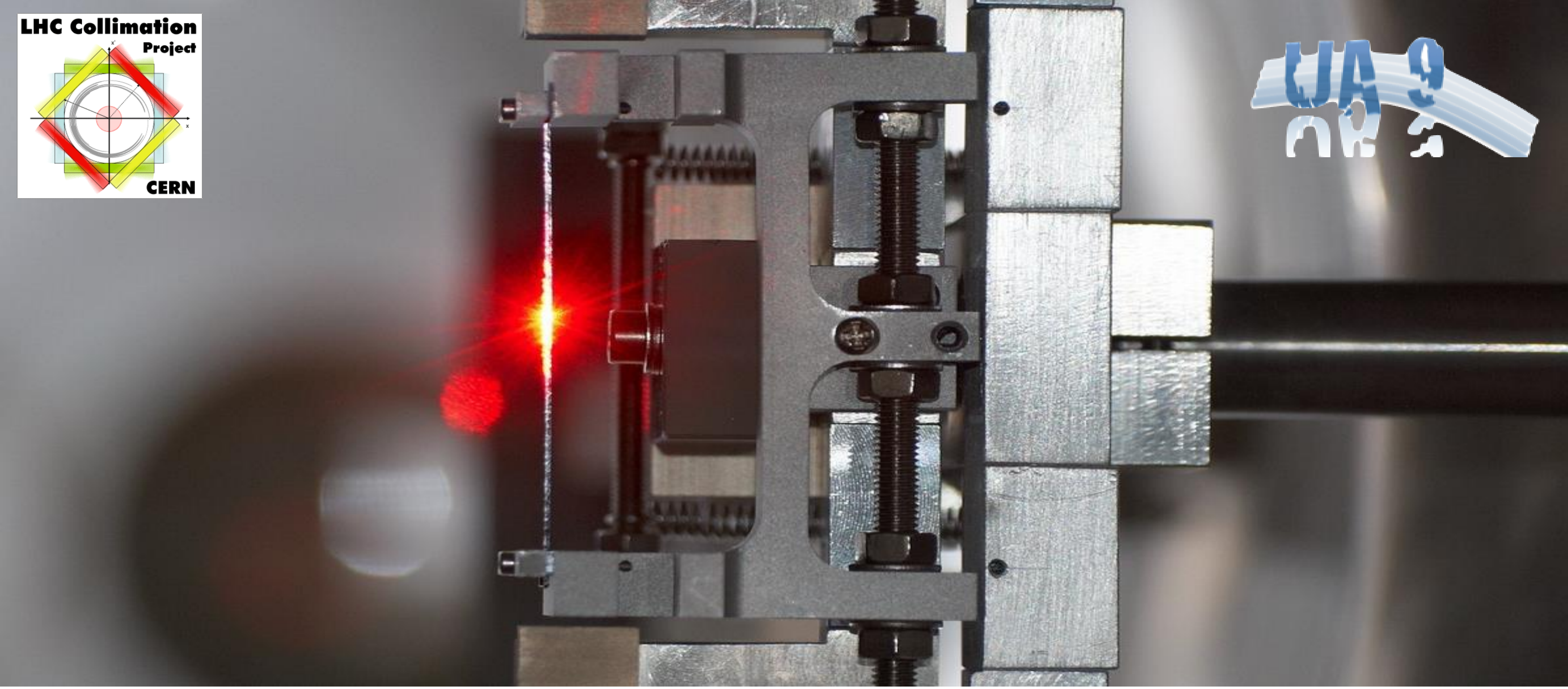


Crystal Collimation for LHC

IoP 2014 Joint High Energy Particle Physics and Astro Particle Physics Groups Annual Meeting

Daniele Mirarchi

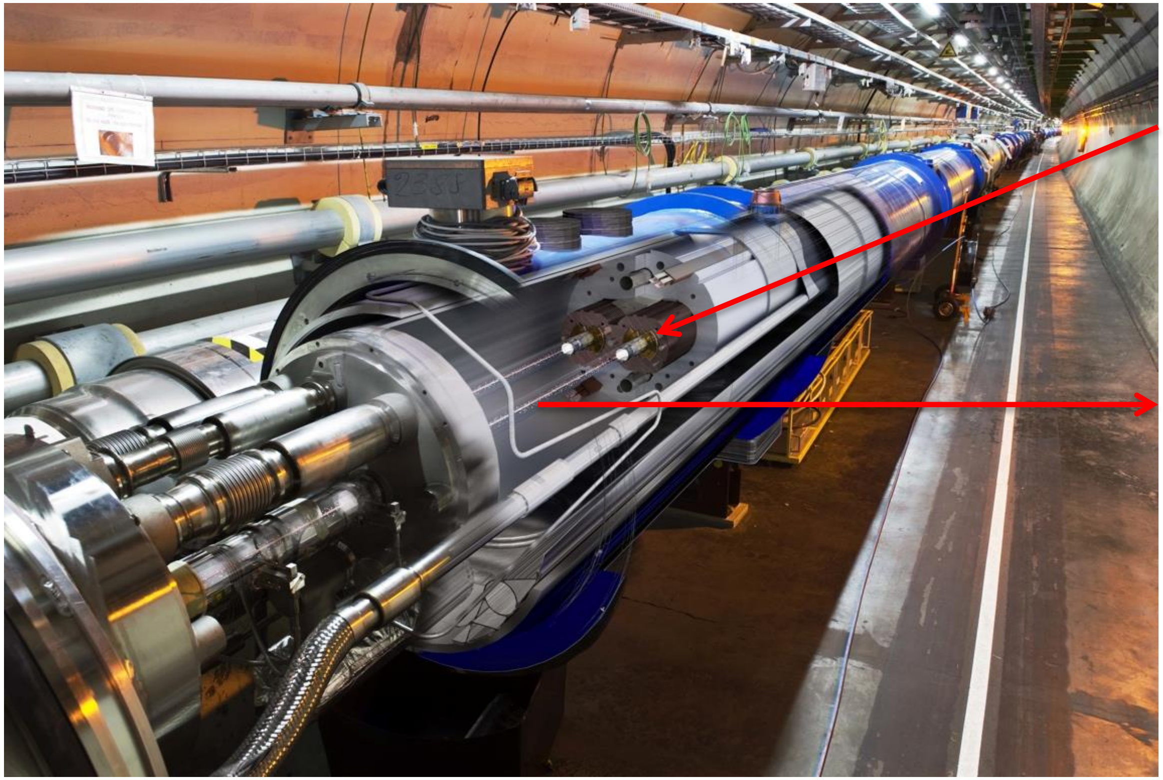
(Imperial College London, CERN)

Outline

- ✓ Introduction on Collimation at the LHC
  - LHC Collimation challenges
  - Present Collimation at the LHC
  - Crystals as possible upgrade
- ✓ Crystal-assisted Collimation
  - Crystal Channeling theory
  - Crystal-assisted Collimation principle
  - Main results in the SPS
- ✓ Simulation tools
  - Simulation environment
  - Main bench-marks and upgrades
- ✓ Towards the LHC
  - LHC layout design
  - Expected performance in the LHC
- ✓ Conclusions

Introduction on Collimation at the LHC

LHC Collimation challenges



Superconducting coil:

- *T = 1.9 K*
- *quench limit* ***~ 15-50mJ/cm³***
- *Aperture: r = 17/22 mm*

Stored energy in the machine:

- *LHC 2012:* ***145 MJ***
- *LHC design:* ***360 MJ***

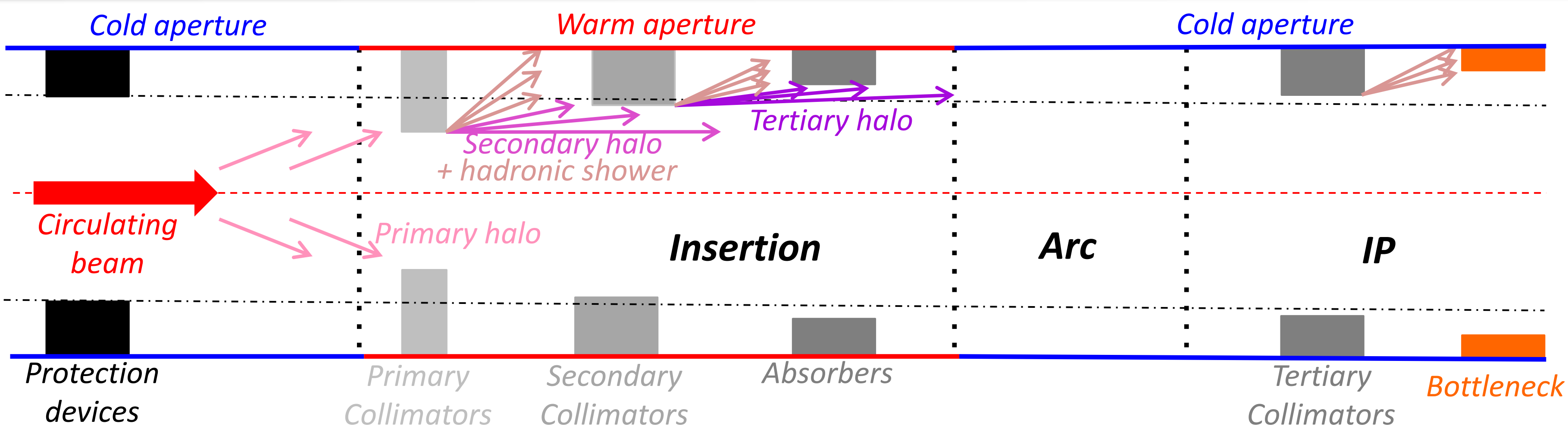
Factor ~ 10^9-10^{10}

No quench with circulating beam in LHC "Run 1" 2010-2013

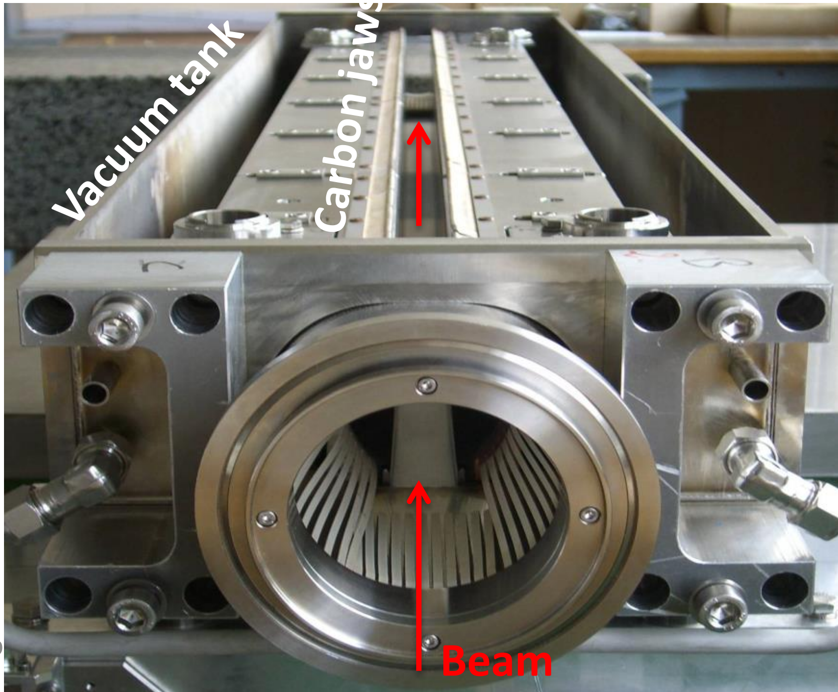
Why do we study a collimation upgrade?

HL-LHC: ***500MJ!***

Present Collimation at the LHC



~50 two-sided collimators per beam



Intrinsic limitation of amorphous collimation system:

- **inelastic interactions**
  - Diffractive events (p)
  - Fragmentation and dissociation (Pb)
    - ✓ Small deflection
    - ✓ Non-negligible Δp/p

*Escape from the collimation insertion and impact on the magnets (➔ **quench**)*

Crystals as possible upgrade

- **Crystal-assisted collimation is a promising technology**

- ***Principle feasibility demonstrated in the last 4 years of tests in the SPS***

- **It is now important to confirm the SPS results with the much more challenging LHC case! Which includes:**

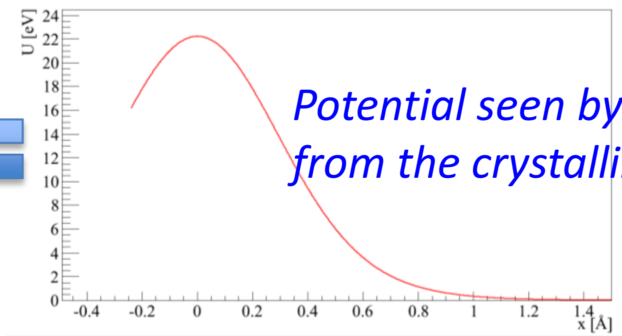
  - **Introduction of crystals in the simulation environment** of the LHC Collimation Project
  - **Upgrade and bench-mark** of simulation tools
  - **Layout design** for integration of crystals in the LHC
  - Define specification for the **first experimental tests** in the LHC

Crystal-assisted Collimation

Crystal Channeling theory

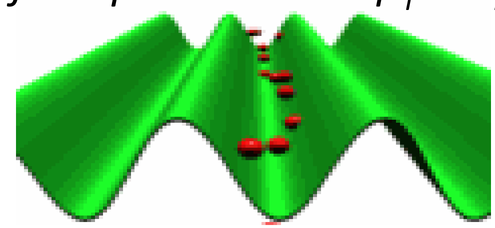
Potential between a particle and an atom described by the Thomas-Fermi model: $V(r) = \frac{Z_i Z e^2}{r}\Phi(\frac{r}{a_{TF}})$

Continuous approximation: $U_p(x) = Nd \iint_{-\infty}^{+\infty} V(x,y,z)dydz$



Potential seen by protons from the crystalline plane

If the protons have $p_T < U_{max}$

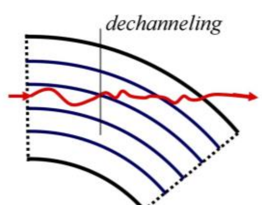


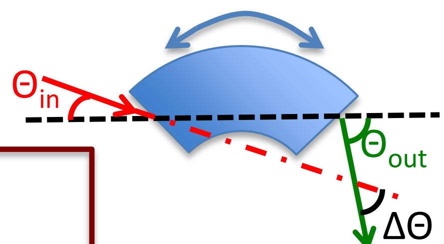
Forced to oscillate in a relatively empty space

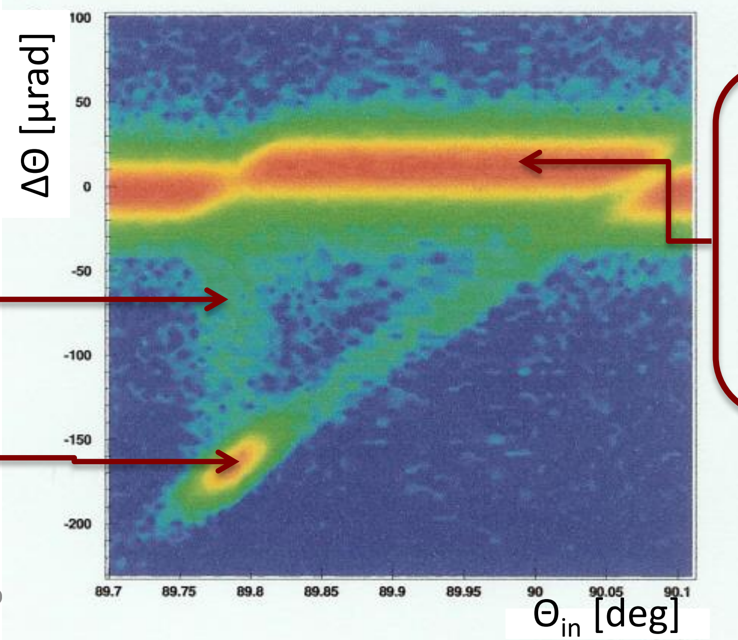
If crystals are bent?

