BREMSSTRAHLUNG AND PAIR PRODUCTION ENHANCEMENT IN STRONG CRYSTALLINE FIELDS

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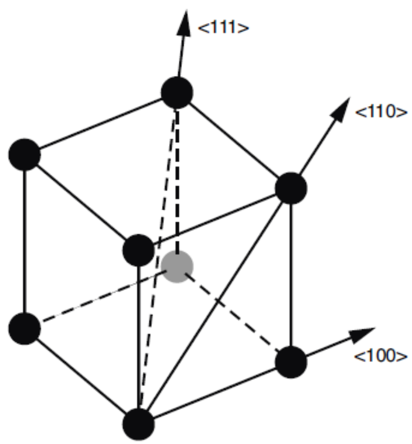
Outlook

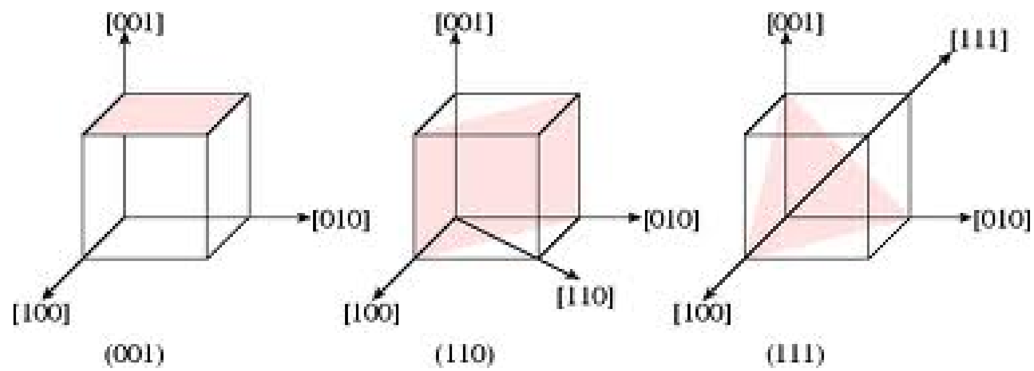
- Historical excursus on e.m. processes in oriented crystals and their well established applications:
  - Coherent Bremsstrahlung sources;
  - Gamma converter with reduced X_0;
- New study of these processes in an oriented high-Z scintillator (a lead tungstate crystal):
  - Possible applications in HEP and astroparticle physics;
- Another novel application:
  - Intense positron source for future colliders;
- Summary.

ELECTROMAGNETIC PROCESSES IN ORIENTED CRYSTALS

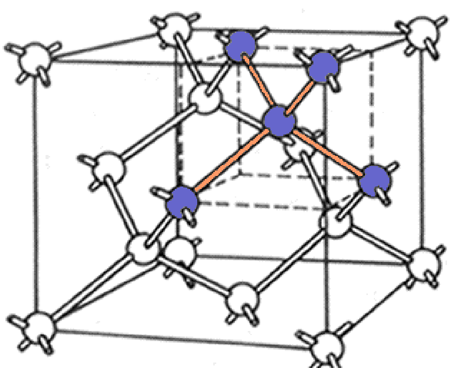
Crystalline solids

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



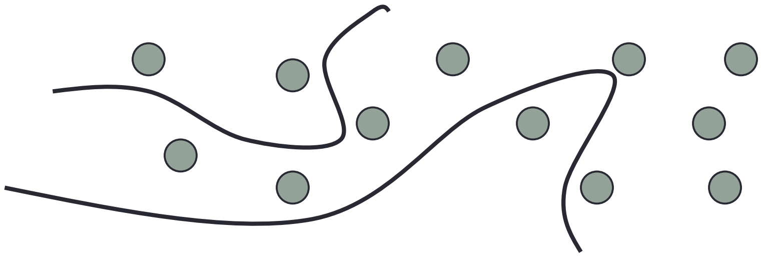


Diamond or Si crystal



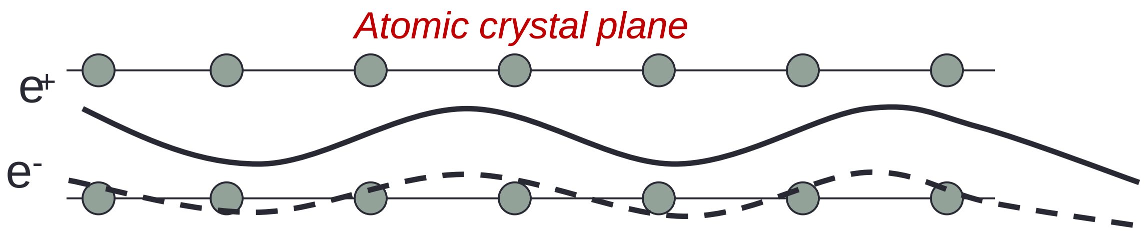
Motion of charged particles in crystals: Channeling

Amorphous or non-crystalline solid



Crystalline solid
(Si, C, Ge, W…)

