Nanostructures, plasma and crystals as extraction devices: challenges and opportunities

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Acknolegments: L.S. Esposito, A. Lechner, P. Schoofs, R. Rossi, W. Scandale,
UA9, STI, CEM, ABT, ABP, BI

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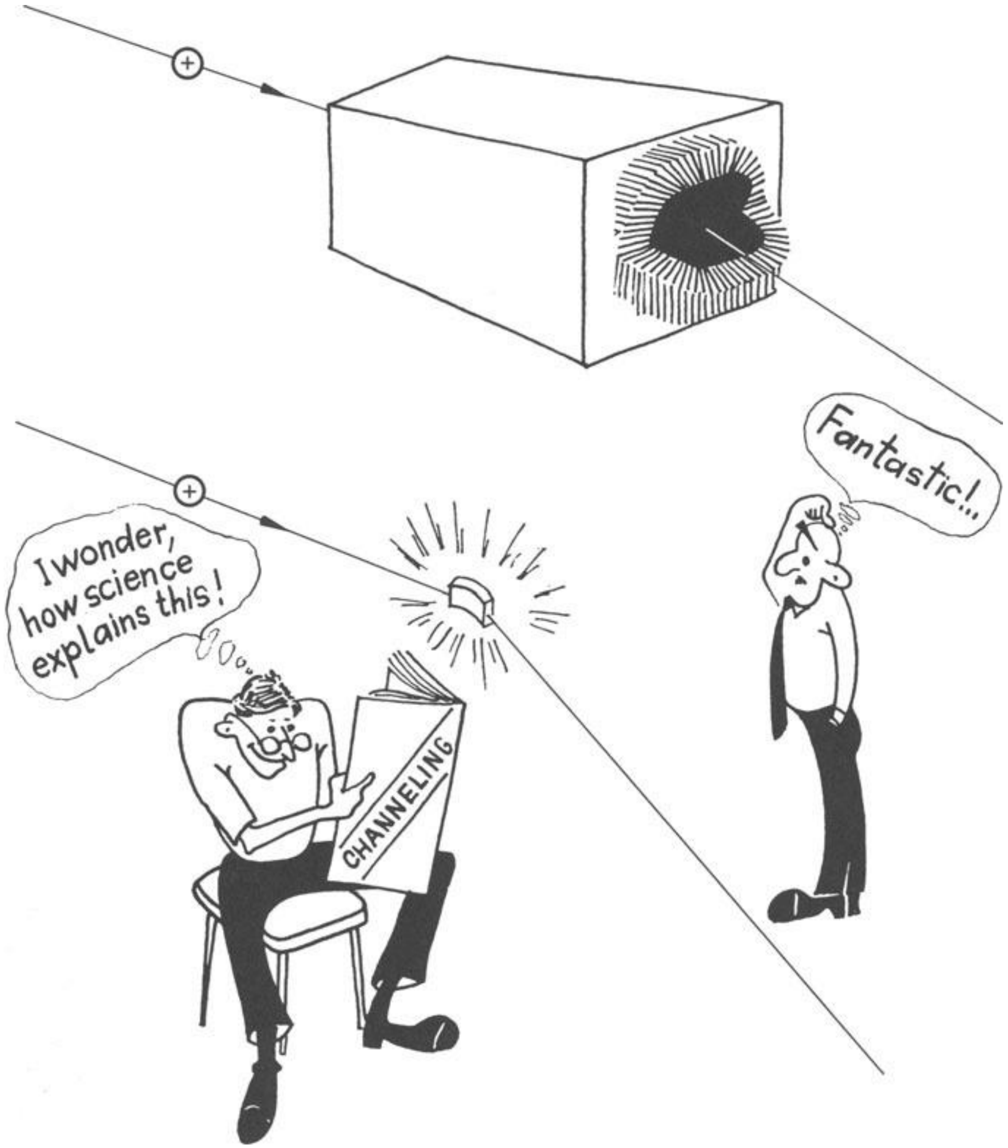
A foreword

Bent crystals, plasma, and dielectric structures can be very powerful deflection media

- Q LHC crystals impart 50 urad bending angle
- At LHC top energy (7 TeV), along the 4-mm length, this corresponds to an equivalent magnetic field of **~290 Tesla!**
- Dielectric and plasma structures driven by laser can be utilized for fast extraction of closely located bunches



V.M. Biryukov et al., Crystal Channeling and Its Application at High-Energy Accelerators (1997)

Content

Crystal Channeling Physics

Bent Crystal applications

- Hadron beam collimation (LHC)
- Beam extraction (SPS)
- Double channeling (LHC)

Crystal characterization and validation

Fast extraction (ideas for the future)

- Laser-driven deflection in dielectric structures
- kT fields from plasma discharge in a single-turn coil

Crystal Channeling Physics

An historical overview

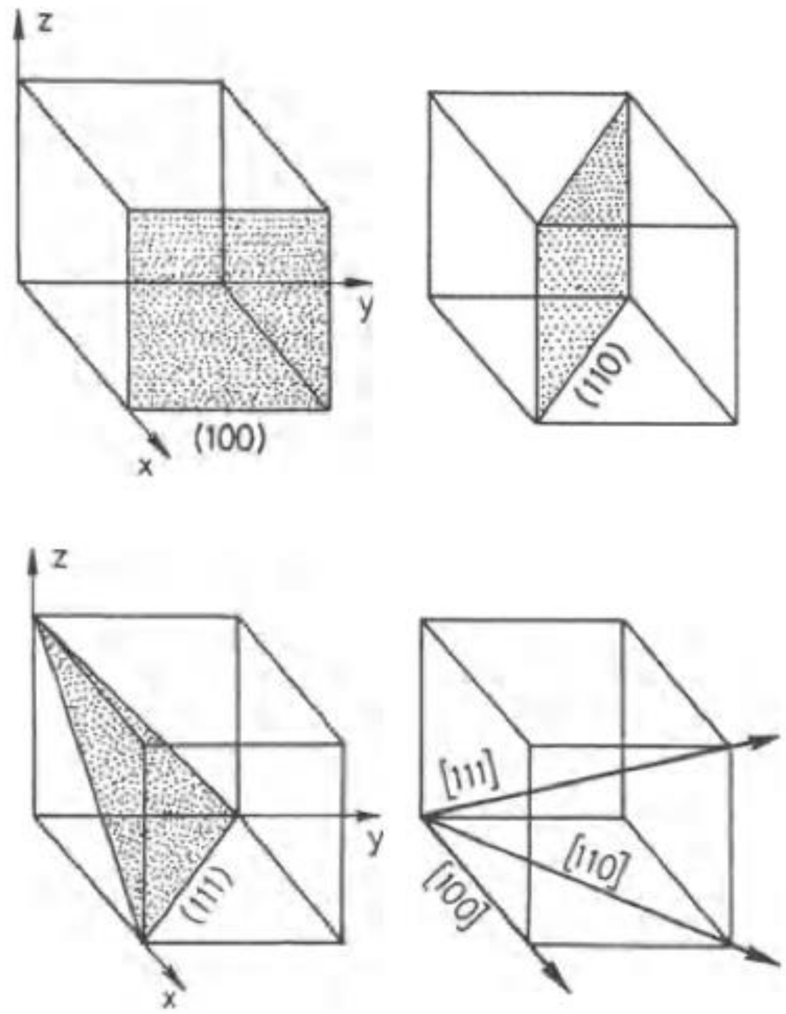
In a 1912 speculative paper, J. Stark (a Nobel laureate) made the hypothesis that particles parallel to crystal channels would pass with a high chance of deep penetration, i.e. they have a reduced probability to lose energy by ionization and to make nuclear interactions.

In the 1960s, experiments observed abnormally large ranges of ions in crystals. The orientational effects for charged particles traversing crystals were found for a number of processes requiring a small impact parameter in a particle-atom collision: nuclear reactions, large-angle scattering, energy loss, and so on.

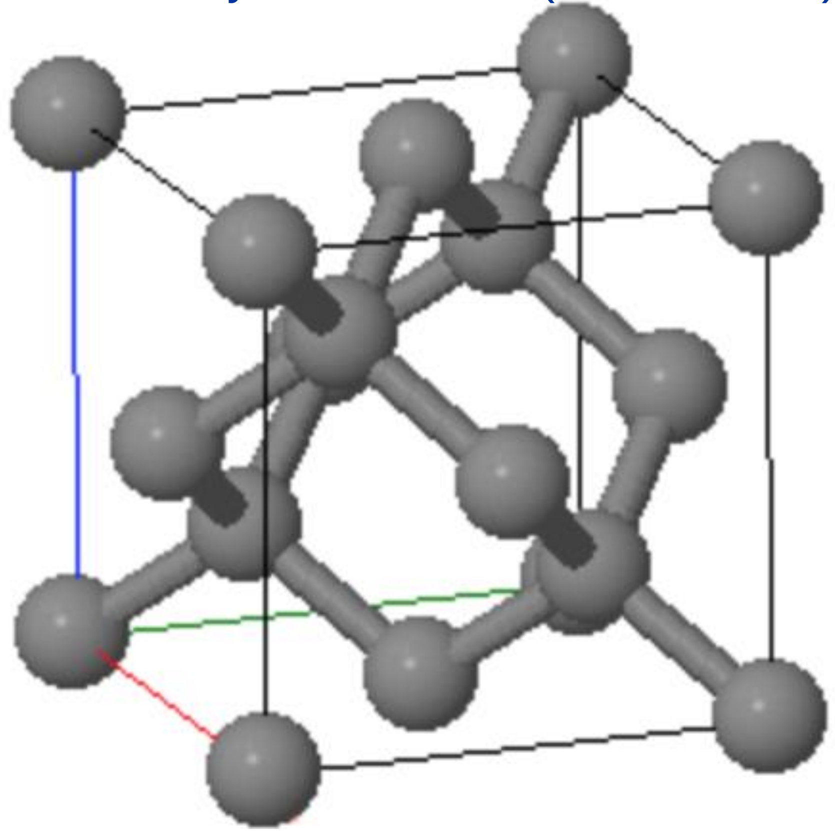
J. Lindhard gave the first theoretical interpretation, showing that channeling is due to coherent interactions of charged particles having a small incident angle with respect to the crystallographic axis (or plane).

In 1976, A.D. Tsyganov proposed to bend a crystal to deflect high energy beam particles. Later experiments carried out at JINR, FNAL and CERN confirmed this idea.

Crystalline Lattice

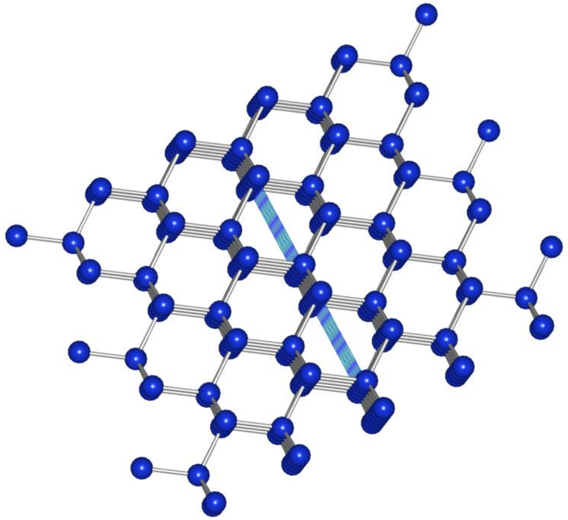


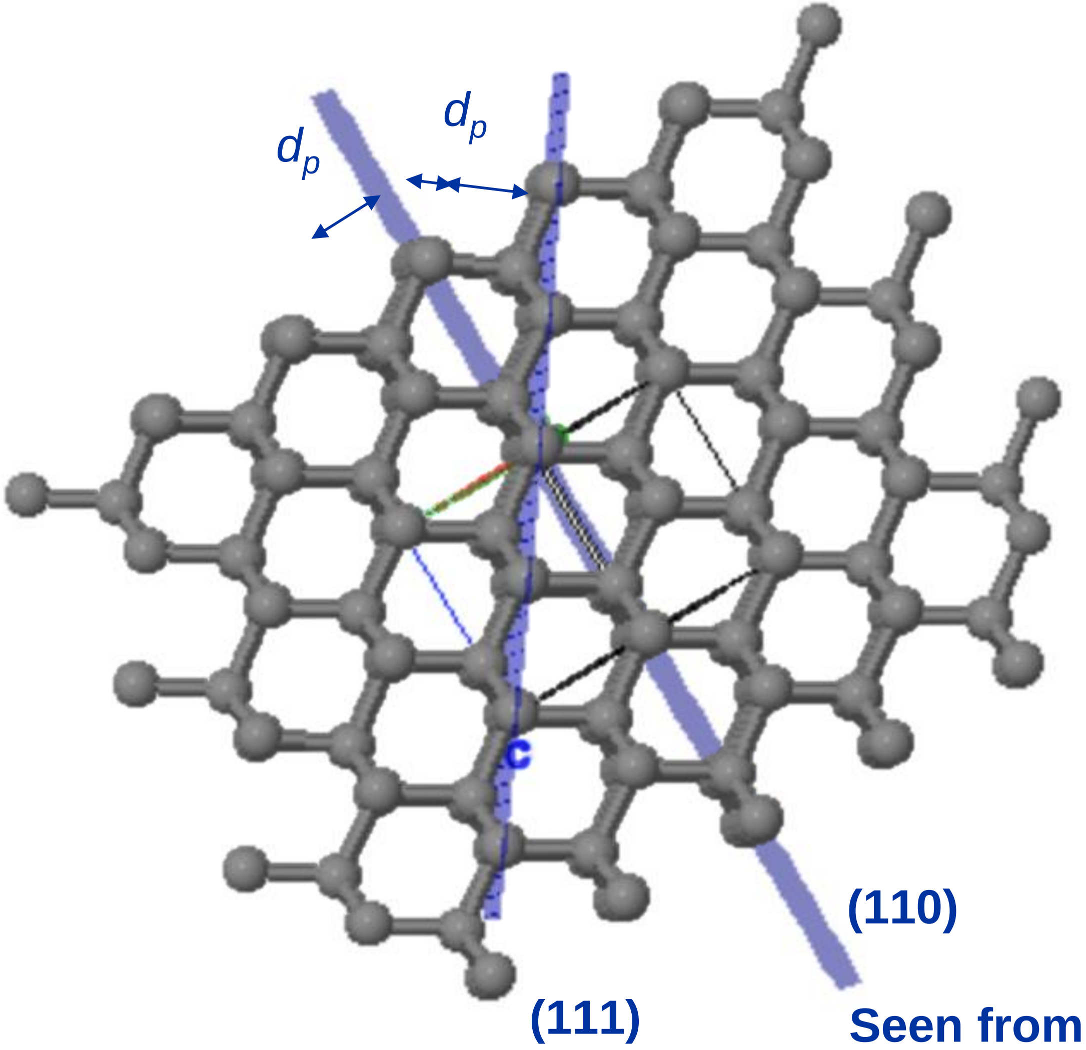
Diamond Crystal structure (C, Si, Ge, W)



