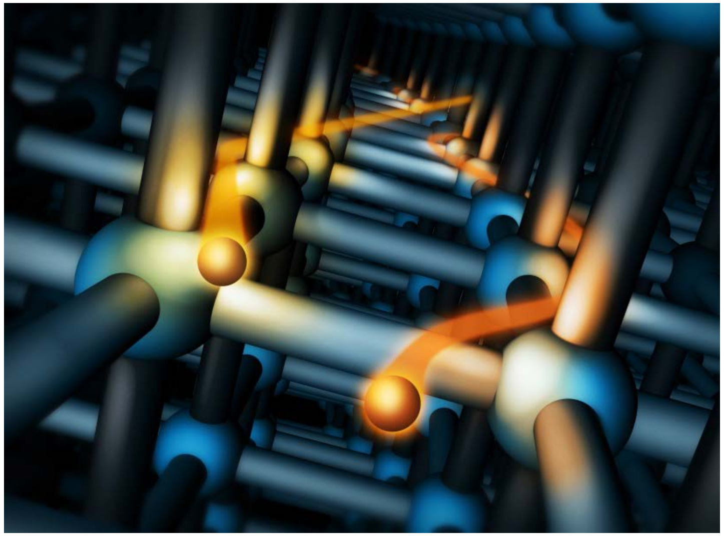
AXIAL

FE-LNL-MIB-TN



Study of axial and quasi-axial phenomena in crystals for beam steering and generation of intense electromagnetic radiation.

Istituto Nazionale di Fisica Nucleare

Supported by CSN 5

L. Bandiera & V. Guidi INFN Ferrara
On behalf of AXIAL group

People

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Motivations

- Up to now, only preliminary results on beam steering through axial and quasi-axial effects because of the need of a 2D, instead of a 1D, crystal-to-beam alignment.

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- Up to now, only preliminary results on beam steering through axial and quasi-axial effects because of the need of a 2D, instead of a 1D, crystal-to-beam alignment.
- **Axial potential is stronger than in the planar case**, thus showing **higher deflection efficiency** and **larger angular acceptance** and

1) Lower nuclear interaction -> Ideal to **steer hadron beams** in future accelerator as FCC;

2) Deflects also unchanneled particles -> Ideal to **steer charged negative beams**;

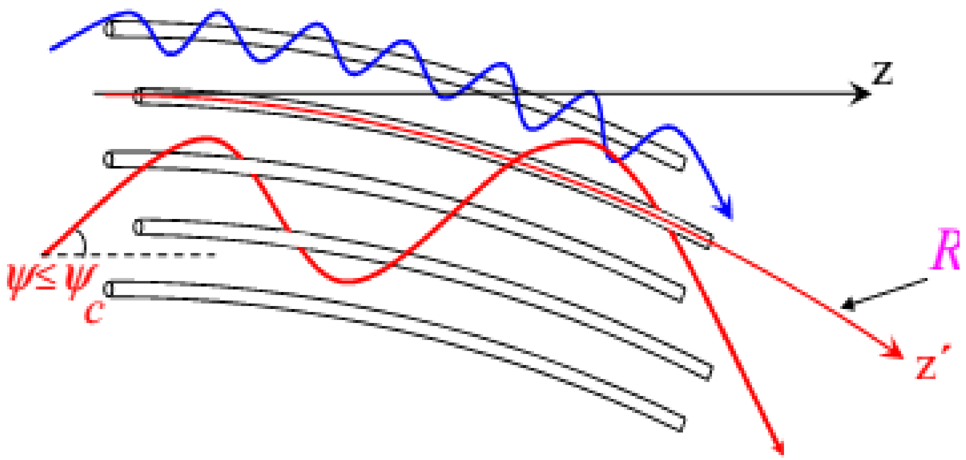
3) Possible application for beam manipulation in the **energy range interesting for protontherapy**;

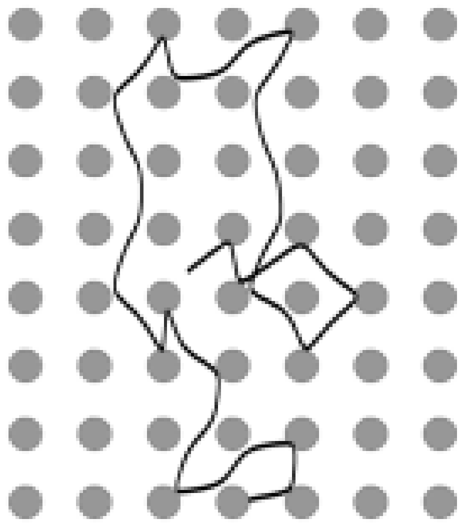
4) Far **stronger e.m. radiation generation than for amorphous medium** -> can be exploited for **electron/positron collimation at future linear colliders** (e.g. ILC, CLIC)

Stochastic deflection mechanism

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

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





Axial Channeling -> affected by dechanneling

Stochastic Deflection

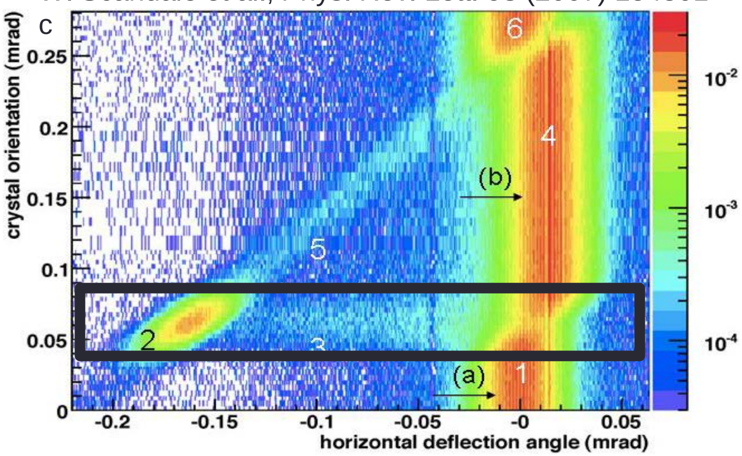
Deflection of overbarrier particles -> high-efficiency deflection also for negative beams

Axial Channeling for beam steering

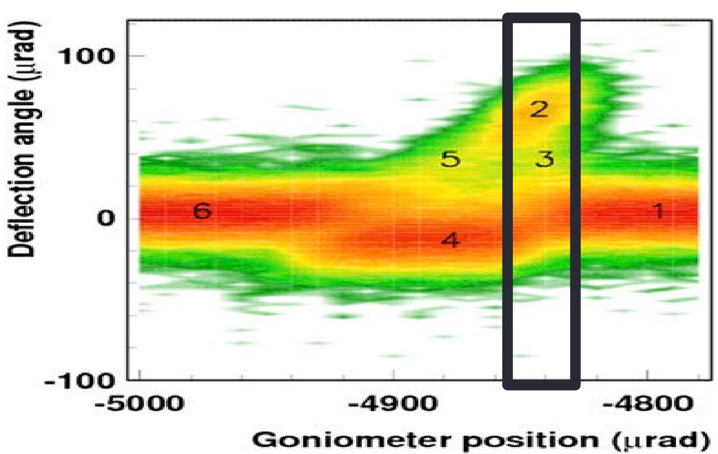
Higher deflection efficiency than planar channeling also for **negative particles**

Planar channeling

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

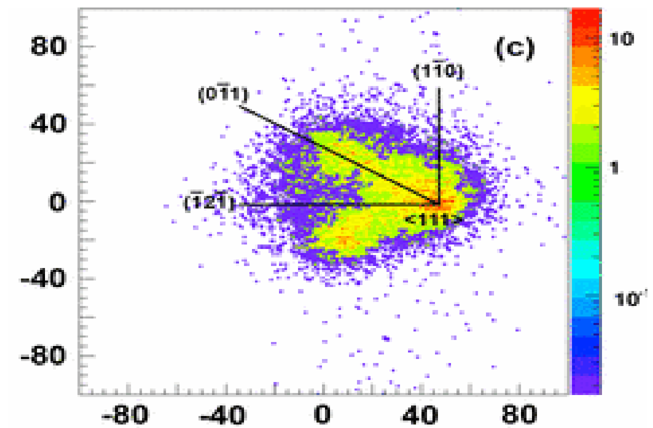


W. Scandale et al., PLB 681 (2009) p. 233–236



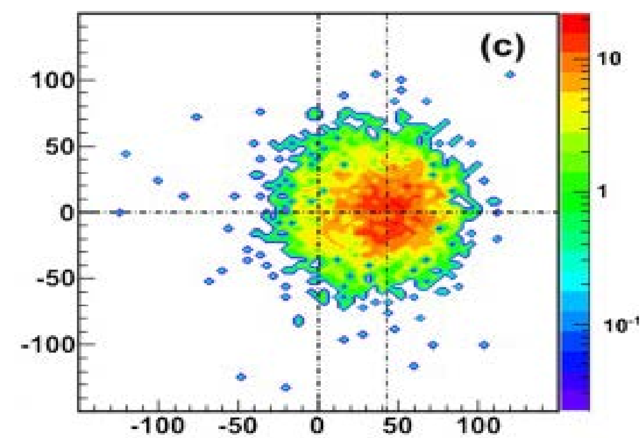
Axial channeling (SD)

