CRYSTAL CHANNELING STUDIES AT MODERN ACCELERATOR FACILITIES

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Istituto Nazionale di Fisica Nucleare

AARP @ Beams Channeling
15th November 2022

Outlook

- Channeling in bent crystals
  - Hadron beam collimation and extraction
  - Spin precession
  - Electron and positron beam extraction
- Channeling radiation of electrons and positrons
  - Intense X- and γ-beam sources
  - Positron source for future electron positron colliders
- Strong Crystalline Field
  - Ultra-compact detectors for the energy and the intensity frontiers
- Summary and Conclusions

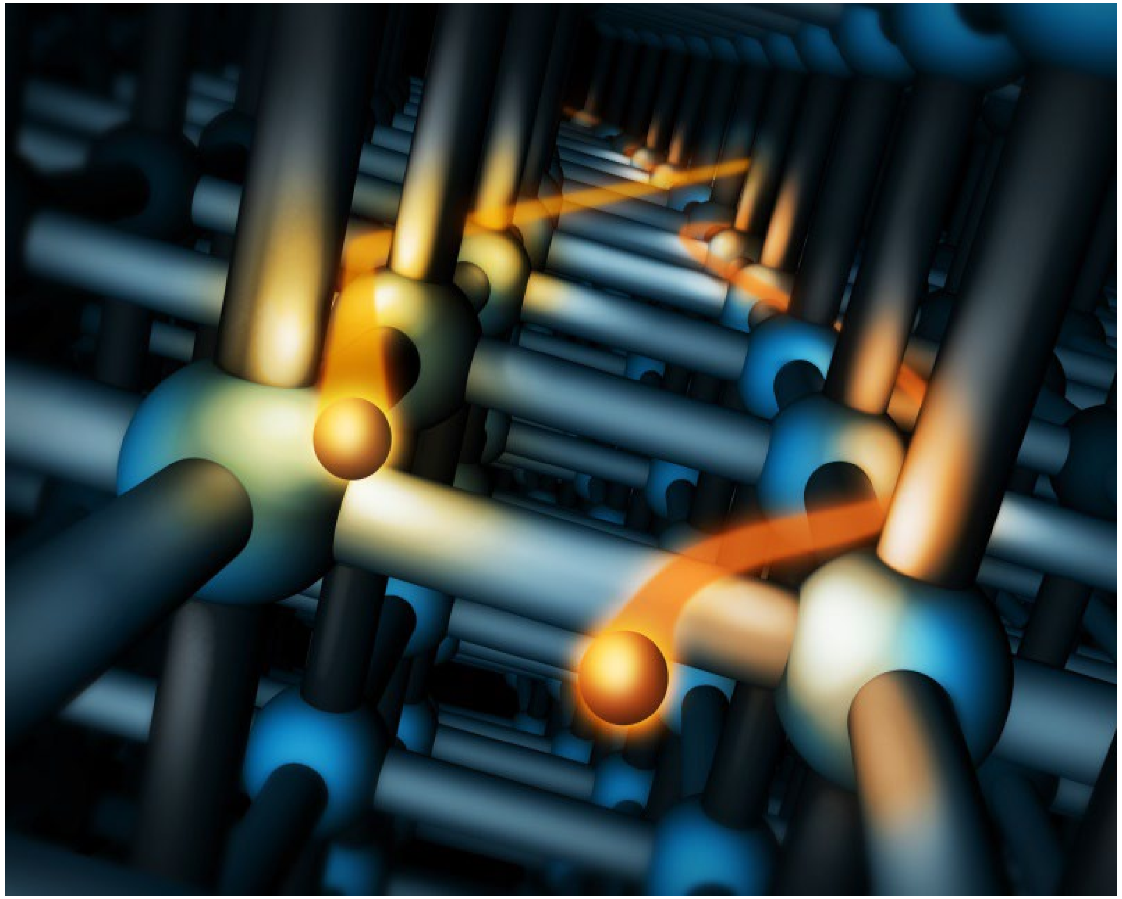


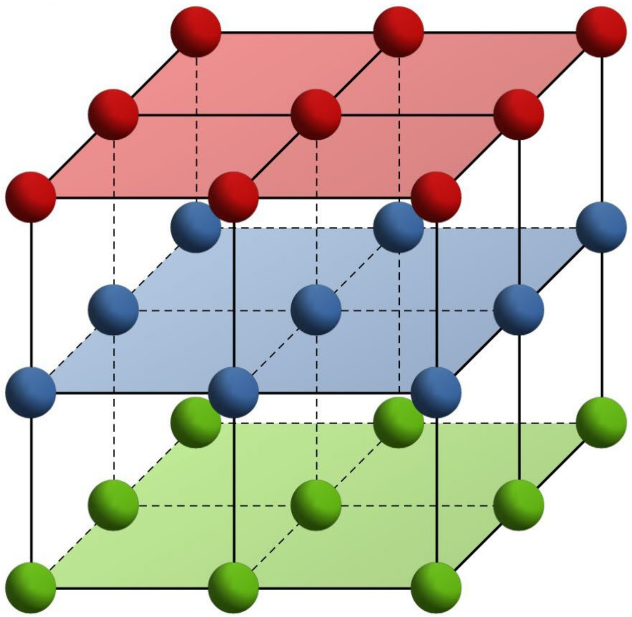
Image from https://www6.slac.stanford.edu/news/2015-02-25-slac-led-research-team-bends-highly-energetic-electron-beam-crystal.aspx

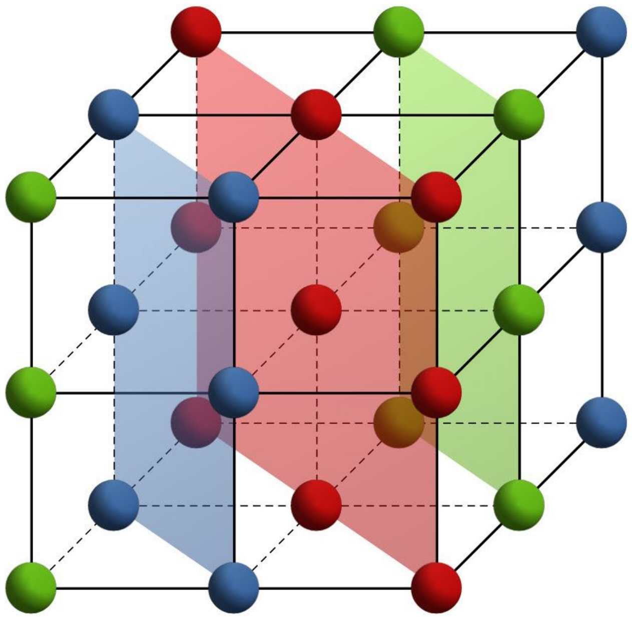
INTRODUCTION

Coherent interactions of charged particle beams in oriented crystals

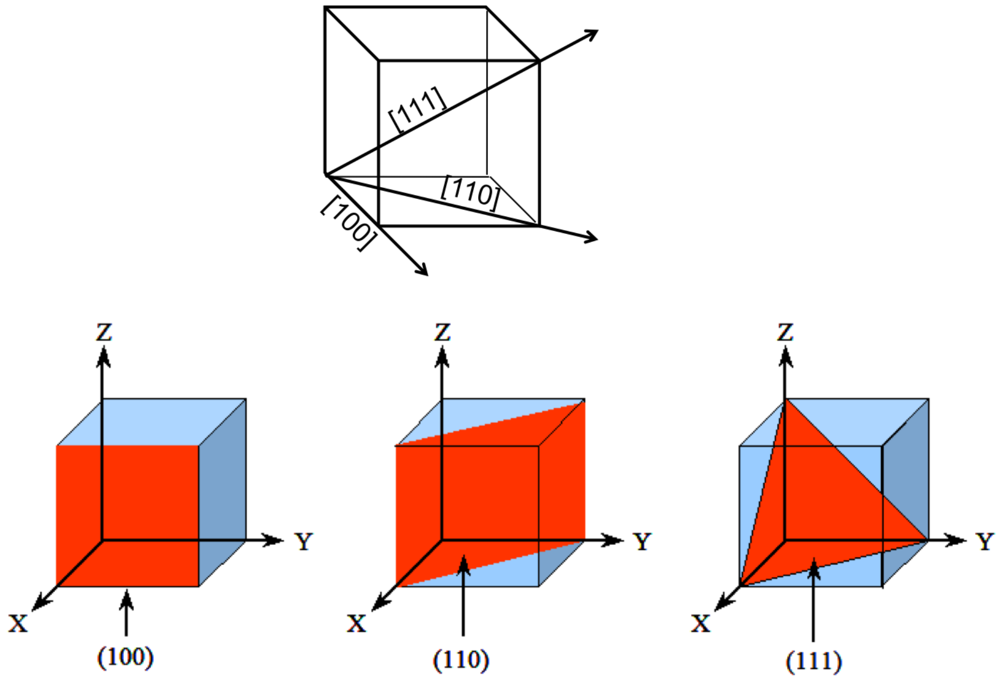
Crystalline solids

A crystal is a solid structure consisting of atoms, molecules or ions having a geometrically regular arrangement, which is repeated indefinitely in the three spatial dimensions, called the **crystal lattice**.

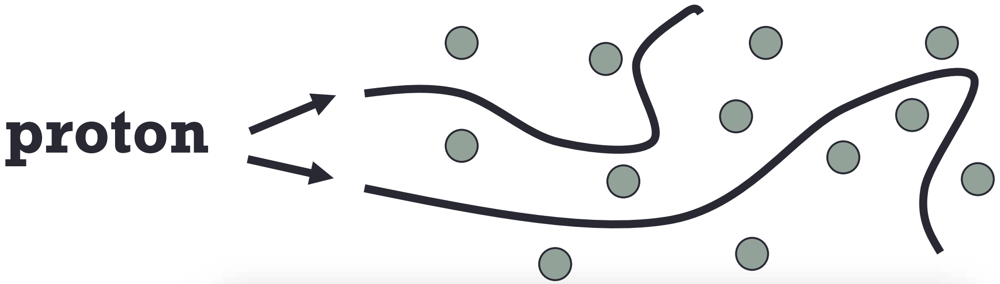


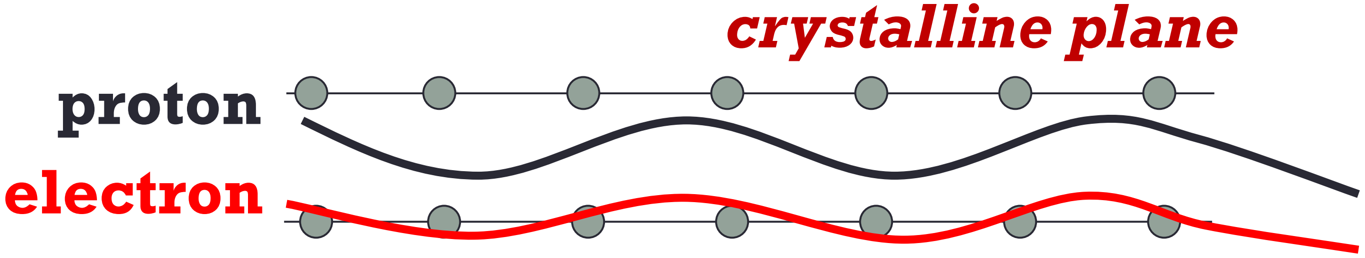


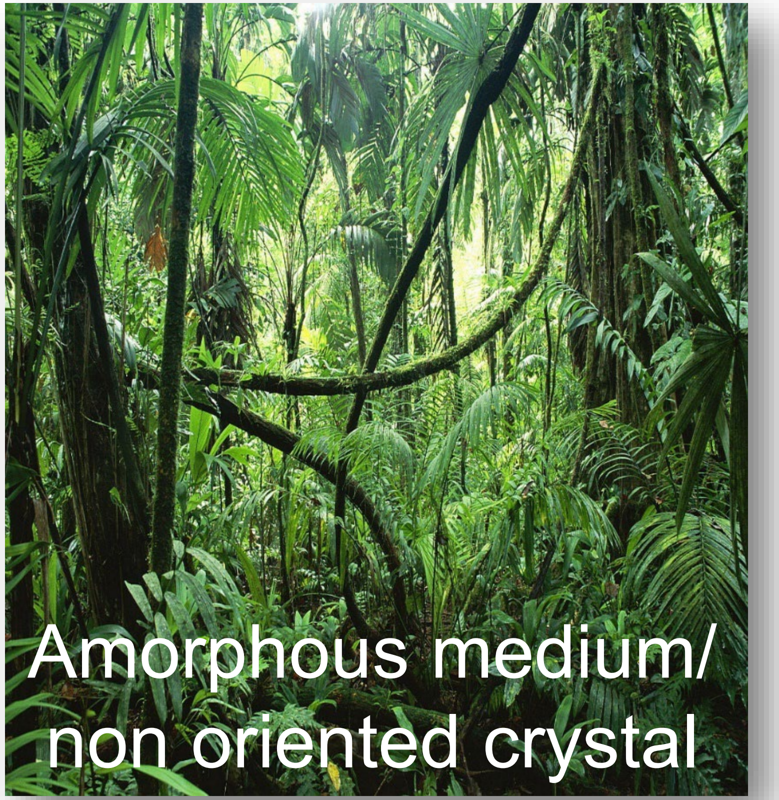
Simmetry: Axes and planes



Channeling


proton


crystalline plane
proton
electron


Amorphous medium/
non oriented crystal


Oriented crystal

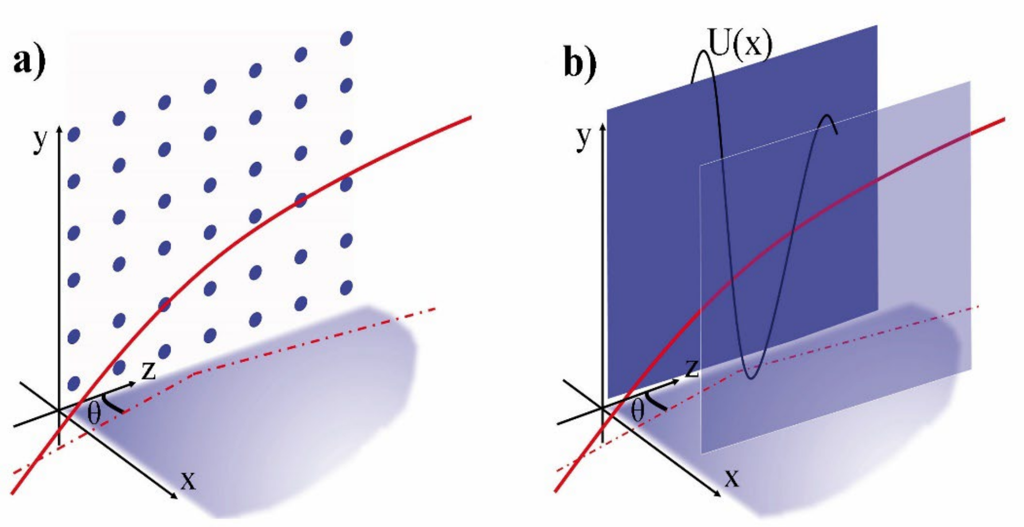
Planar Channeling and Continuous Average Potential

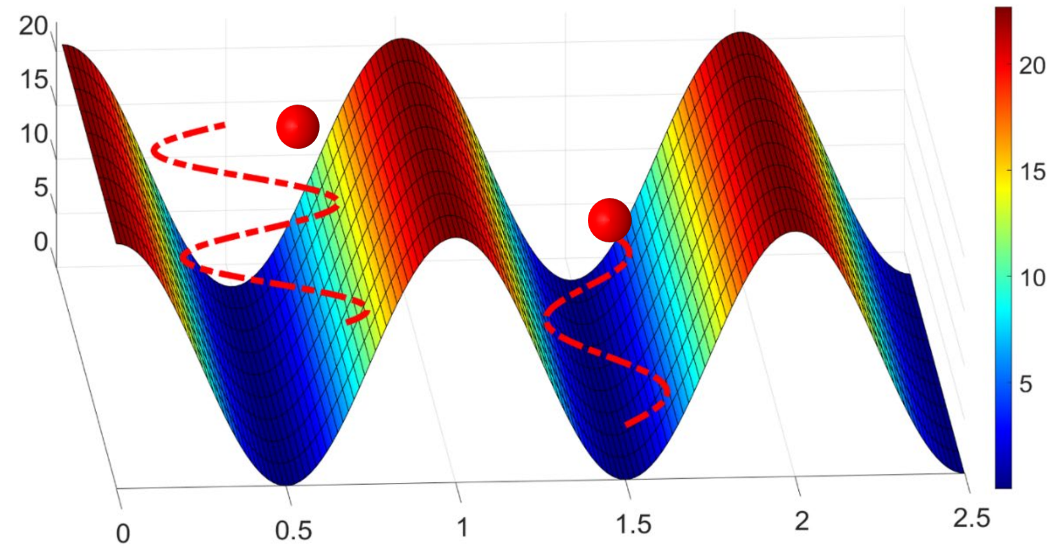
$$U_{pl}(x) = N d_p \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V(x, y, z)\, dy\, dz$$

where

$$V_{TF}(r) = \frac{Z_i Z e^2}{r} \Phi\left(\frac{r}{a_{TF}}\right)$$

is the particle-atom screened Coulomb potential





J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 34 (1965) 14.

Critical angle for channeling:

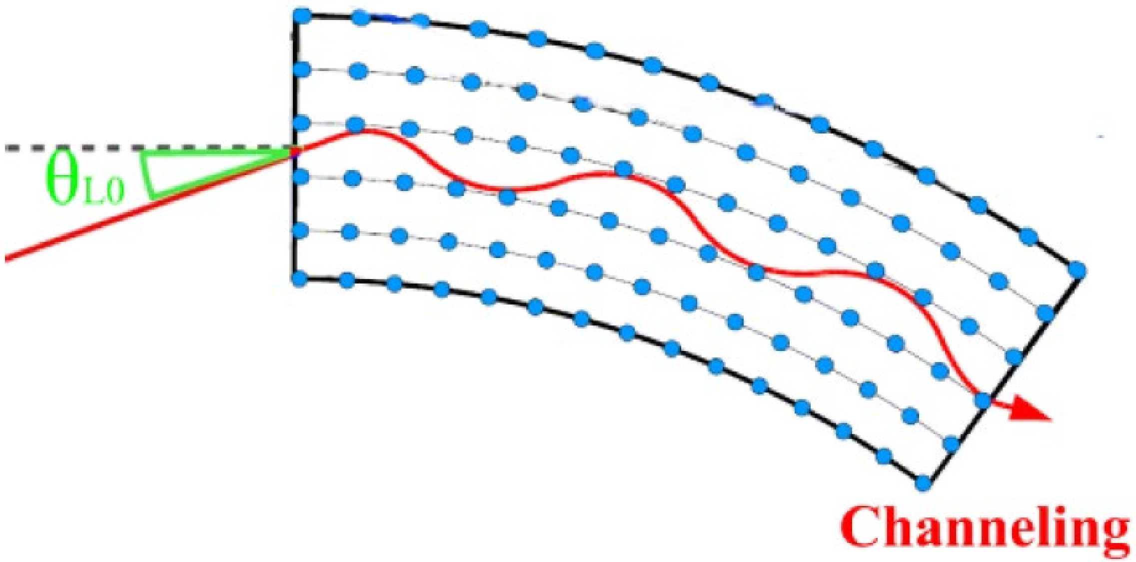
$$\theta_c = \sqrt{\frac{2U_0}{pv}}$$

max of U(x)

momentum*velocity

U_0 = *22.7* eV for Si (110)
$\theta_C \approx$ 200 μ*rad* at *E* ~ *1* GeV
$\theta_C \approx$ 2 μ*rad* at *E* ~ *7* TeV

Channeling in a bent crystal



E. Tsyganov, 1976

Channeling of a charged particle beam in a bent crystal results in steering of its trajectory

⬇

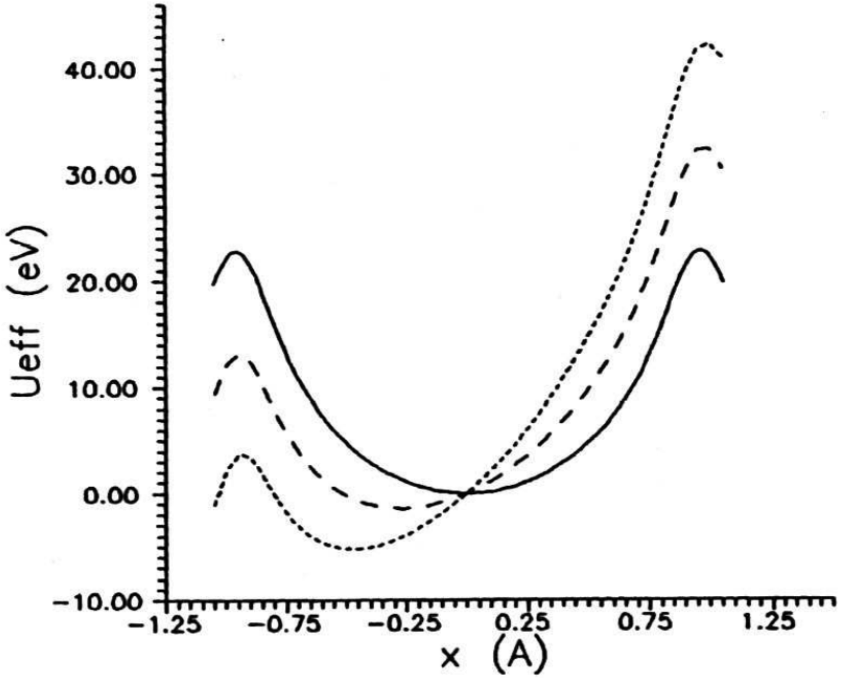
Bent crystals can be used in particle accelerators as elements for collimation or extraction

Channeling in a bent crystal

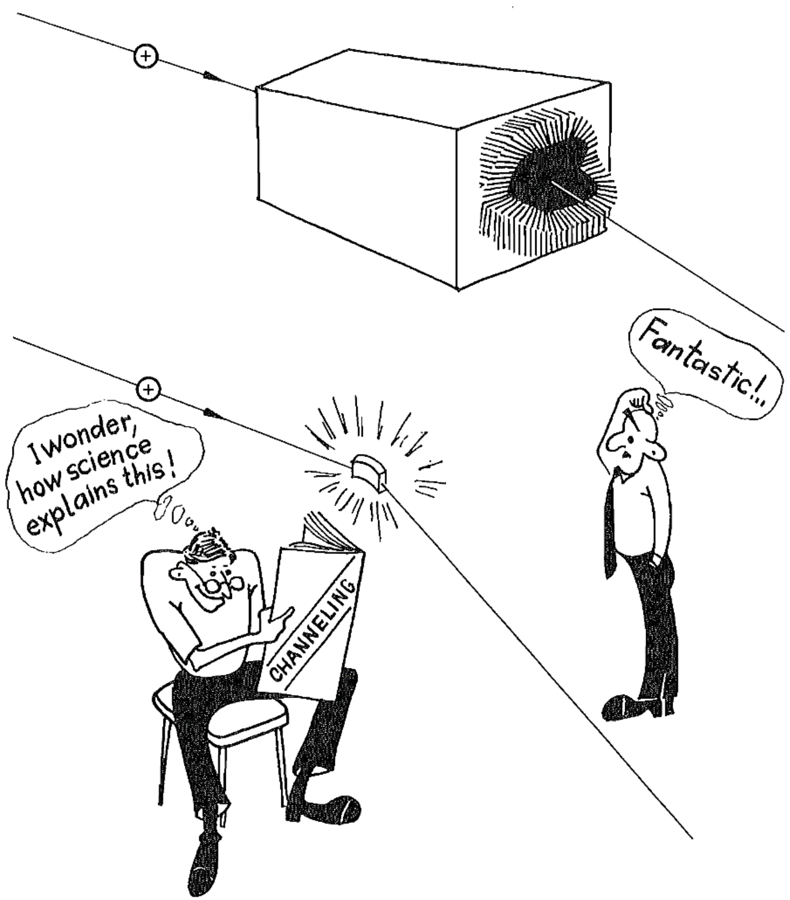
- Bending the crystal lattice planes is equivalent to adding a centrifugal force
  - Curvature radius *R*

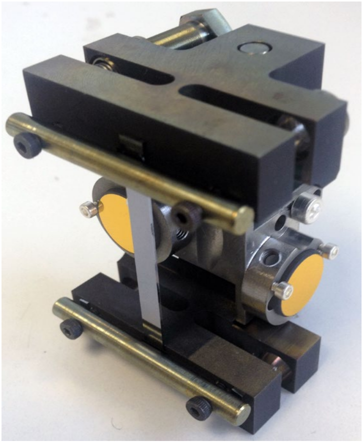
$$U_{eff}(x) = U(x) + \frac{pv}{R}x$$

- Particles can be trapped in channeling and bent!
- Like in a **magnetic** field



Bent crystals to steer ultrarelativisitc particle beams





Bent Si crystal – 4 mm long

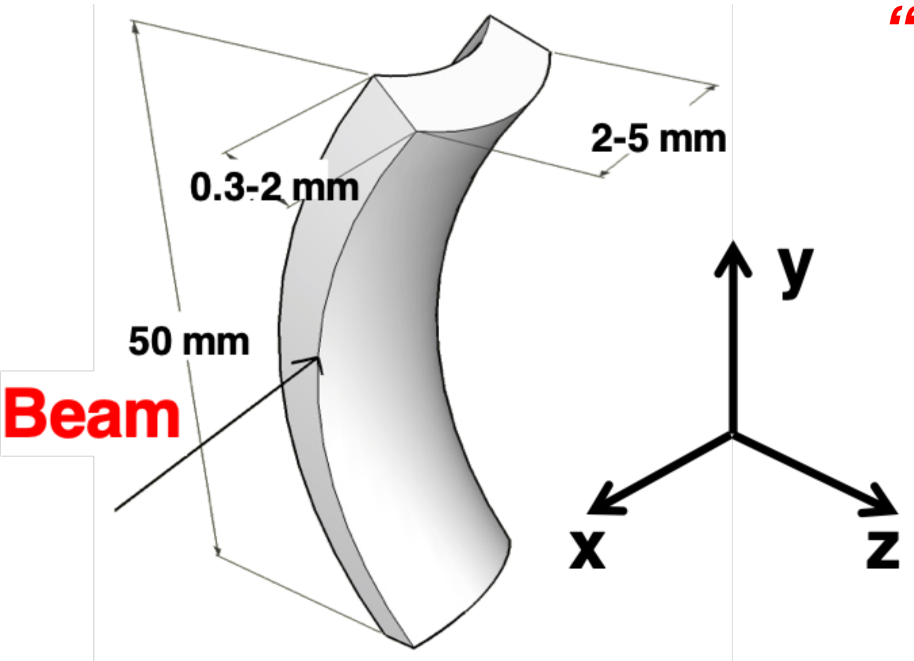
A 50 μrad at 6.5 TeV is equivalent to a 300 T dipole magnet bending!!!

V.S.