***From test beam** on the CERN-SPS extraction line H8*

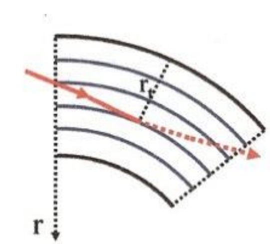
Dechanneling



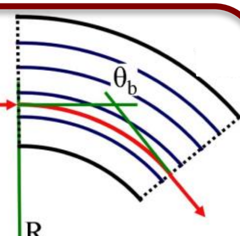




Volume Reflection

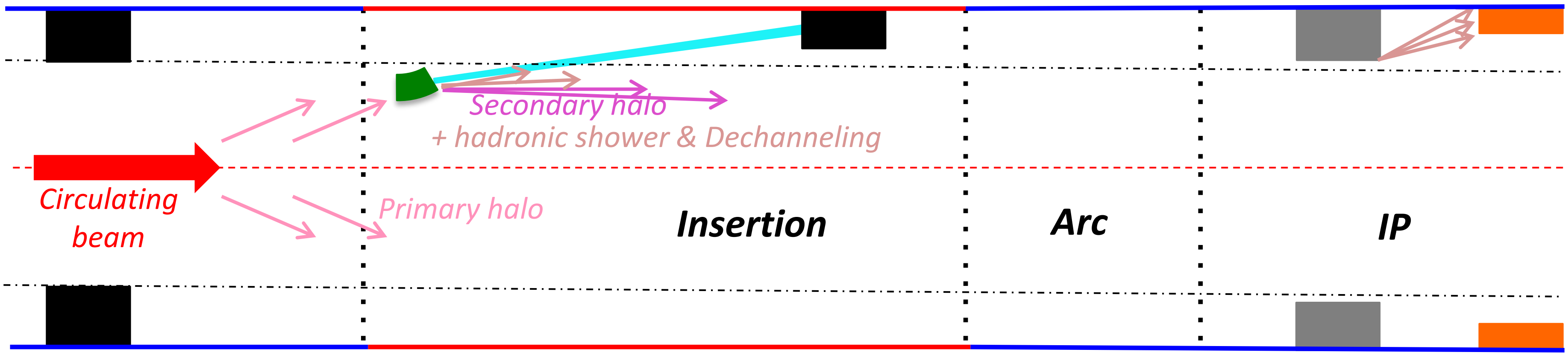


Desired deflection if in **Channeling** for all the path



Imperial College London

Crystal-assisted Collimation



Main gains:

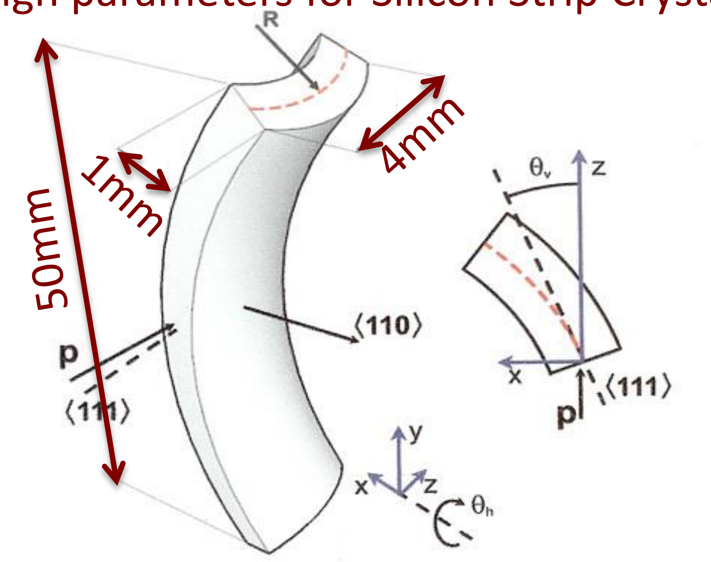
- ✓ More compact system (2 stages)
- ✓ Reduction of inelastic interactions
- ✓ Big deflection angle after 1st stage
- ✓ Impedance reduction

Increasing in L

Main challenges:

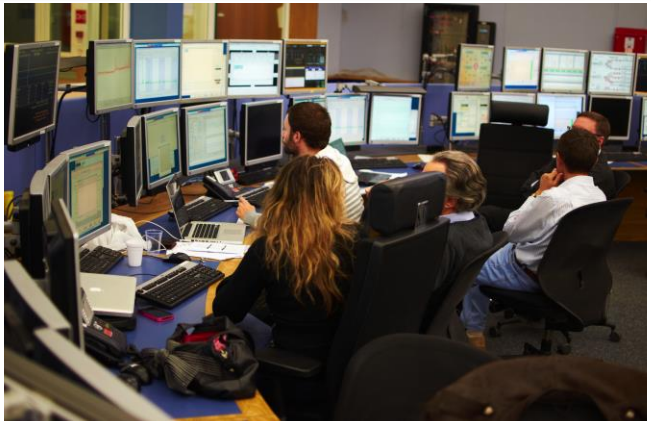
- ➢ $\Theta_c \approx 2.3\mu rad$ @ 7 TeV!
- ➢ Extracted halo absorption

LHC design parameters for Silicon Strip Crystals



Bending 50µrad $\equiv$ B ≈ 300 T @ 7 TeV!

Main results in the SPS



4 years of experimental test *at the CERN Super Proton Synchrotron*

↓

promising results *were achieved*

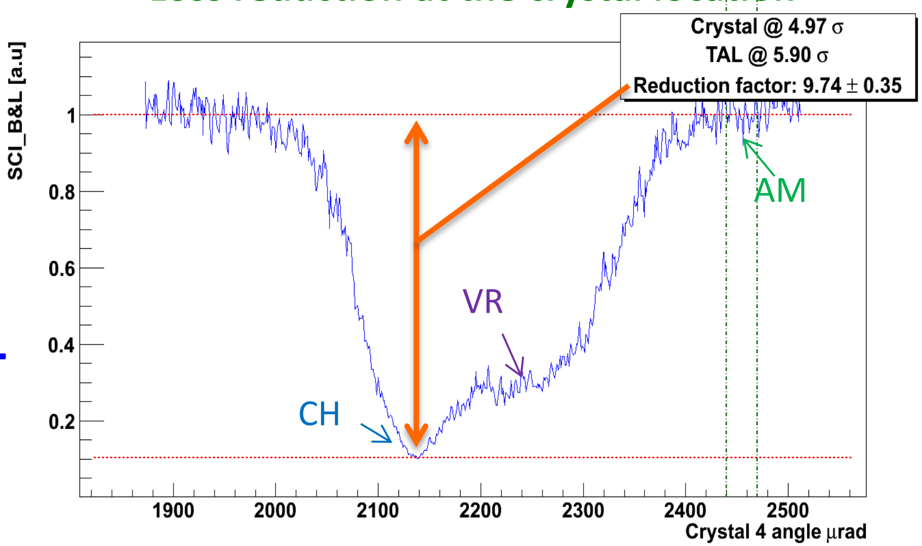
↓

Installation in the LHC *approved!*

Key measurements in the SPS which will be reproduced in the LHC too

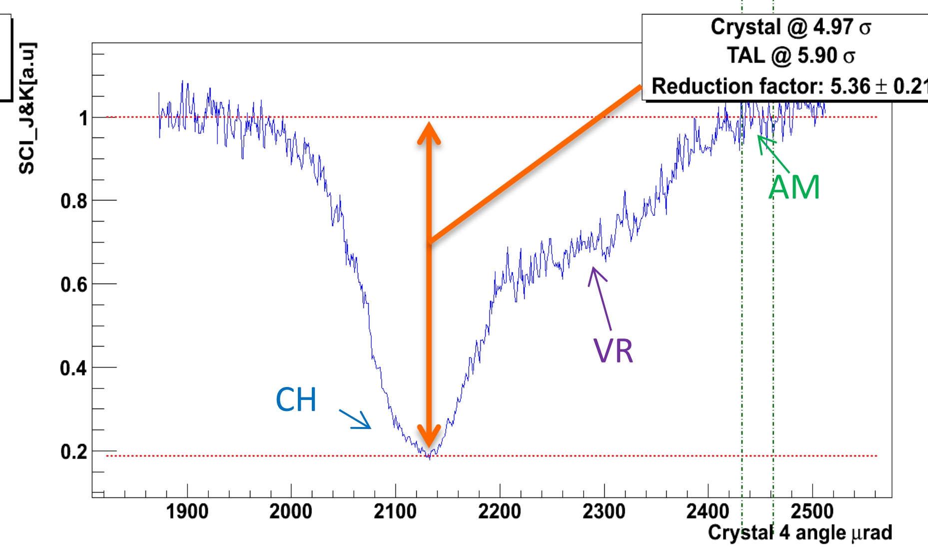
UA9 experimental data

Loss reduction at the crystal location



Evaluation of ***reduction of inelastic interaction***

Loss reduction in high dispersive area



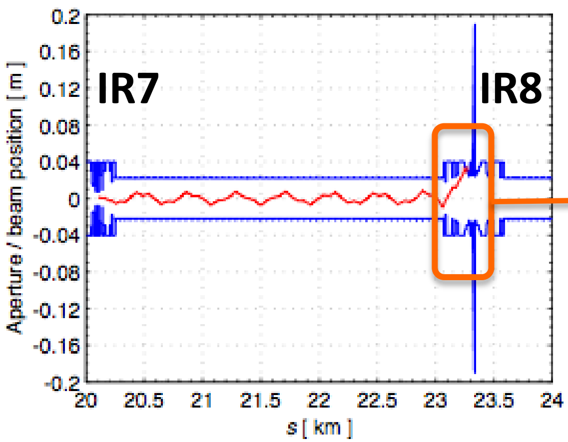
Evaluation of ***leakage of off-momentum particles***

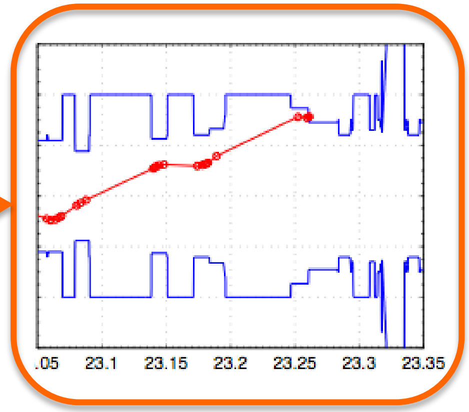
Simulation tools

Simulation environment

Main tools used:

- **SixTrack,** single particle tracking developed for beam dynamics study
- Upgraded for the LHC design, to **include interaction with collimator jaws and aperture model**





Prediction of expected beam loss pattern
with accuracy of 10 cm over 27 Km!