W. Scandale et al., Phys. Rev. Lett. 101 (2008) 164801



400 GeV/c protons

W. Scandale et al., Physics Letters B 680 (2009) 301–304



150 GeV/c pions

H4 beam data taking in 2017 – e^- @120 GeV

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

max of U(x)

momentum velocity

$U_0 \approx$ 100 eV for <110> Si axes

***θ_{C_axial}* ≈ 45 μrad at *E ~ 120* GeV**

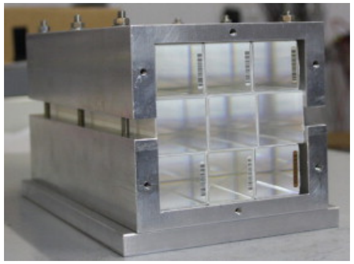
Beam characteristics:

Particle type	Electron/positron
Momentum	120 GeV/c
Purity	~ 90 % for electrons
Spot dimension	About 1x1 cm^2
Spot divergence	close to *2 θ_C in x and y directions ->* *perfect conditions!*

AXIAL setup on H4 in 2017

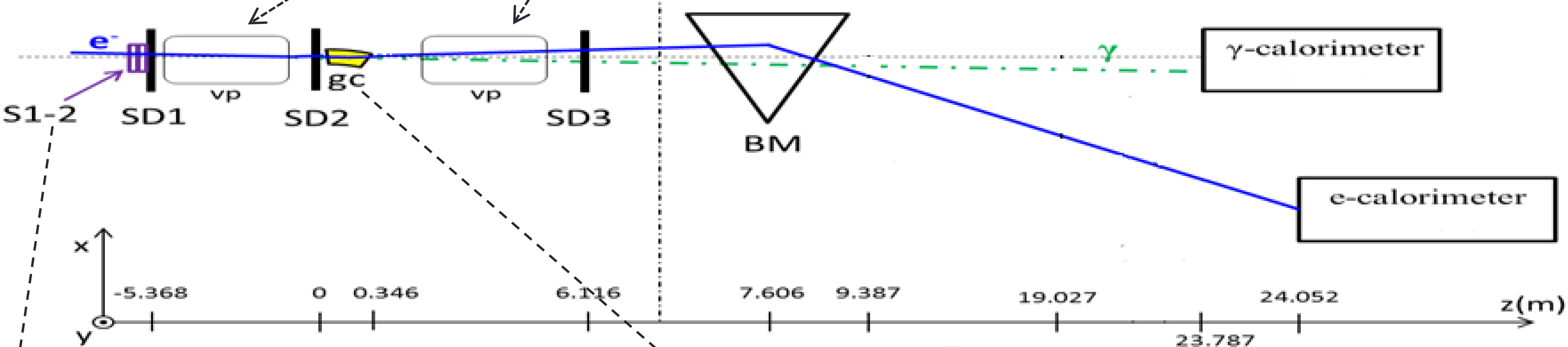
Double sided silicon detectors
1.92x1.92 cm^2 SDi
(300μm thick)
[6-11 μm spatial resolution]

vp = vacuum pipe

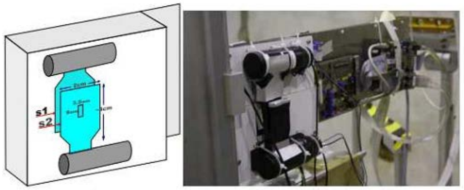


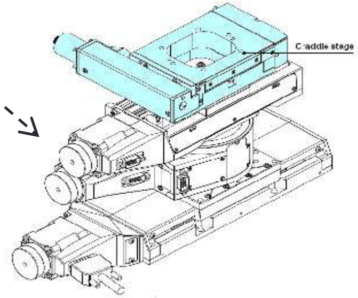
A bending magnet (BM) to separate the charged and the neutral beam
BL=1.041 T m

γ-beam (photo) and e-beam calorimeters to measure the emitted photons and to discriminate $e^{\pm}$ from impurities ($\mu^{\pm}$,$\pi^{\pm}$)



Scintillator Trigger: S2 has an hole (3x9mm^2)
Ainticoincidence



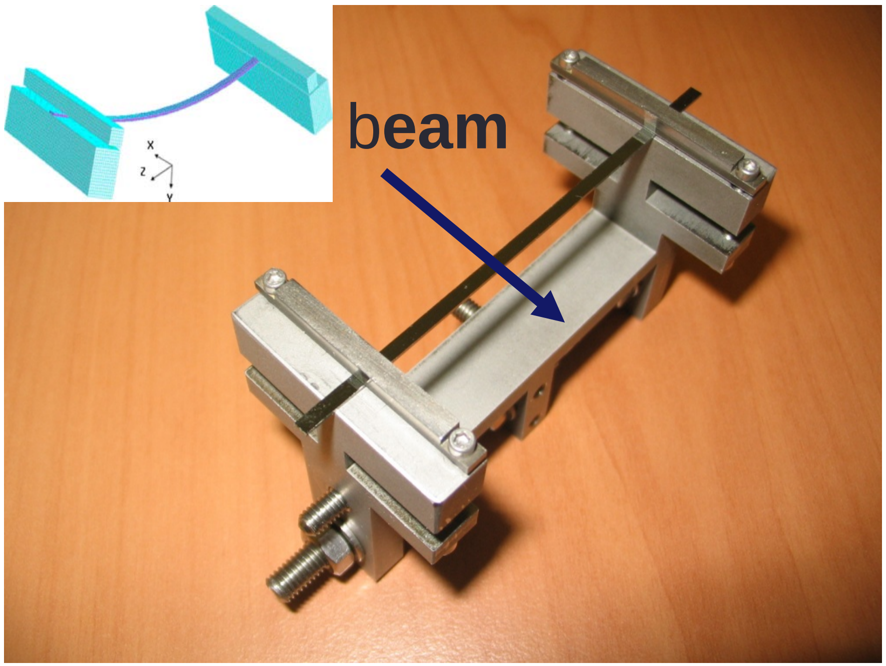


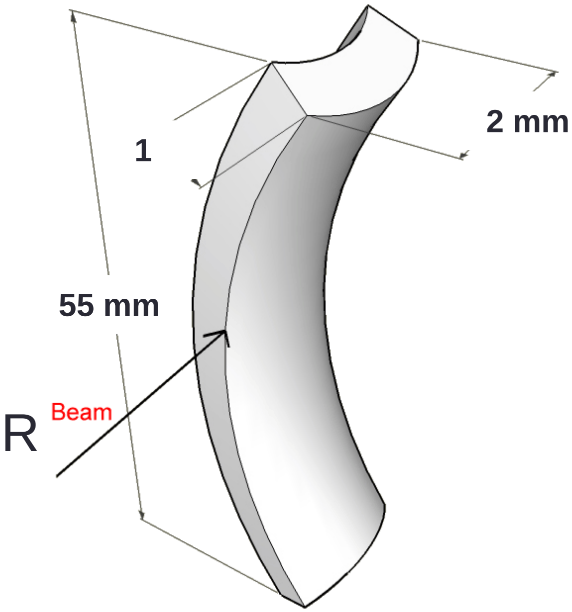
gonio @LNL
High precision goniometer to align the crystals on the beam.
[Few μrad of resolution]