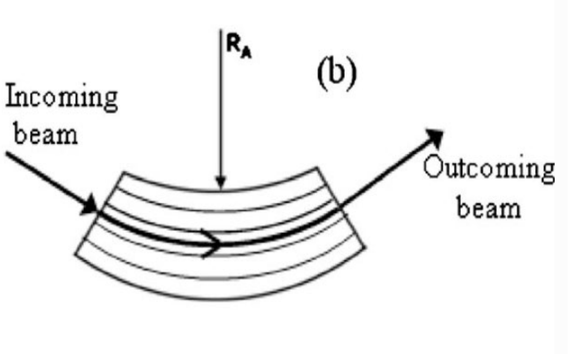
8.3 Tesla supermagnet – 15 m long

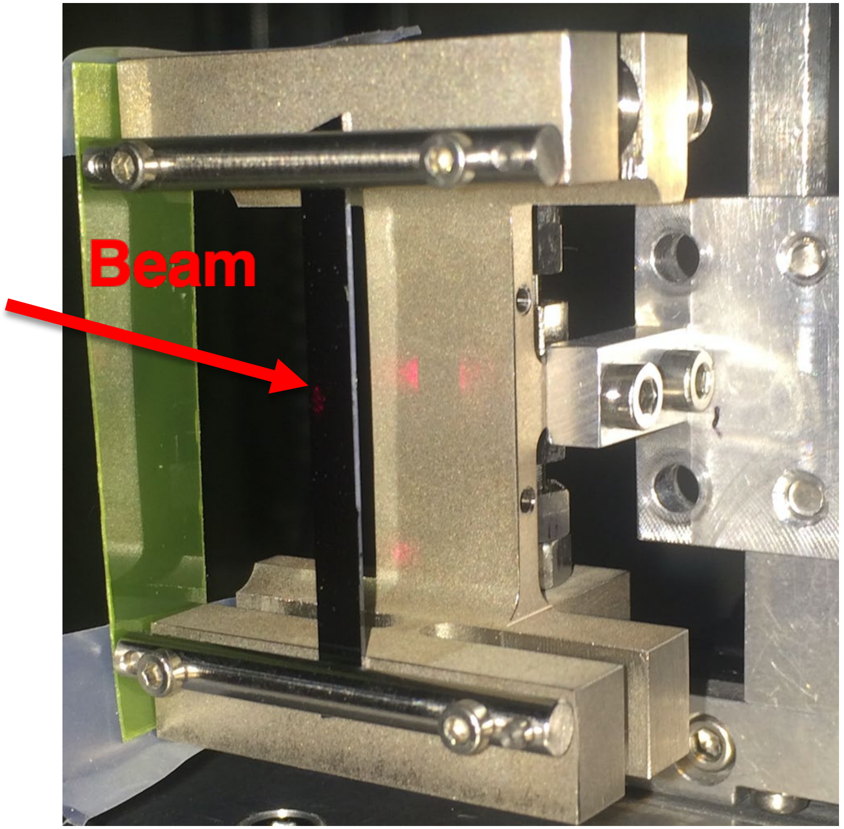
Elective applications in crystal assisted beam collimation and extraction

A bent crystal



"strip-like" crystal





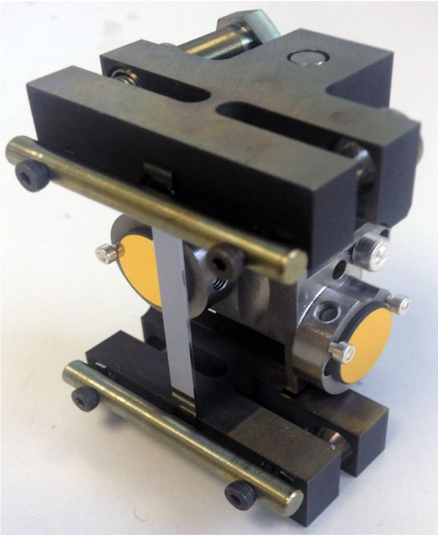
Also

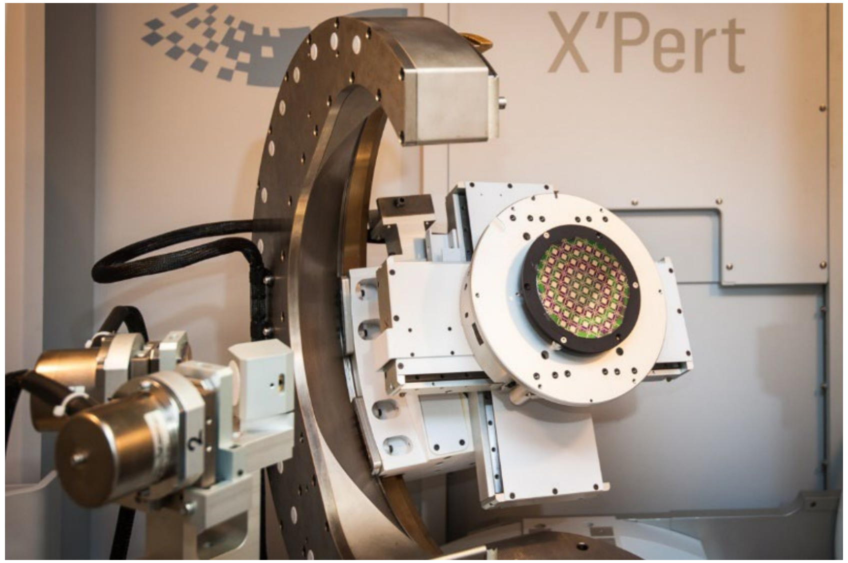
- Primary curvature imparted by a mechanical (Ti or Al) holder
- Secondary curvature (**anti-clastic** reaction) useful for beam steering

Bent Crystal Manufacturing and Characterization @Ferrara lab

Silicon or germanium bent crystals made by revisiting micro and nanoelectronics techniques.

- Photolithographic techniques
- Anisotropic chemical attacks
- Mechanical processes (owner)





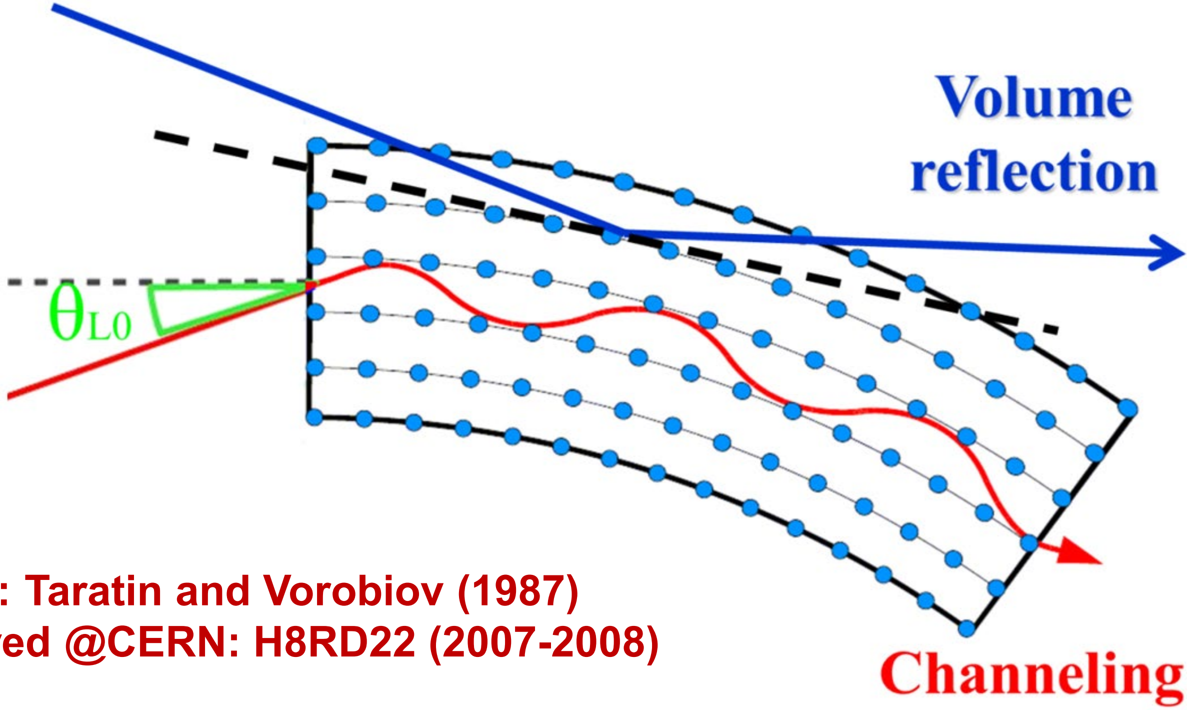
X-ray Diffraction: direct observation of the crystal planes by means of a high resolution difractometer

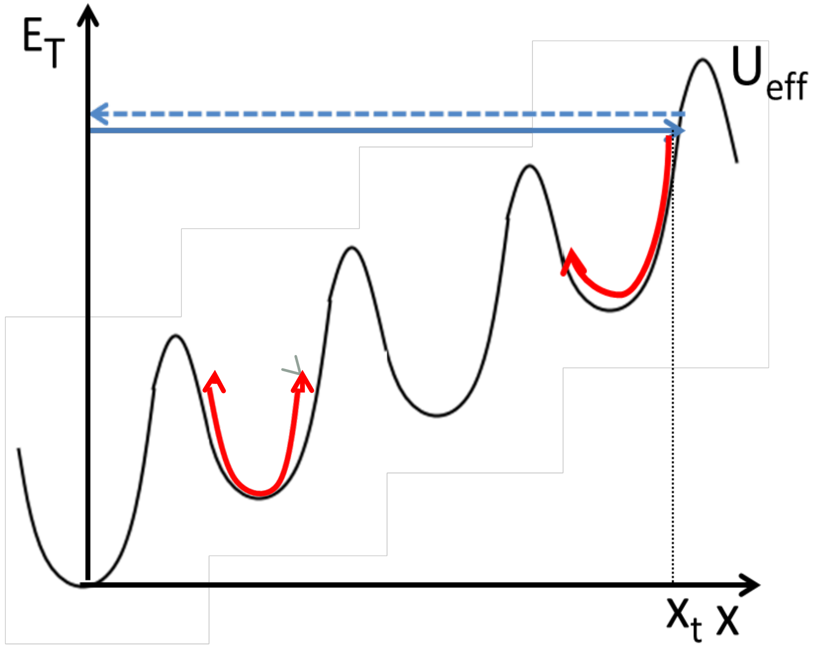
Optical Interferometry: profile analysis of the physical surface of the sample with vertical precision ~ 1 nm

Volume Reflection in a bent crystal

- If crystal is bent, over-barrier particles can be deflected in a direction opposite to crystal bending;
- Angular acceptance equal to the crystal bending angle;
- Deflection angle of the order of the critical angle.

$$U_{eff}(x) = U(x) + \frac{pv}{R}x$$





Theory: Taratin and Vorobiov (1987)
Observed @CERN: H8RD22 (2007-2008)

Coherent interactions in a bent crystal

H8RD22 collaboration

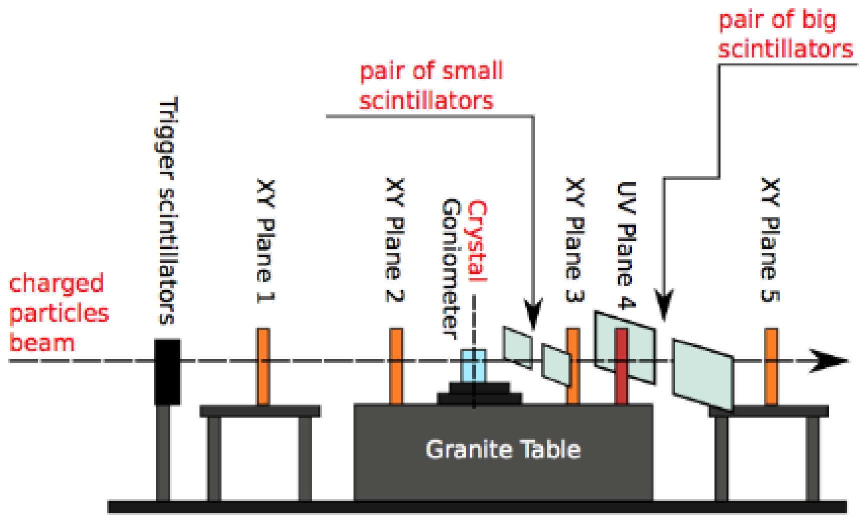
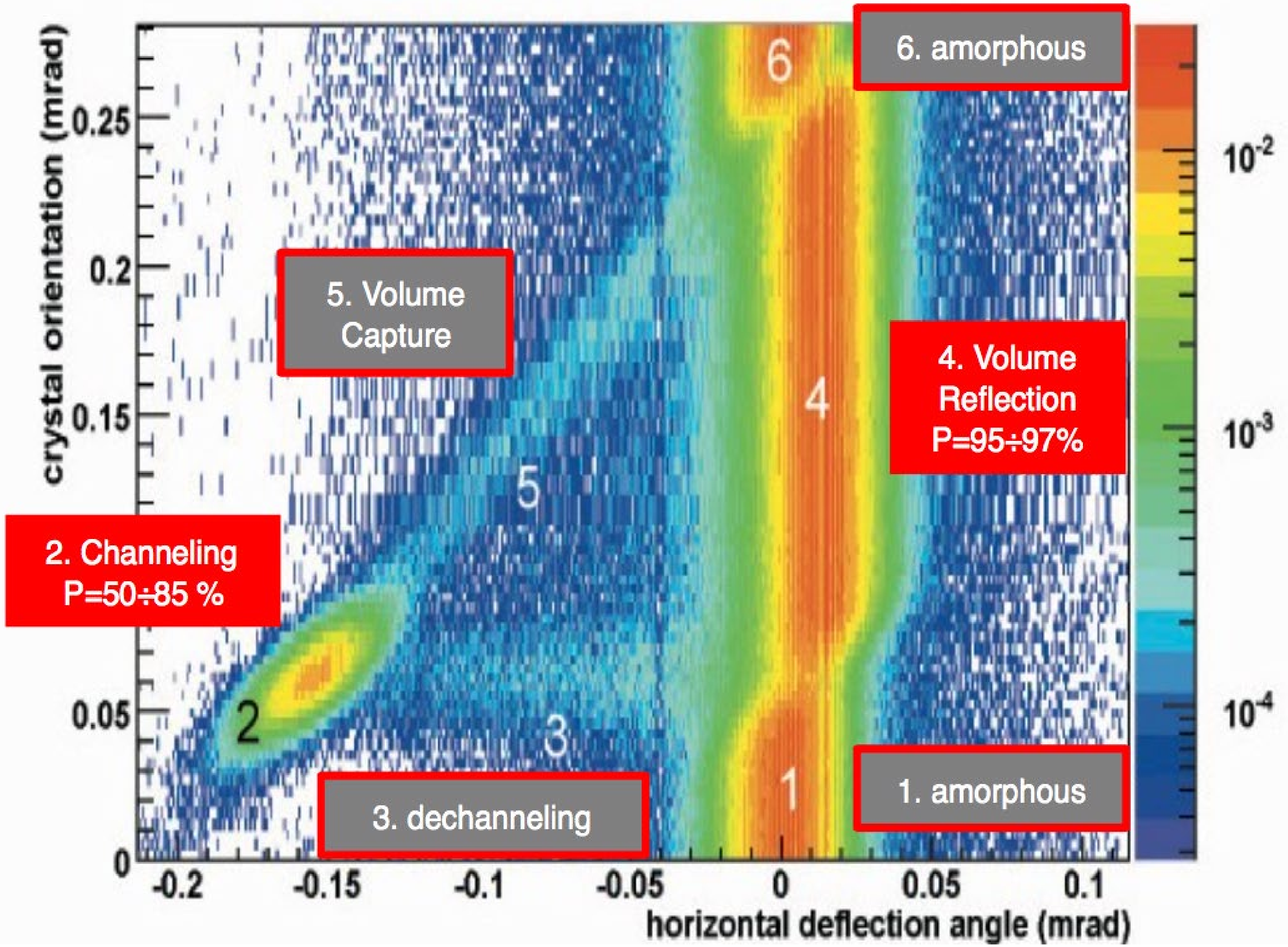


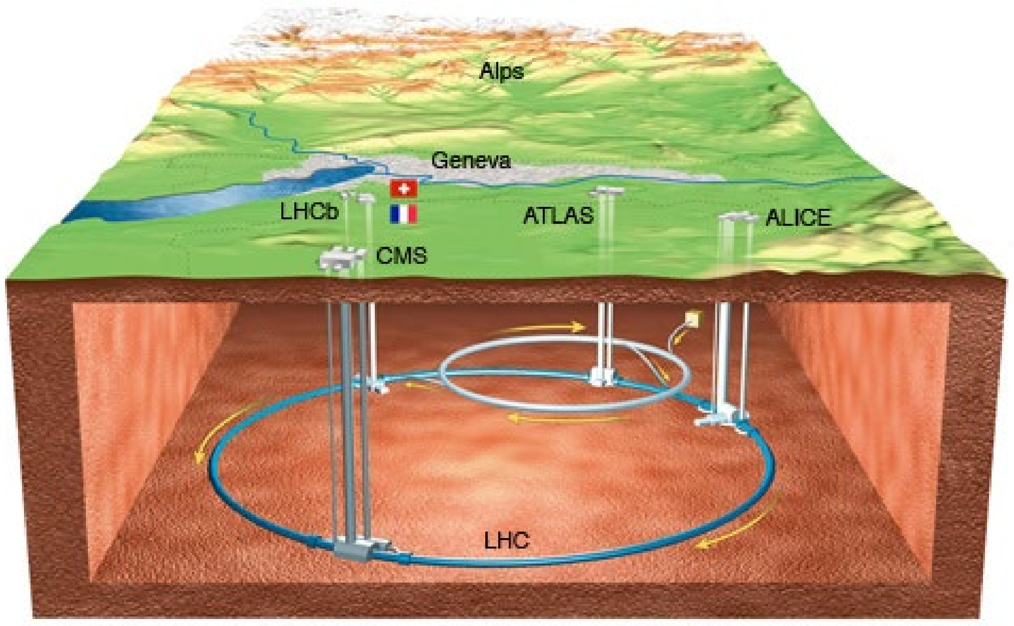
FIG. 1: Experimental layout in the H8 beam line.

W. Scandale et al, PRL 98, 154801 (2007)



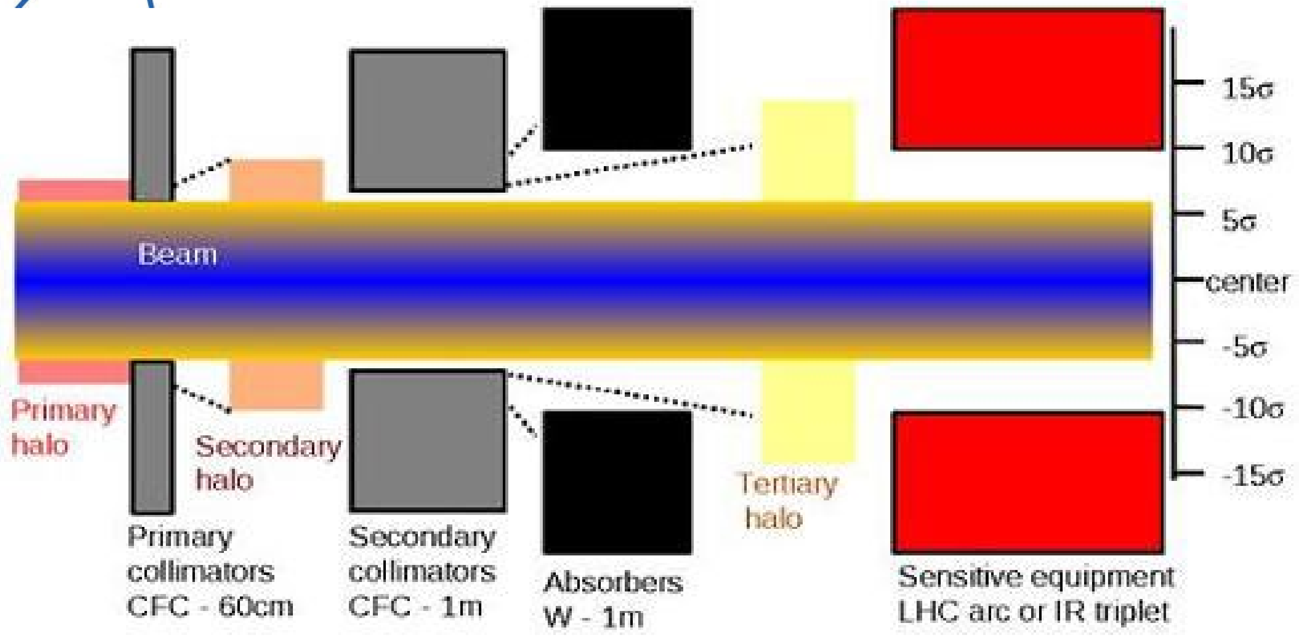
- **400 GeV** protons at North Area H8
- **Low** divergence beam (~critical angle)
- Good goniometer
- **High quality crystals**

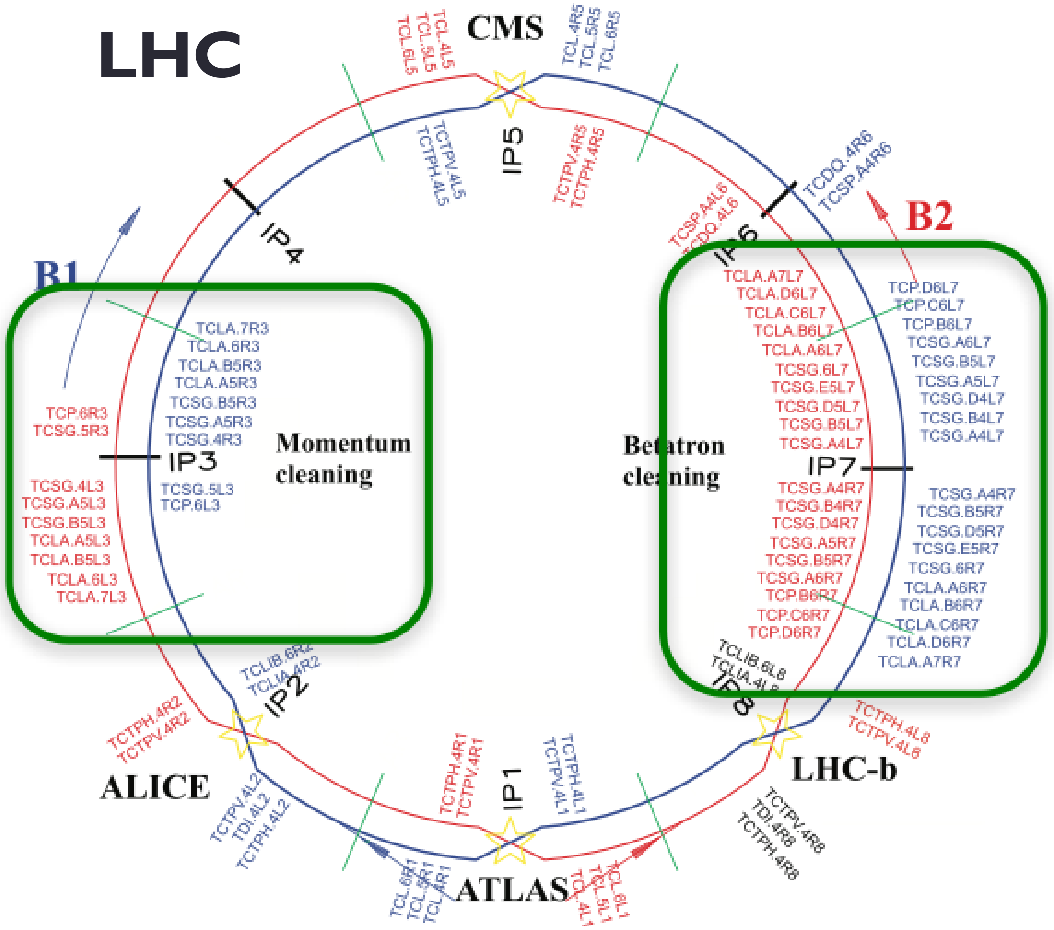
Bent crystals to steer the LHC multi-TeV hadron beam



The Large Hadron Collider (LHC) is the world's largest and highest-energy particle collider and the largest machine in the world. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva. It reached 6.8 TeV per beam in 2022 (13.6 TeV total collision energy, the present world record).

Standard LHC collimation scheme

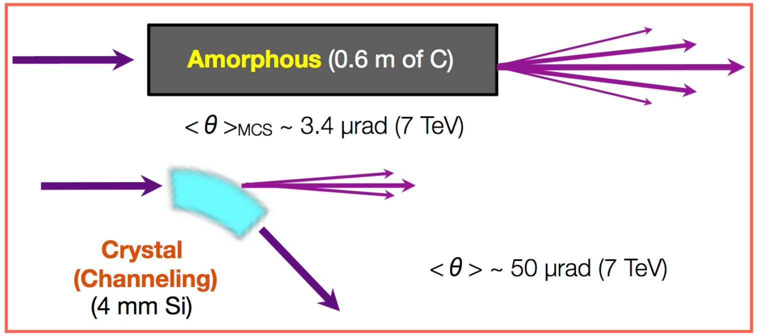


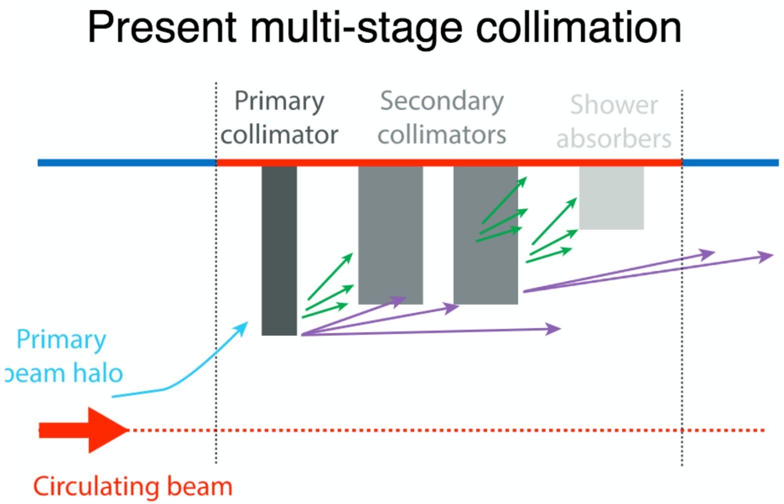


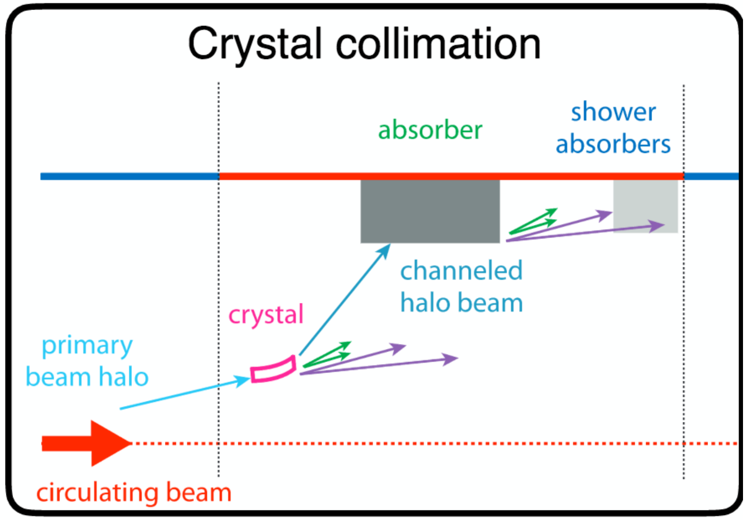
- The **collimation system** protects magnets and experiments by removing the **beam halo** particles
- Big chunks of material very close to the circulating beam: **electromagnetic impedance**

- **Limitation to increase currents (High Luminosity - LHC, especially for lead ion)**

Crystal collimation at LHC







Losses on a single absorber, reduction of machine impedance, higher currents

A possible scheme for upgraded collimation at HL-LHC

- Reduction of losses in **cold** regions (i.e. protect magnets from **quenching**)
- Present **collimation system already at its limit for ions:**

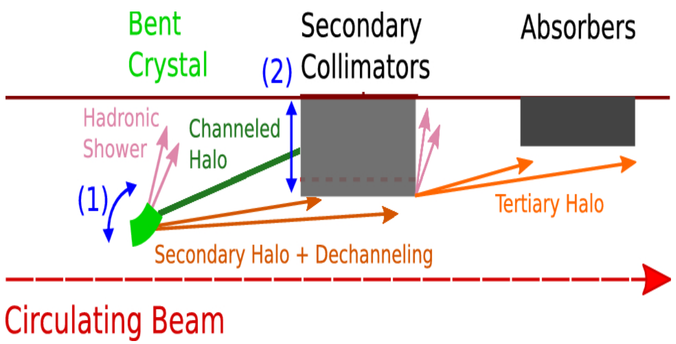
fragmentation of heavy-ion beams in secondary particles of small divergence and Z/A slightly different from the primary beam -> difficult to intercept by the collimation system and can produce significant heat-load in the superconducting magnets.

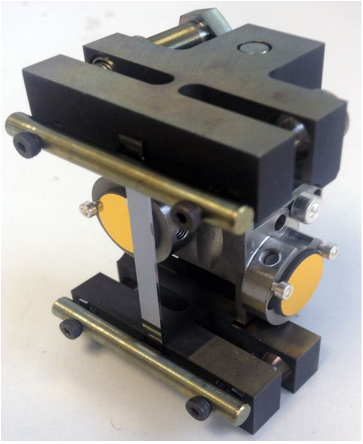
Since **2009, ten years** of experimental **investigation carried on by UA9 collaboration @SPS & @LHC** together with the **LHC Collimation group**.

Crystal channeling with 6.5 TeV protons @LHC

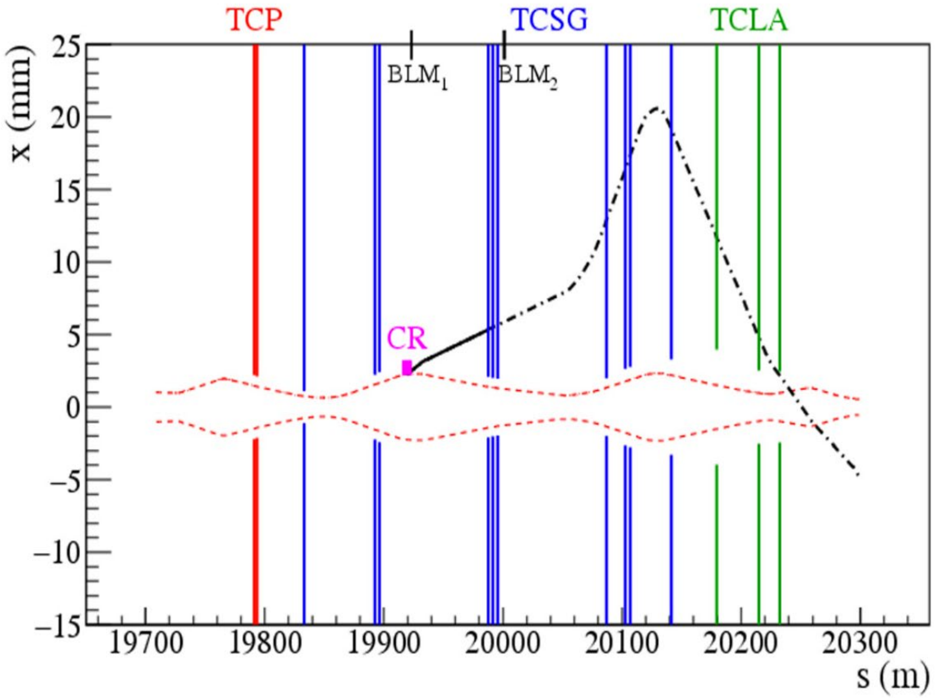
First successful test with **6.5 TeV protons in** Nov 2015!