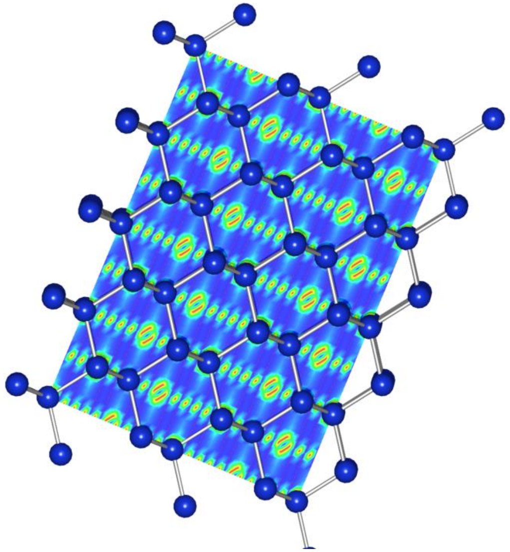
Silicon ingots are widely used in beam manipulation applications because highly available on the semiconductor market:
➔ cheap and with low impurity and defects.

Crystalline planes





Seen from [1 -1 0]



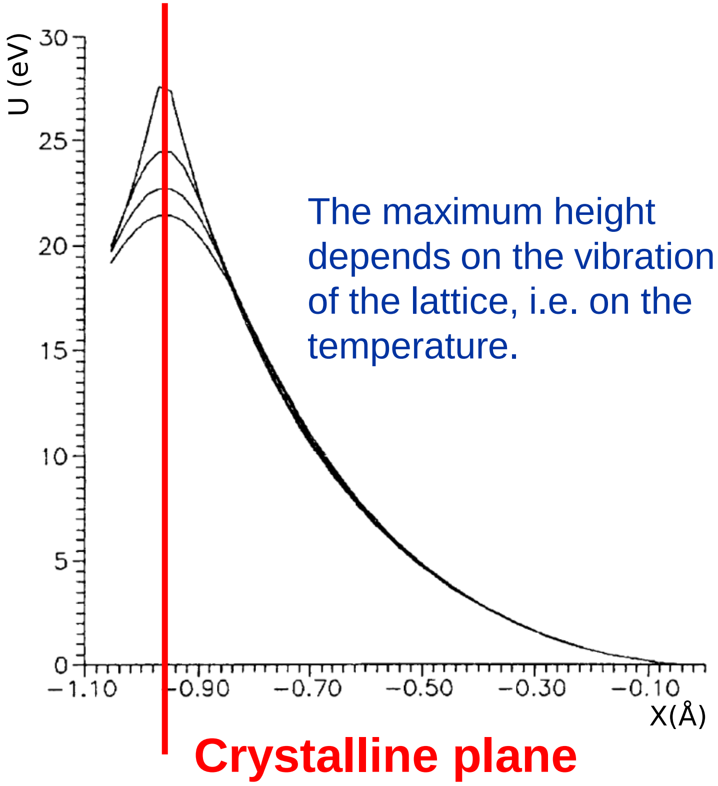
[1 1 0] Plane in Vesta
(nuclear densities)

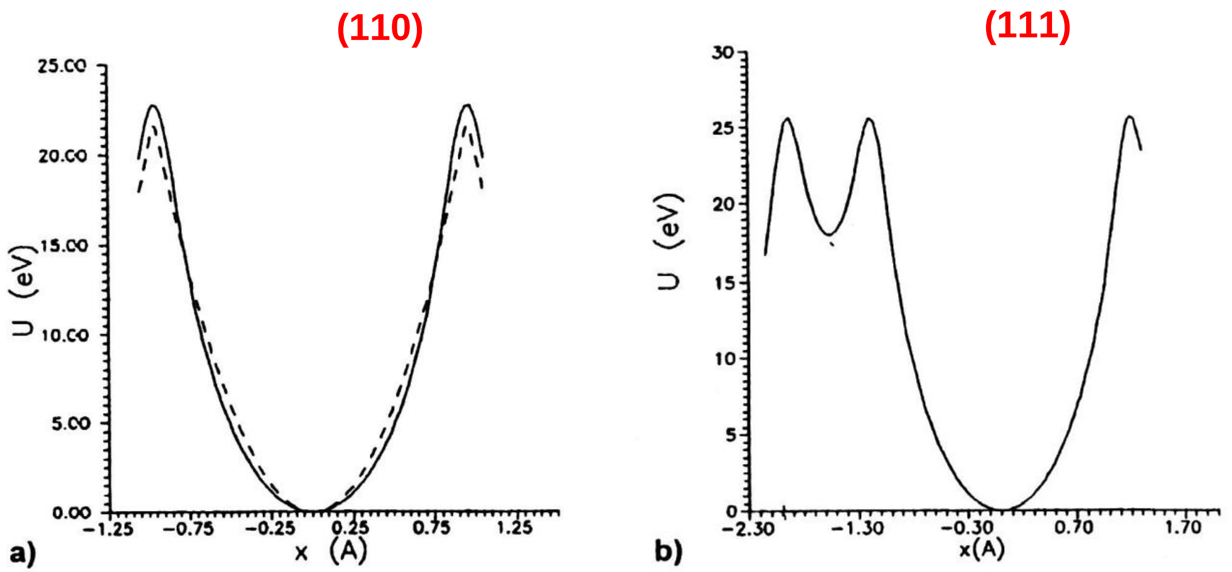
Material	Plane	d_p [Å]
Si	(110)	1.92
	(111) L	2.35
	(111) S	0.78
Ge	(110)	2.00
	(111) L	2.45
	(111) S	0.81
W	(100)	1.58
	(110)	2.24

Crystalline plane potential

Two adjacent planes form a channel.
The width and height of the potential depend on the material and the plane orientation.

Lindhard: “In the hypothesis of low impact angle, the potential generated by the crystalline plane can be approximated by a continuous potential.”





Material	Plane	d_p [Å]	U_{max} [eV]
Si	(110)	1.92	16
	(111) L	2.35	19
	(111) S	0.78	4.2
Ge	(110)	2.00	27
	(111) L	2.45	30
	(111) S	0.81	7.2
W	(100)	1.58	63
	(110)	2.24	105

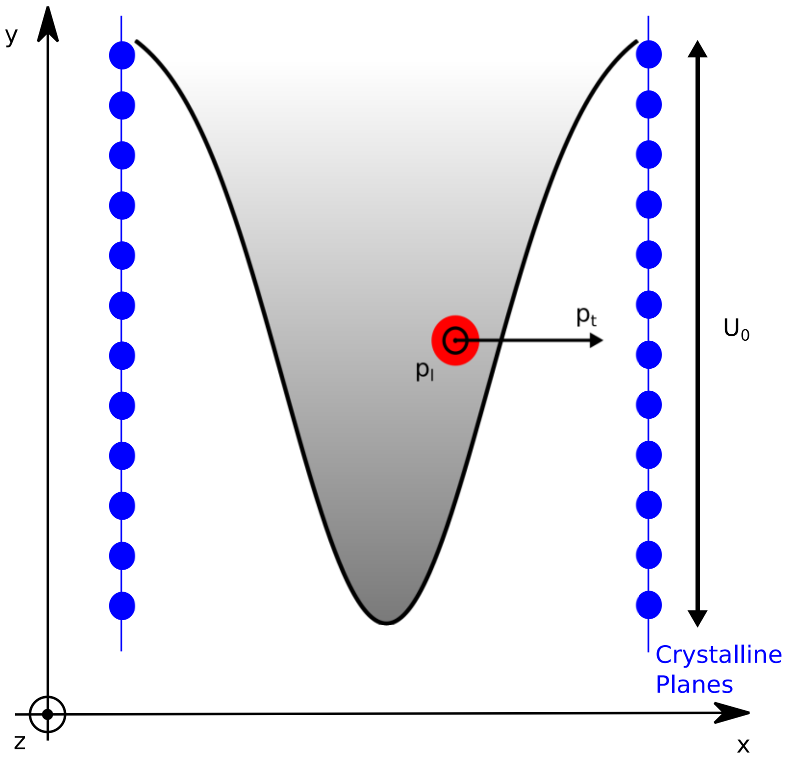
Crystal Planar Channeling

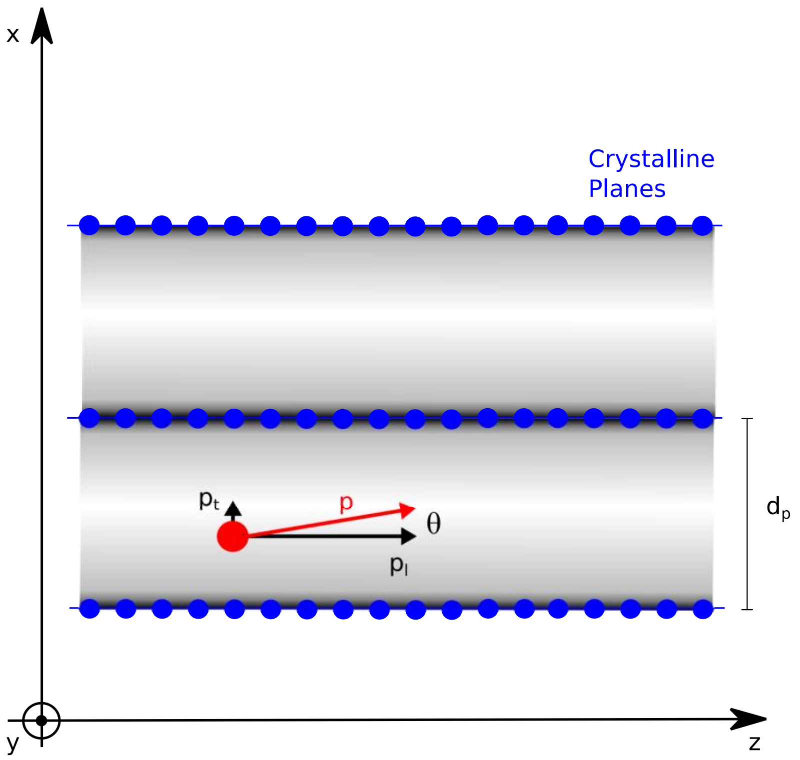
$$\frac{p^2 c^2}{2E}\theta^2 + U(x) \leq U_{max}$$

Critical angle

$$\boxed{\theta_c = \sqrt{\frac{2U_{max}}{pv}}}$$

Channeling condition is defined from the particle transverse momentum and the electrostatic potential generated by the atoms of the crystalline structure



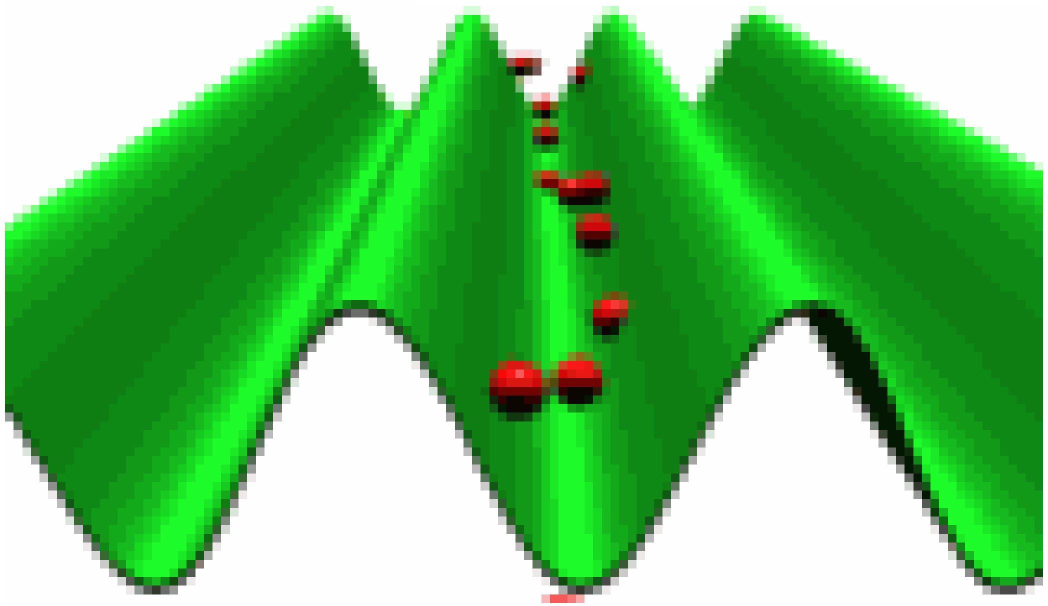


Energy	θ_c
500 MeV	282.8 μrad
120 GeV	18.3 μrad
180 GeV	18.0 μrad
270 GeV	12.2 μrad
400 GeV	10.0 μrad
450 GeV	9.4 μrad
6.5 TeV	2.5 μrad
7 TeV	2.4 μrad
50 TeV	0.9 μrad