Very fast and precise code: 10-20M protons tracked for 200/2000 turns, crystal in channeling/amorphous

***Crystal routine** originally written by I. Yazinin, and implemented in SixTrack by V. Previtali*

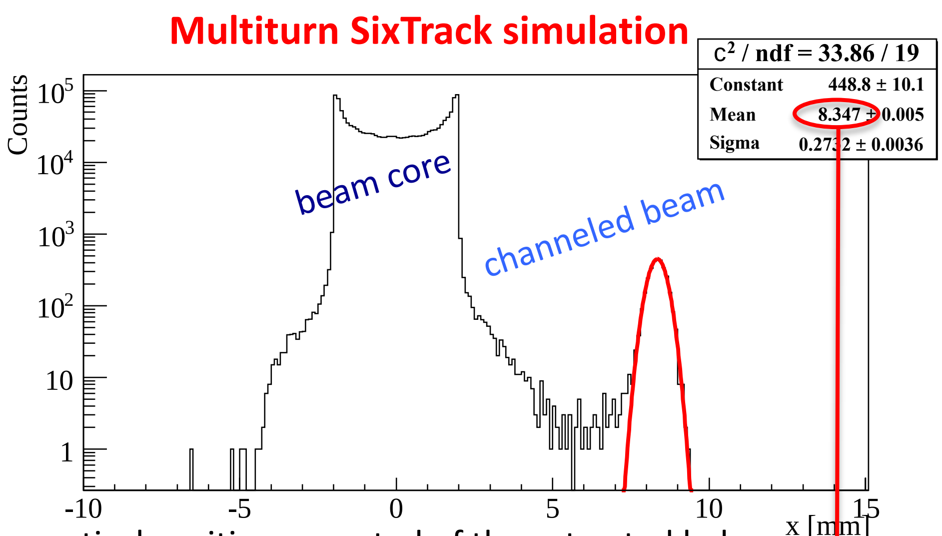
Pure **Monte Carlo emulator** of various interactions:

1. **Physics process** known in bent crystals **well described in literature**
2. **Free parameters tuned on experimental data** taken on the CERN-SPS extraction line H8
3. **Fast high-statistics simulations**

Code bench-mark and improvements

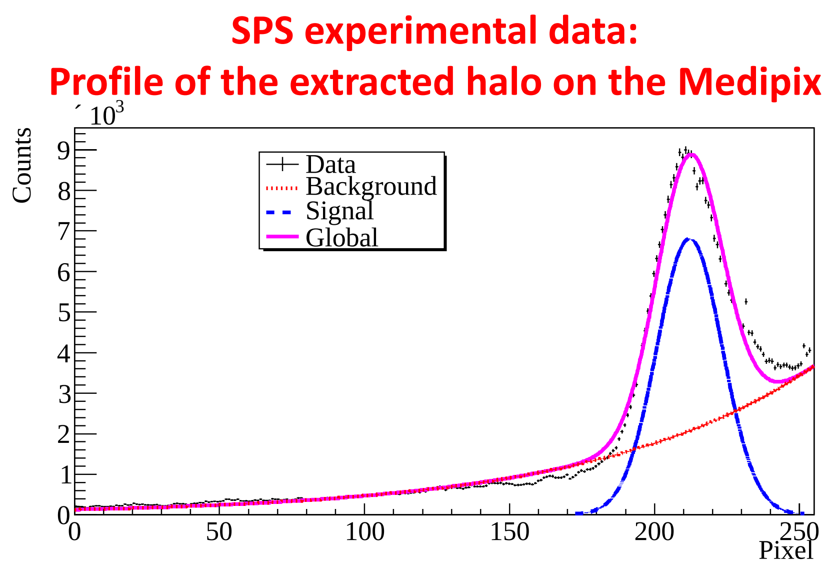
Validation of simulation tools performed:

- ✓ **Crystal routine** itself ➔ w.r.t. data on the CERN-SPS extraction line H8
- ✓ **Coupling** Crystal + SixTrack ➔ w.r.t. data on the SPS
- ✓ **Extrapolations** to 7 TeV ➔ w.r.t. other simulation tools



Theoretical position expected of the extracted halo:

- 8.4 mm and full spot width ~ 700µm



Sigma gauss fit ~ 11.27 pixel * 55µm ➔ ~ 600µm

Main improvements of the crystal routine:

- ➢ **Scattering routine**
- ➢ **Ionization energy loss**
- ➢ **Fine tuning and energy scaling of coherent effects** in bent crystals
- ➢ Implementation of **nuclear interactions for channeled particles**

Towards the LHC

LHC Layout design

Main constraints in the layout design:

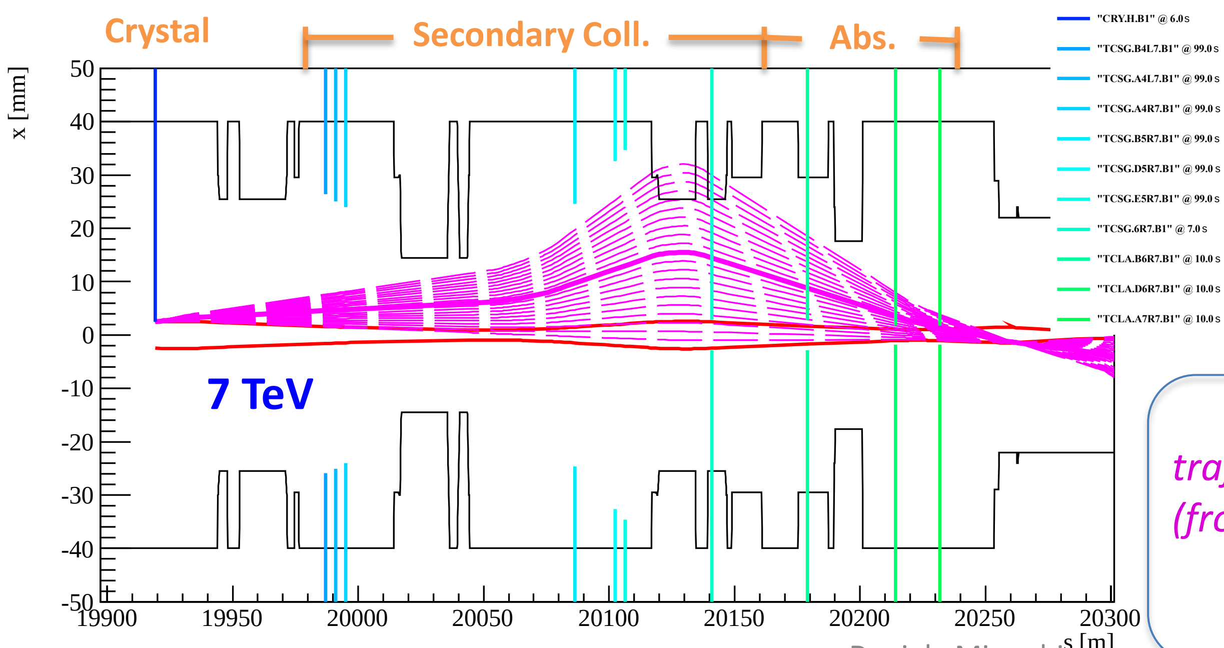
- **Efficient crystal collimation** in the various machine configurations (injection, ramp, squeeze, …)
- **Minimum impact** on present layout and infrastructure (control cabling, supports, etc.)
- **Safe absorption** of channeled and extracted halo
- Conceive optimum layouts for the **nominal IR7 optics**

Main steps:

Identification of **suitable locations**

Sub-set chosen on **Semi-analytical Models**

Loss maps simulations



Definition of:

1. **s location**
2. **Crystal parameters**
3. **Layout configuration**

Color code in the plot

Beam pipe

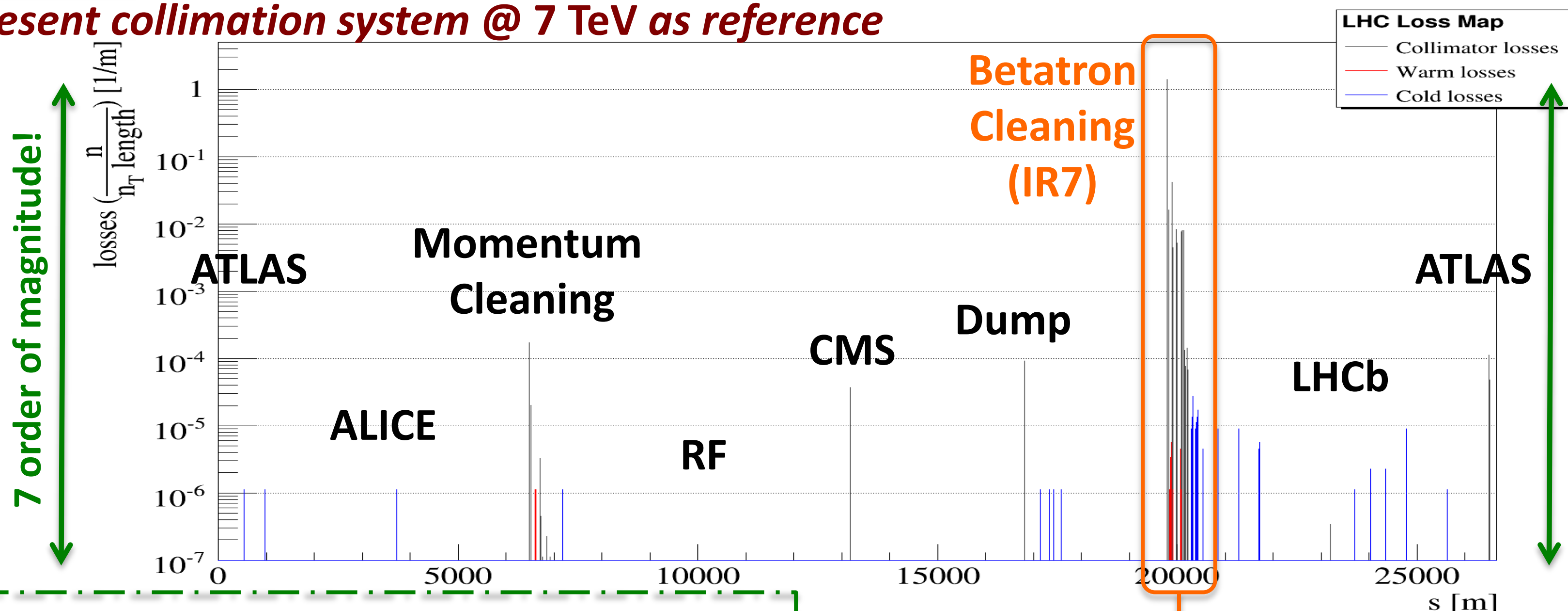
trajectory of kicked particle at the crystal (from 0 to 100μrad with steps of 5μrad)

6σ beam envelope

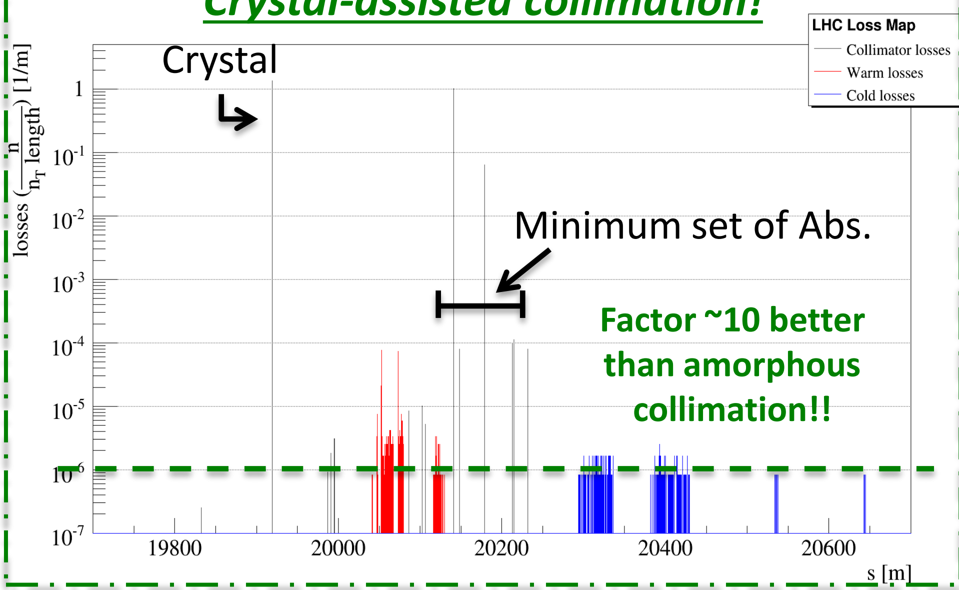
Collimator chain aperture

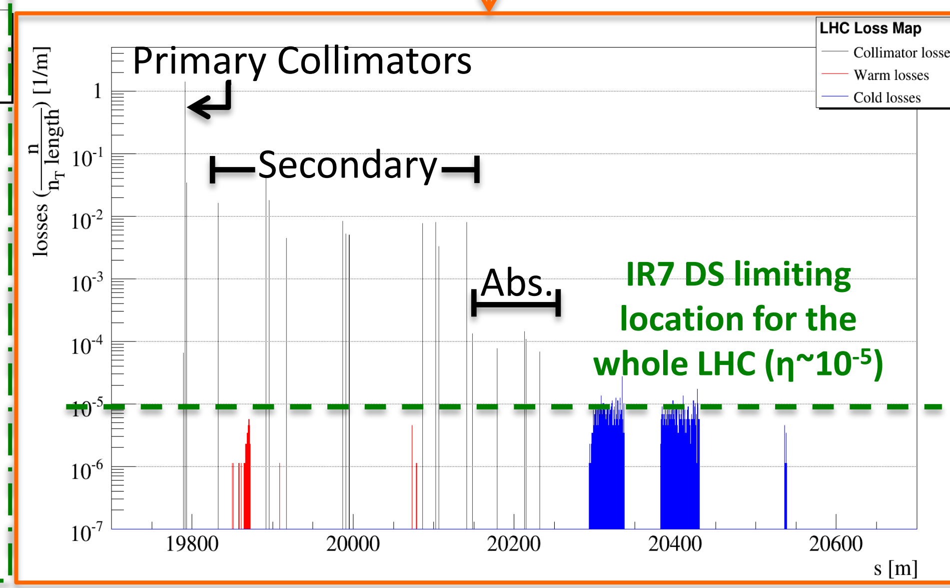
Expected loss-maps in the LHC

Present collimation system @ 7 TeV as reference



Crystal-assisted collimation!

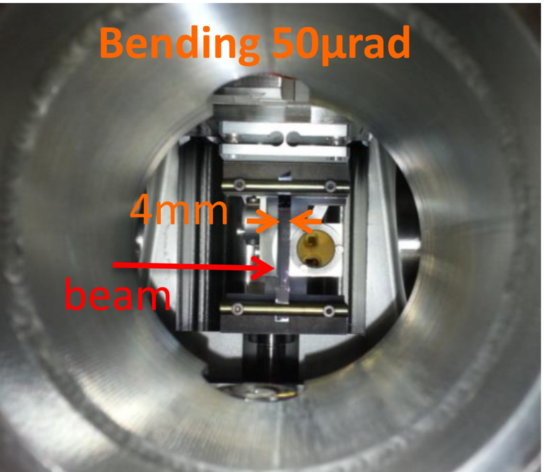




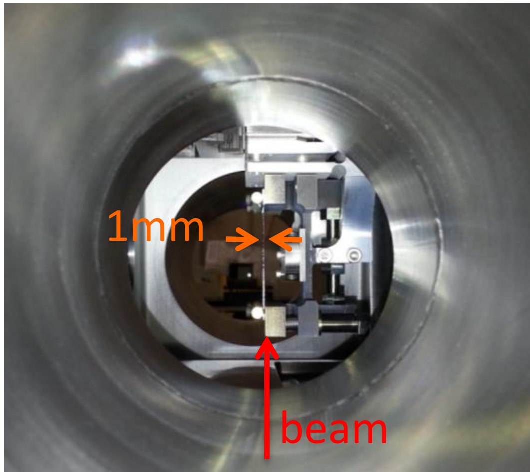
Conclusions

Conclusions

- *Very **promising results** have been achieved during the past 4 years **in the SPS**, leading to the **approval of the installation in the LHC!***
- ***Crystal routine** deeply **revised, upgraded** and **bench-marked***
  - ✓ **Errors** due to the approximations made are **well known and under control**
- **Main outcome of the present study:**
  - ✓ **Definition of the layouts for integration of crystals in the LHC**
  - ✓ **Choice of best crystal parameters**
  - ✓ **Two crystals** in the H&V planes **are being installed in the IR7 of LHC beam 1**
  - ✓ **Improvement of a factor ~10 in cleaning efficiency is expected**



Looking forward for tests in the LHC, foreseen in 2015 after the machine commissioning!!