W. Scandale et al., Phys.Lett. B758 (2016) 129-133





Studies still **on-going** at LHC (2+2 crystals installed): **INFN-CERN contract for bent crystals supply!**

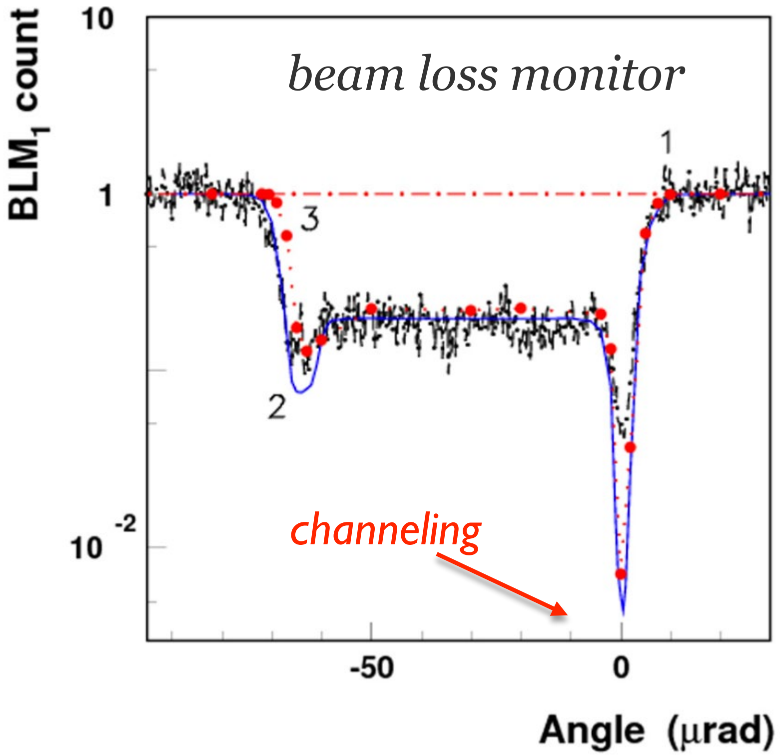


Beam trajectory in LHC

~50 μrad deflection

https://cds.cern.ch/journal/CERNBulletin/2015/49/News%20Articles/2105080?ln=en
http://home.infn.it/newsletter-eu/pdf/NEWSLETTER_INFN_17_italiano_pag3.pdf

In collaboration with LHC Collimation group

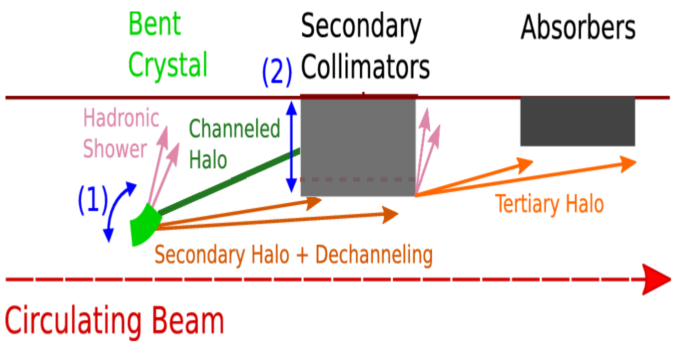


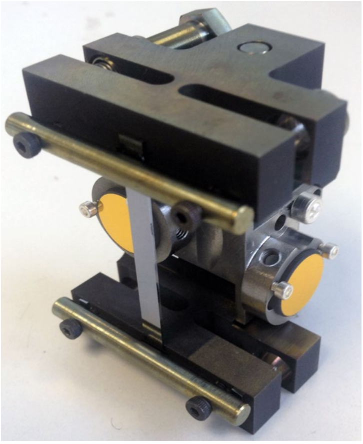
Piezo-goniometer (CERN/EN-STI)
Strip Si crystal (INFN)

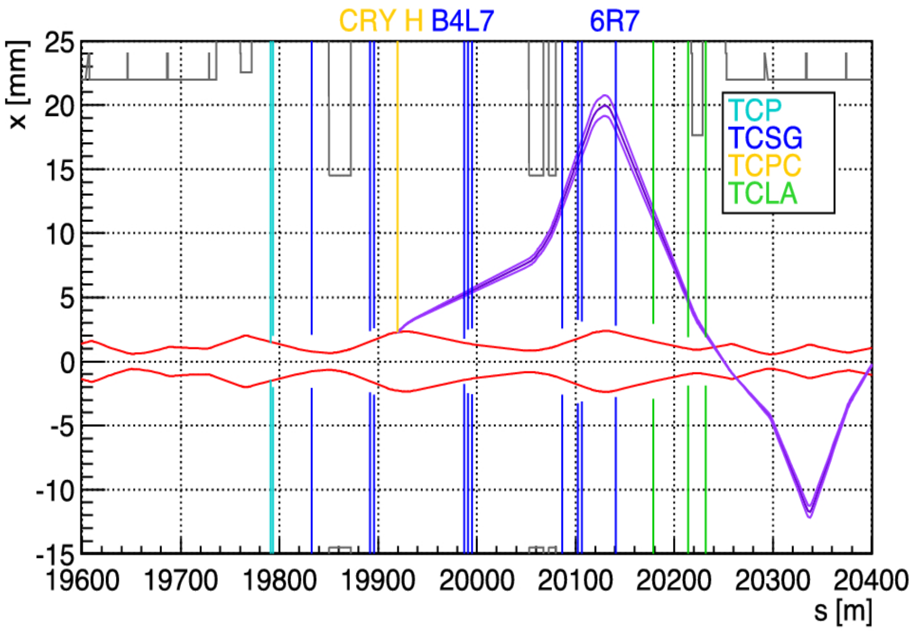
Crystal channeling with 6.5 TeV Z Pb ions @LHC

First successful test with **6.5 TeV Z Pb ions in** 2016!

S. Redaelli et al., Eur. Phys. J. C **81, 142 (2021)**







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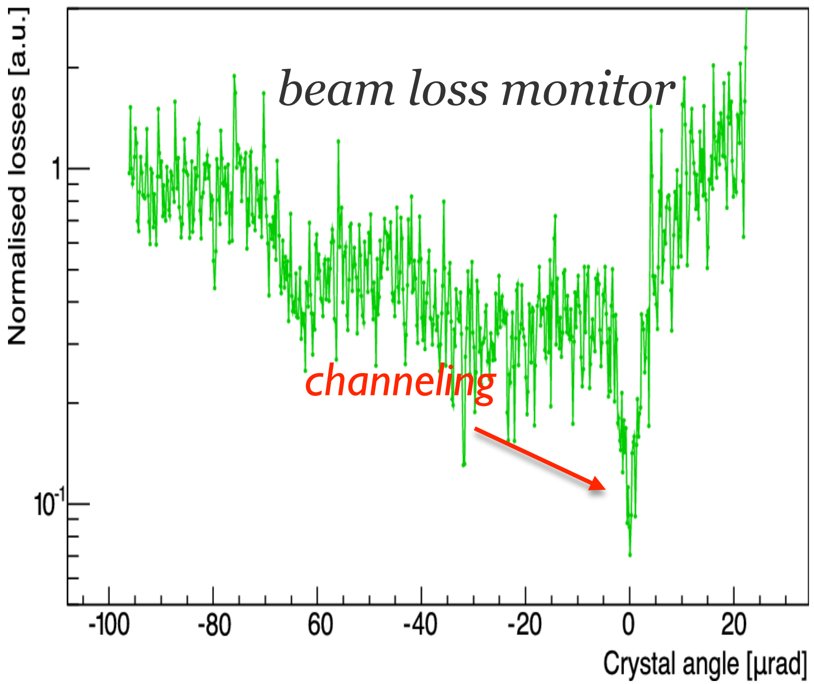

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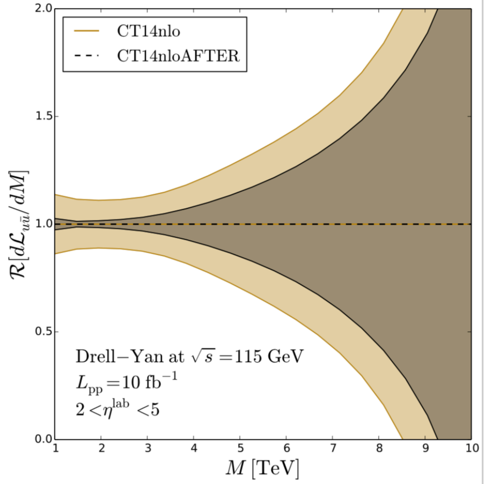
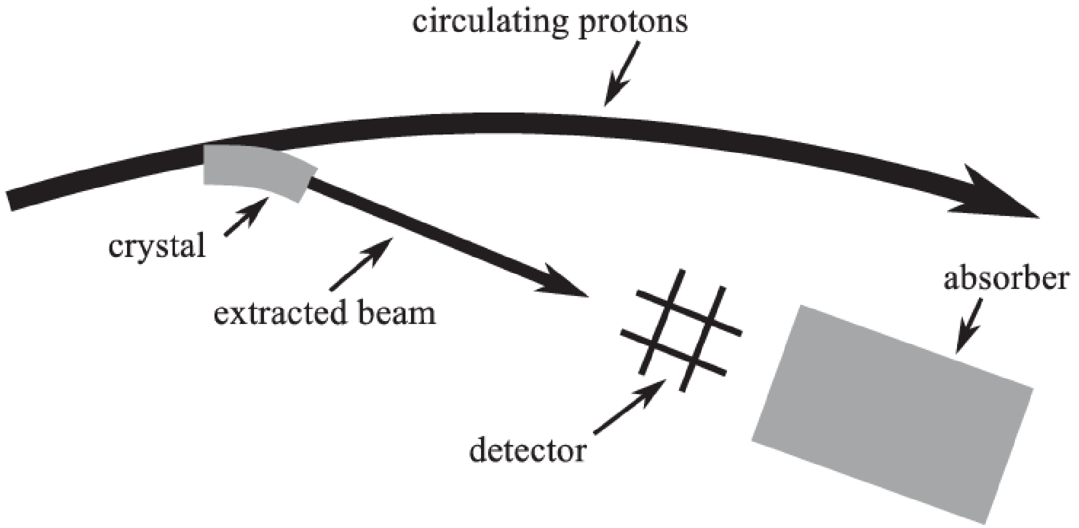
In collaboration with **LHC Collimation** group

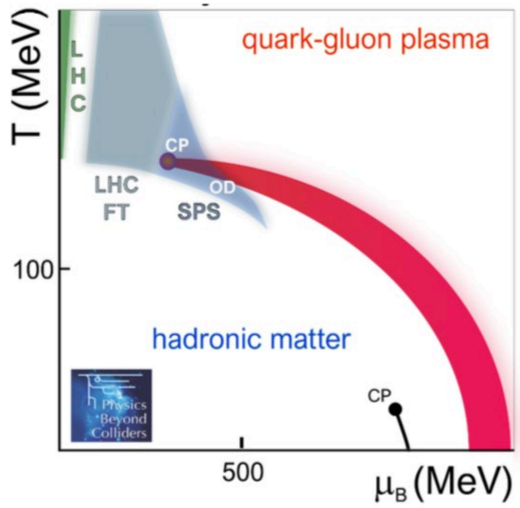
Good perspectives for HI-LUMI ion beam collimation!

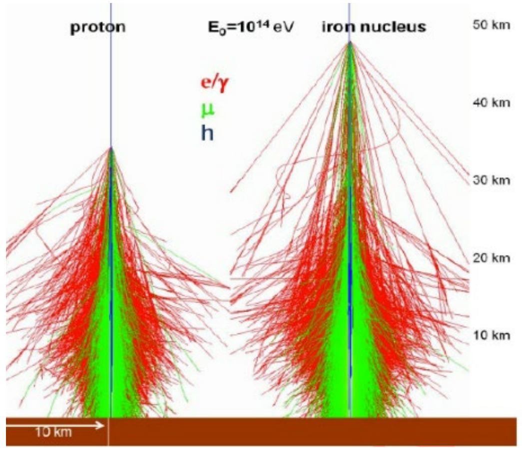
Extraction of the multi-TeV LHC beam for fixed target experiments

Motivation: to address open questions in the domain of proton and neutron spins, Quark Gluon Plasma and what is the nature of cosmic rays?
.. at the highest energy ever reached in the fixed-target experiments!









The challenge: from collimation to extraction…
R&D co-financed by the ERC CoG CRYSBEAM (PI G. Cavoto – Roma)

C. Hadjidakis, et al, A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies - https://arxiv.org/abs/1807.00603

An upgraded **internal gas target** is another competitive solution to for fixed target physics (already operational in LHC-b, **SMOG**)

Future developments for crystals (from the Physics Beyond Colliders WGs)

Search of Magnetic and Electric Dipole Moments in short living particles

- Fundamental particles have non-zero magnetic dipole moments (MDM), e.g. the electron

$$\mu_e = -g_S \mu_B \frac{S}{\hbar}$$

- While composite particles, such as hadrons, have MDM stemming from their constituents, e.g.

proton	2.793
neutron	-1.913

in units of $\mu_N = \frac{e\hbar}{2m_p}$

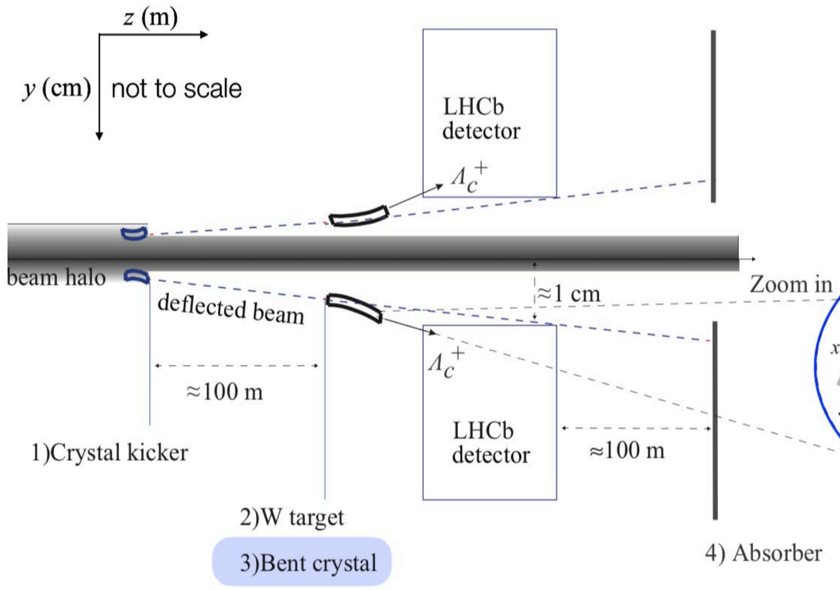
- **No experimental evidence of electric dipole moment (EDM) of any fundamental particles**
- Limited experimental data for **MDM/EDM** of unstable particles, such as $\boldsymbol{\tau}$, $\boldsymbol{\Lambda_c^+}$
- Permanent EDM → P, T and CP violation (assuming CPT);
- Standard Model CP violation → very tiny EDM (e.g. for quarks < 10^{-31} e cm)
- **Observation of EDM in fundamental particles is a direct evidence of physics Beyond Standard Model!**

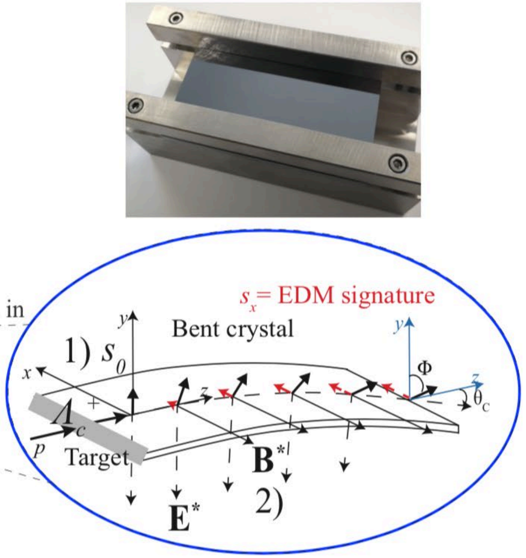
Courtesy of N. Neri

Measuring baryons MDM & EDM @LHC

"Parasitic fixed-target experiments" were proposed for LHC (see SPSC-EOI-012 and Eur. Phys. J. C (2017) 77:181)

- EDM/MDM from spin precession of channeled baryons in **bent crystals**





Sensitive to g-2 of the particle

p extraction Λ_c^+ polarised production channeling spin precession

*Large deflection **(15 mrad)** to enhance the precession effect and to send particles within the LHCb acceptance*

N.Neri, https://indico.cern.ch/event/755856/contributions/3260539/attachments/1779601/2895655/Neri_PBCJan19.pdf

Cofinanced by ERC CoG SELDOM (PI N. Neri, Milano) SELDOM

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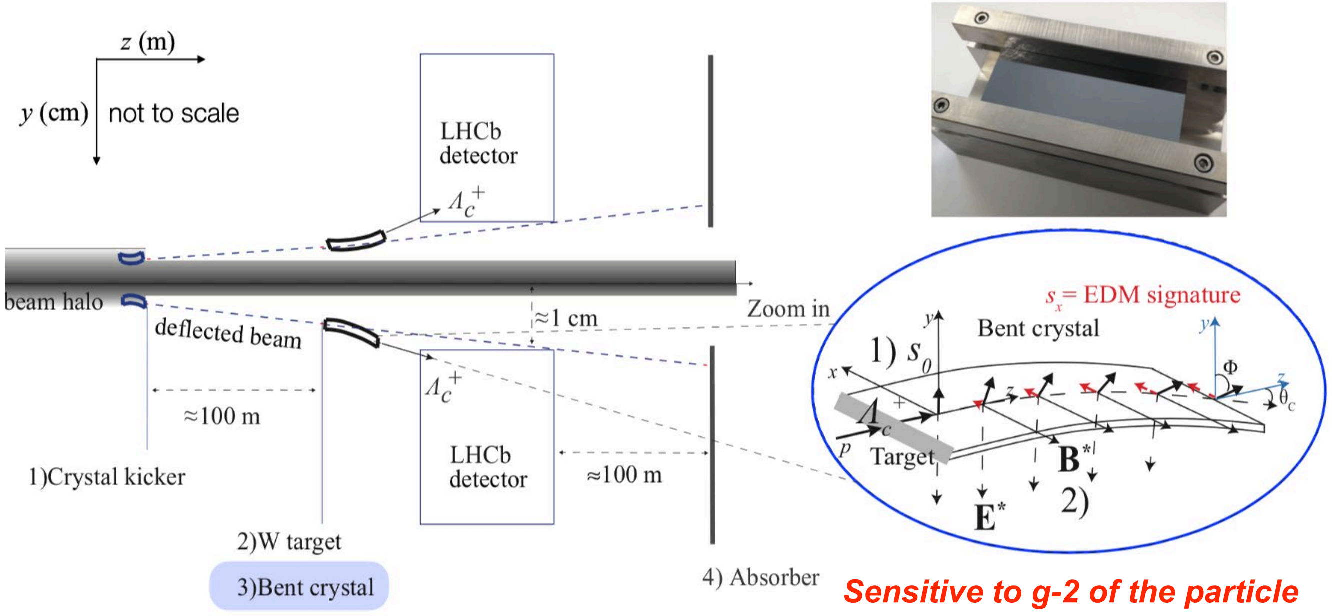

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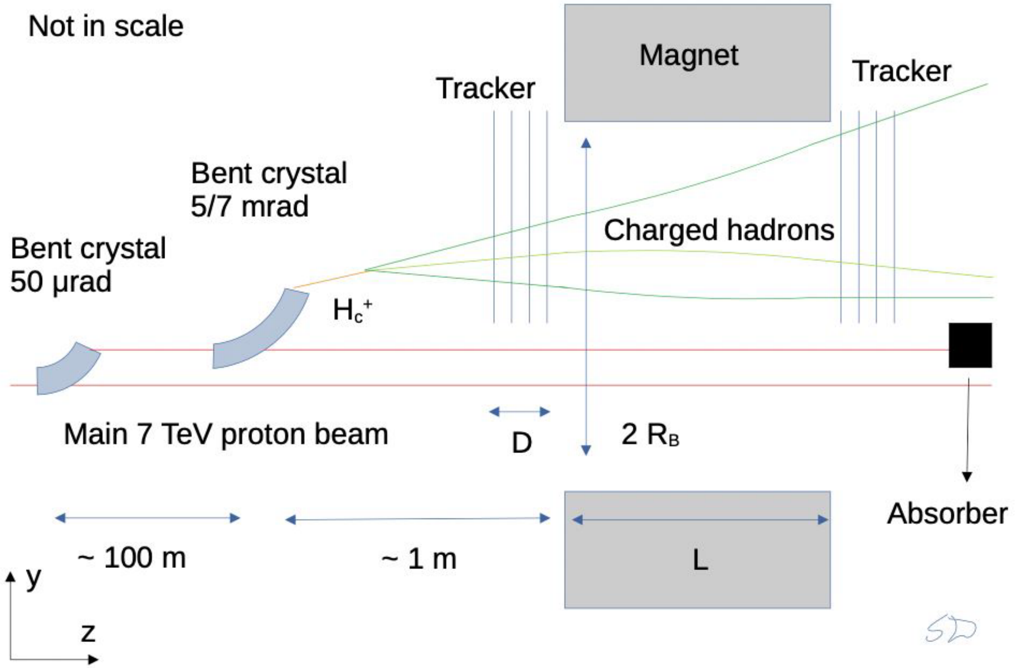
New experiment @IR3

Before a possible test @LHCb detector, a proof-of-principle demonstration in a different LHC point is required @Interaction Region 3 in LHC (IR3).



From: E. Spadaro Norella https://agenda.infn.it/event/31703/timetable/?print=1

Studies extended also to tau-lepton!

Measuring baryons MDM & EDM @LHC

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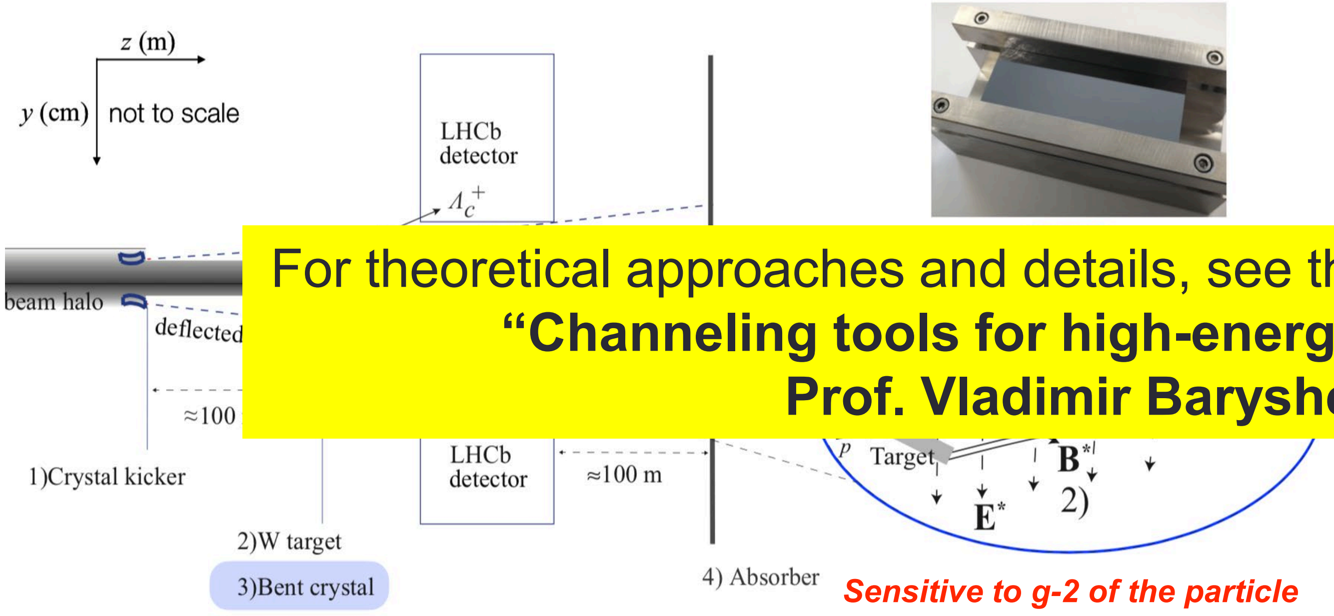

For theoretical approaches and details, see the next seminar on 22nd November
"Channeling tools for high-energy and particle physics"
Prof. Vladimir Baryshevsky (BSU)

p extraction Λ_c^+ polarised production channeling spin precession

Large deflection ***(15 mrad)*** *to enhance the precession effect and to send particles within the LHCb acceptance*

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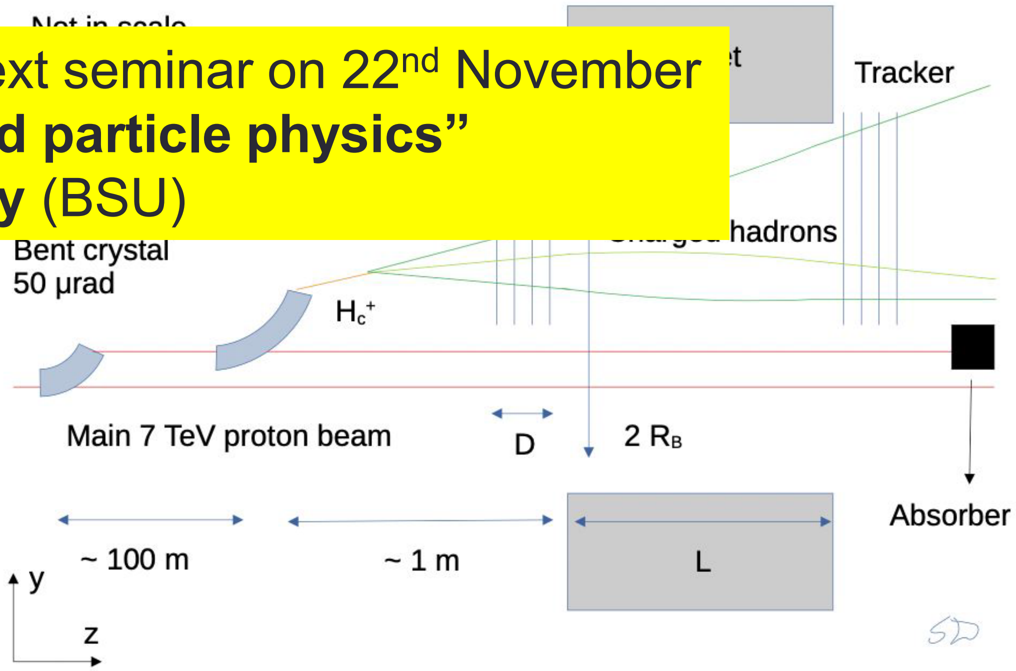

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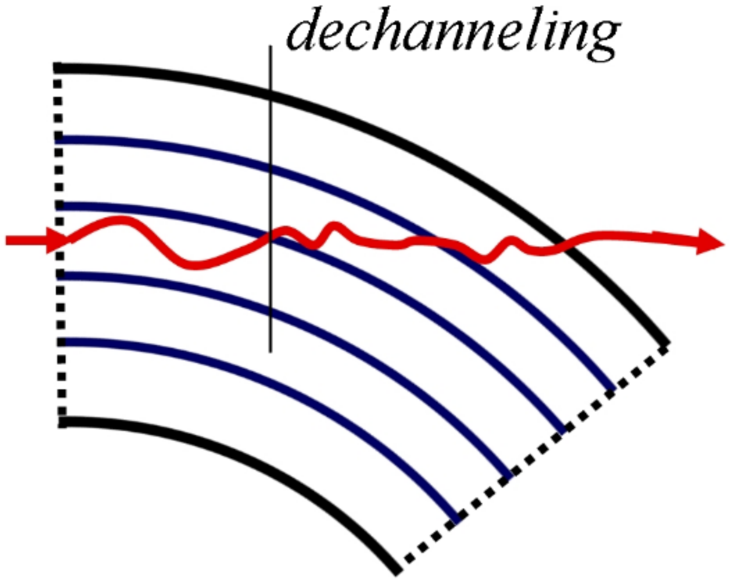
CSN5 Ricerca Tecnologica