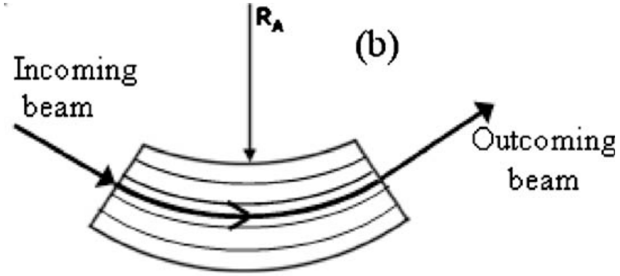
DAQ & Setup @MiB

Bent Si and Ge crystals

Si @Ferrara
Ge @LNL



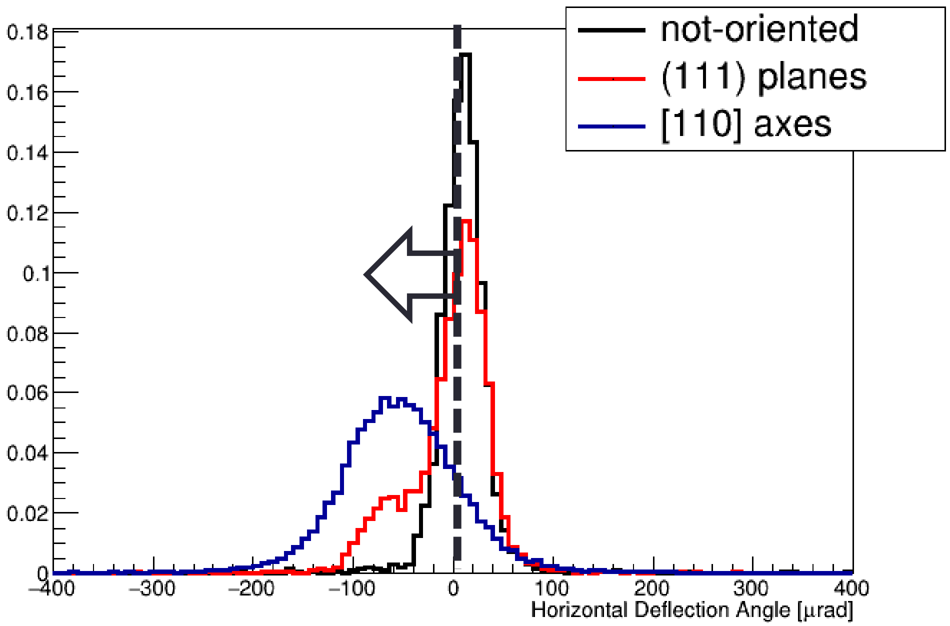




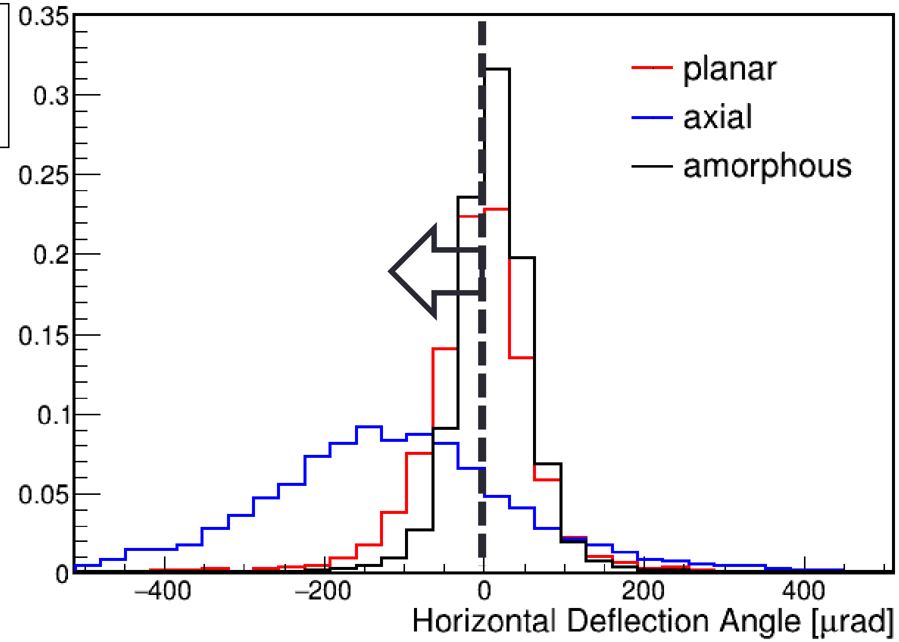
- A primary curvature is imparted by mechanical external forces, which result in a secondary (anticlastic) curvature;
- The mechanical holder used to impart the primary strain can set far apart from the particles and hence it reduces any wanted interaction with the beam.

JAP 107 (2010) 113534

2017 results: Si & Ge crystals
e$^-$ @120 GeV/c - **beam steering**



Silicon crystal (2 mm long)
<110> crystal axis
@90 μrad of bending



Germanium crystal (2.8 mm long)
<110> crystal axis
@100 μrad of bending

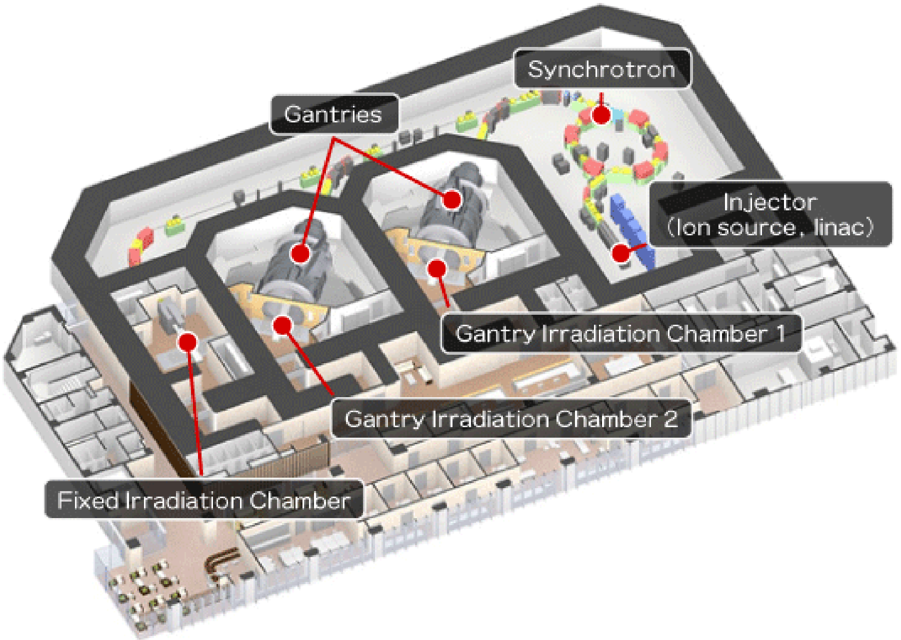
First measurements with electrons and with a Germanium crystal for negative beams.

Higher deflection efficiency than for planar channeling.

Stronger scattering in axial channeling for the Ge crystal has to be ascribed to its higher Z.

Axial channeling at 70 – 250 MeV

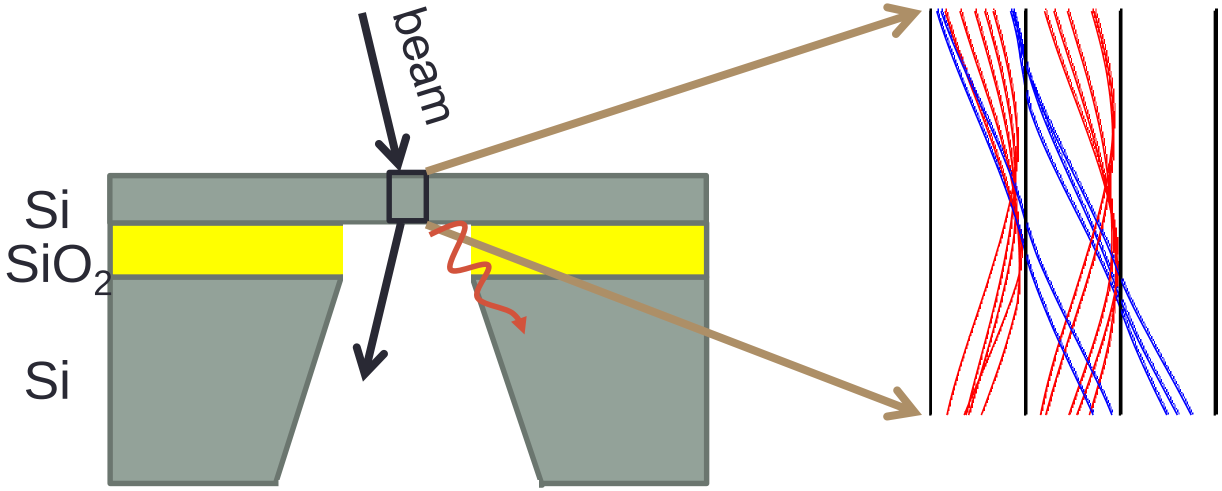
Tests at intermediate energies will be performed for the first time in this field at the Proton Therapy Center of **TIFPA - Trento**.



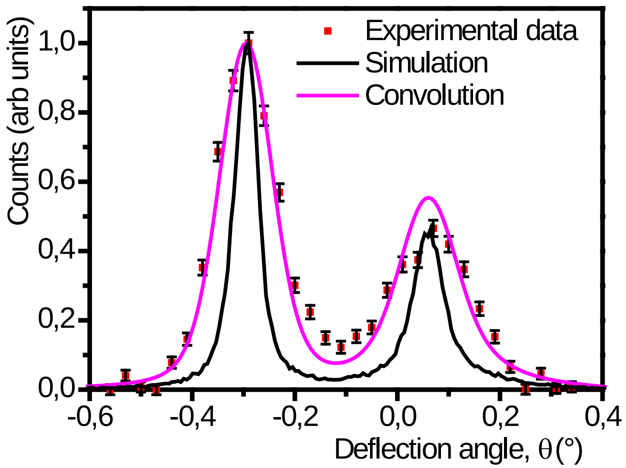
The lower energy case also deserves investigation:

- Very little is known in the literature of axial and quasi-axial effects at non ultrarelativistic energies;
- A deep knowledge can open the possibility of exploitation of such effects in brand new fields.