Crystal Planar Channeling

A solution of the equation of motion (in the approx. of harmonic oscillator) shows that channeled particles oscillate with a wavelength proportional to their energy between crystal planes.

$$x = \frac{d_p}{2}\sqrt{\frac{E_t}{U_0}}\sin\left(\frac{2\pi z}{\lambda} + \phi\right)$$

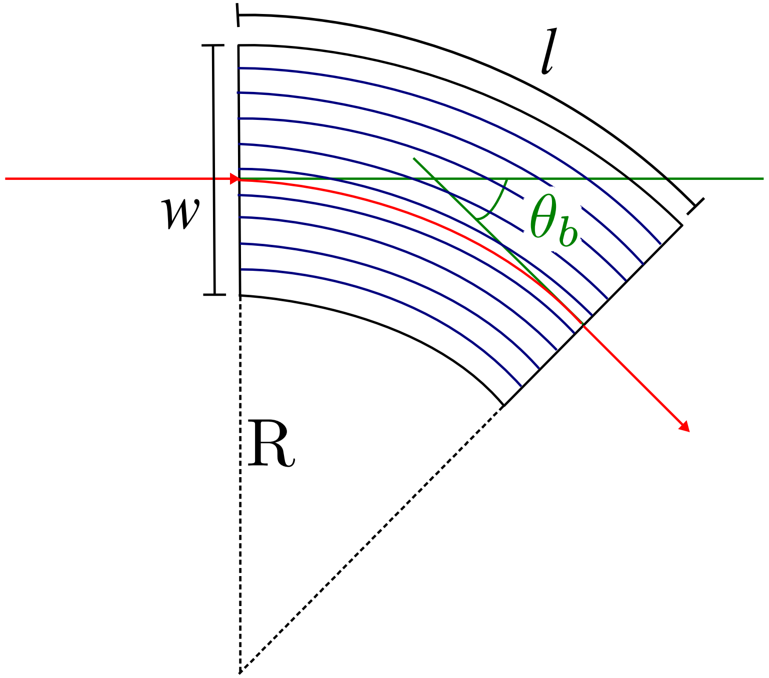


$$\lambda = \pi d_p \sqrt{\frac{pv}{2U_{max}}}$$

Energy	θ_c	λ
500 MeV	282.8 µrad	2.1 µm
120 GeV	18.3 µrad	33.0 µm
180 GeV	18.0 µrad	40.5 µm
270 GeV	12.2 µrad	49.6 µm
400 GeV	10.0 µrad	60.3 µm
450 GeV	9.4 µrad	64.0 µm
6.5 TeV	2.5 µrad	0.24 mm
7 TeV	2.4 µrad	0.25 mm
50 TeV	0.9 µrad	0.67 mm

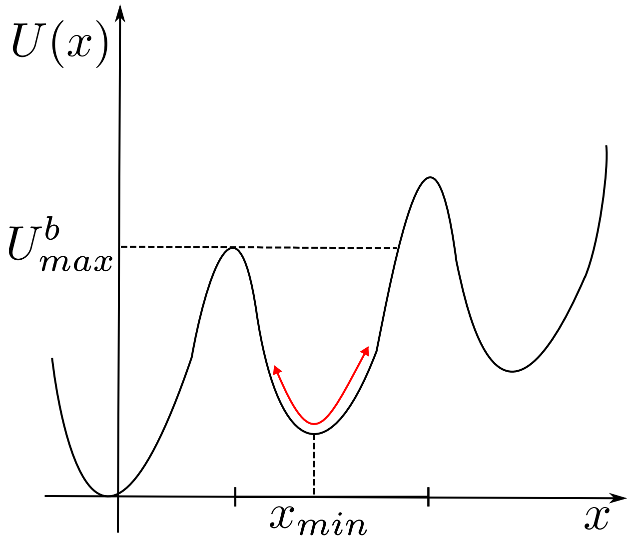
Channeling in Bent Crystals

The particles are trapped in the channel, hence if a curvature is given to the lattice the particles direction will be modified by $\boldsymbol{\theta_b = l/R}$



The bending induces a centrifugal term that deforms the straight potential with an additional term depending on both the crystal curvature and the particles energy:

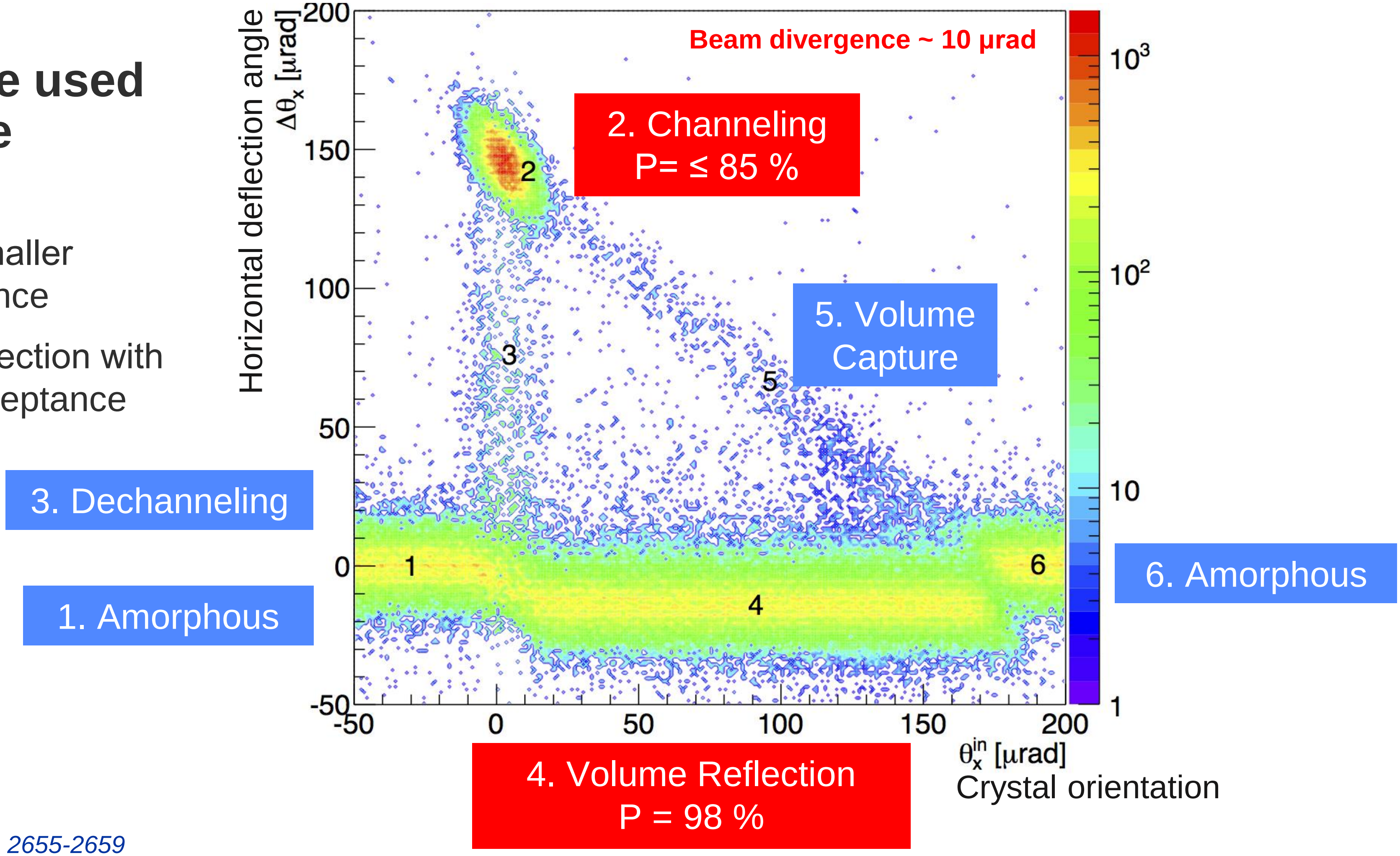
$$pv\frac{d^2x}{dz^2} + U'(x) + \frac{pv}{R} = 0;$$



Beam manipulation with bent crystal

Two coherent effects could be used for beam deflection in particle accelerators:

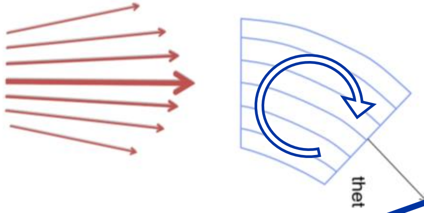
- Channeling → larger deflection with smaller efficiency and smaller angular acceptance
- Volume Reflection (VR) → smaller deflection with larger efficiency and larger angular acceptance

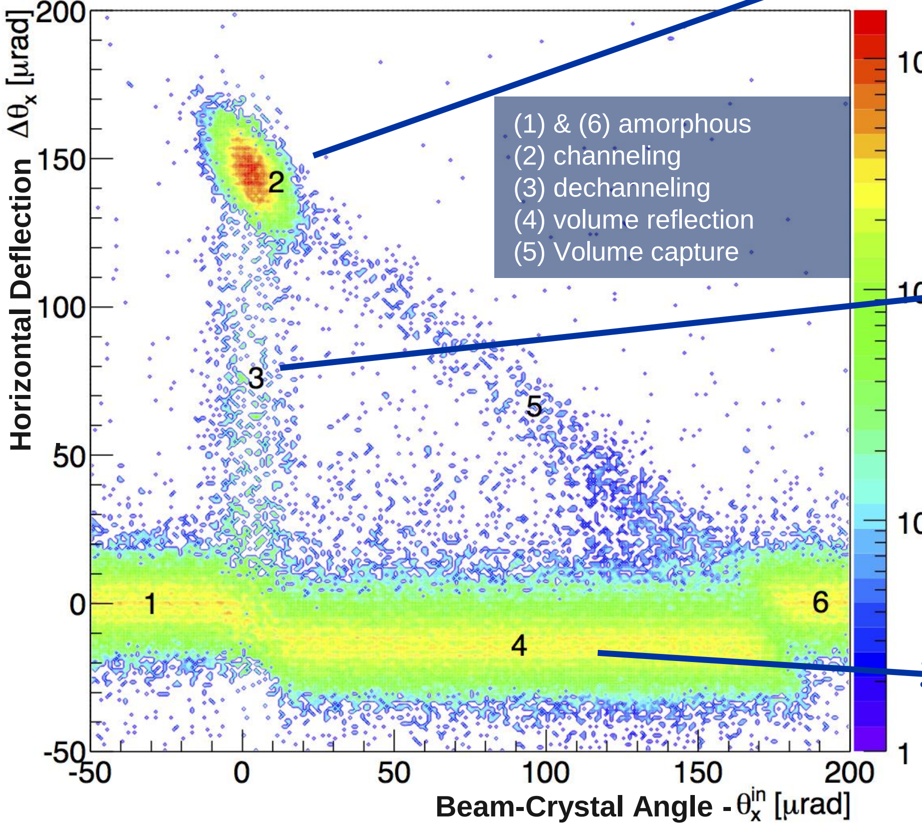


W. Scandale et al, PRL 98, 154801 (2007)
W. Scandale et al., Nucl. Inst. and Methods B 268 (2010) 2655-2659

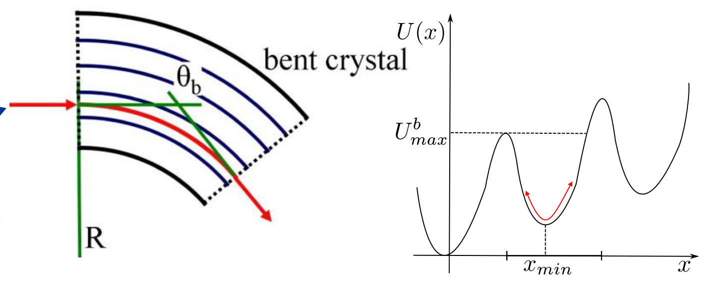
Coherent effects in bent crystals

Single pass measurements with 400 GeV protons.
Strip crystal (110) with a bending of 144 μrad.



