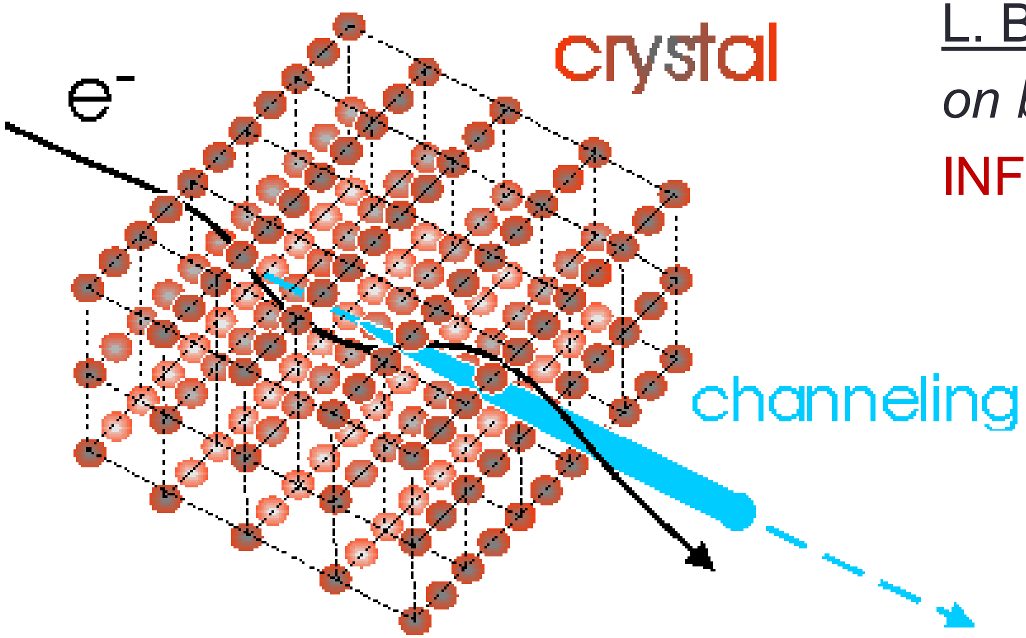
Istituto Nazionale di Fisica Nucleare

Channeling radiation and related phenomena in straight and bent crystals as a tool for intense e.m. radiation generation

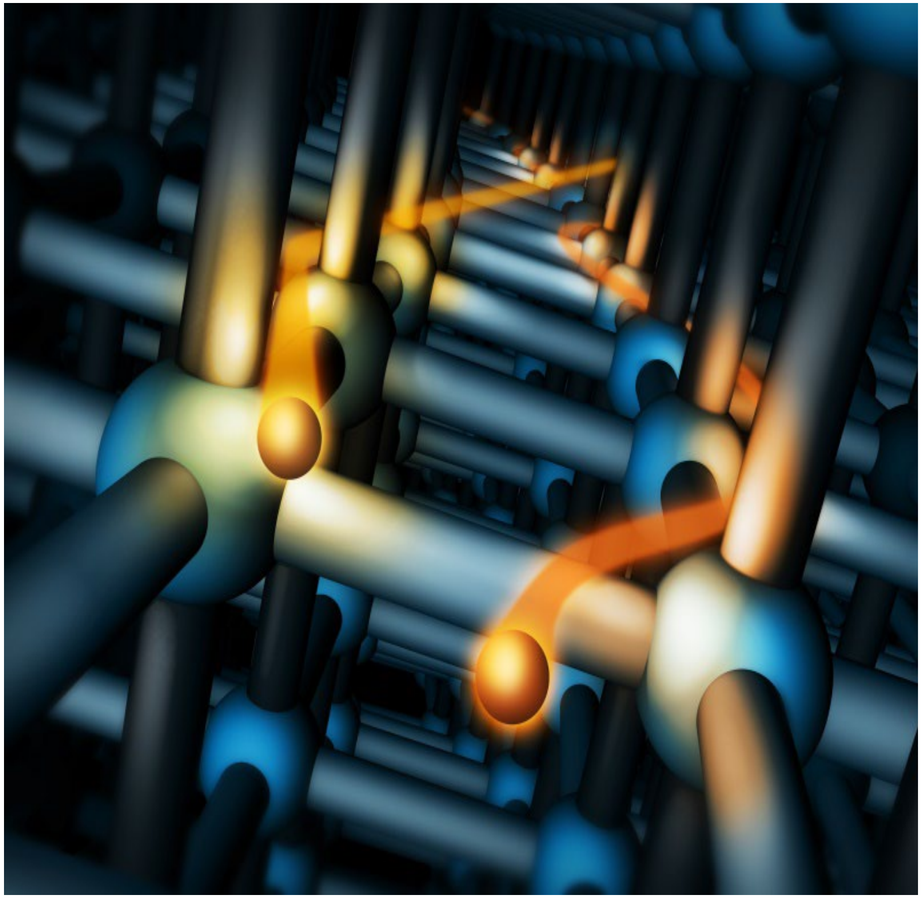


L. Bandiera
on behalf of the ELIOT experiment
INFN- Sezione di Ferrara

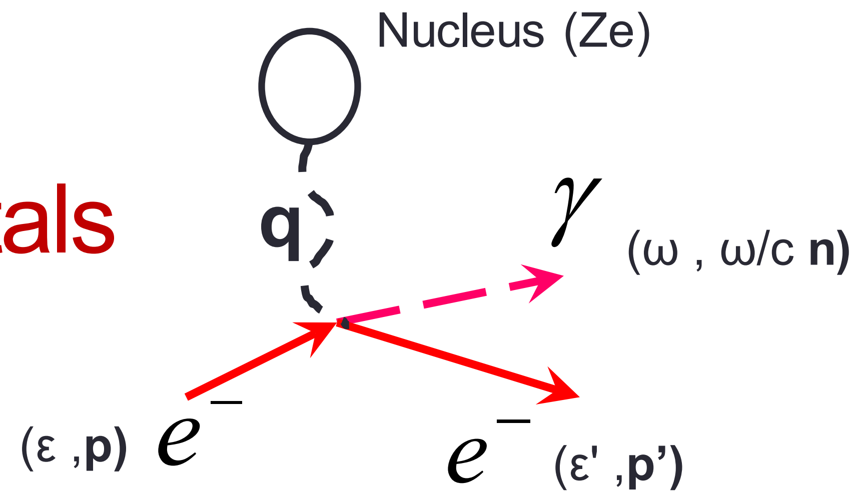
ACN2020
Lausanne, 10/03/2020

Outlook

- Introduction to radiation emission processes in oriented crystals;
- Experiment at MAMI with 855 MeV electrons with bent Silicon and Germanium crystals;
- Monte Carlo simulation based on Baier Katkov quasiclassical method
- Conclusions.

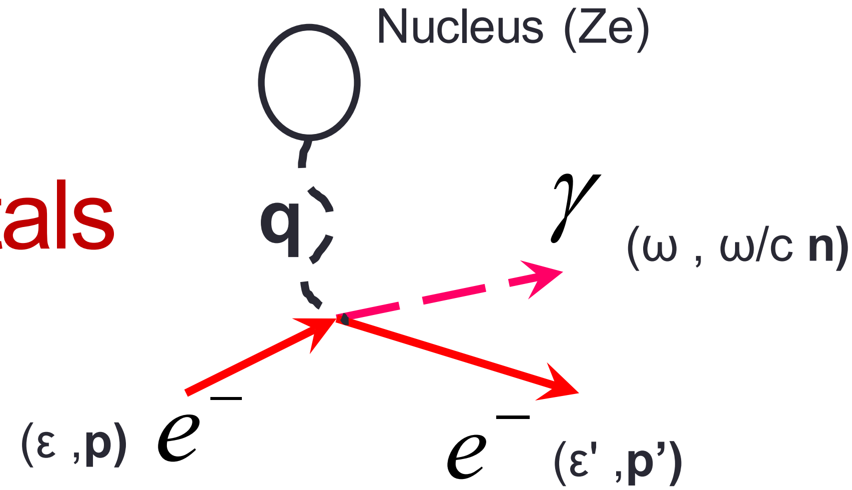


Bremsstrahlung in crystals

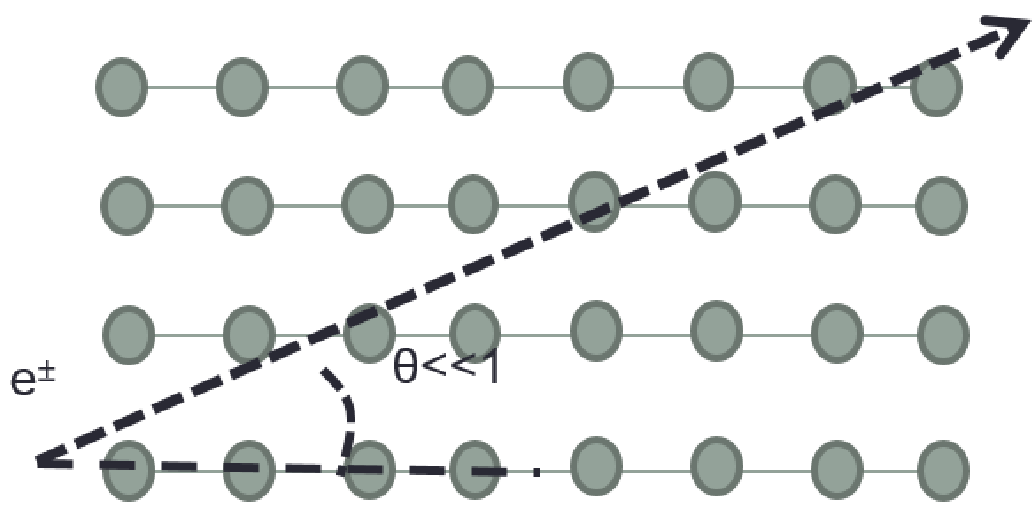


Does the crystal structure influence the process of bremsstrahlung?

Bremsstrahlung in crystals



Does the crystal structure influence the process of bremsstrahlung?

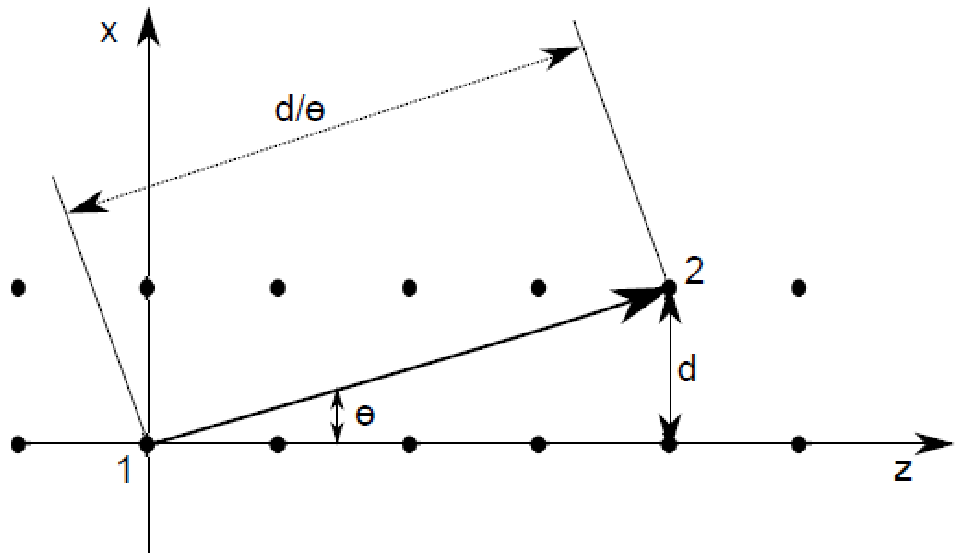


Yes!