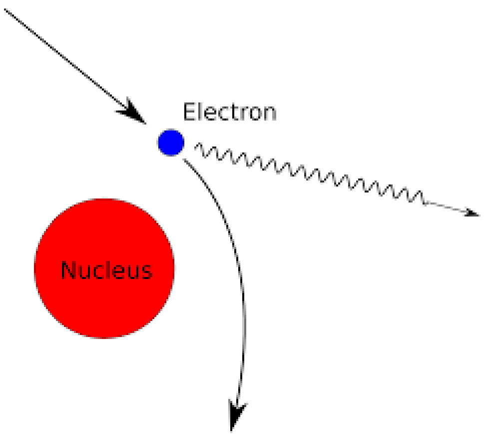
planar channeling



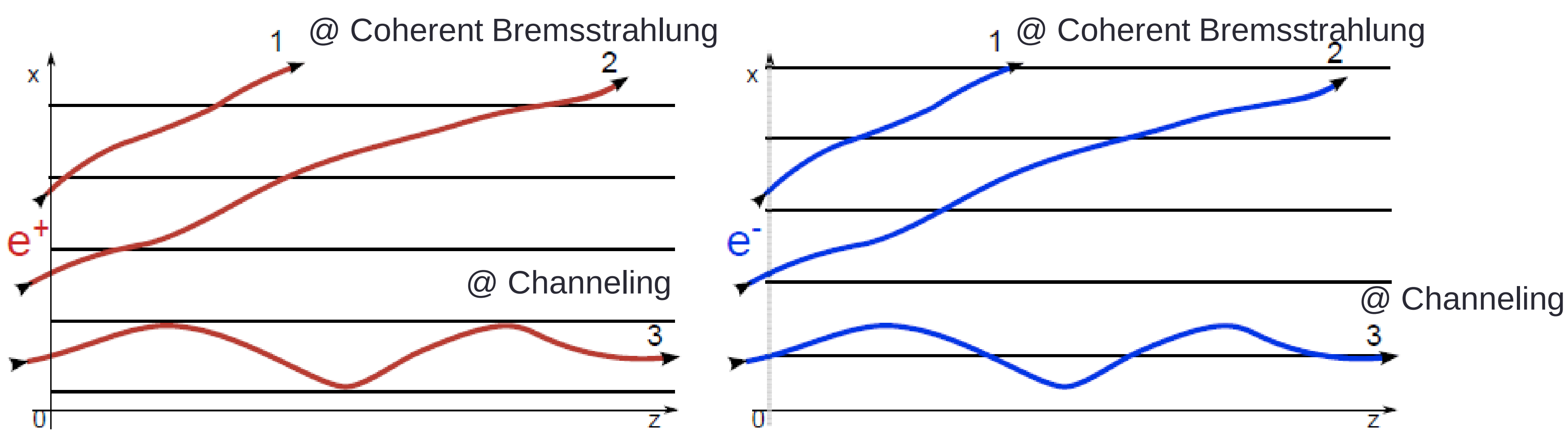
Positively-charged particles <u>are repulsed from the nuclei of the axis (plane)</u> and hence can be captured inside the interaxial (interplanar) potential wells.

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

Unchanneled particles: Coherent Bremsstrahlung



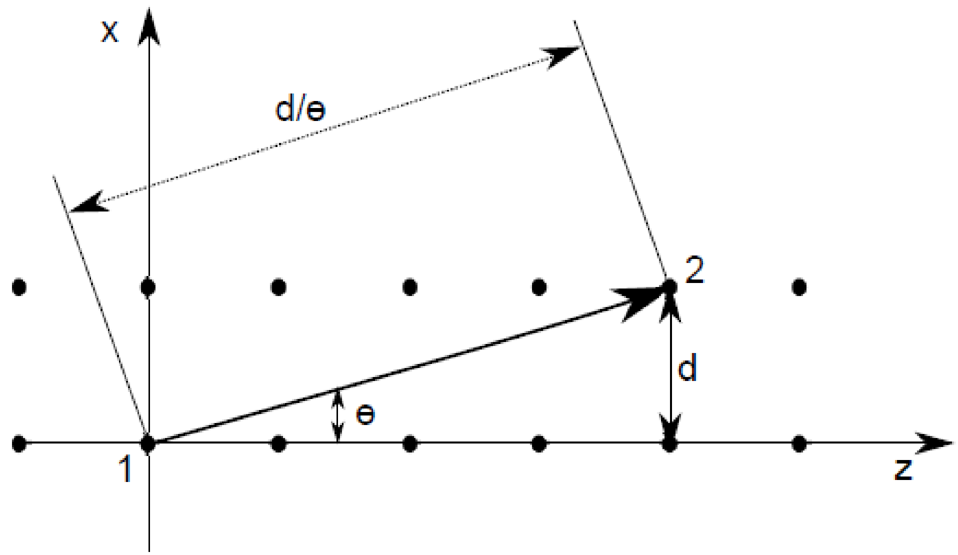
Does the crystal structure influence the process of bremsstrahlung?



(a) (b)

Does the crystal structure influence the process of 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 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 become important in the photon emission, when *lc ≥ d (analogous to Bragg diffraction).*

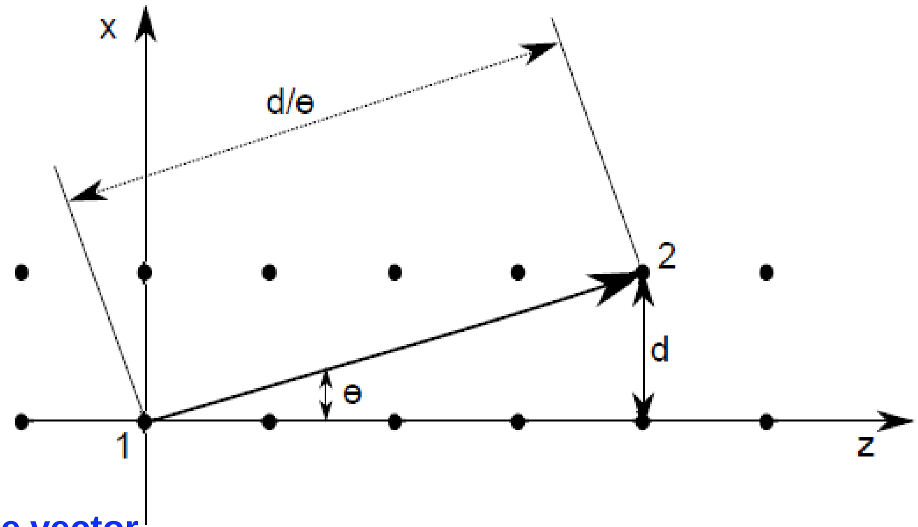
Coherence Length and interference

Constructive interference condition:

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

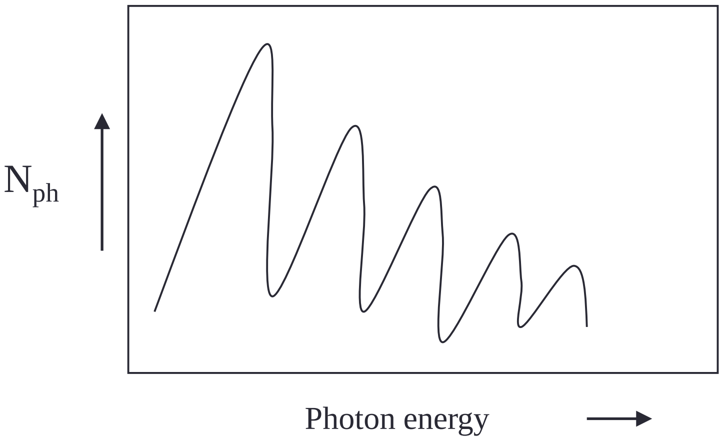
$$\frac{\delta}{\theta}=n\frac{2\pi}{d}$$

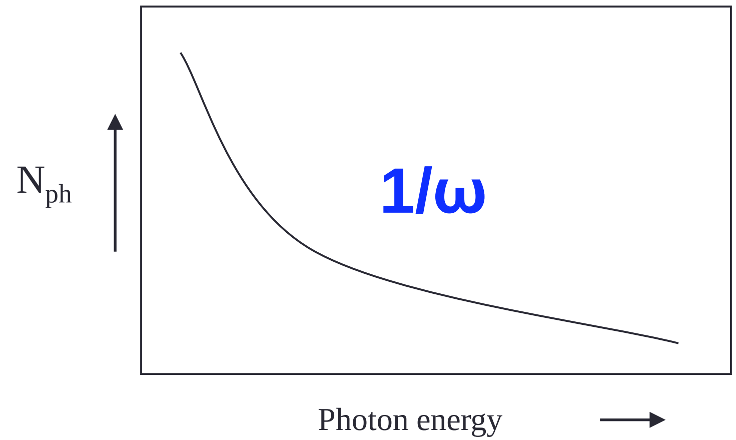
Reciprocal lattice vector



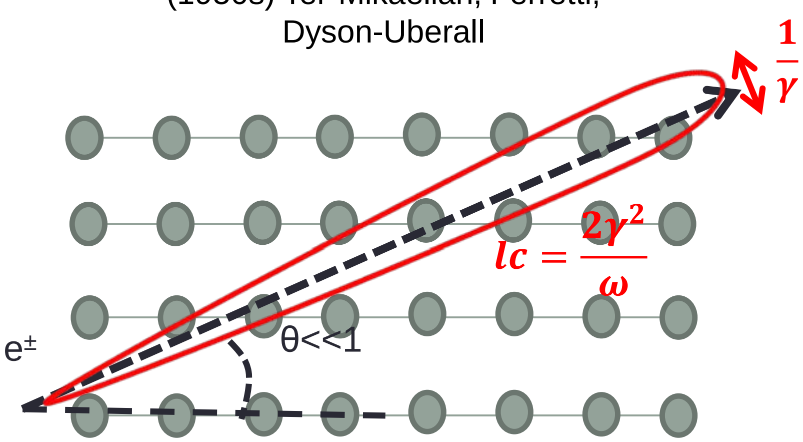
Factor **2π/d** that has the dimensions of a **reciprocal lattice vector** -> the **bremsstrahlung radiation** emitted in a crystal **increases** when the **momentum transferred from the particle to the atoms matches a reciprocal lattice vector.**