Deflection of 2 MeV protons in **planar case**



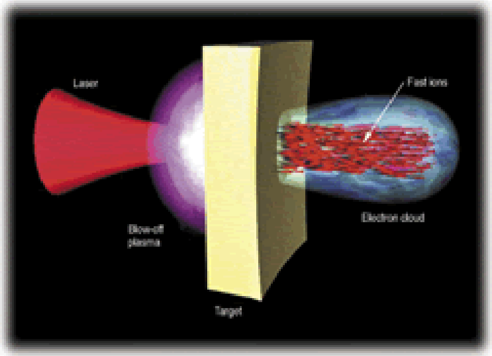
- Deflection of particles using λ/2 thin straight crystals (< 100 nm), prooved to work at 2 MeV at LNL of INFN
- First observation of channeling from a nano-thick membrane



V Guidi, A Mazzolari, D De Salvador, L Bacci hys. Rev. Lett. 108 (2012) 014801

Why 70-250 MeV?
Aims and applications

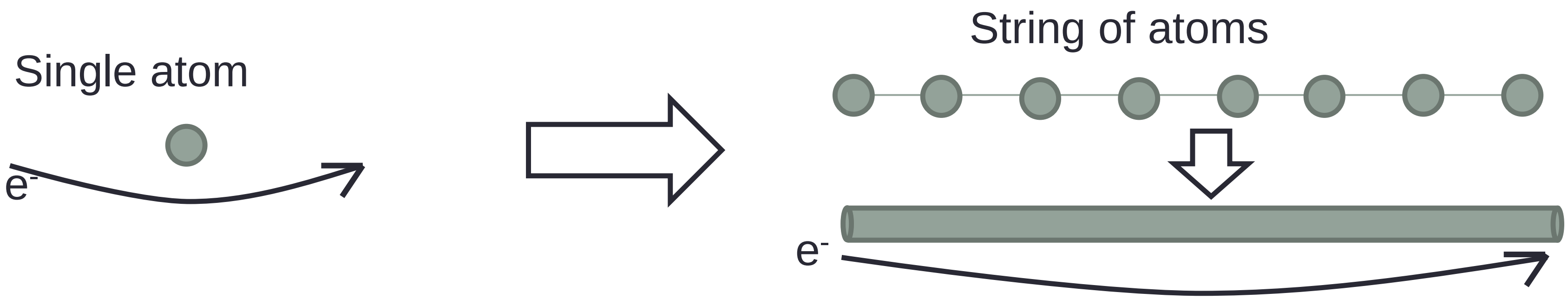
- Axial channeling tests at intermediate energies.
- Hadrotherapy: beam deflection.
- Laser Driven Accelerator: energy and angular selection.



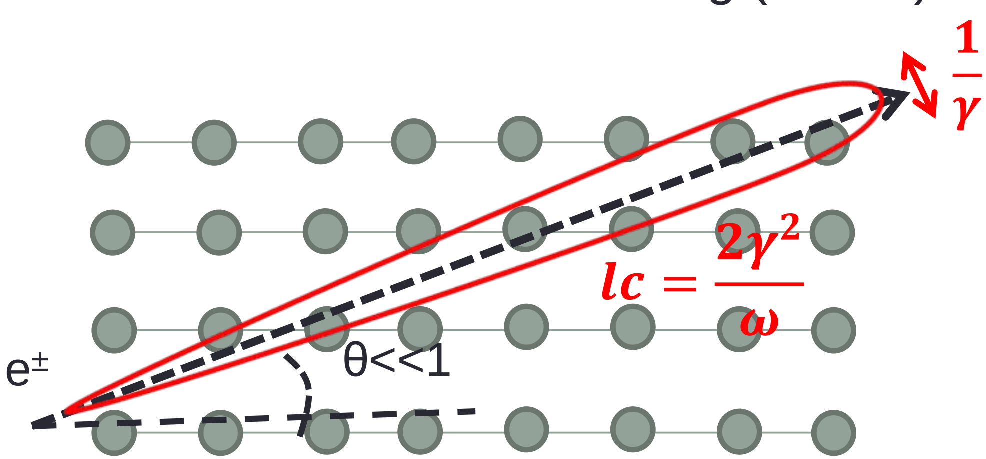
AXIAL

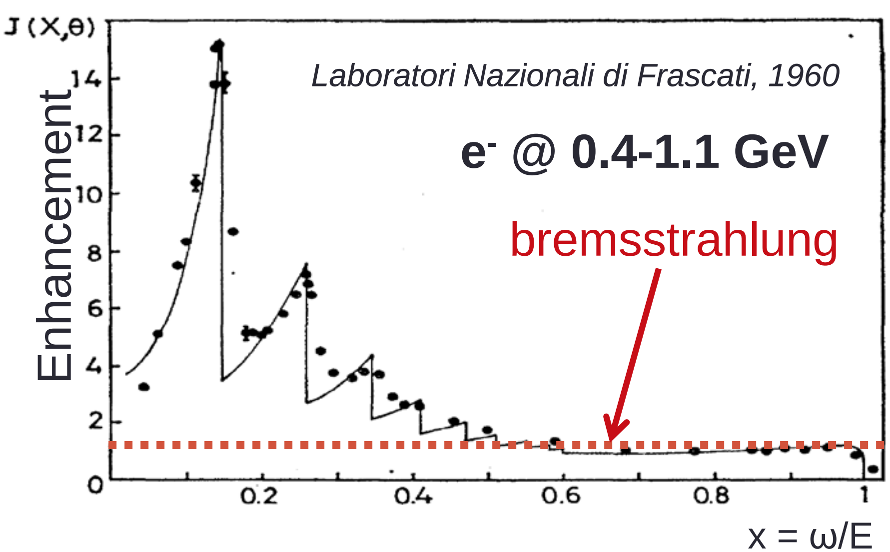
Radiation enhancement studies

Enhancement of bremsstrahlung in aligned crystals



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

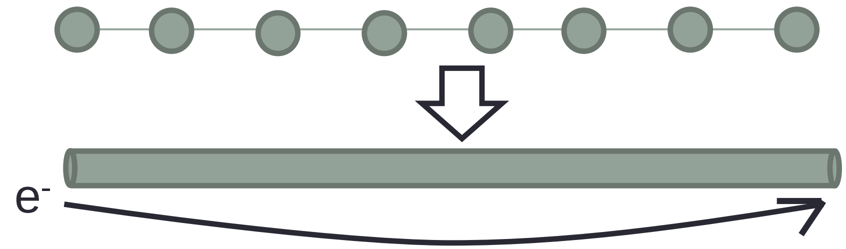




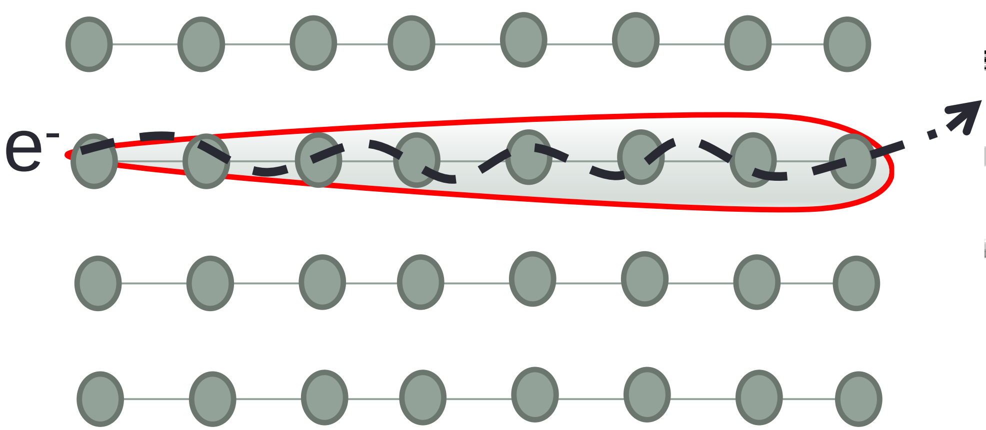
Enhancement of bremsstrahlung in aligned crystals