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, $q_{\parallel}$,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 $\varepsilon \approx \varepsilon'$):

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

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).*

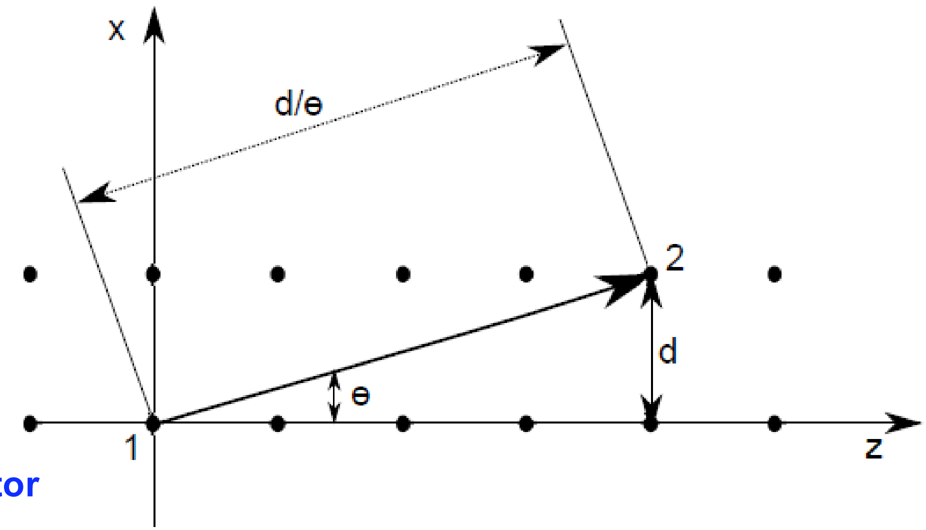
Coherence Length and interference

Constructive interference condition:

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

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

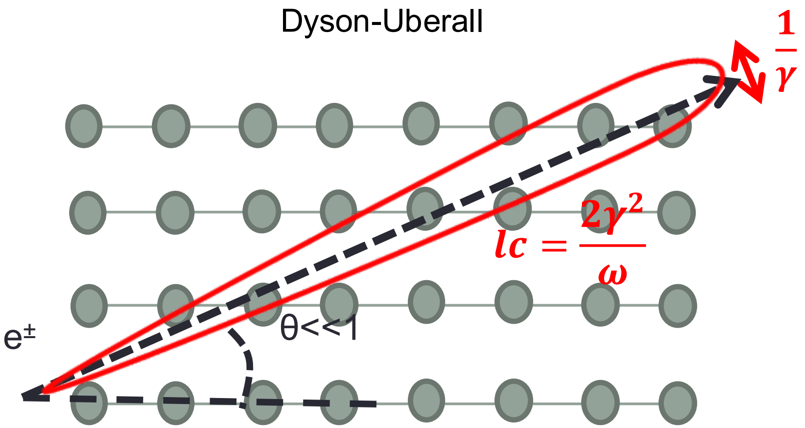
Reciprocal lattice vector

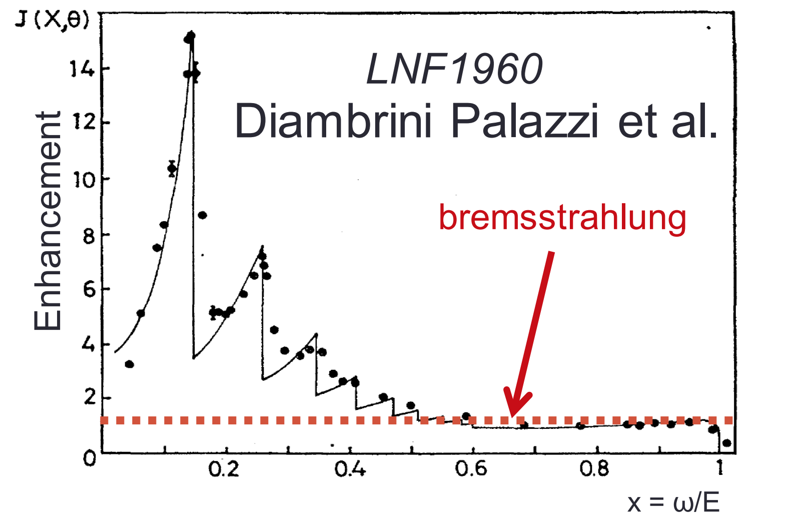


Factor **2π/d** that has the dimensions of a **reciprocal lattice vector** -> the **bremsstrahlung radiation** emitted in a crystal **increases** when the **momentum transferred from the particle to the atoms matches a reciprocal lattice vector.**

Coherent Bremsstrahlung facilities

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



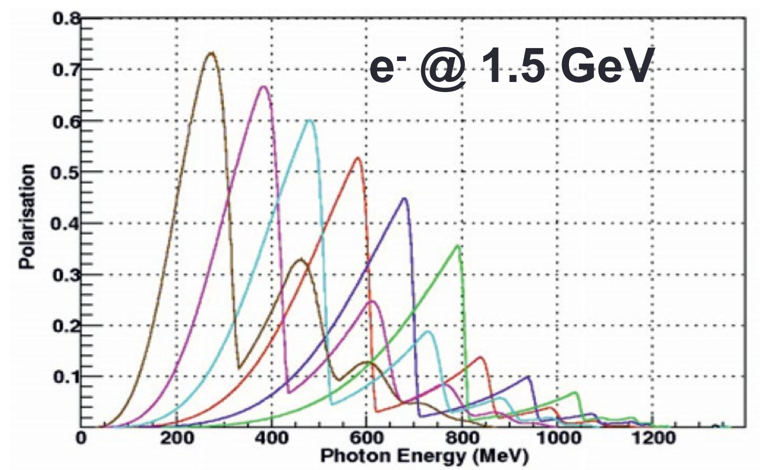


Intense and monochromatic gamma source

Linearly polarized photons

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

usually exploited
for **photonuclear researches**



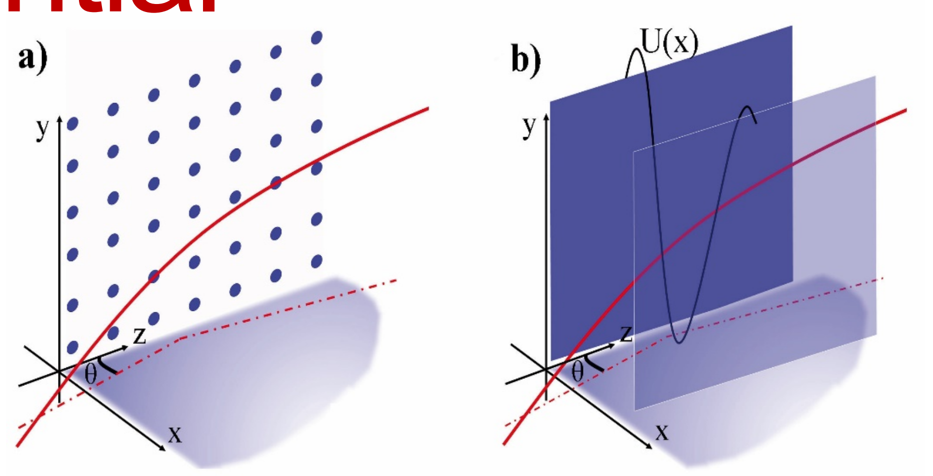
Degree of linear photon polarization achievable at MAMI in a number of diamond orientations.

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 and Continuous Potential

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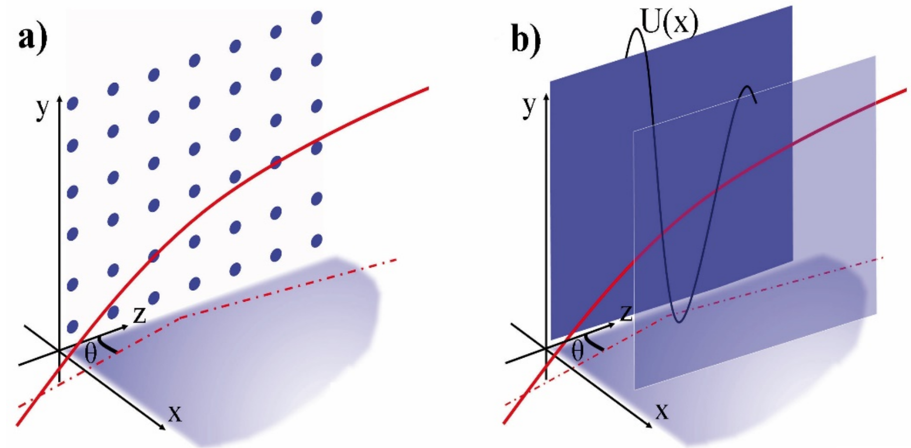
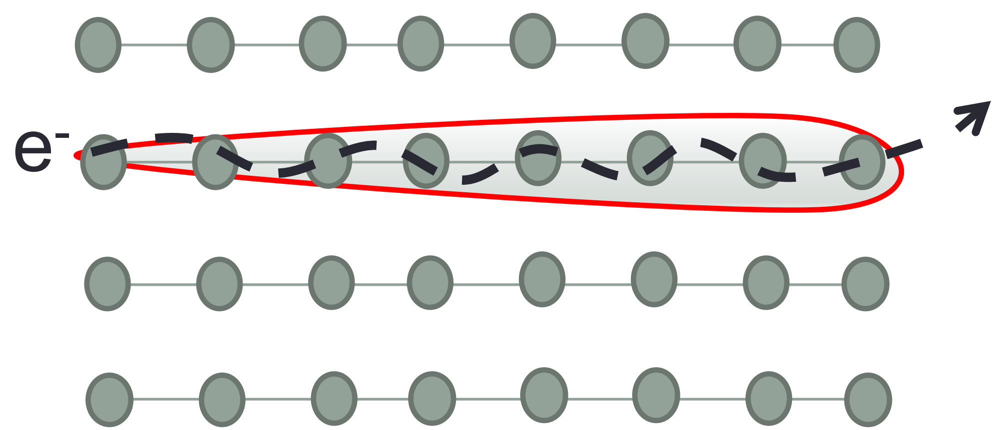


Channeling occurs as the trajectory of particles forms an angle lower than the critical angle:

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

max of U(x)

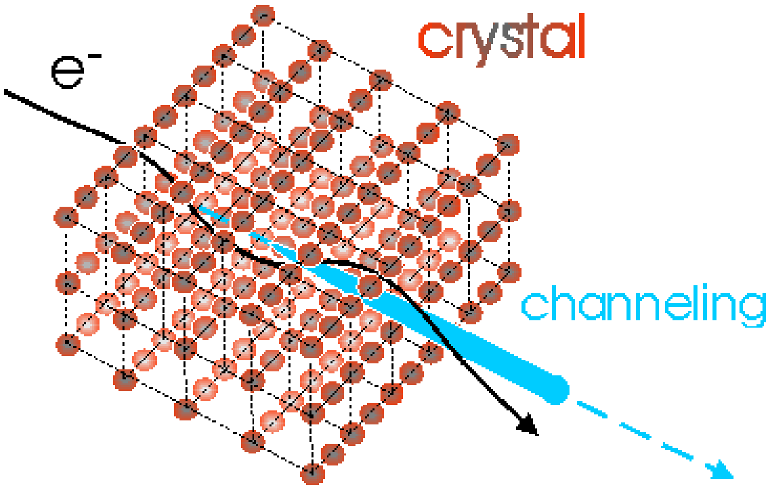
momentum velocity



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

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

Channeling radiation

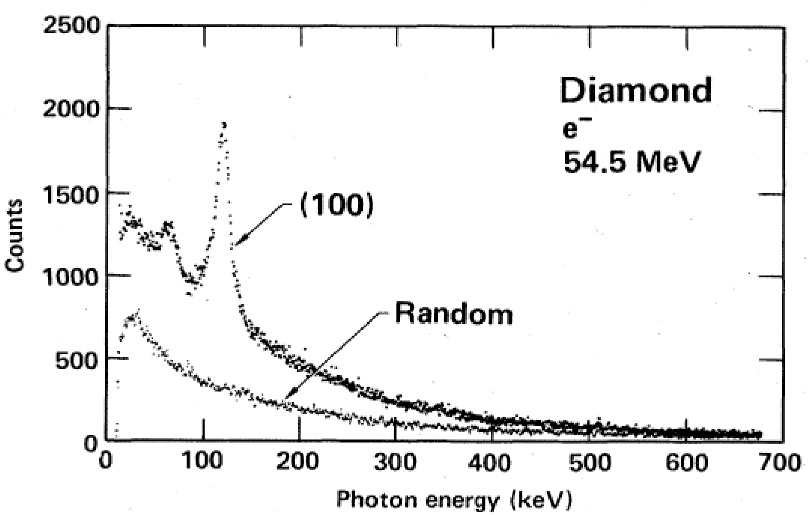


Polarized & forward emission – analogous to undulator

Radiation frequency in the forward direction:

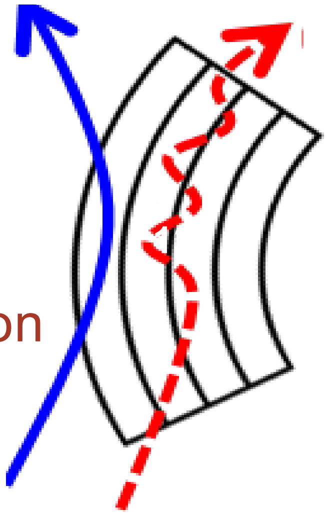
$$\omega \approx 2\gamma^2\omega_0 = \frac{4}{d_p}\sqrt{\frac{2U_0}{m}}\gamma^{3/2}$$

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



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

Motivation of this work: study of radiation emitted by sub-GeV electrons in bent crystals

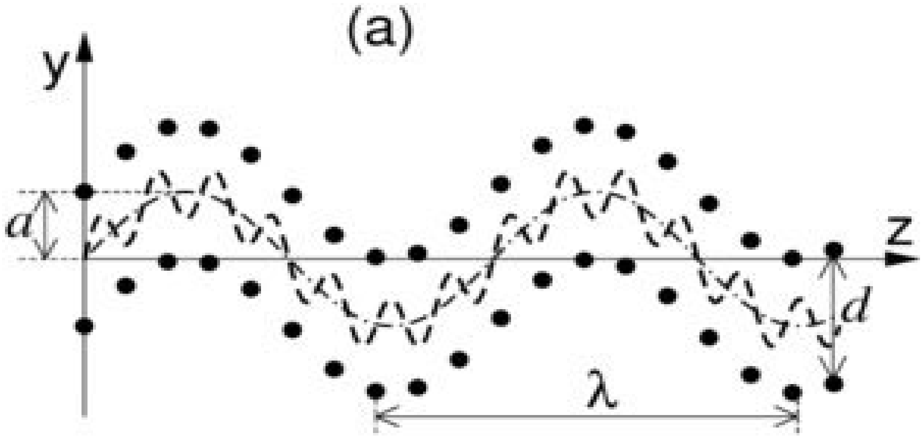


- A lot of attention is devoted to channeling effects of electron around GeV :
  - Interest for alternatives x-ray sources
  - Relatively large availability of accelerators

- Study of the influence of the curvature on Channeling Radiation (CR) and Coherent Bremsstrahlung (CB). This experimental knowledge may be exploited to **determine with more accuracy the CR contribution to crystalline undulators**;

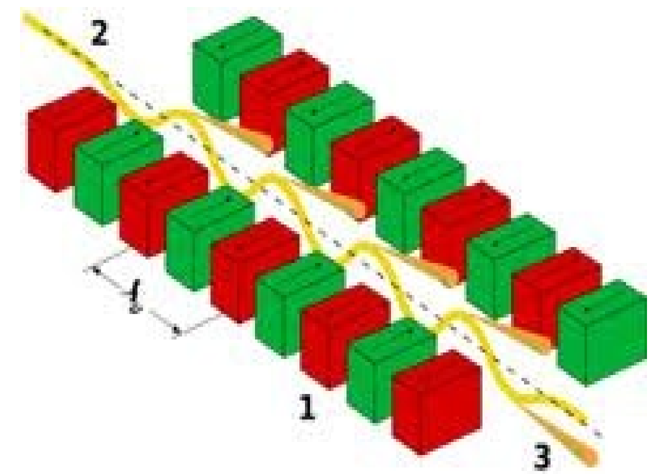
- Steering of sub-GeV electron trajectories through channeling in bent crystals was not possible before due to the lack of thin-enough bent crystals.

Crystalline undulator as an innovative hard x- and gamma-ray source



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

- An operating CU could produce nearly monochromatic X- and γ-ray beams with higher monochromaticity than Channeling and higher intensity than CB

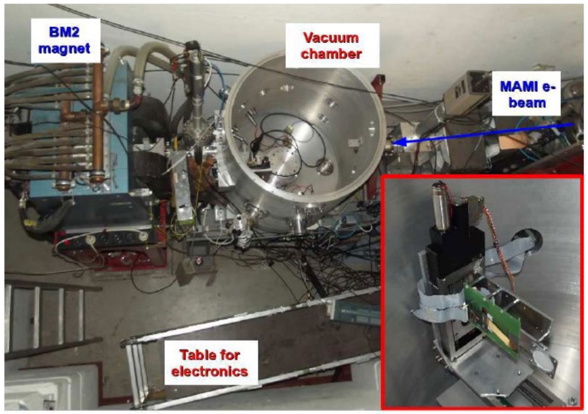


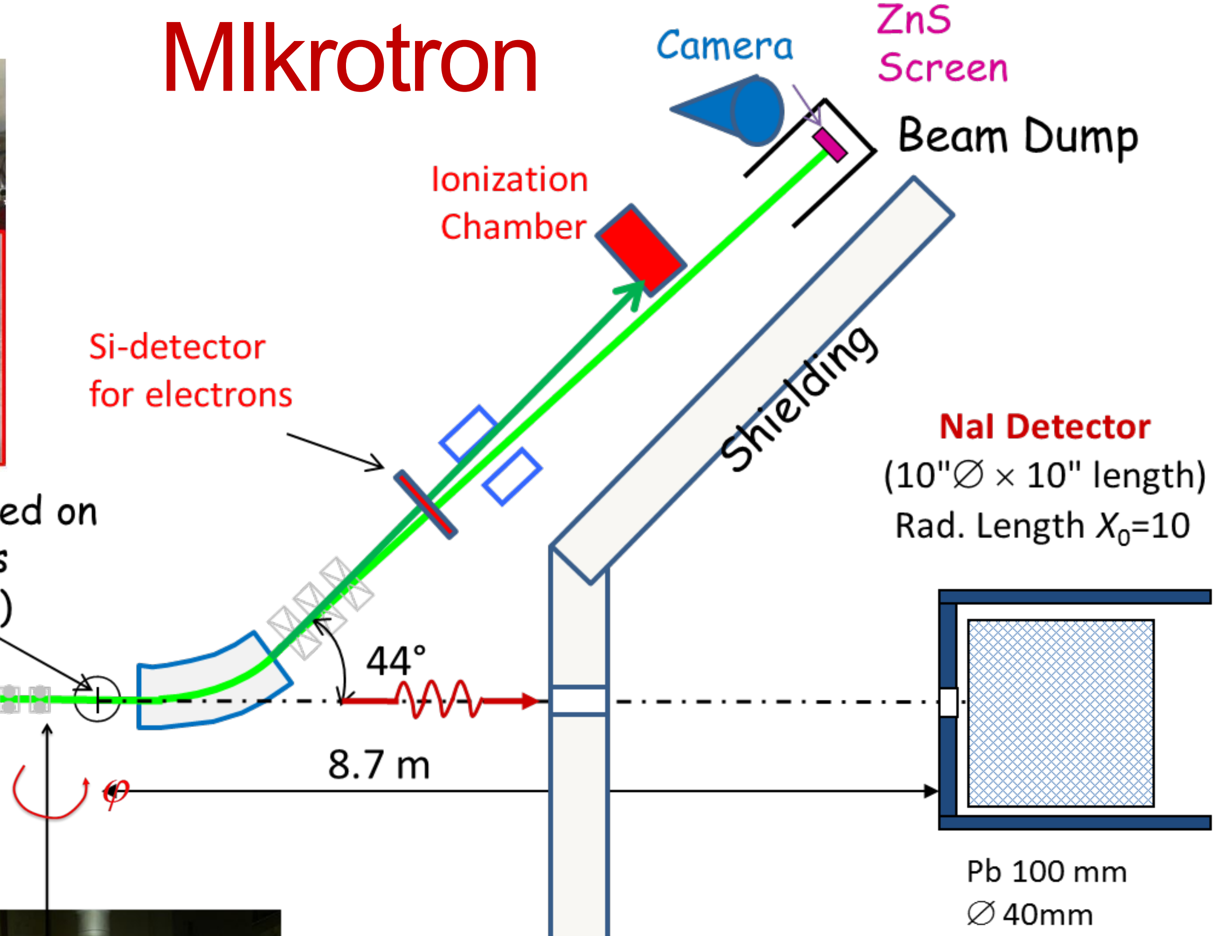
Basic idea - Korol, Solov'yov, Greiner, J.Phys.G, v.24, L45 (1998); PRL, 98, 164801, (2007)
reviews: International Journal of Modern Physics E, v.8, p.49-100 (1999); v.13, p.867-916 (2004); Monograph, Second Edition, Springer–Verlag, Berlin, Heidelberg (2014)

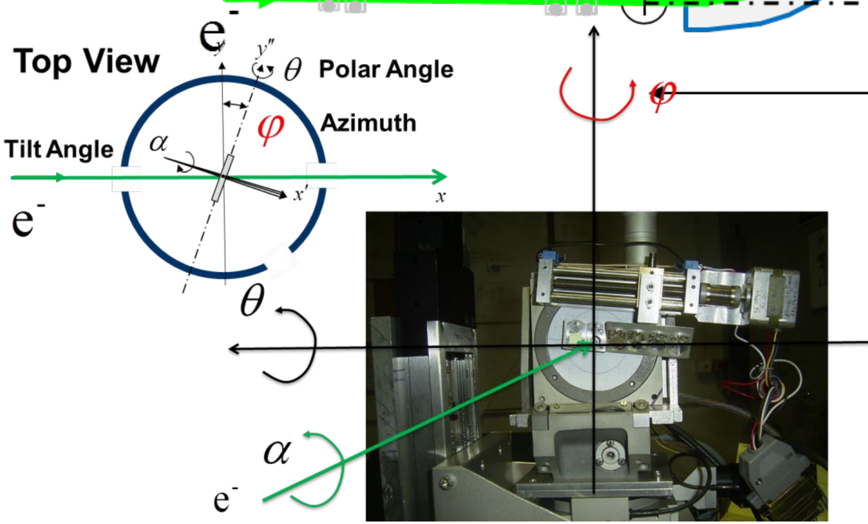
H2020-MSCA-RISE PEARL (2016-2019) & N-Light (2020-2023)
(consortium with several institute that work in the subject of radiation in oriented crystals such as MBN Center, ESRF, MAMI, INP MINSK, AARHUS, **INFN,** UNIFE)

See talk of A. Solov'yov (coordinator of EU RISE projects)

Experimental setup at the MAinzer MIkrotron



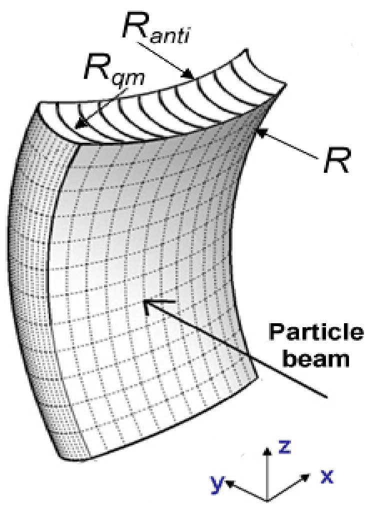


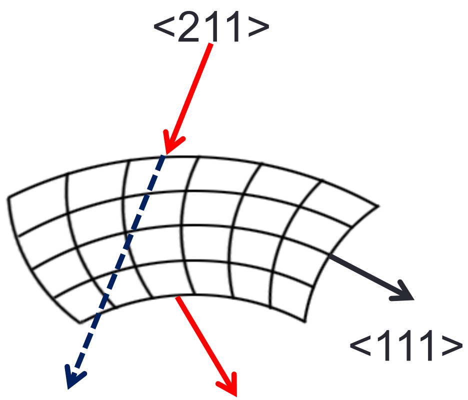


855 MeV electron beam characteristics:

Beam-Spot size σ_{hor} = 200 μm,
Beam Divergence σ'_{hor} = 70 μrad
Beam-Spot size σ_{vert} = 70 μm,
Beam Divergence σ'_{vert} = 30 μrad

