INTENSE CRYSTAL-BASED HARD-X AND GAMMA SOURCES WITH THE DAFNE BEAM

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Frascati, 17th December 2018

Istituto Nazionale di Fisica Nucleare

Outlook

- Introduction to bremsstrahlung radiation enhancement in crystals;
- Possibilities for intense and polarized crystal-based sources at DAFNE, relying on:
  - Coherent Bremsstrahlung (> MeV);
  - Channeling Radiation (100 keV-1 MeV);
  - Crystalline Undulator (10-100 keV).
- INFN expertise on crystals fabrication and characterization for experiments with sub-GeV leptons;
- Summary.

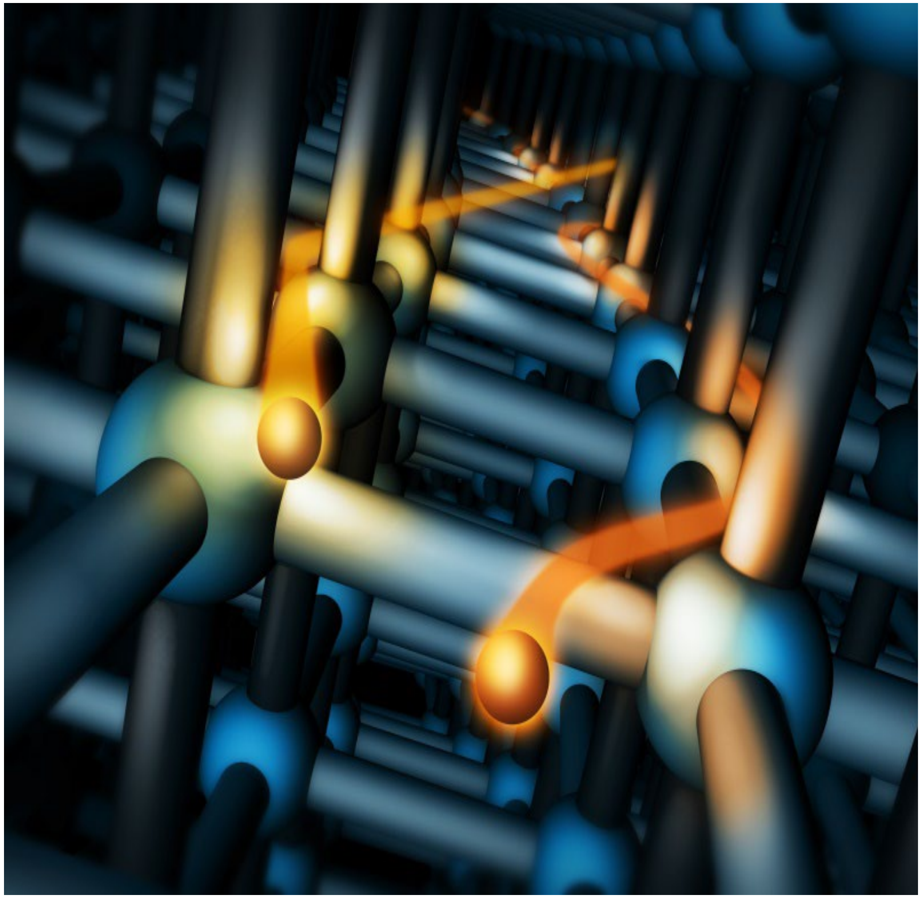
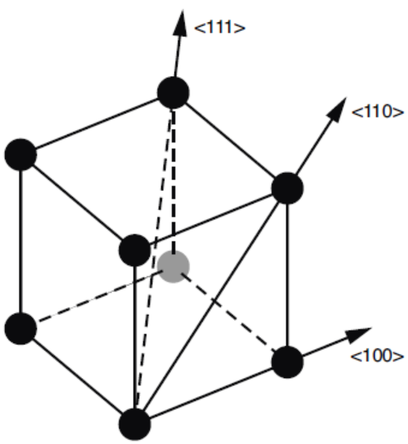
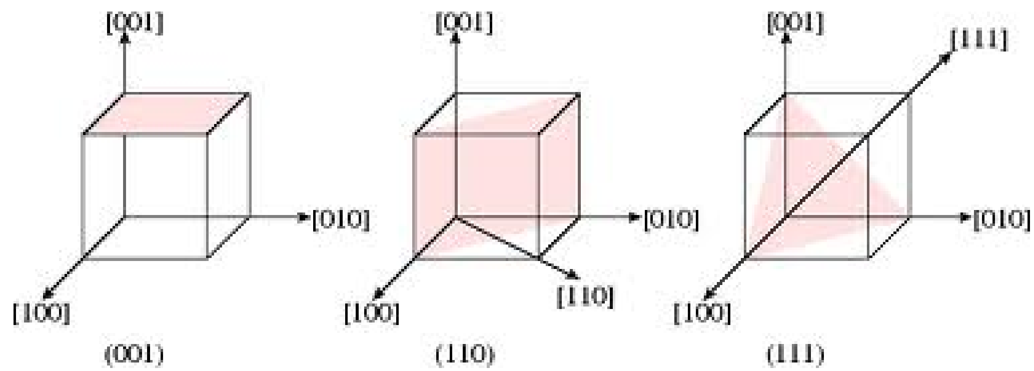


Image from https://www6.slac.stanford.edu/news/2015-02-25-slac-led-research-team-bends-highly-energetic-electron-beam-crystal.aspx

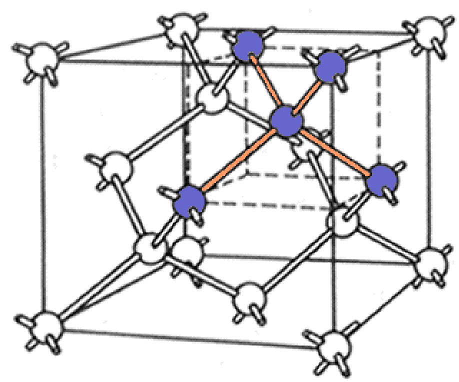
Crystalline solids

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**.