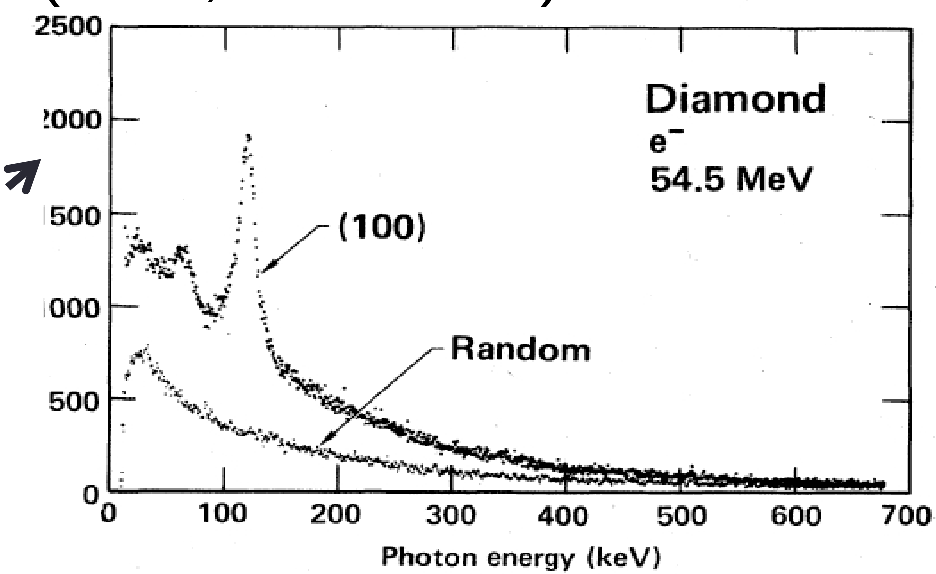
Single atom

String of atoms

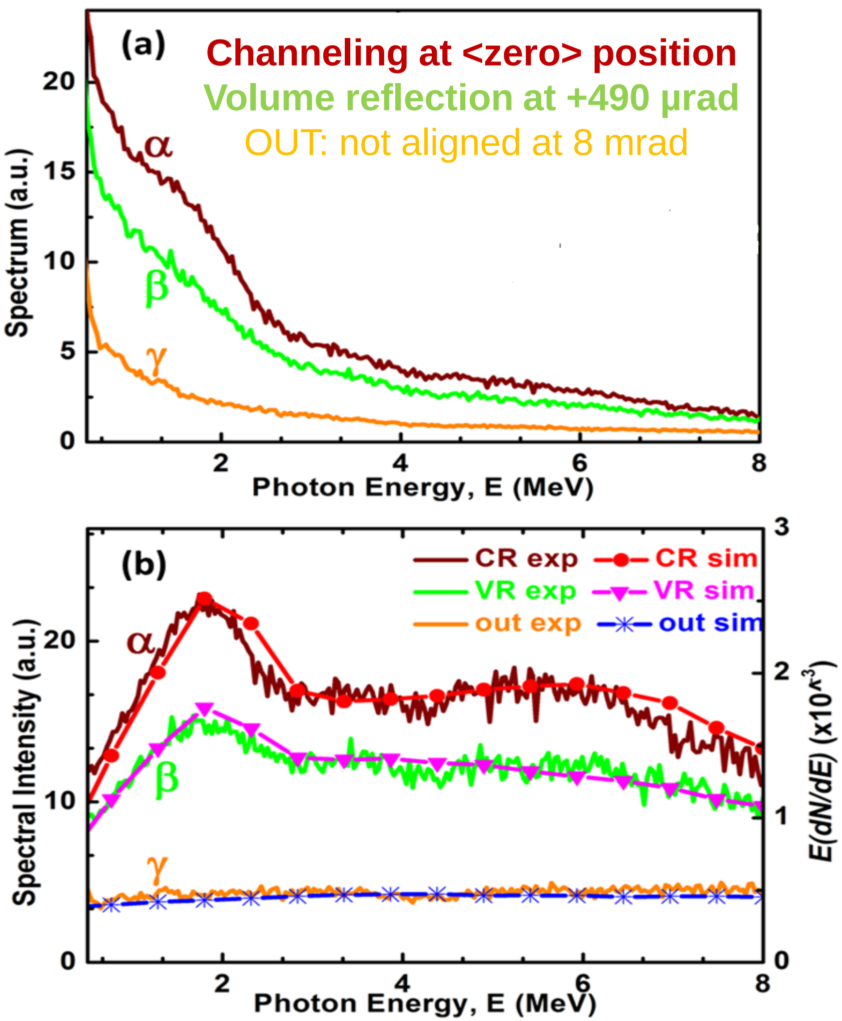


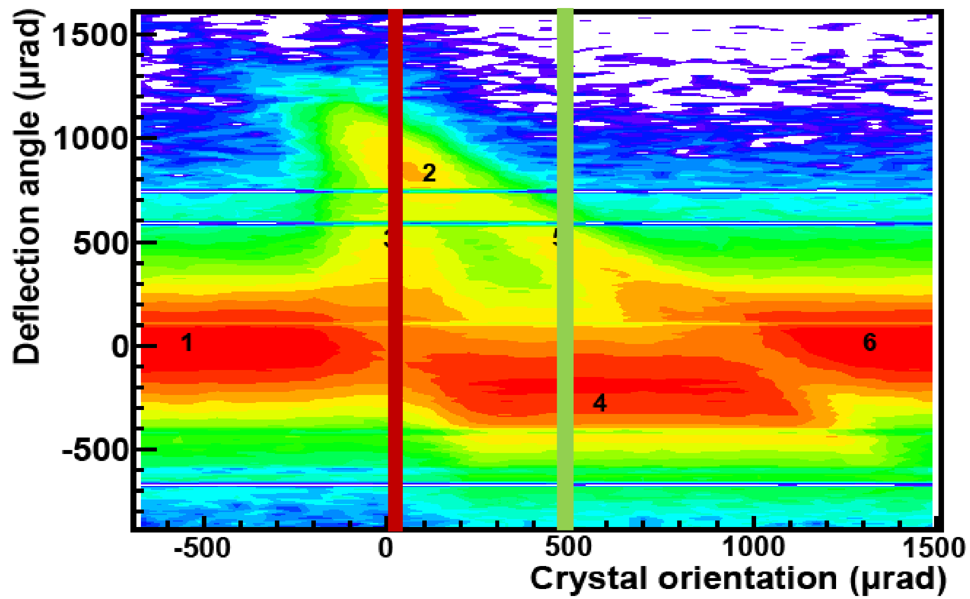
Channeling Radiation (1976, Kumakhov)





Planar Radiation in Bent Crystals @ subGeV energies





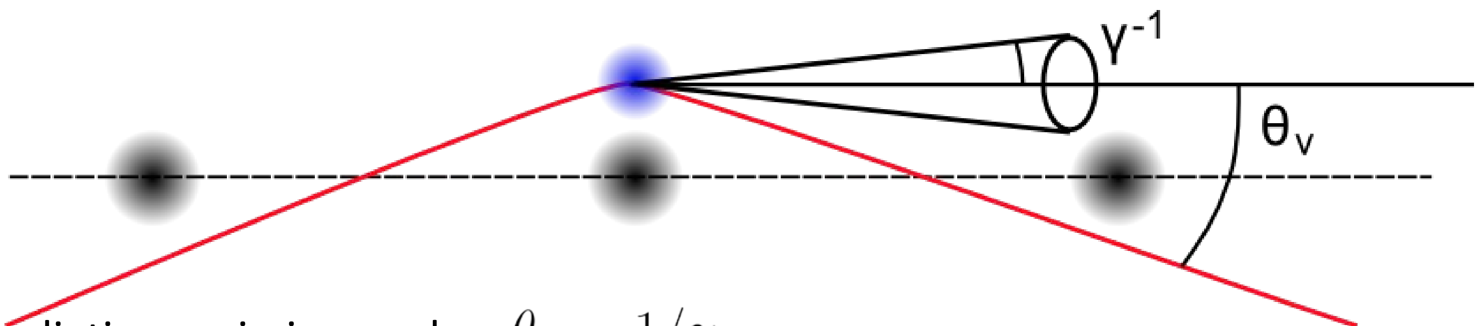
Channeling & VR peak at $E_\gamma \sim 2$ MeV for 855 MeV electrons in (111) Si bent planes

Volume Reflection Radiation has a larger acceptance than for Channeling radiation

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

Synchrotron-like radiation in crystals

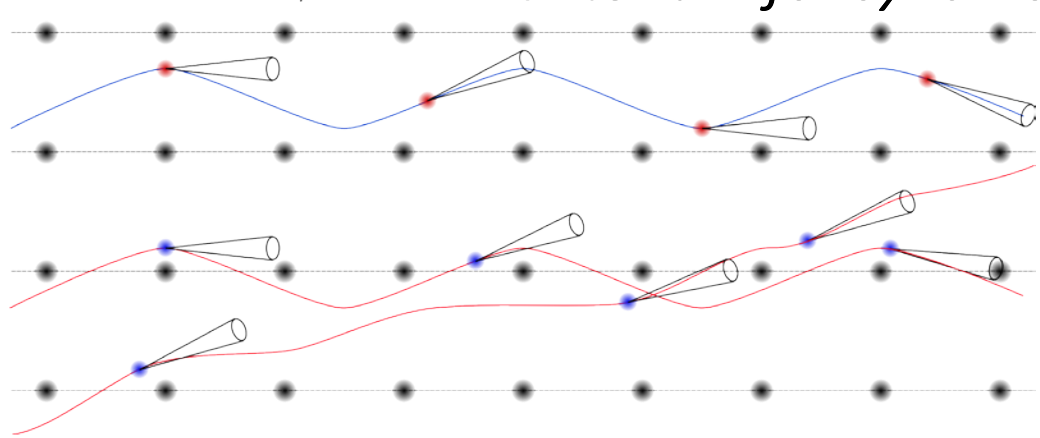
At energies of >10 GeV



Radiation emission angle: $\theta_\gamma = 1/\gamma$

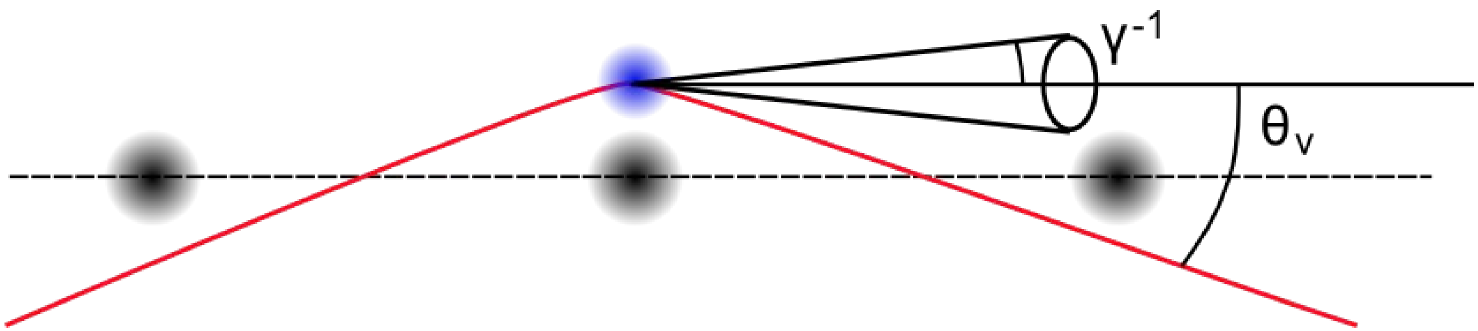
Deflection angle: $\theta_v = V_0/m$

$\theta_\gamma \ll \theta_v$ *Criterium for synchrotron radiation*



Strong field regime of Synchrotron Radiation

At energies >10 GeV (100 GeV) depending on atomic number Z



Relevant for linear colliders, astrophysical objects like magnetars, heavy ion collisions and more. When the magnetic/electric field reaches the