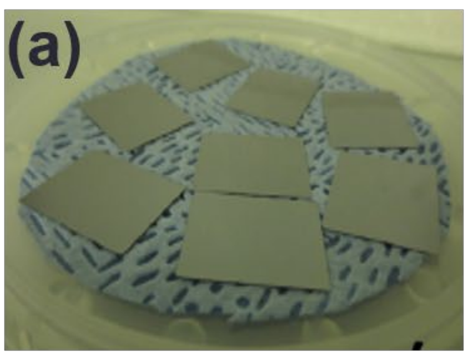
Manufacturing of ultra-short bent silicon crystals





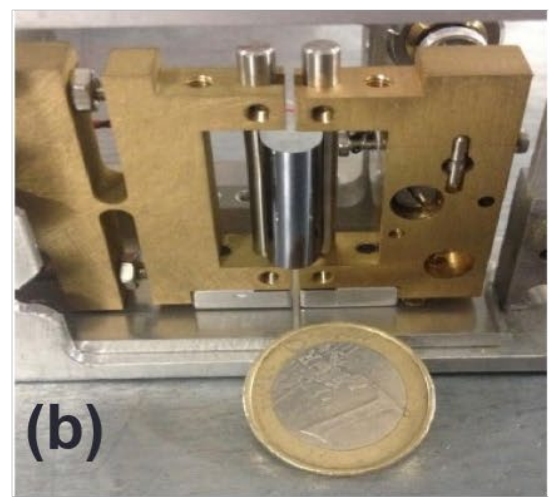
Channeled negative particles are dechanneled faster than positive ones due to higher probability to scatter on nuclei;

Ultra thin bent crystals are required for efficient deflection of negative particles



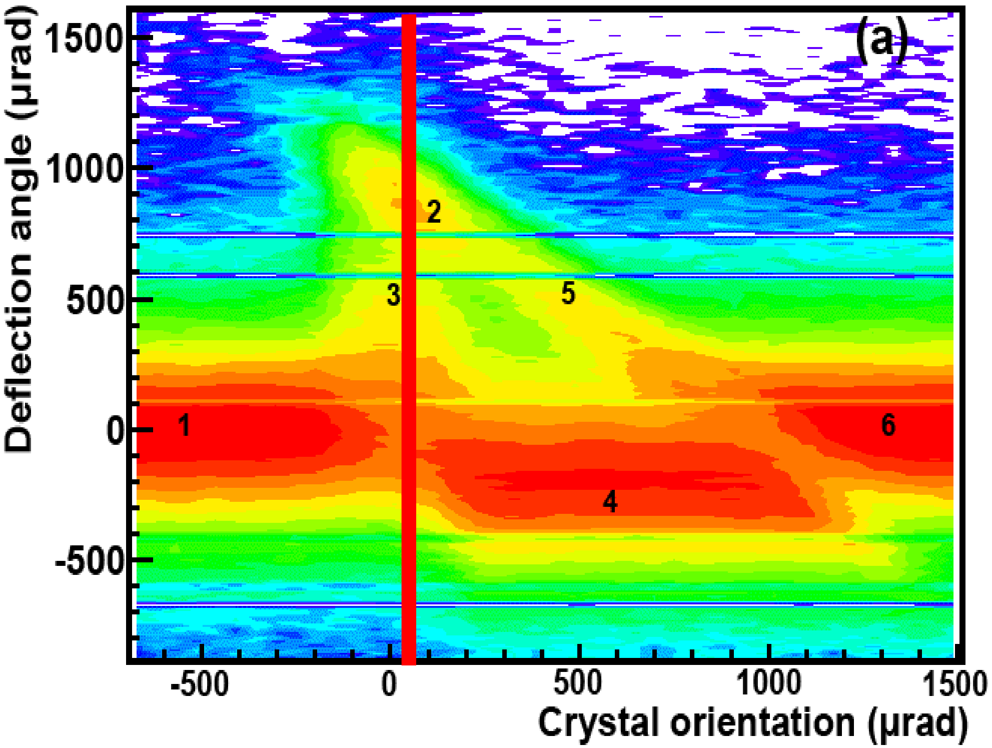
Realization of **tens micron Si membranes** **(a)** and their **bending (b)**:
- determine the **dechanneling length** and deflection capability
- study **channeling radiation**

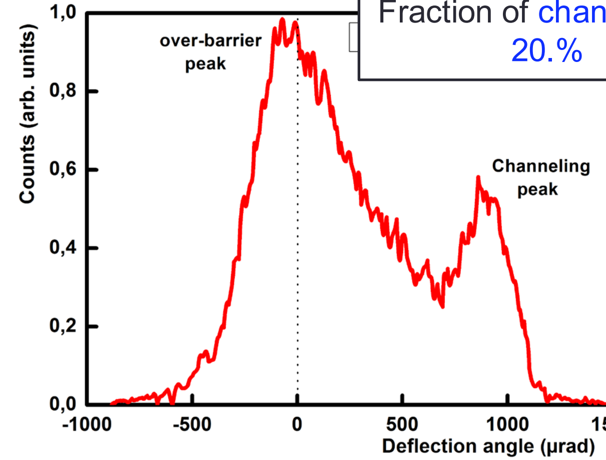
in the **sub-GeV energy range**



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

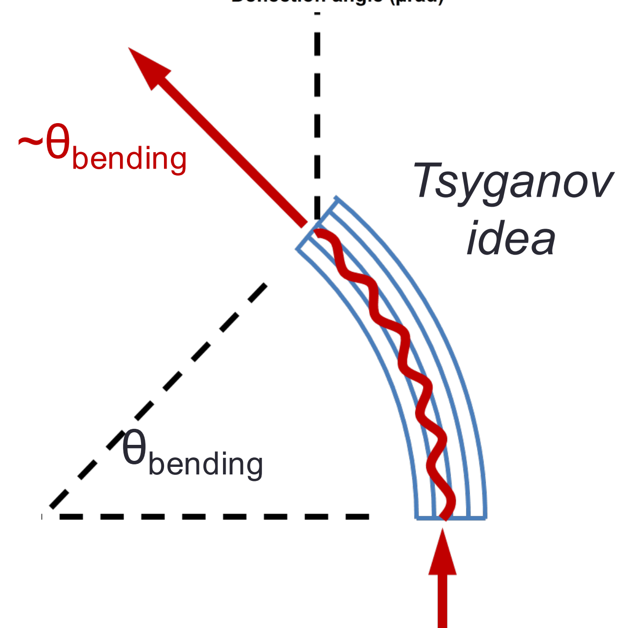
Experimental results on beam steering with 0.855 GeV electrons





Deflection angle = 910 µrad

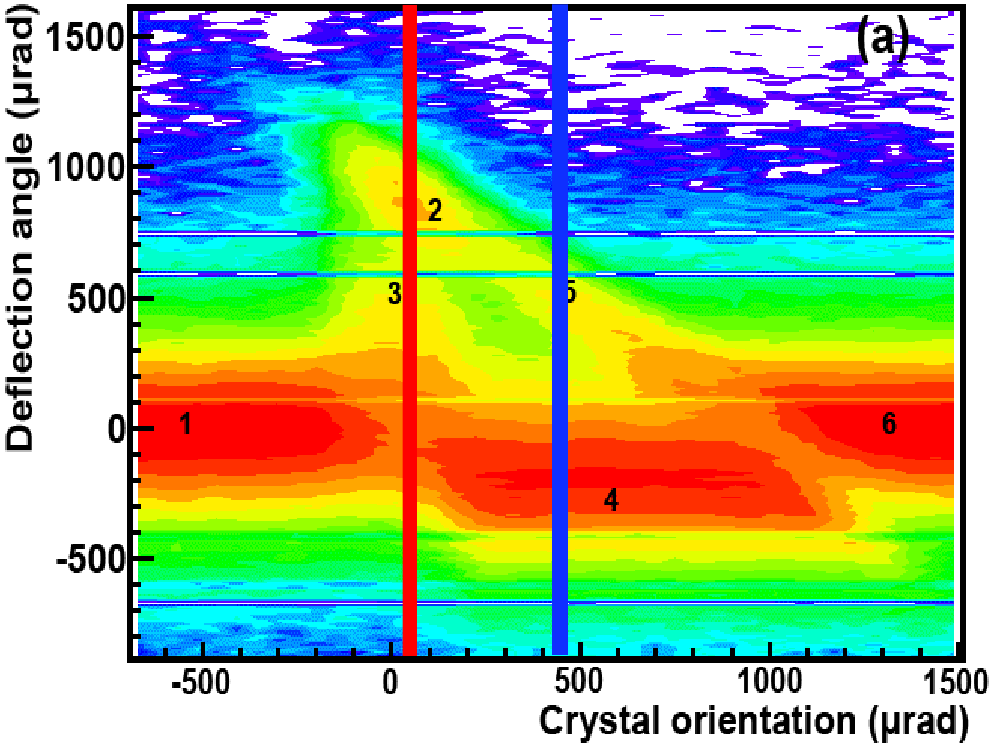
Fraction of channeled is 20.%



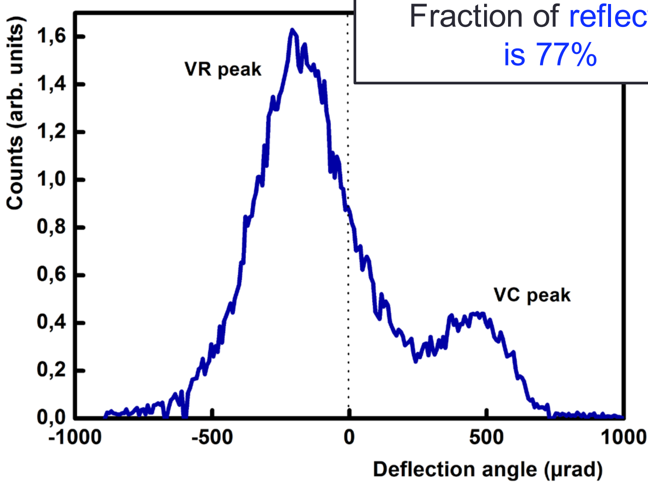
First experimental observation of **channeling of negative particles** in the sub-GeV energy range

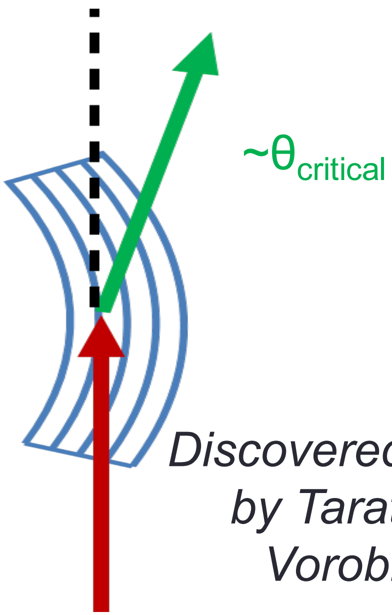
The **Si bent crystal was 30 µm thick with 0.9 mrad bending**-> 1.5 times the dechanneling length for 0.855 GeV e-, limiting the deflection efficiency

