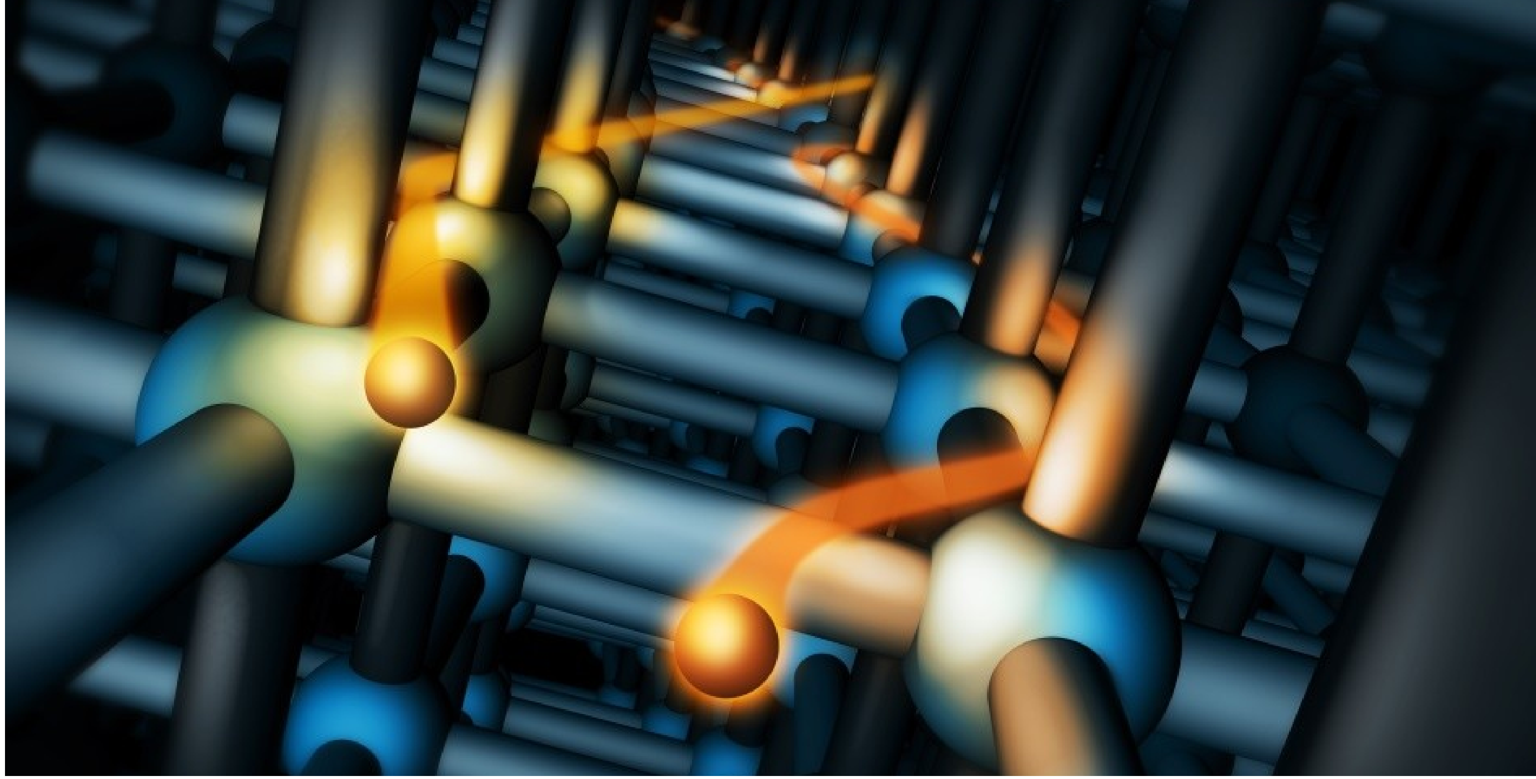
Experimental results from crystals

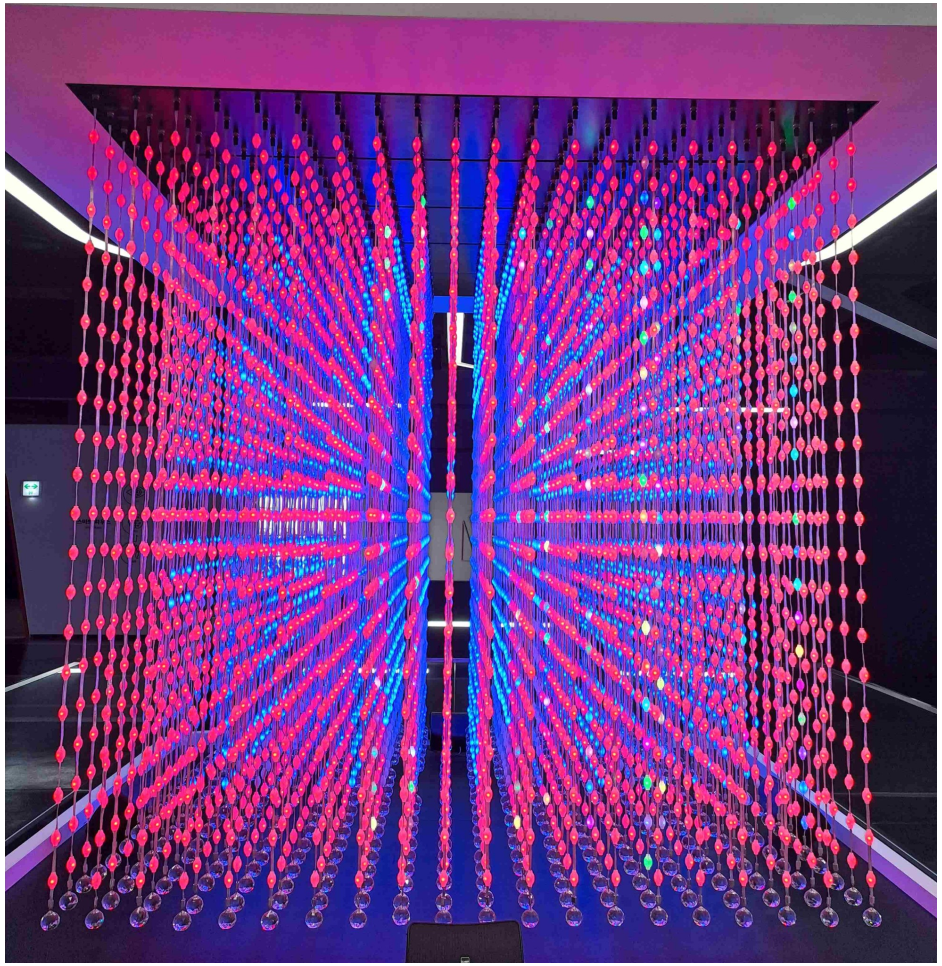


Alexei Sytov
on behalf of INFN Ferrara

Quarta Giornata Acceleratori
03/04/2025 INFN-LNL

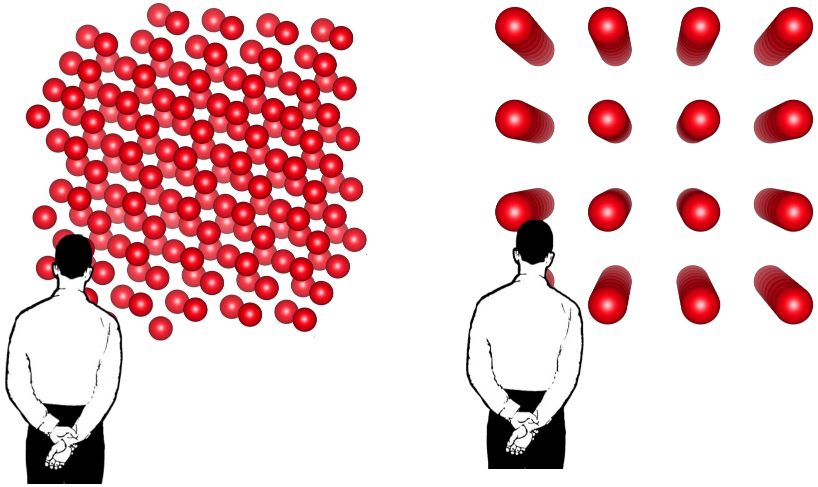
INFN
FERRARA
Istituto Nazionale di Fisica Nucleare

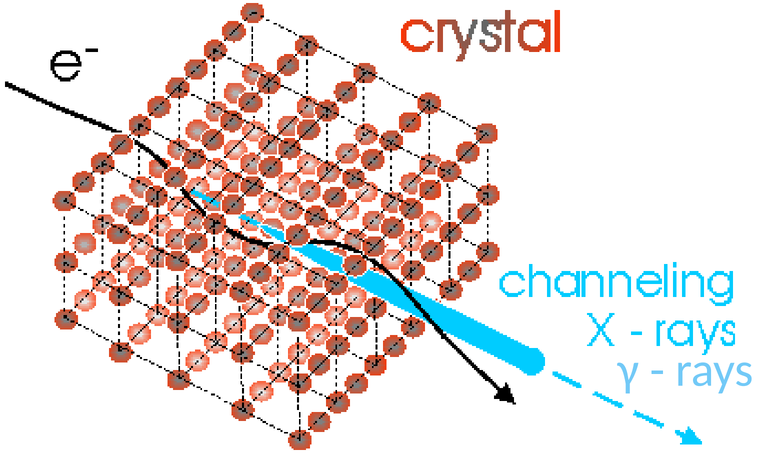
How an oriented crystal looks like



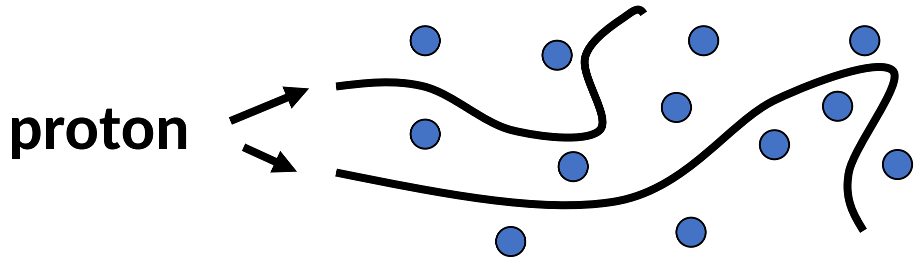
from National Science Museum, Daejeon, Korea

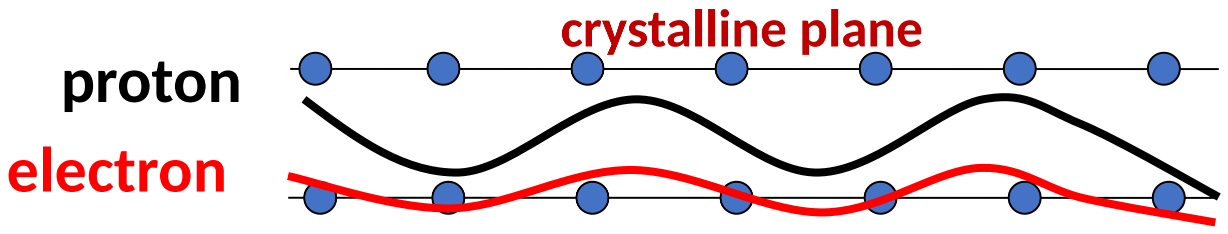
Non-oriented crystal | **Oriented crystal**