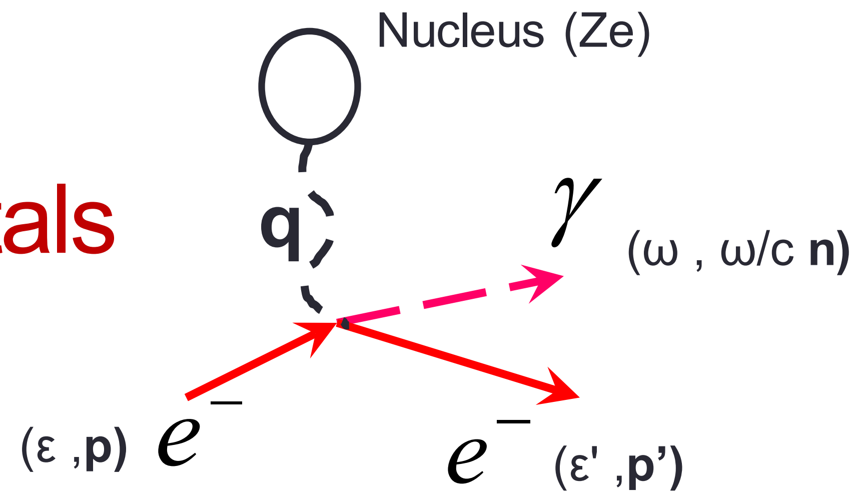




Diamond or Si crystal

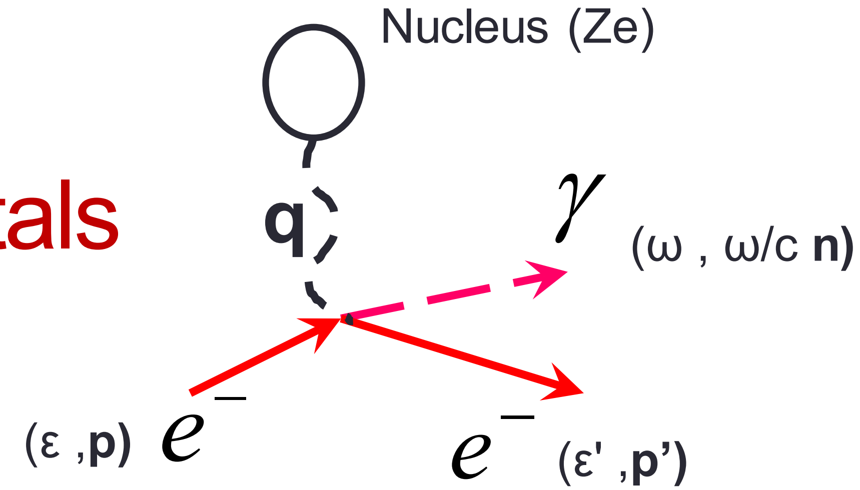


Bremsstrahlung in crystals

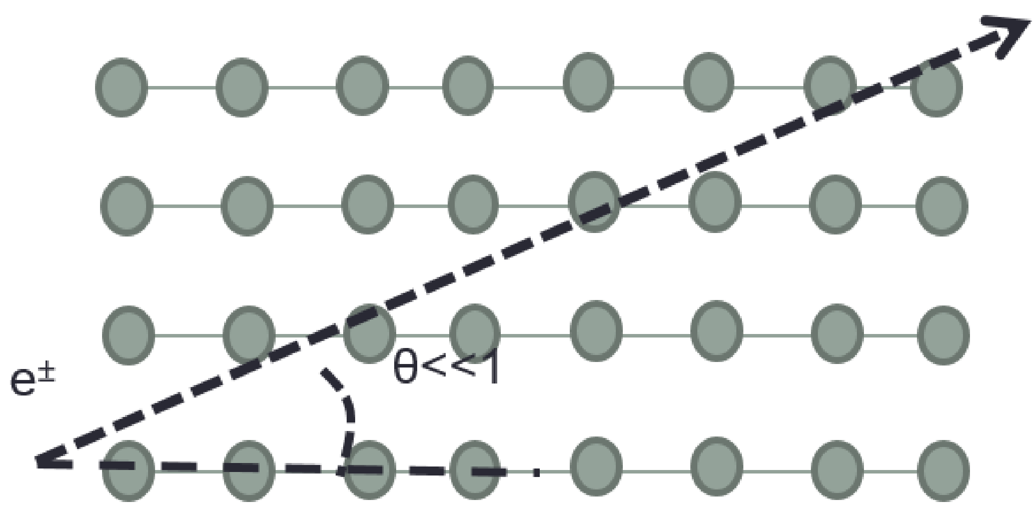


Does the crystal structure influence the process of bremsstrahlung?

Bremsstrahlung in crystals



Does the crystal structure influence the process of bremsstrahlung?

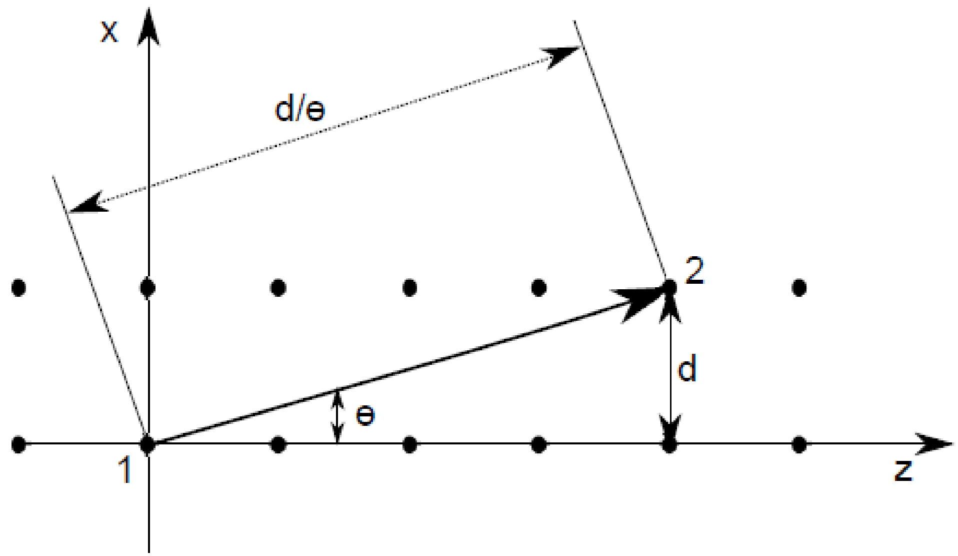


Yes!

In case of small incidence angle with some crystal lattice direction.

Coherent Bremsstrahlung

- Crystal lattice constant **d**;
- **Electron impinges** onto a crystal with **velocity v** and with **a small angle θ** with respect to a **crystal direction**.
- Bremsstrahlung radiation is emitted at point 1 at the instant t_0, while at point 2 at $t_0+d/(\theta v)$, v being the particle velocity.
- Since the first e.m. wave reaches the point 2 at the time instant $t_0+d/(\theta c)$, the **constructive interference condition is:**



$$\frac{\omega d}{\theta}\left(\frac{1}{v}-\frac{1}{c}\right)=2\pi n.$$

we use the units: $\hbar = 1$

Coherence (or formation) Length

The **minimal value of transferred momentum** along the direction of motion of the primary particle, $q_{\|}$,is:

$$\delta = \frac{\omega mc^2}{2\varepsilon\varepsilon'} mc$$

The **inverse of this value has a dimension of a length** (in classical case of ε ≈ ε'):

$$l_c = \frac{2\varepsilon^2}{\omega mc^2} \frac{1}{mc} \simeq \frac{c}{\omega(1 - v/c)}$$

At high energy, *lc* may become large enough to introduce the idea that the emission of a photon is not a sudden process, while instead is formed in certain distance along the electron trajectory.

In crystals, the lattice structure becomes important in the photon emission, when *lc ≥ d (analogous to Bragg diffraction).*

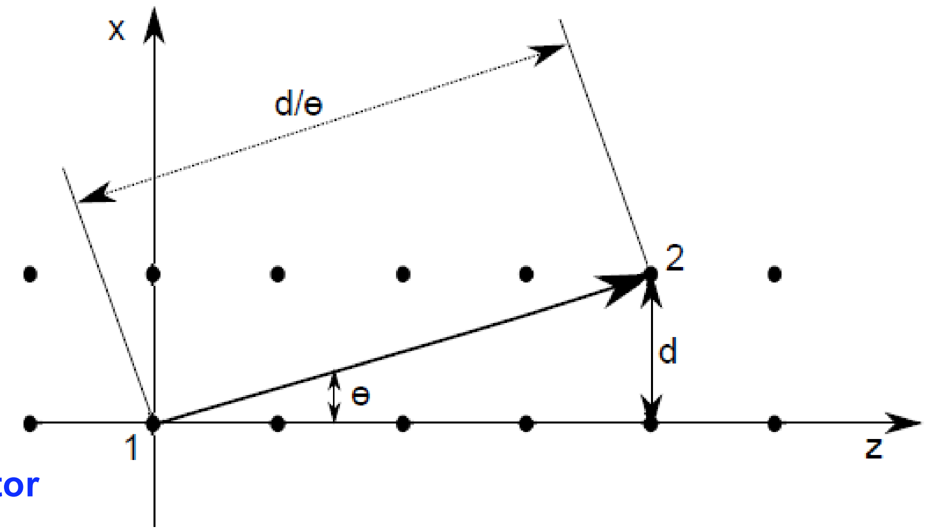
Coherence Length and interference

Constructive interference condition:

$$\frac{\omega d}{\theta}\left(\frac{1}{v}-\frac{1}{c}\right)=2\pi n.$$

$$\frac{\delta}{\theta}=n\frac{2\pi}{d}$$

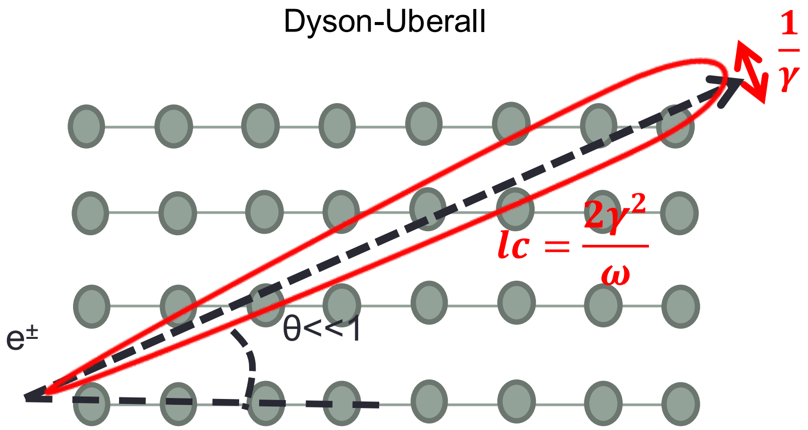
Reciprocal lattice vector

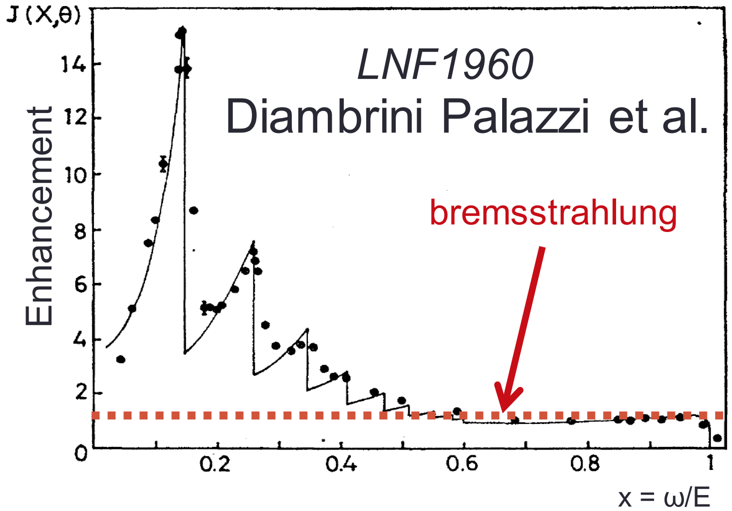


Factor **2π/d** that has the dimensions of a **reciprocal lattice vector** -> the **bremsstrahlung radiation** emitted in a crystal **increases** when the **momentum transferred from the particle to the atoms matches a reciprocal lattice vector.**

Coherent bremsstrahlung facilities

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



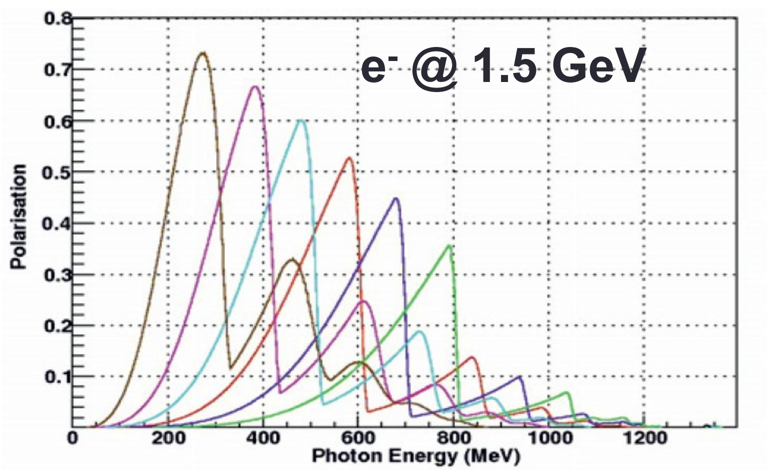


Intense and monochromatic gamma source

Linearly polarized photons

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

usually exploited
for **photonuclear researches**

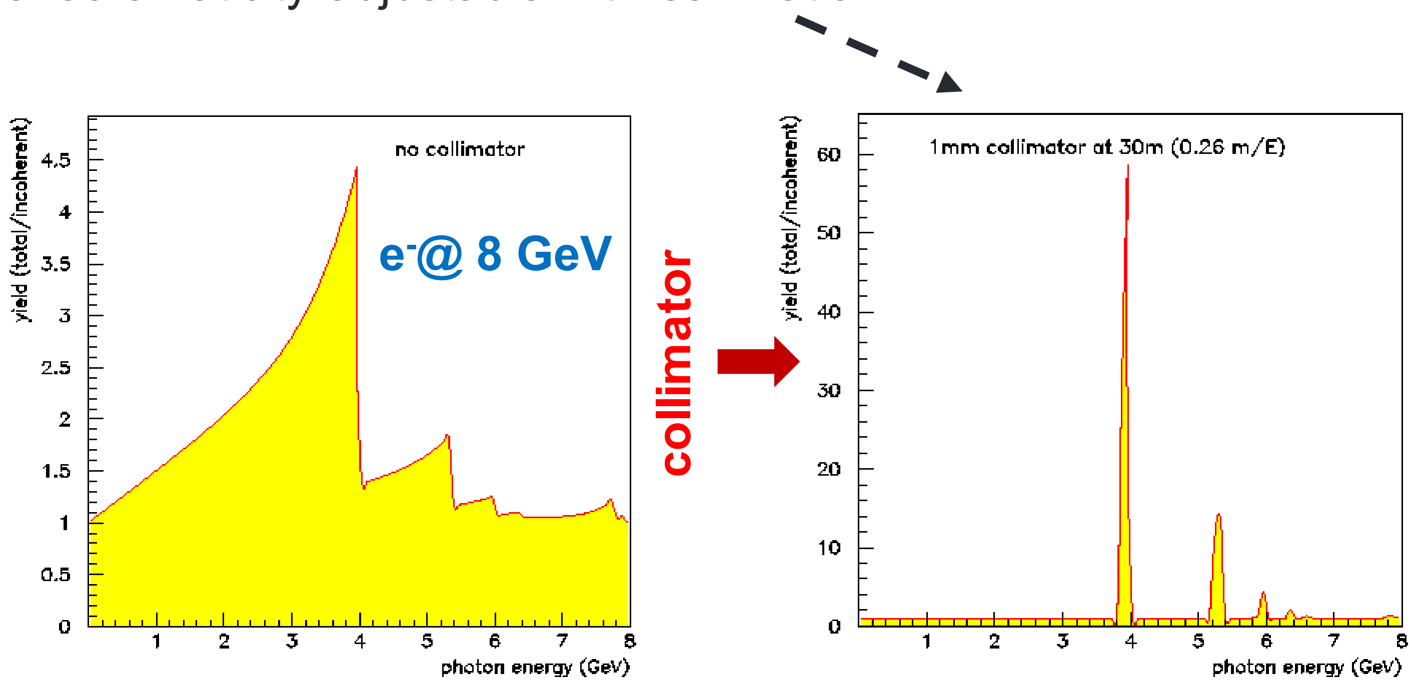


Degree of linear photon polarization achievable at MAMI in a number of diamond orientations.

Coherent bremsstrahlung @ DAFNE

Gamma-ray @10-100 MeV with e^- @ 0.5 GeV

- Higher intensity compared to usual bremsstrahlung (interference);
- Higher photon energy as compared to magnetic undulators (smaller period – d/θ ≈ hundreds of nm) and comparable to ICS sources;
- High degree of linear polarization;
- Monocromaticity adjustable with collimation.