Experimental results on beam steering with 0.855 GeV electrons



Deflection angle = 191 μrad
Fraction of reflected is 77%





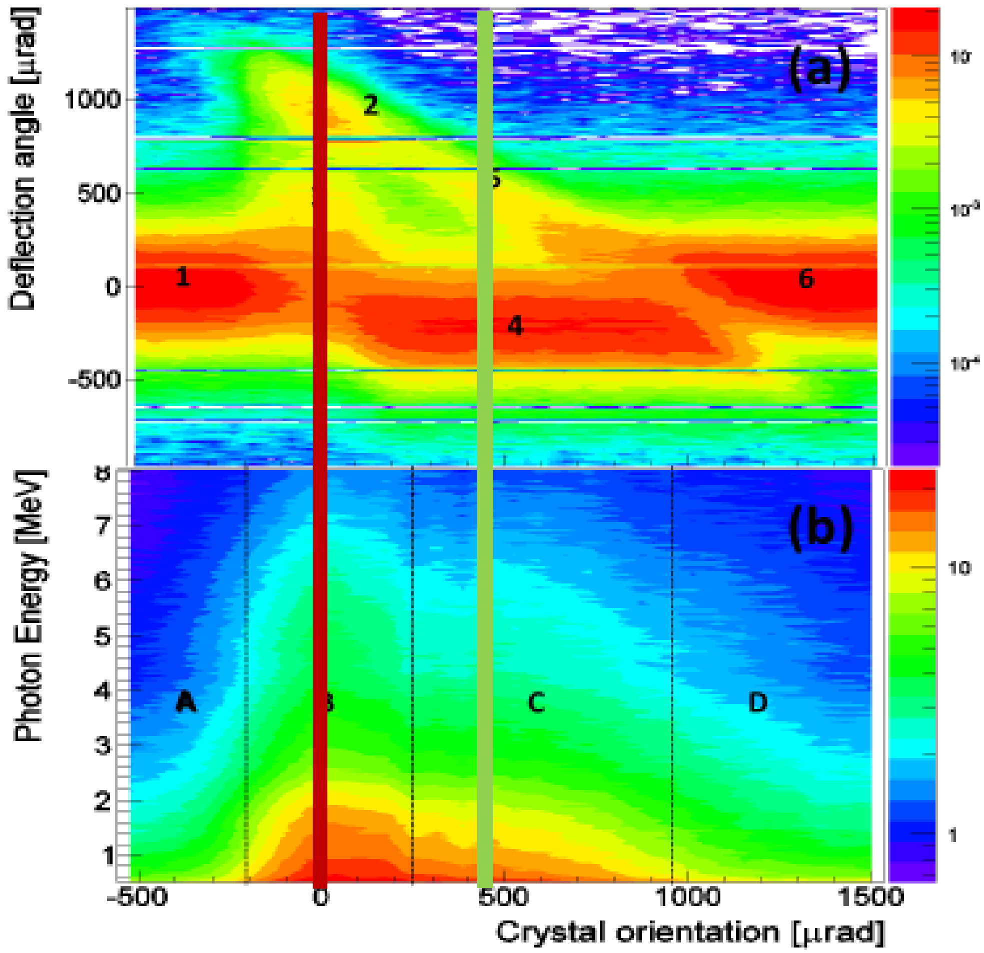
VOLUME REFLECTION

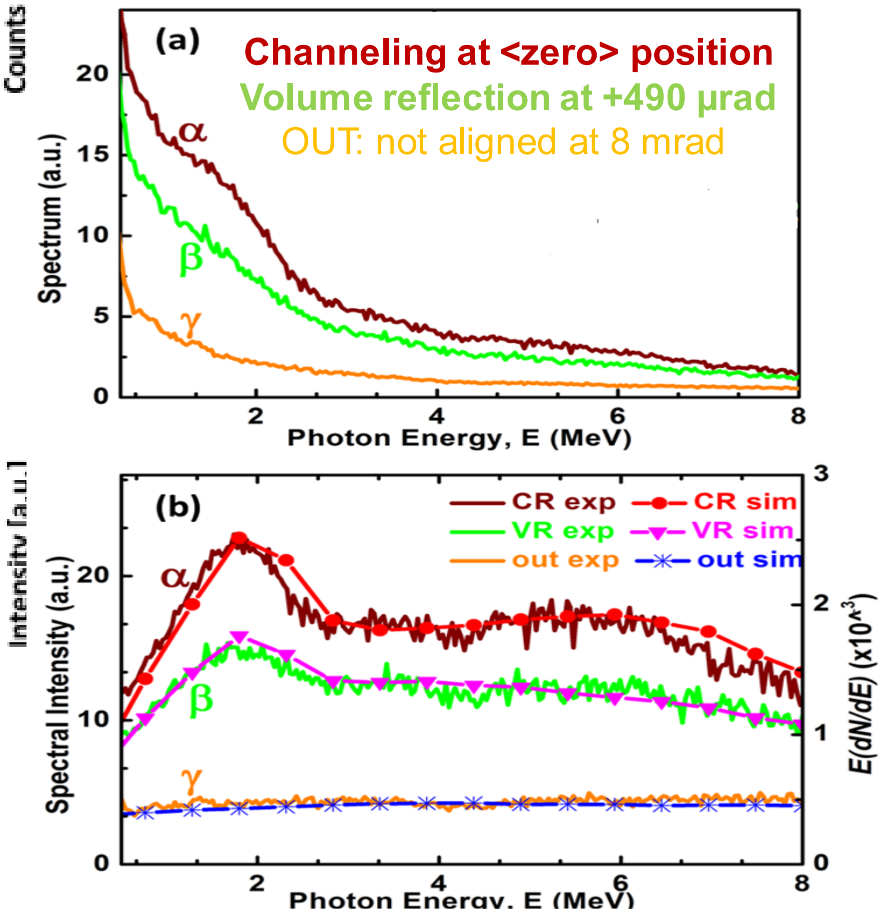
Higher deflection efficiency and angular acceptance ($\sim\theta_{bending}$) than Channeling, but smaller deflection angle

Discovered in MC by Taratin & Vorobiev

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

Experimental results on radiation emission





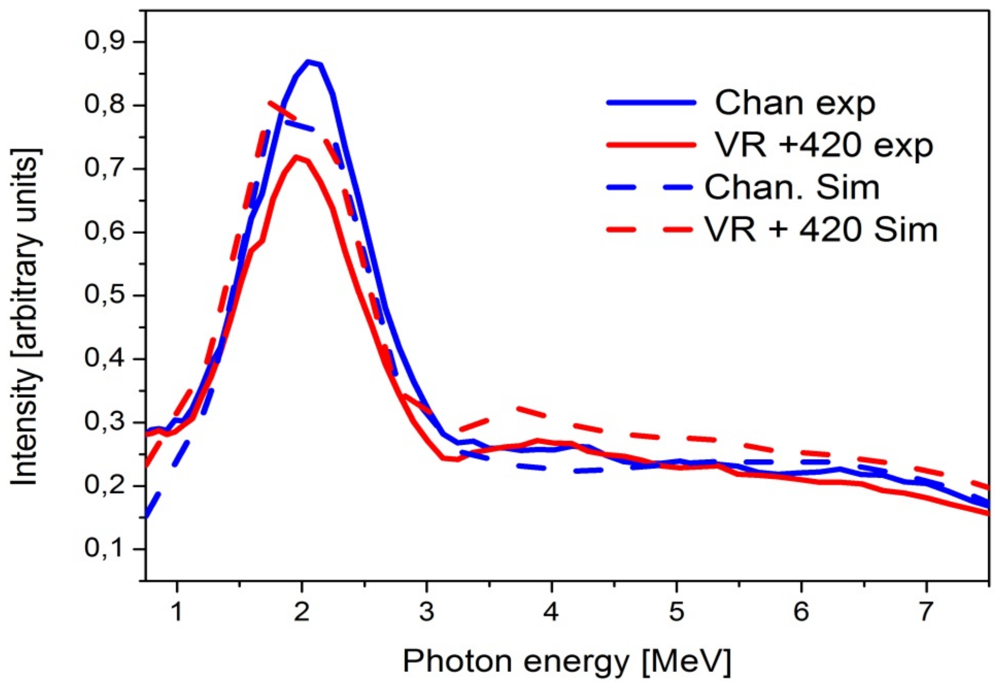
in VR orientation, emitted radiation seems to remain soft and intense as for channeling with a much higher angular acceptance

Channeling at <zero> position
Volume reflection at +490 μrad
OUT: not aligned at 8 mrad

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

40 mm collimator aperture

Smaller collimator aperture: 4 mm



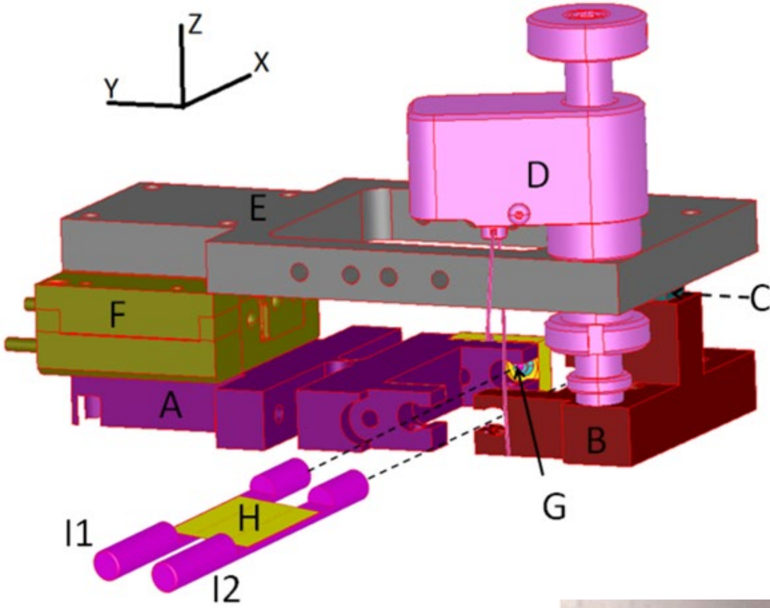
Peak at $E_\gamma \sim 2$ MeV
for 855 MeV electrons
in (111) Si bent planes

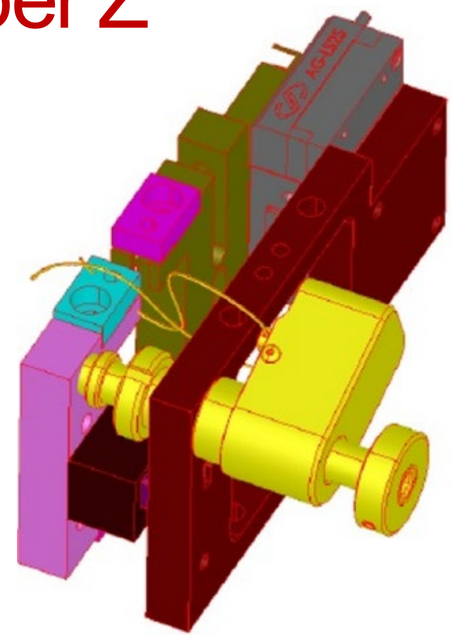
Collimator aperture of about 500 μrad (instead of 5 mrad)

For straight crystals, the radiation intensity falls off very rapidly out of the channeling region, which is as large as 2θcritical = 440 μrad. **The strongest intensity for VR as compared to CB, that makes this kind of radiation more similar to CR**