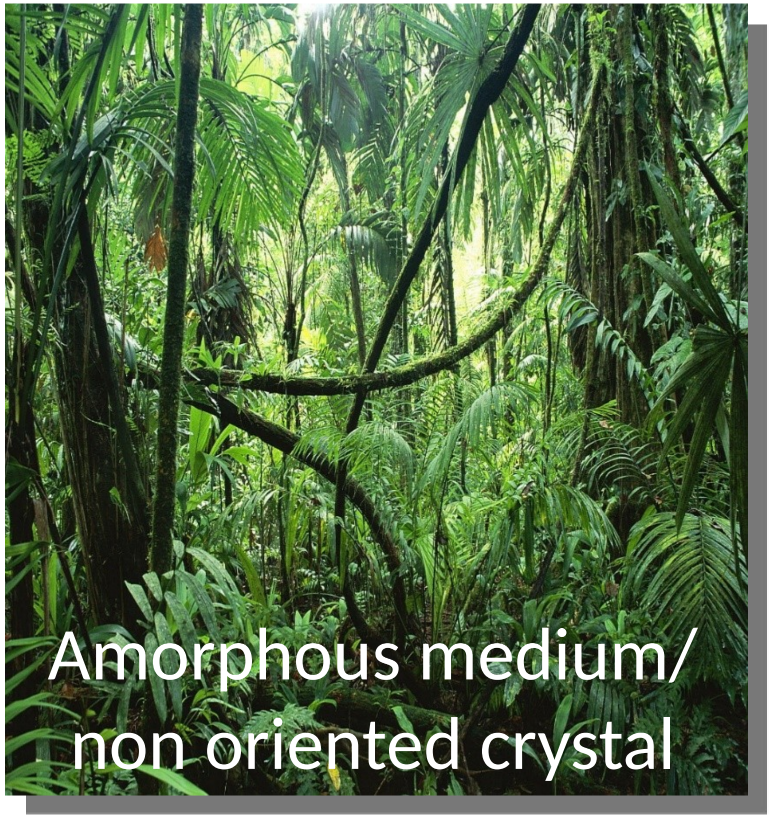




Channeling: trapping of charged particles



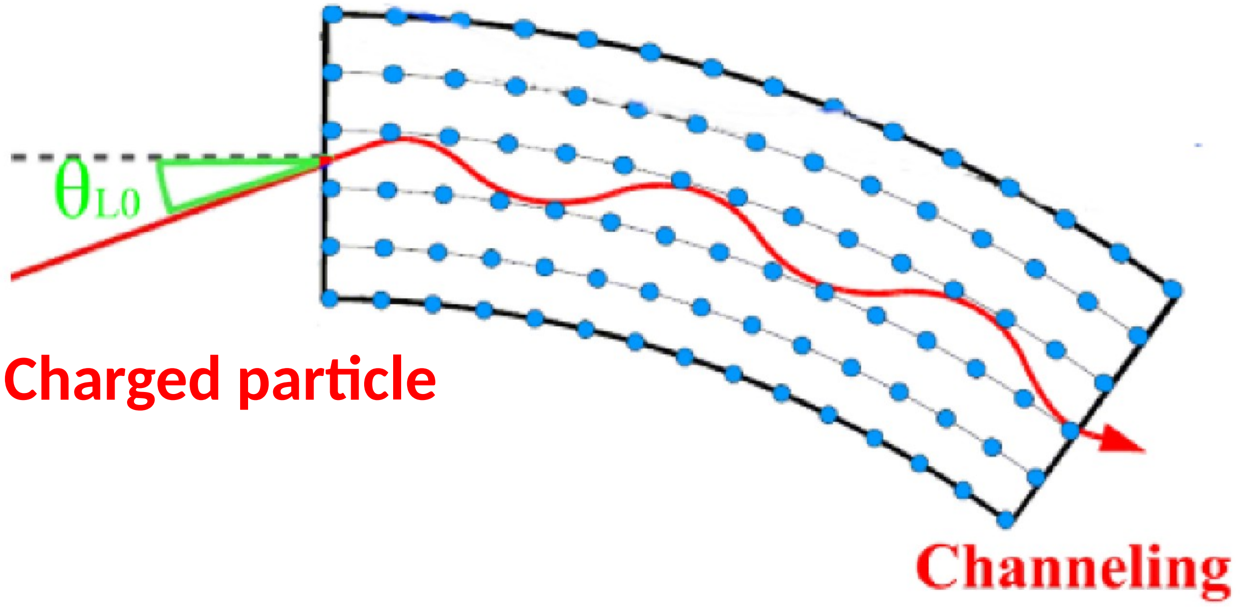


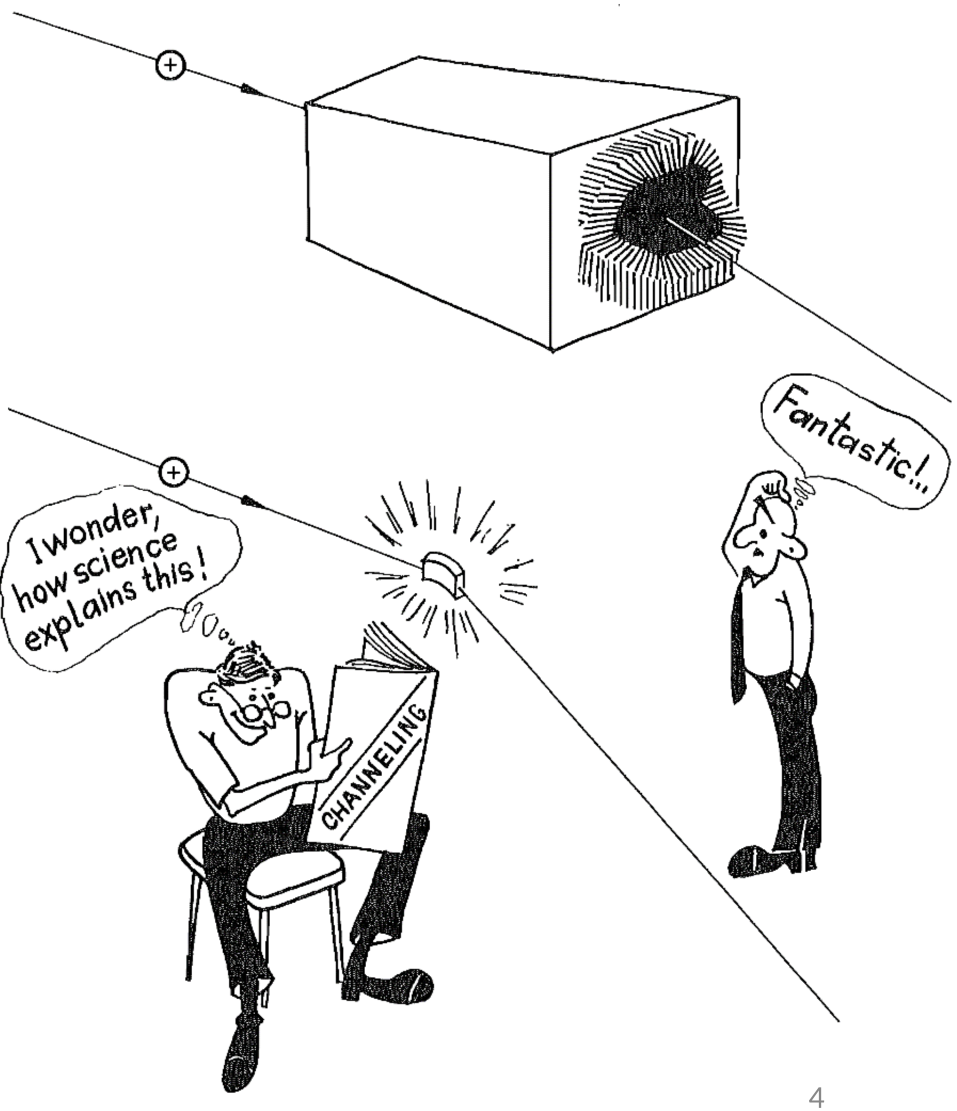


J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

Channeling in a bent crystal

E. Tsyganov, 1976





Critical angle for channeling:

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

max of U(x)

momentum*velocity

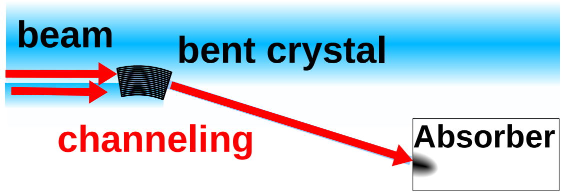
U_0 = *21.3* eV for Si (110)

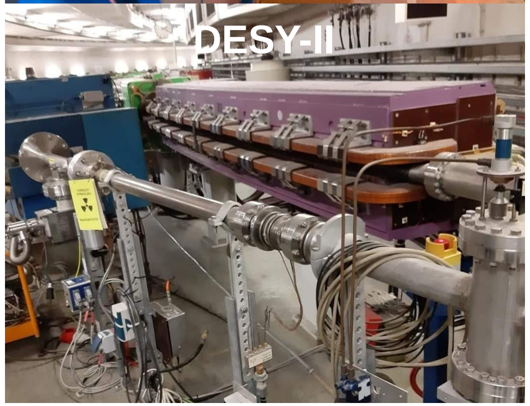
$\theta_c \approx$ 200 μ*rad* at *E* ~ *1* GeV

$\theta_c \approx$ 2 μ*rad* at *E* ~ *7* TeV

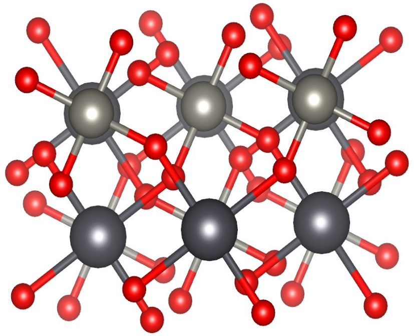
Experiments with Crystals

Crystal-based collimation or beam extraction from an accelerator

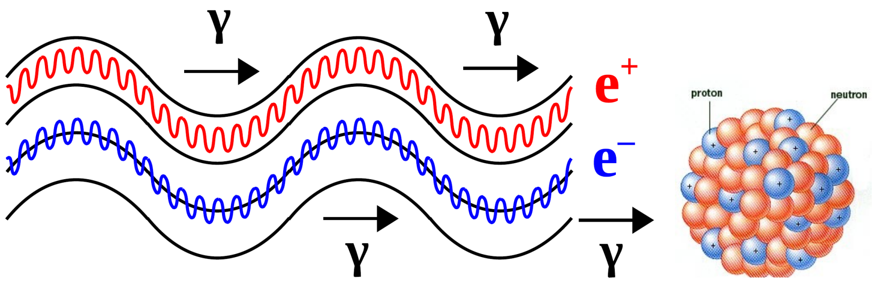




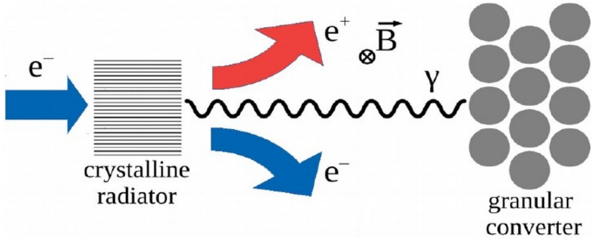
Oriented crystals

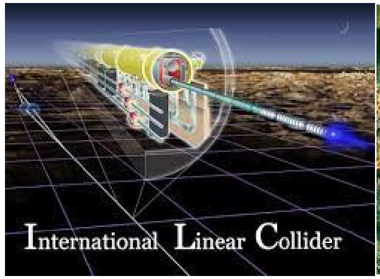


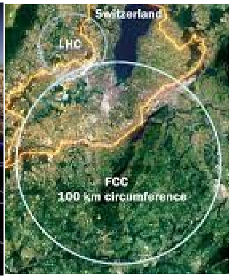
X and γ-ray source



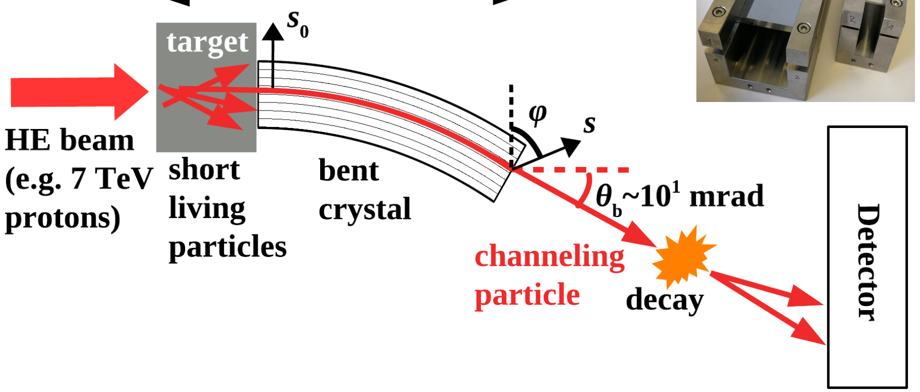
Positron source for future colliders

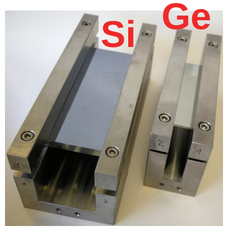






Measurement of dipole magnetic and electric moments of exotic particles





Experiments with Crystals

INFN
Istituto Nazionale di Fisica Nucleare

CERN

Collimation & beam steering
Innovative radiation & positron sources
Pair production studies
Innovative detectors

MAMI – MAINZER MIKROTRON

Beam steering
Innovative radiation sources

DESY.

Innovative radiation sources
Innovative detectors
Beam extraction

Fermilab

Beam steering

SLAC

Innovative radiation sources
Beam steering

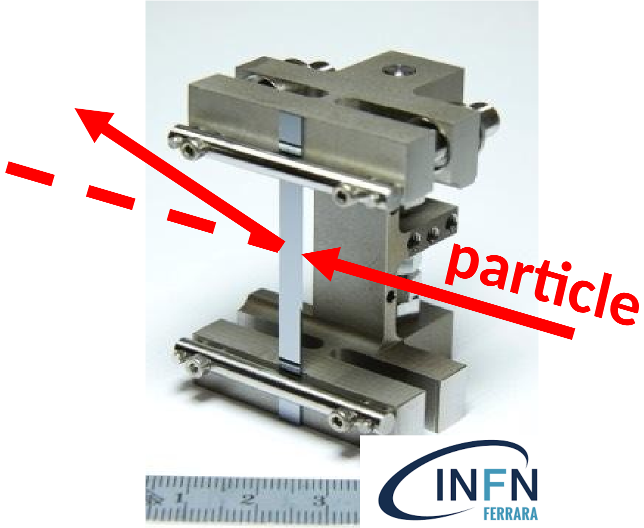
erc
European Research Council
Established by the European Commission

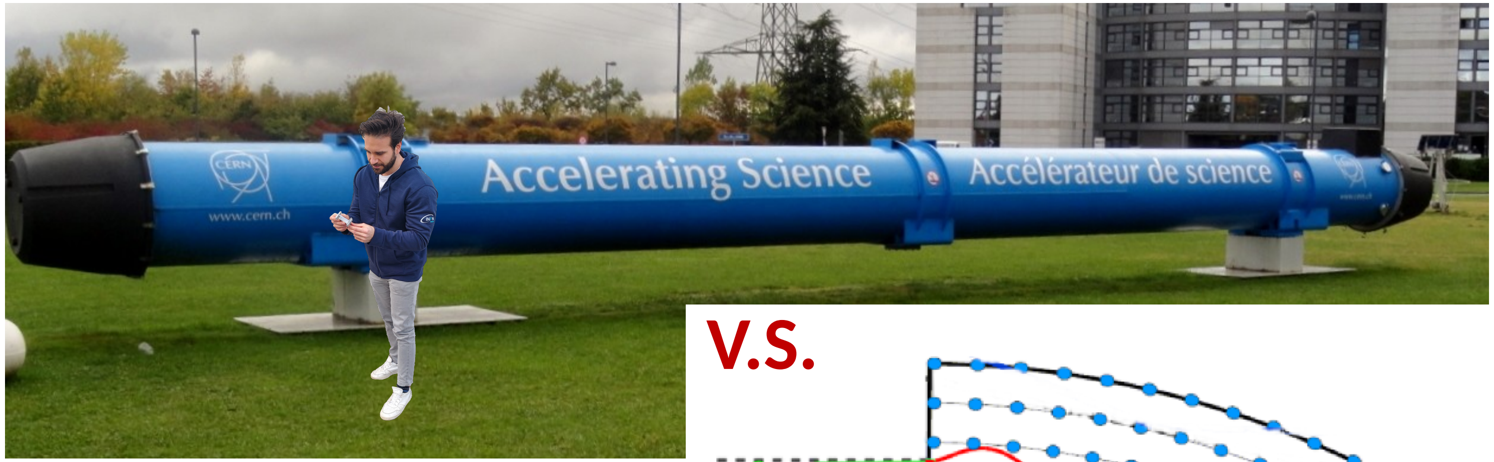
ERC-CoG CRYSBEAM (LHC beam extraction)
ERC-CoG SELDOM (Studies of MDM and EDM of charmed baryons)
MCA-IRSES CUTE (crystalline undulators)
MSCA-RISE PEARL (crystalline undulators)
MSCA-RISE N-LIGHT (crystalline radiation sources)
EIC-PATHFINDER-OPEN TECHNO-CLS (crystalline radiation sources)
PRIN2022 E+BOOST (intense positron source)
MSCA GF TRILLION (simulations with Geant4)

Involved in Channeling activities for about 20 years

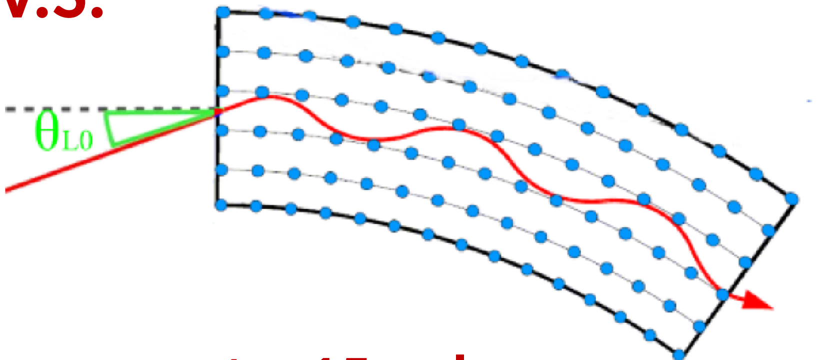
Bending a crystal:
A way to steer a particle beam

Bent Si crystal @LHC – 4 mm long



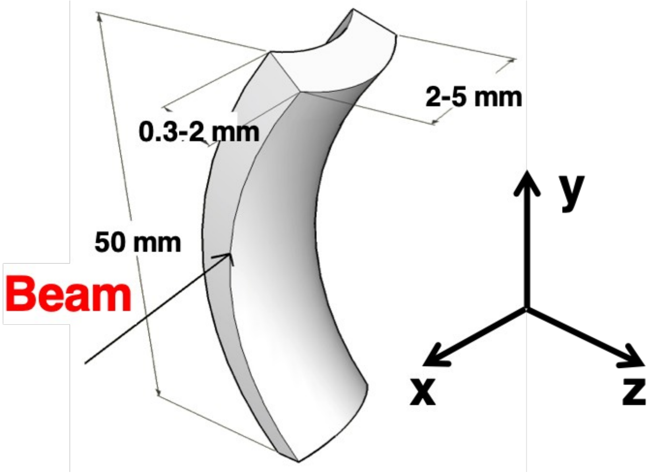


V.S.