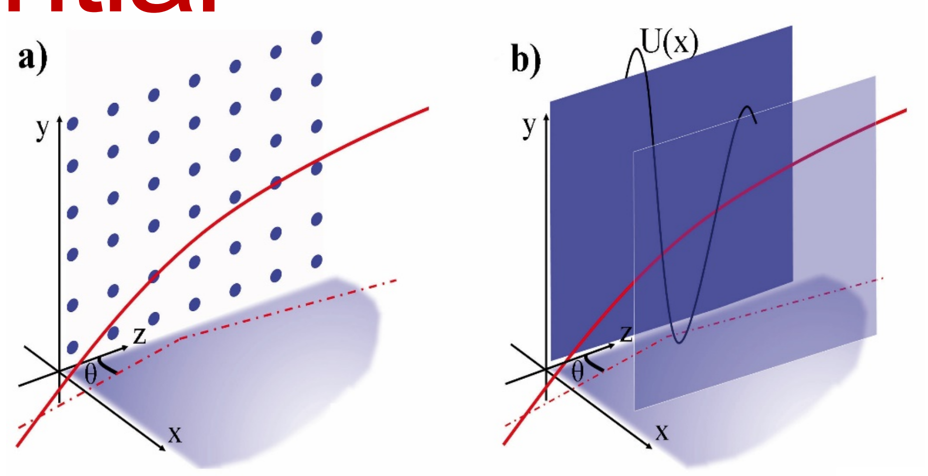


Channeling and Continuous Potential

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

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

is the particle-atom screened Coulomb potential

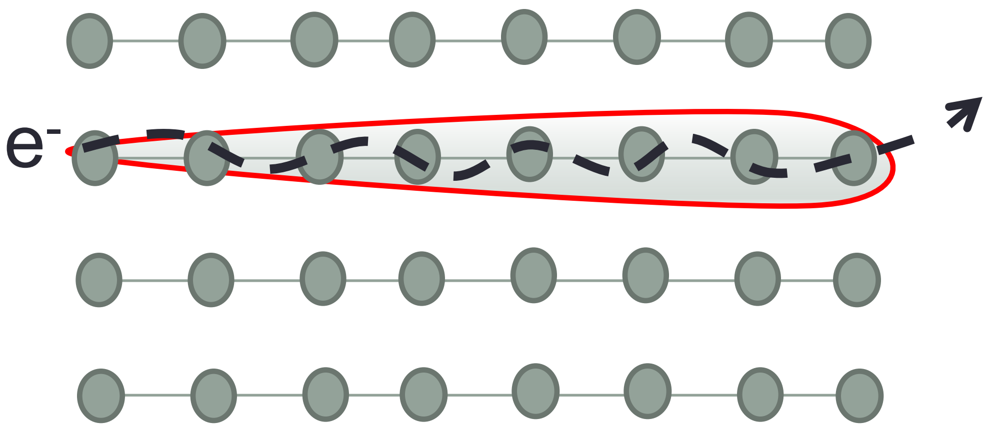


Channeling occurs as the trajectory of particles forms an angle lower than the critical angle:

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

max of U(x) (U_0)

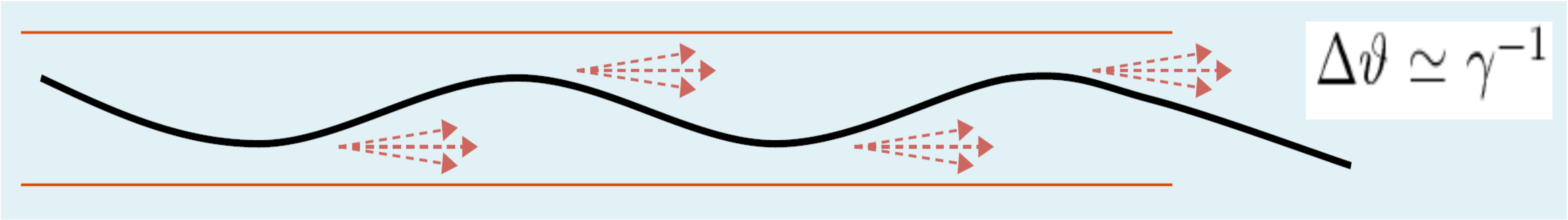
momentum velocity (pv)



U_0 = 22.7 eV for (110) Si planes
$\theta_C \approx$ 250 μrad at $E \sim 0.5$ GeV

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

Channeling radiation



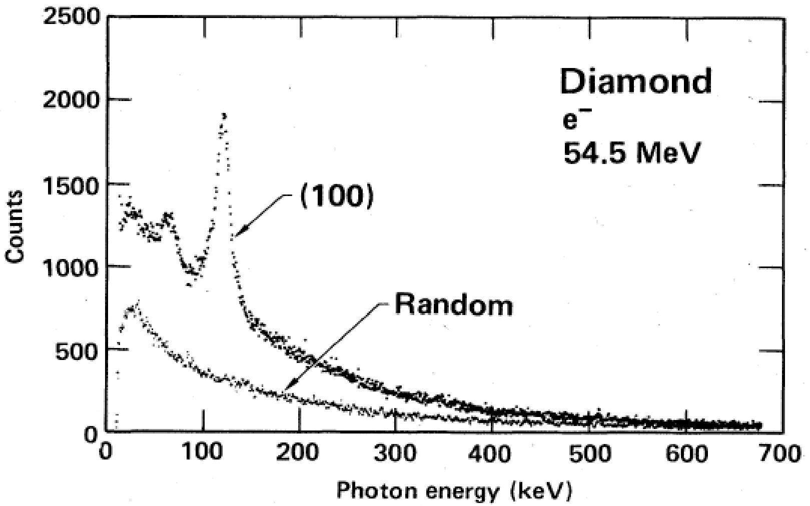
Polarized & forward emission – analogous to undulator

Radiation frequency in the forward direction:

$$\omega \approx 2\gamma^2\omega_0 = \frac{4}{d_p}\sqrt{\frac{2U_0}{m}}\gamma^{3/2}$$