Experiments in a wide range of energies

sub-GeV
10-15 µm thick crystals

3-20 GeV
60 µm thick crystal

100 GeV - 1 TeV
~mm thick crystals



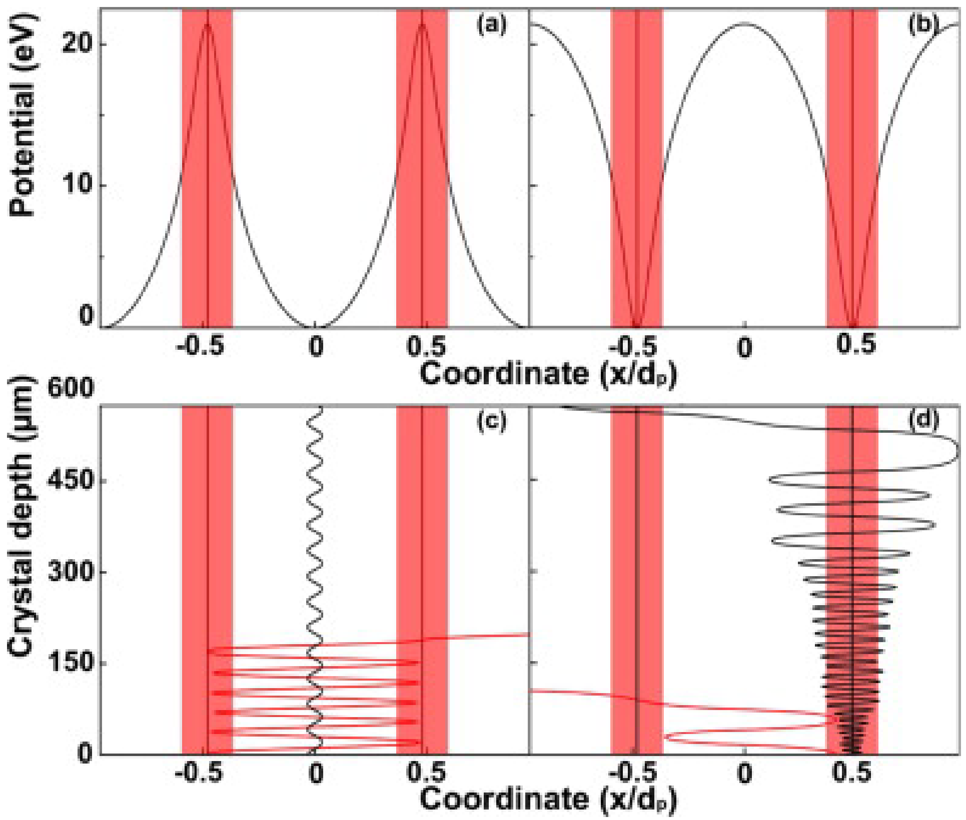
Dechanneling lenght increase with particle energy

Crystal thickness should be optimized for different E

Crystal R&D and experimental tests co-financed in the last 10 years by the INFN CSN5

Dechanneling: positive vs. negative

Positive vs Negative



Channeled negative particles are dechanneled faster than positive ones due to higher probability to suffer nucler incoherent scattering

Ultra thin bent crystals are required for efficient deflection of electrons

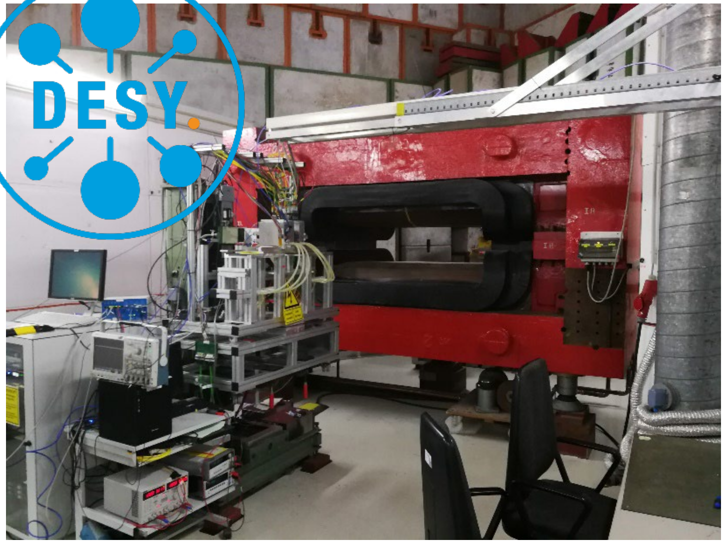
Steering of sub-GeV and GeV electron trajectories through channeling in bent crystals was not possible before due to the lack of thin-enough bent crystals ->extraction from accelerators

Test facilities

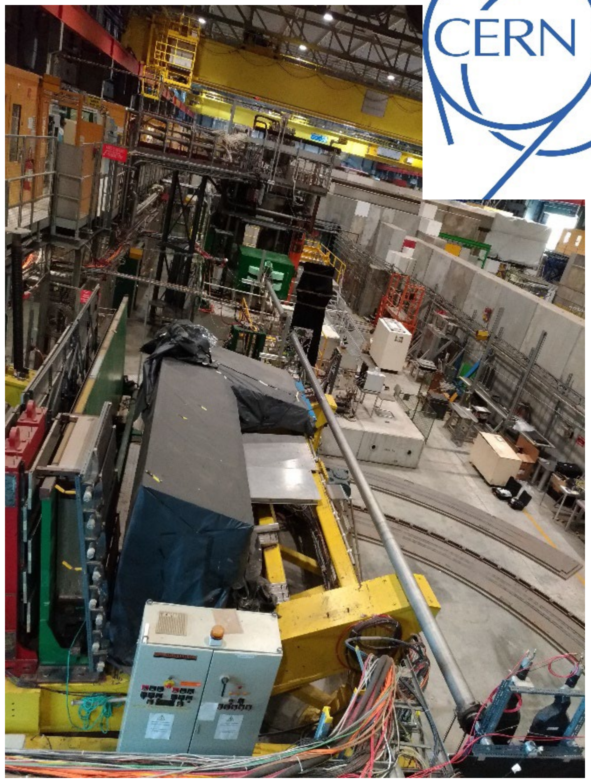
e^- @ subGeV
MAMI (Mainz, Germany)

e^- @multi-GeV
SLAC (Stanford, USA)

CSN5 ICE-RAD, CHANEL, AXIAL & ELIOT (Ferrara, LNL, Milano Bicocca)



$e^\pm$ @6 GeV
DESY (Hamburg, Germany)



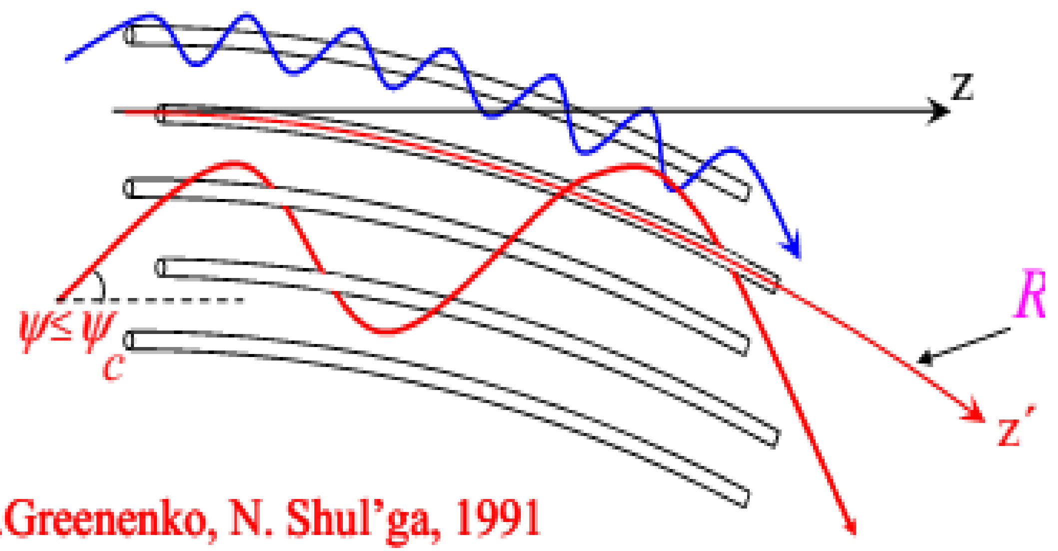
p, $e^\pm$, $\pi^\pm$ @ (1-400) GeV
CERN EA&NA
(Geneve, Switzerland)

Axial Channeling

- Stochastic Deflection proposed by A.A. Greenenko and N.F. Shul'ga in 1991 [Pis'ma Zh. Eksp. Teor. Fiz. 54 (1991) 520]

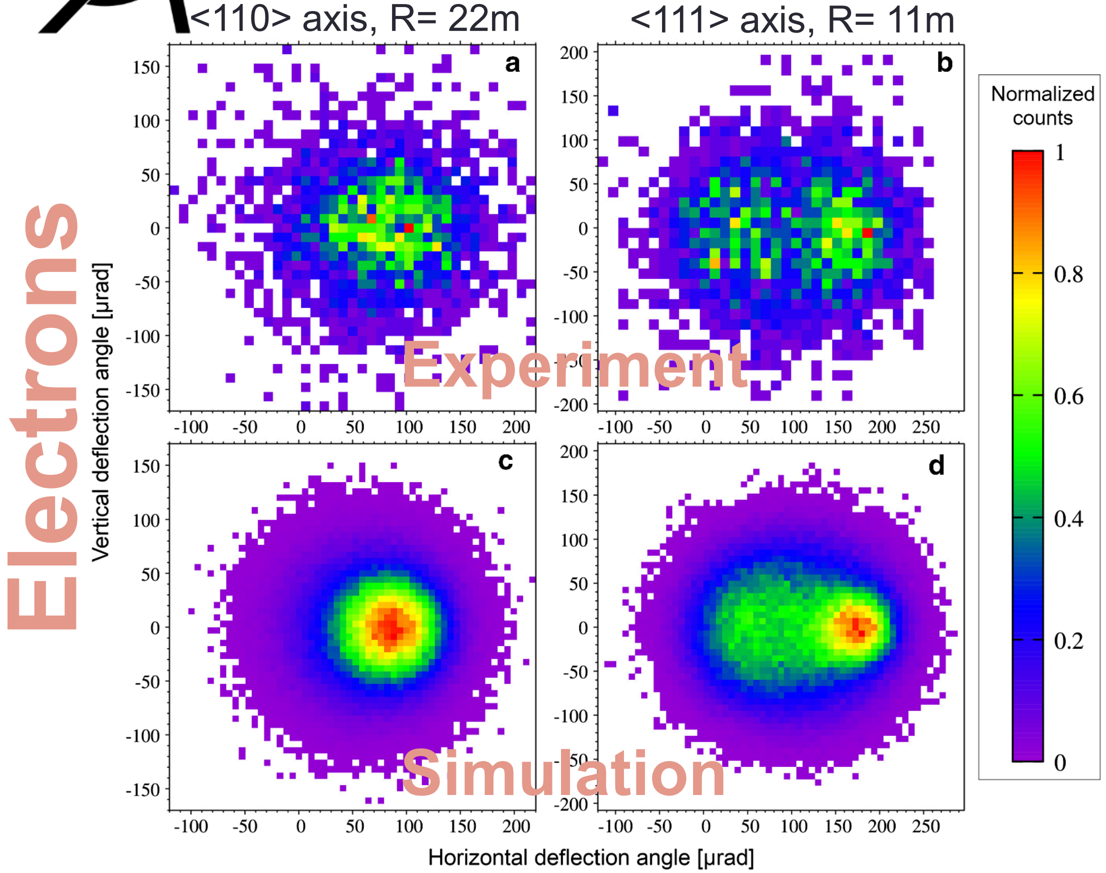
- Experimentally observed by H8-RD22/UA9 collaboration at CERN in 2008 for protons and in 2009 for π^--mesons

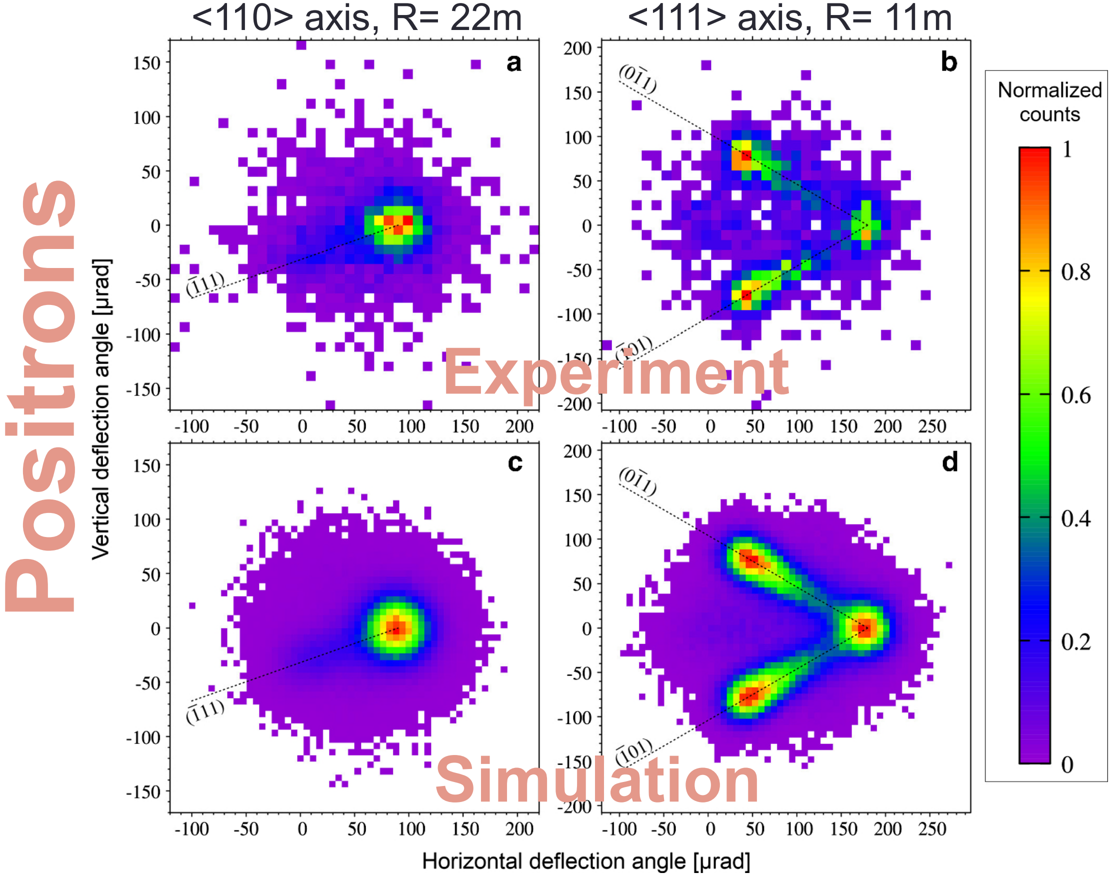
In case of axial alignment, most of the particles are deflected through multiple scattering by atomic strings (**Stochastic Deflection**) rather than by axial channeling (or **hyperchanneling**)



A.Greenenko, N. Shul'ga, 1991

Recent results with 120 GeV electrons & positrons

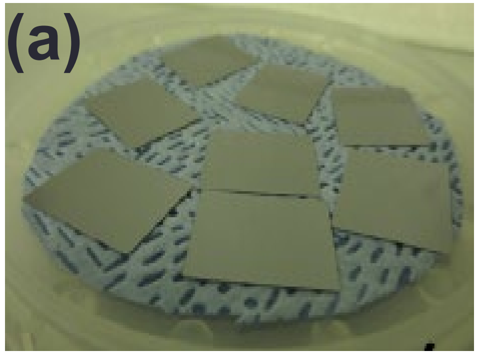




L. Bandiera, I. V. Kyryllin,… N. F. Shul'ga,.. et al. Eur. Phys. J. C 81 (2021) 238

Deflection of more than 90% of the electron beam. **Since planar deflection could be highly inefficient to steer TeV negative beams, axial deflection could be really a good option.**

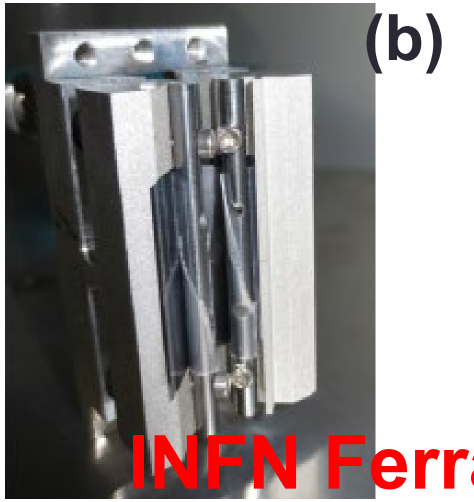
Fabrication and characterization of crystals to manipulated sub-GeV and GeV electrons



Realization of **tens micron Si membranes (a)** and their **bending (b)**:
- determine the **dechanneling length** and deflection capability
- study **channeling radiation**

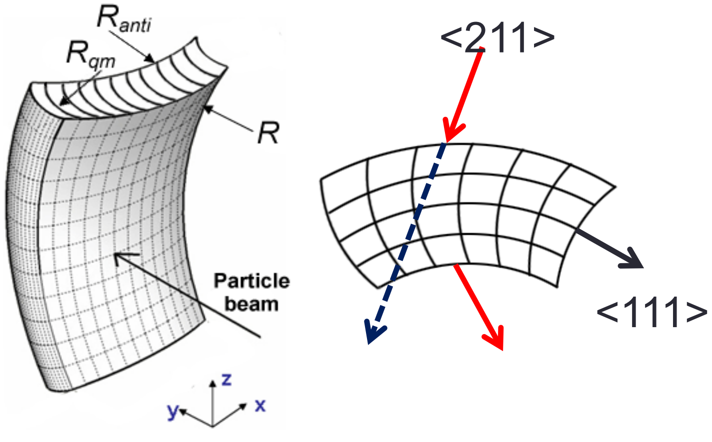
in the **sub-GeV energy range**

G. Germogli et al. NIM B 355 (2015) 81–85

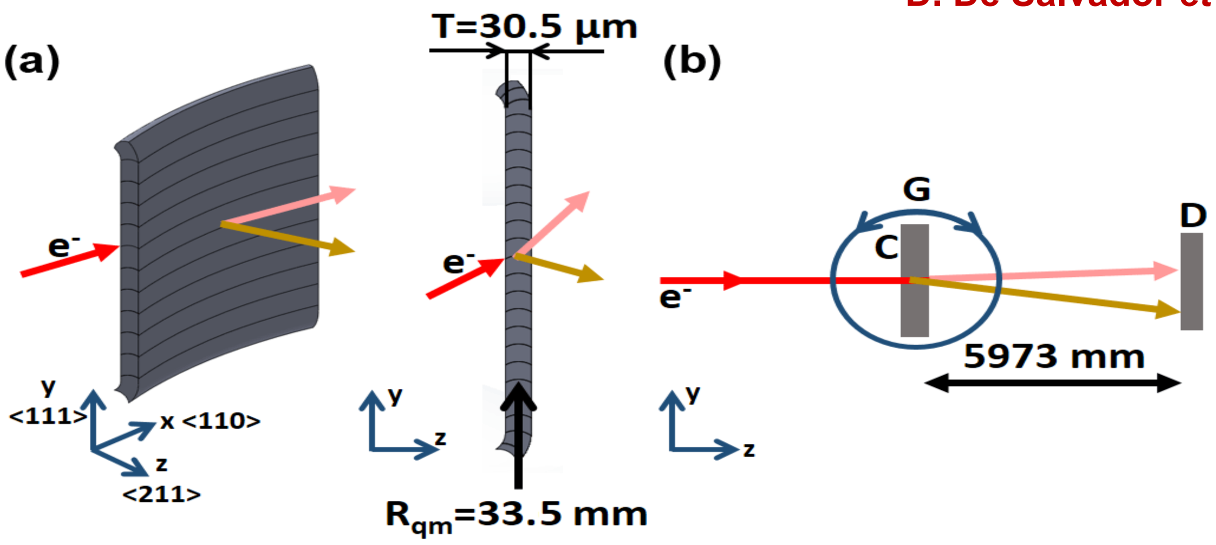


INFN Ferrara &LNL

D. De Salvador *et al* 2018 *JINST* 13 C04006



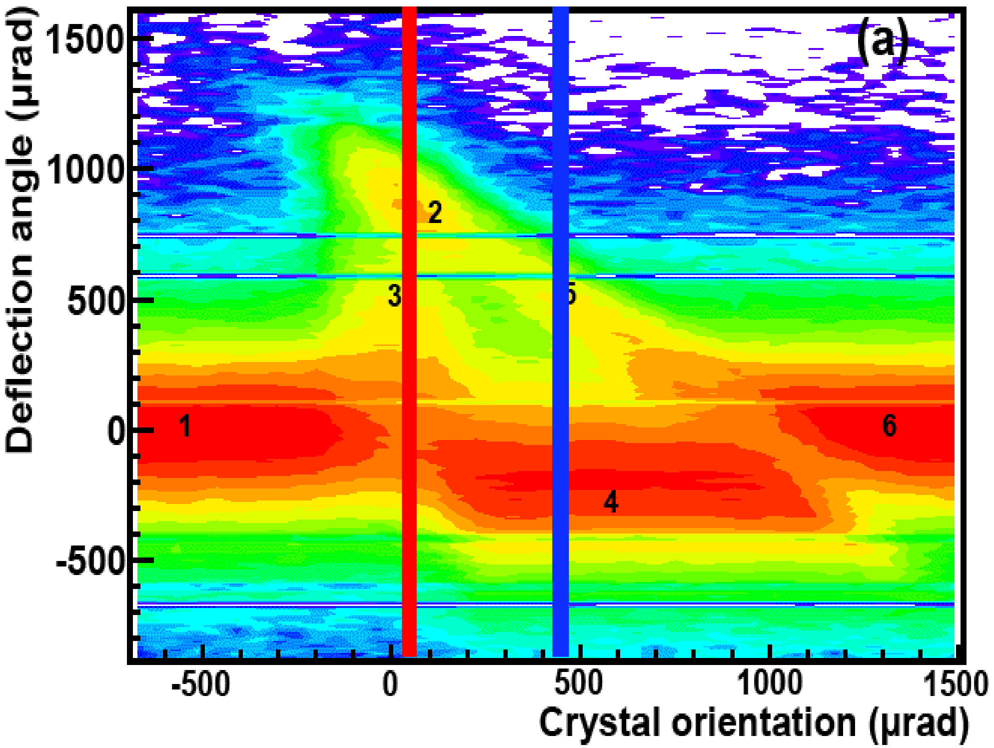
Quasimosaic effect (Ivanov et al., 2005)



Experiments with **0.855 GeV electrons** at the MAMI B line

D.Lietti et al. Rev. Sci. Instrum. 86, 045102 (2015)

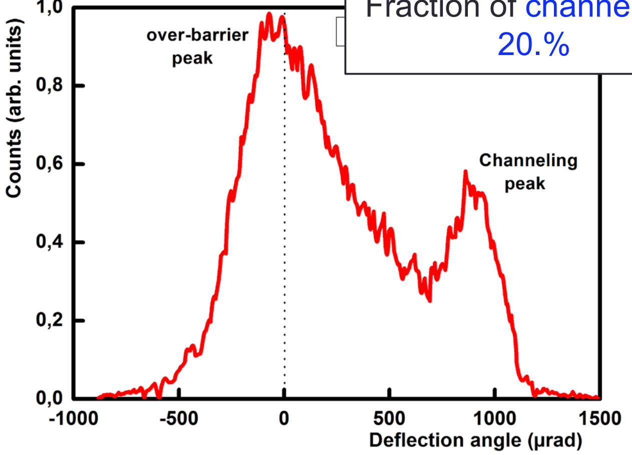
Experimental results on beam steering



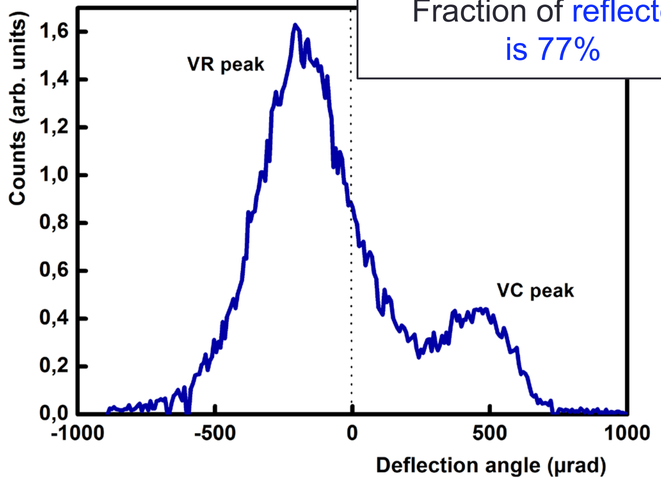
First observation of sub-GeV particle beam deflection in a bent crystal !

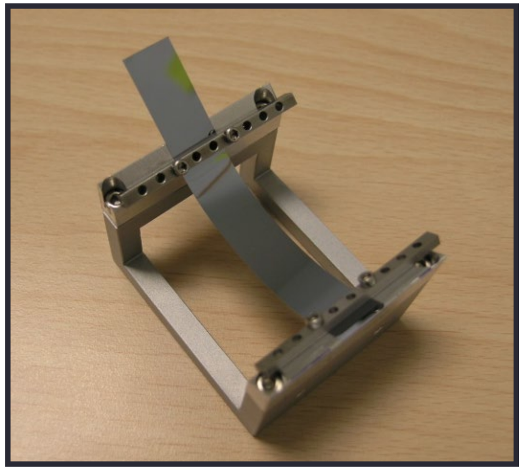
A. Mazzolari et al., Phys. Rev. Lett. 112 (2014) 135503

Deflection angle = 910 μrad
Fraction of channeled is 20.%

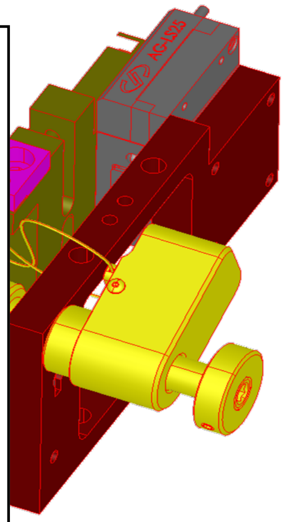


Deflection angle = 191 μrad
Fraction of reflected is 77%





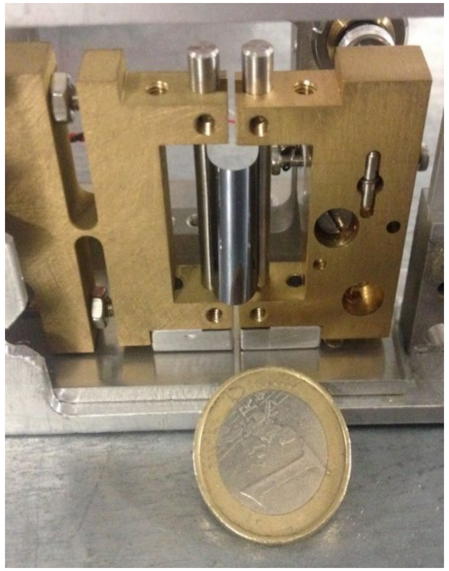
30.5 μm bent Si crystal
(111) Bent planes
900 μrad deflection angle