8.3 Tesla supermagnet – 15 m long

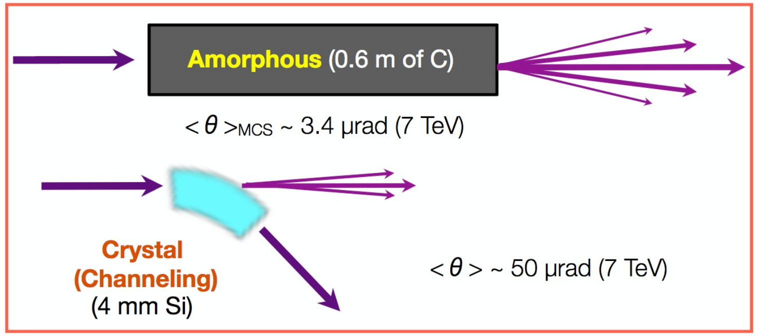
Channeling

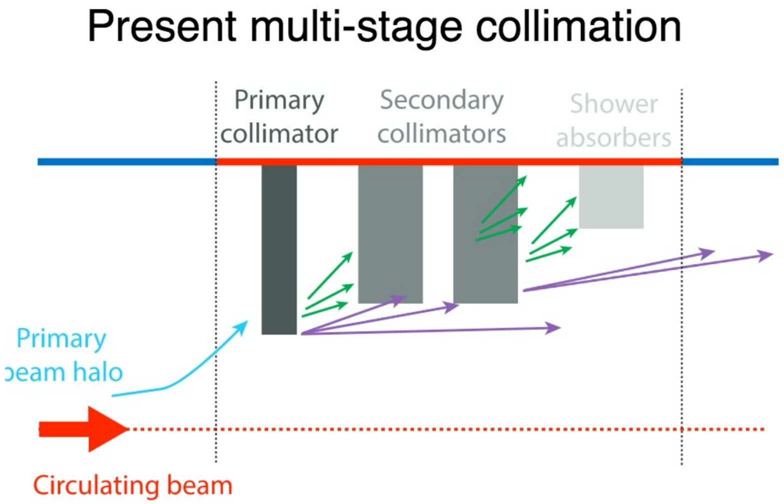


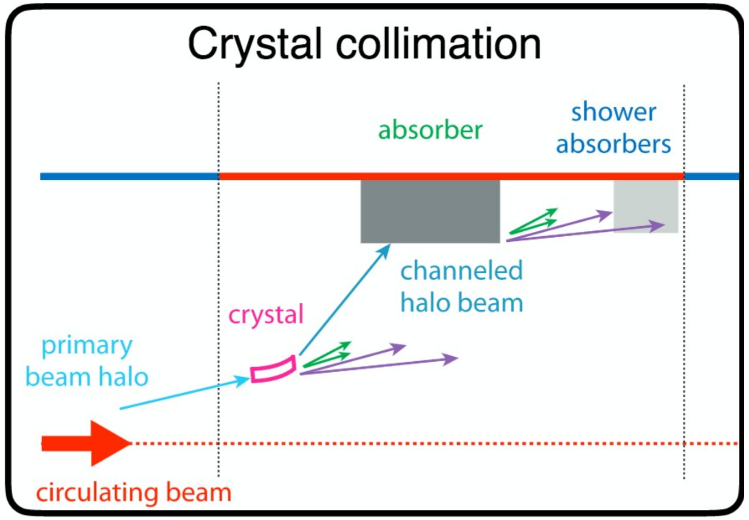
Deflection of 50 μrad at 6.5 TeV is equivalent to a 300 T dipole magnet bending!

The High Luminosity LHC:
The crystal collimation system

Courtesy of S. Redaelli (coordinator) & D. Mirarchi







A possible scheme for upgraded collimation at HL-LHC
- ❑ Reduction of losses in cold regions (i.e. protect magnets from quenching)

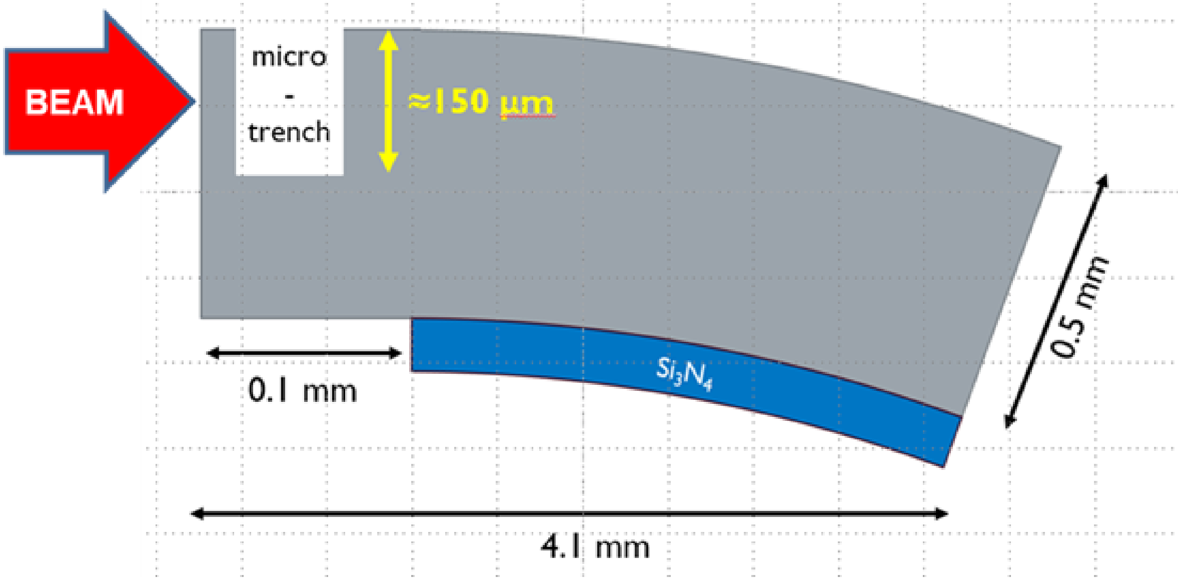
Present collimation system already at its limit for ions:
- ❑ fragmentation of heavy-ion in secondary particles of small divergence and Z/A slightly different -> difficult to intercept by the collimation system

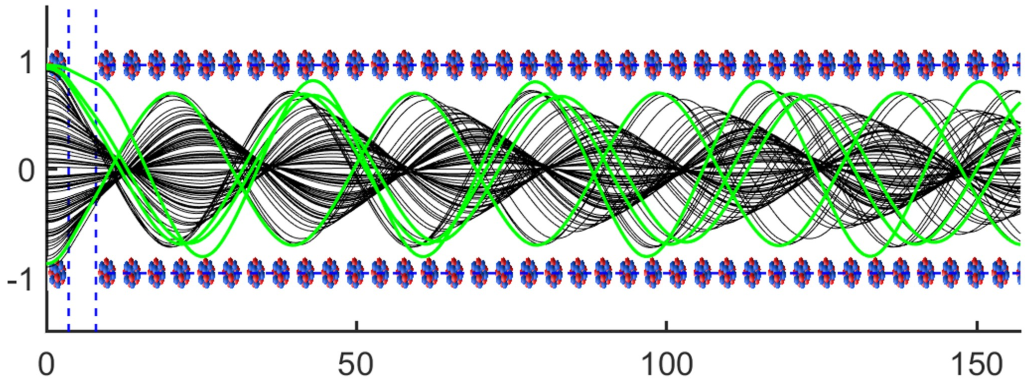
Since **2009, ten years** of experimental **investigation carried on by UA9 collaboration @SPS & @LHC** together with the **LHC Collimation team**.

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

W. Scandale et al., Phys. Lett. B758 (2016) 129-133
D. Mirarchi et al., Eur. Phys. J. C (2017) 77:424
M. D'Andrea et al., NIM A (2024) 1060:169062

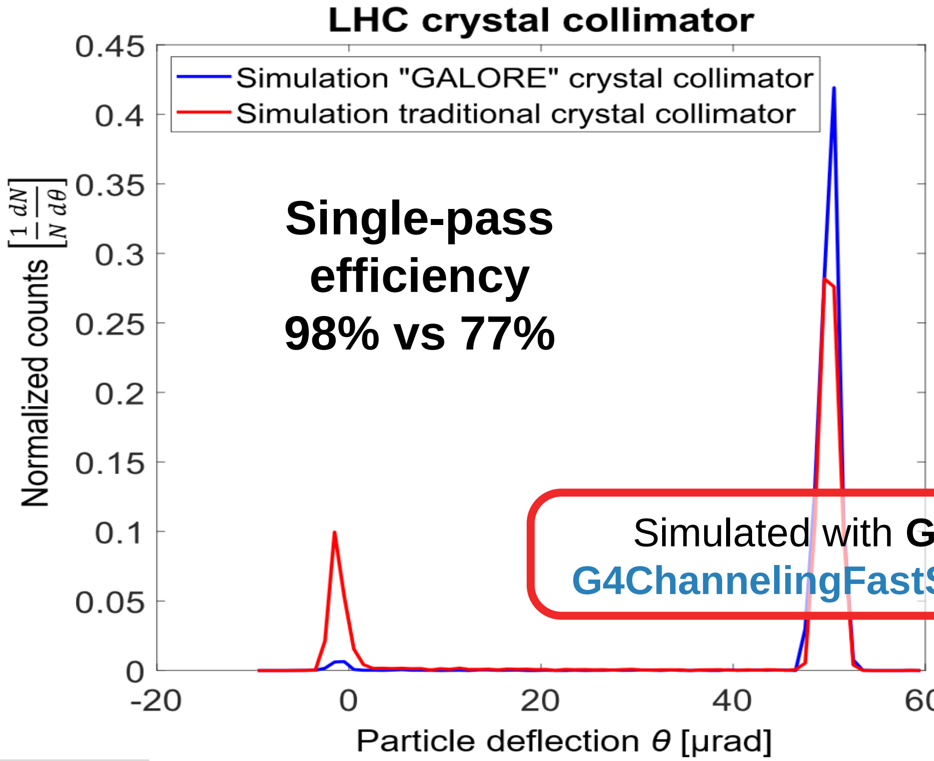
Promising new technique





Micro-trench at the beginning of crystal **focus** particles into **stable** channeling condition, **enhancing** channeling efficiency

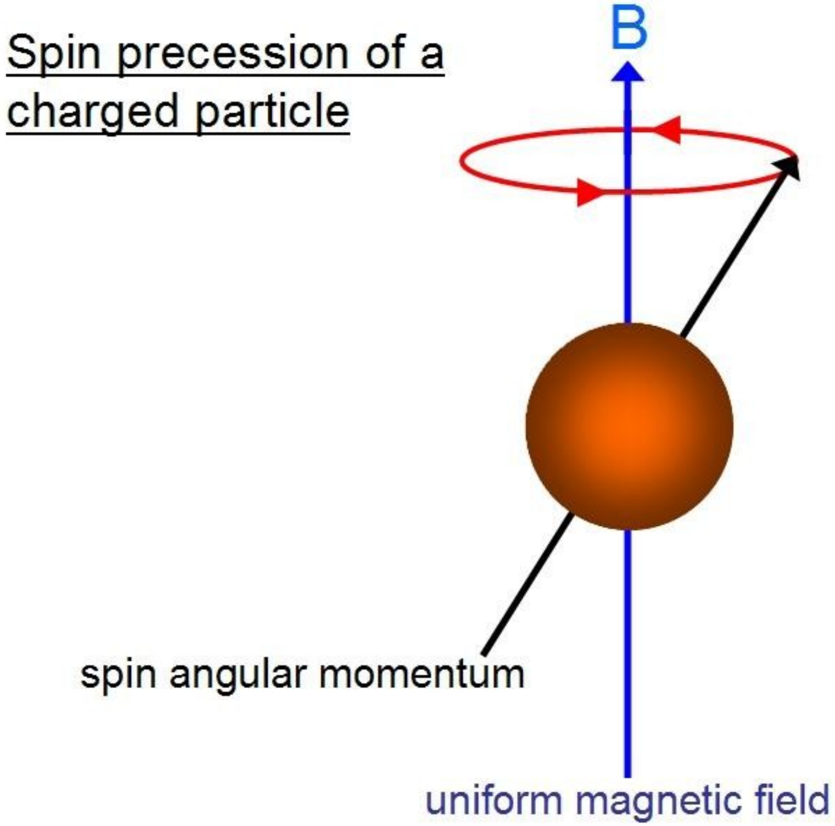
This was first **theorized*** in 2007, and finally **experimentally**** **tested at CERN SPS** in 2023 by GALORE project of INFN-CSN5

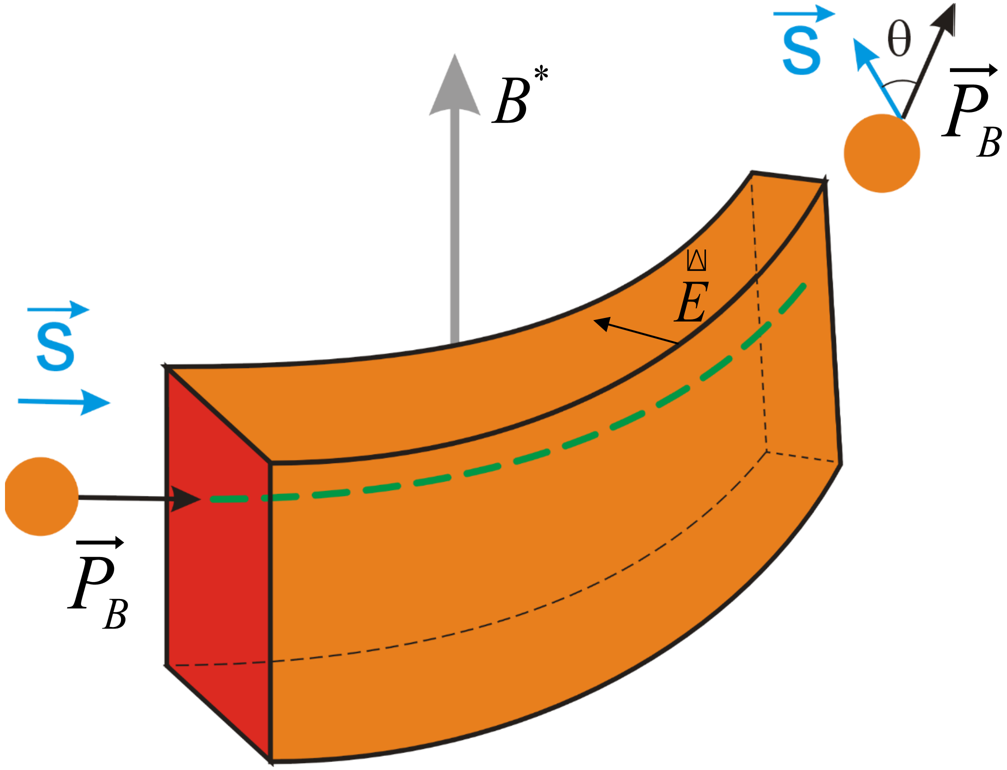


Simulated with **Geant4**
G4ChannelingFastSimModel

*V. Tikhomirov JINST 2, P08006 (2007)
**M. Romagnoni et al. Eur. Phys. J. D 76, 135 (2022).