Acknowledgments

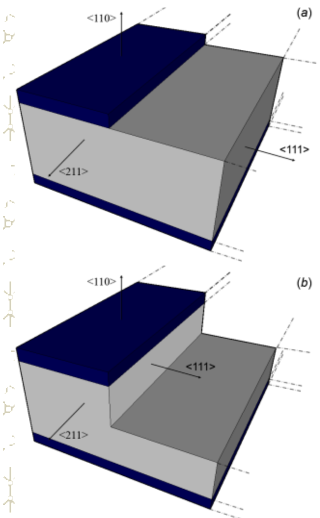
A Special Thanks goes to my supervisors for the always useful support:

At Imperial: **Prof. Geoff Hall**
At CERN: **Dr. Stefano Redaelli, Walter Scandale**

Without forgetting the whole **UA9 Collaboration** with which I did my Master thesis, and the whole **LHC Collimation team**.

BACKUP SLIDES

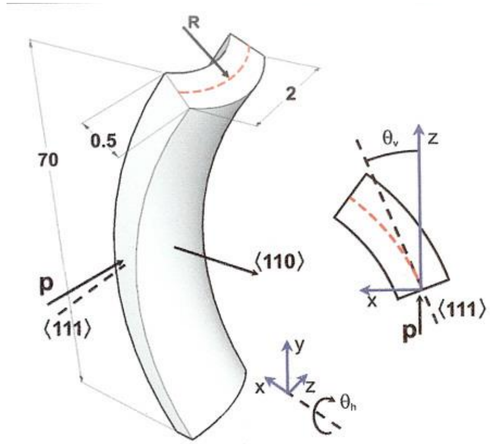
Strip Crystals Production



Anistropic etching is a feasible way to realize sub-surface damage free crystals entirely by wet chemical methods

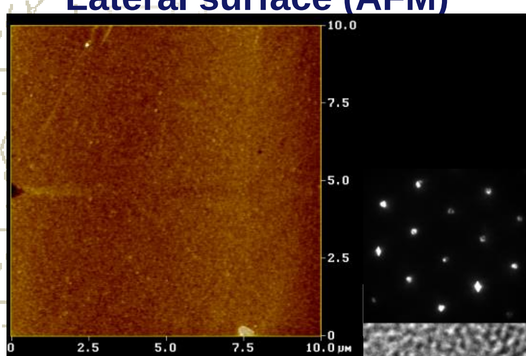
Etch rate on different silicon planes for KOH 20% at 40 °C

(100)	(110)	(111)
7.1 mm/h	10.7 mm/h	Negligible



Parameter	Expected	Crystal 1	Crystal 2
Crystal thickness (mm)	~ 4	4.10	4.02
Bending angle (interferometer, μrad)	~ 50	52±2	52±2
Bending angle (X-Ray, μrad)		51±1	53±1
Miscut (X-Ray, μrad)	< 10	6±1	6±1
Torsion (interferometer, μrad/mm)	< 1	<1 μrad/mm	<1 μrad/mm
Torsion (X-ray, μrad/mm)		< 1 μrad/mm	< 1 μrad/mm
Heating compatibility	Yes	Yes	Yes

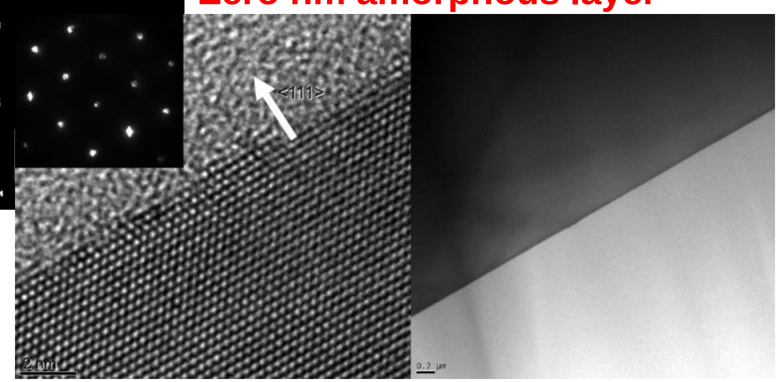
Lateral surface (AFM)



Sub-nm roughness achieved (0.2 nm)

Entry surface (High Resolution transmission electron microscopy).

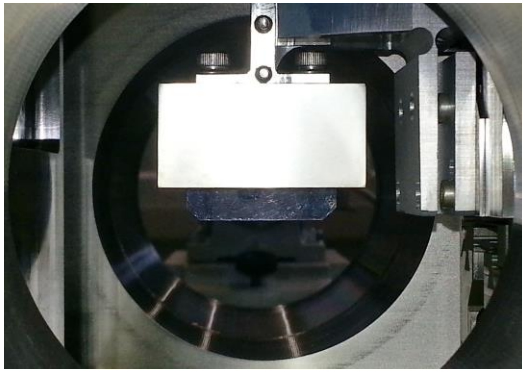
Zero nm amorphous layer

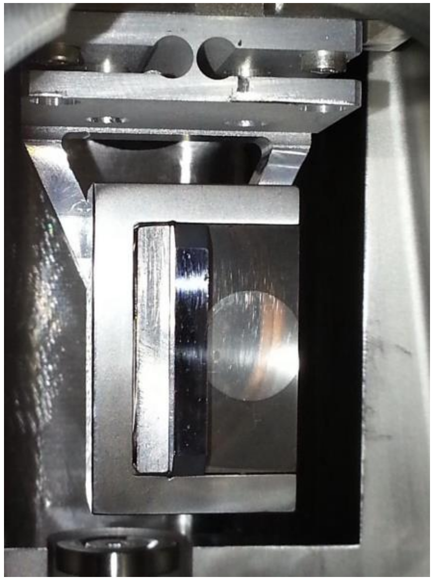


Courtesy of A. Mazzolari

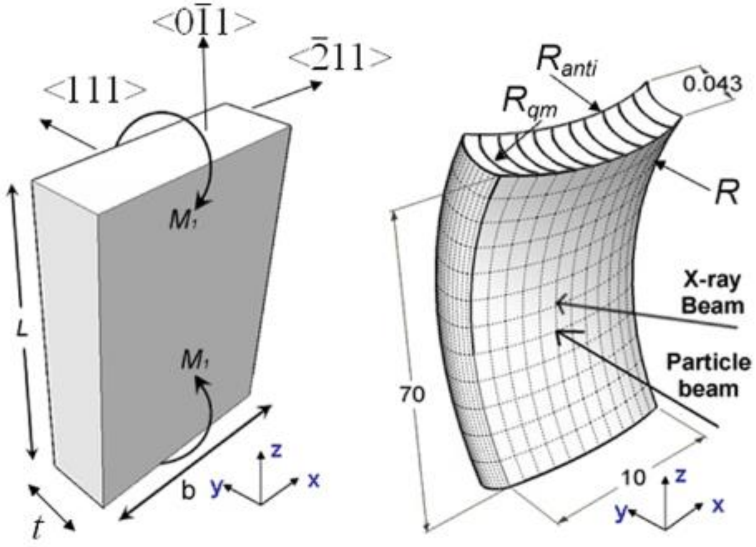
Quasi-Mosaic Crystals

Crystal installed in the LHC



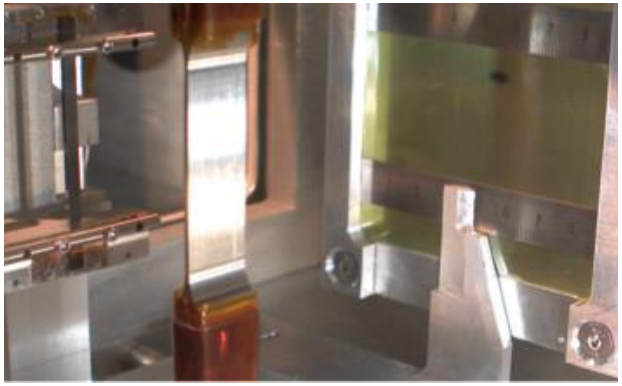


Bending mechanism



Resistance of the crystal

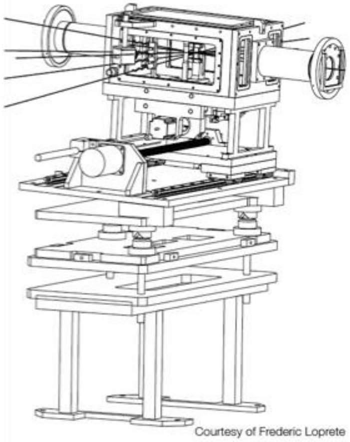
Resistance of the crystal to irradiation tested in different scenarios:



- 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

  ✓ 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} p/cm^2 in total) ➔ 5÷10 years of nominal operation in LHC

  ✓ channeling efficiency reduced by 30%.

- HRMT16-UA9CRY (HiRadMat facility, November 2012):

  440 GeV protons,
  288 bunches, 1.1 x 10^{11} protons per bunch
  3 x 10^{13} protons in 7.2 μs ➔ Energy deposition comparable to asynchronous beam dump in LHC

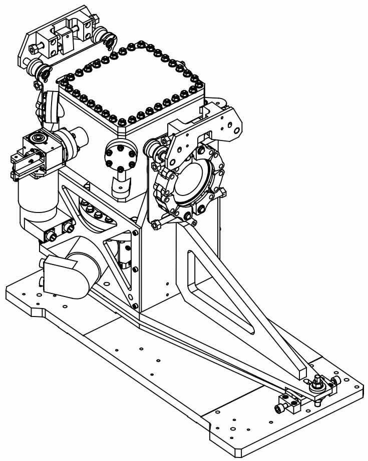
  ✓ no damage to the crystal after accurate visual inspection,
  more tests planned to assess possible crystal lattice damage.

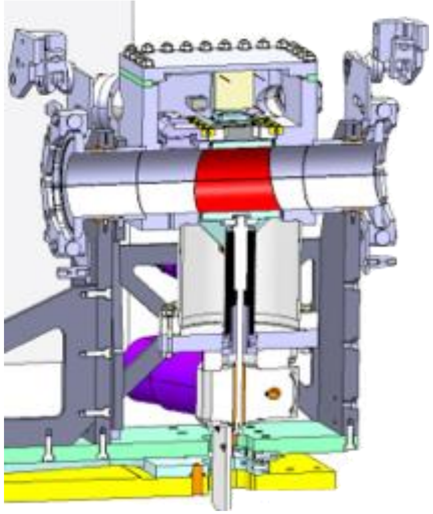
  ✓ accurate FLUKA simulation of energy deposition and residual dose.

Goniometers for the LHC

- Alignment of the crystal with respect to incoming particles is critical:
  - 1 μrad accuracy required at 7 TeV,
  - dynamic accuracy of the motion essential to obtain collimation during beam acceleration.

- Design of the goniometers in collaboration with industrial partners:
  - ✓ closed-loop piezoelectric angular movement (range: 20 mrad, accuracy 1 μrad)
  - ✓ motorized linear axis (5 μm resolution)
  - ✓ integrated high-precision alignment system
  - ✓ minimal impact on machine impedance during normal LHC operation (movable beam pipe section with RF contacts)
  - ✓ quick-plugin on the collimator supports (including all cable connections)

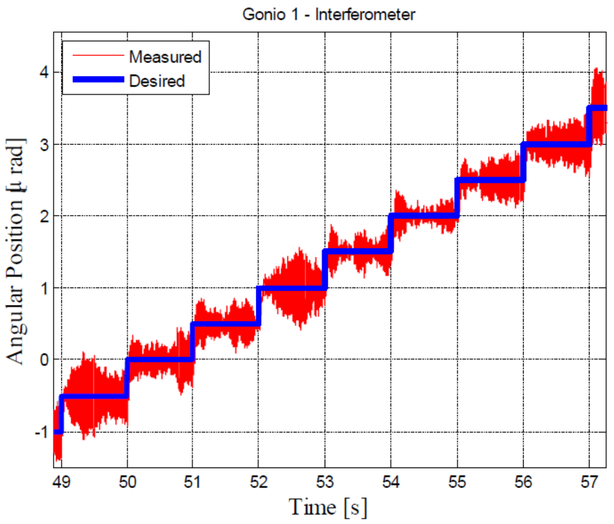


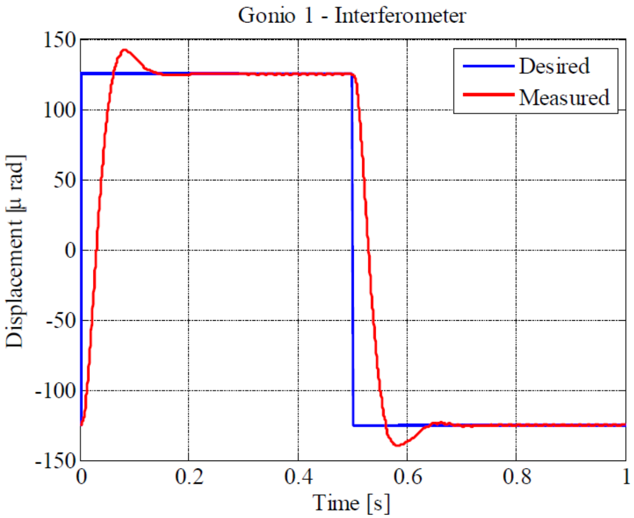


Performance of the goniometers

- Linear motion:
  - 4 guides based on linear roller ceramic bearings
  - special cage (AISI 316L) to guarantee a minimal parasitic angle of 1 μrad/mm
  - elastic support on one guide to allow dilatation during bake-out

- Angular motion:
  - piezoelectric rotational stage including a feedback mirror and the crystal holder
  - closed-loop control based on 3 linear interferometric measurements (Attocube FPS3010)
  - From the acceptance tests:
    - ✓ +/- 0.5 μrad accuracy in angular position
    - ✓ 8% overshoot well below the specifications





Toward the LHC test

LHC restart planned for beginning of 2015

→ All efforts focused in the **machine commissioning**

→ Few hours of **experimental tests foreseen**

Main questions to be addressed:

- ✓ **Can crystal collimation do better** than the present very good cleaning system?
- ✓ **Uncertainty** in energy scaling (e.g.: single diffractive losses)
- ✓ **Operational** challenges (ramp, squeeze, etc...)
- ✓ Some outstanding **machine protection** concerns

Preliminary plan for machine conditions:

- **low intensity** (single pilot bunch)
- **top energy** (main goal) & injection
- full chain of secondary collimators (TCSG) in place

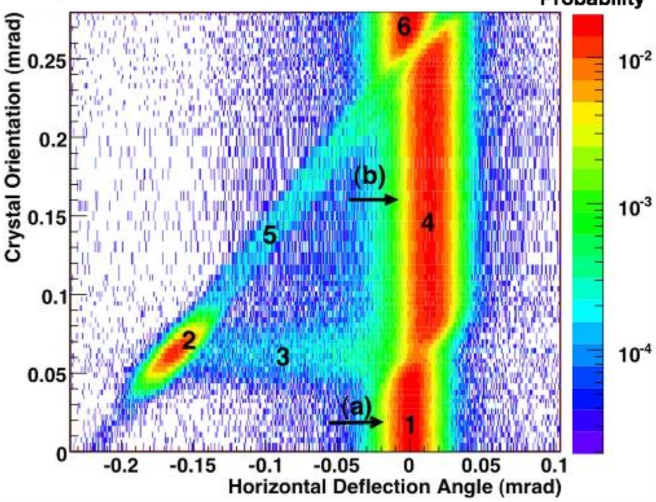
then…

- **higher intensity**, still within safe boundaries ➔ total intensity: ~5e11 p @ 450GeV, ~5e9 p @ 7TeV
- possibility "to play" with the TCSGs settings

Channeling vs Volume Reflection

- Particles impinging on a crystal can undergo different coherent effects – depending on the incident angle:
  - Channeling (2):
    - "large" deflection angle
    - "small" angular acceptance, decreasing with energy
      → high precision goniometer for crystal alignment
  - Volume reflection (4):
    - "large" angular acceptance
    - "small" deflection angle, decreasing with energy
      → multi-strip crystal to use multiple reflections

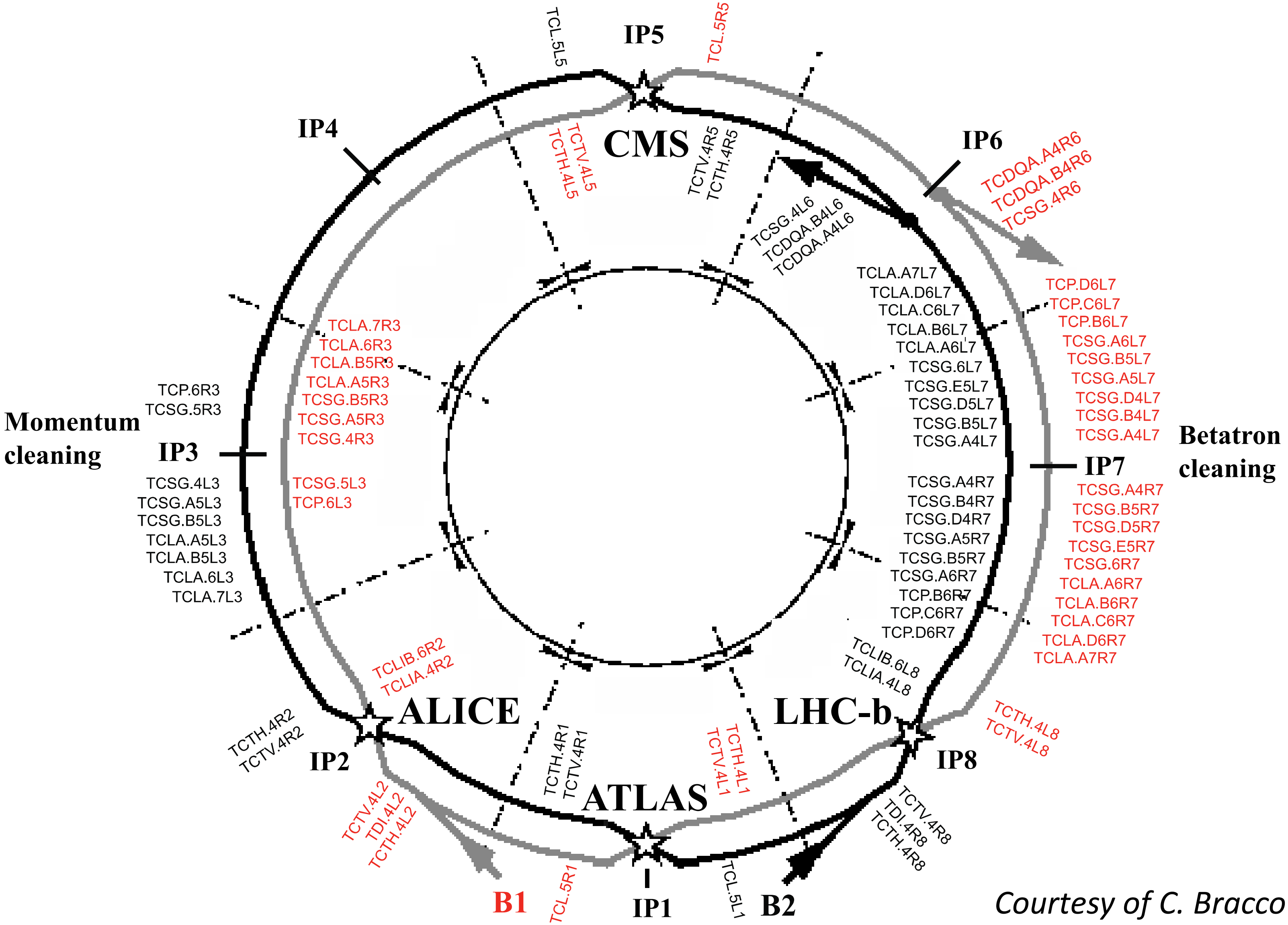
W. Scandale *et al.* (H8RD22 Collaboration)
Phys. Rev. Lett. 98, 154801 (2007)



- At present it is easier to build high-precision goniometers than to align multiple crystals:
  - Channeling is preferred for crystal collimation

	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	
In LHC (7 TeV)	α = 50 μrad θ_c = 2 μrad		

Collimation at the LHC



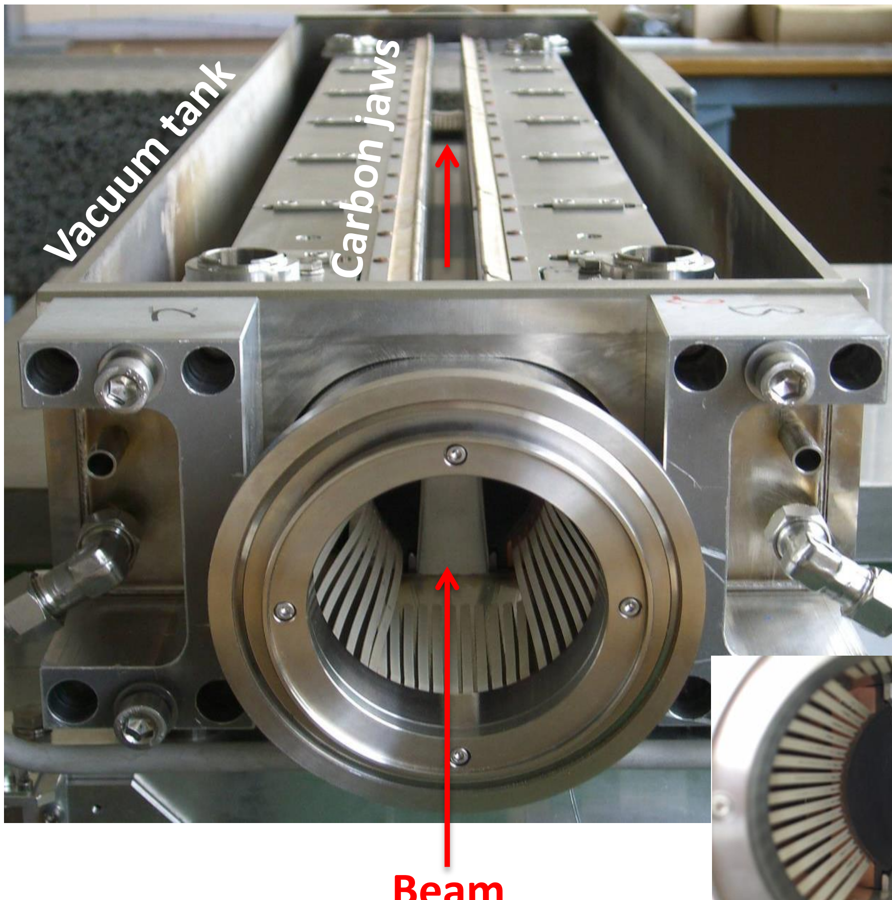
Courtesy of C. Bracco

Collimation at the LHC

Ideally **Liouville's theorem** ensure stability on initial orbit

→ Various mechanism can lead to **emittance growth**

→ ***Halo creation and repopulation***

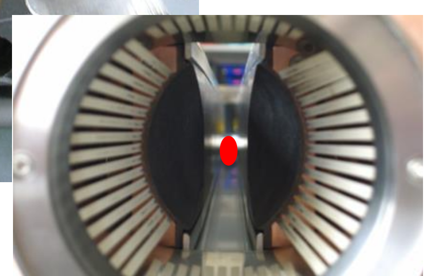


- **Background** for the experiments at the IPs
- Radiation **damage**
- Uncontrolled losses on the superconducting magnets: **quench**

Needed a continuous and controlled halo removal

~50 two-sided collimators per beam devoted to:

- ✓ Betatron cleaning
- ✓ Momentum cleaning
- ✓ Protection of sensitive devices
- ✓ Injection scraping
- ✓ Physics debris absorption



Crystal routine

Crystal routine originally written by I. Yazinin, and implemented in SixTrack by V. Previtali

*Pure **Monte Carlo emulator** of various interactions*

no solving of eq. of motion

fast high-statistics simulations

"All" **physics process** known in bent crystals

well described in literature

Free parameters tuned on experimental data

taken on the CERN-SPS extraction line H8

Main improvements:

- ✓ "Brand new" **scattering routine**
  - *Updated **Single Diffractive, Nuclear and p-p Elastic** events*
  - *Updated **cross sections and energy scaling***
  - *Implementation of **Rutherford Scattering***
- ✓ **Energy scaling** of ionization losses
- ✓ **Fine checks of coherent effects** in bent crystals and energy scaling → ***Dechanneling length*** *fine tuned w.r.t. data*
- ✓ Implementation of **nuclear interactions for channeled particle** → ***Were not taken into account,*** *much better agreement w.r.t. data*

Main bench-marks

With respect to data taken on the CERN-SPS extraction line H8: **(crystal routine itself)**

- ✓ Single pass **channeling efficiency**
- ✓ **Nuclear dechanneling** length
- ✓ **Nuclear interaction probability** as function of crystal orientation

With respect to SPS data: **(coupling SixTrack + crystal routine)**

- **Extracted halo** reproduced and fully characterized
  - → *Can a present **collimators jaw withstand its absorption?***
- Reduction of **off-momentum leakage** from collimation insertion
  - → ***Main mechanism of losses** in the LHC*
- **Beam loss pattern** along the whole SPS ring still on-going

With respect to other simulation tools: **(extrapolations to 7TeV)**

- ➢ **FLUKA for scattering** in amorphous material
  - → *Presently used at CERN as **reference tool** for such study*
- ➢ **Fully-analytical crystal simulator** by A. Taratin, for coherent effect in bent crystals
  - → ***First code which predicted VR**, extensively used in UA9*

Single-pass channeling eff.

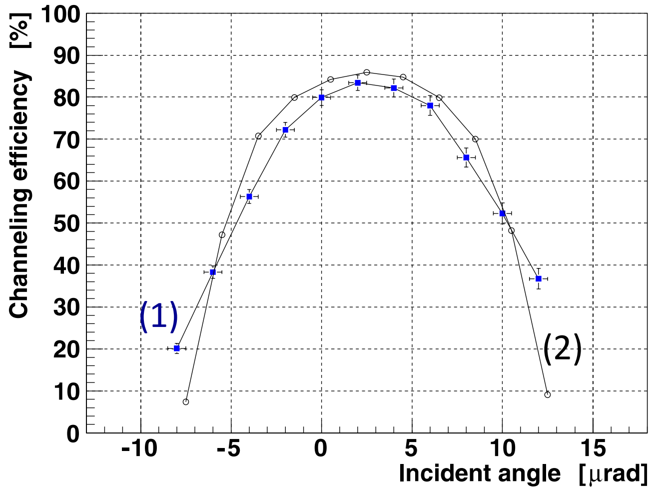
Comparison made w.r.t. H8RD22 data

W. Scandale et al., “Observation of nuclear dechanneling for high-energy protons in crystals”, Phys. Lett. B 680 (2009) 129-132

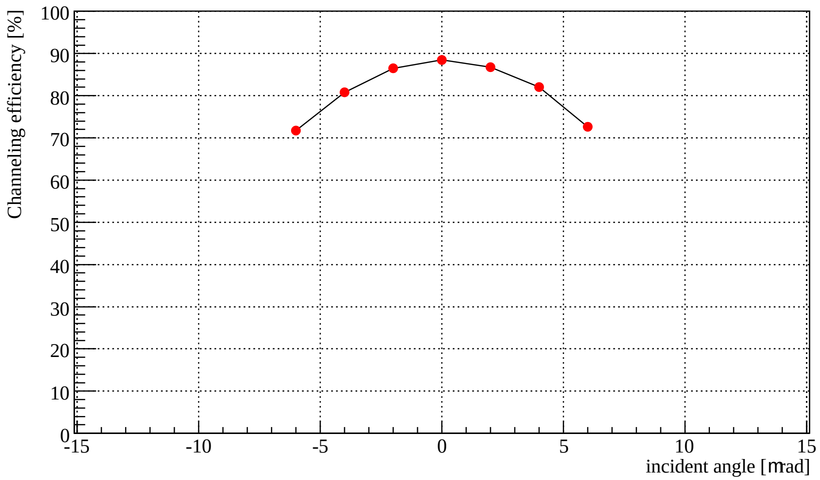
Simulations performed accordingly to the experimental setup, same cuts on incoming particles are applied:

From the paper

(1) Experimental data (2) Taratin’s simulations



From “SixTrack” simulations



Good agreement w.r.t. Taratin’s simulation found (within 2%)

Nuclear Dechanneling (1)

<u>From the same previous paper:</u>

Nuclear Dechanneling dominant w.r.t. Electronic one using that setup

In the routine in SixTrack no direct parameterization of Nuclear Dechanneling

→ Tabulated in a BLOCK DATA the Electronic Dechanneling Length for 400GeV impinging protons

→ Nuclear Dechanneling modelled assuming that 10% of the particles dechanneled due to interaction with electrons will interact with nuclei.