L. Bandiera et al., PoS (ICHEP2016) 069

Channeling and VR radiation vs. bending R and atomic number Z



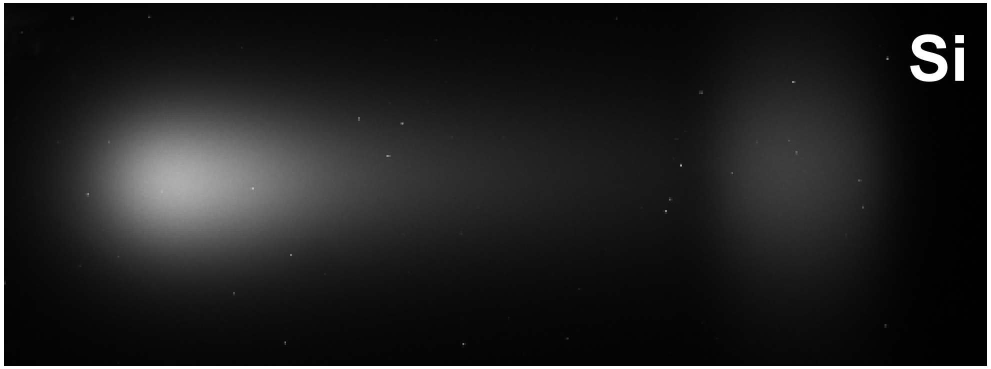


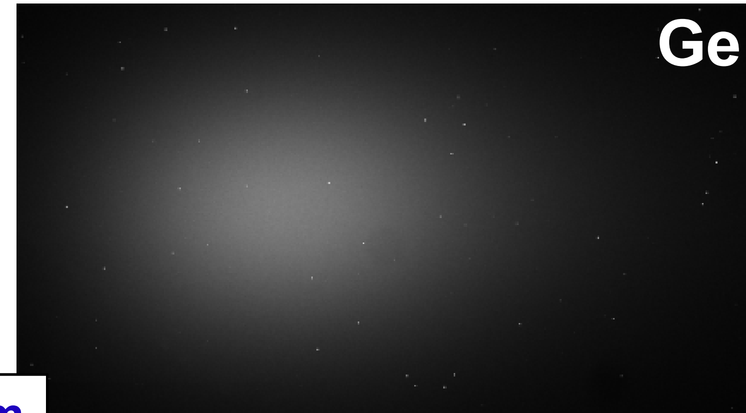
- **Si**
  - Crystal length: **15 µm**
  - Bending angles:
    - 315 µrad
    - 550 µrad
    - 750 µrad
    - 1080 µrad

- **Ge**
  - Crystal length: **15 µm**
  - Bending angles:
    - 820 µrad
    - 1200 µrad
    - 1430 µrad

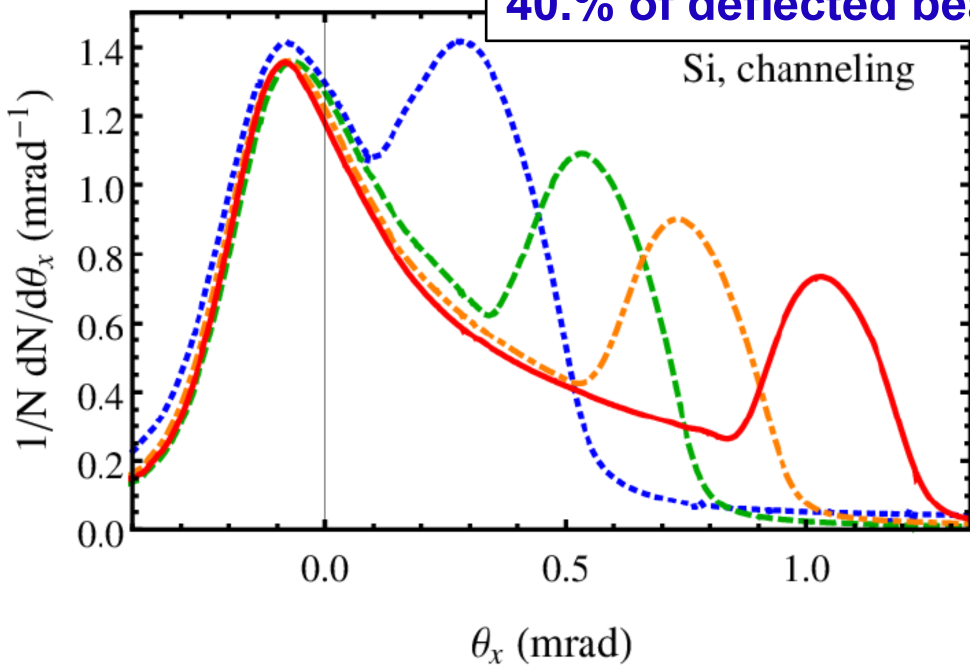
D. De Salvador et al. JINST 13, C04006 (2018))