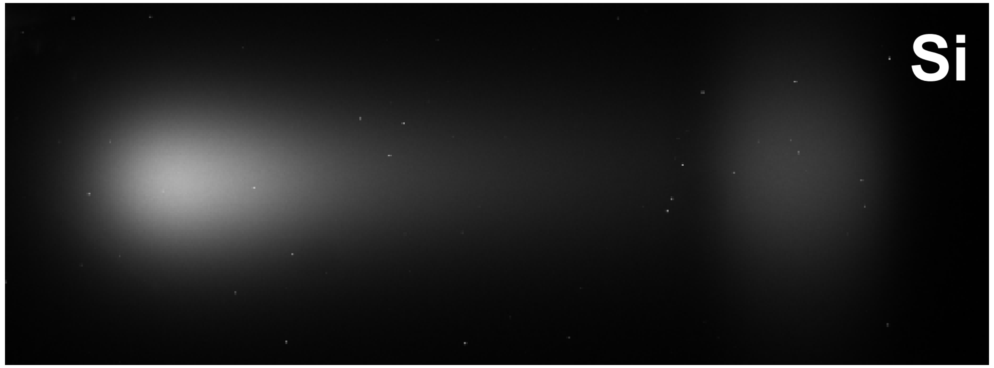


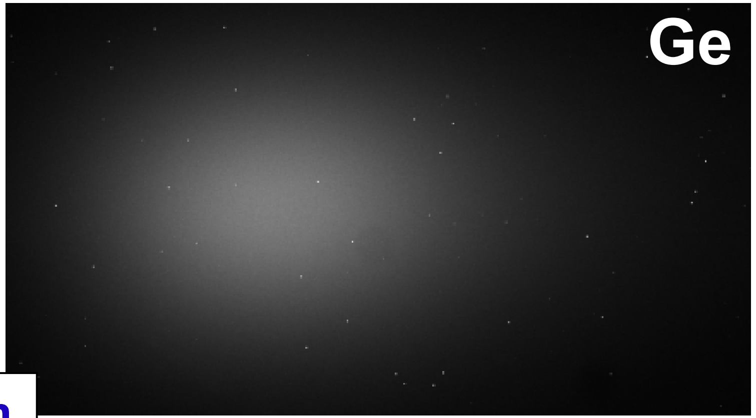
Developed by INFN Ferrara & LNL

D. De Salvador *et al* 2018 *JINST* 13 C04006

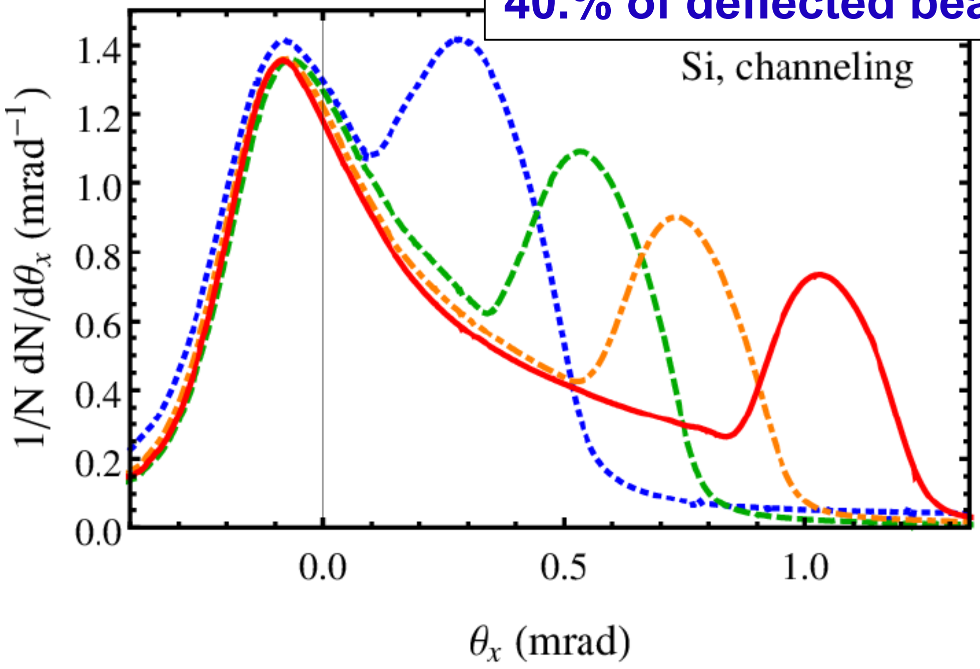
Results with bent crystals: deflection

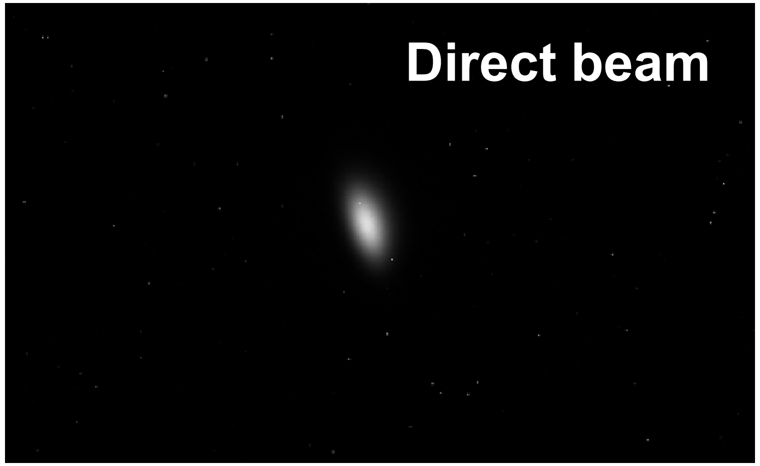






40.% of deflected beam





Beam angular divergence: **21.4 μrad**

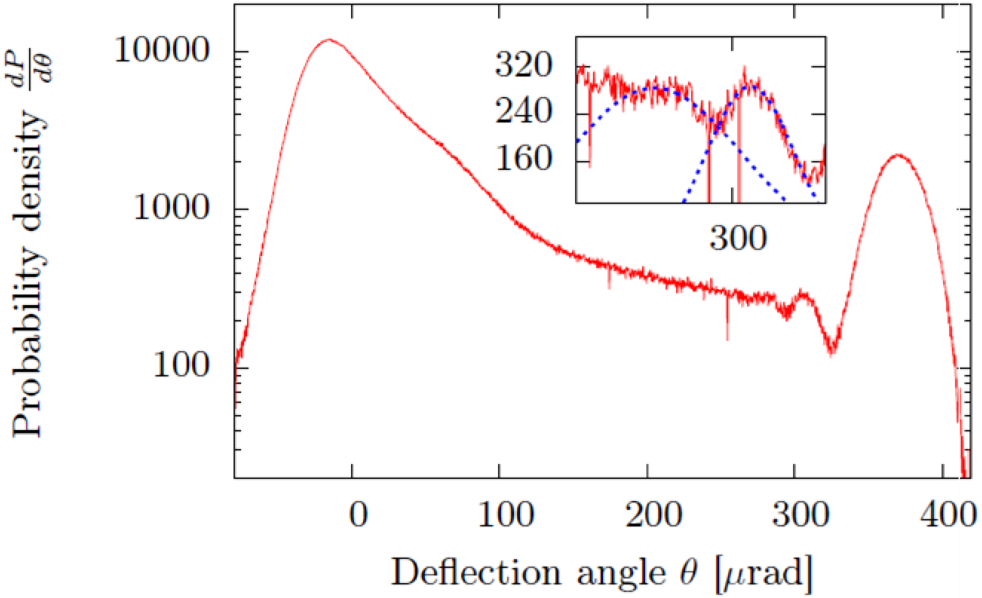
Si and Ge crystals:
15 μm thick
bent planes (111)

A.I. Sytov, L. Bandiera et al. Eur. Phys. J. C 77, 901 (2017)

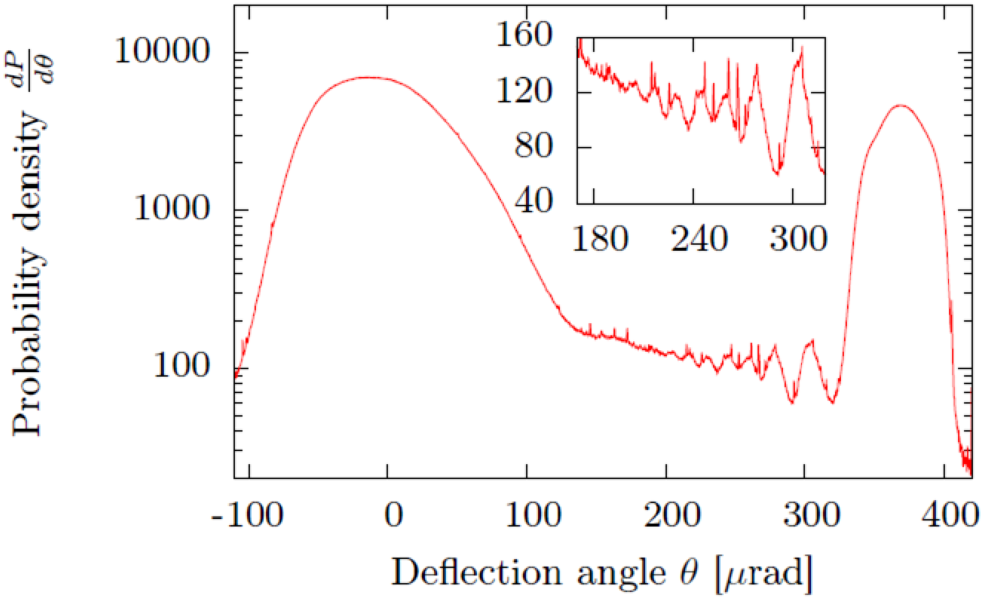
Channeling experiments @SLAC (Stanford, US)

FACET-II
Facility for Advanced Accelerator Experimental Tests

60 µm bent Si crystal
(111) Bent planes
400 µrad deflection angle



20.53 GeV e-



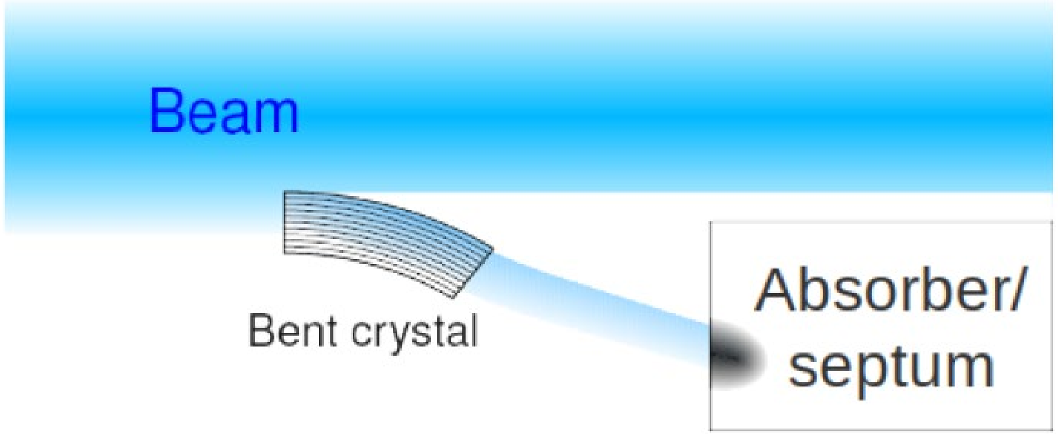
20.53 GeV e+

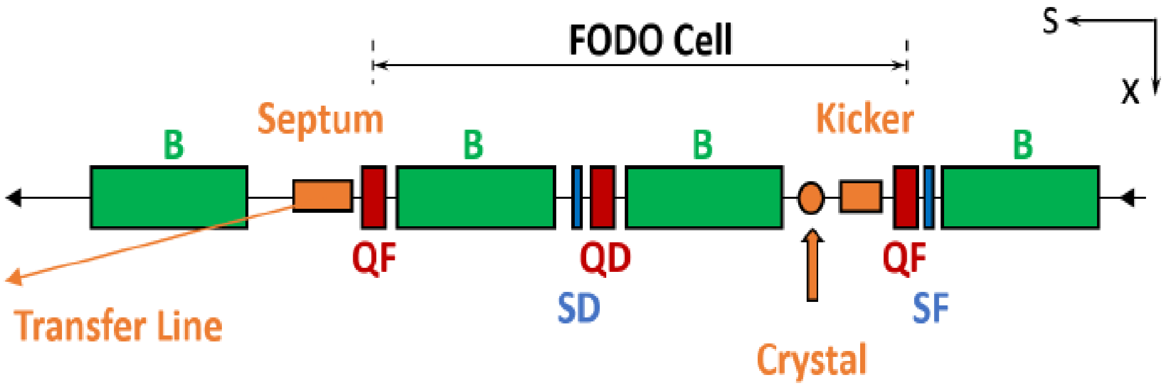
SLAC E-212 Collaboration
(Aarhus University, SLAC, California Polytechnic State University and INFN Ferrara)

Phys. Rev. Lett. 119 (2017) 024801

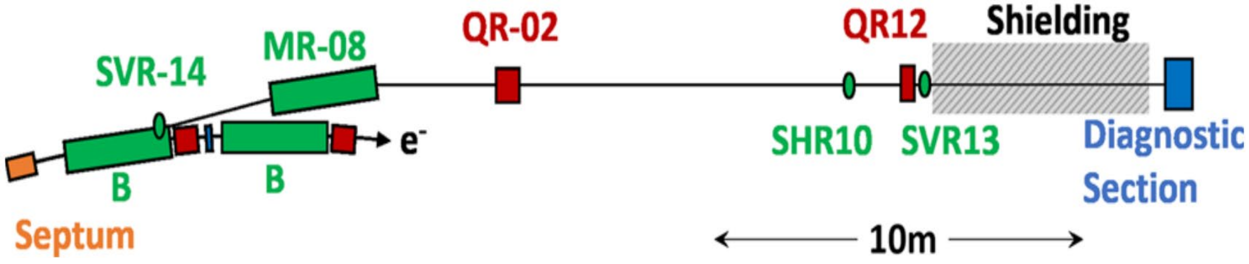
Crystal-based Extraction of 6 GeV Electrons from the DESY-II Booster Synchrotron

A. Sytov et al. Eur. Phys. J. C 82, 197 (2022).





Transfer line



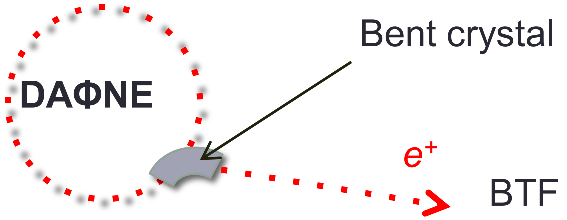
Motivation:

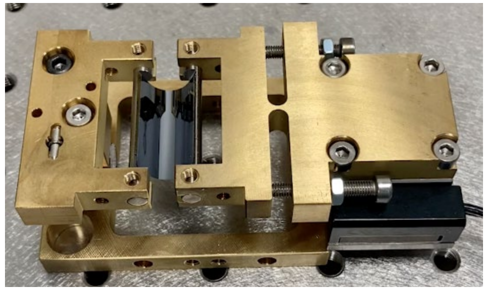
- Provide **multi-GeV electron beams in a parasitic mode**, allowing to supply fixed-target experiments by intense **high-quality monoenergetic electron beams**.
- Electron crystal-based extraction may provide an access to **unique experimental conditions for ultra-high energy** fixed-target experiments including searches for New Physics Beyond Standard Model in **future Colliders**.

SHERPA

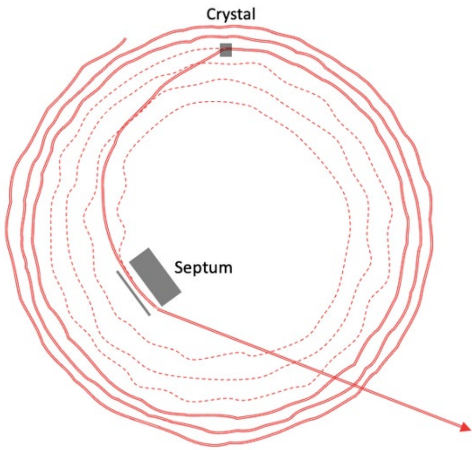
(CSN5 Young Researcher Grant 2020-2022 - P.I.: Dr. M. Garattini)

R&D study to extract a high-quality e^+ *(or e^-)* beam from one of the DAΦNE rings
The idea is to use coherent processes in a bent crystal to steer the positron beam





INFN-Fe/LNL



Preliminary simulation studies @DAFNE, without changing the layout of the rings (but only the currents), show that with a crystal deflection of 1 mrad it is possible to obtain
pulses of 0.1 ms (damping ring) and up to 0.4 ms (main ring)

Target spill parameters:
- Energy spread: $\Delta p/p < 10^{-3}$
- Emittance: $\varepsilon < 10^{-6}$ rad·m
- **Length: $\Delta t \sim$ ms**

VS

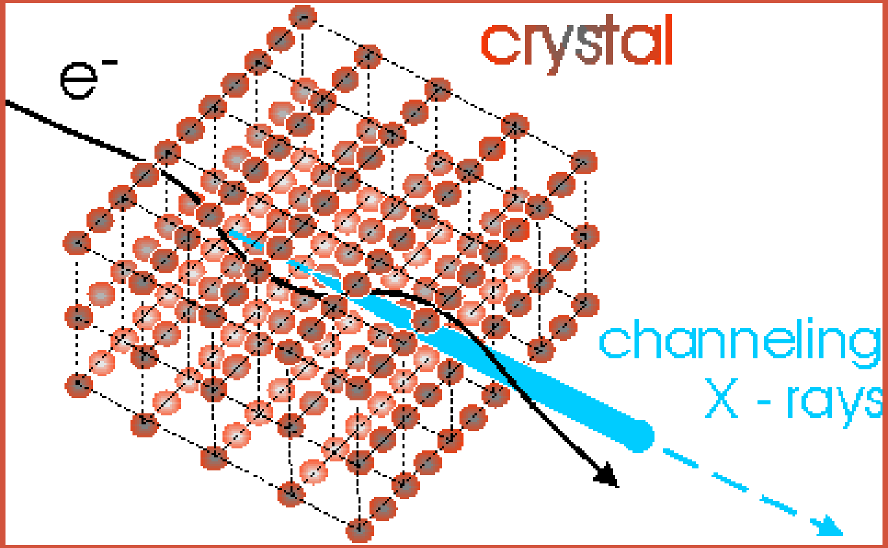
Current BTF spill parameters:
- Energy spread: $\Delta p/p < 0.5 \times 10^{-2}$
- Emittance: $\varepsilon < 10^{-5}$ rad·m
- **Length: $\Delta t \sim 300$ ns**

Immediate application:

With the **SHERPA beam**, **PADME** (“**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment”) could increase the **statistics by a factor ~10^4** and its **sensitivity by a factor ~10^2**, largely extending the discovery potential

Courtesy of M. Garattini

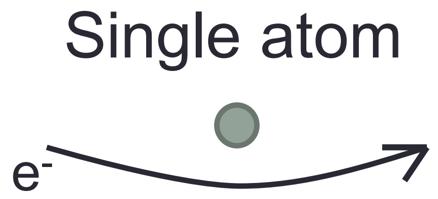
M. Garattini et al., Phys. Rev. Accel. Beams 25 (2022) 033501

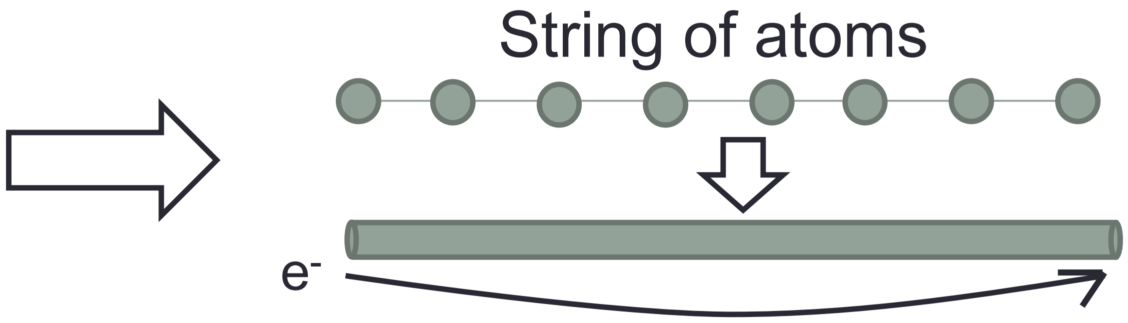


CHANNELING RADIATION…

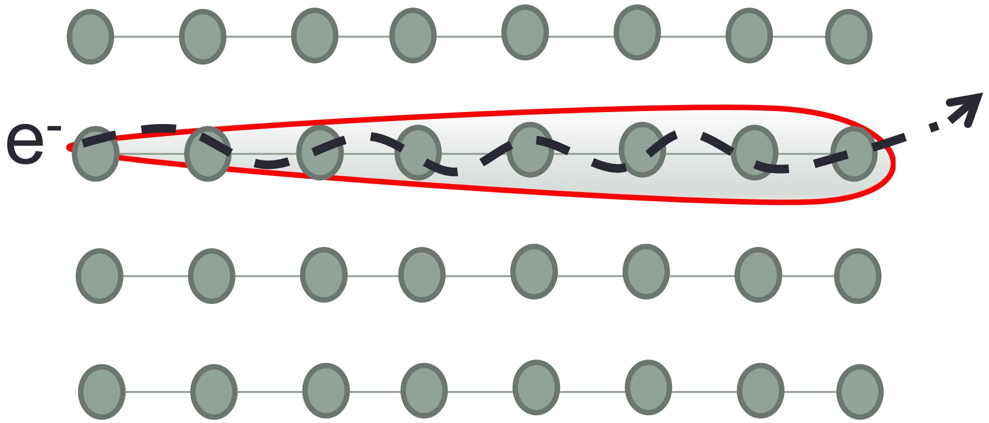
- Intense X and gamma beam sources
- Positron source for future electron positron colliders

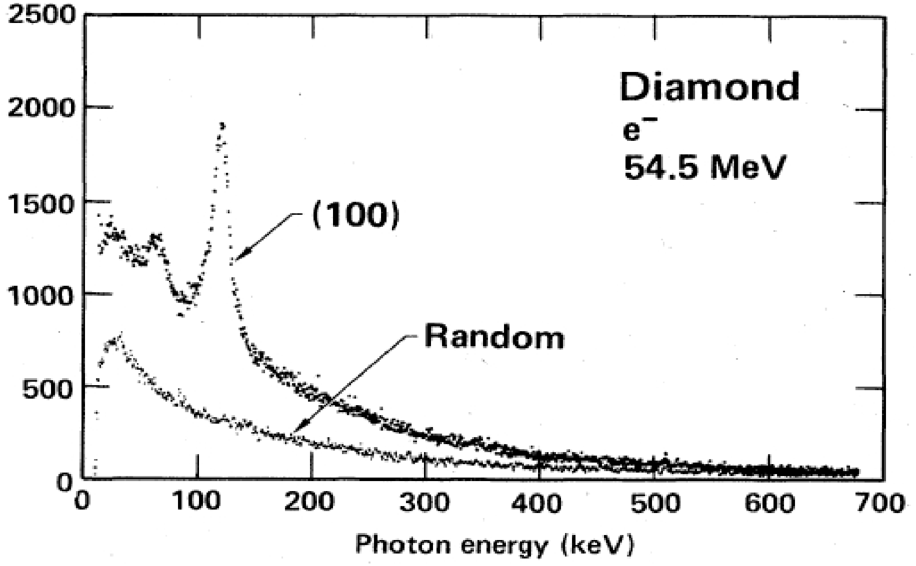
Enhancement of bremsstrahlung in aligned crystals



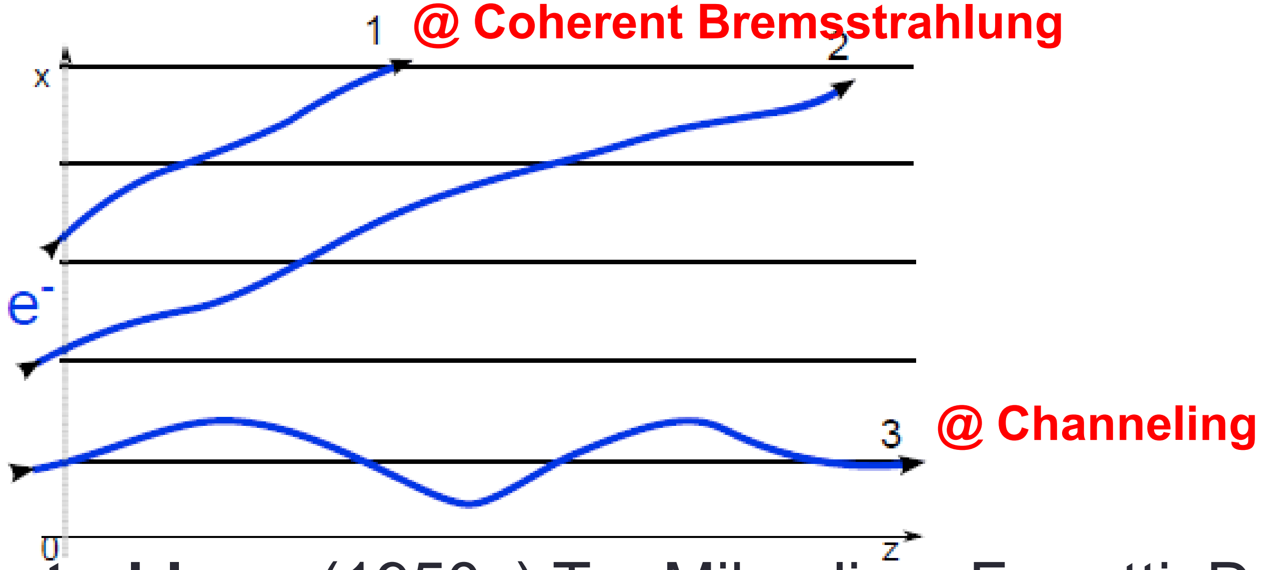


Channeling Radiation (1976, Kumakhov)

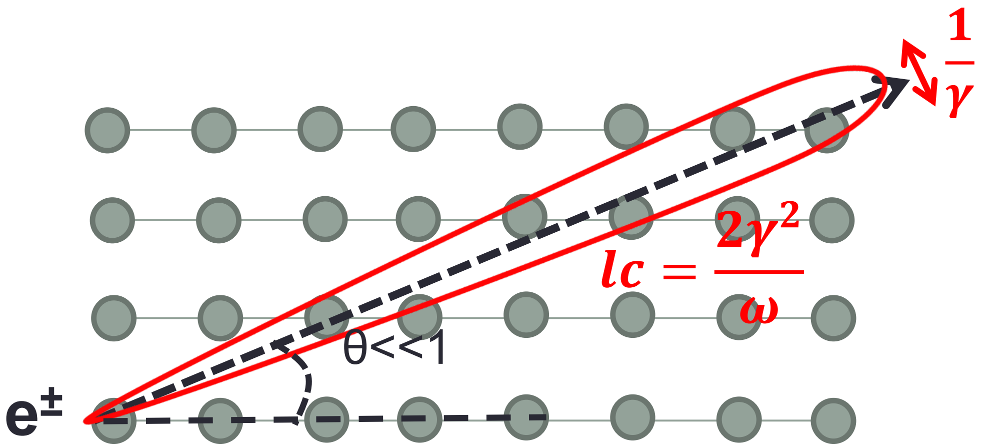


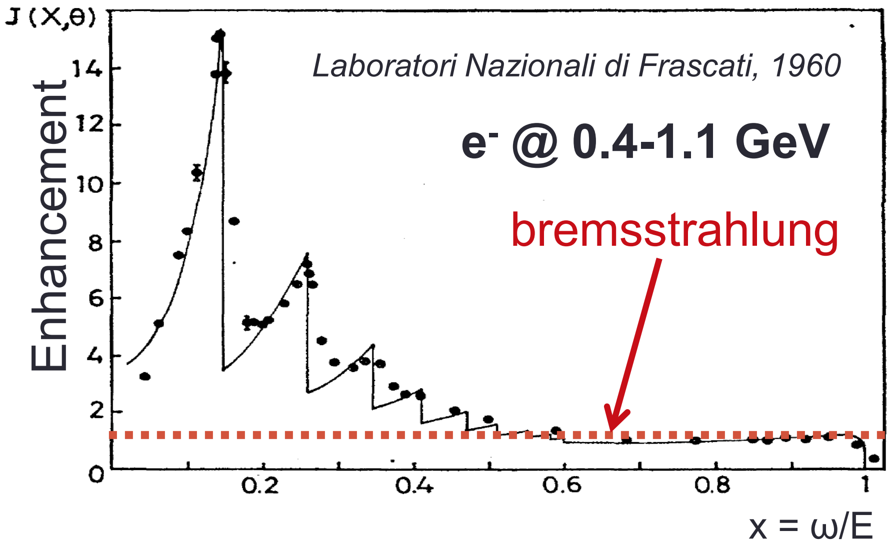


… and in nearly aligned crystals

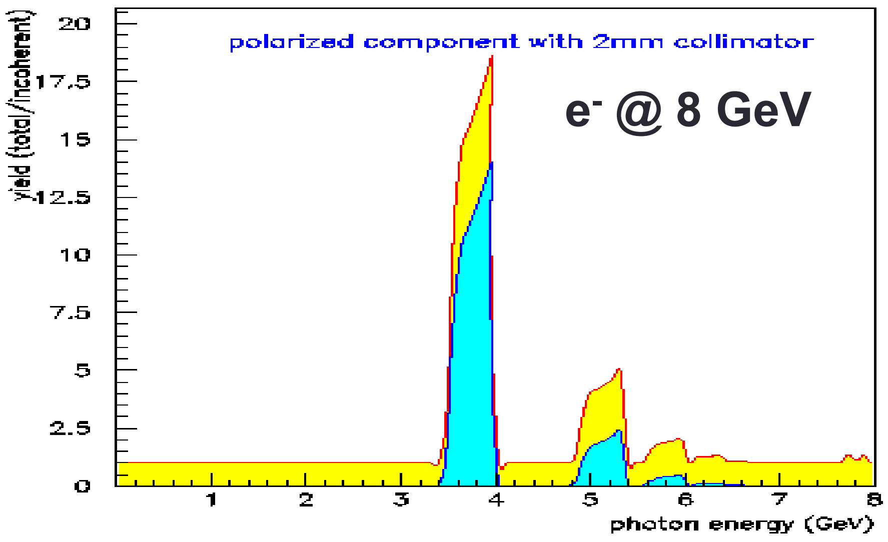


Coherent Bremsstrahlung (1950s) Ter-Mikaelian, Ferretti, Dyson-Uberall





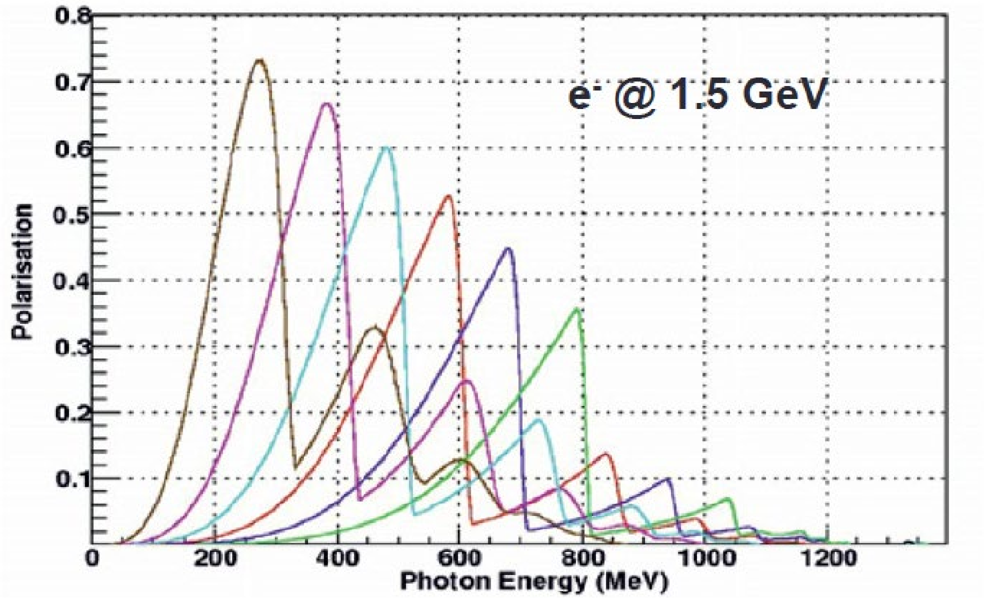
Gamma-ray Coherent Bremsstrahlung sources with GeV electrons



Intense and monochromatic gamma source
Linearly polarized photons

usually exploited
for **photonuclear researches**

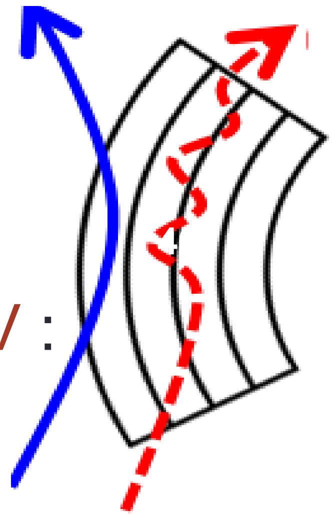
MAMI – Germany
JLAB – USA
MAXLAB – Sweden
ELSA - Germany



Degree of linear photon polarization achievable @MAMI in different diamond orientation

JLAB example: underlying symmetry of the quark degrees of freedom in the nucleon, the nature of the parity exchange between the incident photon and the target nucleon.