Extraction of the multi-TeV LHC beam
Spin rotation of ultra-relativistic particles





E761 Collaboration, FERMILAB
"First observation of spin precession of polarized hyperons channeled in bent crystals", LNPI Research Reports (1990-1991) 129.
Energy: 200 – 300 GeV

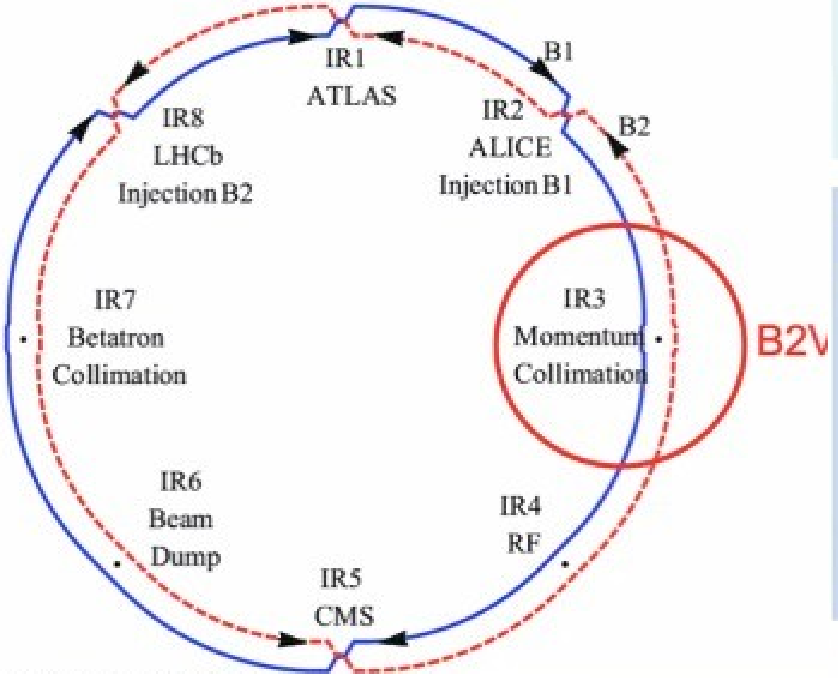
Prediction: V. Baryshevsky "*Spin rotation of ultrarelativistic particles passing through a crystal*", Sov. Tech. Phys. Lett, 1979

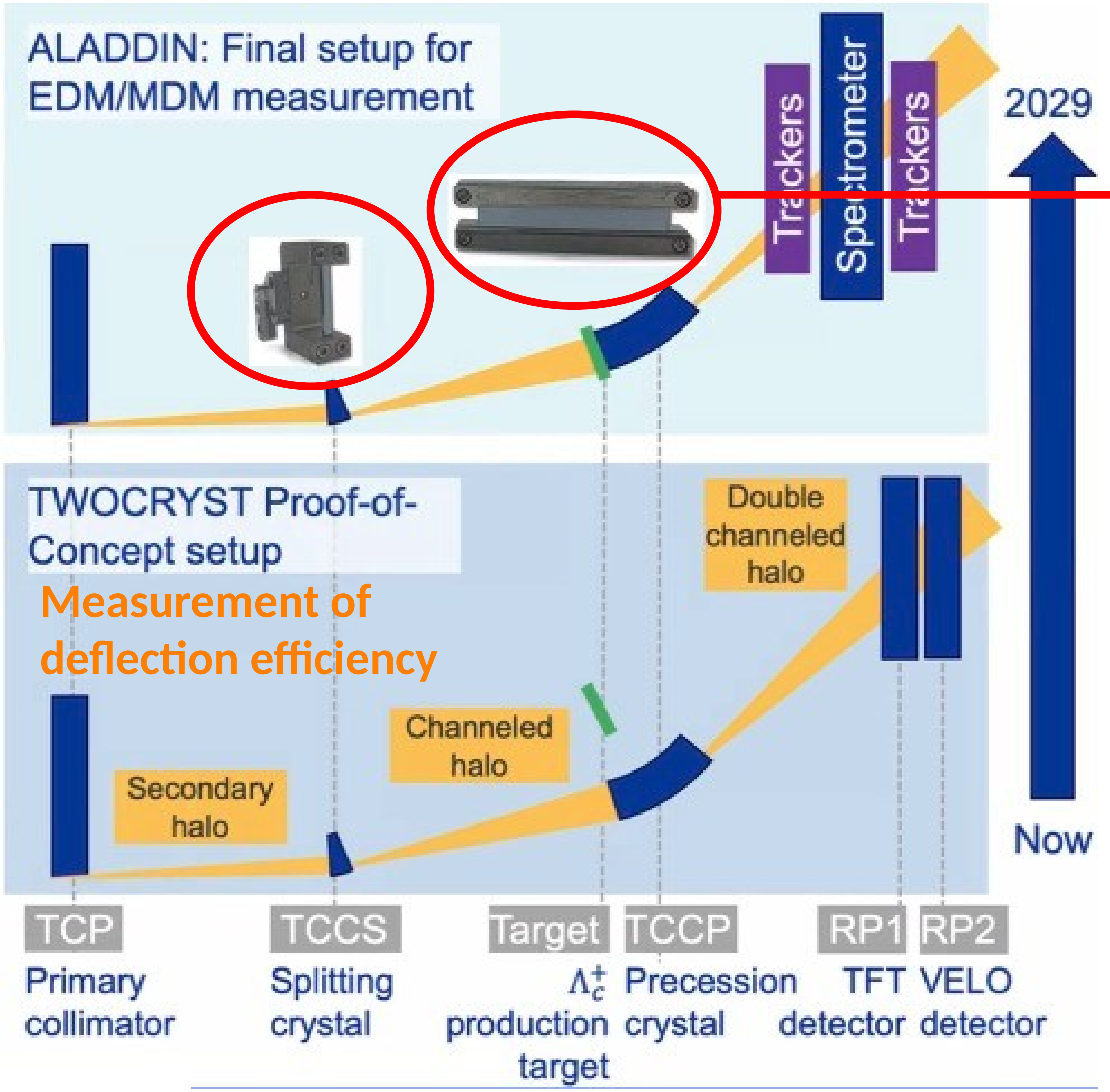
D. Chen et all "*First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals*", Phys. Rev. Lett. 69 (1992) 3286.

A.V. Khanzadeev, V.M. Samsoov, R.A. Carrigan, D. Chen "*Experiment to observe the spin precession of channeled relativistic hyperons*" NIM 119 (1996) 266.

MDM and EDM of fast-decaying particles (Λc, τ, ...)

TWOCRYST: a double crystal proof-of-concept setup to measure MDM and EDM of charmed particles





Both crystals already installed in **January 2025**; Ready for a MD test June 2025 - 2026 (before LS3)

SELDOM
G.A. 771642 PI N. Neri

Courtesy of P. Hermes (coordinator) & R. Cai

MDM and EDM of fast-decaying particles (Λc, τ, ...)

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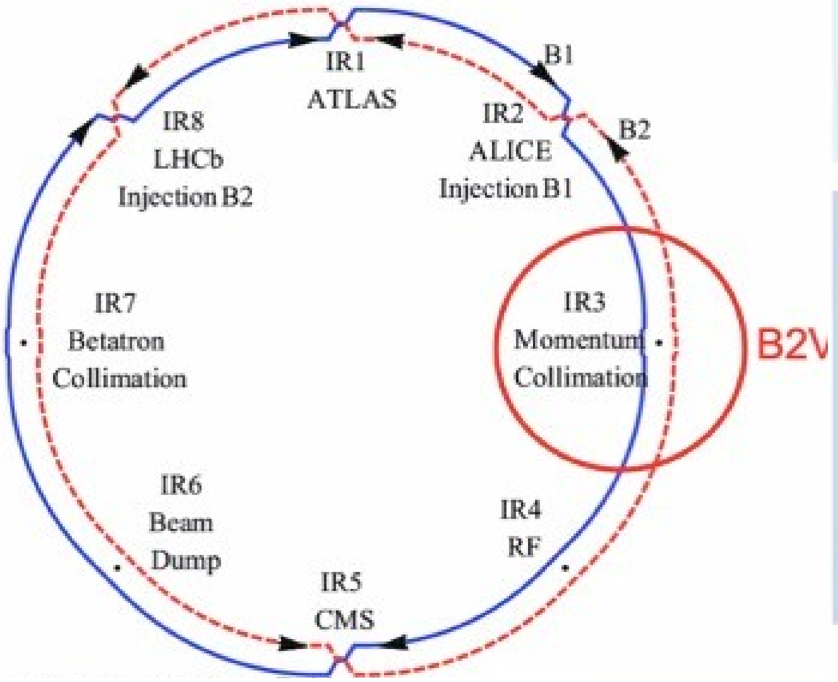
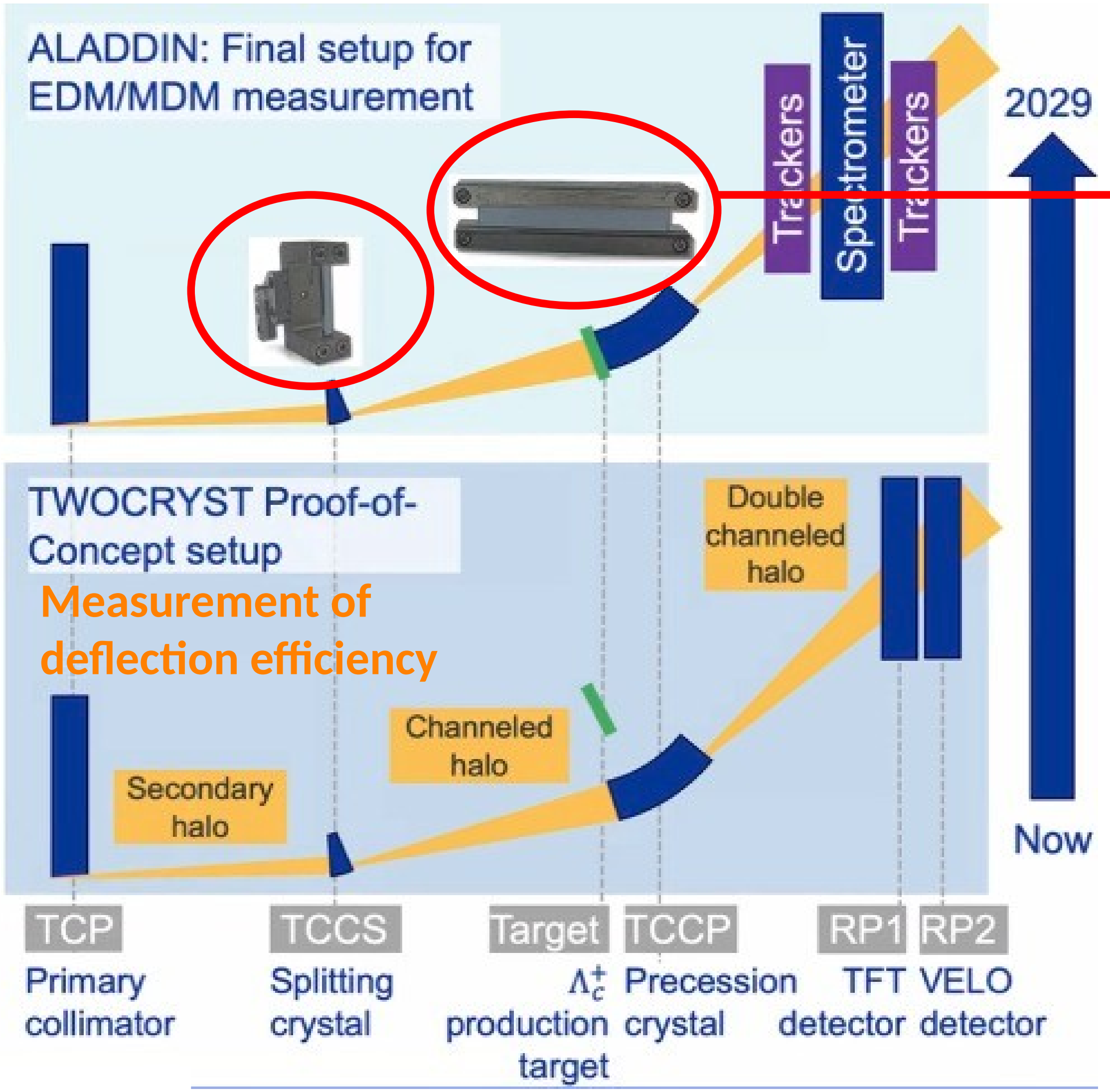
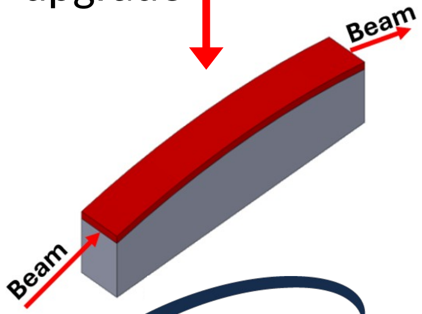




Both crystals already installed in **January 2025**; Ready for a MD test June 2025 - 2026 (before LS3)

future upgrade



Istituto Nazionale di Fisica Nucleare

CSN5 Call BOND
RN A. Mazzolari
(2025-2027)

European Research Council
Established by the European Commission

SELDOM

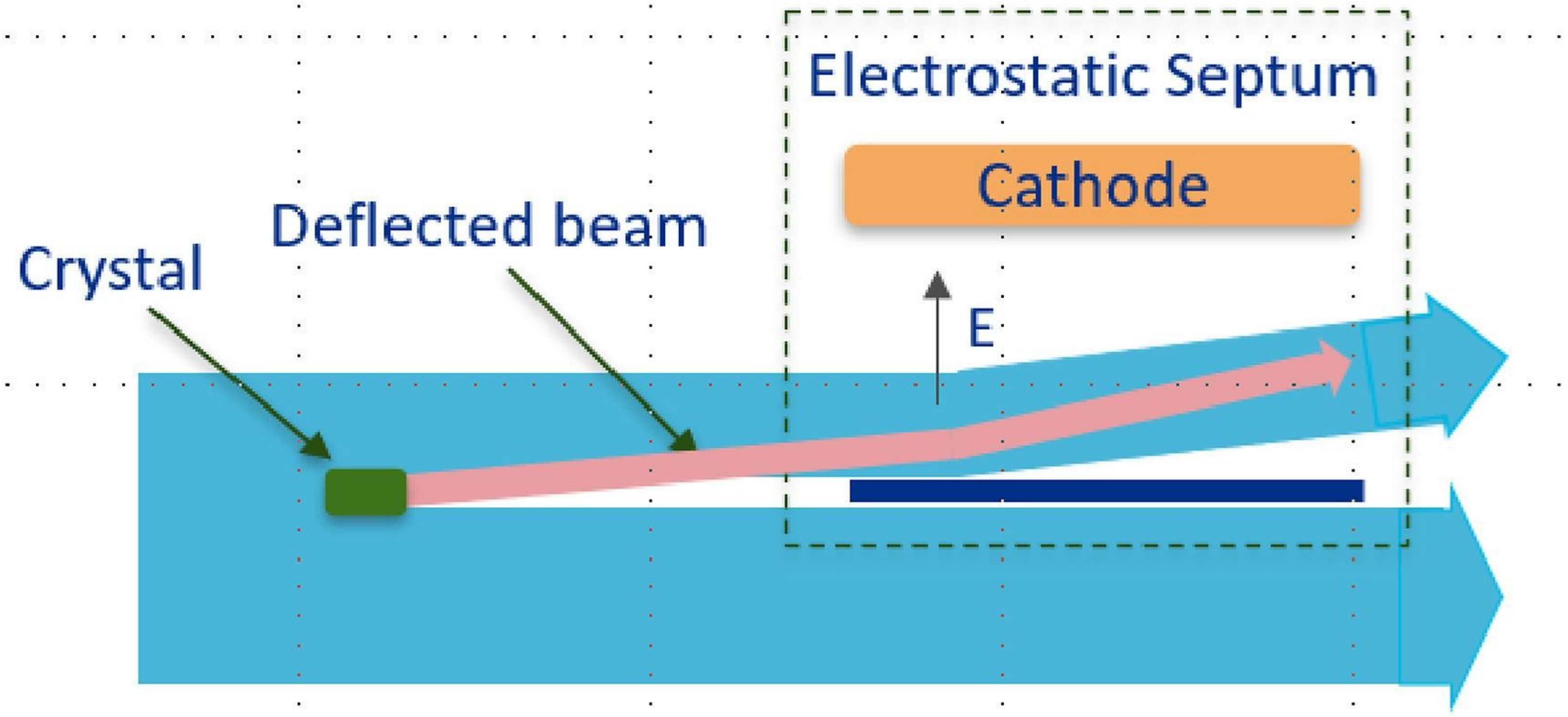
G.A. 771642 PI N. Neri

Courtesy of P. Hermes (coordinator) & R. Cai

Not only at LHC: Fermilab

The goal of **Mu2e** is to looking for the **conversion of muons to electrons without the emission of neutrinos**, in search of New Physics

A very intense muon beam is needed!