Critical Schwinger QED field:

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

In the rest frame of the particle, the Lorentz contracted field can be computed as:

$$\gamma E = E_0$$

Being the Planar/Axial field *E* = $10^9/10^{11}$ V/cm

"Quantum" synchrotron-like radiation is observable in crystals

TABLE I. Certain parameters of the averaged potentials of the principal axes and planes of a number of crystals.

Element	Z	(Plane) ⟨Axis⟩	d_{pl} (d_{ax}), Å	T, K	u_1, A	V_{max}, eV	$\mathscr{E}_{max}$, GV/cm	$\varepsilon_{\chi=1}$
Diamond	6	(110)	1.26	293	0.04	20.8	7.7	890
		⟨110⟩	2.52	293	0.04	137	68	100
Si	14	(110)	1.92	293	0.075	21.5	5.7	1193
		⟨110⟩	3.84	293	0.075	133	46	145
Ge	32	(110)	2.00	293	0.085	37.7	9.9	684
		(110)	2.00	0	0.036	44.0	14.9	454
		⟨110⟩	4.00	293	0.085	229	78	87
		⟨110⟩	4.00	100	0.054	309	144	47 GeV
W	74	(110)	2.24	293	0.05	127	43	158
		(110)	2.24	0	0.025	142	57	119
		⟨111⟩	2.74	293	0.05	931	500	13.6
		⟨111⟩	2.74	0	0.025	1367	1160	5.8

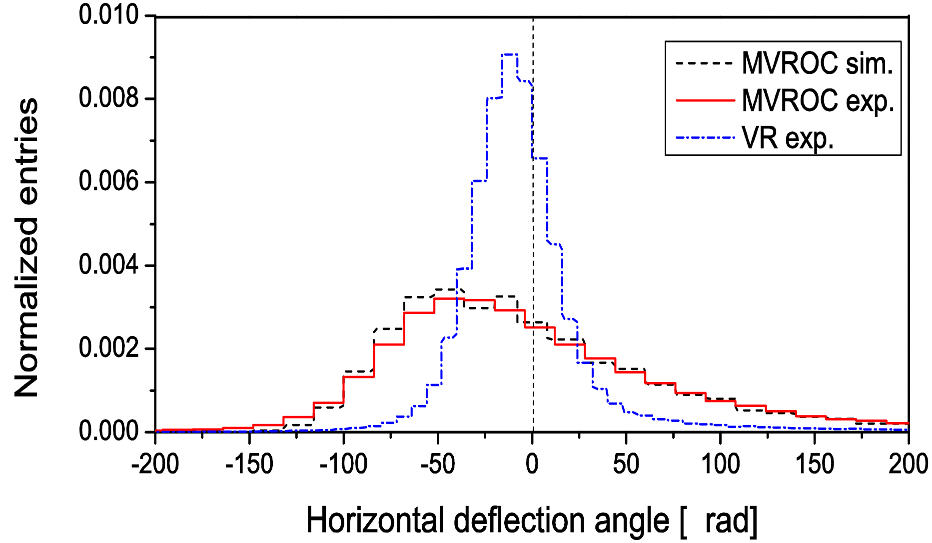
At $X = \gamma E/E_0 \geq 1$ – quantum strong field limit

Emission of hard photons with energy comparable to the primary electron/positron – cannot be treated classically -> Strong increase in the energy lost by the primary particle.

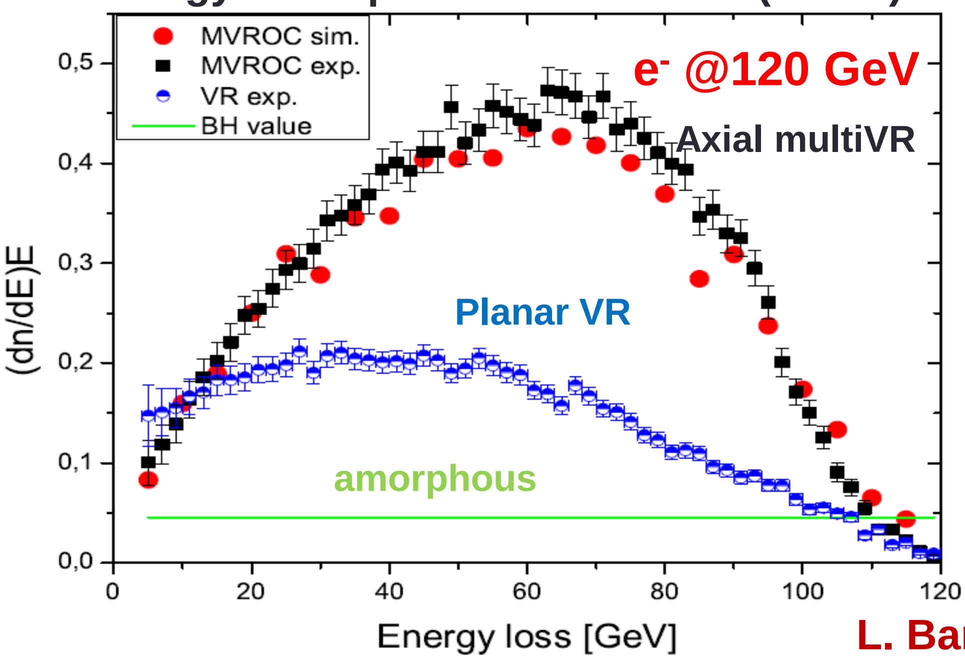
Axial case of multiple Volume Reflection

First study on quasi-axial radiation in a bent crystal

Higher deflection efficiency than planar Volume Reflection (VR) –
several VR in planes intercepting the bent Si [111] axis



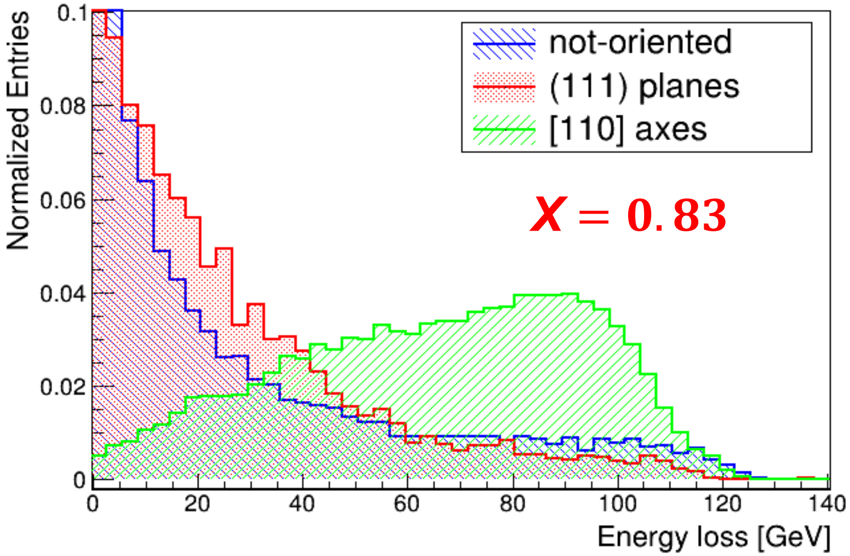
Energy loss spectral intensities: (dn/dE)*E