Study of radiation emitted by sub-GeV and multi-GeV electrons and positrons in bent crystals



- A lot of attention is devoted to channeling effects of electrons around GeV :
  - Interest for alternatives x-ray sources
  - Relatively large availability of accelerators

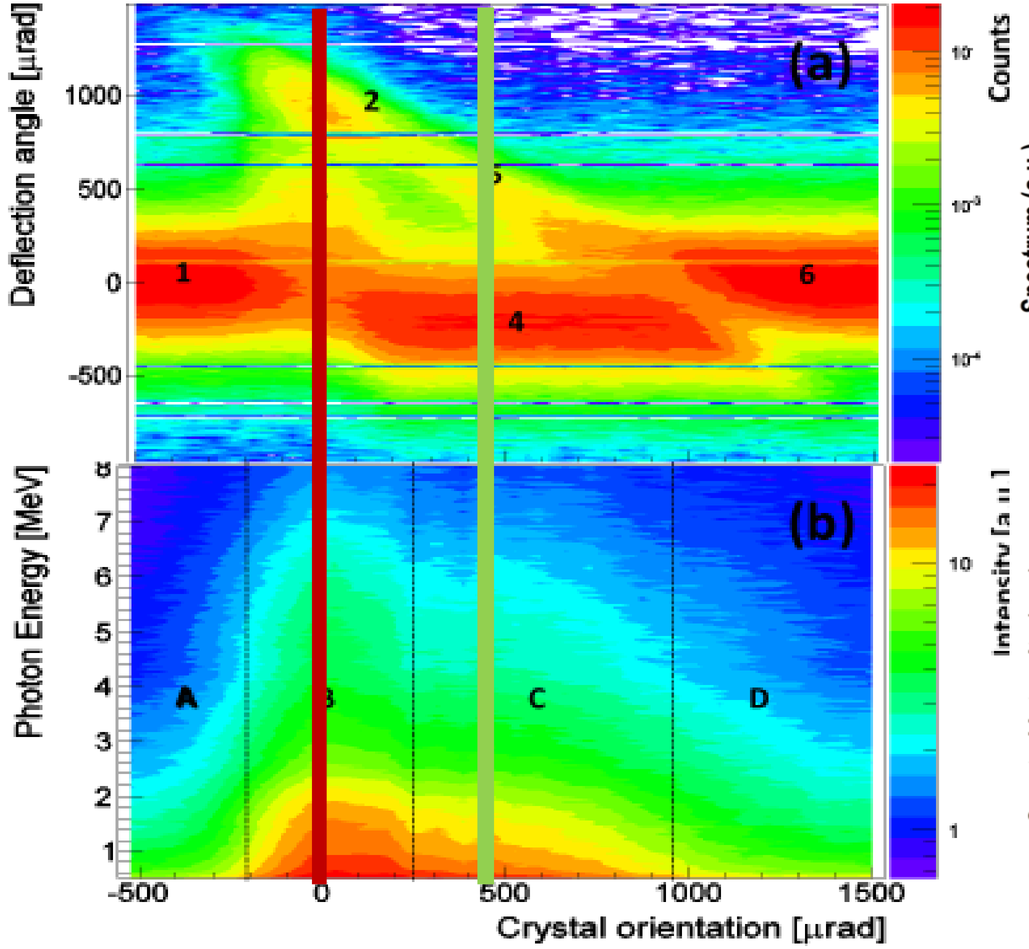
- Study of the influence of the curvature on Channeling Radiation. This experimental knowledge may be exploited to **determine with more accuracy the Channeling Radiation contribution to crystalline undulators**

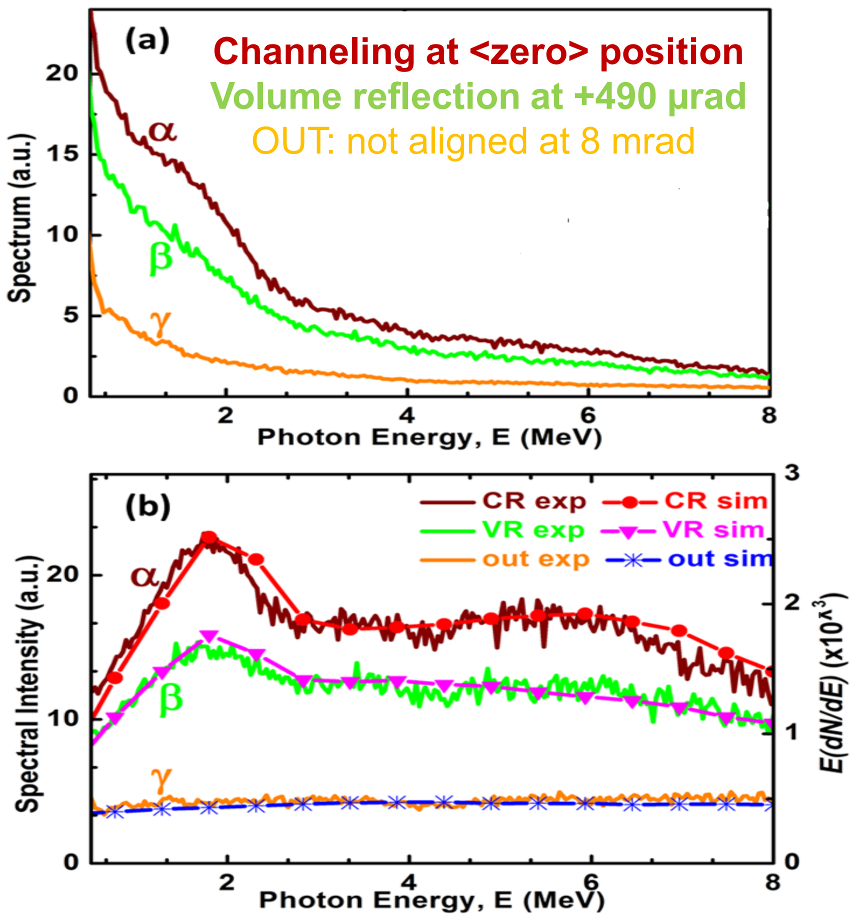
- Radiative losses during **extraction from electron and positrons accelerators**

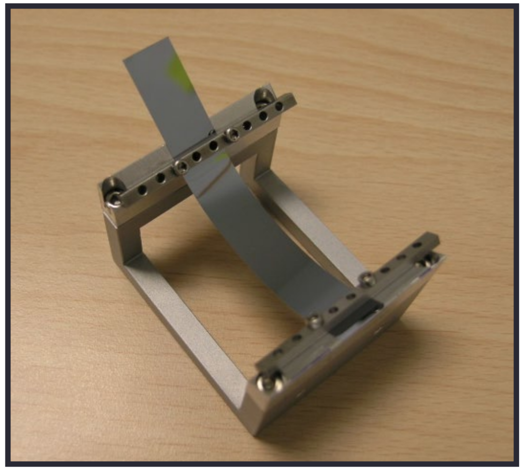
CSN5 Ricerca Tecnologica

Studies co-financed by the CSN5 (ICE-RAD, CHANEL, AXIAL &ELIOT) and EU H2020 MSCA RISE projects PEARL (2014-19) & N-LIGHT (2020-ongoing)

Experimental results on radiation emission







30.5 μm bent Si crystal
(111) Bent planes
900 μrad deflection angle

Volume Reflection and Channeling peak @1.8 MeV and in total a larger acceptance for enhancement than for straight crystals

Conversion of poor emittance e^- beams to γ-beams – base element for crystalline undulators

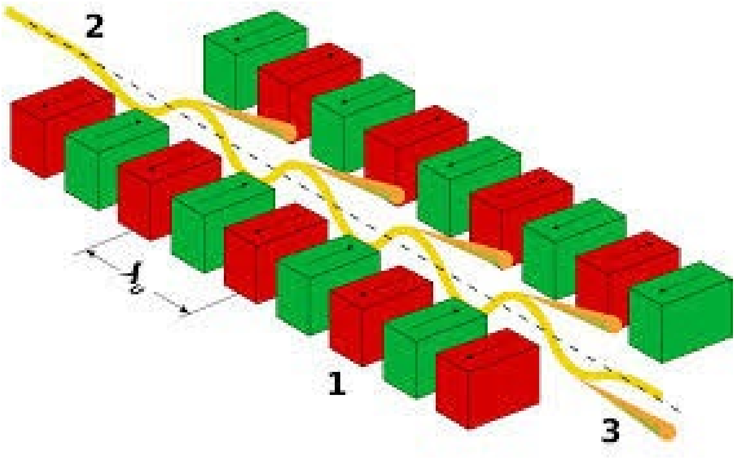
L. Bandiera et al. Phys. Rev. Lett. 115 (2015) 025504.

Crystalline undulator
as an intense X- and γ-ray source

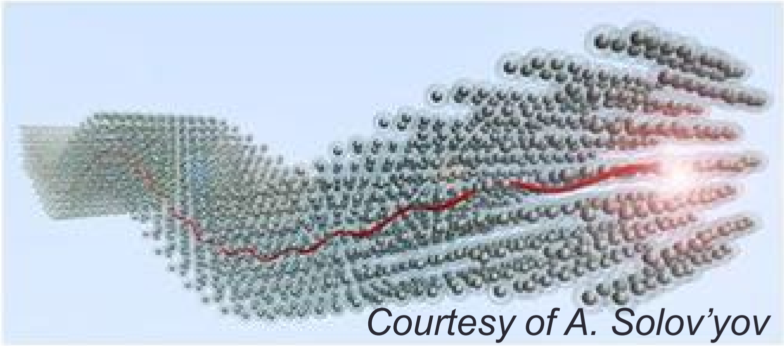
Classical scheme: magnetic undulator in a free electron laser

keV X-rays

λu~ cm



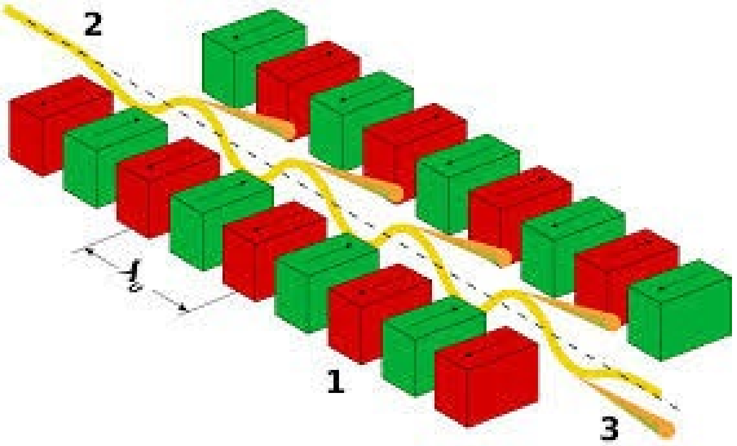
Crystalline undulator as an intense X- and γ-ray source



Artistic view of a Crystalline Undulator based Light Source

Theo: V.V. Kaplin, S.V. Plotnikov, and S.A. Vorobiev, Zh. Tekh. Fiz. 50, 1079-1081 (1980). V.G. Baryshevsky, I.Ya. Dubovskaya, and A.O. Grubich, Phys. Lett., 77A, 61-64 (1980). Korol, Solov'yov, Greiner, J.Phys.G, v.24, L45 (1998)
1st exp: S. Bellucci, et al. Phys. Rev. Lett. 90 (2003) 034801

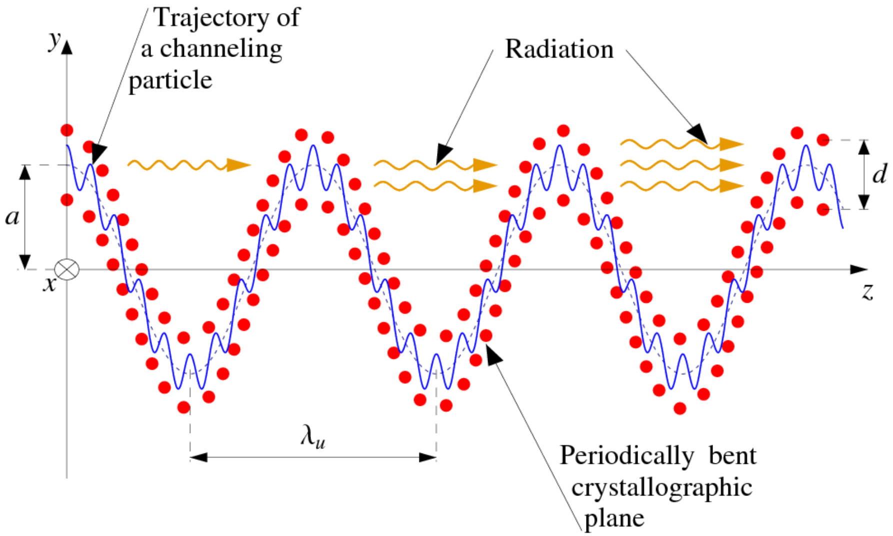
Classical scheme: magnetic undulator in a free electron laser
keV X-rays
λu~ cm



***d*=1…2 Å – the interplanar spacing**
***a*=(10…50)*d* – the amplitude of bending**
λ_u=(10⁴…10⁵)*a* – the period of bending

d << a << λ

Innovative scheme: Crystalline undulator->
Hard X-rays and gamma rays
λu < mm



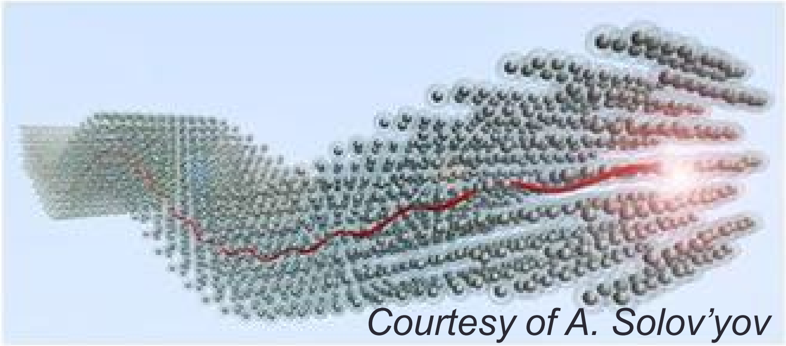
Magnetic undulator:
λu~1 cm, ħω~10 keV

Crystalline undulator:
λu~10 μm, ħω~0.1 …10 MeV

Application in basic science, medical physics and industries.

An operating CU could produce highly monochromatic X- and γ-ray beams

Crystalline undulator as an intense X- and γ-ray source

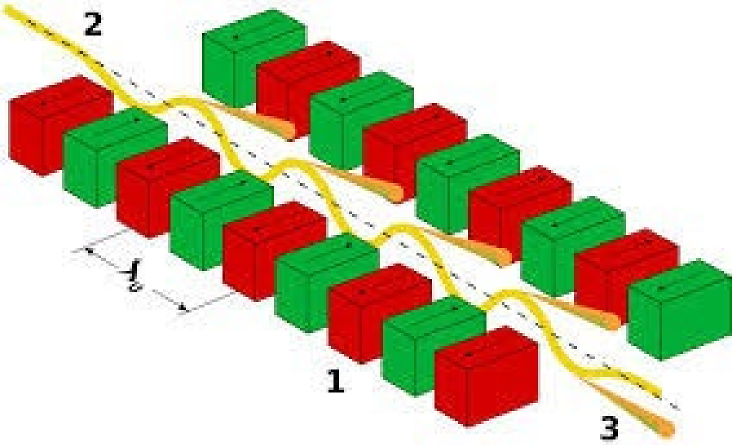


Artistic view of a Crystalline Undulator based Light Source

Classical scheme: magnetic undulator in a free electron laser

keV X-rays

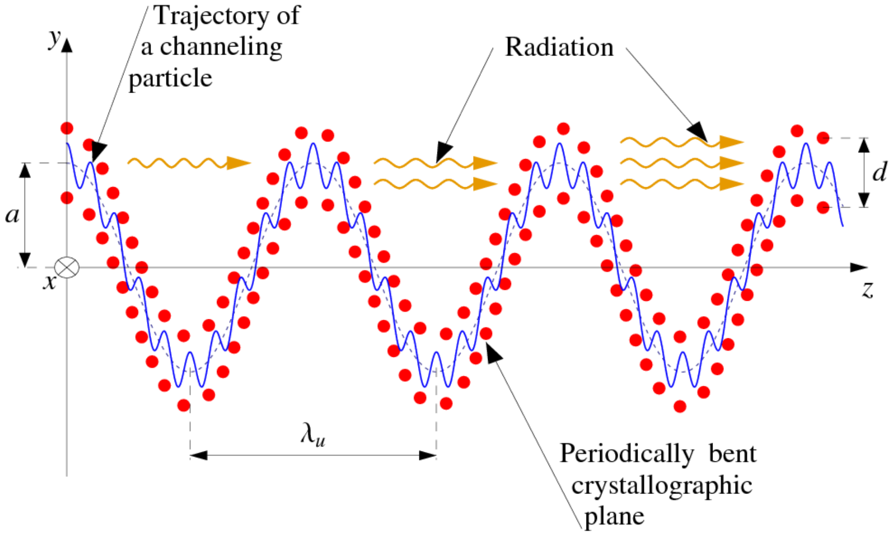
$\lambda_u \sim$ cm



Innovative scheme: Crystalline undulator->

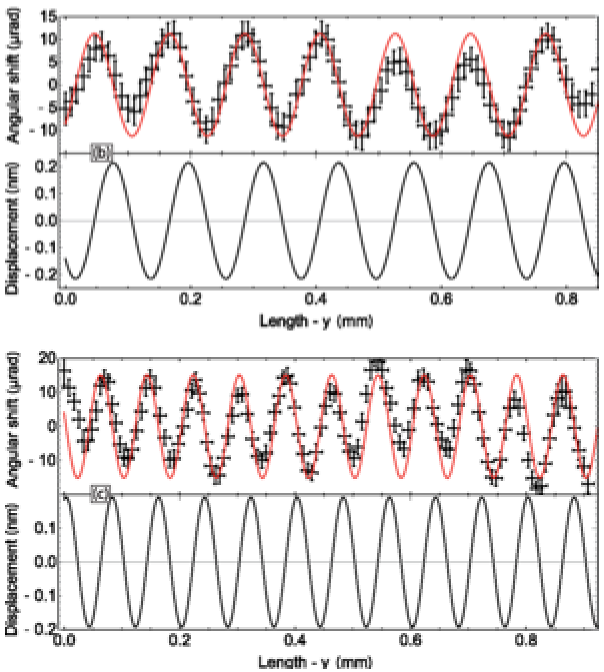
Hard X-rays and gamma rays

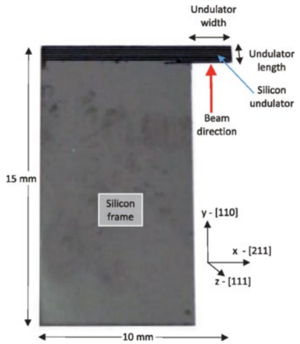
λ_u < mm



Application in basic science, medical physics and industries.

Crystalline undulators made by mechanical processes @INFN Ferrara





ESRF The European Synchrotron

An operating CU could produce highly monochromatic X- and γ-ray beams

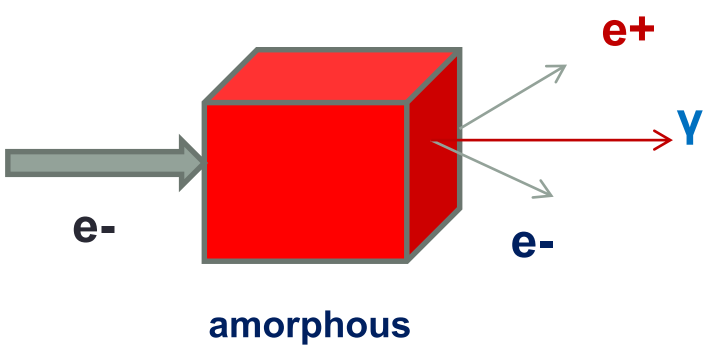
*R. Camattari et al., PRAB **22** (2019) 044701*

CRYSTAL BASED POSITRON SOURCES FOR FUTURE ELECTRON POSITRON COLLIDERS

Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

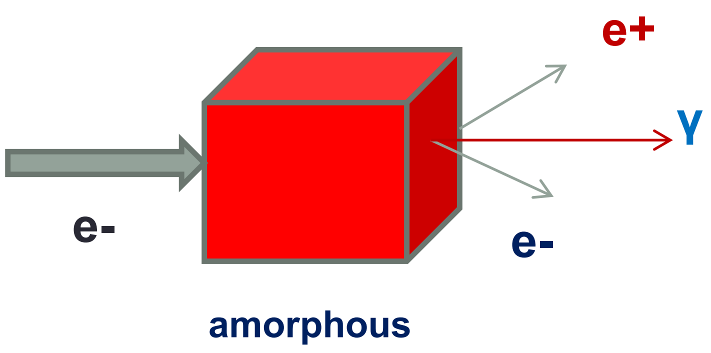
1. **Conventional**



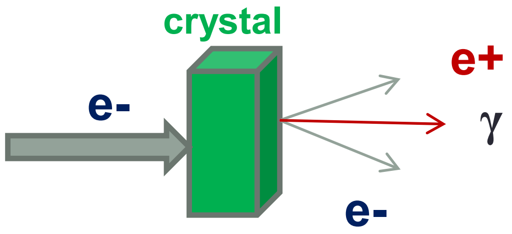
Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

1. Conventional



2. e+ from channeling radiation

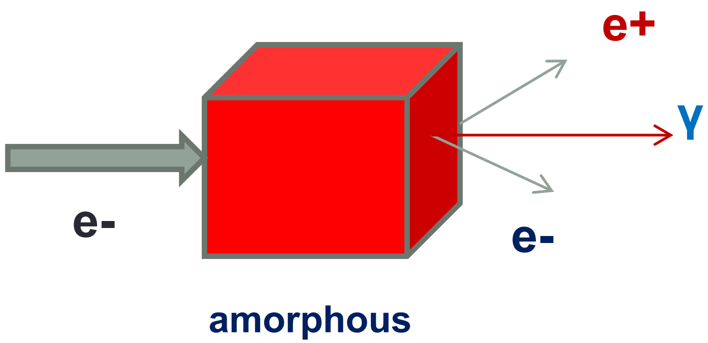


Tests performed at CERN (WA 103) and at KEK

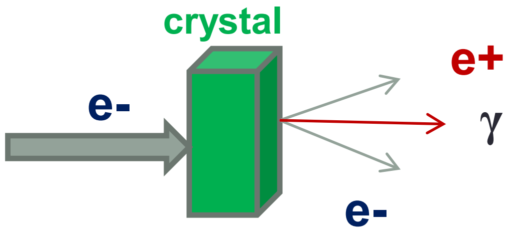
Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

1. Conventional

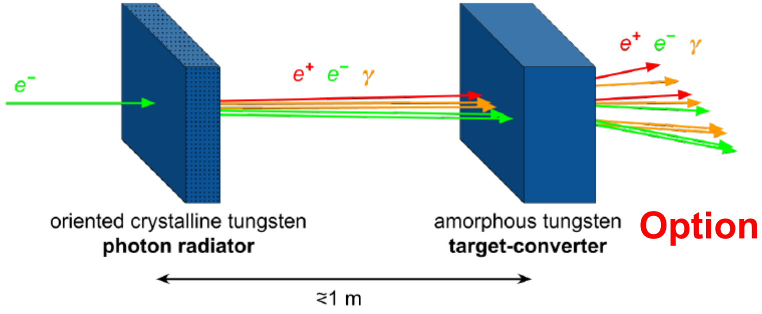


2. e+ from channeling radiation



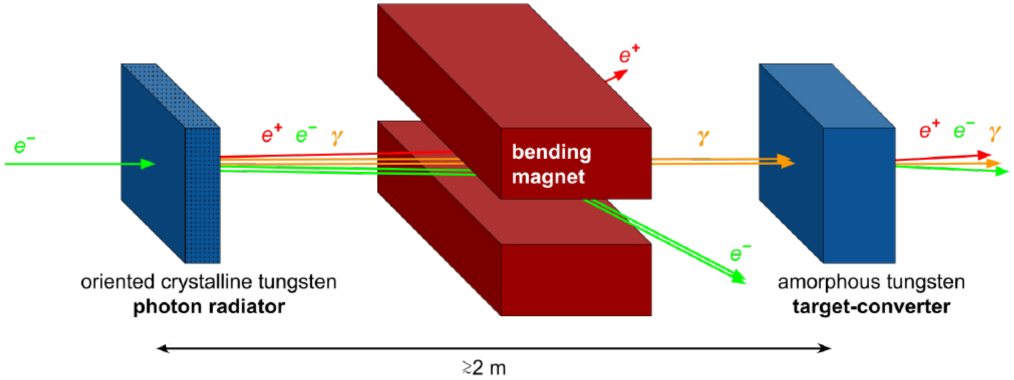
Tests performed at CERN (WA 103) and at KEK

3. Hybrid crystal based positron source



Option for FCCee

Ideal for linear colliders or LEMMA



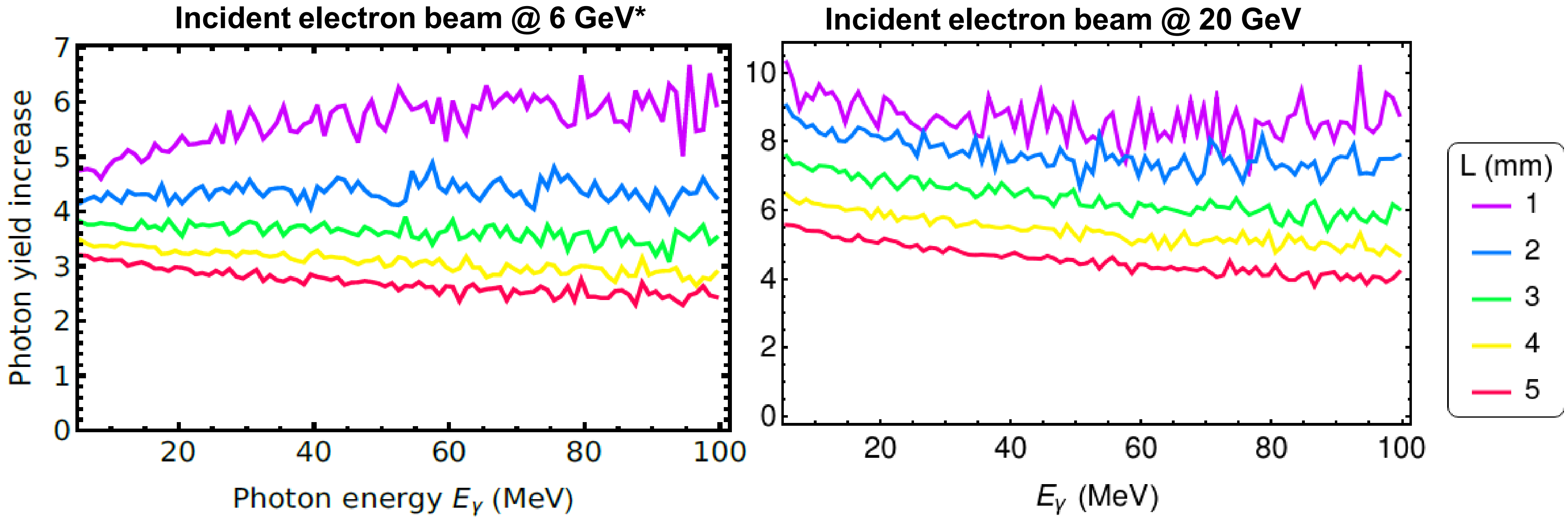
Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868

Hybrid crystal based positron source for future colliders

The main concern for all positron sources is not only the yield but also the energy deposition and the associated PEDD (Peak Energy Deposition Density)