→ Rescaling factor is applied to the Electronic Dechanneling Length to get a dechanneling length comparable with H8 data.

Main actions taken:

✓ Implemented Electronic Dechanneling parameterization and calculated for each impinging particle (mainly related to fine corrections on the energy scaling)

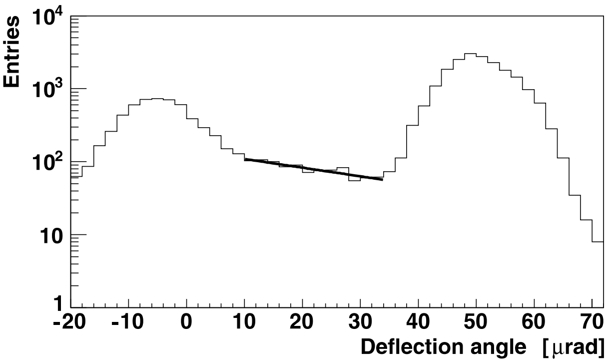
✓ Studied the effects of the two free parameters:

- 10% because is roughly the ratio between crystal planes and channels width, so influences the ratio between Electronic and Nuclear Dechanneled particles
- Rescaling factor gives the slope of the population of Nuclear Dechanneled particles

Nuclear Dechanneling (2)

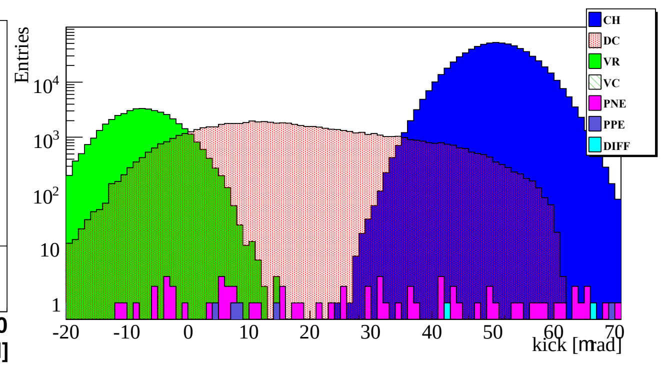
Simulations performed accordingly to the experimental setup, same cuts on incoming particles are applied:

Experimental Data

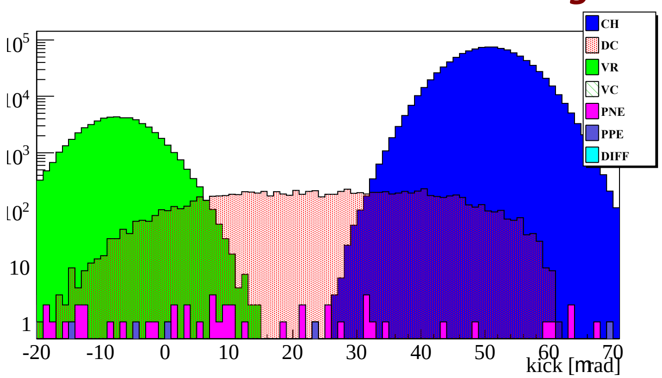


"SixTrack" simulations

With Nuclear Dechanneling



Without Nuclear Dechanneling



10% ratio gives a good agreement between the relative populations

Rescaling factor previously set to 250 → Nuclear Dechanneling Length of ~900μm

Measured Nuclear Dechanneling Length ~1.5mm

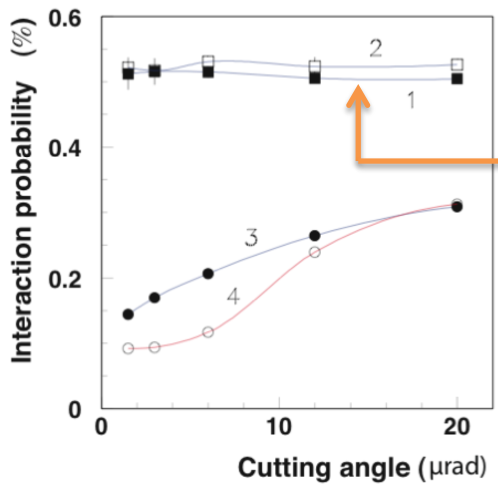
Rescaling factor modified to 200, in order to get a Nuclear Dechanneling Length of ~1.35mm

Nuclear Interactions (1)

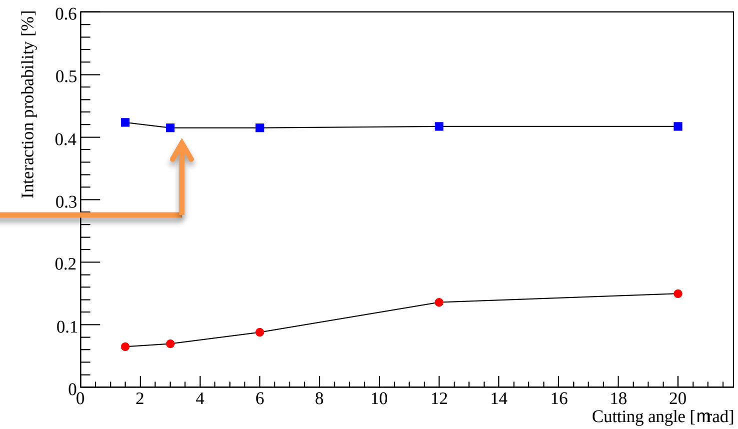
Nuclear interactions for channeled particles were not taken into account at all in the routine

Checks made on such assumption comparing simulations w.r.t. experimental data reported in:
W. Scandale et al., "Probability of inelastic nuclear interactions of high-energy protons in a bent crystal", NIMB 268 (2010) 2655-2659

From the paper:



"SixTrack" simulations



(1) Cr. in AM orient. – Data
(2) Cr. In VR orient. – Data.
(3) Cr. in CH orient. – Data
(4) Cr. in CH orient. – Taratin's sim

Difference in AM orient. Due to nuclear inelastic cross section implemented
- In the paper used 0.504 b (Glauber's approx.)
- In the code used 0.430 b (using pdg)

Clear indication that Nuclear interactions for channeled particles need to be implemented!!

Nuclear Interactions (2)

Nuclear interaction implementation strategy:

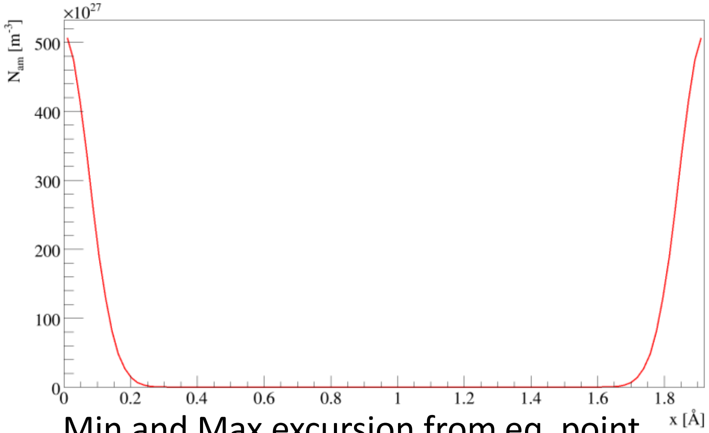
Calculation of the average nuclear density along the trajectory of channeled particles

Rescaled nuclear (total and inelastic) cross sections and nuclear collision length accordingly with the average nuclear density seen

Choose a "zero-order" approach to get something analytical instead of needs of numerical integration

Nuclear density between crystalline planes described by:

$$\rho(x) = N_{am}\frac{d_P}{\sqrt{2\pi u_1^2}}\left(\exp\left(-\frac{x^2}{2u_1^2}\right) + \exp\left(-\frac{(x-d_P)^2}{2u_1^2}\right)\right)$$



Particle trajectory in bent crystal described by:

$$x = -x_c\frac{R_c}{R} + x_c\sqrt{\frac{E_T}{E_c}}\sin\left(\frac{2\pi z}{\lambda} + \phi\right)$$

Min and Max excursion from eq. point

$$x_m = -x_c\frac{R_c}{R} - x_c\sqrt{\frac{E_T}{E_c}}$$

$$x_M = -x_c\frac{R_c}{R} + x_c\sqrt{\frac{E_T}{E_c}}$$

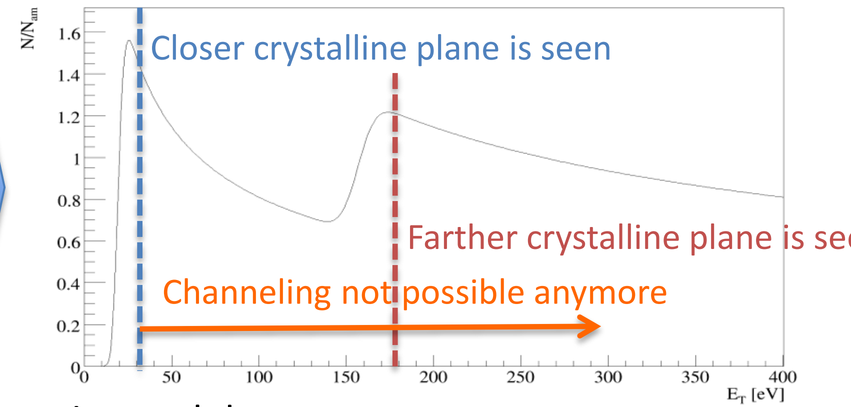
Nuclear Interactions (3)

Being: $$\int \rho(x)dx = N_{am}\frac{d_p}{2}\left[erf\left(\frac{x}{\sqrt{2u_1^2}}\right) - erf\left(\frac{d_p - x}{\sqrt{2u_1^2}}\right)\right]$$

With strong approximation:
Possible to calculate analytically the average density seen along the trajectory,

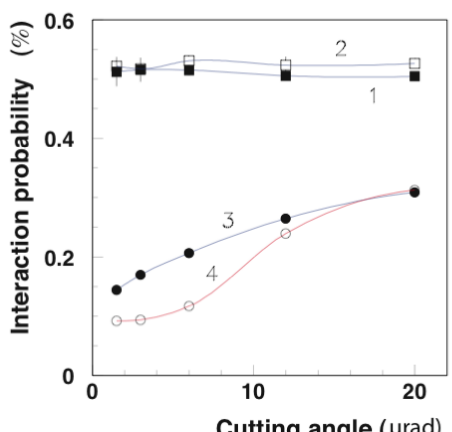
$$\overline{\rho} = \frac{\int_{x_m}^{x_M} \rho(x)dx}{x_M - x_m}$$

Which gives, as example:

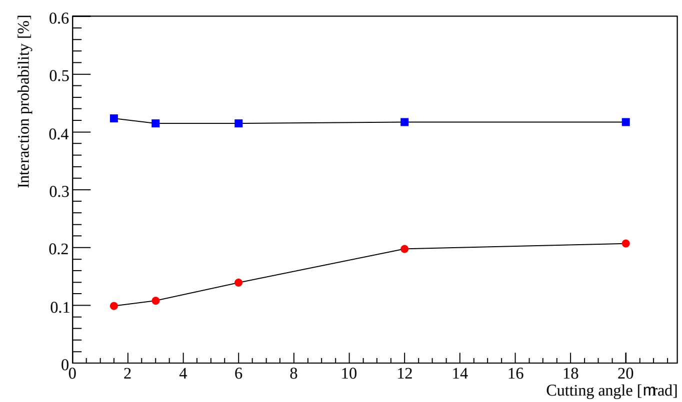


Comparing now Simulations and Experimental data we get:

From the paper:
(same as previous slide)



"SixTrack" simulations:



Not yet perfect agreement at "large" angles,
anyway for SixTrack goals much more important the agreement at "small" angles (at least w.r.t. Taratin's sim.)