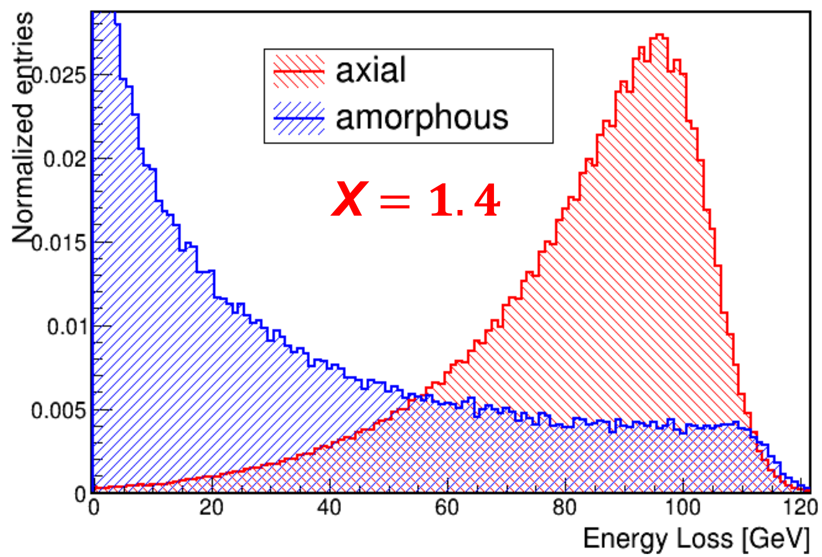


The stronger intensity of multiVR radiation **is due to the contribution of the [111] axes, which generates stronger e.m. fields.**

L. Bandiera et al., Phys. Rev. Lett. 111(2013) 255502

2017 results: Si & Ge crystals e⁻ @120 GeV/c – **radiation generation under axial alignment**





Silicon crystal (2 mm long)
<110> crystal axis
@90 μrad of bending

Germanium crystal (2.8 mm long)
<110> crystal axis
@100 μrad of bending

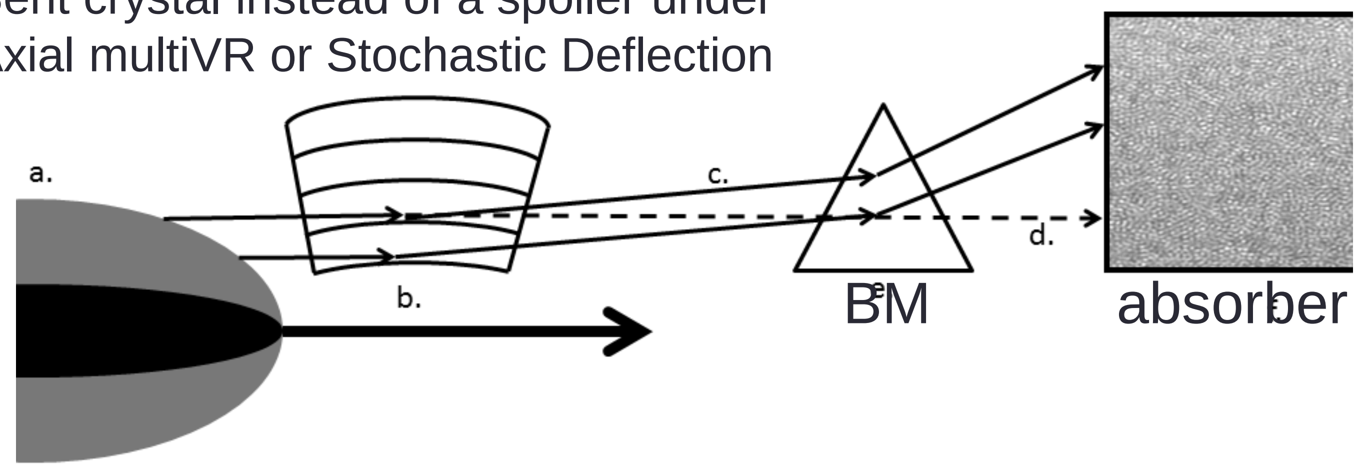
Energy loss spectrum

Stronger Energy loss for Ge is mainly due to its higher Z and larger *X* parameter

Collimation for Linear Colliders

- such as ILC (E_{beam} = 500 GeV) or CLIC

Bent crystal instead of a spoiler under Axial multiVR or Stochastic Deflection



➢ The insertion of a short Si crystal (some mm) instead of a long spoiler (some cm or more) would diminish the wakefield damages.

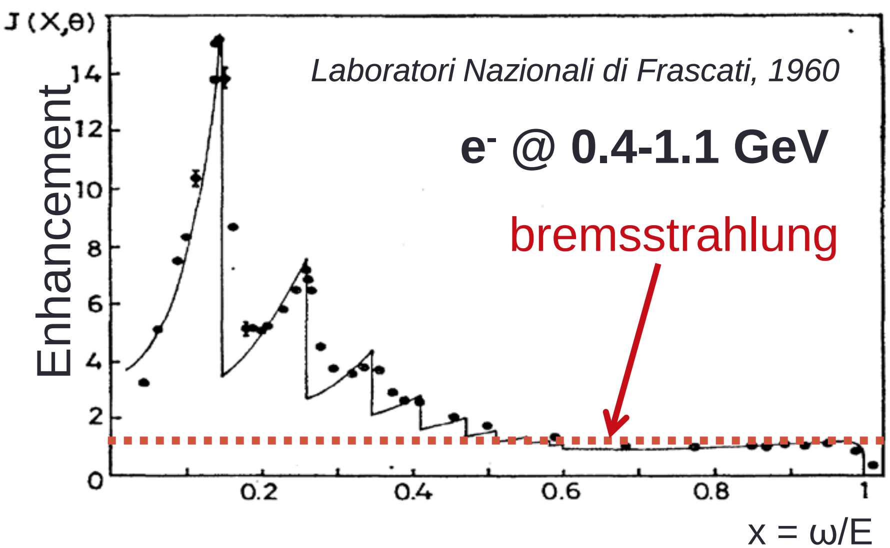
➢ **The beam deflection under MultiVR or SD and the strong increase in energy loss compared to the amorphous case would improve the discrimination of halo particles**.

L. Bandiera et al., et al., Journal of Physics: Conference Series 517 (2014) 012043

A CRYSTAL-BASED X- AND GAMMA-RAY SOURCE

Possibilities for sub-GeV/GeV facilities (such as DAFNE @LNF)

Existing crystal-based gamma source with electron beams
Coherent bremsstrahlung facilities

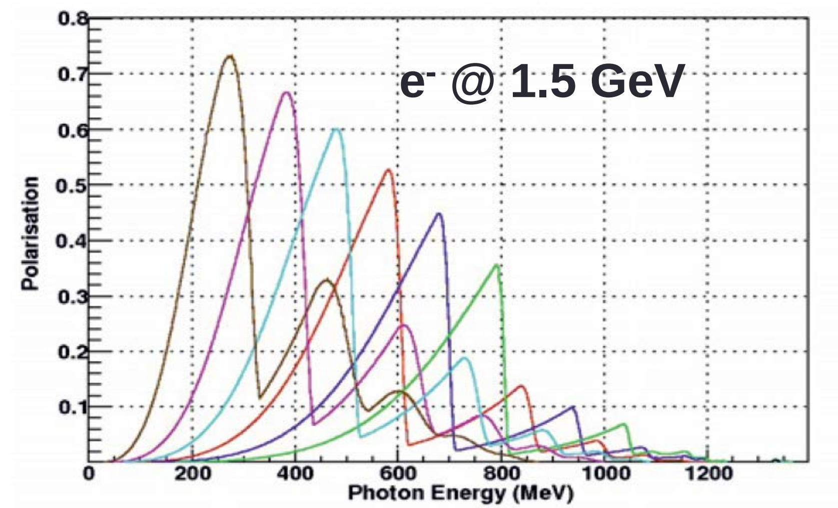


Intense and monochromatic gamma source

Linearly polarized photons

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

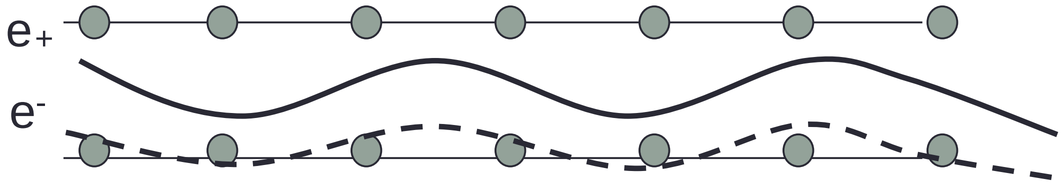
usually exploited for **photonuclear researches**

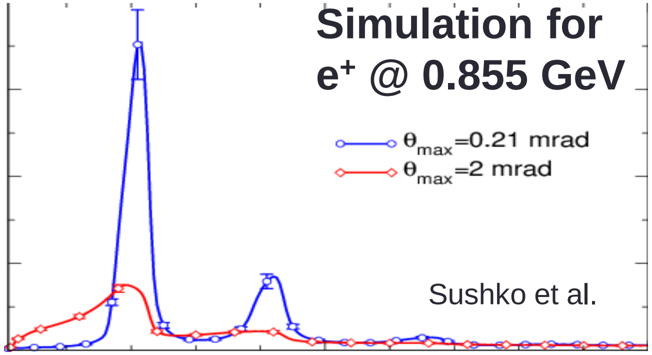


Degree of linear photon polarisation achievable at MAMI in a number of diamond orientations.

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.