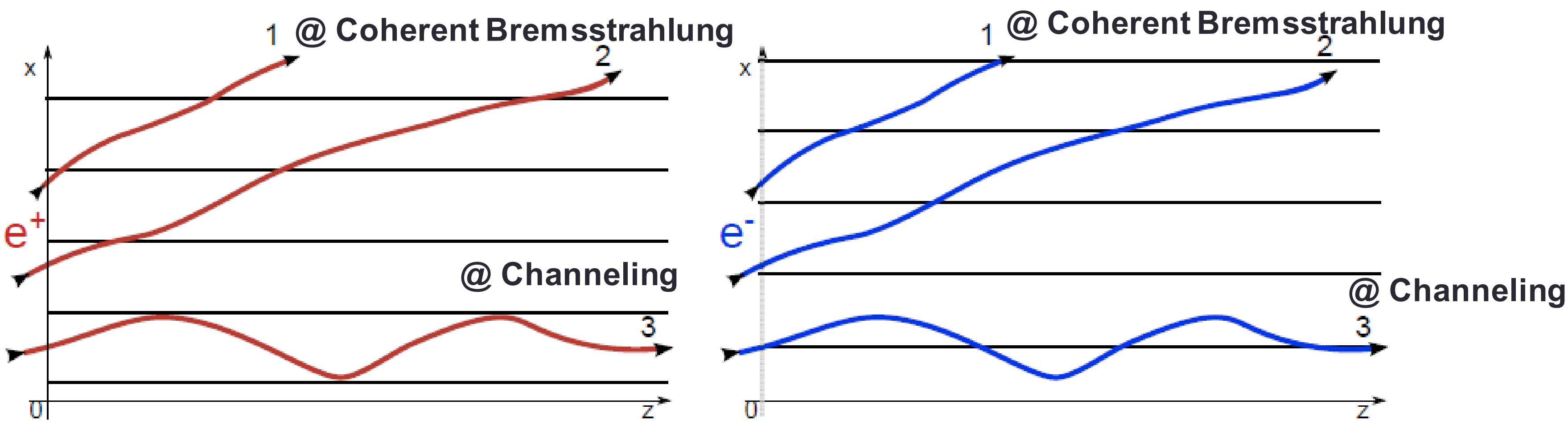
Lorentz + Doppler effect

$\omega_0 = 2\pi/\lambda$ – frequency of motion



M. Kumakhov, Physics Letters A 57, 17 (1976).

Electron vs. positron channeling

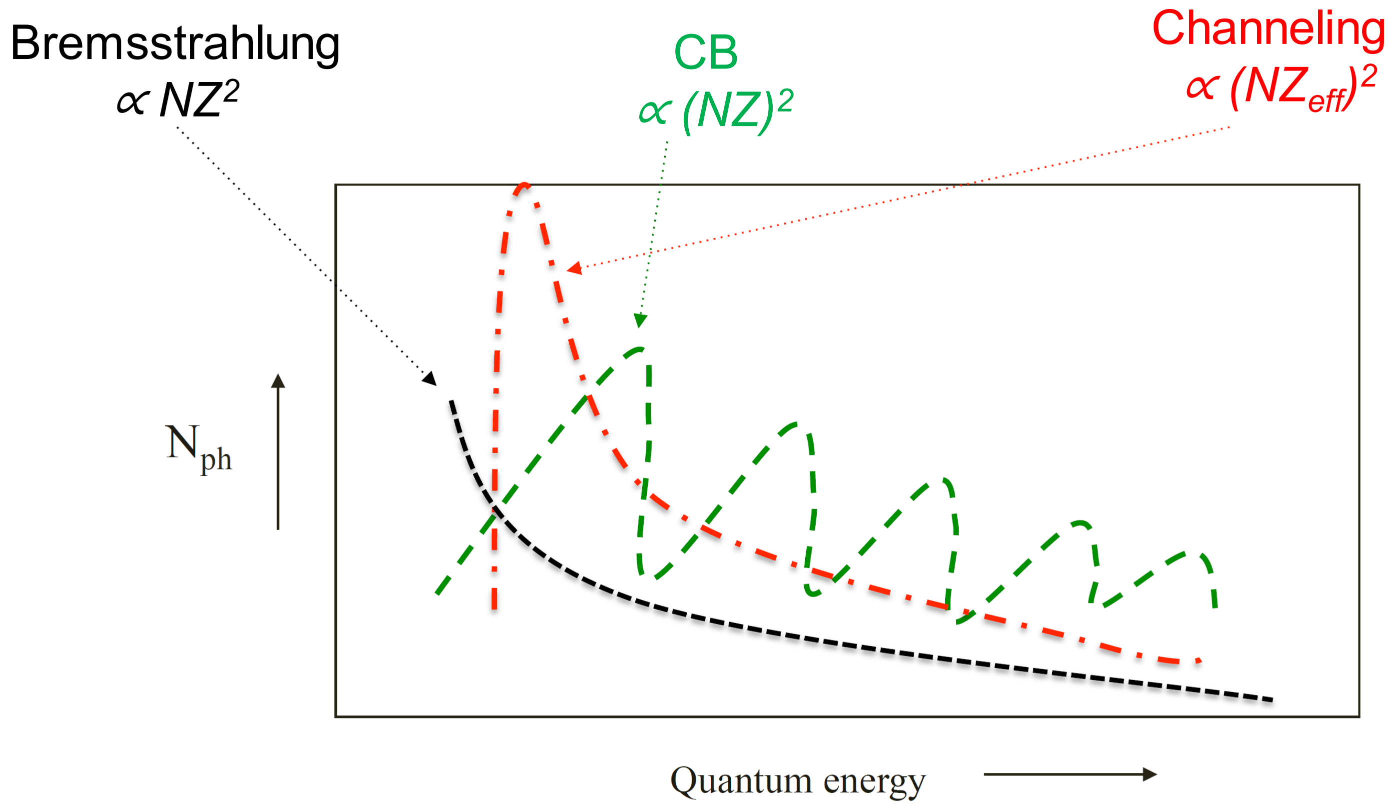


Positively-charged particles are repulsed from the nuclei of the axis (plane) and hence can be captured inside the interaxial (interplanar) potential wells.

Negatively-charged particles are attracted towards the positively-charged nuclei of the axis (plane), thus oscillate around the atomic axes (or planes).

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

.. with positrons one may also exploit Channeling Radiation

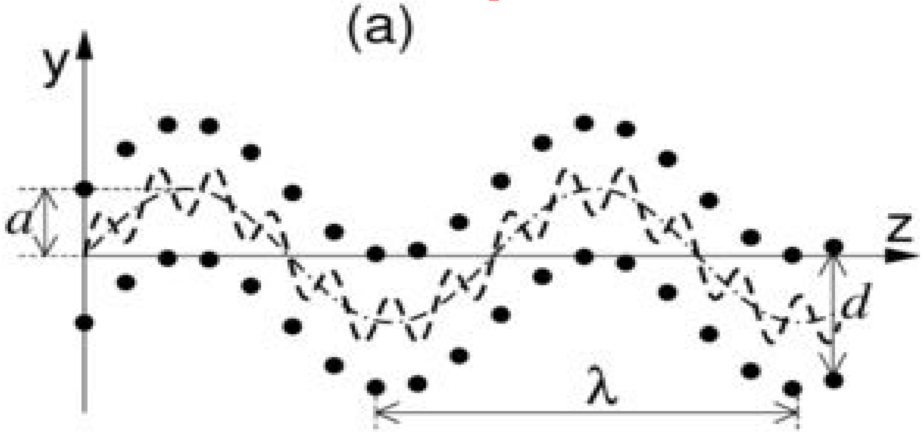


In hard x-ray is more intense than both Bremsstrahlung and CB!

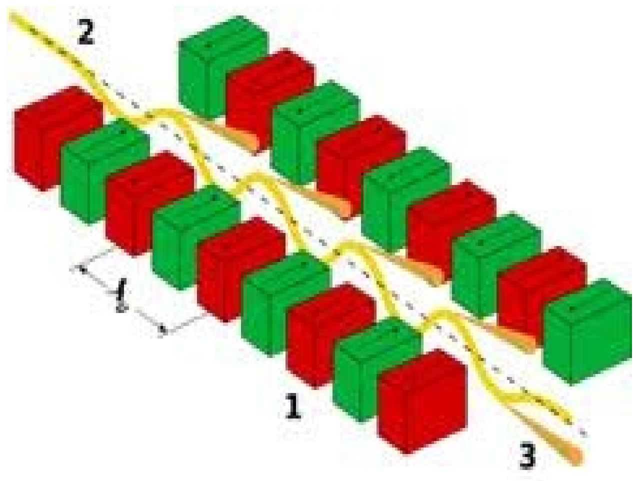
The usage of the DAFNE positron beam will open the way to the realization of the **first CR source** with intense and nearly-monocrhomatic radiation in the **hundreds keV – MeV energy**.

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

Crystalline Undulator



Mehdi Tabrizi et al., Phys. Rev. Lett. 98, 164801 (2007)



- **A Crystalline Undulator may play the same role as a magnetic undulator.**
- **It consists in a Periodically Bent Crystals can be built with millimetric-submillimetric period, increasing the energy of radiated photons than in a magnetic undulator with the same beam energy.**
- **An operating CU could produce highly monochromatic X- and γ-ray beam.**

European Research Council

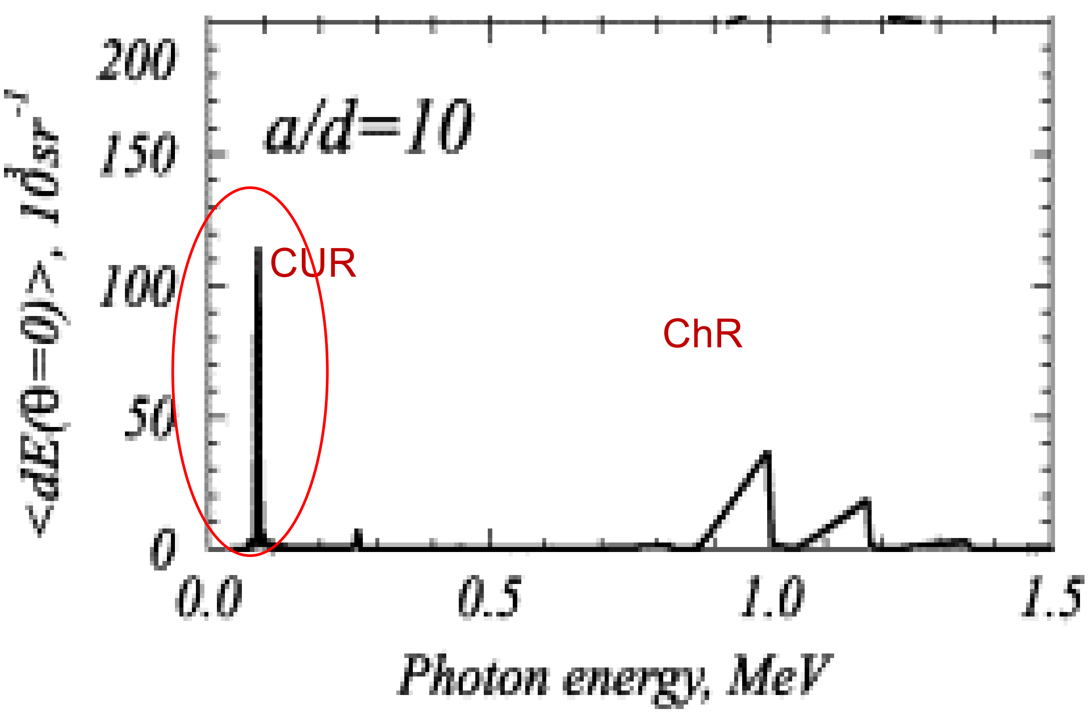
H2020-RISE PEARL (2016-2020)
(consortium with several institute that work in the subject of radiation in oriented crystals such as MBN Center, ESRF, MAMI, INP MINSK, AARHUS, **INFN & UNIFE**)