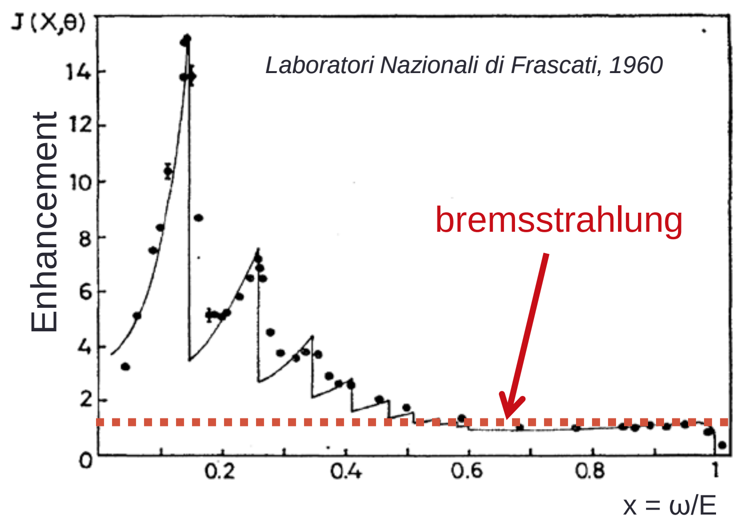
CB vs. bremsstrahlung



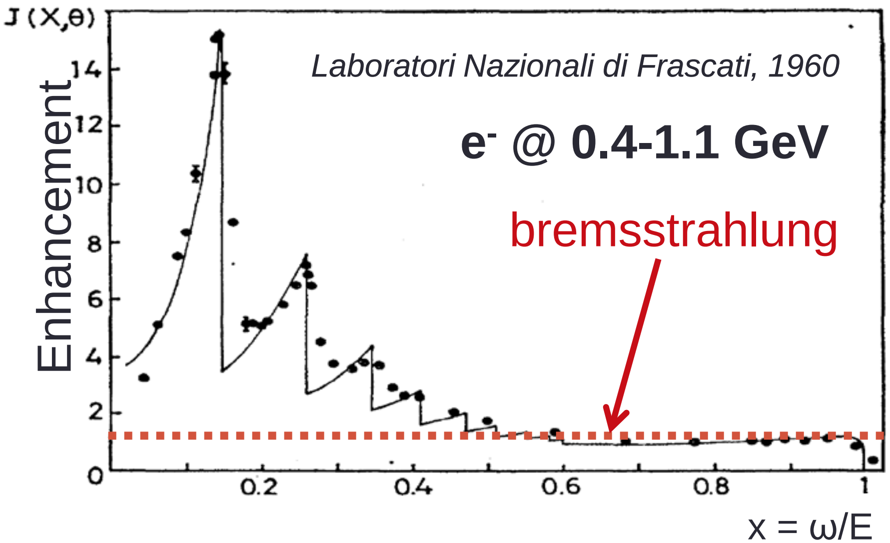


Coherent Bremsstrahlung
(1950s) Ter-Mikaelian, Ferretti,
Dyson-Uberall





Coherent bremsstrahlung facilities

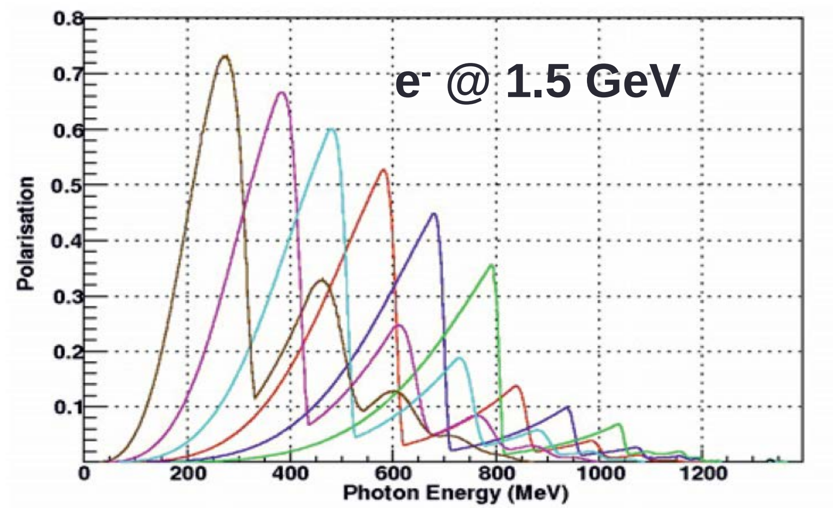


Intense and monochromatic gamma source

Linearly polarized photons

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

usually exploited
for **photonuclear researches**



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

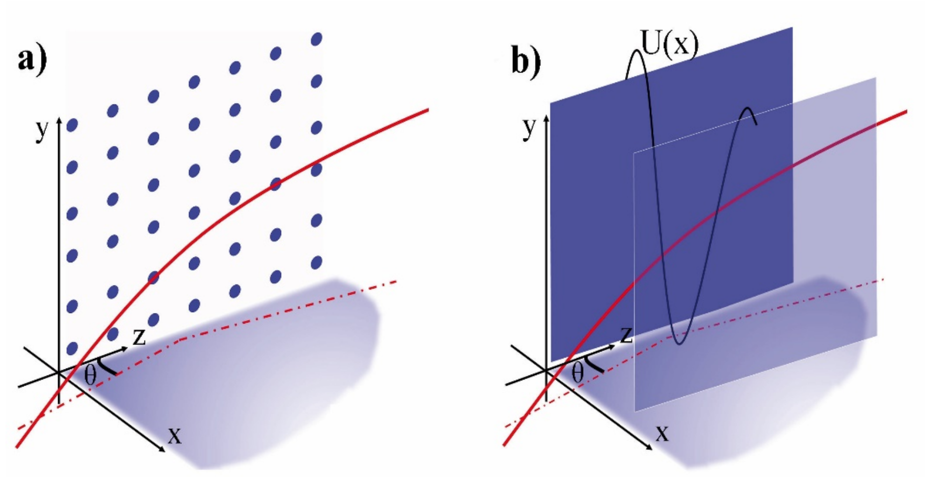
JLAB example: underlying symmetry of the quark degrees of freedom in the nucleon, the nature of the parity exchange between the incident photon and the target nucleon.

Channeling and Continuous Average 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 Average Potential

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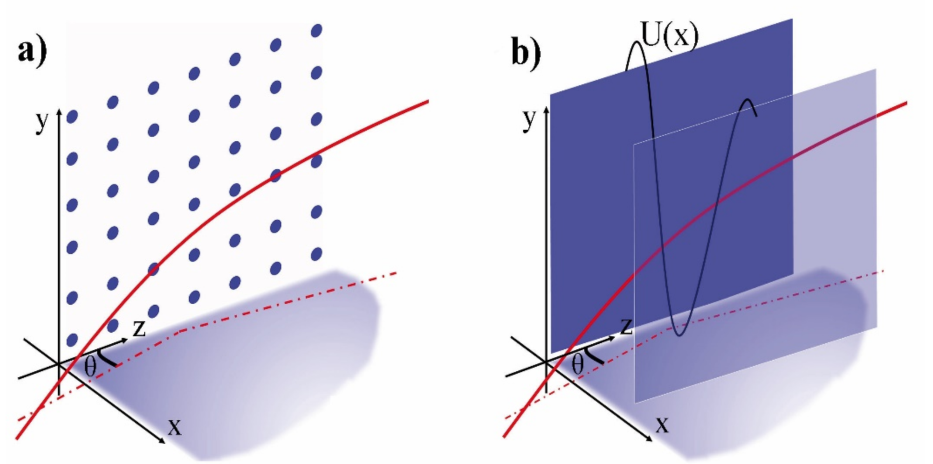