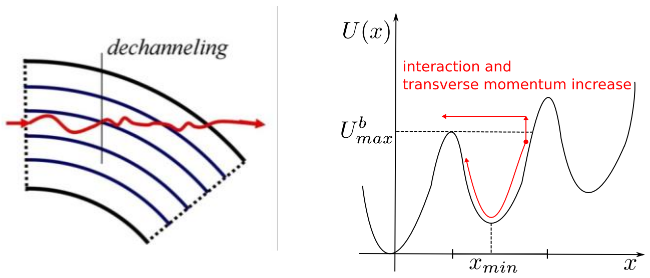


Planar channeling (CH)



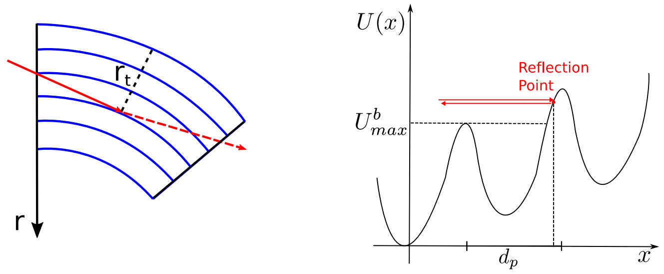
- Particles oscillate in relatively empty space
- Large deflection
- ~ 70-80% efficiency

Dechanneling (DC)



- Reduces with particles *pv*
- Larger probability for particles oscillating close to crystalline planes
- Particles obtain a deflections < θ_b

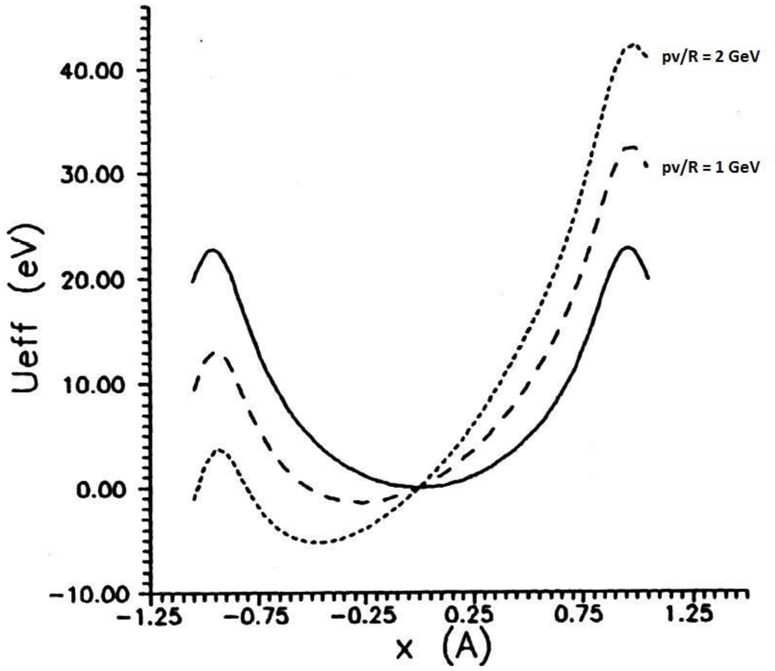
Volume Reflection (VR)



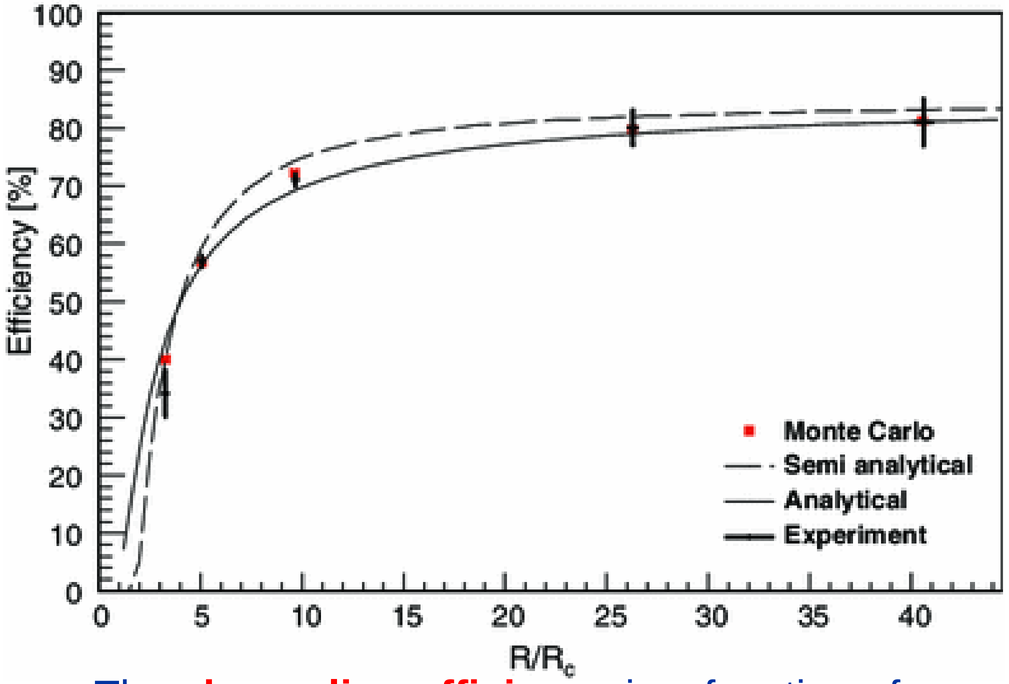
- Deflection in opposite direction to CH
- ~ 1.5 θ_c (i.e. function of *pv*)
- Same MCS effects (RMS same as amorphous)
- Higher nuclear density at the reflection point

Critical Radius

The asymmetry of the planar potential increase with the **particles energy** and decrease with the **radius of curvature (R)**



E. Bagli et al., Steering efficiency of a ultrarelativistic proton beam in a thin bent crystal, Eur. Phys. J. C, 74 (1) (2014), pp. 1-7



A **critical radius (R_c)** can be defined:

$$R_c = \frac{pvx_{\max}}{2U_{\max}} \Longrightarrow \theta_c^b = \theta_c\left(1 - \frac{R_c}{R}\right)$$

The **channeling efficiency** is a function of the ratio **R/R_c**

Bent Crystal applications

Standard collimation system in LHC

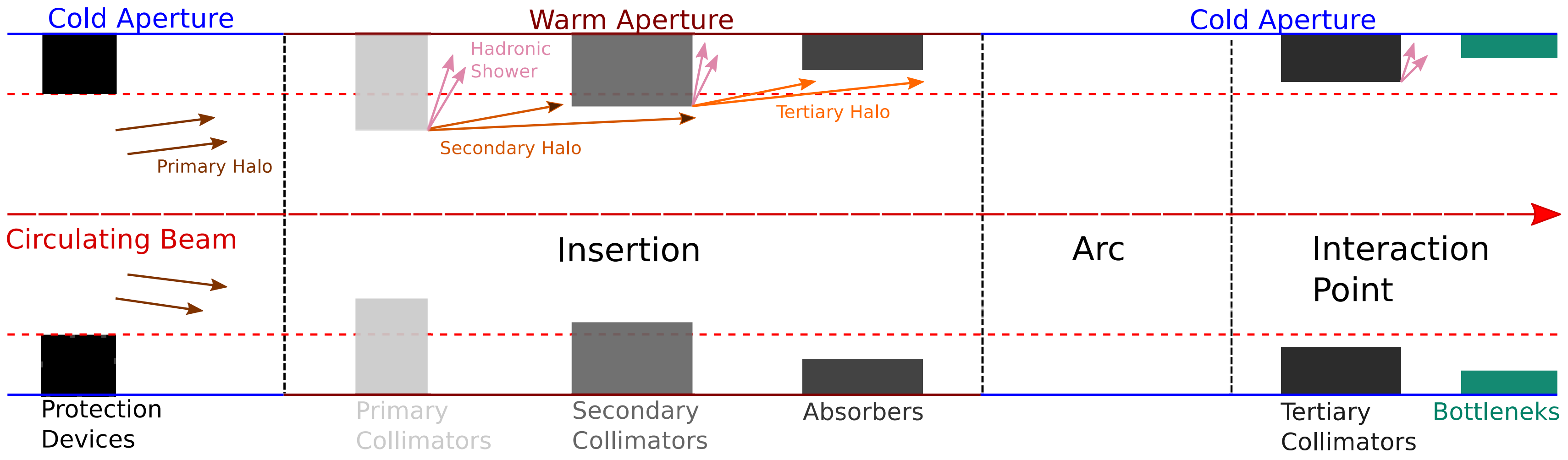
Stored energy in the machine:
- LHC design: **360 MJ**

Superconducting magnets (T = 1.9 K)
- quench limit ~ **15-50mJ/cm³**

To protect the superconductive magnets from energy deposition induced by lost particles

Collimation system is needed!

$\eta = 10^{-4}$ is the actual performance in LHC

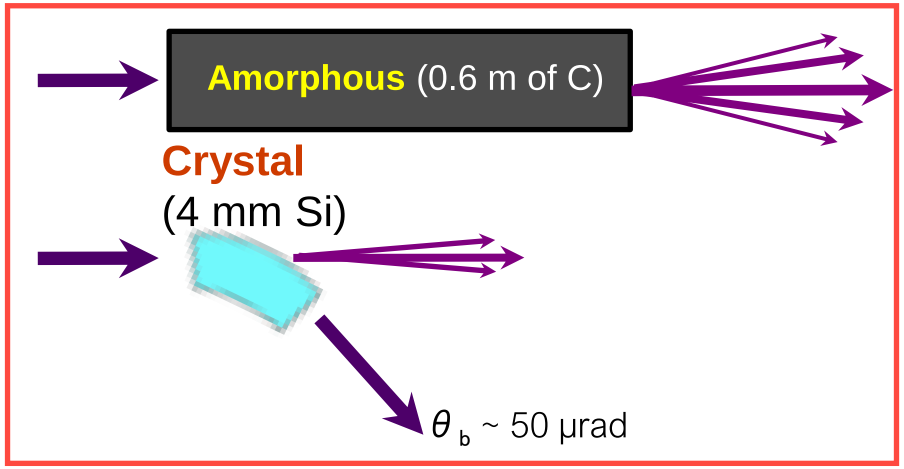


- **Halo cleaning**: reduce the risk of magnet quenches
- **Concentration of losses/activation in controlled areas**

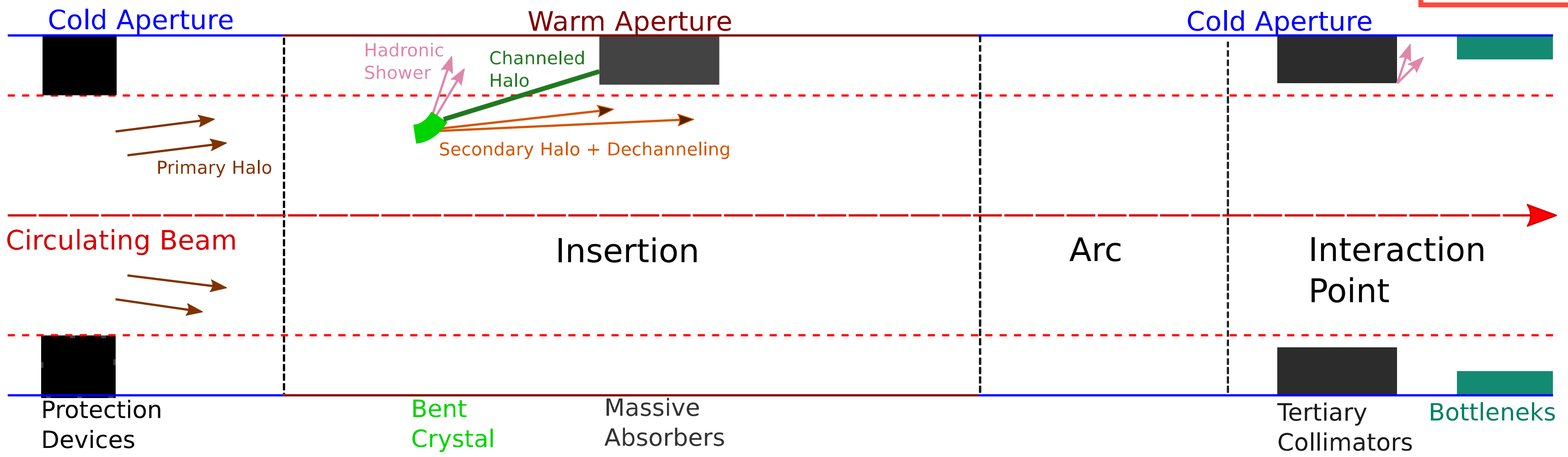
Multi-stage system with ~50 collimators per beam

The cleaning inefficiency with ions drops to 10^{-2}!

Crystal-based collimation system



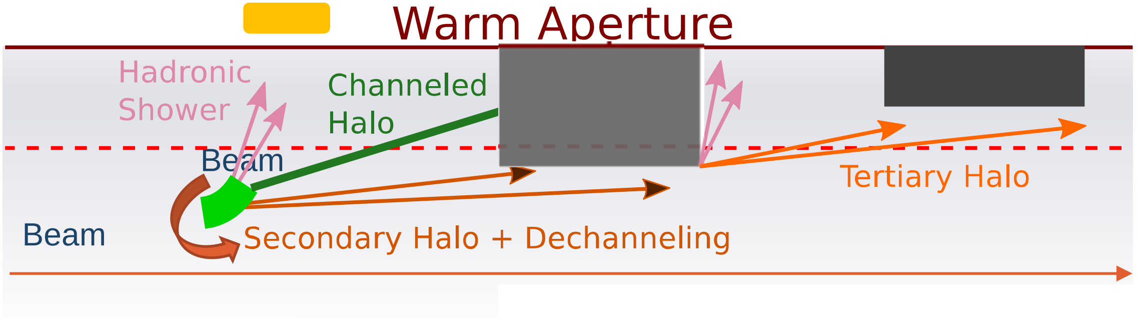
- Cleaning upgrade required to prevent quenches in DS magnets at IR7
- 11T dipoles not available for TCLD cleaning
- New baseline Nov 2020 using TCPC crystal collimators for ion runs



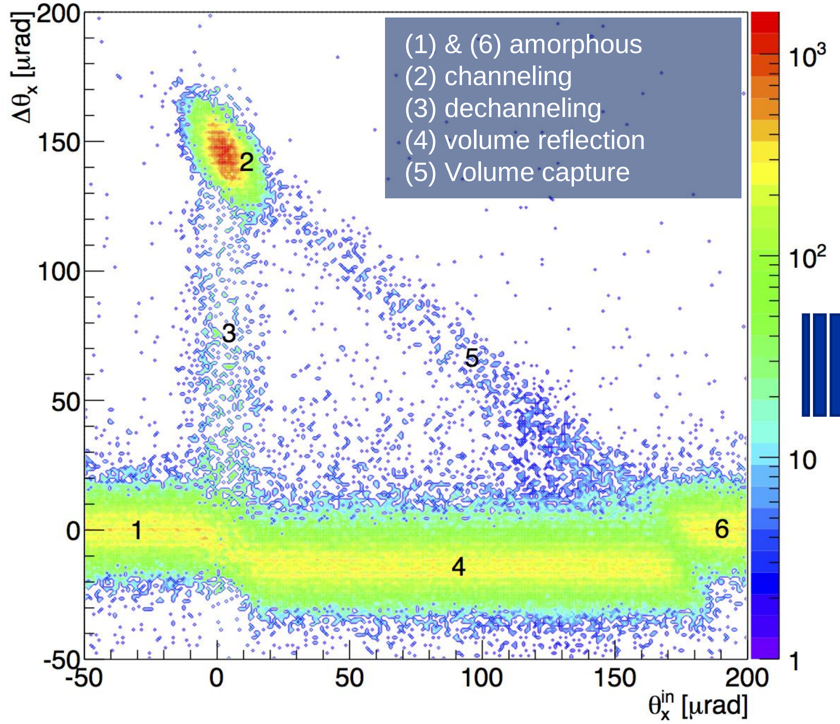
Operational only for ion-runs (HL-LHC protons runs would require additional absorbers)