.. with positrons one may exploit also Channeling Radiation





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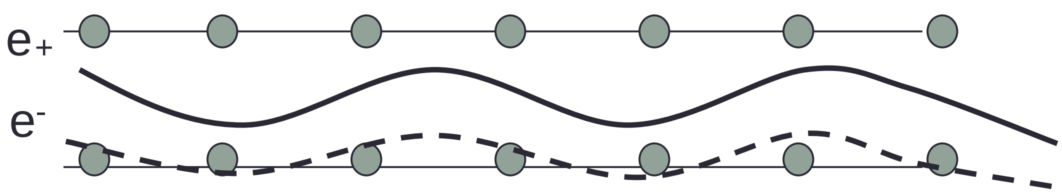
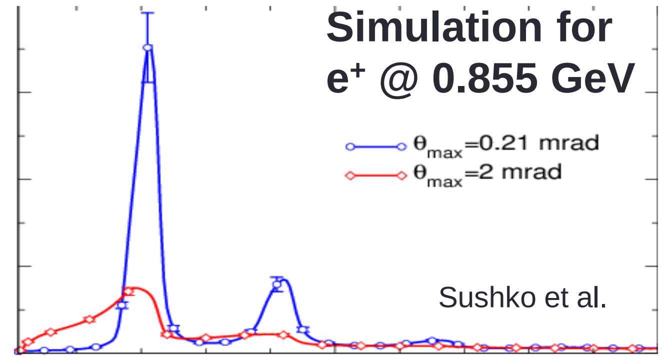
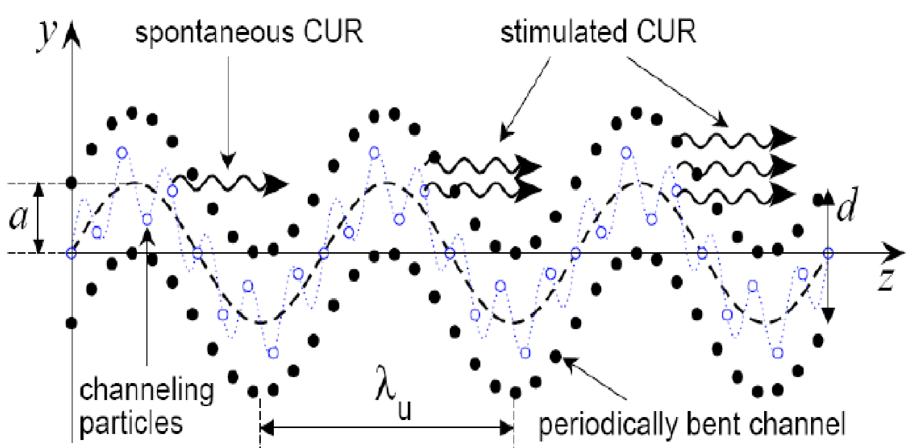




And the possibility to realize an innovative x- and gamma-ray source: Crystalline Undulator



The motion of a projectile in a CU is very similar to that in a magnetic undulator. However, it can be built with submillimetric period instead of standard cm-long, increasing the energy of radiated photons with the same beam energy.

European Research Council

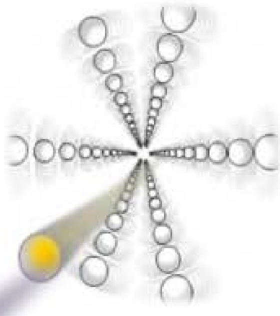
H2020-RISE PEARL (2016-2020)

(consortium with several institute that work in the subject of radiation in oriented crystals such as ESRF, MAMI, INP MINSK, AARHUS, **INFN & UNIFE**)

LNF DAFNE possibilities

1. The study of bremsstrahlung radiation enhancement is born at LNF and currently is exploited for gamma-ray sources only at foreign facilities;
2. INFN possesses the technology to realize and/or characterize the crystals;
3. And the knowledge to exploit Coherent Bremsstrahlung and to investigate Channeling, CU and related phenomena;
4. And, more important, a unique positron facility.

With these premises, LNF may become a **leader in crystal-based x- and gamma-ray sources for application in medical and nuclear physics**. For instance a intense source of photons in the energy range of tens of KeV to tens of MeV may be exploited in radiation therapy.



The 8th International Conference
CHARGED & NEUTRAL PARTICLES
CHANNELING PHENOMENA

CHANNELING 2018

23-28 September 2018
Ischia (Napoli), Italy

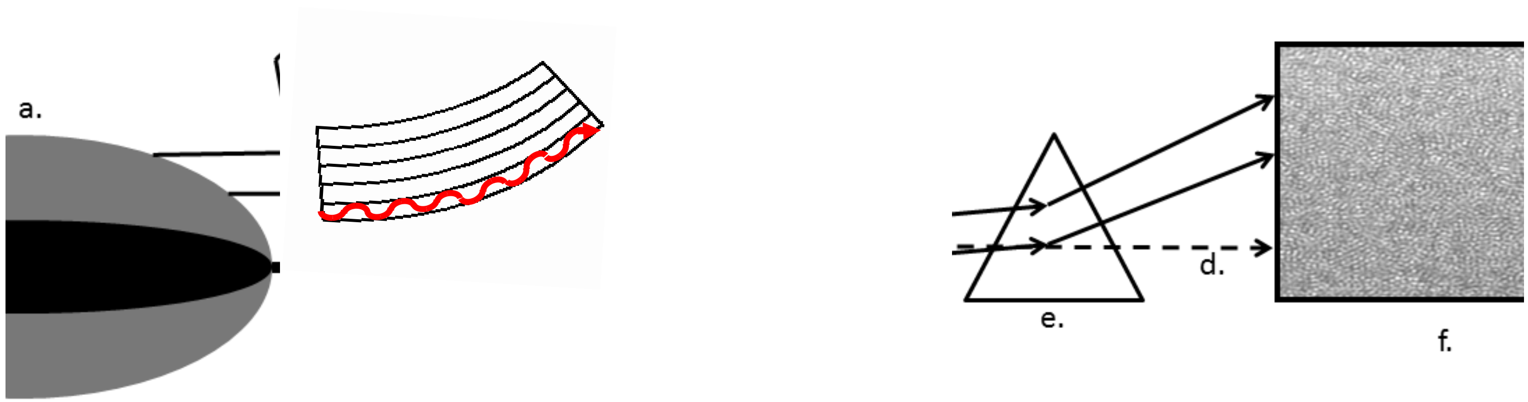
For information:channeling2018@lists.lnf.infn.it

THANK YOU FOR THE ATTENTION!

BACKUP

Possible applications at large $\gamma_{Lorentz}$

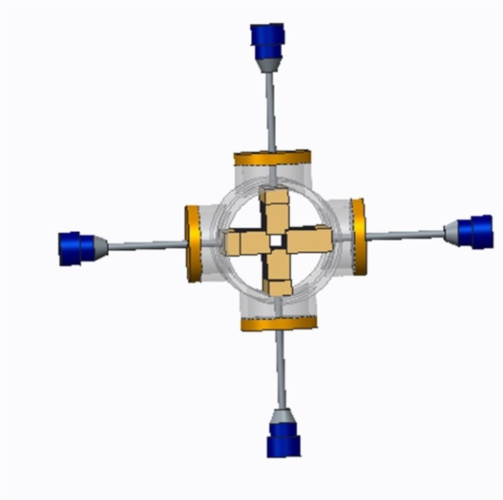
- The combination of deflecting power of a bent crystal and intense radiation generation can be exploited for a new scheme of **beam manipulation in future electron-positron colliders**, such as ILC or CLIC.
- **Collimation for future linear colliders**, such ILC (E_{beam} = 500 GeV):

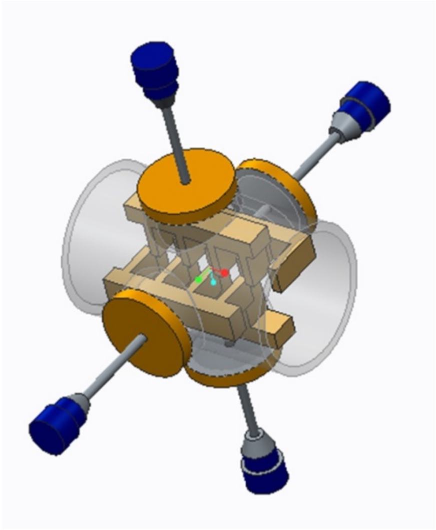


- ➢ The insertion of a short Si crystal (some mm) instead (nore) would diminish the wakefield damages.
- ➢ The beam deflection under MultiVR or SD and the strong increase in energy loss compared to the amorphous case would improve the discrimination of halo particles.

L. Bandiera et al., et al., Journal of Physics: Conference Series 517 (2014) 012043

Collimator for protons at 70-230 MeV





For the first time the channeling of protons in the range between 70 and 230 MeV will be explored both in reflecton and in transmission through thick crystals.

For this purpose, a collimator is under costruction for producing a low divergence beam for protons at these energies.

The collimator is designed with two remotely controlled slits suitable for producing cross sections lower than 0.1 mm.

The two slits will be connected by a 2 m long pipe under vacuum in order to avoid scattering with air, which is detrimental to the beam divergence.

First tests are planned for the middle of 2018.