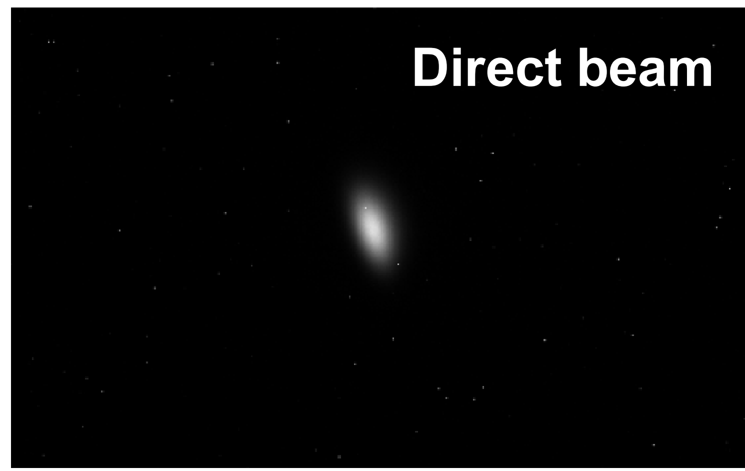
Beam deflection at different bending





40.% of deflected beam

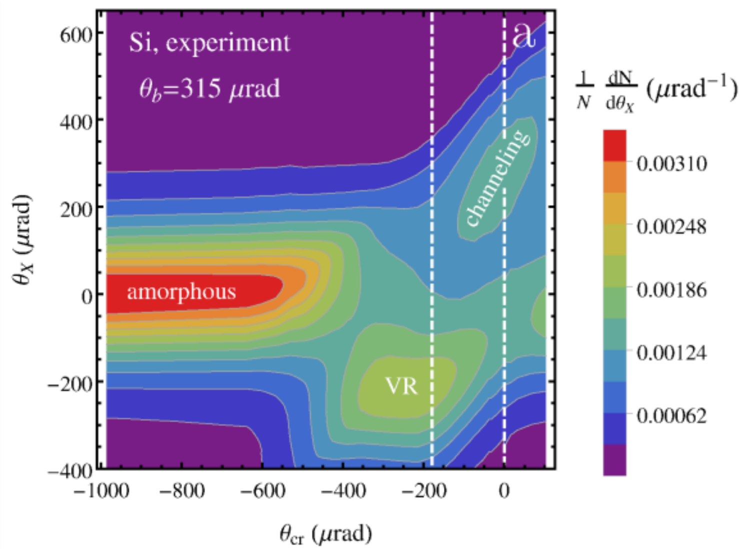


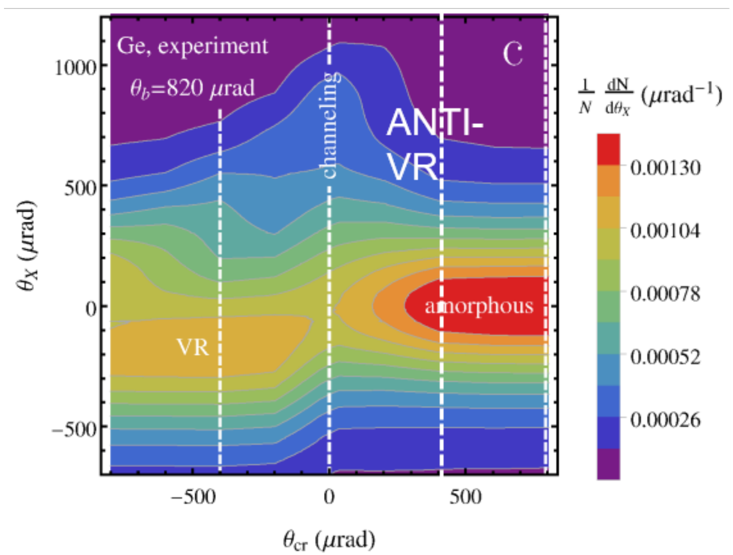


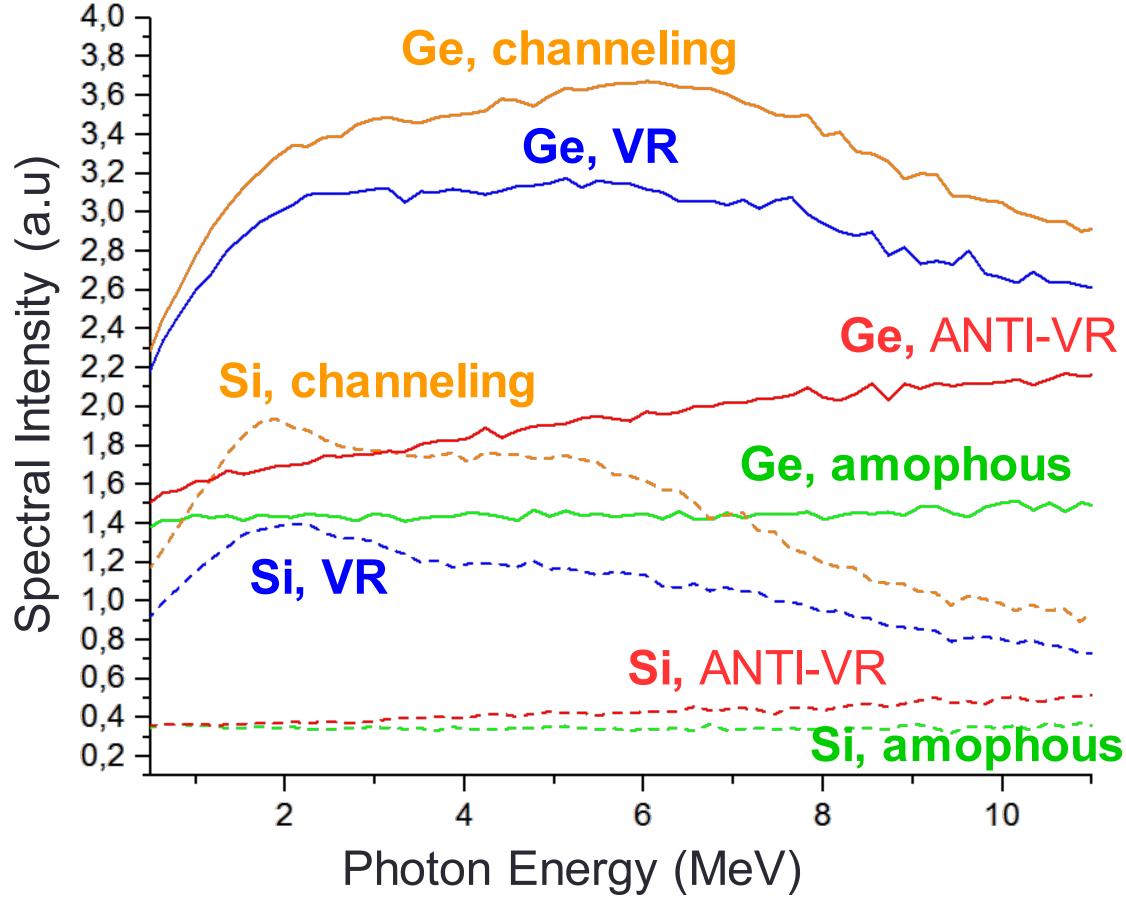
Beam angular divergence: **21.4 μrad**

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

Investigation on Channeling & VR radiation vs. atomic number Z

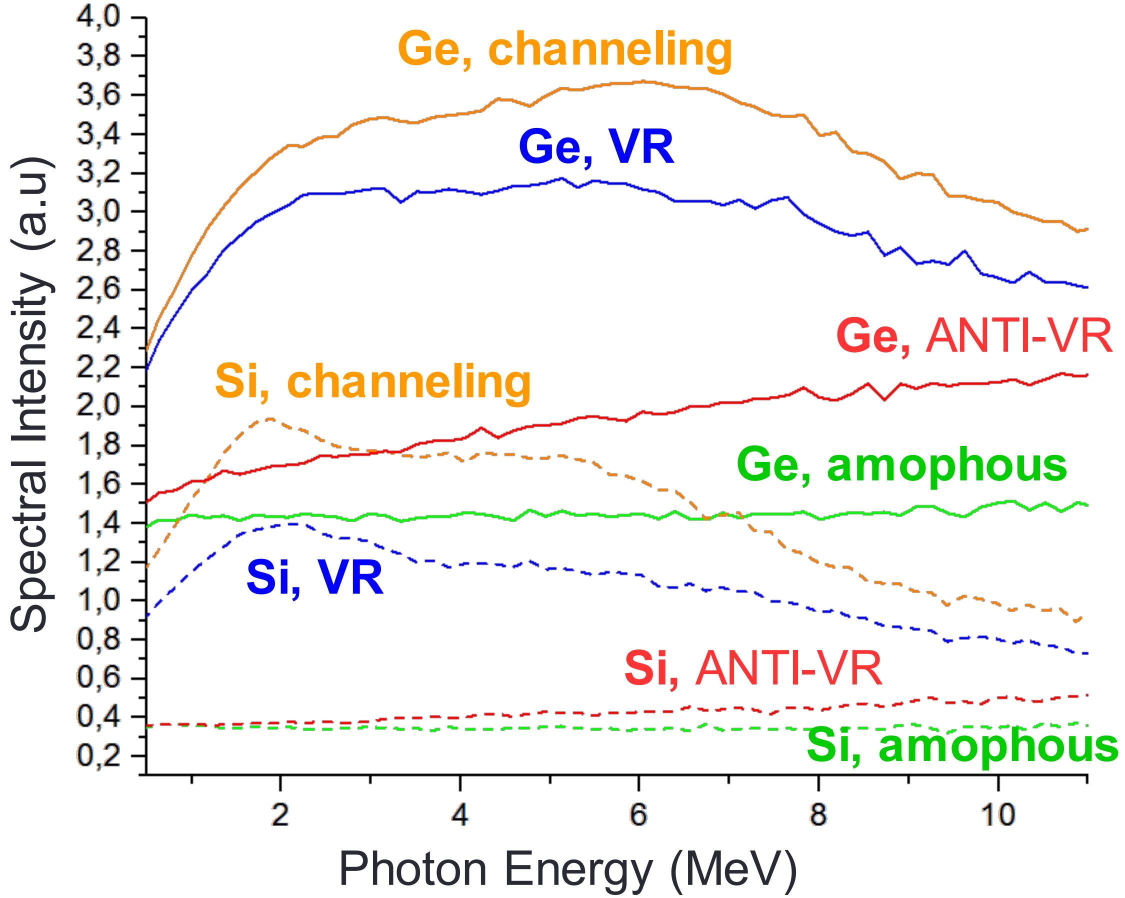






Investigation on Channeling & VR radiation vs. atomic number Z

- In **germanium crystal** the **increase in the radiation production** rate is evident**,** **while the channeling peak is less pronounced** and seems to occur at higher energy than for silicon;



Possible applications

- **The radiation accompanying Volume Reflection (VR) possesses an adjustable and broad angular acceptance**, which can be used for high-intensity radiation generation with poor emittance beams:
  - Since VR is less sensitive to crystalline defects as compared to channeling → higher-Z materials such as Ge and W, which usually cannot be grown with the same perfection as a Si crystal, can be used.

- Information on coherent radiation in bent crystals may be useful for the design of a **crystalline undulator**.

An algorithm for computation of radiation emission in oriented crystals

Based on the Baier Katkov general method for calculation of radiation generated by e± in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[\left(E^2+E'^2\right)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)} \quad (1)$$

where the integration is made over the classical trajectory.

The generality of the Baier-Katkov operator method permits to simulate the electromagnetic radiation emitted by e± in very different cases, e. g., straight, bent and periodically bent crystals, and for different beam energy range, from sub-GeV to TeV.

Baier-Katkov quasiclassical operator method (1967-1968)

General method for calculation of radiation generated by $e^{\pm}$ in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[\left(E^2+E'^2\right)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)} \qquad (1)$$

where the integration is made over the classical trajectory.

Why classical trajectory?

2 types of quantum effects :

- the quantization of particle motion $\sim\hbar\omega_0/E$
  In crystals: nearly negligible for electron/positron energy >10-100 MeV
- the quantum recoil of the particle when it radiates a photon with energy $\hbar\omega\sim E$
  NOT negligible for electron/positron energy >50 GeV

An algorithm for radiation in crystals

Integration of the BK formula

SMALL ANGLE APPROXIMATION: Since the angle between particle trajectories and crystal planes or axes is small and at ultrarelativistic energies the radiation angle 1/γ is much smaller than unity the particle velocity **v** and photon momentum **k** can be represented in the form :

$$\mathbf{v}(t) \simeq \mathbf{v}_\perp(t) + \mathbf{e}_z \left[1 - 1/2\gamma^2 - v_\perp^2(t)/2\right],$$
$$\mathbf{k} = \mathbf{n}\omega \simeq \mathbf{e}_\perp \omega\theta + \mathbf{e}_z\omega\left(1 - \theta^2/2\right),$$

where the angle $\theta \ll 1$ represents the radiation angle. The formula (1) can be rewritten as:

$$\frac{dE}{d^3k} \sim \frac{\alpha}{8\pi^2}\frac{\varepsilon^2 + \varepsilon'^2}{\varepsilon'^2}\omega^2 C, \qquad (2)$$

where $$C = |\, \boldsymbol{I}_\perp \,|^2 + \gamma^{-2}\frac{\omega^2}{\varepsilon^2 + \varepsilon'^2}\,|\, J \,|^2 \qquad (3)$$

V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903]

L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015).

An algorithm for radiation in crystals

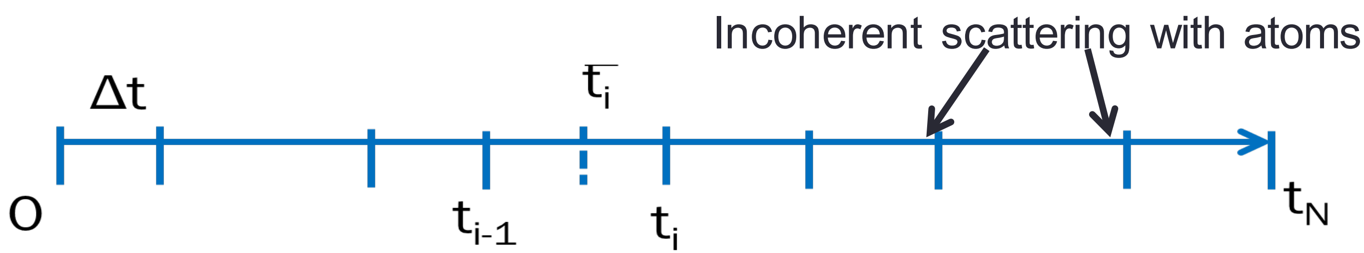
Integration of the BK formula

SMALL ANGLE APPROXIMATION: the integrals of eq. (1) can be represented as follows:

$$\begin{pmatrix} \boldsymbol{J} \\ \boldsymbol{I}_\perp \end{pmatrix} = \int_{-\infty}^{+\infty} dt \frac{1}{(\boldsymbol{v}_\perp - \boldsymbol{\theta})} e^{-i\phi(t)} \qquad (4)$$

being $\phi(t) = \frac{\omega'}{2} \int_{-\infty}^{t} dt' [\gamma^{-2} + (\boldsymbol{v}_\perp(t') - \boldsymbol{\vartheta})^2]$ and $\omega' = \omega\varepsilon/\varepsilon'$.

ACCOUNT OF INCOHERENT SCATTERING:



The **particle trajectory is then divided in N small steps**, within which the particle trajectory is calculated through the integration of equation of motion in the continuous potential. **At the end of each step the scattering by nuclei and electrons is sampled** and the transverse velocity for the i-step becomes

$$\mathbf{v}_{\perp,\mathbf{i}} \rightarrow \mathbf{v}_{\perp,\mathbf{i}} + \theta_{\mathbf{s},\mathbf{i}}$$

The integration over θ leads to the radiation spectral intensity, ωdN/dω.

MC code based on BK

The algorithm for direct integration of the BK formula (RADCHARM++) [1,2] has been implemented in a MC program that simulate the particle trajectory in oriented crystals [2,3].

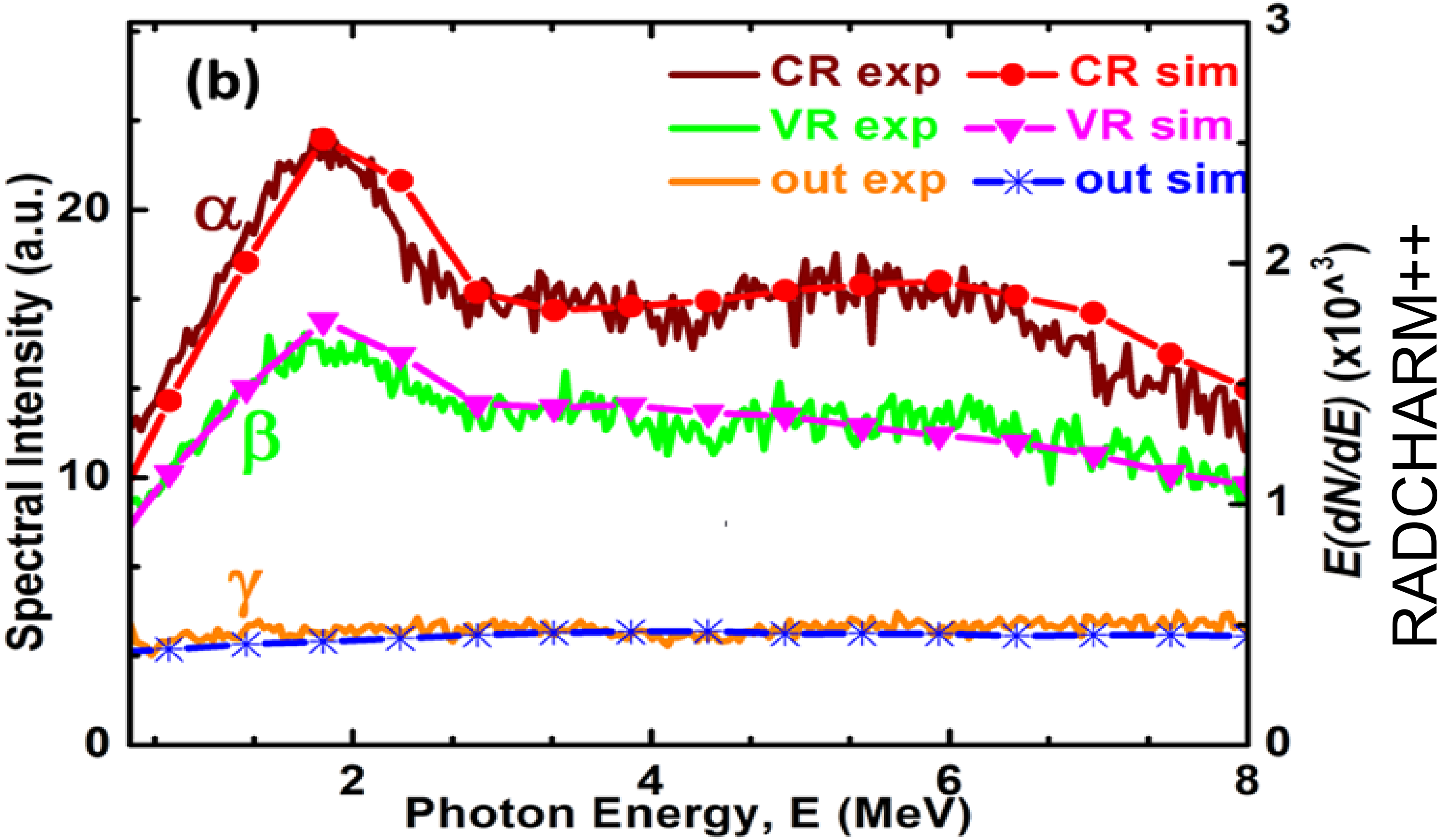
- The electrical characteristic of the crystal are evaluated by using the atomic form factors from x-ray diffraction data;
- Numerical integration of the classical equation of motion of particle trajectories under the continuum potential approximation;
- At the end of each step the multiple and single scattering by nuclei and electrons is sampled.