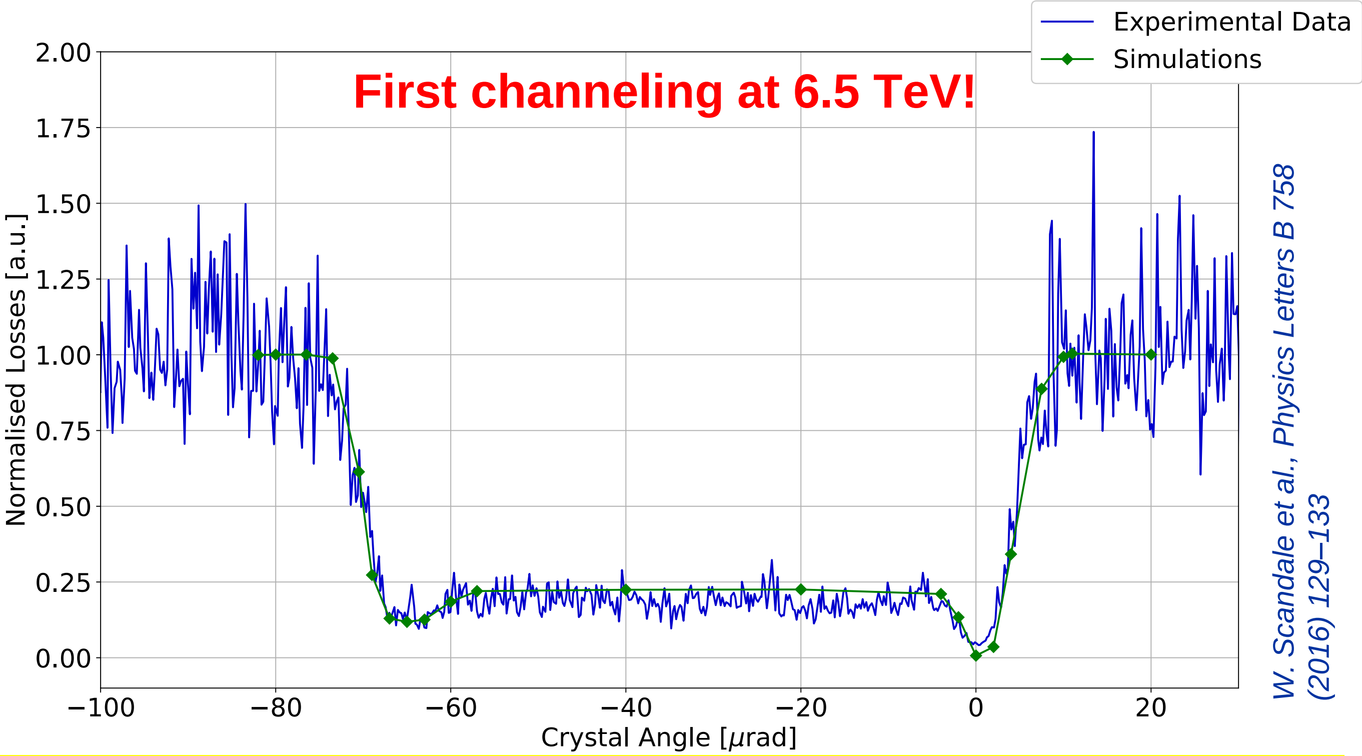
Channeling Assessment in Circular Machines

Angular Scan



BLM local losses
vs
crystal rotational orientation

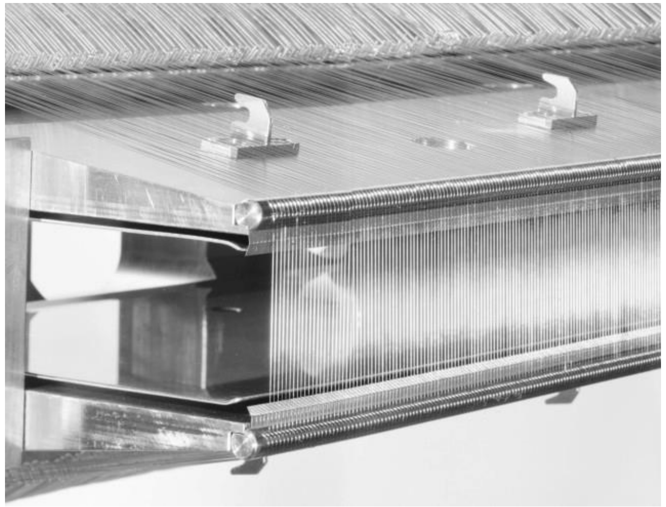




W. Scandale et al., Physics Letters B 758 (2016) 129–133

Result achieved after 10+ years R&D, thanks also to the UA9 test-bench in the SPS LSS5

Beam Extraction from SPS



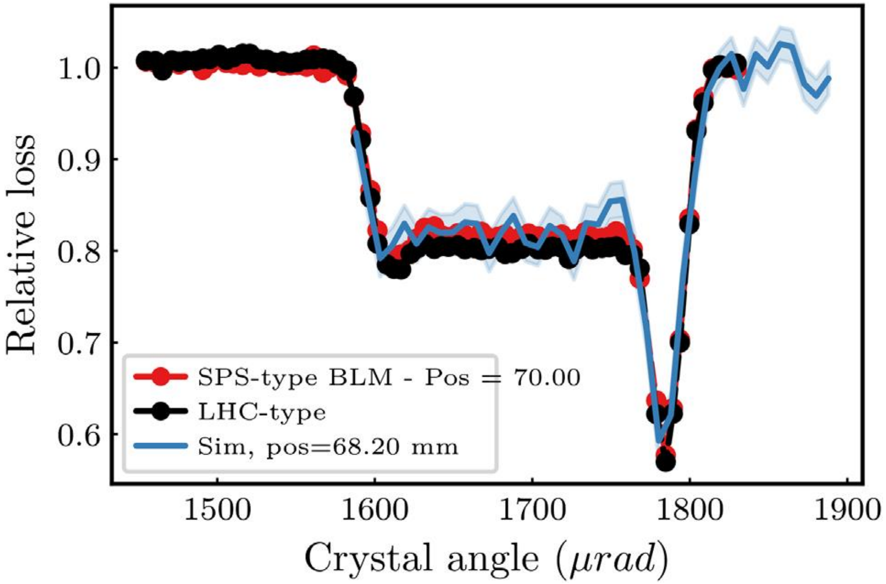
http://cds.cern.ch/record/969071

The use of a bent crystal as extraction device was one of the first application in circular machines (RD22)

At SPS, during the third-order resonance slow extraction, it is expected that about 3-4% of extracted particles hit the Electrostatic Septum (ZS) wires inducing secondary particle showers

Even higher extracted flux (up to 4 x 10^{19} pot/year) required by future Fixed Target programs at CERN SPS (i.e. Beam Dump Facility) is a limiting factor because of the induced radioactivation of the extraction equipment

Crystal-assisted slow extraction is now operational and used to locally shadow the ZS and effectively reduce the losses



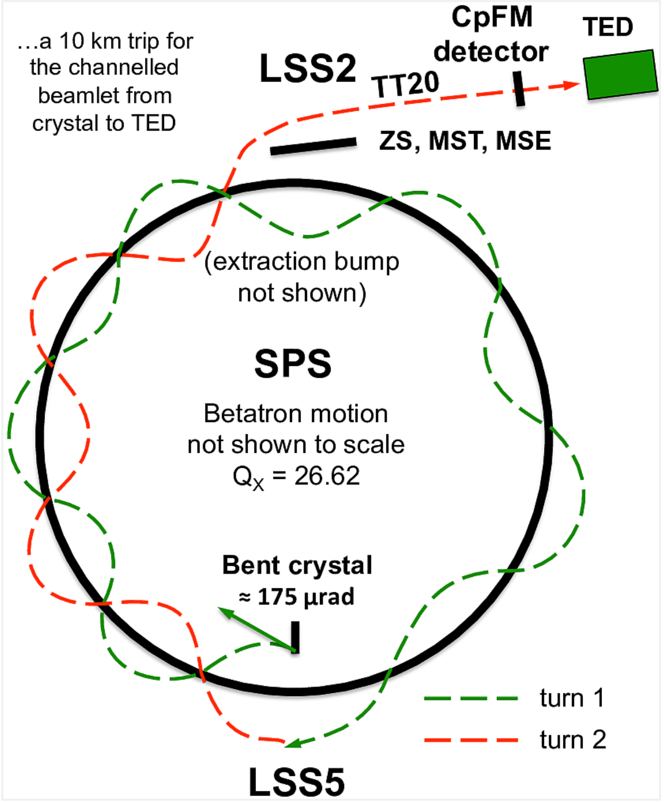
F. Velotti et al., Phys. Rev. Accel. Beams 22, 093502

Beam Extraction – non resonant

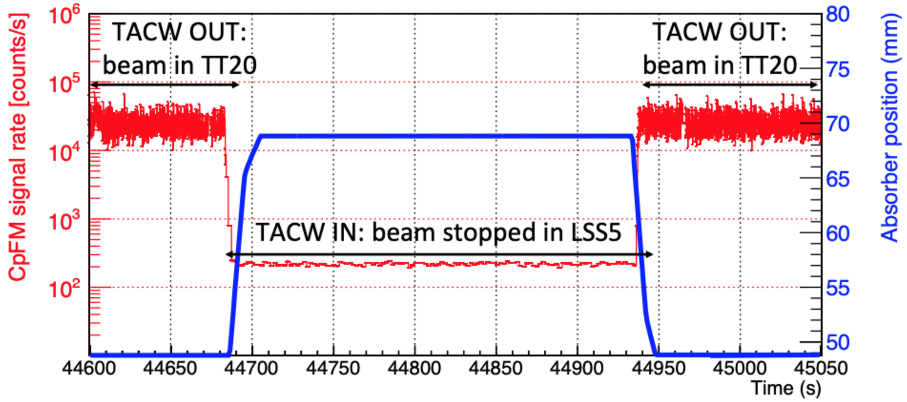
A bent crystal as an extraction device in a circular machine was proven in Russia (currently used at U-70 IHEP)

In 2016, it was tested in SPS with the UA9 infrastructure (goniometers with crystals, absorbers, detectors) in LSS5 + an on-purpose Cherenkov detector (CpFM) down the extraction line TT20

Non-local halo extraction from crystal in LSS5 and + particle diffusion from the beam core enhanced by means of the Transverse Adiabatic Damper (ADT, random transverse kicks)



M. Fraser et al., arXiv:1707.05151 (2017



Double Channeling

Magnetic moment of channeled particles should precess in a bent crystal

$$\Omega_{spin} = \frac{g-2}{2}\gamma\Omega_{crystal}$$

See V.G. Baryshevskii, Pis'ma Zh. Tekh. Fiz.5, 182 (1979) and PLB 757 (2016) 426-9.

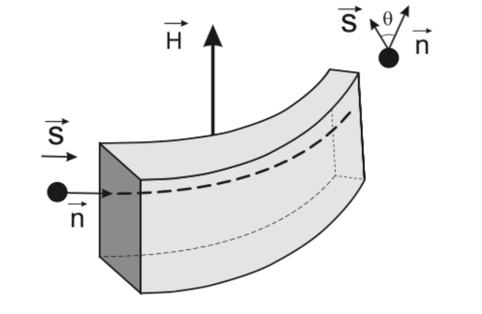
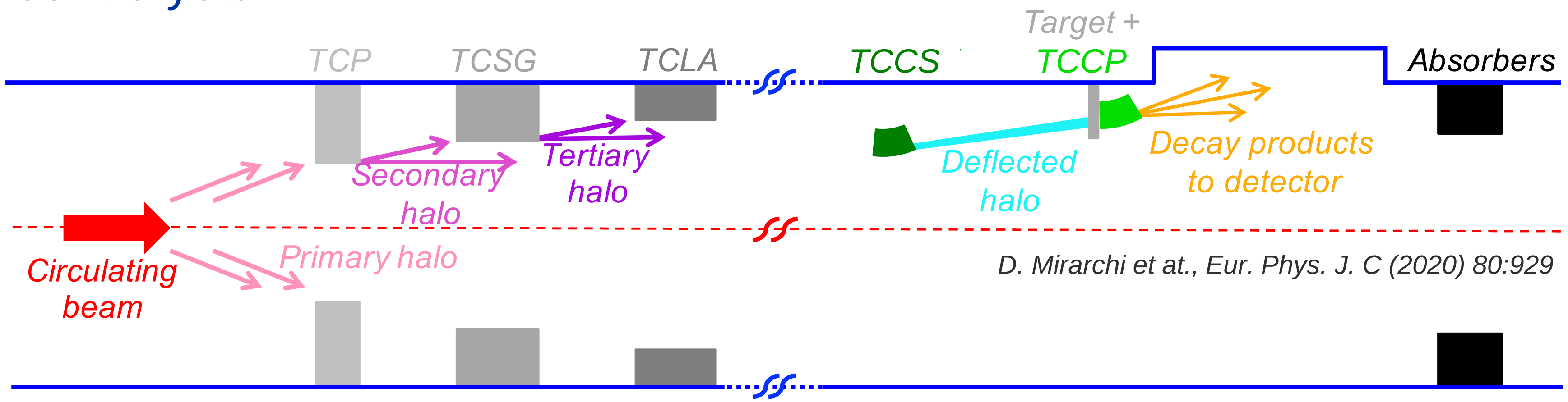