Crystalline Undulator @DAFNE

@DAPHNE:

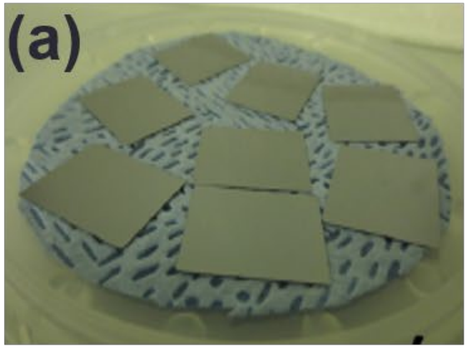
ε = 500 MeV,
a/d =10 (PBC amplitude)
λu =23.35 μm << λch = 2μm
L= 15 λu = 350 μm
Si (110) planes

ω_u ~ 90 keV for CUR
(crystalline undulator radiation)
ω_{ch} ~ 1.190 MeV for ChR
(channeling radiation)



CU Radiation can be much more monochromatic than for CR And tunable without changing the beam energy but only changing the undulator period λu

INFN expertise in fabrication and characterization of crystals to manipulated sub-GeV electrons

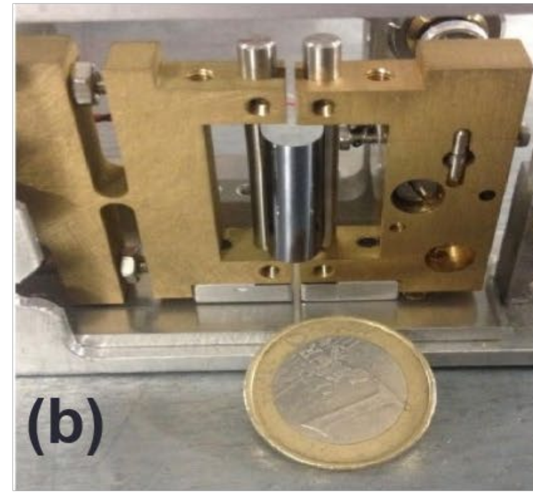


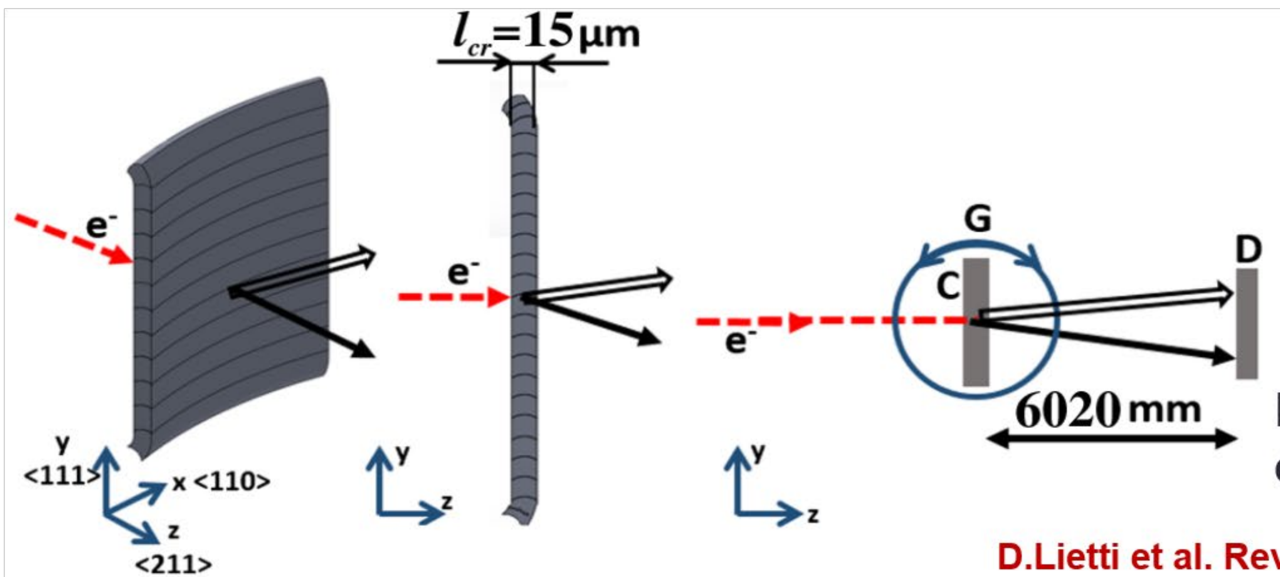
Realization of **tens micron Si membranes (a)** and their **bending (b)**:

- 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



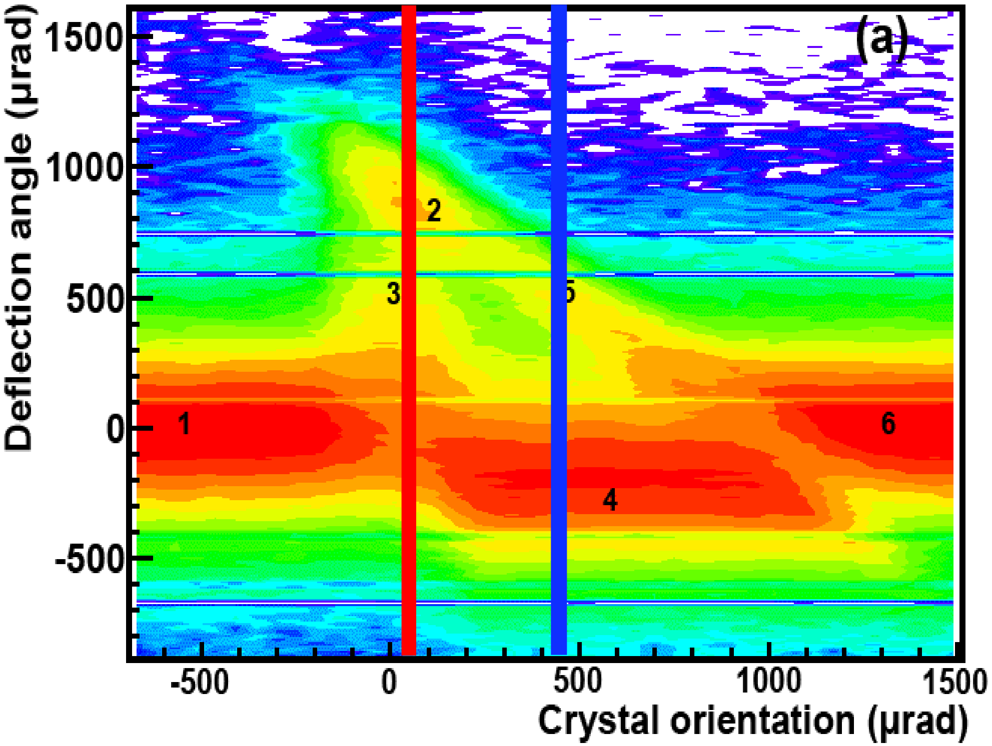


Experiments with **0.855 GeV electrons** at the MAMI B line

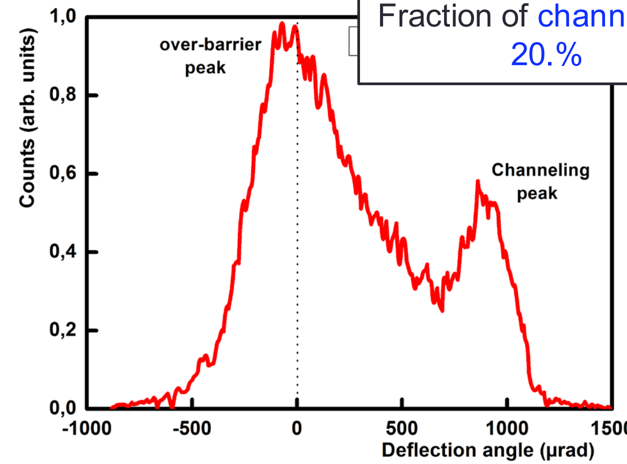
D.Lietti et al. Rev. Sci. Instrum. 86, 045102 (2015)

arXiv:1709.01482

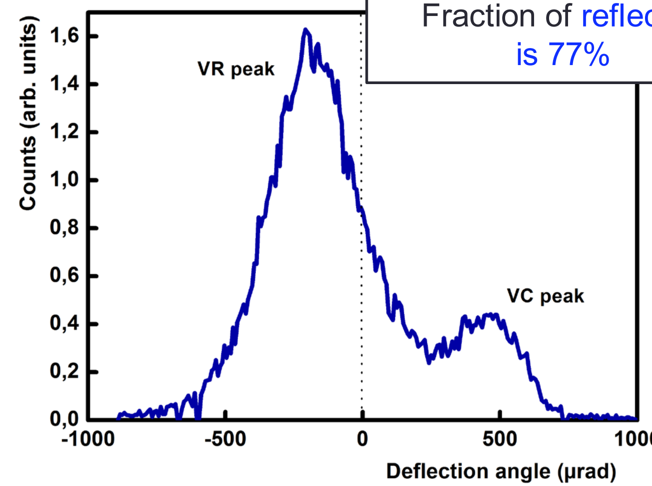
Experimental results on beam steering with 0.855 GeV electrons



Angular scan for deflected beam distribution: (1) and (6) nonchanneling regime; (2) channeling; (3) dechanneling; (4) volume reflection; and (5) volume capture.