$$V_{TF}(r) = \frac{Z_i Z e^2}{r}\Phi\left(\frac{r}{a_{TF}}\right)$$

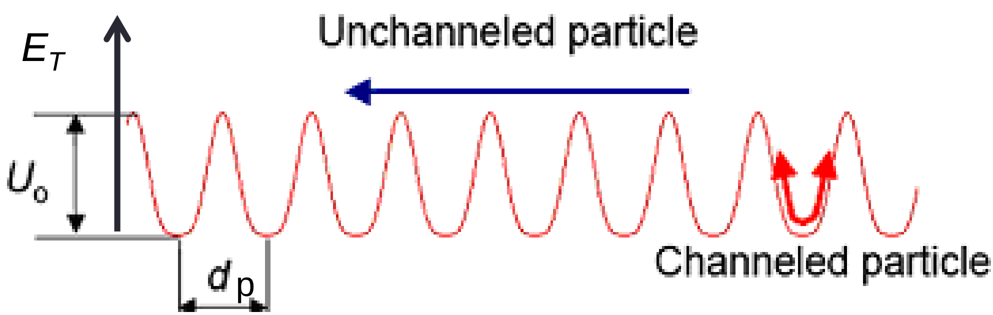
is the particle-atom screened Coulomb potential

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)

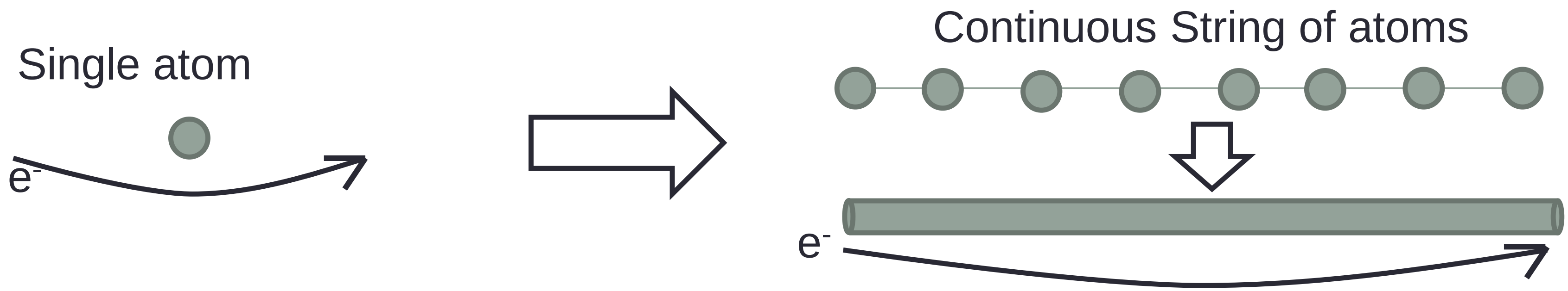
momentum velocity

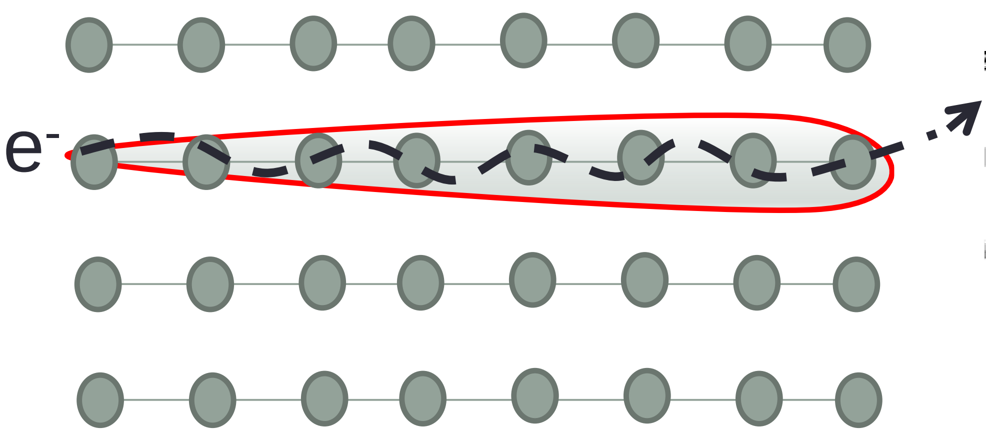


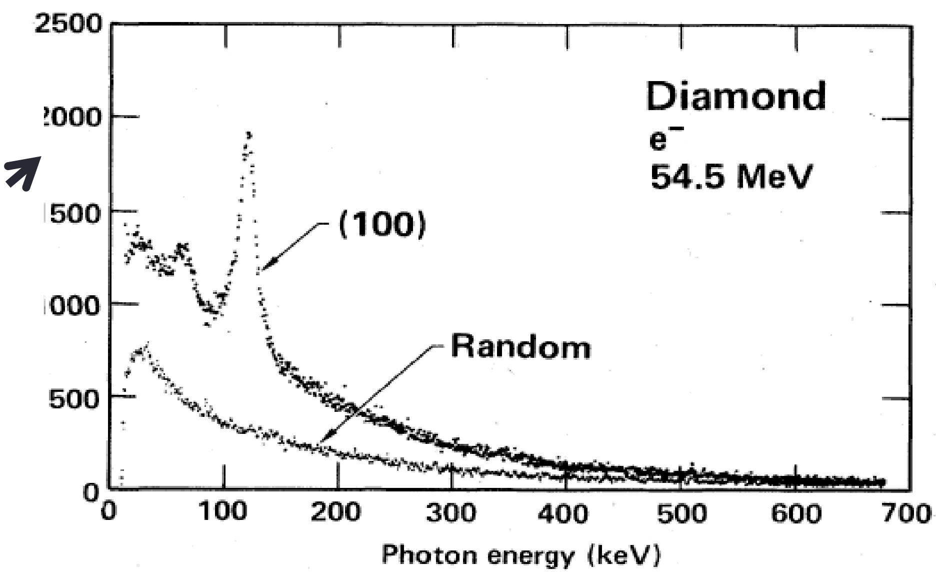
U_0 = *22.7* eV for (110) Si planes
θ_C ≈ 20 μ*rad* at *E* ~ *100* GeV