Figure 1. Spin rotation in a bent crystal

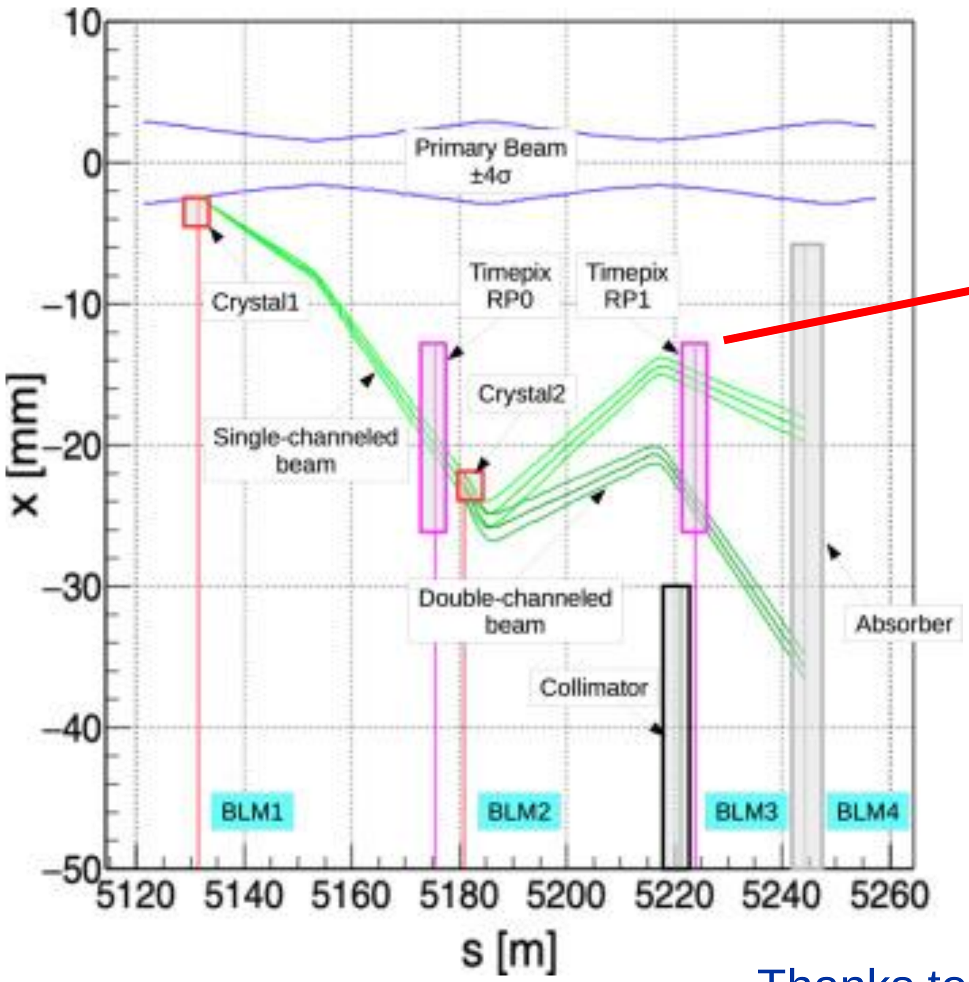
In the framework of future fixed target experiment in LHC a double crystal layout has been proposed to measure magnetic moment precession of short living particles, thanks to the high equivalent magnetic field generated by a bent crystal.

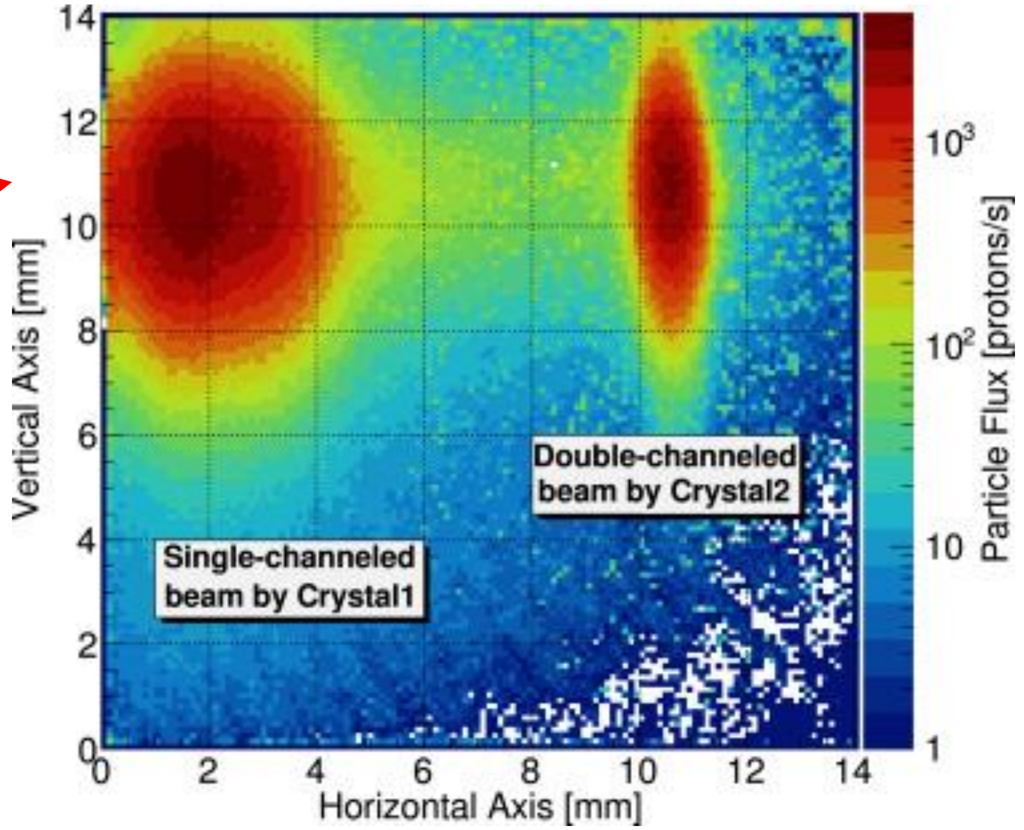


In this scheme:

1. Secondary **halo deflected by a bent crystal** (Target Collimator Crystal Splitting) at larger aperture than TCP, **similar to a LHC crystal for collimation**
2. Deflected **halo impacts on a target**
3. Interaction products **channelled by a second bent crystal** (Target Collimator Crystal Precession), **with a bending angle in the range of 10-20 mrad**
4. Dedicated **absorber** to intercept deflected halo that did not interact with target

UA9 Proof of principle in the SPS LSS5





W. Scandale et al. NIM A Volume 1015, 165747 (2021)

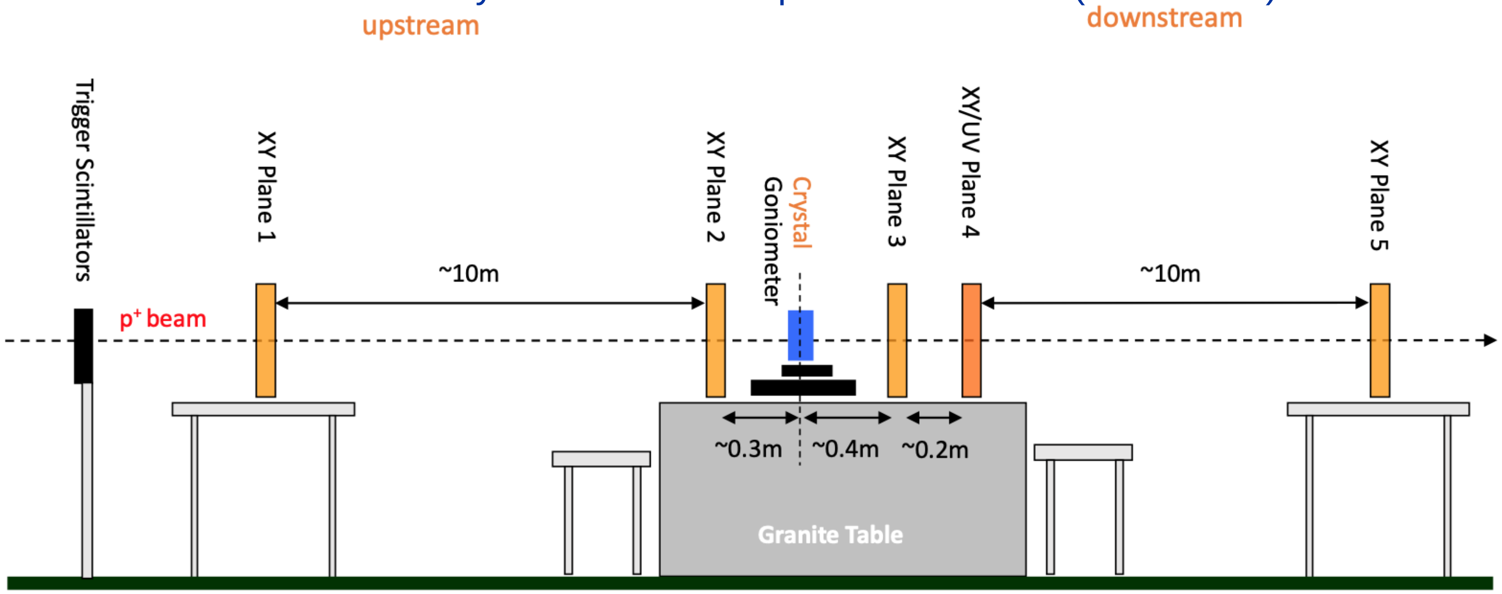
Thanks to TimePix's (Beam Halo Monitor), the online measurement was easier, and the double channeling was comfortably achieved during all the 2018 data

Crystal validation with beam

The tracker telescope is configured to achieve high angular accuracy/precision with long upstream and downstream arms

Observables: efficiency, bending angle, crystal torsion and, possibly also Inelastic Nuclear Interactions

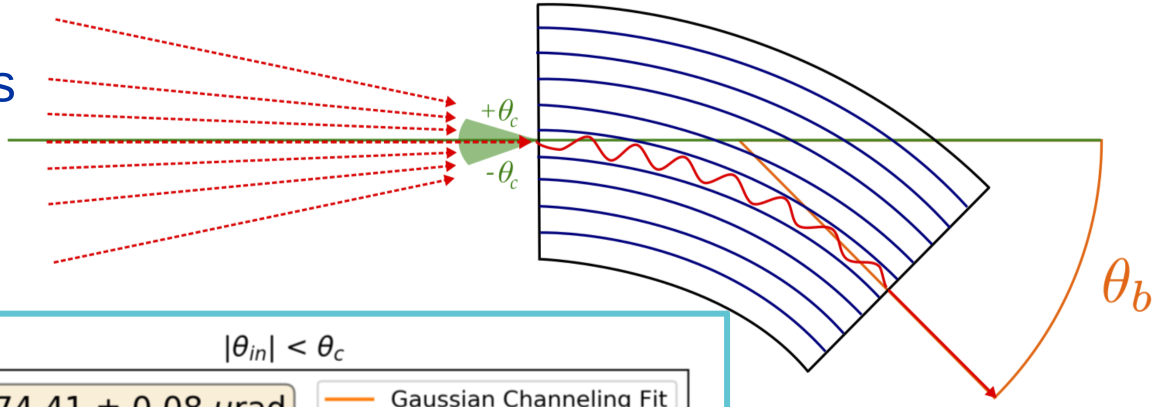
Schematic layout of the telescope installed in H8 (North Area)

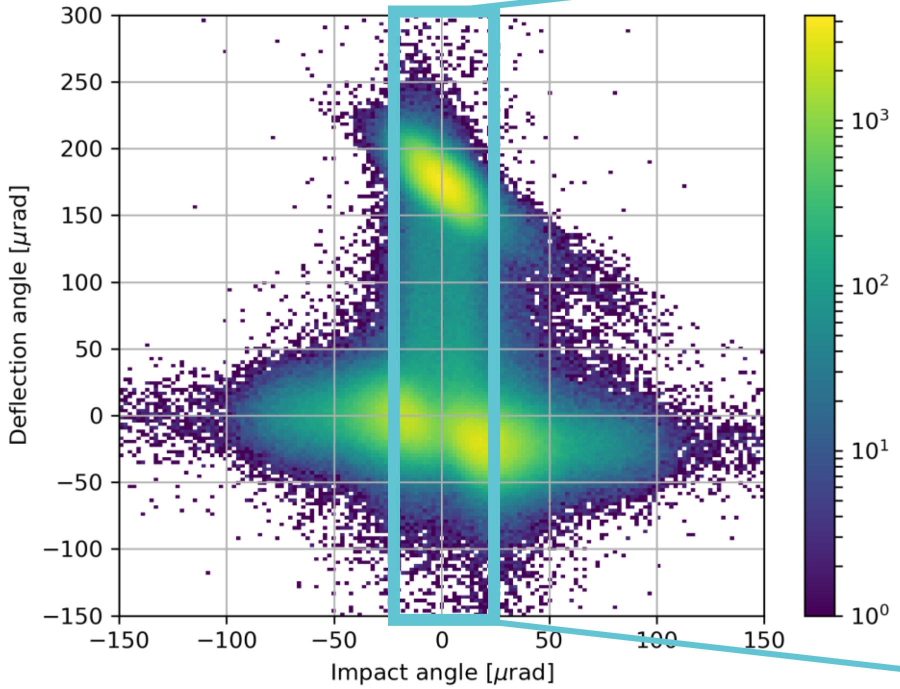


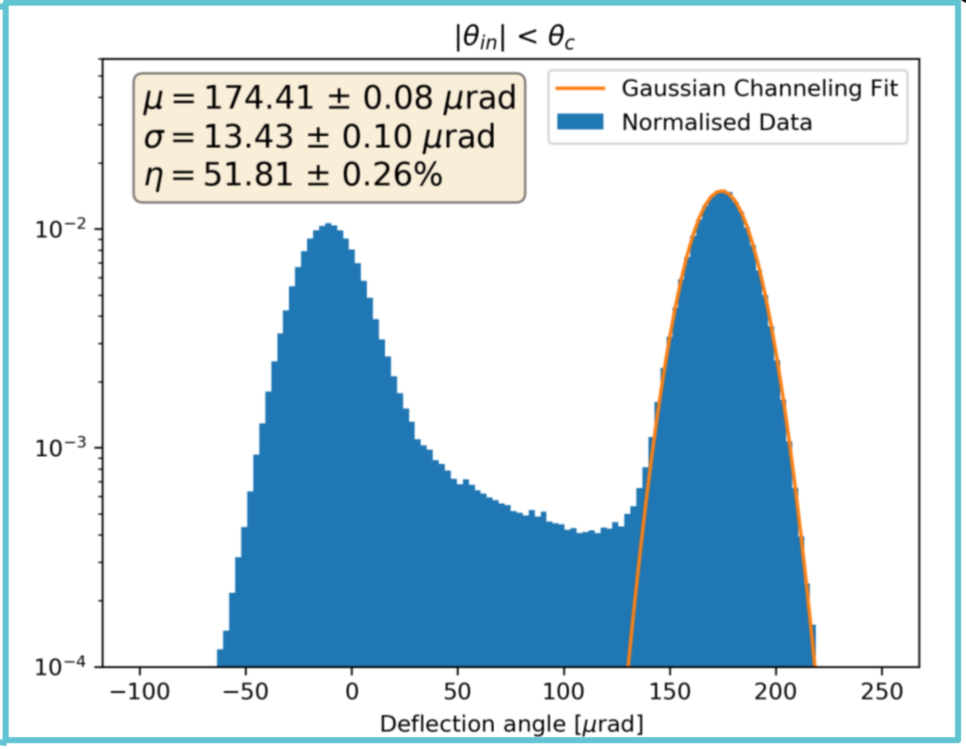
M Pesaresi *et al* 2011 JINST **6** P04006