V. Nagaslaev et al., NIM A 1058 (2024) 168892

Insertion of a bent crystal in the 8 GeV proton beam at the extraction (**beginning 2026**): avoid the interaction with the septum

-> decreases the beam losses

-> increases the extracted proton beam intensity

-> increases the muon beam intensity

… And also at lower energies

100 GeV - 1 TeV

~mm thick crystals

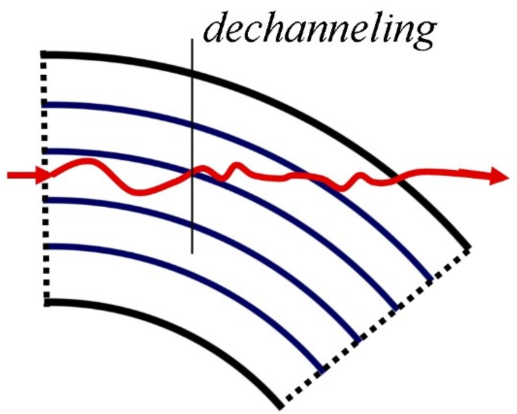
3-20 GeV

60 µm thick crystal

We are involved in E336 SLAC experiment on plasma acceleration. PI: T. Tajima, S. Corde.

sub-GeV

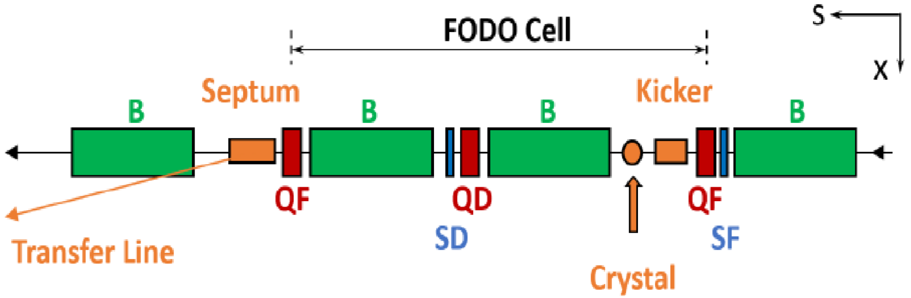
10-15 µm thick crystals



Dechanneling lenght increase with particle energy

Crystal thickness should be optimized for different E

Example of application: DESY e-beam extraction

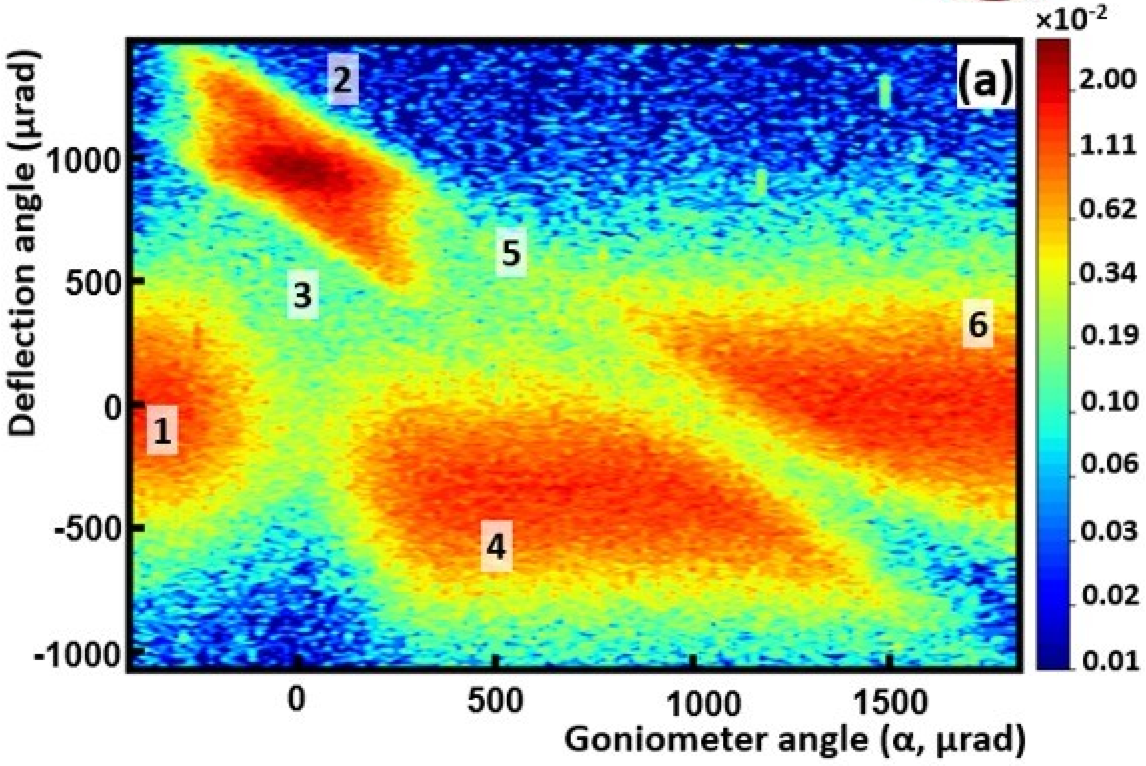


A. Sytov et al. Eur. Phys. J. C 82, 197 (2022)

Crystal R&D @INFN FE&LNL and experimental tests co-financed by the INFN CSN5

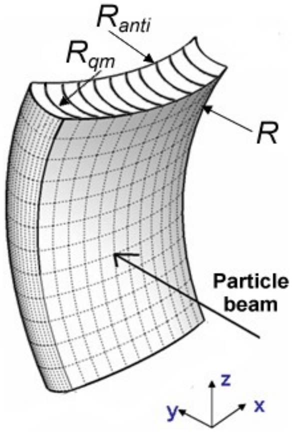
Experimental results on beam steering of 530 MeV positrons

GA 101046458

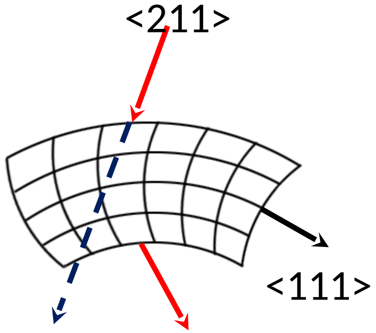


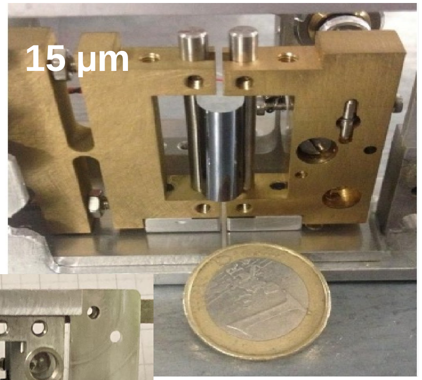
A. Mazzolari et al. (2024) arXiv:2404.08459

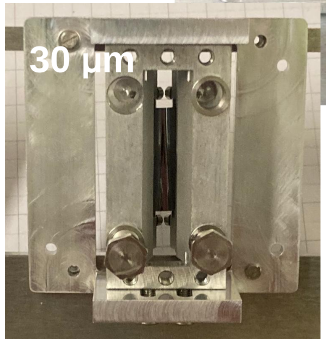
Under review in Phys. Rev. Lett.



Quasimosaic effect (Ivanov et al., 2005)







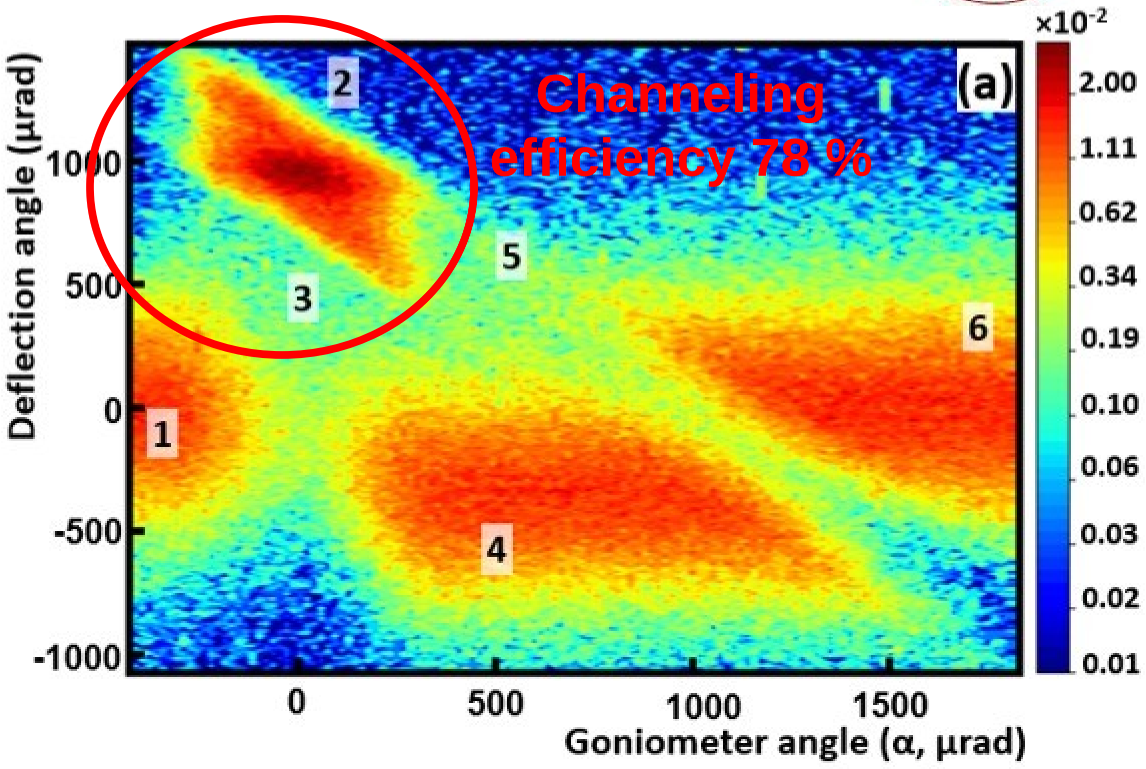
D. De Salvador et al 2018 JINST 13 C04006
G. Germogli,NIM B, 2015. 355: p. 81-85

First high-efficient deflection of sub-GeV positron worldwide !!!

Fallout in :

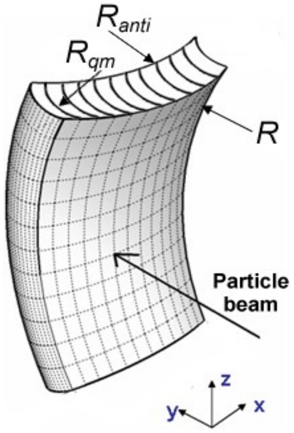
- ❑ **Crystal-Light-Source**
- ❑ **Channeling based technologies**
- ❑ **Accelerator technologies: for beam steering, extraction, focusing..**

Experimental results on beam steering of 530 MeV positrons



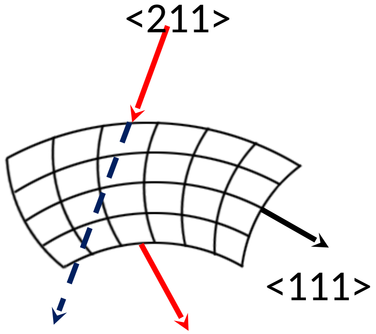
A. Mazzolari et al. (2024) arXiv:2404.08459

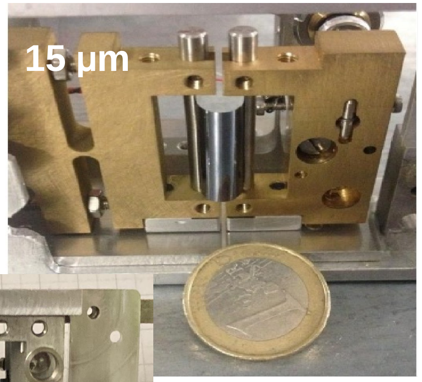
Under review in Phys. Rev. Lett.

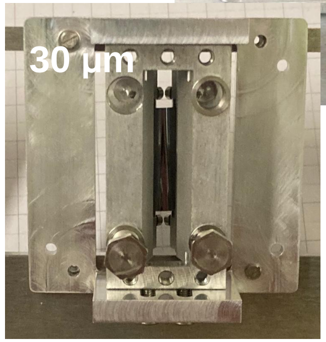


Quasimosaic effect (Ivanov et al., 2005)

GA 101046458







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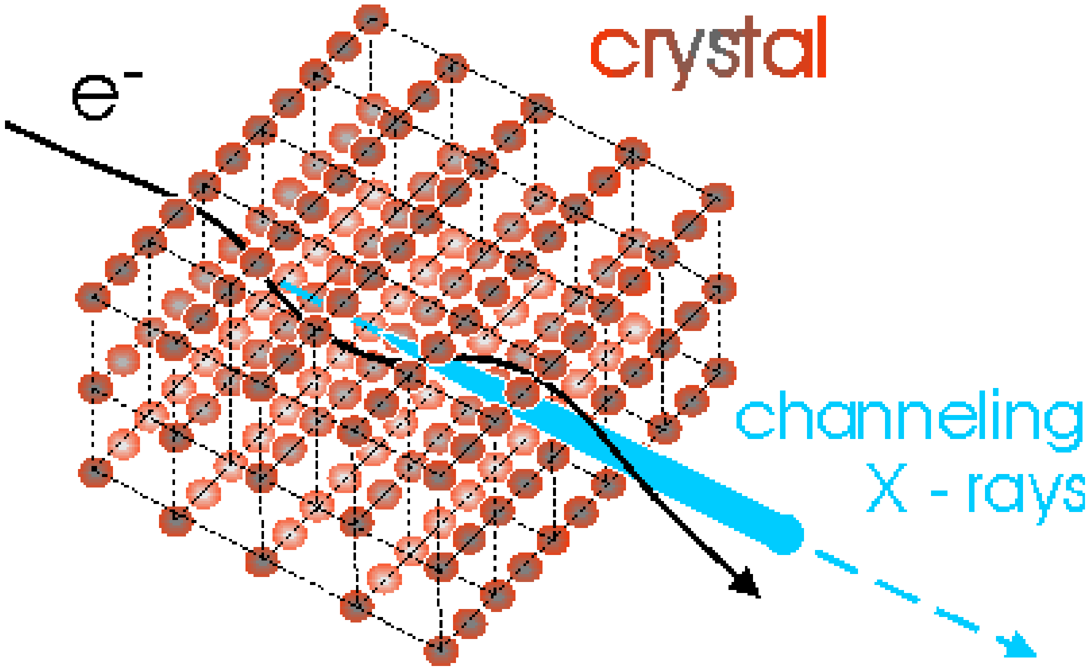
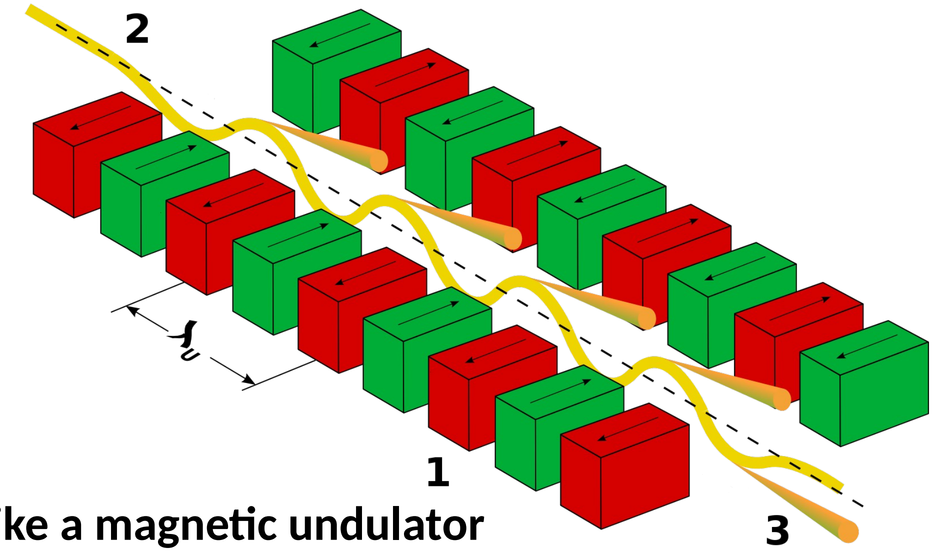
Does the crystal structure influence the process of bremsstrahlung?