Main advantages of the hybrid source:

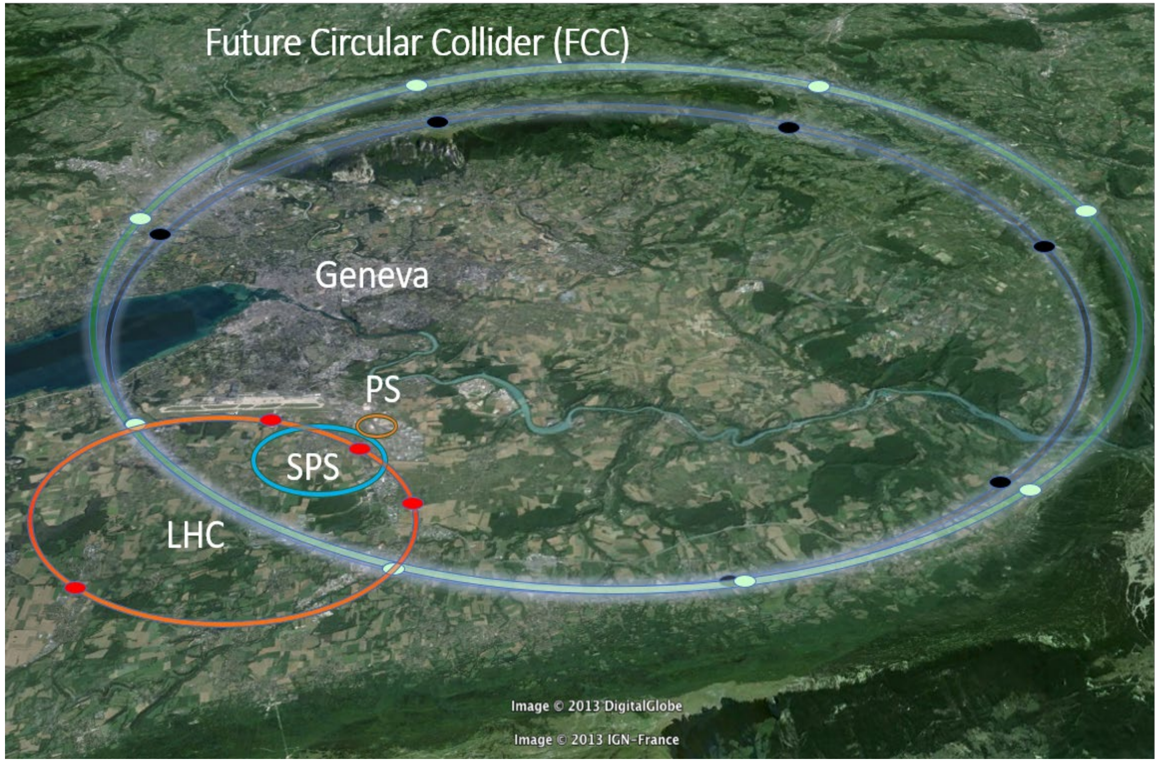
- **Enhancement of photon generation in crystals in channeling conditions ➔ enhancement of pair production in the converter target (Axial potential of a high-Z crystal, e.g., W, provides highest enhancement).**
- **High rate of soft photons ➔ creation of soft e^+ easily captured in matching systems**
- **Decrease of the PEDD in the converter target**



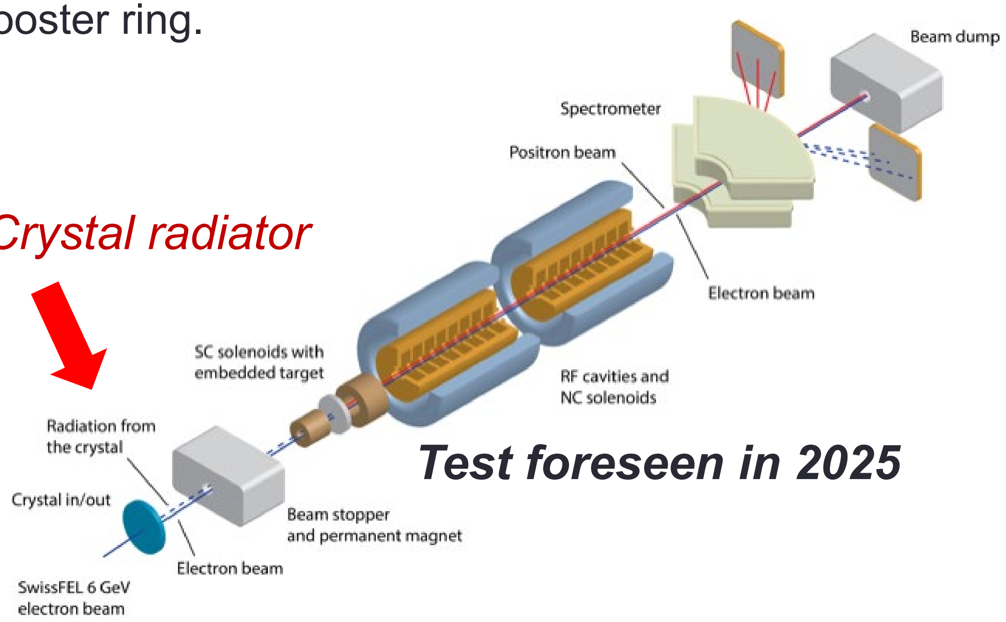
***L. Bandiera et al., Eur. Phys. J. C (2022) 82:699**

FCCee Positron Source

- A positron **bunch intensity of 2.1 × 10^{10} particles** is required at the injection into a pre-booster ring allowing for **a positron yield of 0.5 Ne+/Ne−**. These constraints about intensity and emittance results in a strong heat load, with constraints in the reliability of the targets.
- **The positron source could be inserted at the injection (6 GeV).** As an alternative option for the FCC-ee injector, **a 20 GeV linac is proposed** to provide the direct injection into the booster ring.



Crystal radiator



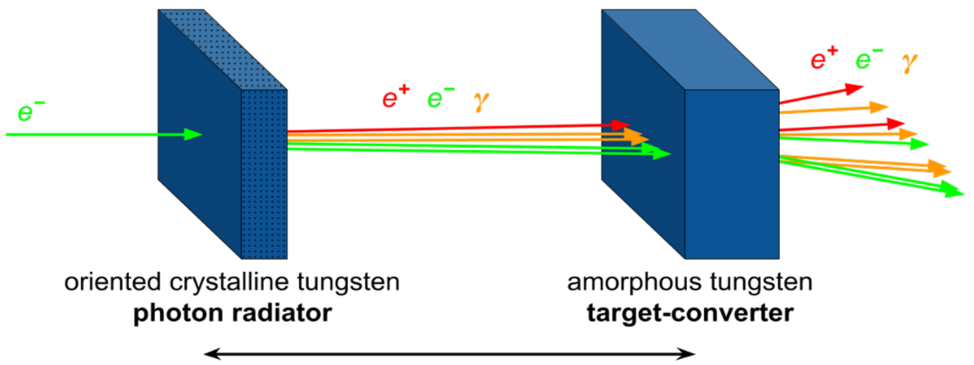
Test foreseen in 2025

Project in CHART on the FCCee Injection System: Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), INFN-LNF (Frascati), SuperKEKB (interested in the P3 project) – ***observer, INFN-Ferrara – radiation from crystals***

Hybrid source - preliminary optimization for FCCee

GEANT4 simulation with the inclusion of radiation in oriented crystals* validated with an experimetal test at DESY with a 5.6 e-beam interacting with a 2.24 mm long W crystal within the CSN5 STORM project.

L. Bandiera et al., Eur. Phys. J. C (2022) 82:699



e+

For more details, see the next seminar of **Prof. Robert Chehab** (IJCLab Orsay)

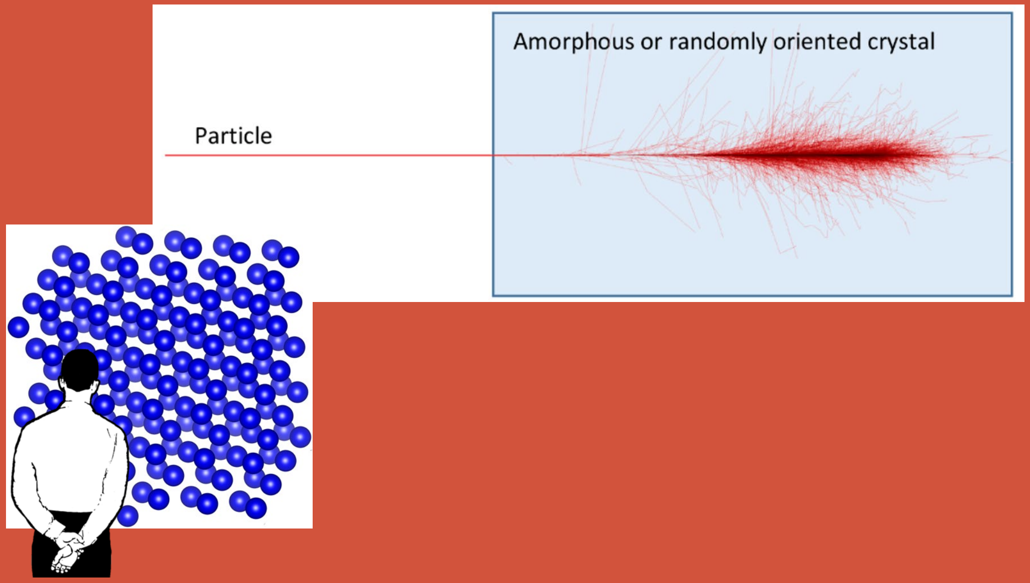
configuration	tgt. PEDD $\left[\frac{GeV}{e^- * mm^3}\right]$	e+ rate [e+/e-]	e+ beam size [mm]	e+ beam divergence [mrad]	e+ mean energy [MeV]
conventional, 17.6 mm W am	0.038	13.7	0.67	25.915	48.7
hybrid, 2mm W cry + 1 m distance + 11.6 mm W am	0.008	15.1	1.24	26.841	45.6
hybrid, 2mm W cry + 2 m distance + 11.6 mm W am	0.004	14.9	1.55	29.208	46.1
hybrid, 2mm W cry + 0.6 m distance + 11.6 mm W am	0.013	15.1	1.05	27.392	46.2

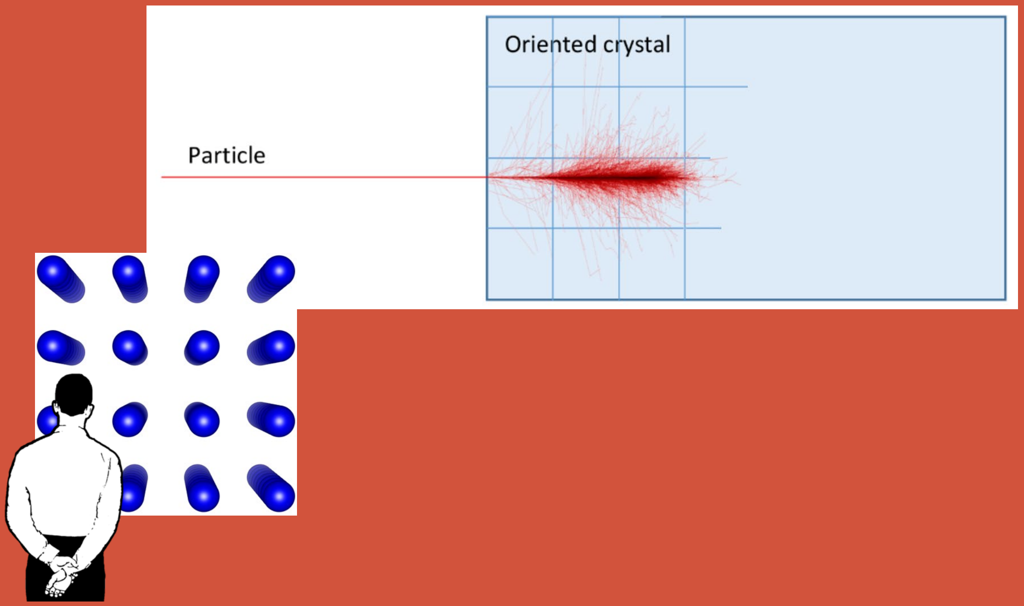
Comparable e+ rate at the target exit, but much less PEDD in the converter target!

We are also conducting irradiation tests at MAMI to measure the resistance of the targets (Co-financed by CSN1 RD-MUCOL)

Sept 2022: 3 years MoU between INFN-Ferrara and CNRS-IJCLab

*Synergy with the H2020 MSCA IF Global TRILLION of A. Sytov
**Work done by M. Soldani and A. Sytov under the supervision of I. Chaikovska (IJCLab)*

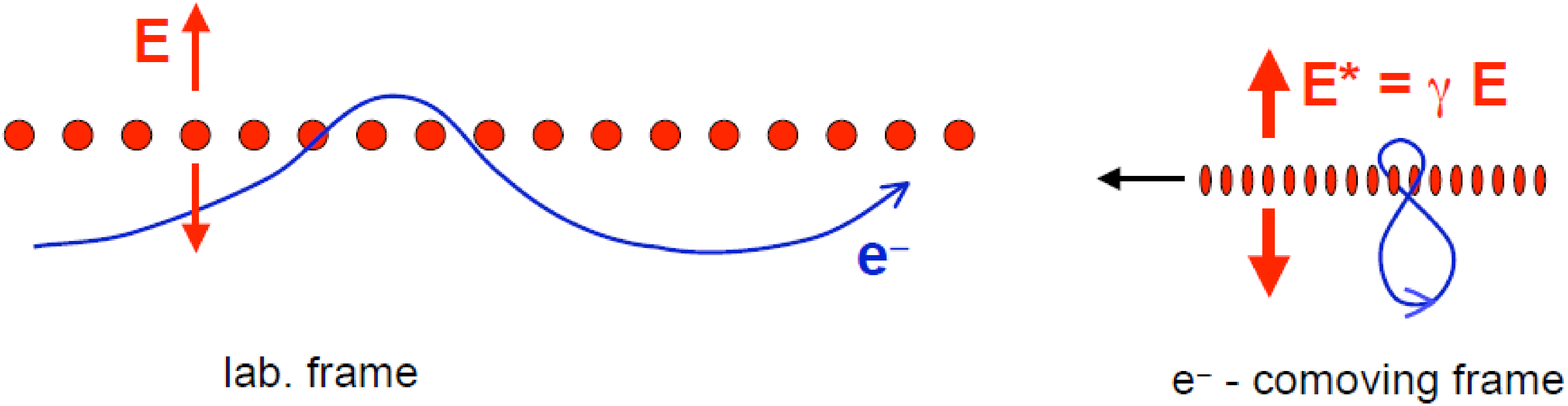




STRONG CRYSTALLINE FIELD

- Ultra-compact detectors for the energy and the intensity frontiers
- The NA62 & KLEVER experiment @CERN

Strong field in oriented crystals



In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

Being the Axial field of high-Z crystals *E* ≈ 10^{11} V/cm

At beam energies > 10 GeV, E* can reach the **Critical Schwinger QED field**:

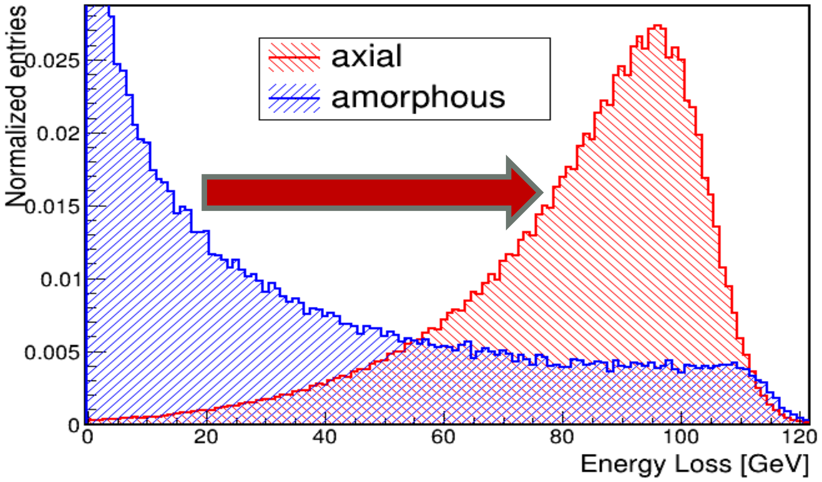
$$E_0 = m^2c^3/e\hbar \simeq 1.3 \times 10^{16} V/cm$$

above which electrodynamics becomes non linear

V. N. Baier and V. M. Katkov, J. Exp. Theor. Phys. 26, 854 (1968)
U. I. Uggerhøj, Rev. Mod. Phys. 77, 1131 (2005)

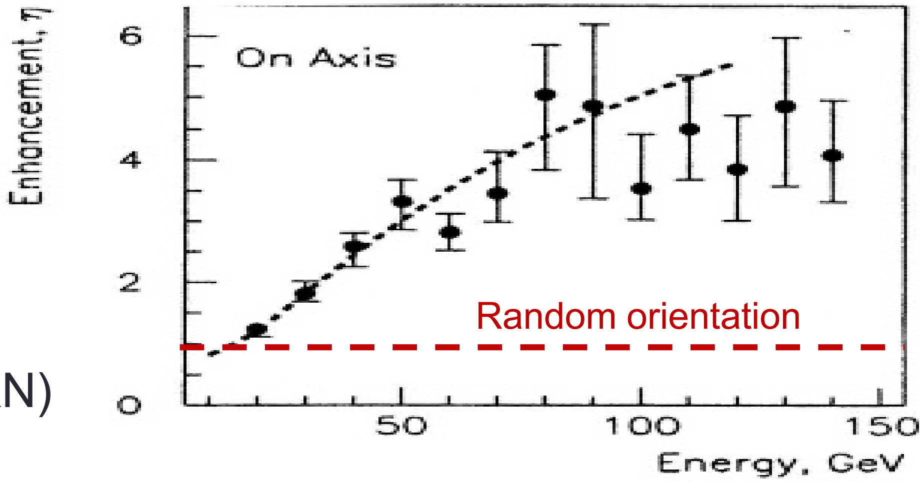
Radiation and pair production in axial alignment

Radiative energy loss spectrum of 120-GeV e^- aligned with the <110> axis of a 2.8 mm long Ge crystal



Enhancement of pair production in a W crystal axially oriented – compared to random orientation Vs. photon energy

(NA43 exp. @CERN)



Strong field regime

$$E^* \geq E_0$$

- ***Radiation length reduction***
  - **X_0 decreases with initial energy increase.**
- ***Angular range:***
  - **few mrad up to 1°** of misalignment between particle direction and crystal axes;
  - Does **NOT** depend on particle energy.

Strong increase in the energy radiated by the electrons and in the pair production probability by high-energy photons!

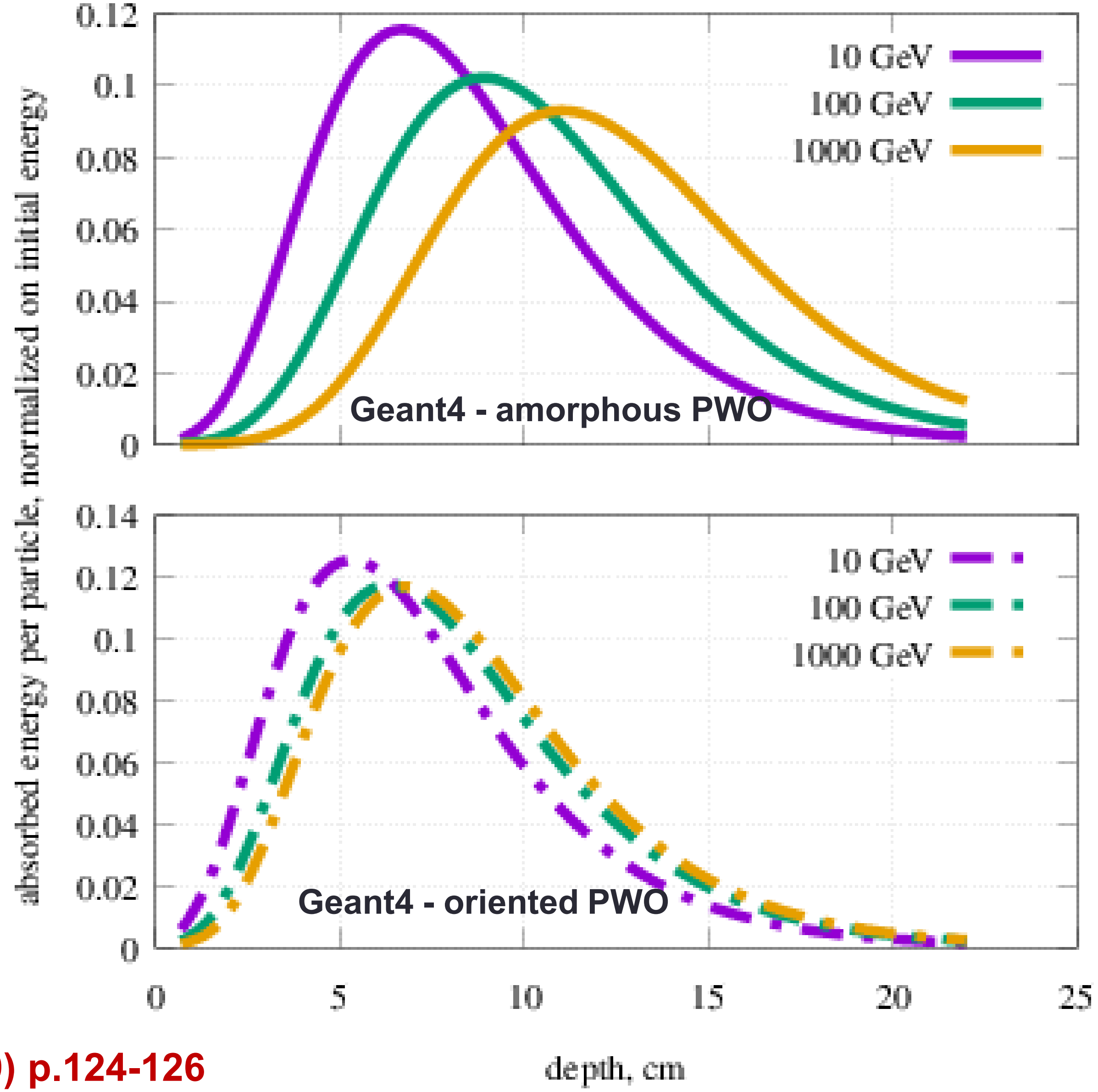
..e.m. shower acceleration

electromagnetic shower is way more compact

or equivalently

effective radiation length X_0 is much shorter

The modern electromagnetic calorimeters are designed for experiments at energies of hundreds of GeV/TeV and these enhancement effects are expected to be quite important in this energy range.



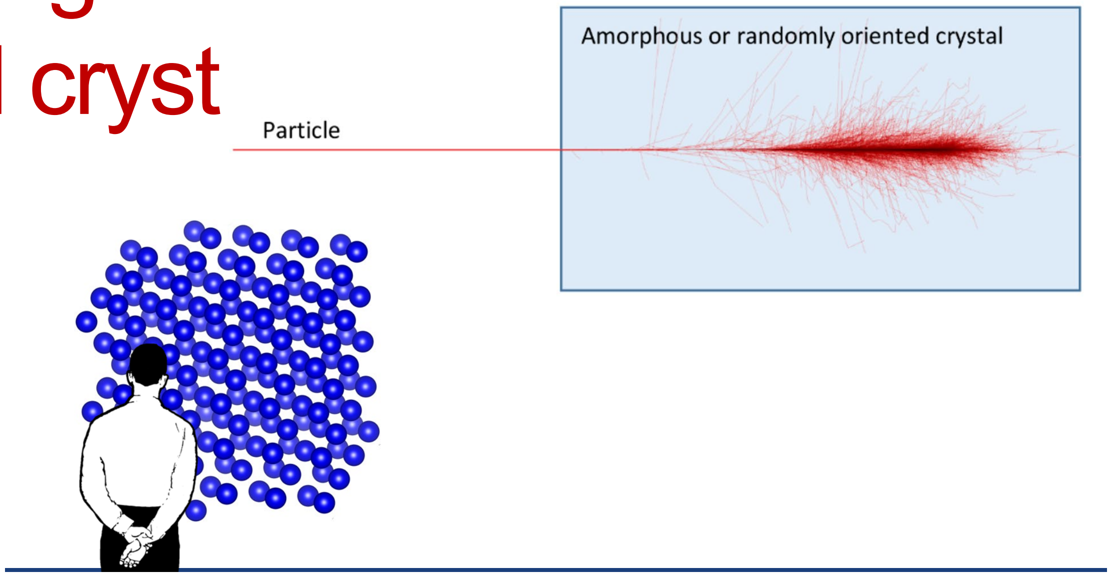
L. Bandiera, V.V.Haurylavets, V. Tikhomirov NIM A 936 (2019) p.124-126

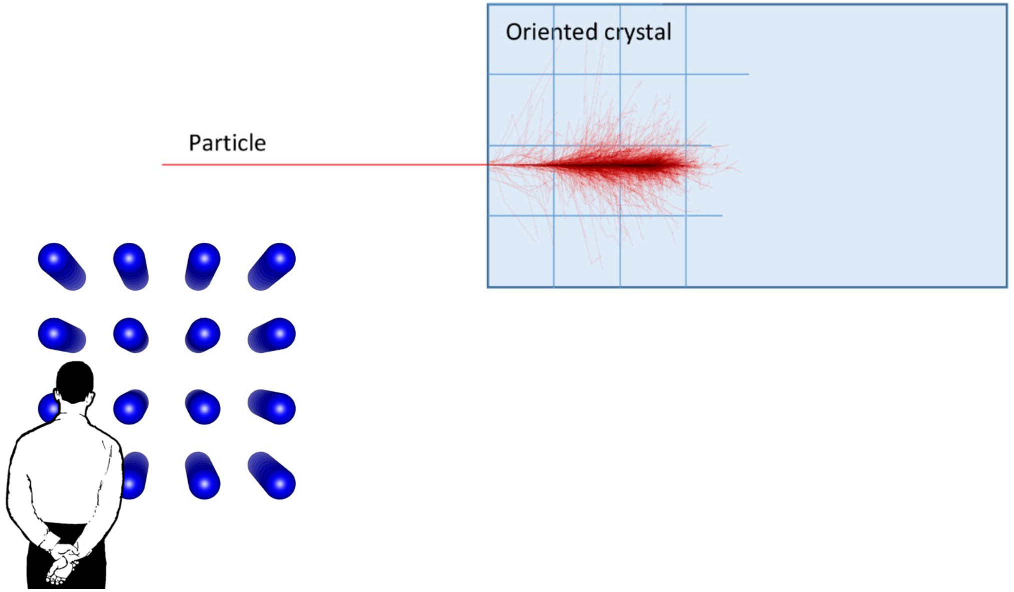
What happen if the electromagnetic calorimeter is made of oriented cryst

- Using oriented scintillator crystal one may **containing e.m. showers initiated by particles with energies even above 100 GeV in a reduced volume/weight;**

- **Cost reduction!!!**

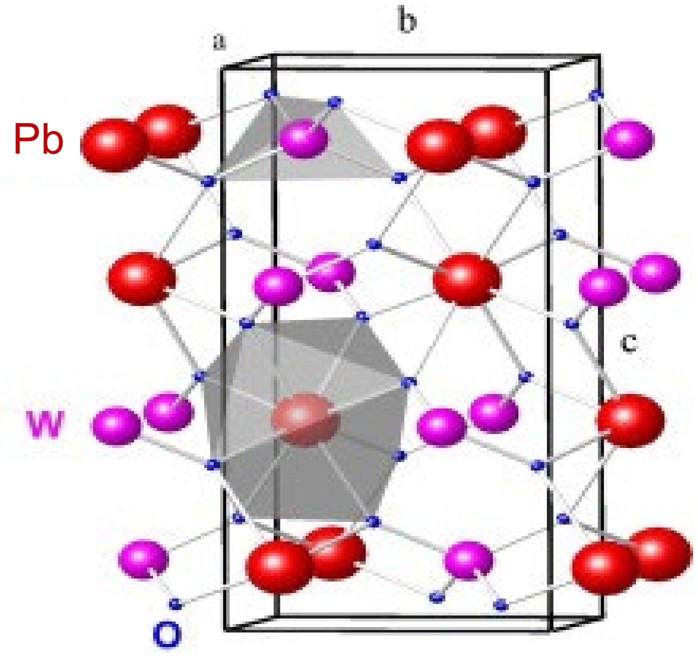
- **Interesting application in particle and astroparticle phyiscs!!!!!**