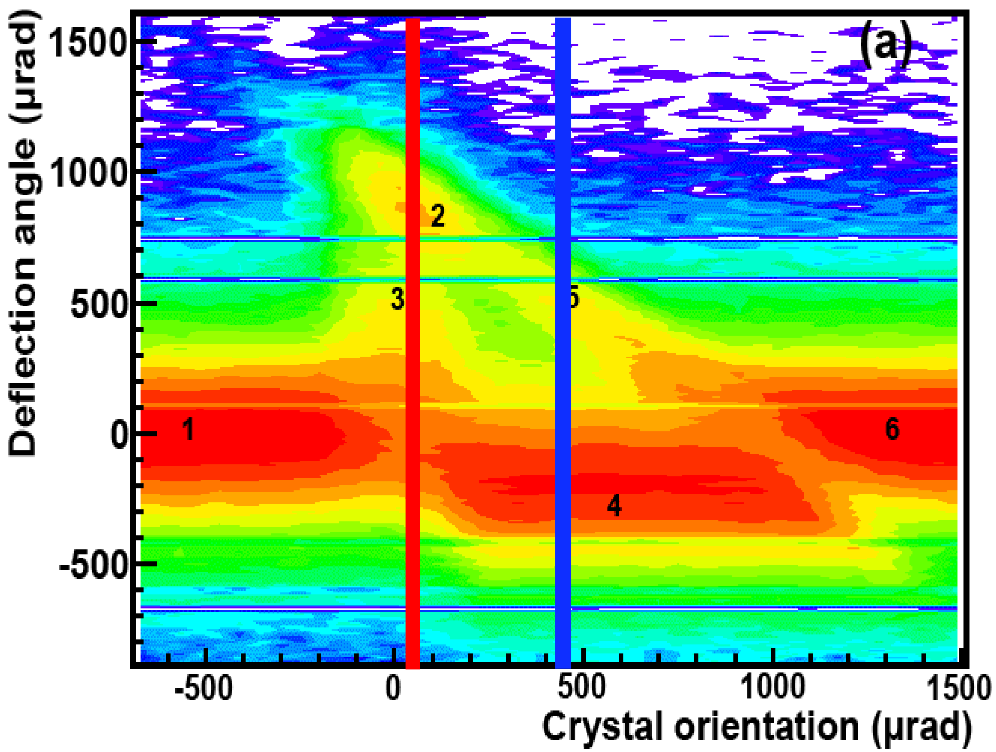
Deflection angle = 910 μrad
Fraction of channeled is 20.%