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

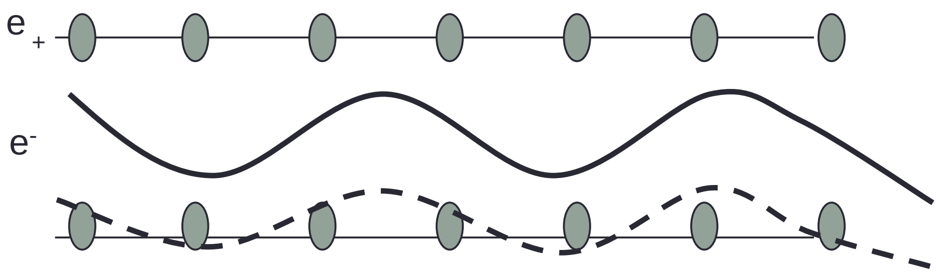
Channeling Radiation (1976, Kumakhov)

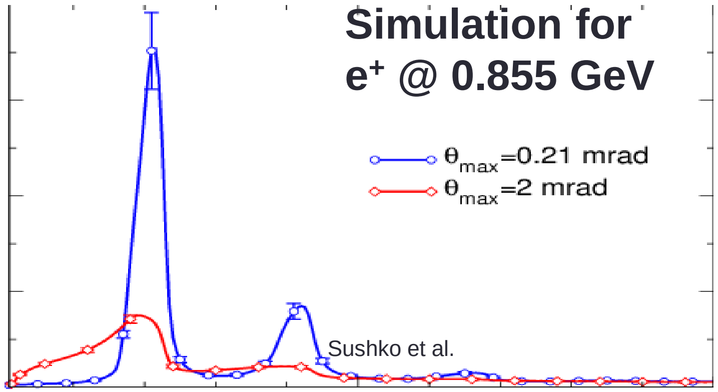






.. with positrons one may exploit also Channeling Radiation as intense radiation source -> **Possibility for LNF-DAφNE**





Radiation is similar to CB, but more soft photons are produced with the same beam and crystal, since the channeling period is longer than for CB -> interesting for production of intense photon beam in a wide frequency range !

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

Radiation for beam energy > few GeV

U_0 ~x^2 ⟶ oscillatory motion ⟶ emitted radiation increases with respect to the amorphous case (BH)

2 LIMIT CASES at HE:

if the incident angle θ_0 with respect to the crystal axis (or plane) is:

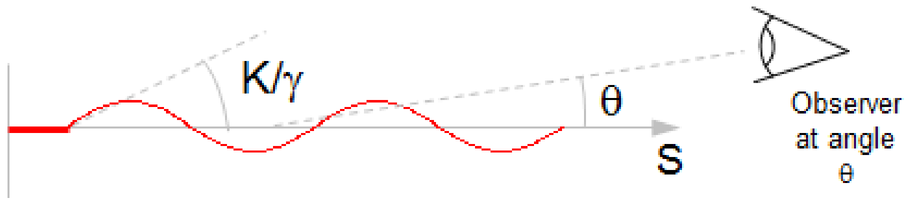
$$\theta_0 \ll \frac{V_0}{m}$$

- **Synchrotrone-like radiation**

$$\theta_0 \gg \frac{V_0}{m}$$

- **Coherent Bremsstrahlung**

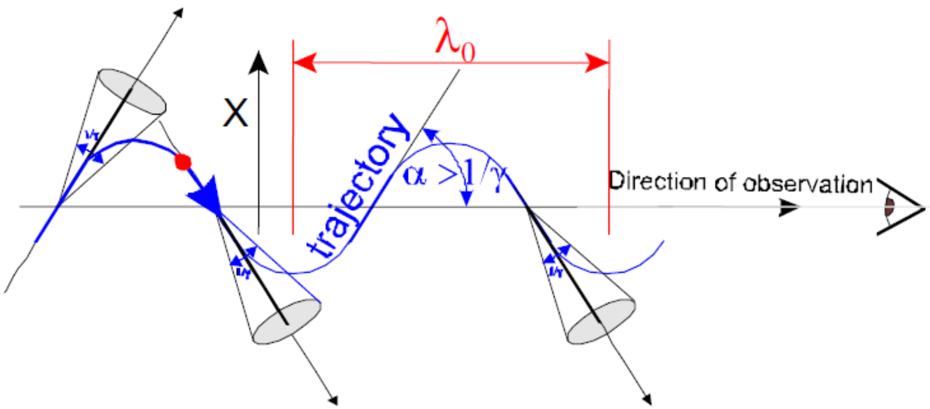
…Like Magnetic Undulators



Nearly monochromatic spectrum –
Few harmonics are emitted

Undulator: K << 1

The max angular deflection is much less than the cone opening angle. The observes sees the radiation form the whole undulator length