Yes!

In case of small incidence angle with some crystal lattice direction
(electron periodic oscillation -> radiation emission)

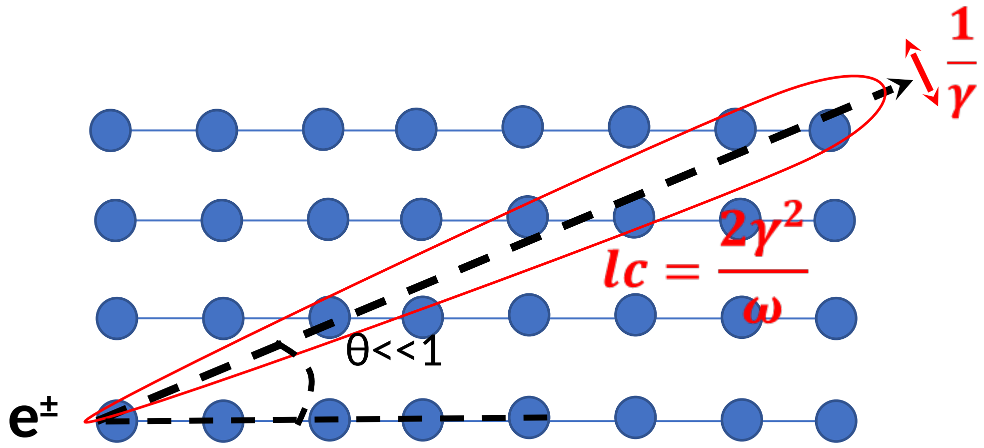


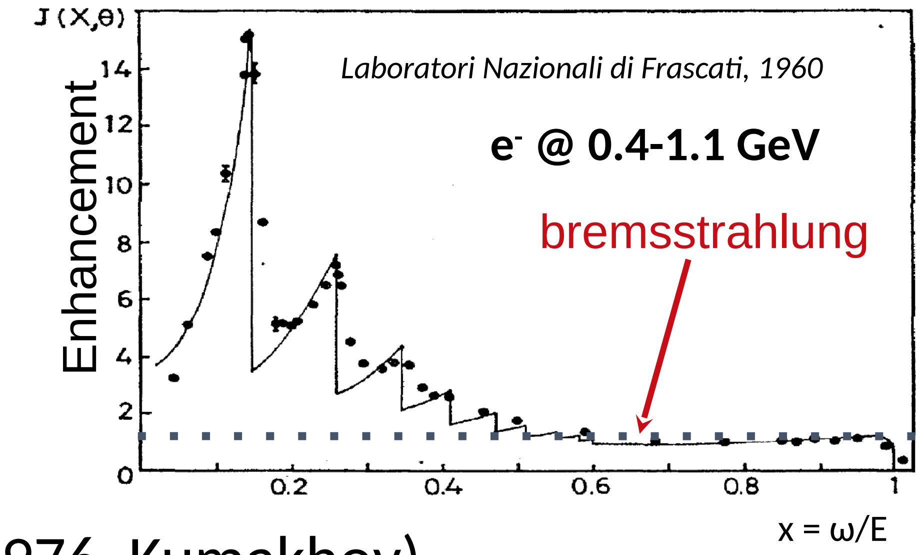


Like a magnetic undulator

Enhancement of radiation in aligned crystals

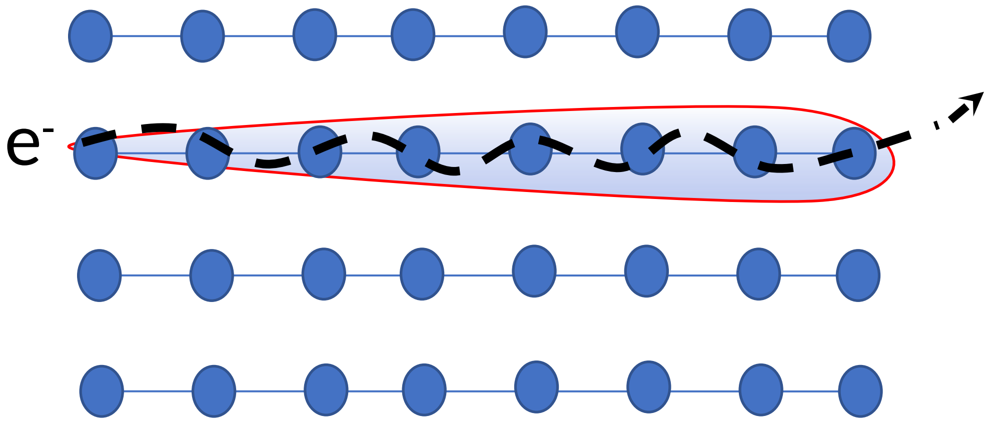
Coherent Bremsstrahlung (1950s) Ter-Mikaelian, Ferretti, Dyson-Uberall

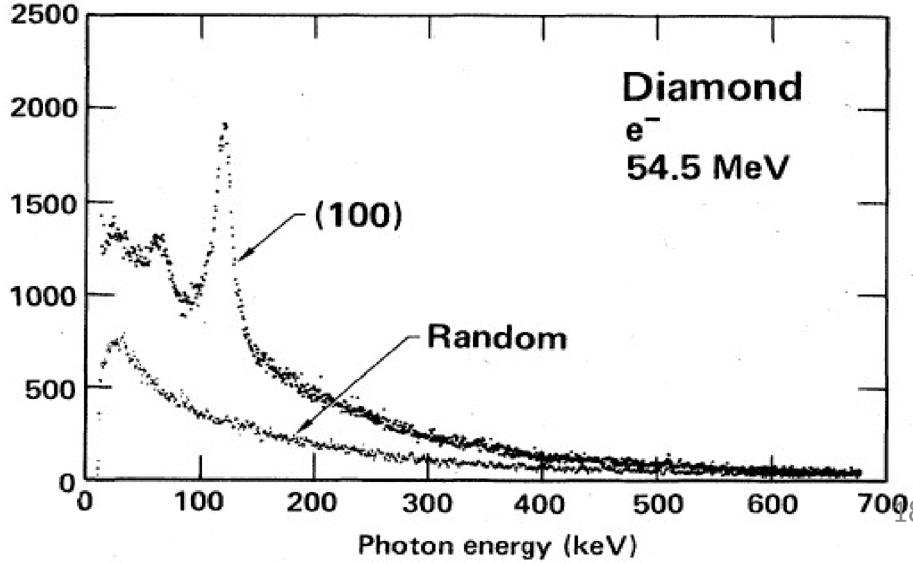




lc – coherence (formation) length of the photon

Channeling Radiation (1976, Kumakhov)



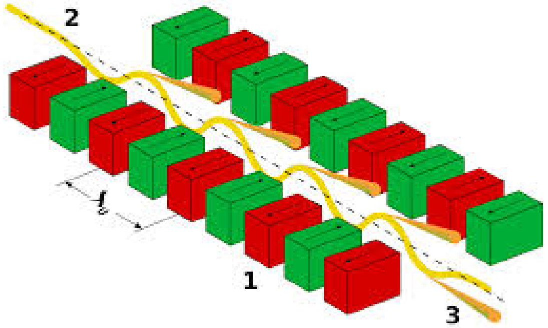


A crystalline undulator: γ-ray source

Classical scheme: magnetic undulator in a free electron laser

Soft X-rays (10 keV)

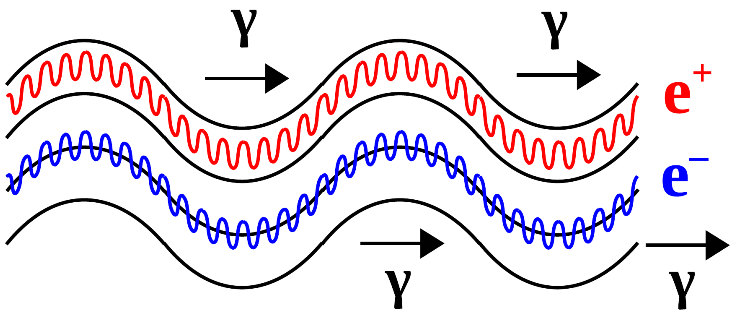
$\lambda_u \sim$ cm



Innovative scheme: Crystalline undulator (CU) ->

Hard X-rays and gamma rays (100 keV - 10 MeV)

λ_u << mm



Korol, A.V., Solov'yov, A.V. Eur. Phys. J. D 74, 201 (2020).

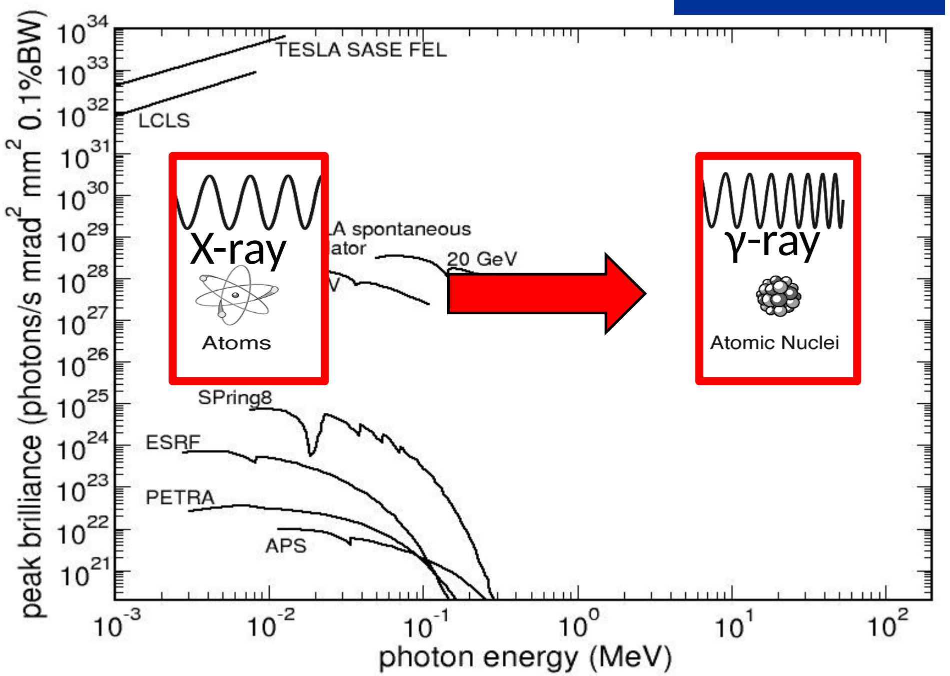
Applications: nuclear physics, technologies and life science.

Marie Skłodowska-Curie Actions

H2020 MSCA RISE PEARL GA 690991 (2015-2019) & N-LIGHT GA 872196 (2020-2025) & TRILLION GA 101032975 (2021-2025)

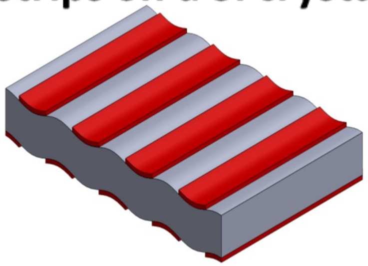
European Innovation Council

Horizon EU EIC PATHFINDER OPEN TECHNO-CLS GA 101046458 (2022-2027)



Crystalline undulator via patterning by tensile Si_3N_4 strips on a Si crystal

Tested at CERN SPS in August 2024

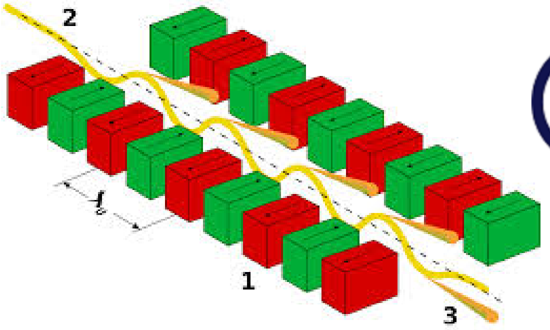


Collaboration with CNR of Bologna (Fulvio Mancarella e Filippo Bonafè)

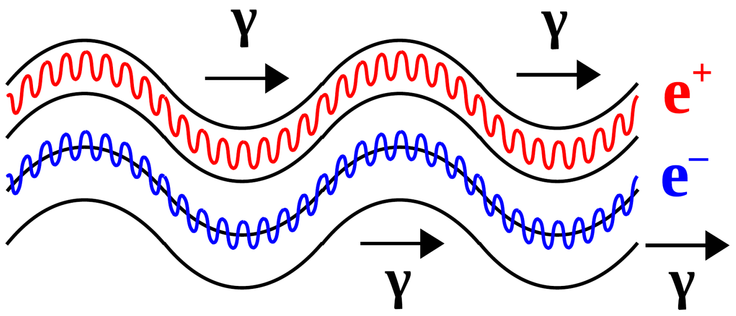
- L. Malagutti (INFN FE) et al. NIM A 2025 (under review)
- Original design from: V. Guidi, L. Lanzoni, A. Mazzolari, G. Martinelli, A. Tralli, APL 90, 2007, 114107

A crystalline undulator: γ-ray source

Classical scheme: magnetic undulator in a free electron laser
Soft X-rays (10 keV)
$\lambda_u \sim$ cm



Innovative scheme: Crystalline undulator (CU) ->
Hard X-rays and gamma rays (100 keV - 10 MeV)
λ_u << mm



Korol, A.V., Solov'yov, A.V. Eur. Phys. J. D 74, 201 (2020).

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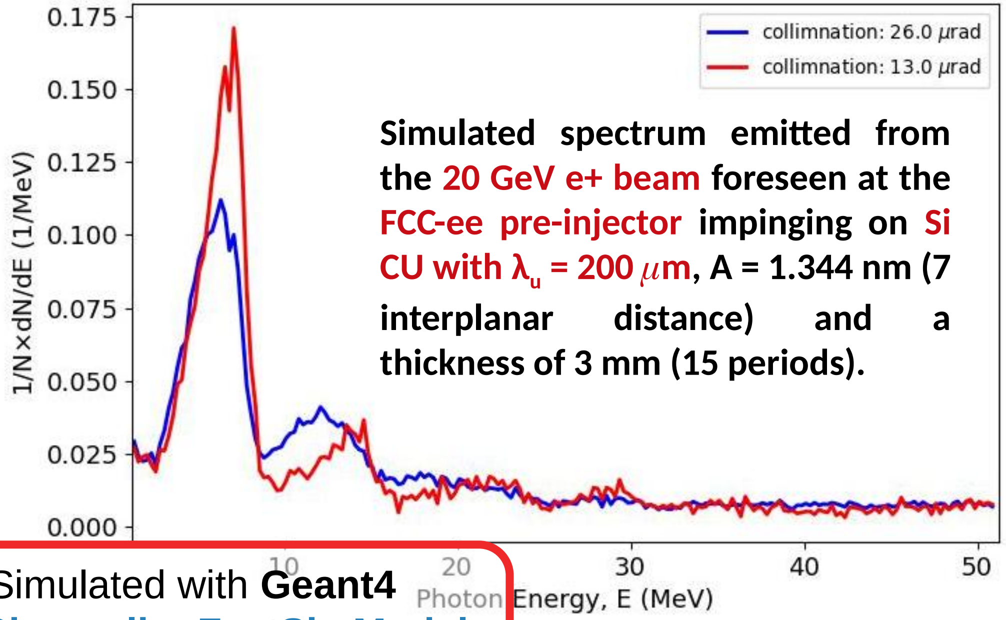
Horizon EU EIC PATHFINDER OPEN TECHNO-CLS GA 101046458 (2022-2027)

FUTURE CIRCULAR COLLIDER Other Science Opportunities at the FCC-ee



Simulated spectrum emitted from the 20 GeV e+ beam foreseen at the FCC-ee pre-injector impinging on Si CU with λ_u = 200 μm, A = 1.344 nm (7 interplanar distance) and a thickness of 3 mm (15 periods).