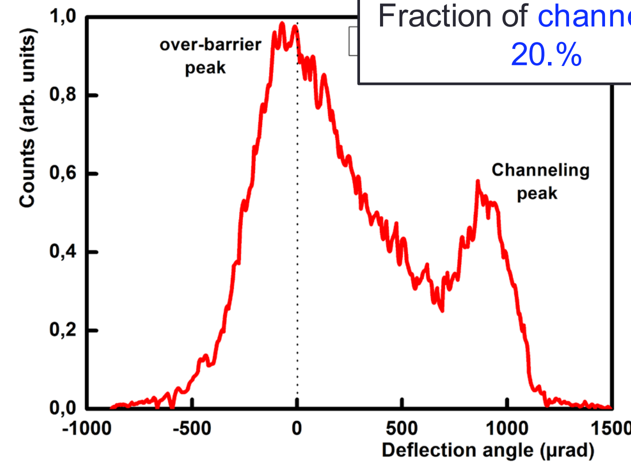


Deflection angle = 191 μrad
Fraction of reflected is 77%

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

Experimental results on beam steering with 0.855 GeV electrons



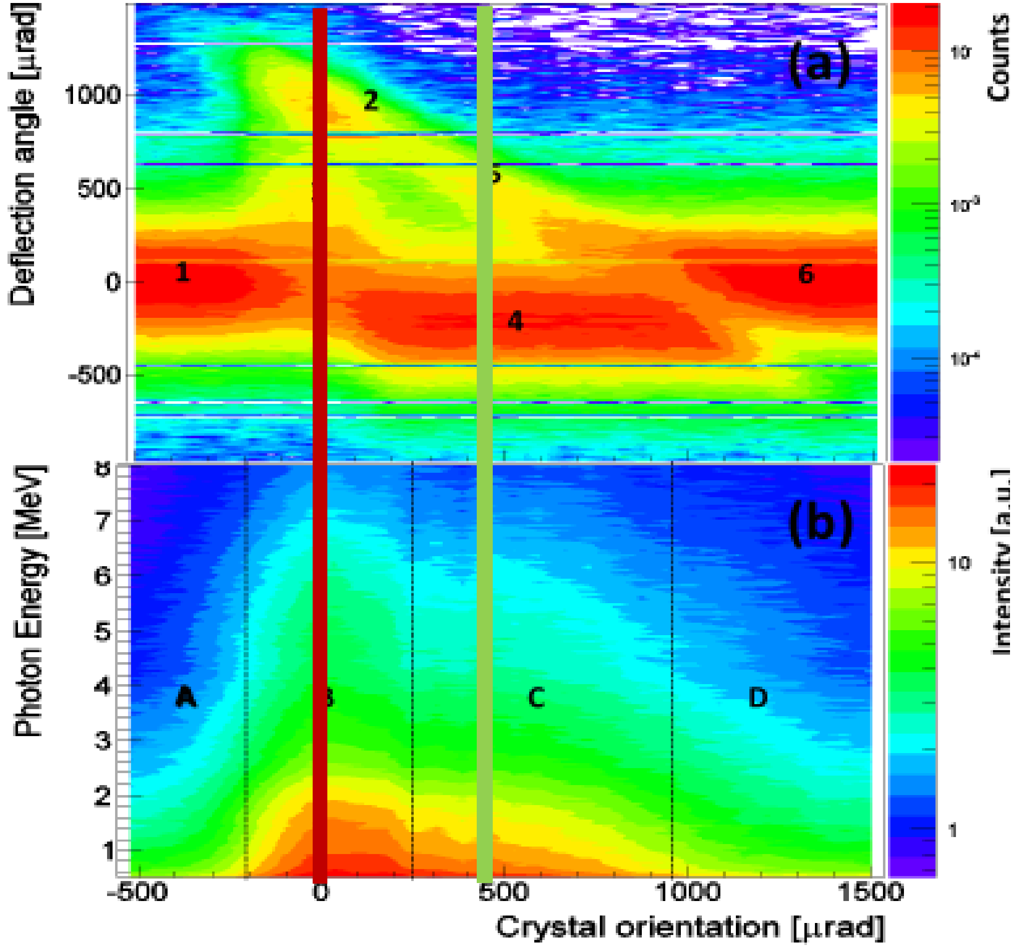


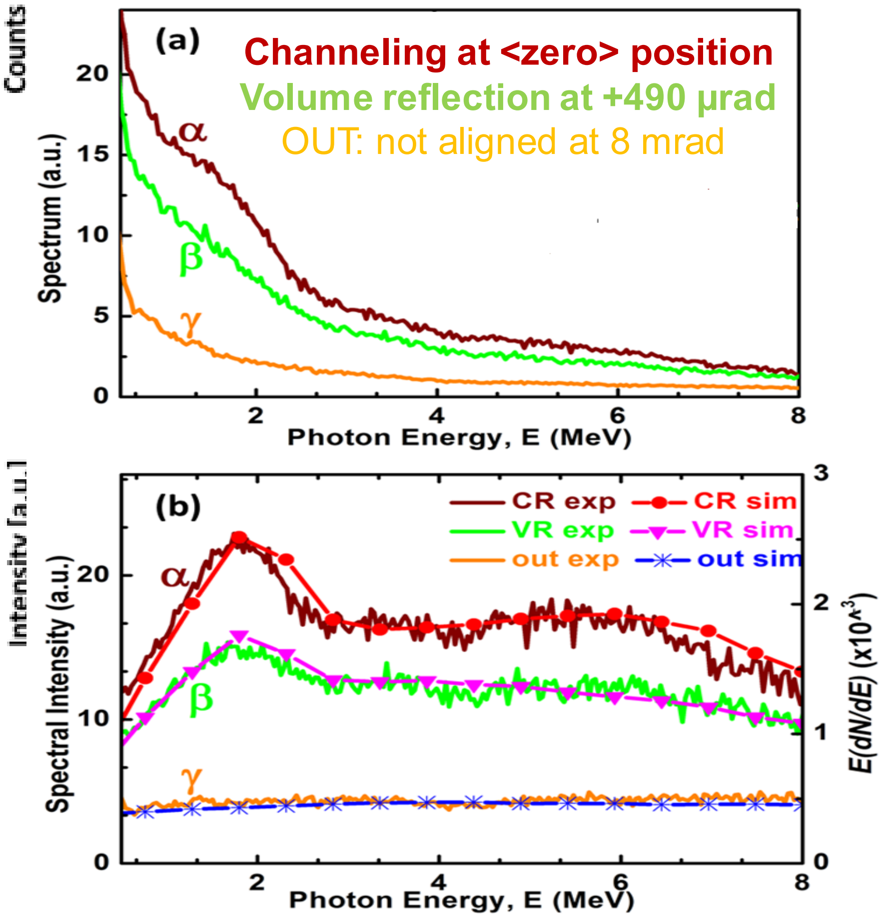
Deflection angle = 910 μrad
Fraction of channeled is 20.%

The **Si bent crystal was 30 μm thick with 0.9 mrad bending**-> 1.5 times the dechanneling length for 0.855 GeV e-, limiting the deflection efficiency

In case of 0.5 GeV positrons the dechanneling lenght is about 300 μm, so 10 times longer than the crystal length -> **Expected about 90% or more of deflection efficiency**

Experimental results on radiation emission





For positrons the Channeling radiation peak is expected to be more intense and monochromatic!

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

Channeling & CB vs. bremsstrahlung and other gamma-ray sources

- One can achieve photon fluxes on the order of 10^{12}/s in the primary peak, with reasonable values for the beam current (@ μA) and crystal lifetime.

- Cheap compared to Compton or Thomson scattering, requiring a intense laser, with similar performances regarding the emitted radiation energy and intensity.

- Incoherent scattering and so a background radiation in a range from 0 to the beam energy is always present, thereby limiting the monochromaticity.

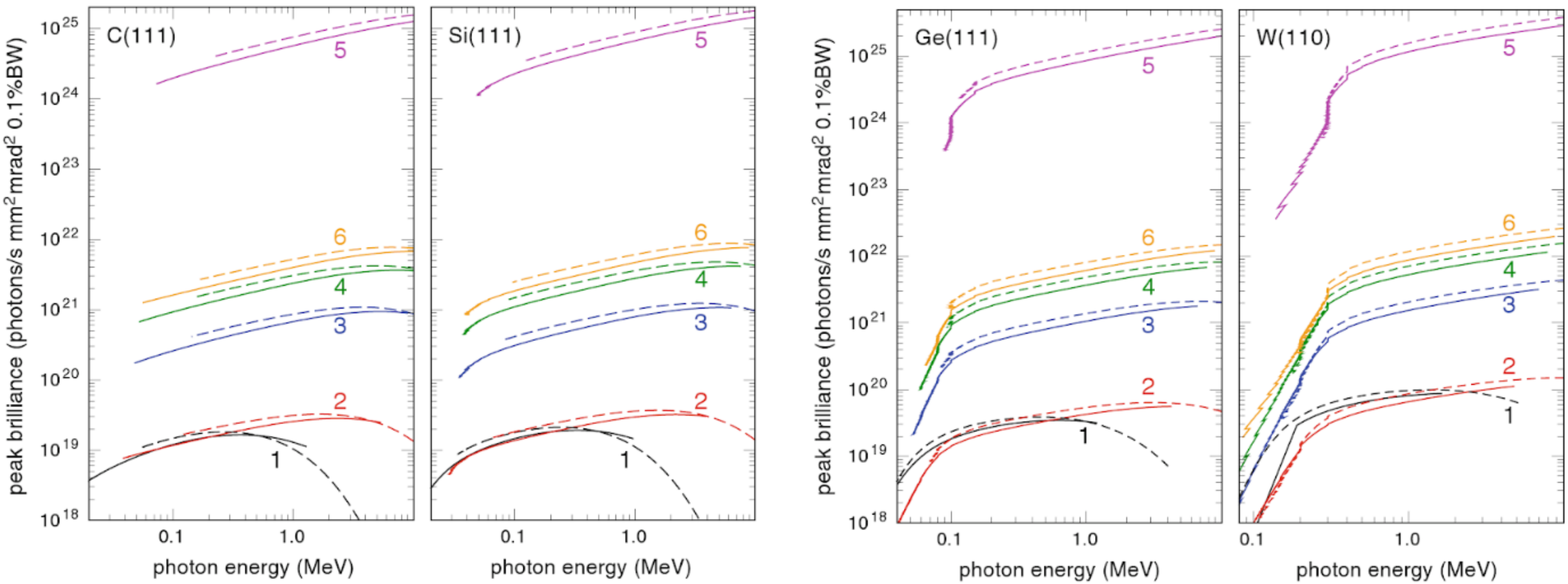
LNF DAFNE possibilities

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, with the possibility to realize the first working CR source and to demonstrate for the first time the feasibility of a CU.
4. And, more important, a unique positron facility.

With these premises, LNF may become a **leader in crystal-based hard x- and gamma-ray sources for application in medical and nuclear physics**.

THANK YOU FOR THE ATTENTION!

CU radiation – peak brilliance



Peak brilliance in the forward direction – curve 1 for DAFNE

Andrey V. Korol, Andrey V. Solov'yov, Walter Greiner, Channeling and Radiation in Periodically Bent Crystals

Channeling Radiation and Thomson Scattering

$$\omega_{lab}^{ChR} \approx \frac{2\gamma^2}{1+\theta^2\gamma^2}\omega_0^{ChR}$$ $\propto \gamma^{3/2}$

- radiation frequency -

$$\omega_{lab}^{TS}\left\{\begin{array}{c}\vartheta=0\\ \vartheta=\pi/2\\ \vartheta=\pi\end{array}\right\} \simeq \left\{\begin{array}{c}1\\2\\4\end{array}\right\}\frac{\gamma^2}{1+\vartheta^2\gamma^2}\omega_0^{TS}$$ $\propto \gamma^2$

$$\left(\frac{dN_{ph}}{dt}\right)_{ChR} \propto \gamma^{1/2}$$

- number of photons per unit of time -

$$\left(\frac{dN_{ph}}{dt}\right)_{TS} \propto Const$$

$$P \propto \gamma^2$$

- radiation power -

$$P \propto \gamma^2$$

@ comparison factor: $f \simeq \frac{\mathbf{A}_{Ch}^2}{\mathbf{A}_{TS}^2}\frac{L_{Ch}}{L_{TS}}$

→ $L_{Ch}(z) \simeq \int_0^z N_{ch}(z)\,dz$

→ Laser beam size & mutual orientation

@ strength parameters – crystal & field:

	Si ⟨110⟩	C ⟨100⟩	W ⟨111⟩
$\mathbf{A}_{Ch}^2$, eV/Å^3	~ 520	~ 580	~ 10000

$\mathbf{A}_{TS}^2$ ~ 700 eV/Å^3 for the 10 TW laser with a beam diameter of 0.1 mm

Courtesy of S. Dabagov