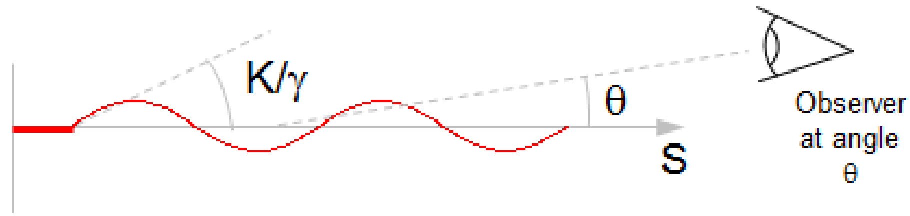


Continuous spectrum

Wiggler: K ~ 1 or K >> 1

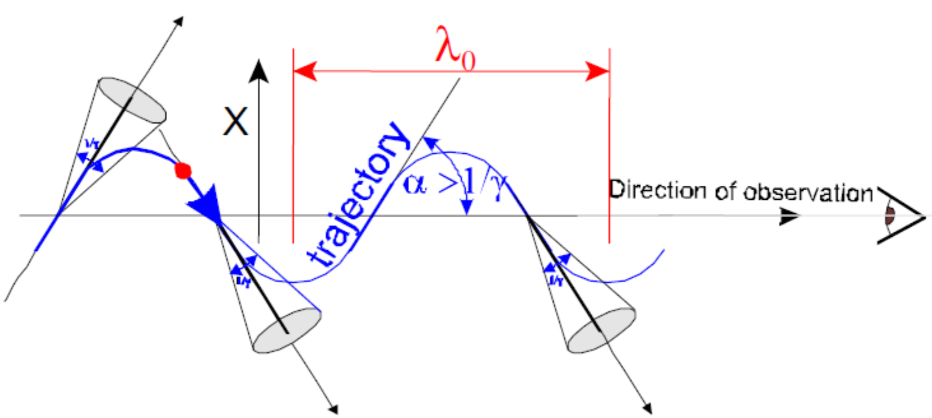
The max angular deflection is larger than the cone opening angle. The observer misses part of the radiation as the radiation fan sweeps right/left