Simulated with **Geant4**
G4ChannelingFastSimModel

Included in **Other Science Opportunities at the FCC-ee** led by F. Zimmermann and G. Arduini, being CUs one of the elective applications [**F. Zimmermann NIM A 1075 (2025) 170371**].

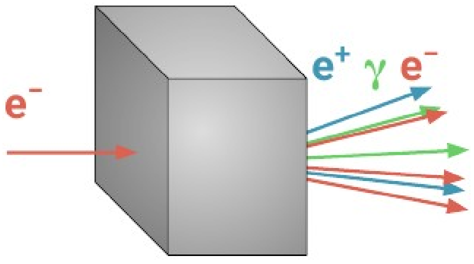
H2020-MSCA-GF **TRILLION** (G.A. 101032975) project

Crystal based positron source for future colliders

INFN Istituto Nazionale di Fisica Nucleare · cnrs · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis · université PARIS-SACLAY

UNPOLARIZED POSITRON SOURCES

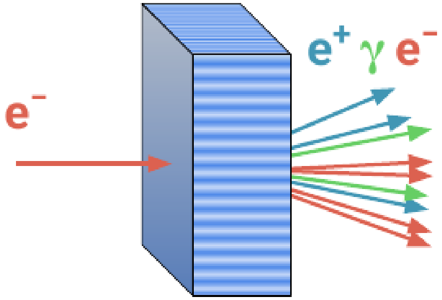
1. Conventional



Luminosity constraint

Target heating

2. e+ from channeling radiation



Option for FCCee

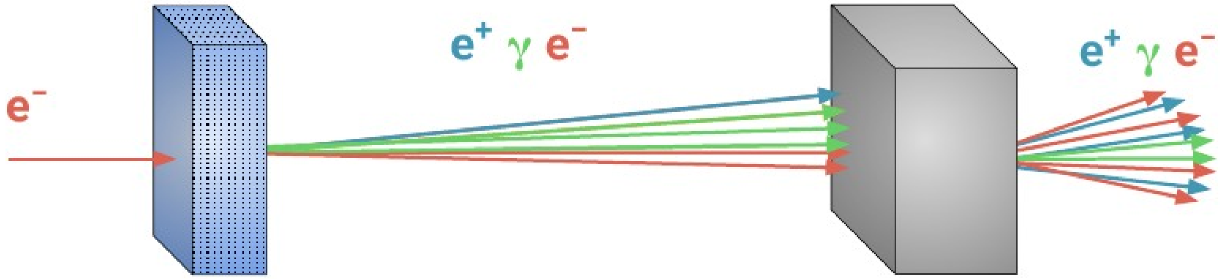
More positrons

Less heating and background

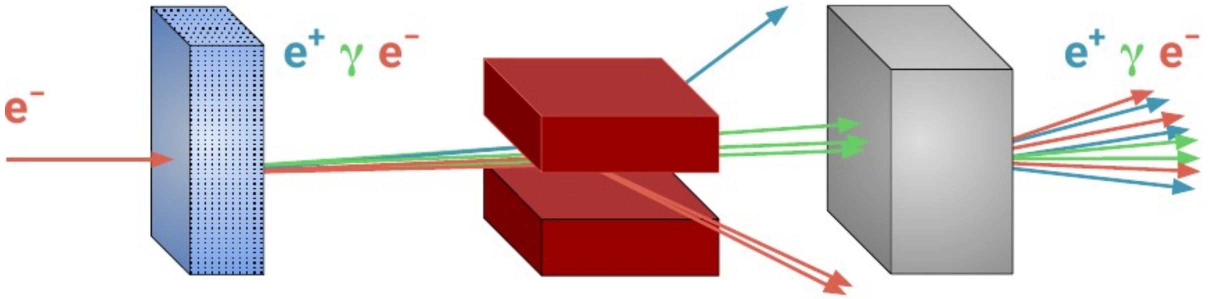
Leader: R. Chehab
Tests performed at CERN (WA 103) and at KEK

Activity born in the past CSN5 STORM project (2021-22) and CSN1 RD-MUCOL (for LEMMA), currently in CSN1 RD-FCC

3. Hybrid crystal based positron source



Ideal for linear colliders (CLIC or ILC)



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

Toward future colliders

Ultimate Goal: Overcome positron source limits → higher reliability, more sustainable, compatible with existing collider designs

R&D objectives

FUTURE CIRCULAR COLLIDER

I. FCC-ee

A single thick crystal converter

- **Nearly zero additional cost**: no design change compared to baseline (conventional)

II. Other Colliders (requirement cannot be fullfilled with conventional source)

CLIC & ILC: e+ rate 20-30 x FCC-ee rate

LHeC, LEMMA: e+ rate > 100 x linear collider

Issue: **target resistance → improved scheme**:

- Crystal radiator + magnets & collimators
- Advanced converter targets

e+BOOST PI: L. Bandiera
PRIN2022-2022Y87K7X

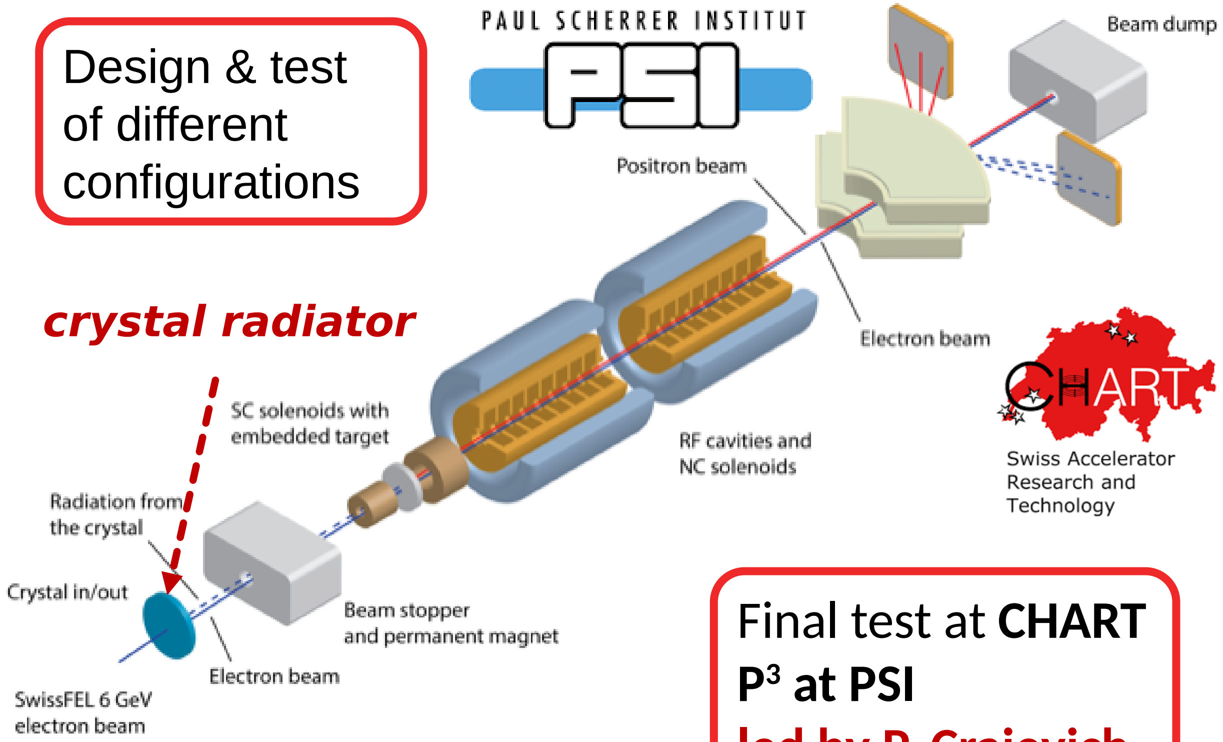
Funded by the European Union
NextGenerationEU

INFN Istituto Nazionale di Fisica Nucleare · cnrs · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis · université PARIS-SACLAY

Plan for the next 5 years

Design & test of different configurations

crystal radiator



Final test at **CHART P^3 at PSI**
led by P. Craievich

Partnership

INFN: Ferrara, LNL, Milano, MiB, Naple

FCC-ee Injector Studies (**I. Chaikovska, IJCLab**) **IJCLab-INFN MoU**

CHART P^3 project update at **PSI** of **Full Injector Chain**

Toward future colliders

Ultimate Goal: **Overcome positron source limits** → **higher reliability, more sustainable, compatible with existing collider designs**

R&D objectives

FUTURE CIRCULAR COLLIDER

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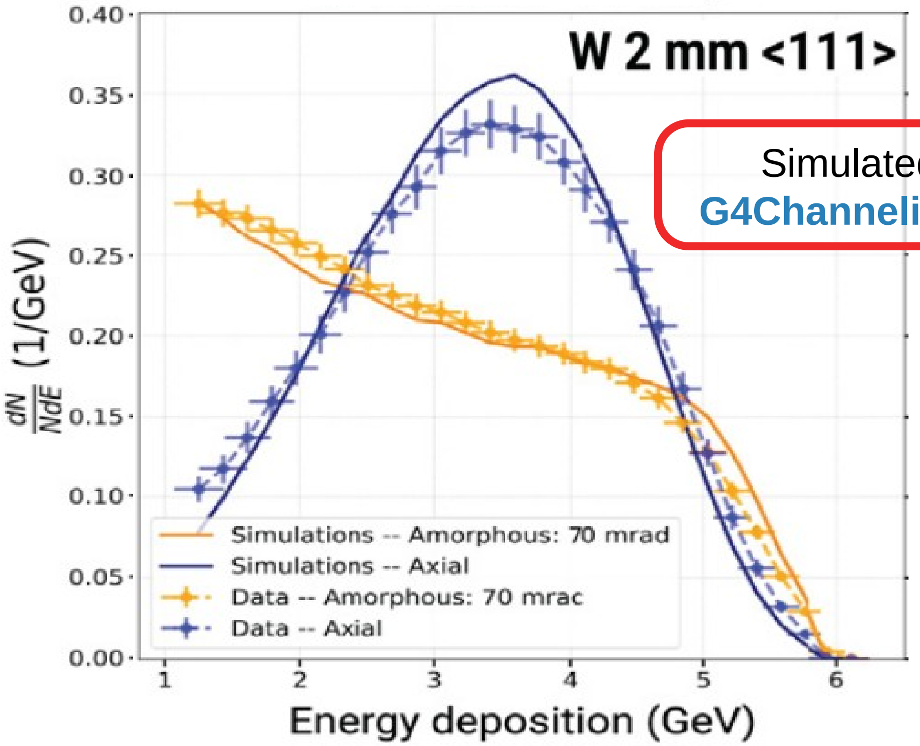
e+BOOST PI: L. Bandiera
PRIN2022-2022Y87K7X

Funded by the European Union
NextGenerationEU

Experimental validation

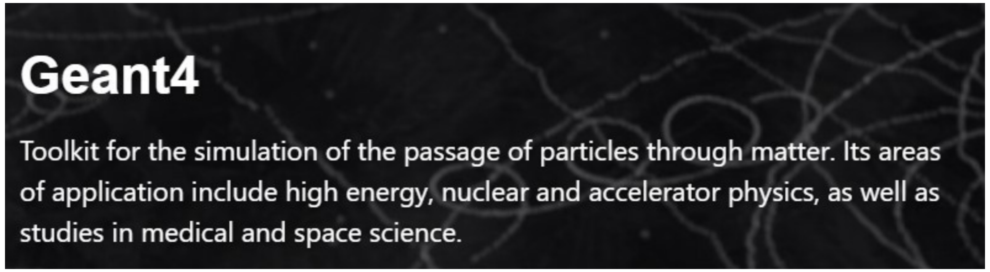


Simulated with **Geant4**
G4ChannelingFastSimModel

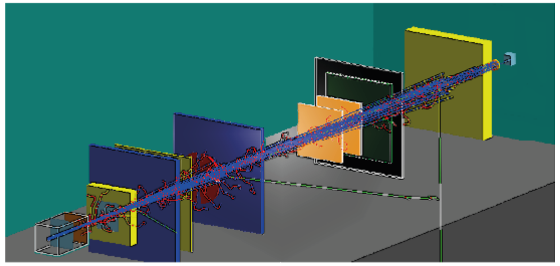
N. Canale et al. NIM A 1075 (2025) 170342

L. Bandiera et al. Eur. Phys. J. C 699 (2022) 82
I. Chaikovska et al. 2022 JINST 17 P05015
M. Soldani et al. NIM A 1058 (2024) 168828
D. Boccanfuso et al. IL NUOVO CIMENTO 48 C (2025) 108
F. Alharthi et al. NIM A 1075 (2025) 170412

Monte Carlo simulation: Geant4 implementation



Coord: G. Paternò, A. Sytov



Implementing the “crystal physics” in Geant4: G4ChannelingFastSimModel

MSCA Individual Global Fellowships of A. Sytov, GA 101032975
https://www.fe.infn.it/trillion/

Simulated applications

- ❑ Deflection&radiation: Geant4 examples **ch1-ch2**
- ❑ **Crystal-based positron source**
  https://github.com/paternog/PositronSource
- ❑ **Crystal-based extraction** (applicable also for collimation)
  https://github.com/asytov00/G4ChannelingFastSimModel
  BDSim
- ❑ **Crystalline undulator**: Geant4 example **ch2**.
- ❑ **Electromagnetic shower** in oriented crystal: Geant4 example **ch3**.

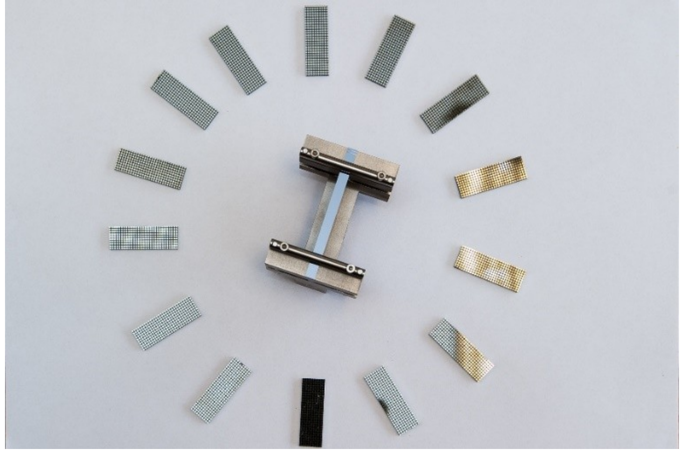
Physics

- ❑ Deflection
- ❑ Radiation (through Baier-Katkov method)
- ❑ Pair production (through Baier-Katkov method)

[1] V. Guidi, L. Bandiera and V. Tikhomirov, PRA 86 (2012) 042903.
[2] L. Bandiera et al., NIM B 355 (2015) 44.
[3] A. Sytov, V. Tikhomirov, L. Bandiera, PRAB 22 (2019) 064601.
[4] A. Sytov, L. Bandiera et al., JKPS 83 (2023) 132.
[5] R. Negrello, ..., A. Sytov. NIM A 1074, 170277 (2025).