Analysis – Crystal Efficiency/Bending angle

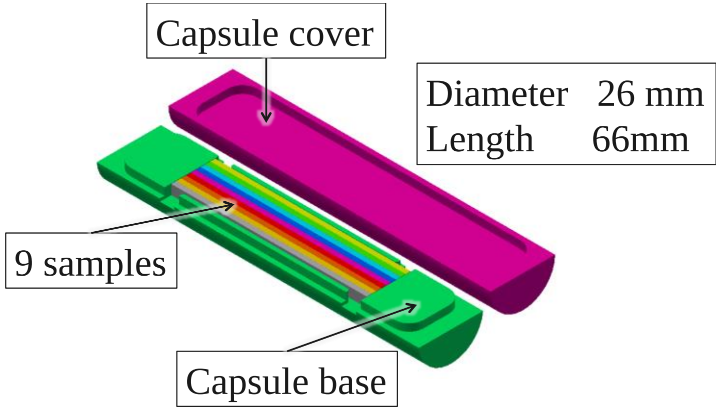
The main goal is to measure the **channeling efficiency** of the crystal, as a function of the particles impact angle.
This value gives information about the crystalline lattice that cannot be measured by optical tests.

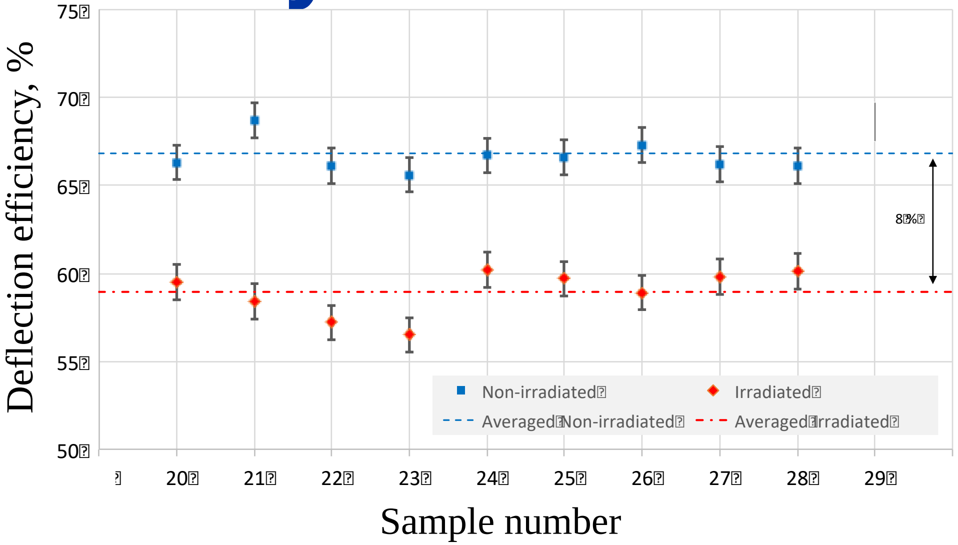






Efficiency/Robustness of irradiated crystals





W. Scandale et al 2021 JINST **16** P08015

9 crystal samples (unbent) have been irradiated with 2.5 x 10^{21} neutrons/cm^2 at SCK-CEN BR2 reactor (Belgium) in 2018 with a neutron spectrum range meV < E < 10 MeV

The crystal samples were tested (bent) before and after the irradiation in the same conditions

On average, a channeling efficiency reduction of ~ 8% was observed after the neutron irradiation (equivalent to several LHC operation years)

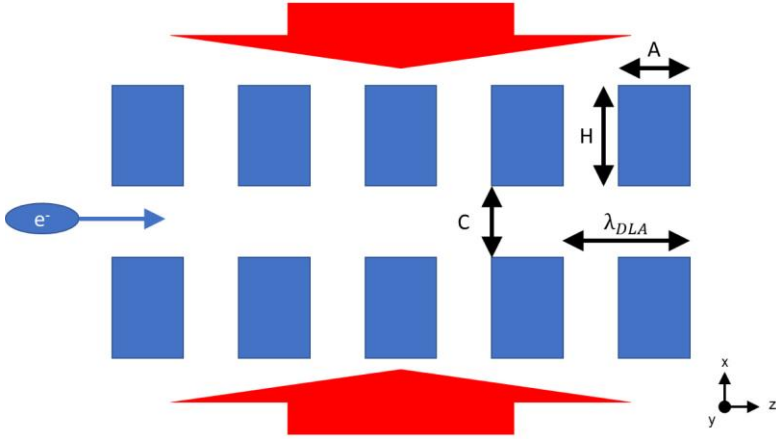
Eur. Phys. J. C 79, 933 (2019))

Fast extraction (ideas for the future)

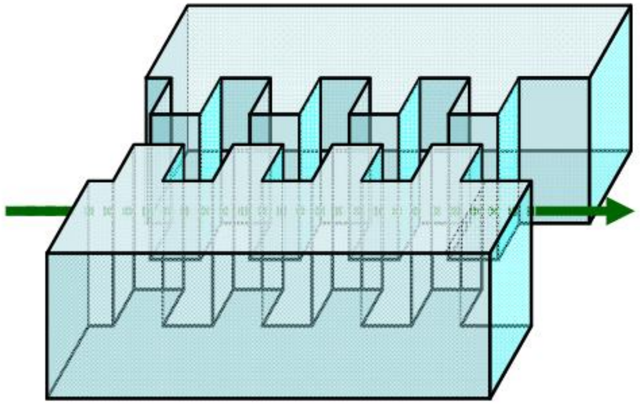
Laser-driven deflection in dielectric structures

A, B

$$\mathbf{E}_1(x,y,z,t) = \begin{pmatrix} E_{x,1} \\ E_{y,1} \\ E_{z,1} \end{pmatrix} \cdot \sin(\omega_0 t + \varphi_{01})$$



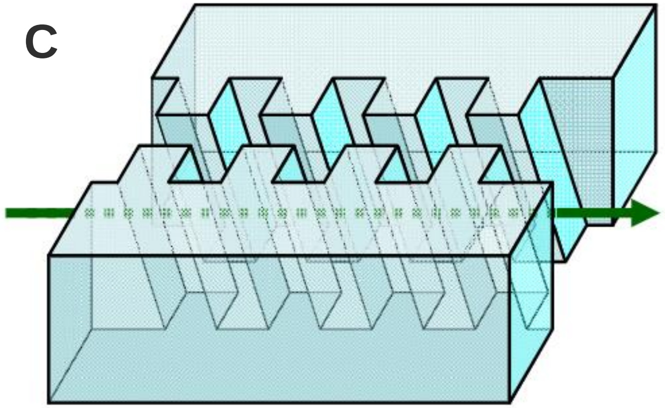
$$\mathbf{E}_2(x,y,z,t) = \begin{pmatrix} E_{x,2} \\ E_{y,2} \\ E_{z,2} \end{pmatrix} \cdot \sin(\omega_0 t + \varphi_{02})$$



$$\left\langle \vec{E}_\perp + \left(\vec{v} \times \vec{B}\right)_\perp \right\rangle = 0$$

$$\left\langle \vec{E}_\parallel \right\rangle \sim \tfrac{1}{2} E_{laser} \to \sim 4\ \mathrm{GeV/m}$$

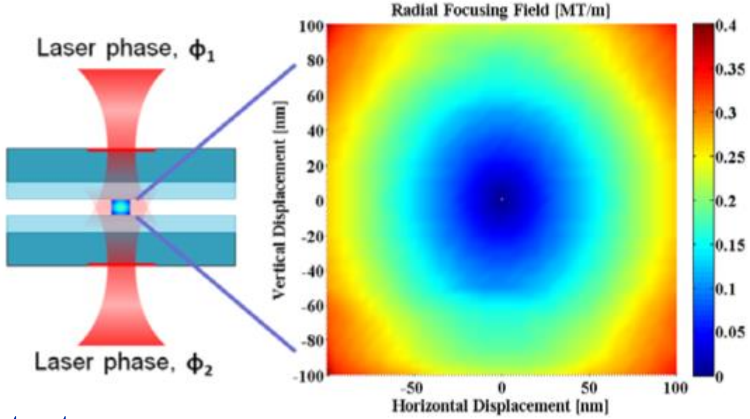
C



$$\left\langle \vec{E}_\perp + \left(\vec{v} \times \vec{B}\right)_\perp \right\rangle \neq 0$$

$$\left\langle \vec{F}_\perp / q \right\rangle \sim \tfrac{1}{5} E_{laser} \to \sim 2\ \mathrm{GeV/m}$$

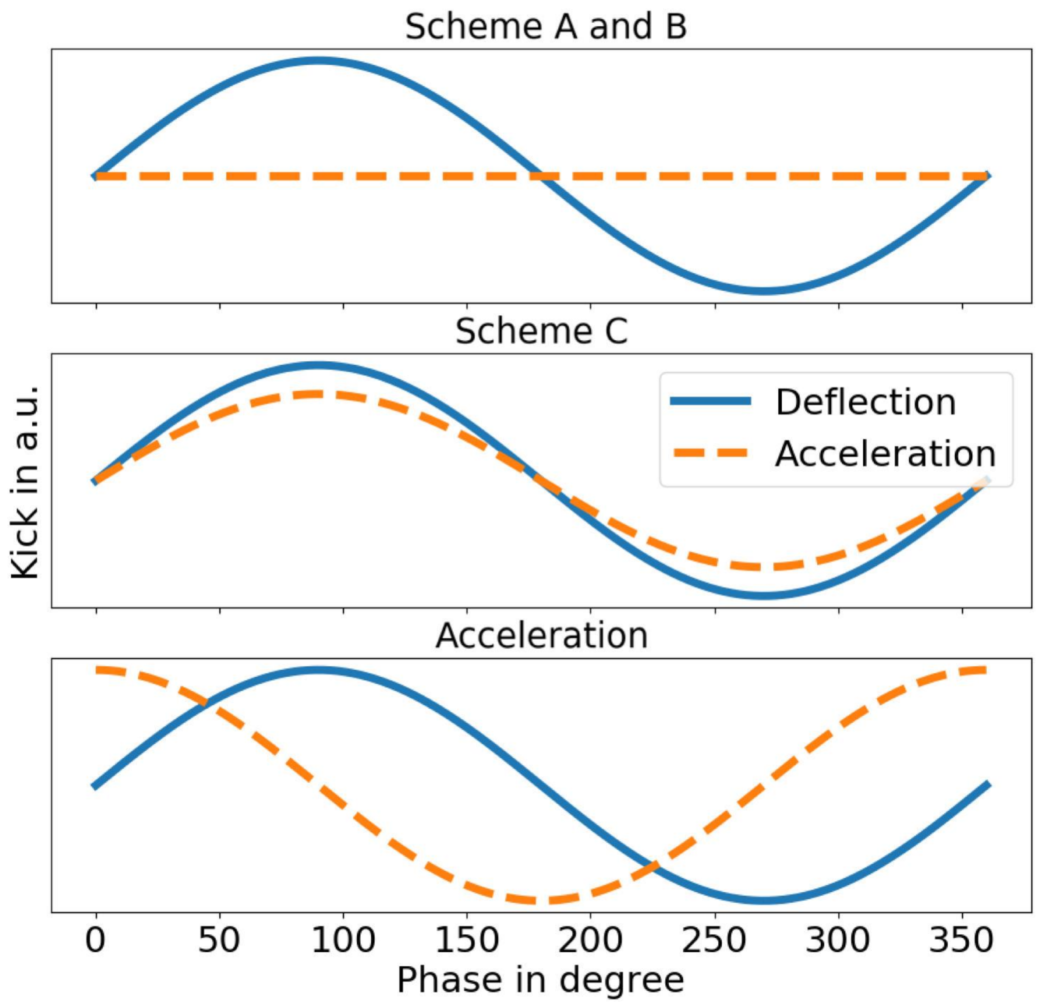
Key idea: **Introduce phase shift for incident driving lasers or tilted grating**