We also started the implementation of the electromagnetic processes enhancement in crystals in the GEANT4 toolkit [4].

[1] L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res. B 355, 44 (2015).
[2] V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903]
[3] A. I. Sytov, V. V. Tikhomirov, and L. Bandiera, Phys. Rev. Accel. Beams 22, 064601 (2019).
[4] L. Bandiera, V.V.Haurylavets, V. Tikhomirov Nucl. Instrum. Methods Phys. Res. A 936 (2019) 124.

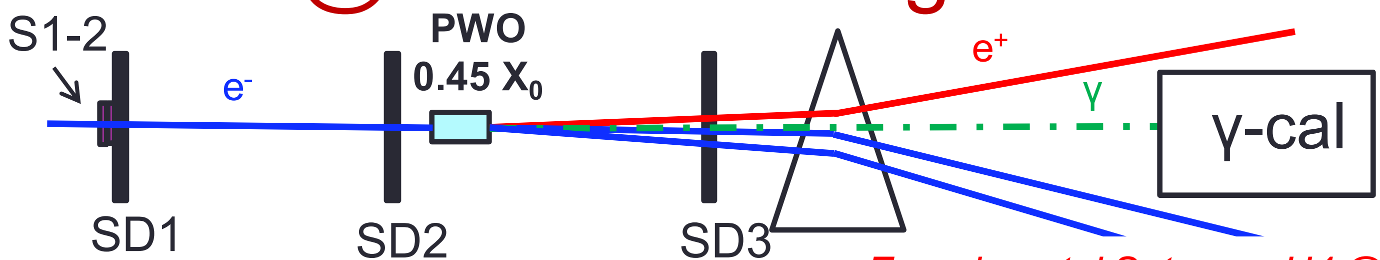
Comparison with MAMI experiments

Comparison with experiment performed at the Mainzer Mikrotron with 855 MeV electrons interacting with a 30.5 μm bent Si crystal along the (111) planes

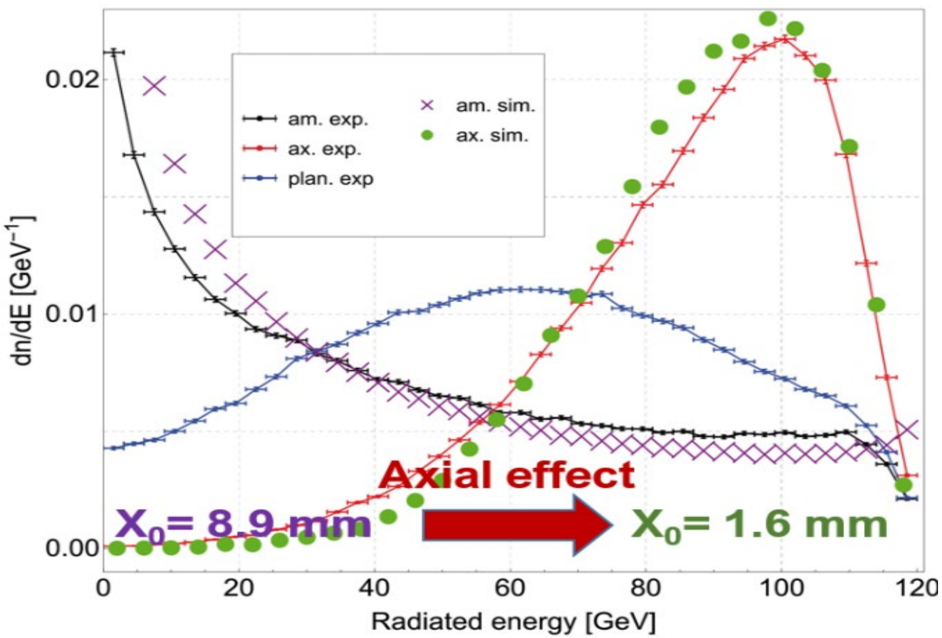


L. Bandiera et al., Phys. Rev. Lett. 115 (2015) 025504.

Comparison with experiments @ 120 GeV energies



Experimental Setup on H4 @CERN SPS

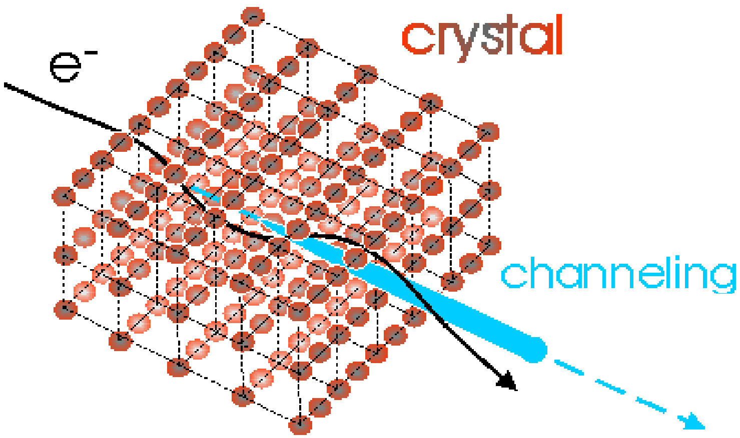


The **radiation length** in the oriented **scintillator crystal** (PWO, *which is the material of the CMS ECAL*) is **reduced by a factor 5** in comparison to the random orientation.

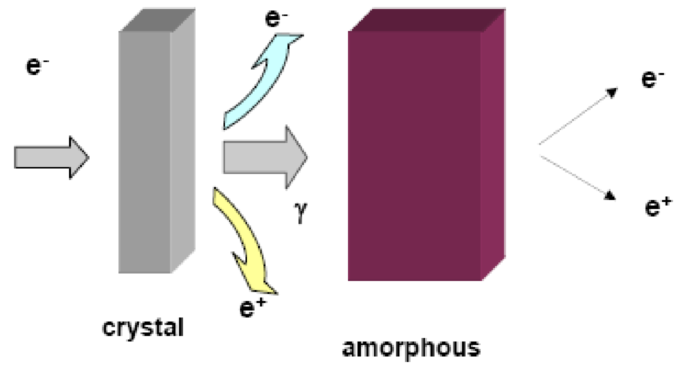
Possible application for compact forward e.m. calorimeters

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

…Applications

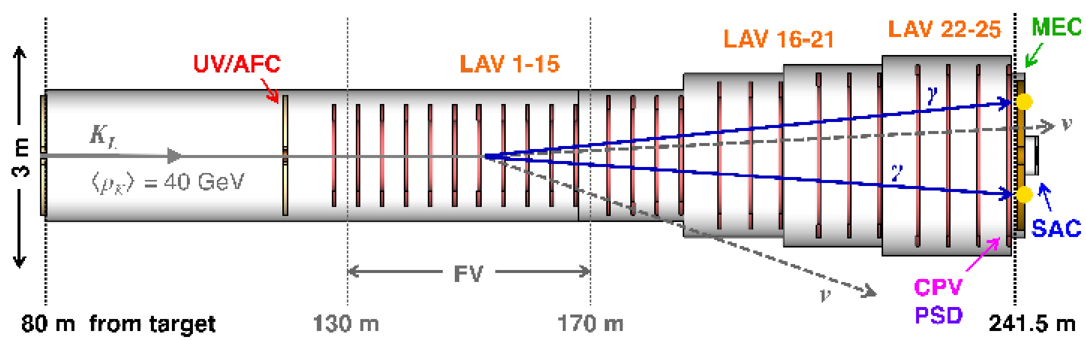


Crystal-based gamma source



Crystal-based positron source

new collaboration with the IJCLab/IN2P3/CNRS team (see I. Chaikovska talk tomorrow).



Oriented crystal based Converter/ Small Angle E.M. Calorimeter

Onging collaboration with NA62/KLEVER @CERN SPS

Conclusions and perspectives

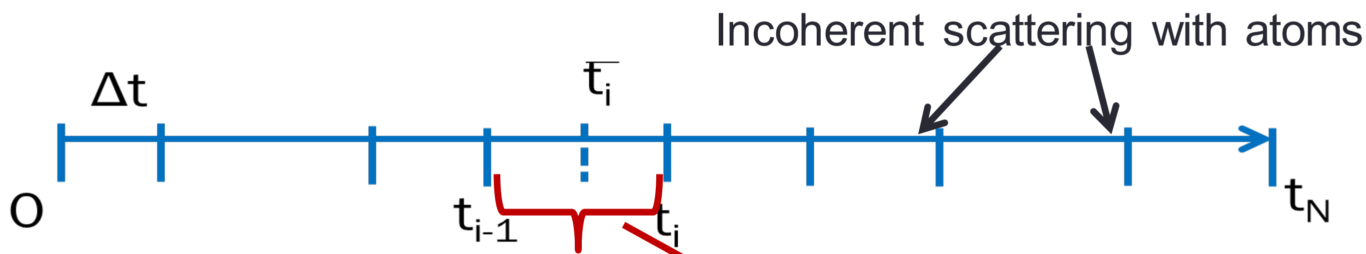
- ✓ **Experiments on Channeling and Volume Reflection radiation emitted by 855 MeV electrons in a 15-30 μm Si and Ge bent crystals have been carried on at the Mainzer Mikrotron**:
  - ✓ First results on electron beam steering in sub-GeV energy range. For the first time a deflection efficiency of about 40% was achieved for sub-GeV electrons;
  - ✓ Possible applications of radiation emission in bent crystals have been highlighted.

- **An algorithm to compute of radiation emitted by relativistic e± in crystals based on the Baier-Katkov method has been realized**:
  - Comparison with experiments show a very good agreement in a wide energy range (from 1 GeV to 100 GeV);
  - Wide range of applications of the BK algorithm in HEP and applied physics.

THANK YOU FOR THE ATTENTION!

An algorithm for radiation in crystals

Integration of the BK formula



In order to improve the convergence of its integration over t and $\boldsymbol{\theta}$ (photon emission angle), the integrals of eq. 4 are computed as follows after an integration by parts:

$$J \approx i\sum_{i=1}^{N}\left\{\exp\left[i\phi(t_i)\right]\left[\frac{1}{\dot{\phi}_{t_i+0}}-\frac{1}{\dot{\phi}_{t_i-0}}\right]-\exp\left[i\phi(\bar{t}_i)\right]\left[\frac{2\ddot{\phi}}{\dot{\phi}^3}\bigg|_{\bar{t}_i}\sin\left(\left[\phi(t_i-0)-\phi(t_{i-1}+0)\right]/2\right)\right]\right\}$$

If incoherent scattering is switched off, it is go to zero.

$$\dot{\phi}(t<t_i)=\frac{\omega'}{2}\left[1/\gamma^2+\left(\mathbf{v}_\perp(t)-\boldsymbol{\theta}\right)^2\right], \qquad \ddot{\phi}(t)=\omega'\left(\mathbf{v}_\perp(t)-\boldsymbol{\theta}\right)\dot{\mathbf{v}}_\perp(t),$$

$$\dot{\phi}(t_i+0)=\frac{\omega'}{2}\left[1/\gamma^2+\left(\mathbf{v}_\perp(t)+\theta_{\mathbf{s},\mathbf{i}}-\boldsymbol{\theta}\right)^2\right], \qquad \dot{\mathbf{v}}_\perp=-\frac{1}{\varepsilon}\frac{\partial U(\mathbf{r})}{\partial \mathbf{r}_\perp},\ U(\mathbf{r})\text{ being the continuous potential.}$$

The contributions of the trajectory ends are not taken into account, thus neglecting the soft contribution of transition radiation.

The integration over θ leads to the radiation spectral intensity, ωdN/dω.