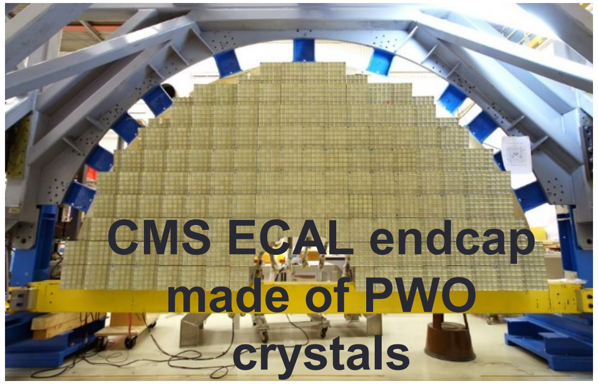


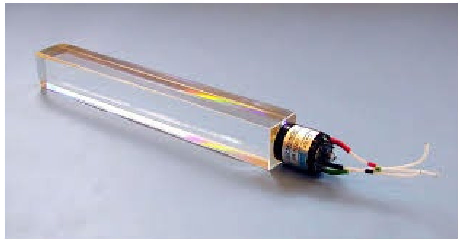


Lead tungstate ($PbWO_4$) – a high-Z crystal scintillator

- scintillator, with well-peaked light emission in the blue
- optically transparent
- exploited by the CMS ECal → well known
- **high density, high *Z* (X_0= 0.89 cm)**
- **radiation hard**
- **cheap fabrication into big samples and with good crystalline quality** (mosaicity around 0.1 mrad vs. ~mrad of strong field)







Axial potential

	[100]	[001]
interatomic pitch	5.456 Å	12.020 Å
U_0	~700 eV	~500 eV
$\gamma E=E_0$	~25-30 GeV	

Different PWO samples investigated

N.B. Within ELIOT and STORM experiments, several scintillator (PWO, BGO, CsI, YAG) and a Cerenkov (PbF2) crystals has been tested. All the tests demonstrated an increase in the electromagnetic processes even at sub-GeV energies (experiment at MAMI in Germany)

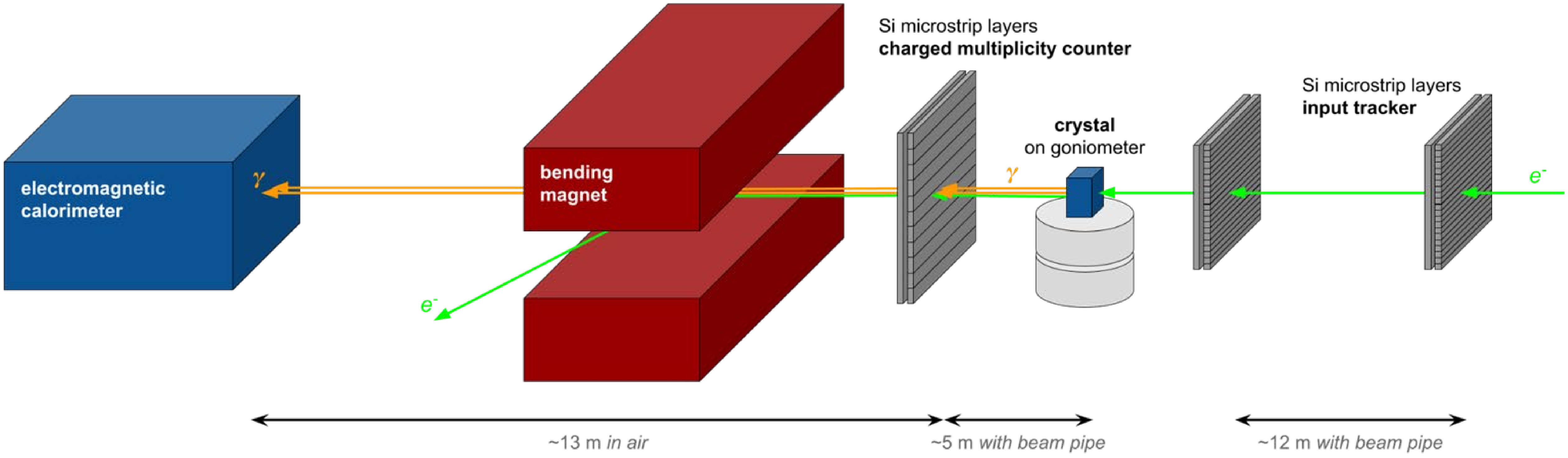
INFN CSN5 STORM project

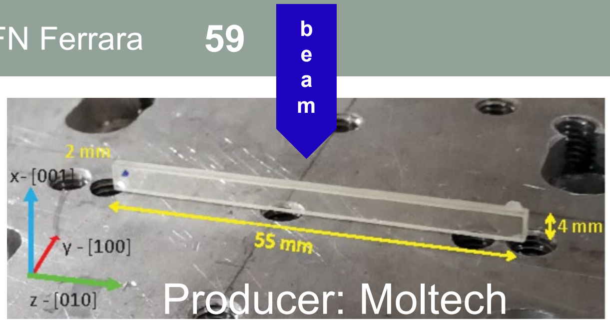
Status of the investigation

Different tests with **electron and positron beams**, in particular at

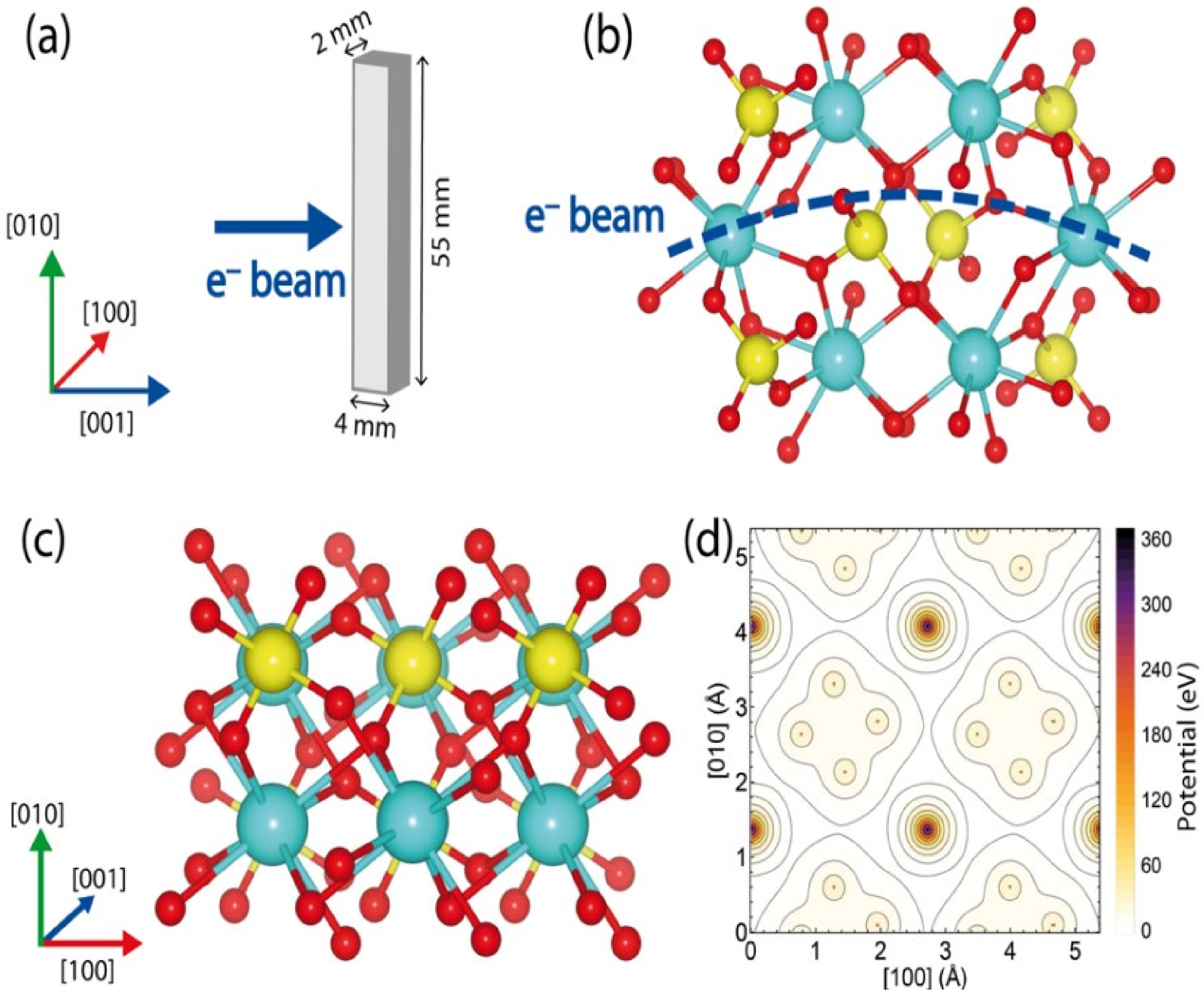
CERN H4/H2 lines e^+ & e^- at **120 GeV/*c***

PWO in full Strong Field regime

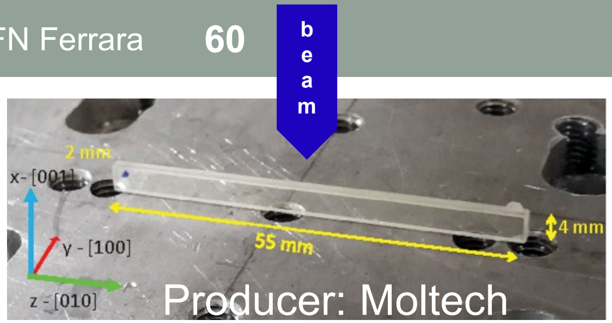


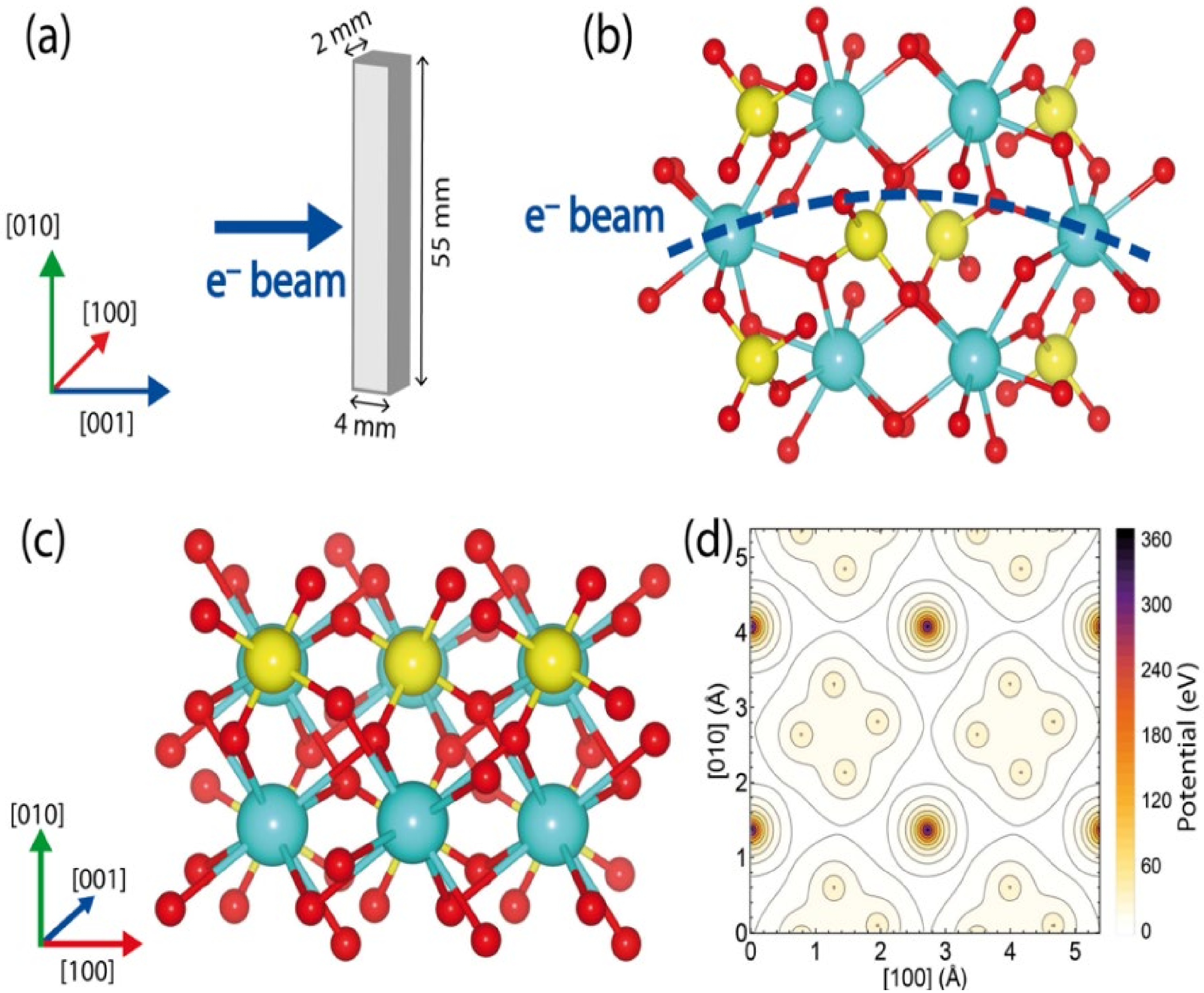


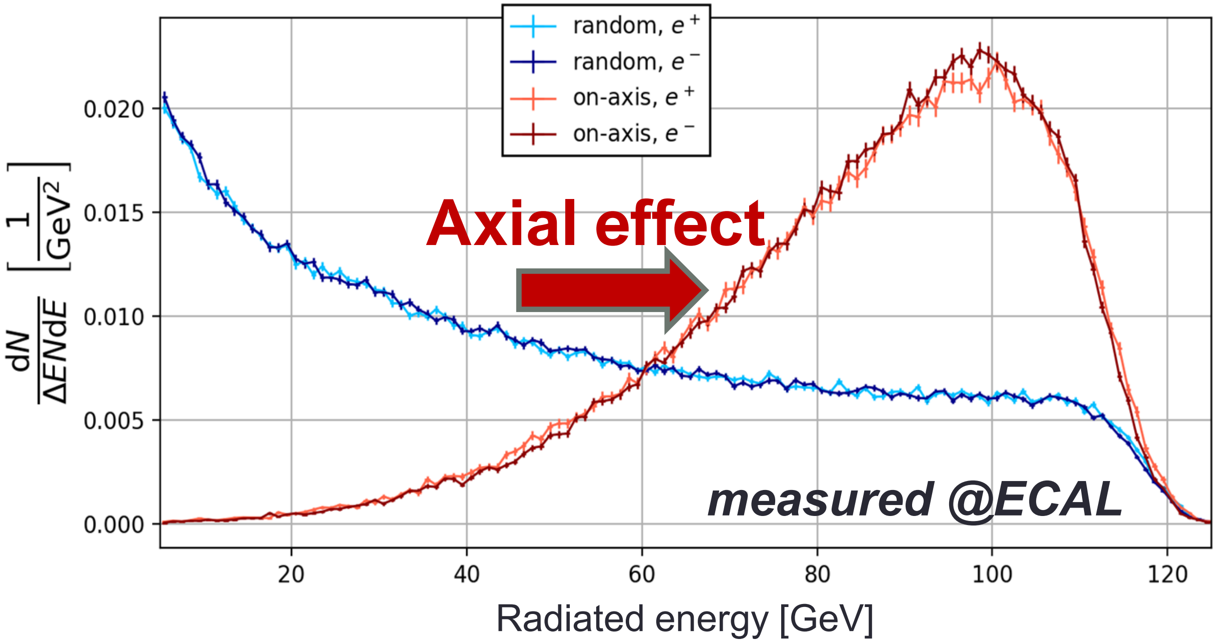
First test with a 0.45 X_0 PWO crystal



First test with a 0.45 X_0 PWO crystal







random spectra: standard Bremsstrahlung (Bethe-Heitler)

≠

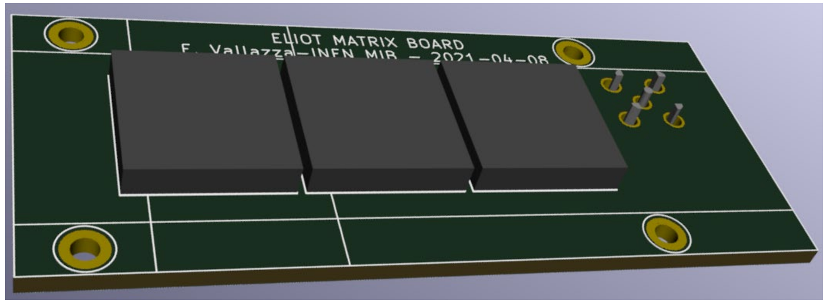
on-axis spectra: <u>enhancement in high-energy component</u>

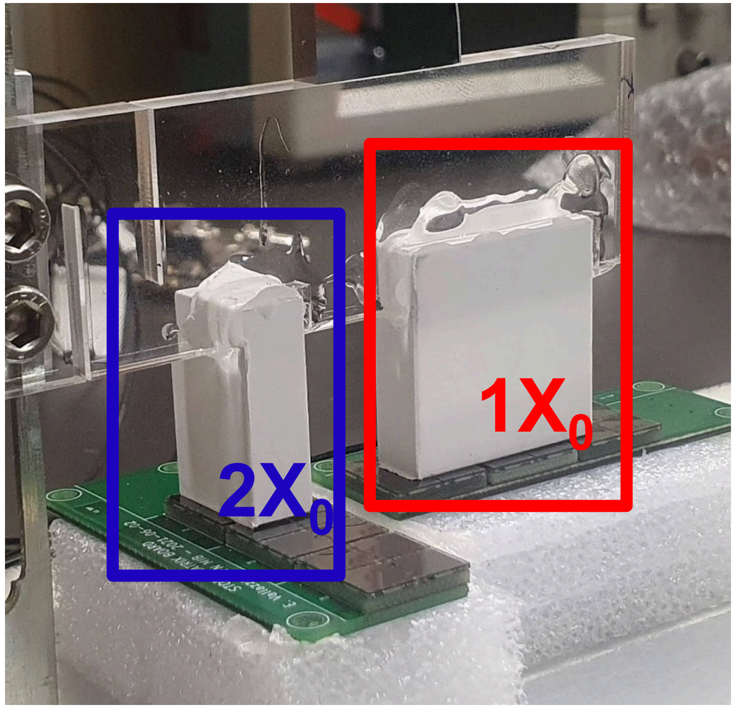
(peaked @ ~100 GeV)

L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

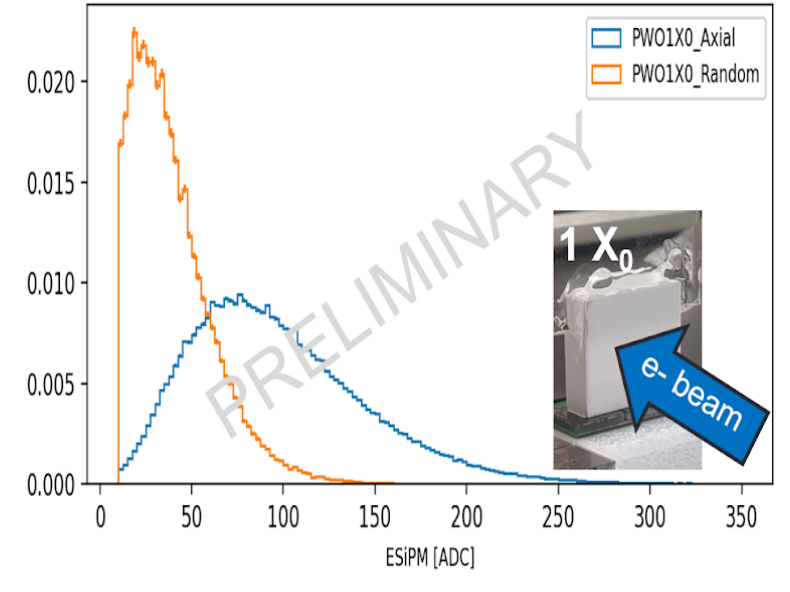
STORM experiment

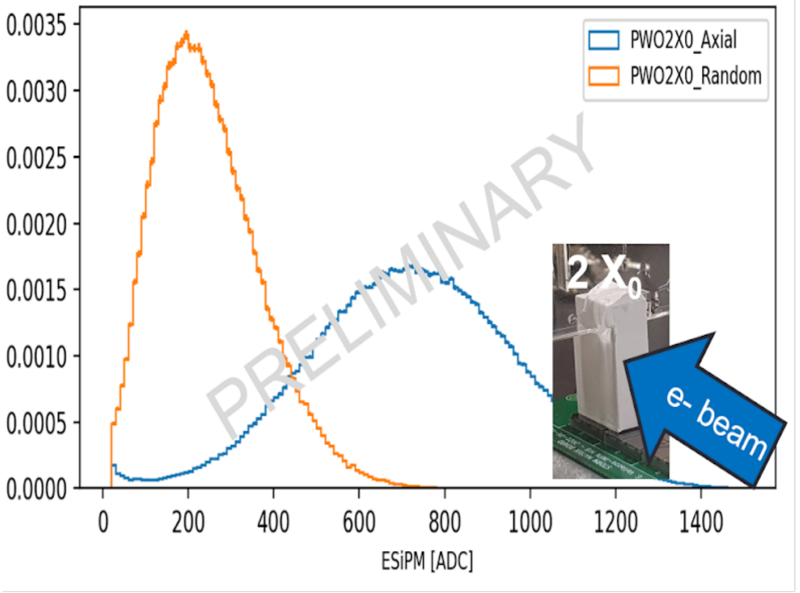
Results with single crystals: Light yield





Scintillation light enhancement in axially oriented crystals





axial / random ratio ≈ 2.5 *axial / random ratio ≈ 3*

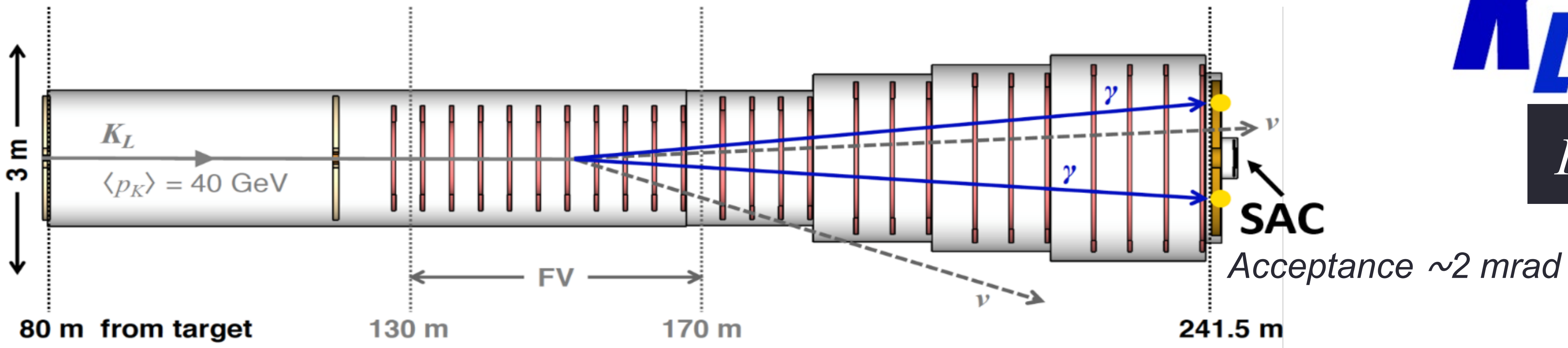
e^- at **120 GeV/*c*** interacting with PWO crystals

Good agreement with preliminary simulation with modified Geant4

Elective application: the KLEVER Small Angle Calorimeter

KLEVER is a proposed experiment in North Area @CERN as successor of NA62 in the same experimental area

$K_L \rightarrow \pi^0 \nu\nu$



from K^+ (charged – NA62 experiment) to K_L (neutral) → new challenges

High-performance e.m. calorimeter is required for the **reconstruction of the π^0 coming from $K_L \rightarrow \pi^0 \nu\bar{\nu}$**, while any extra photons must be vetoed with very high efficiency!

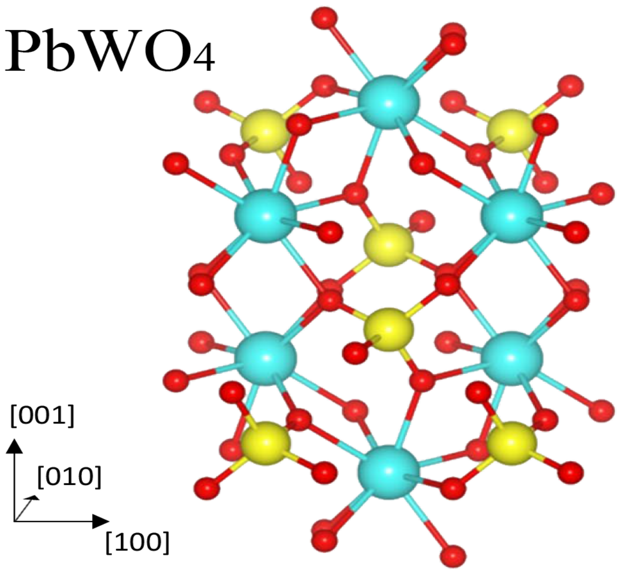
This performance must be attained **while maintaining insensitivity to more than 500 MHz of neutral hadrons** in the beam

An ultra-compact Small Angle Calorimeter for KLEVER

Requirements:

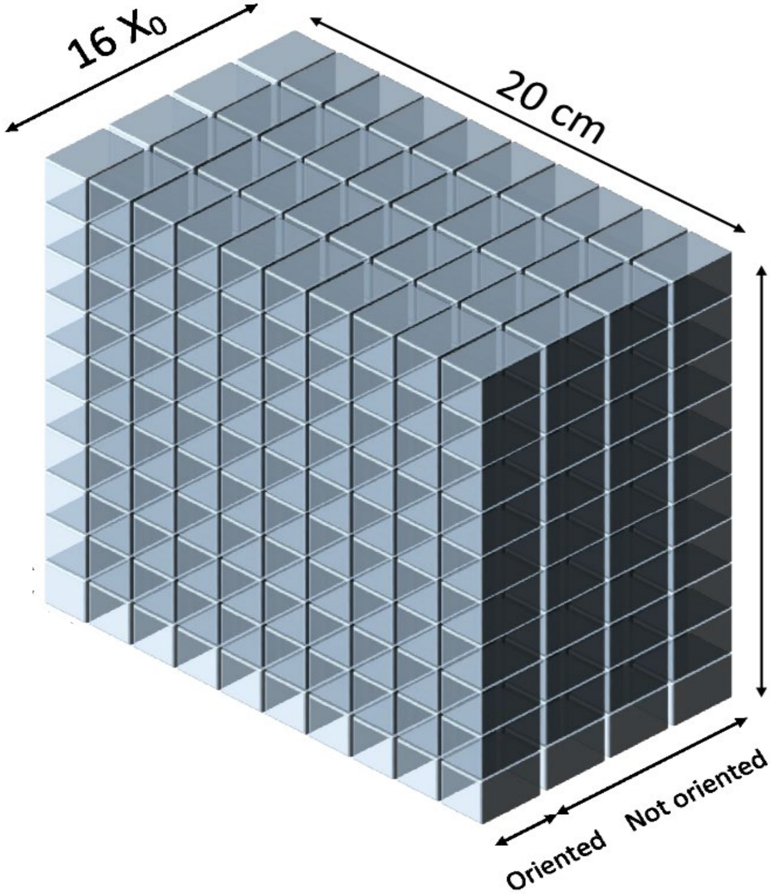
- Smallest X_0/λ_{int} possible in order to provide maximum transparency to beam hadrons while maintaining high photon-conversion efficiency- > **high-Z oriented crystals with reduced X_0**
- Excellent time resolution -> **Cerenkov readout**

PbWO4



INFN CSN5 OREO project

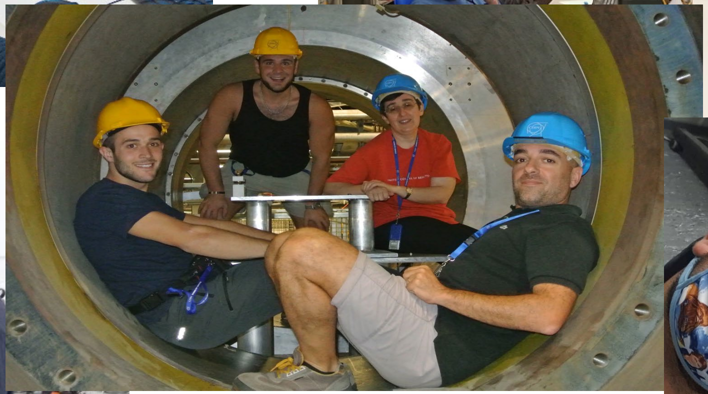
POSSIBLE KLEVER SAC DESIGN



Transverse and longitudinal segmentation for a better n/γ discrimination

INFN Ferrara team and collaborators on Crystal Channeling





INFN and University of Ferrara
INFN Legnaro Lab and University of Padua
INFN of Milan Bicocca and Insubria University
INFN and University of Milan
INFN and Sapienza University of Rome
INFN Frascati Lab



Main external collaborations
CERN, MAMI, DESY, MBN Center, ESRF, Kharkiv, INP Minsk, IJCL Orsay

Summary and Conclusions

We introduced briefly…

- Channeling of charged particle beams in bent crystals with application in the CERN LHC collimation, in experiments on spin precession for search of physics Beyond Standard Model and in beam extraction from electron and positron accelerators
- Channeling radiation with application in intense beam and positron sources
- Strong crystalline field and the possibility to realize ultra-compact calorimeters with interesting application in fixed-target experiments at CERN (NA62&KLEVER)
- In conclusion, **crystal channeling is a tool for a lot of application in high-energy physics and we are confident that new adventures and surprises await us in this exciting research field!**

THANK YOU FOR THE ATTENTION!