Energy scaling of coherent effects

Comparisons made with respect to Taratin's code at 7 TeV

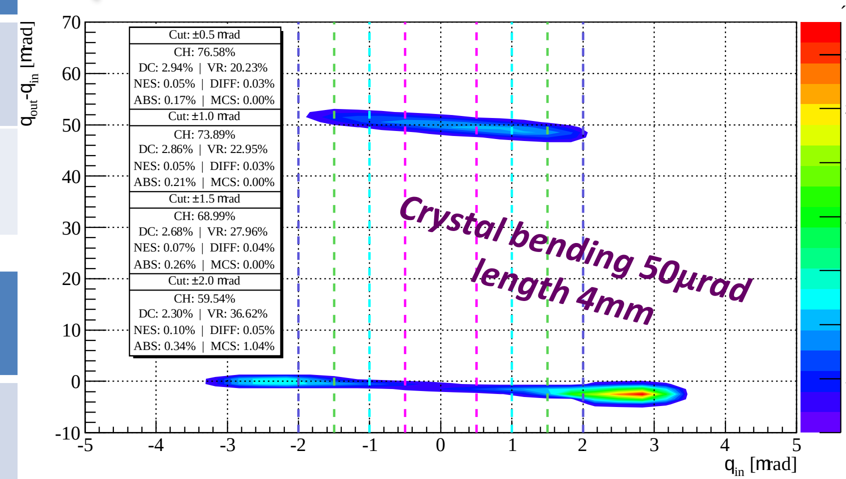
Simulations made without any stand-alone routine, but generating "a fake halo" in SixTrack

To avoid any problem during "updates migration" between codes

Example of analysis output for SixTrack simulations "H8-like"

θ[μrad]→ l[mm]↓	20	40	60	80
3	CH: 84.18% VR: 13.55%	CH: 72.98% VR: 24.49%	CH: 61.84% VR: 35.38%	
4	CH: 86.38% VR: 10.86%	CH: 77.97% VR: 19.01%	CH: 69.76% VR: 26.99%	CH: 61.10% VR: 35.37%

Using crystal emulator in SixTrack



θ[μrad]→ l[mm]↓	20	40	60	80
3	CH: 83.19% VR: 14.00%	CH: 74.15% VR: 22.40%	CH: 63.05% VR: 33.50%	
4	CH: 84.98% VR: 12.00%	CH: 78.82% VR: 18.00%	CH: 70.81% VR: 25.20%	CH: 62.54% VR: 33.30%

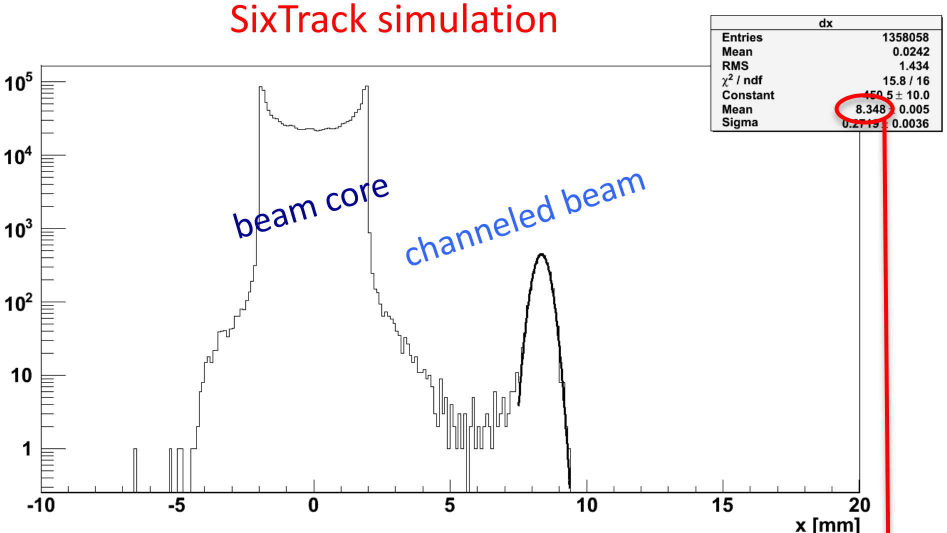
Using stand-alone fully analytical crystal simulator

Extracted Halo

SixTrack simulations made for the UA9 Layout in the SPS

Screen placed at the Medipix location to evaluate the particle distribution

SixTrack simulation



Theoretical position expected of the extracted halo:

- 8.4 mm and full spot width ~700µm

Many impacting halo distribution tested: from an average b of <2µm up to 100µm

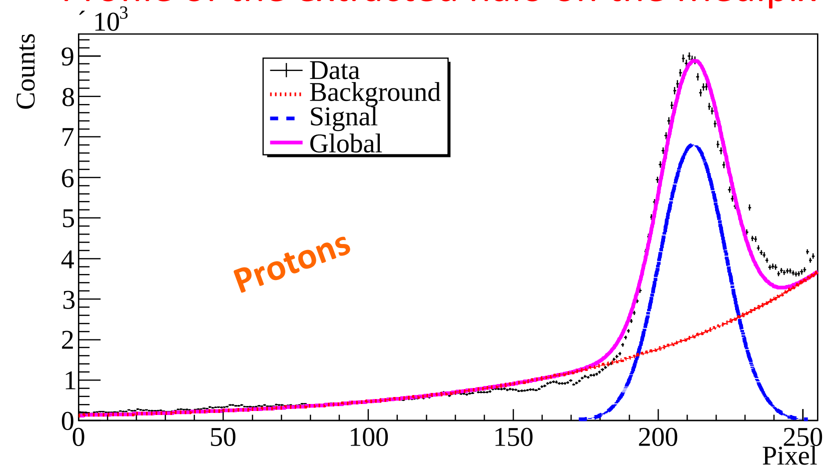
Spot of channeled beam on absorber determined by: crystal angular acceptance and optics

$$\Delta x = \Delta\theta\sqrt{\beta_{Cr}\beta_{Abs}}\sin\left(\Delta\varphi_{Cr-Abs}\right)$$

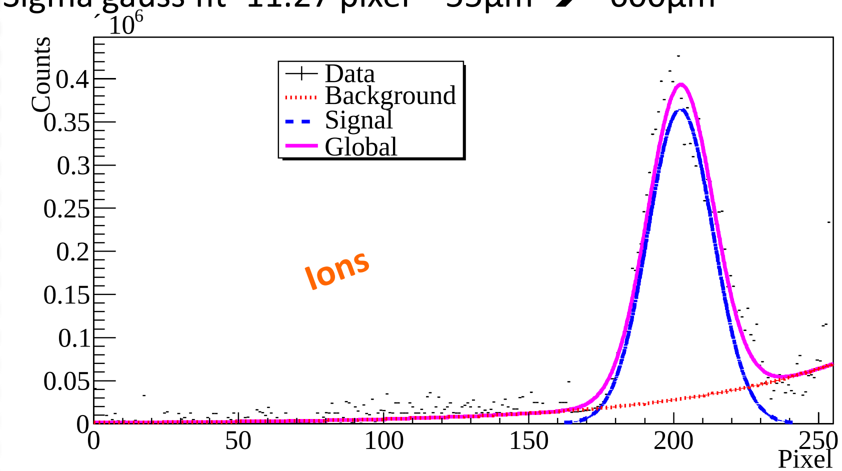
Dimension in the orthogonal plane: "natural" beam size at the Abs. (i.e. only optics)

Experimental data:

Profile of the extracted halo on the Medipix



Sigma gauss fit~11.27 pixel * 55µm ➔ ~600µm



Sigma gauss fit~11.30 pixel * 55µm ➔ ~600µm

Parameter constraints

Very challenging to find the best compromise between parameters, which satisfies injection and top energy!

Main constraints		***Parameters needed***
Best cleaning performance in the IR7 DS	→	Small bending Short crystals
Safe margins for IR7 magnet aperture	→	Small bending
Large impacts parameter of extracted halo on the TCSG	→	Big bending
Same layout for 450 GeV and 7 TeV	→	Big bending

<u>Where: "Big" and "Small" bending ranges between 20-100μrad,</u>
<u>"Short" and "Long" crystals ranges between 2-5mm</u>

Subset of crystal parameters taken into account:

@ 7TeV:

$$\lambda = \pi d_P \sqrt{\frac{E}{2U}} \sim 250 \mu m$$

$$R_c = \frac{d_p}{2} \frac{E}{2U} \sim 16.8 m$$

Considered only R>3Rc

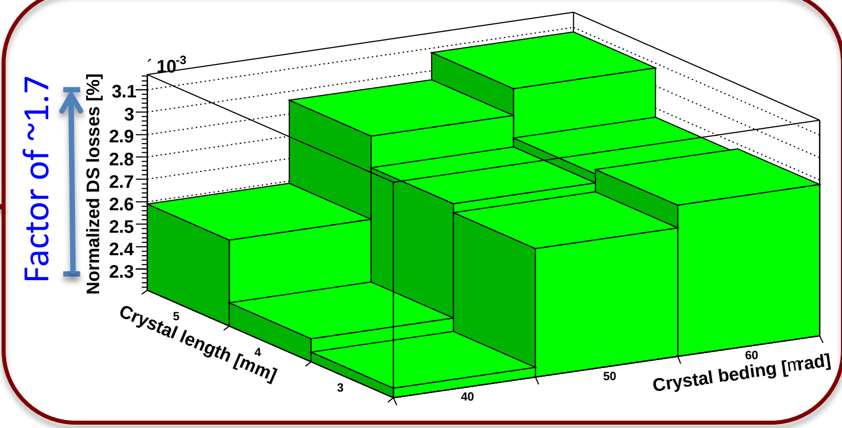
R[m]

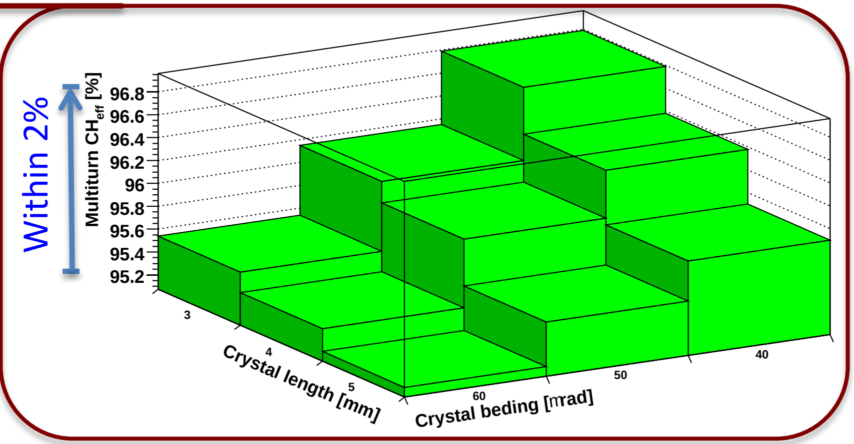
θ[μrad] → l[mm]↓	40	50	60
3	75	60	50
4	100	80	66.7
5	125	100	83.3

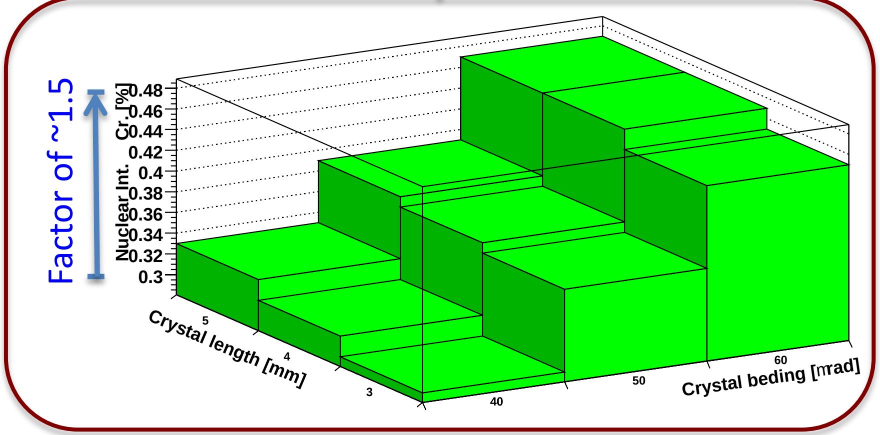
Multiturn effects

Main "observables" taken into account:
(simulations done in the H plane)

- ✓ Sum of the losses in the IR7 DS (normalized)
- ✓ Multiturn CH efficiency
- ✓ Nuclear Interaction probability at the crystal







Horizontal Layout

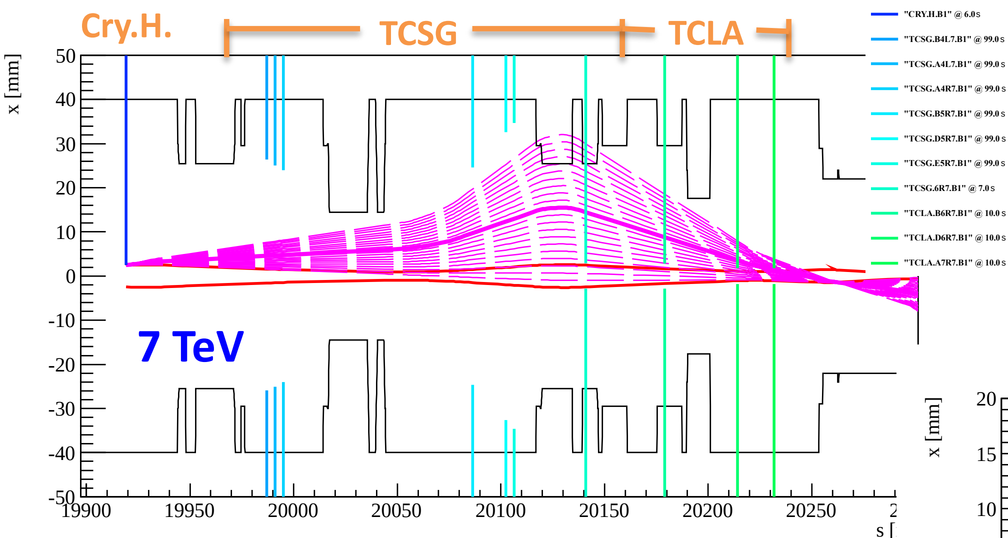
Two TCSG (B4L7 & 6R7) in the H plane possible to be used, but situation much harder then in the V plane

If TCSG.B4L7 is used to catch the extracted beam have to be closed too:

- TCSG.A4L7 and TCSG.A4R7 to intercept what is not absorbed in the B4L7 (otherwise same leakage of std. coll.)
- TCSG.6R7 to cover phase space seen by a TCSG at point 6 (which lead to a peak in the loss maps bigger than in the DS)

If TCSG.6R7 is used to catch the extracted beam:

- No other TCSG needed, since it is placed just in front of the TCLA



Color code in the plots

Beam pipe

trajectory of kicked particle at the crystal (from 0 to 100μrad with steps of 5μrad)

6σ beam envelope

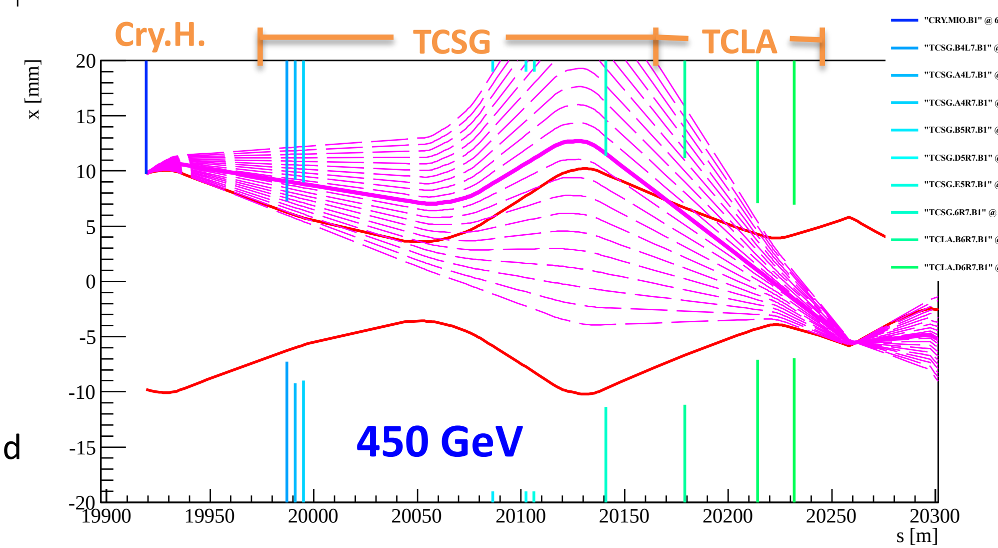
Collimator chain aperture

Upper limitation:

Maximum bending angle allowed equal to 65μrad (~5mm minimum clearance @7TeV)

Lower limitation:

Minimum bending angle needed at 450GeV equal to 50μrad

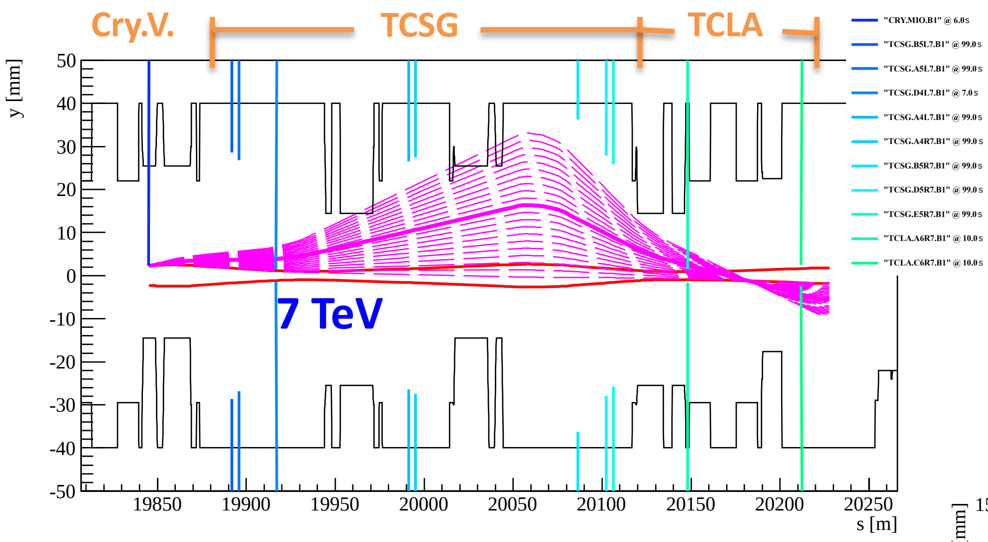


Vertical Layout

Very good conditions from optics point of view

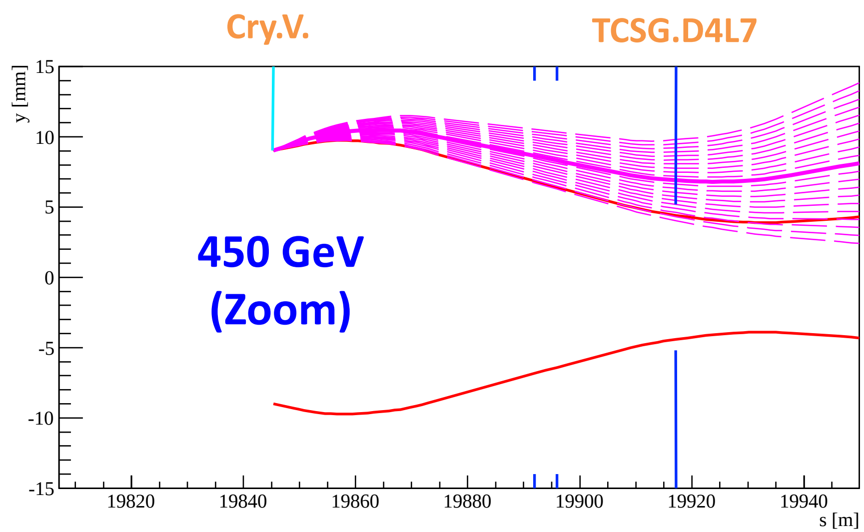
Only one TCSG (D4L7) in the V plane, and at same phase of the TCLAs

everything is able to emerge from the TCSG, it is then absorbed by the TCLAs



Impact parameter on TCSG (@ 7sigma) @ 7TeV:

kick [urad]	b [mm]
40	2.01
50	2.58
60	3.16



Upper limitation:

No limitation since TCSG very close to Cry.V.

Lower limitation:

Minimum bending angle needed at 450GeV equal to 50µrad

Proposed Nominal Parameters

SixTrack simulations shows that at 7TeV particles still channeled when crystal tilted of 5μrad (i.e. ~2 critical angle), w.r.t. perfect orientation of extraction

Additional deflection to the extracted beam which has to be taken into account

In order to be safe during angular scans, taken a "channeling margin" (i.e. additional kick) of 4 critical angle (i.e. ~10μrad)

Optimal bending choose 50μrad

Crystal length: 4mm to have a bending radius bigger than 4 critical bending radius

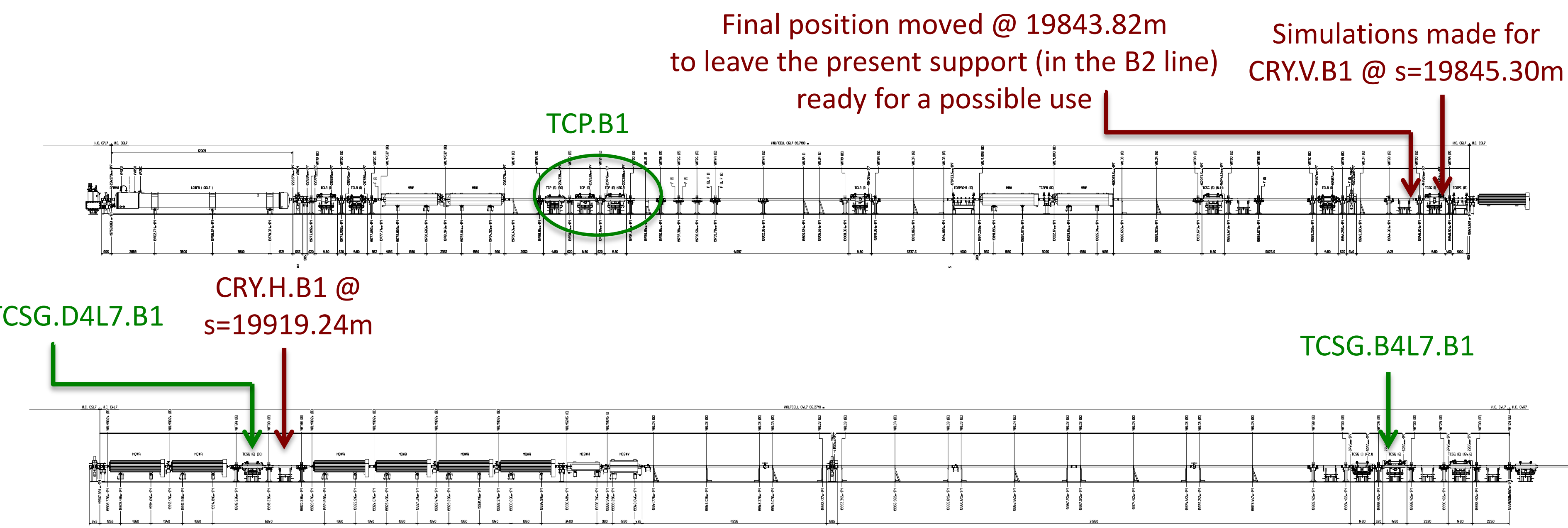
We are confident that these parameters will allow us to achieve conclusive measurements at 450 GeV and 7 TeV in both planes!
(Note: different sets of settings for TCSGs are required!)

LHC installation layout

Main steps to achieve optimum layouts with nominal IR7 optics and minimum impact on standard collimation:

- ✓ Suitable candidates identified with semi-analytical analysis of channeled beam trajectories
- ✓ Conceived set of setting for the whole collimation system (~50 collimators each beam) to achieve MD goals
- ✓ Complete tracking simulations to predict loss maps

Proposed two positions for installation of H&V crystals on beam1:



Simulation Setup

Different scenarios have been investigated:

- ✓ crystals in the horizontal and vertical planes separately
- ✓ 7TeV beam with nominal collision optics (β*=55cm), and at injection (450GeV beam) (only 7TeV case shown here)
- ✓ only one secondary collimator inserted to absorb the channeled and extracted beam
- ✓ full collimation chain downstream the crystal in place (only one TCSG case shown here)
- ✓ Statistics of >10^7 protons intercepted by the collimation system, to allow estimation of losses ~10^{-6}.

Simulations have been done for a perfect machine and crystal:

- no optics and orbit errors
- no collimator setup errors
- no miscut angle, amorphous layer

IR7 Collimation chain settings used for the simulation in the next:

Coll. Name	s [m]	Orient.	Setting [σ] Hor. plane	Setting [σ] Ver. plane
CRY.H.B1	19919.24	Hor.	6	99
CRY.V.B1	19845.30	Ver.	99	6
TCP.*	-	H/V/S	99	99
TCSG.*	-	Skew	30	30
TCSG.D4L7	-	Ver.	30	7
TCSG.6R7	-	Hor.	7	30
TCLA.*	-	H/V	10	10

IR7 for Std. Collimation ref.:

Coll. Name	Setting [σ]
TCP.*	6
TCSG.*	7
TCLA.*	10

IR3 in both cases:

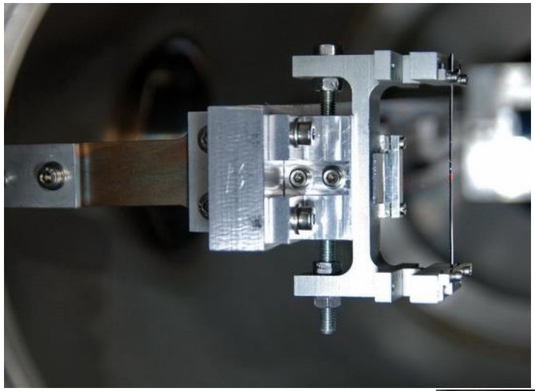
Coll. Name	Setting [σ]
TCP.*	15
TCSG.*	18
TCLA.*	20

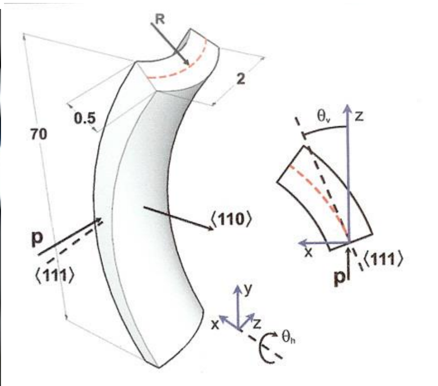
Experimental apparatus in the SPS

Crystals of Si:

- ✓ Two Strip Crystal (1&4)
- ✓ Two Quasi Mosaic Crystal (2&3)

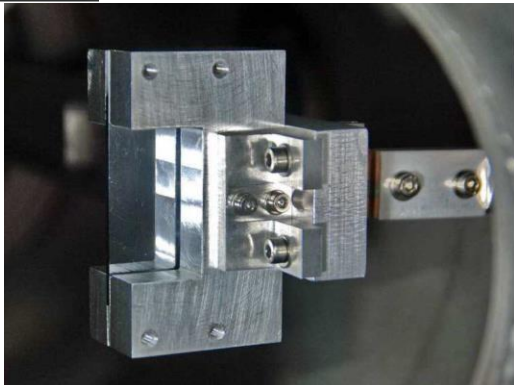
Bending given by anticlastic and molecular forces





In SPS:

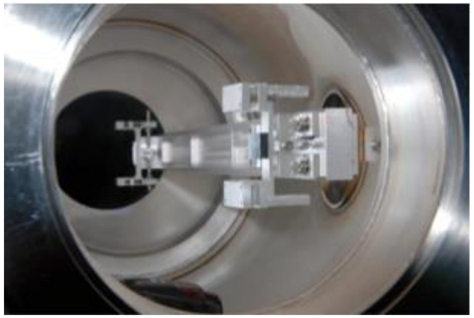
Longitudinal dimention~2mm,
Bending 150÷180 μrad



Goniometers:

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

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

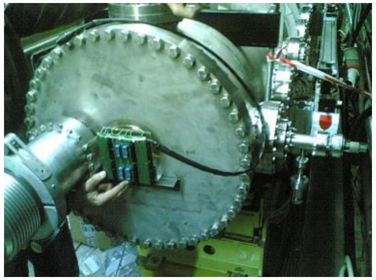


Goniometers with high precision and repeatability
~10 μrad per SPS,
~1 μrad per LHC

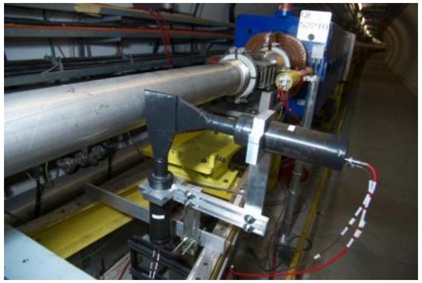
Experimental apparatus in the SPS

Dectectors:

- *Out of beam pipe*



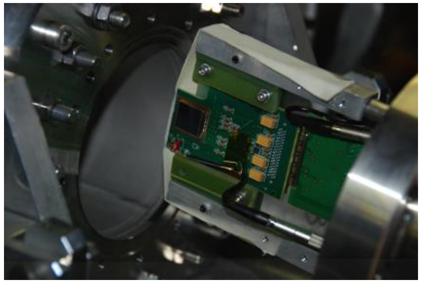
GEM, anode of 128 pad, area 10x10cm^2



Plastic scintillator, ~10x10x1cm^3

BLM-LHC Type, 2πx4.5x50cm^3

- *Secondary vacuum*



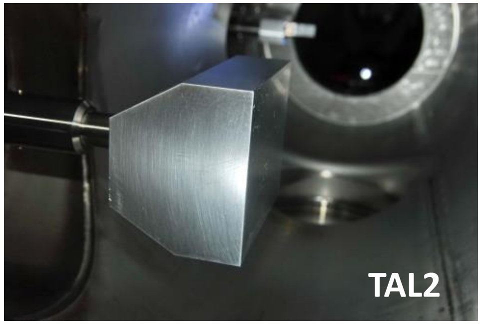
Medipix, 256x256 pixel, 55x55 μm^2 each

- *Primary vacuum*

Quartz, Cherenkov radiator

Absorbers:

- TAL, 60cm W
- LHC-Coll Phase II, 1m Cu
- TAL2, 10cm Al



LHC-Coll