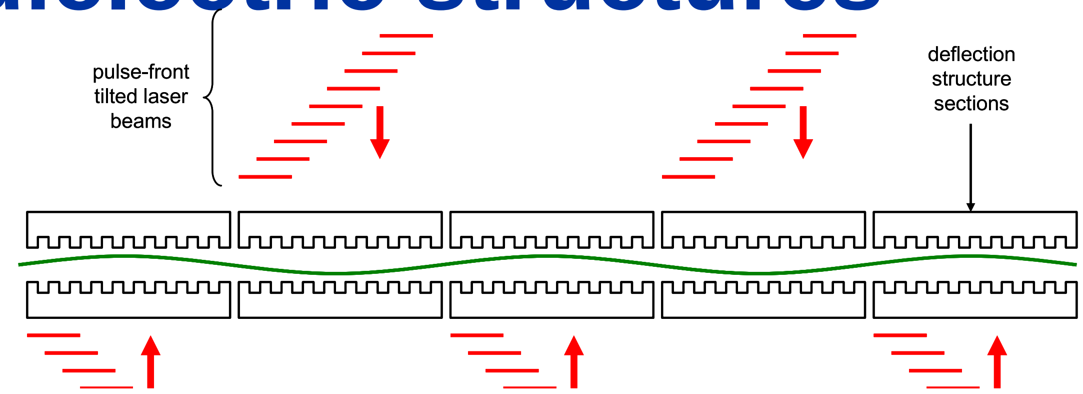
	$\Delta\phi = 0^\circ$	$\Delta\phi = 180^\circ$
TM	Focusing	Vertical Def.
TE	Horiz. Def.	No Effect

T. Plettner et. al. Photonic-based laser driven electron beam deflection and focusing structures
K. Soong et. al. Grating-Based Deflecting, Focusing, and Diagnostic Dielectric Laser Accelerator Structures

Laser-driven deflection in dielectric structures



W. Kuropka et. al. "Simulation of deflecting structures for dielectric laser driven accelerators"



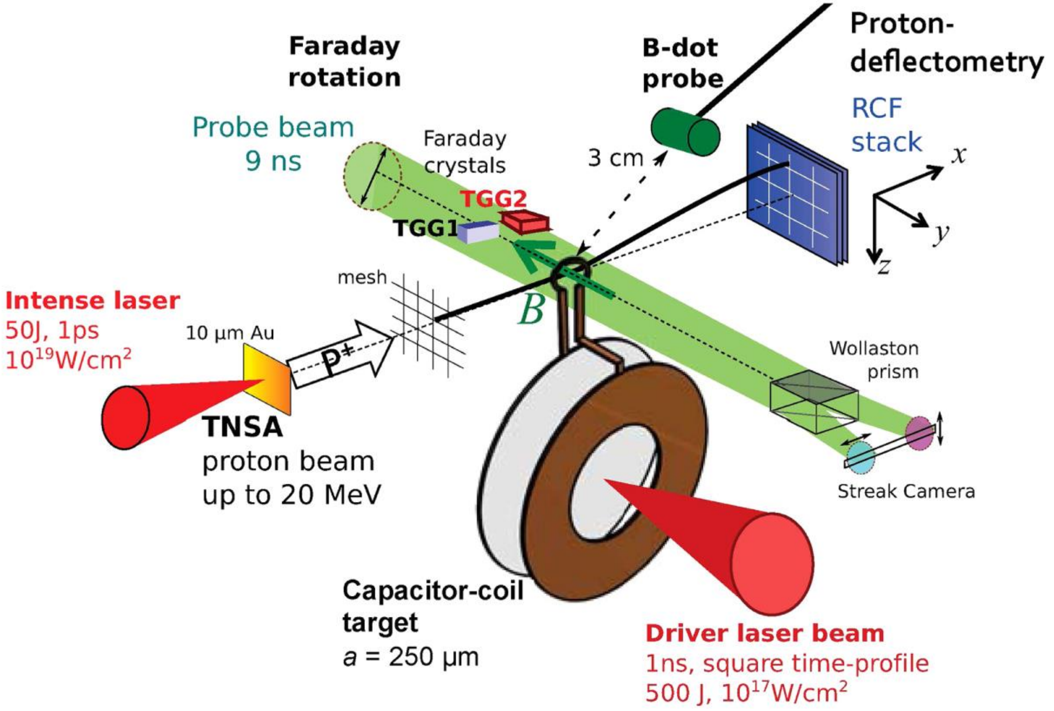
Field parameter	Accelerator	Scheme A	Scheme B
$E_{x,1}$	0	0	0
$E_{y,1}$	0	$E(x,y,z,t)$	0
$E_{z,1}$	$E(x,y,z,t)$	0	$E(x,y,z,t)$
$E_{x,2}$	0	0	0
$E_{y,2}$	0	$E(x,y,z,t)$	0
$E_{z,2}$	$E(x,y,z,t)$	0	$E(x,y,z,t)$
$\phi_{01} - \phi_{01}$	0	0	180°

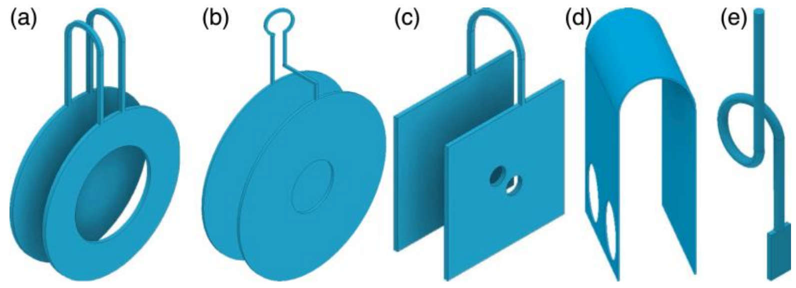
Scheme	A	B	C	Acceleration
Maximum deflection	4 μrad	20 μrad	34 μrad	0.5 μrad
Deflection plane	Unlimited	Limited	Unlimited	Focusing

Strong magnetic fields from laser driven capacitor-coil target

Impressive idea from astrophysics

- **Laser creates plasma discharge after interaction with the front capacitor plane**
- **Created current creates short pulse magnetic field of ~kT order**
- **Properties depend on laser pulse structure and material of the coil and capacitor**





Laser parameters			
Power: 500 J	τ - 1 ns	λ -1.06 μm	Intensity ~ 10^{17} W/cm^2

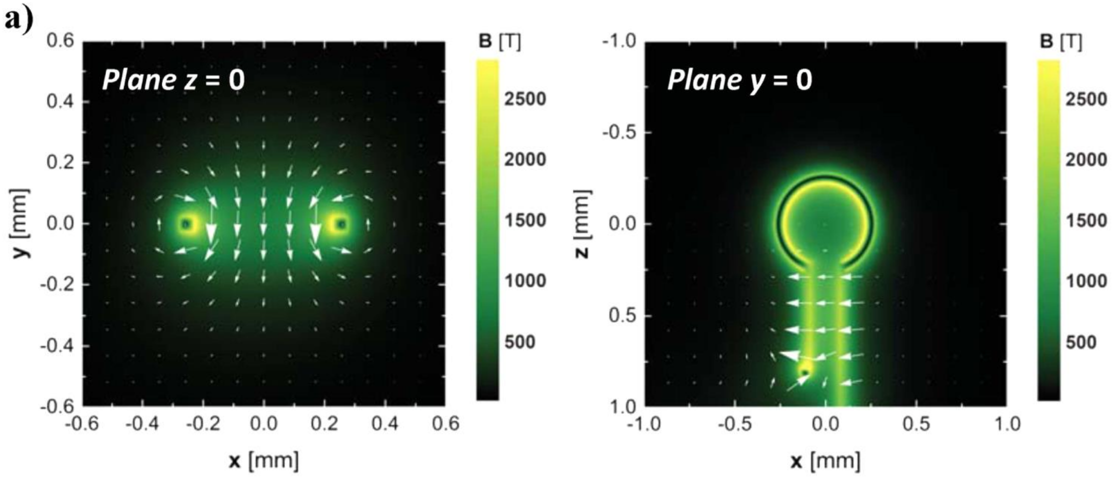
J.J. Santos Physics of Plasmas **25**, 056705 (2018)

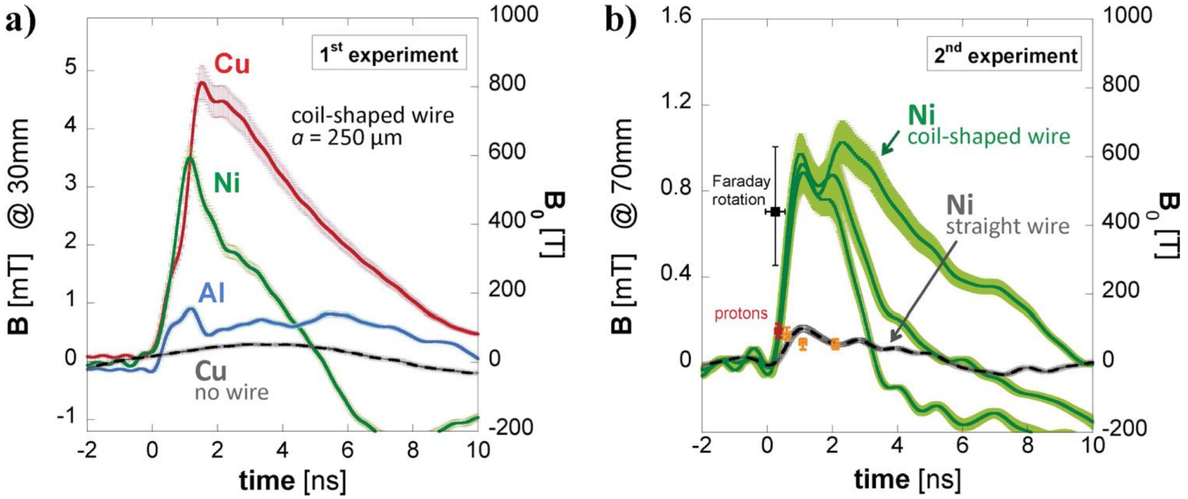
Strong magnetic fields from laser driven capacitor-coil target

- Indirect estimations of the field were performed utilizing three independent approaches

- The first method relies on B-dot probe field measurements at ~4 cm distance from the coil

- Faraday rotation of the direction of polarization of an optical probe laser through field-sensitive crystals

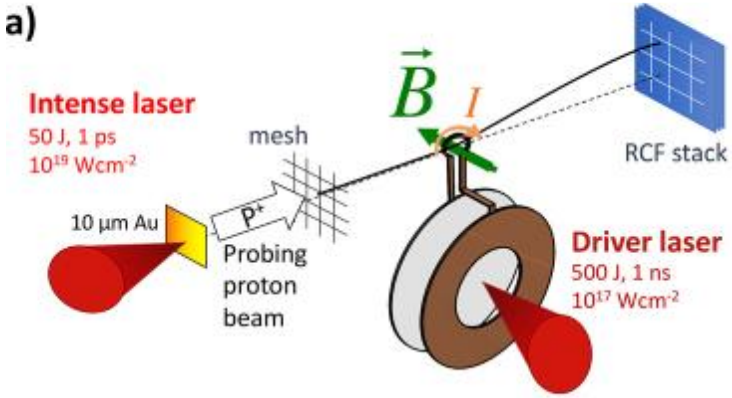


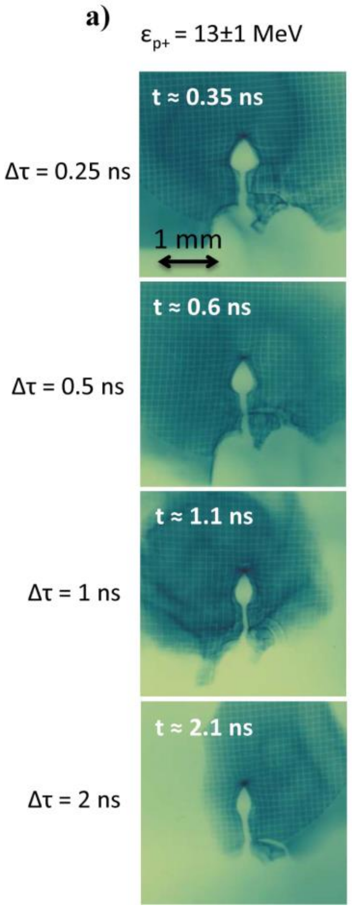


Field probing with the proton beam

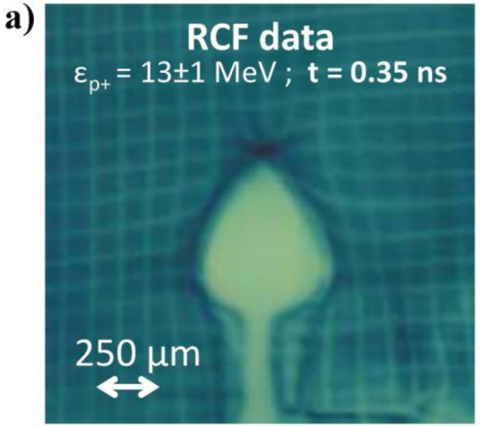
- Another method of indirect measurements of the B-field at the coil center were possible by proton beam deflectometry.

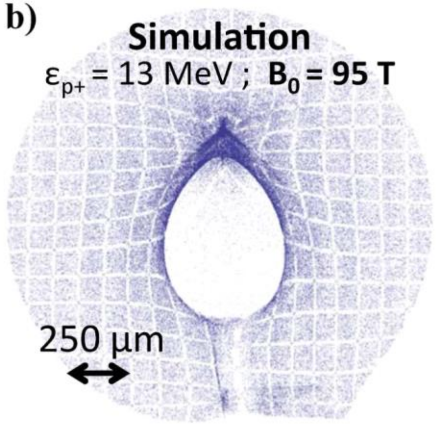
- The probing proton beam was accelerated by an intense laser pulse interacting with a backlighter foil target.





- Field value reconstructed from PIC tracking simulations on base of estimated 3D field maps and via plasma simulations in EPOCH.





Summary

Nowadays, bent crystals are deemed as a reliable technology for various applications in charged beam manipulation. But we still need to master the technology from wafer procurement to assembly design and final validation for CERN future projects.

Slow extraction using multi-stage crystal setup still requires improvement of channeling efficiency.

Several proposals of fast deflectors for high energy particles are on the table, but they were not studied in detail or applied for bunch extraction purposes home.cern