Crystal preparation and characterization

INFN
FERRARA



Laboratory fully equipped & Clean room (130 m^2)

Coord: A. Mazzolari, M. Romagnoni

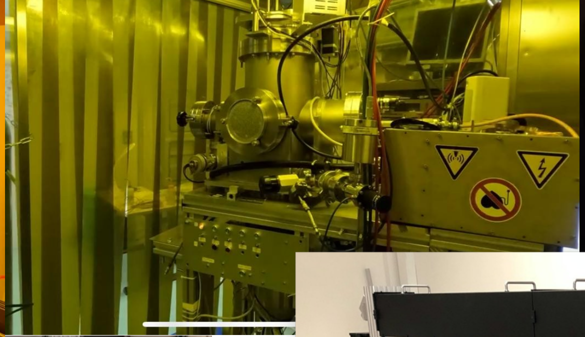
Crystal preparation and characterization

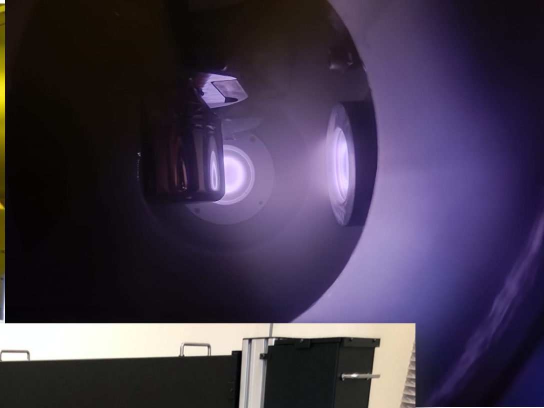
Università degli Studi di Padova

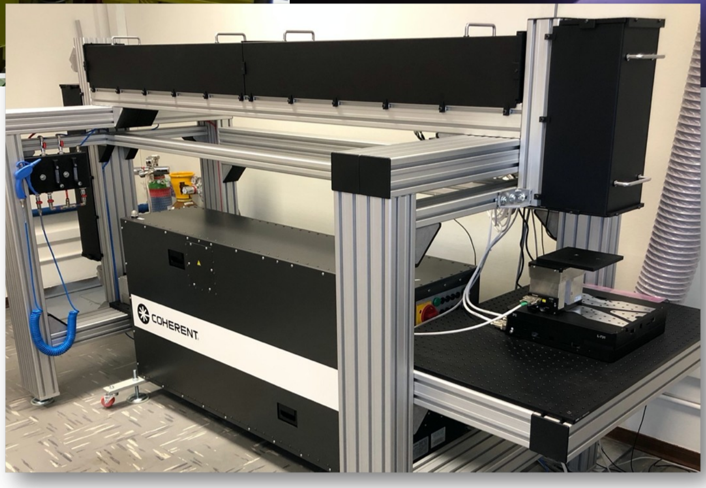
INFN LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Coor. Prof. Davide De Salvador

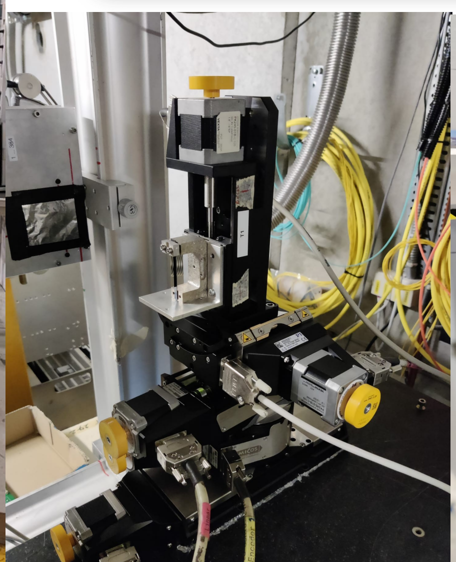
Crystal processing and lithography

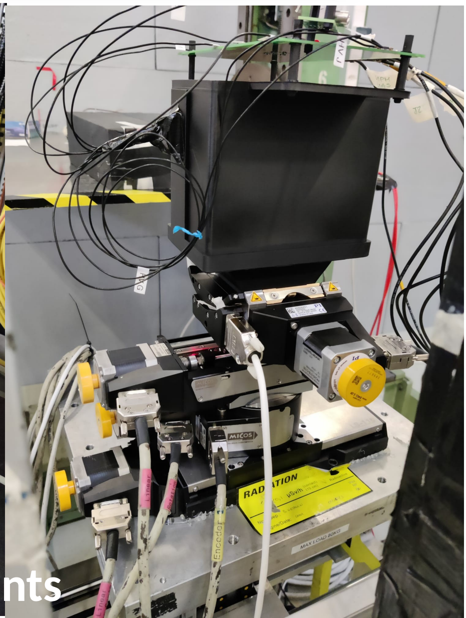






Crystal characterizations

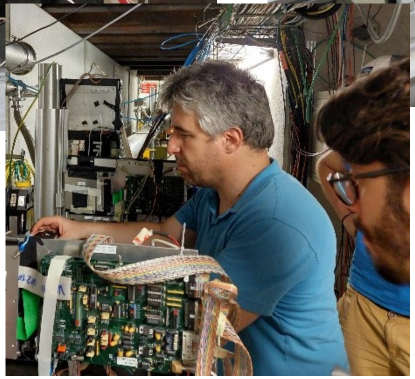


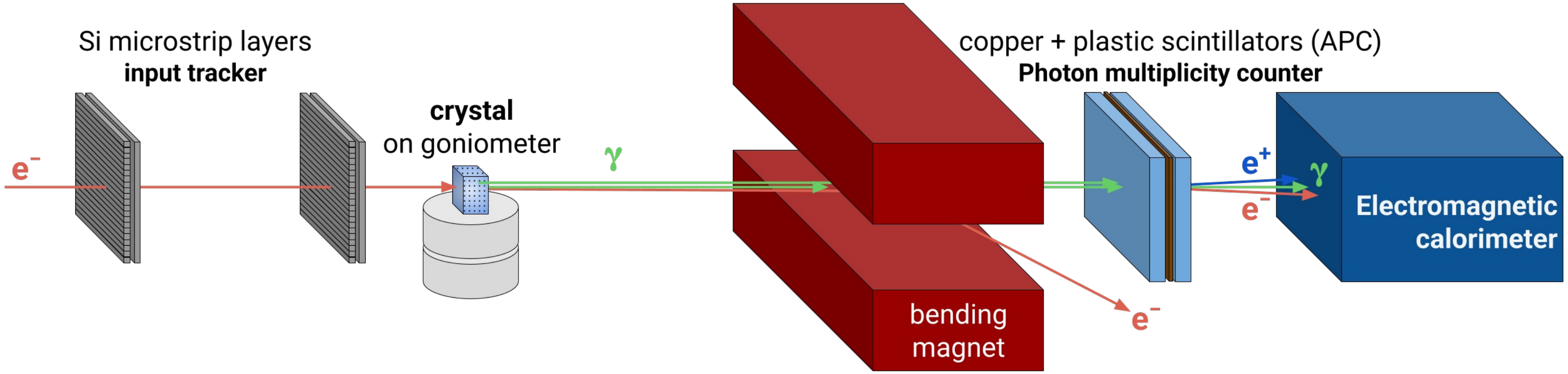


High precision crystal alignment for channeling experiments

Experiments on beam

Coord: L. Bandiera, M. Prest





INFN Ferrara, Legnaro National Laboratories and Milan Bicocca

Acknowledgment

INFN teams

L. Bandiera, N. Canale, M. Cavallina, F. Cescato, P. Fedeli, A. Forlani, V. Guidi, L. Malagutti, A. Mazzolari, R. Negrello, G. Paternò, M. Romagnoni, A. Saputi and A. Sytov (INFN Ferrara and University of Ferrara)
D. De Salvador, S. Carturan, M. D'Andrea, G. Maggioni, F. Nicolasi, F. Sgarbossa and D. Valzani (INFN Legnaro National Laboratories and Univeristy of Padova)
G. Simi, M. Zanetti (INFN Padova and University of Padova)
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A. Bacci, I. Drebot, M. Rossetti Conti (INFN Milano)
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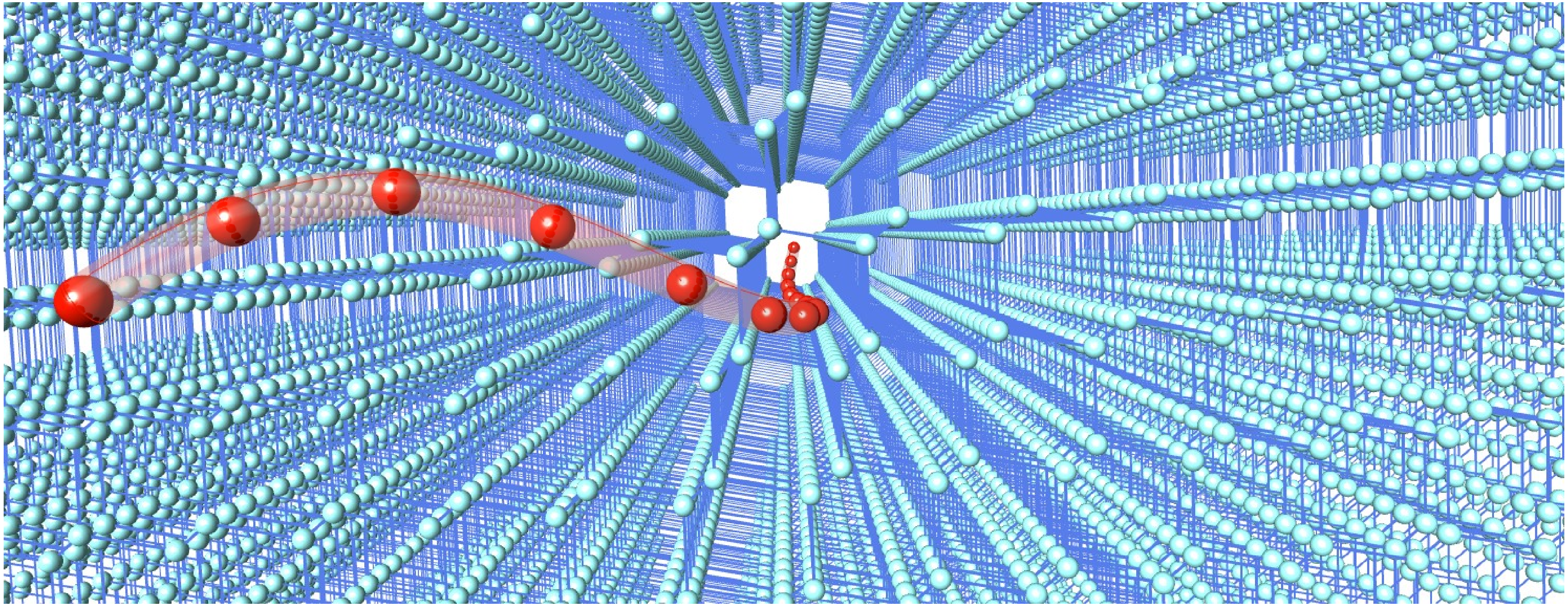
D. Boccanfuso, A. O. M. Iorio, S. Perna (INFN Napoli)
S. Bertelli, S. Dabagov, E. Diociaiuti, D. Di Giovenale, L. Foggetta and M. Soldani (INFN Frascati National Laboratories)
F. Arfelli (INFN Trieste)
G. Lamanna, J. Pinzino, M. Sozzi, N. Turini (INFN Pisa and Pisa University)

International Collaborations: **FCC-ee injector studies CHART P^3, LHC collimation WG, MU2E, TWOCRYST, TECHNO-CLS**

Thank you for the attention



….. Not the end of the story since there are many more ideas and applications of crystals….
---Beam focusing or merging and channeling acceleration in crystals…
(ideas from: F. Zimmerman, T. Tajima, S. Corde, A. Variola, etc.)

Plasma acceleration in solid state targets => towards a chip-scale accelerator

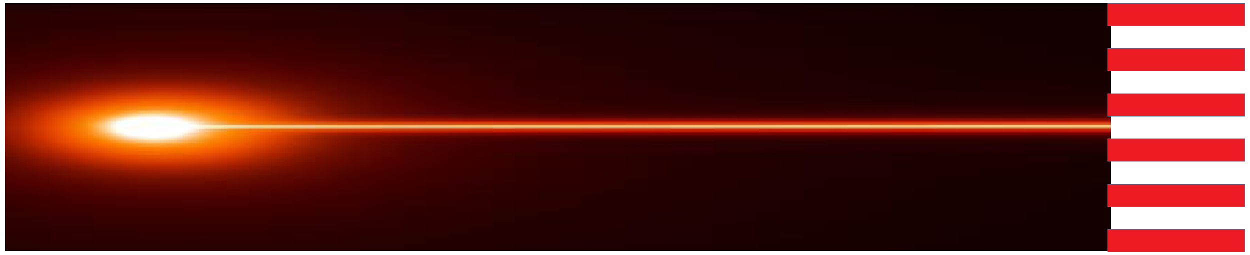
Acceleration gradient*

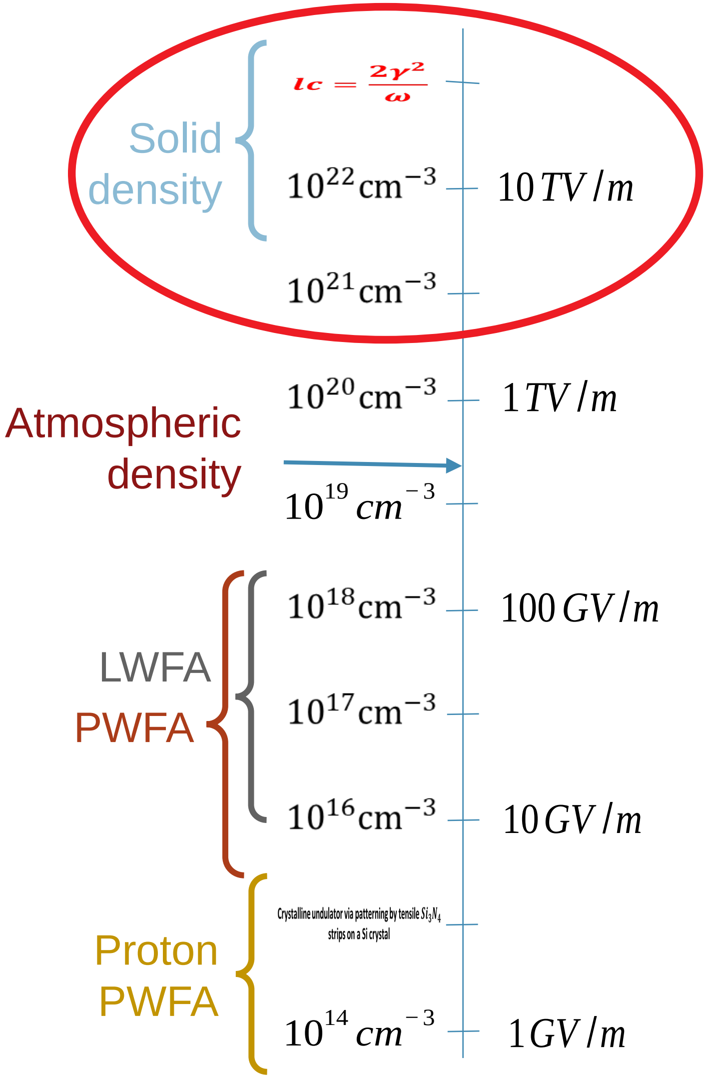
$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

Solid density plasma accelerators can produce fields of **10 TV/m**

All you need:

drive beam **target**





* Max F. Gilljohann, …, A. Sytov, L. Bandiera, …, T. Tajima, V. Shiltsev and S. Corde JINST 18 P11008 (2023)

Electromagnetic dipole moments

Electromagnetic dipole moments are static properties of particles, never measured for **short-lived charm**, **beauty** baryons, and **τ lepton**

μ= magnetic dipole moment (MDM) $\boldsymbol{\mu} = g\mu_N \frac{\mathbf{S}}{2}$

- MDM provide stringent **test of the Standard Model** for leptons (e.g. anomalous muon g-2) and QCD models for baryons

δ= electric dipole moment (EDM) $\boldsymbol{\delta} = d\mu_N \frac{\mathbf{S}}{2}$

- EDM searches are sensitive to **new physics**. Violation of P, T and CP via CPT
- Standard Model CP violation → very tiny EDM (e.g. for quarks < 10^{-31} e cm)
- **EDM observation in fundamental particles is a direct evidence of New Physics**