…Like Magnetic Undulators



Nearly monochromatic spectrum –
Few harmonics are emitted

Coherent Bremsstrahlung – crossing crystal planes/axes with angle > V_0/m

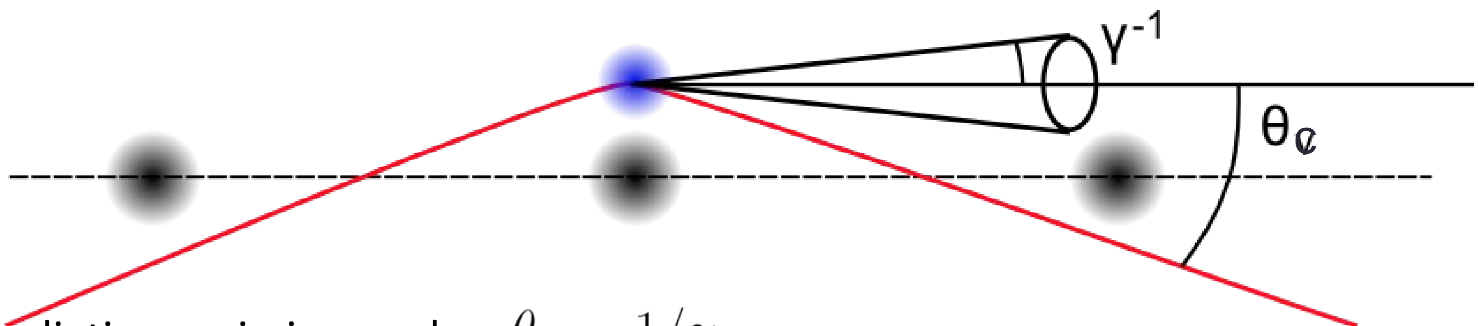


Continuous spectrum

Channeling Radiation – parallel to planes/axes

Synchrotron-like radiation in crystals

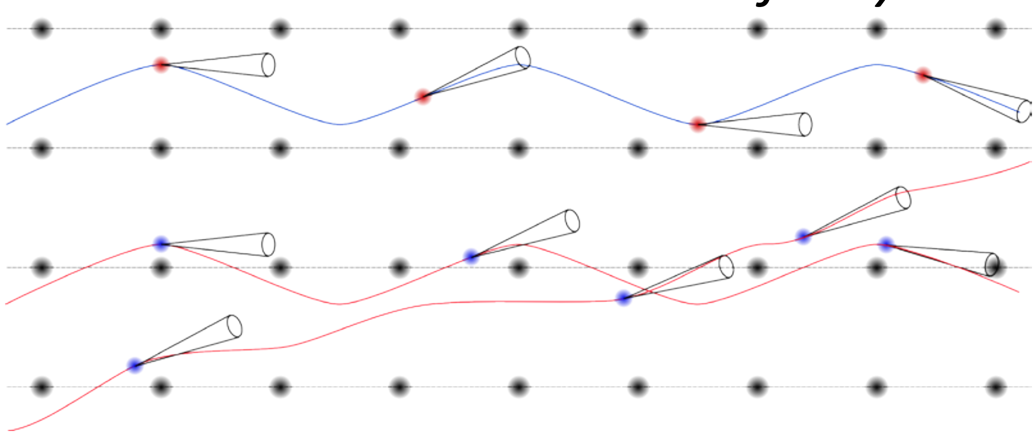
At energies > few GeV



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

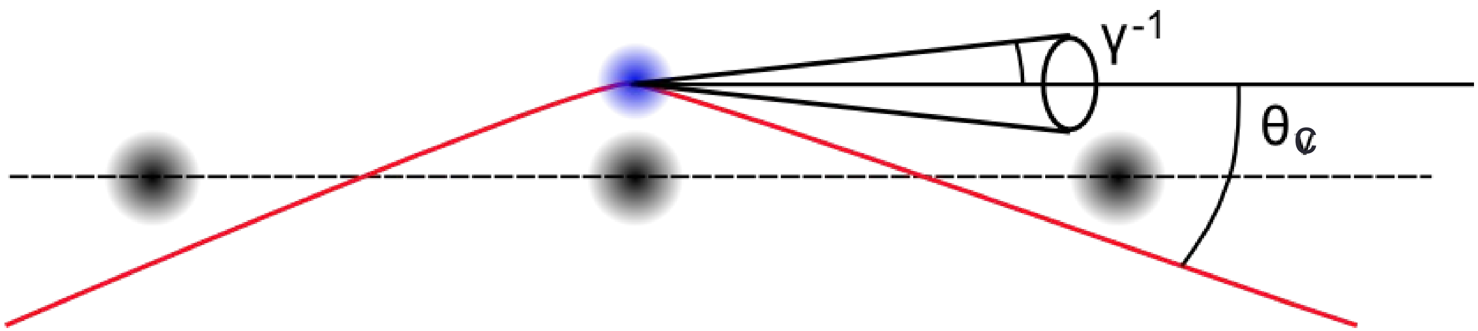
Threshold angle: $\theta_v = V_0/m$

$\theta_\gamma \ll \theta_v$ *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, Å	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 $\chi = \gamma E/E_0 \geq 1$ – 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.

The main point: total radiated energy can strongly increase!

VOLUME 54, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 1985

Measurement of the Total Energy Radiated by 150-GeV Electrons in a Ge Crystal

A. Belkacem, M. Chevallier, A. Clouvas, M. J. Gaillard, R. Genre,
R. Kirsch, J. C. Poizat, and J. Remillieux,
Institut de Physique Nucléaire and Institut National de Physique Nucléaire et de Physique des Particules, Université Claude Bernard Lyon I, 69622 Villeurbanne Cedex, France

and

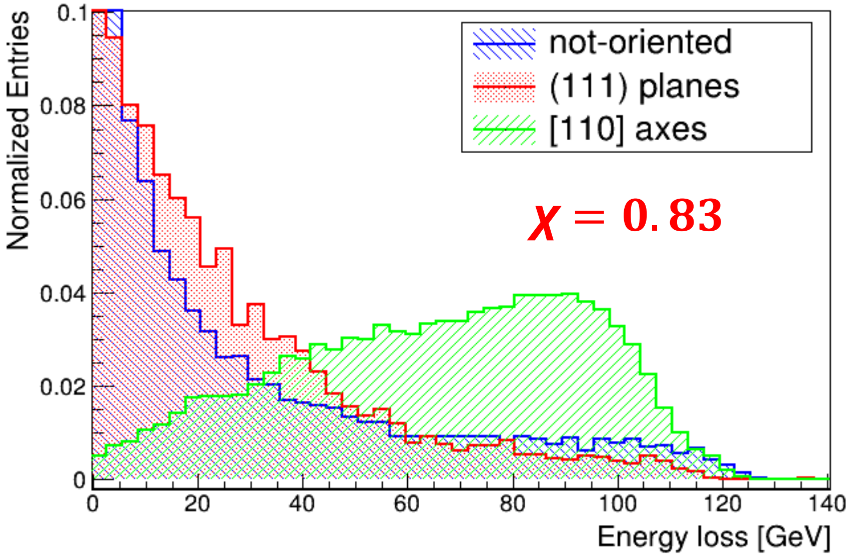
G. Bologna,[a] J. P. Peigneux, D. Sillou, and M. Spighel
Laboratoire d'Annecy-le-Vieux de Physique des Particules, Laboratoire de Physique des Particules and Institut National de Physique Nucléaire et de Physique des Particules, 74019 Annecy-le-Vieux Cedex, France

and

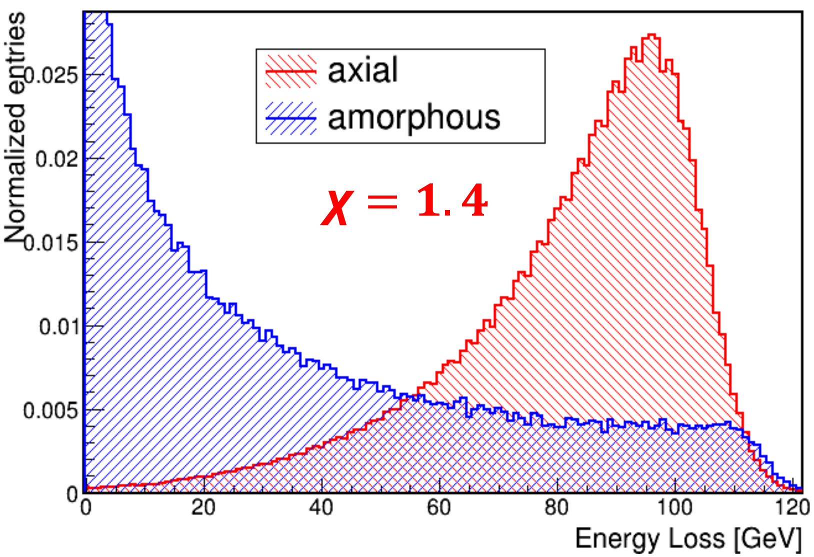
N. Cue, J. C. Kimball, B. Marsh, and C. R. Sun
Physics Department, State University of New York at Albany, Albany, New York 12222
(Received 11 February 1985)

We have measured the radiation emitted by 150-GeV e^- incident along the ⟨110⟩ axis of Ge crystals. The on-axis total radiated energy is 25 times larger than for nonaligned directions for 0.4-mm-thick Ge. The distribution of the radiated energy versus the angle of the electron beam yields a half-width much larger than the channeling critical angle. The on-axis results confirm the predictions of the crystal-assisted radiation theory. The Born approximation to the coherent bremsstrahlung fits the data at large angles.

INFN AXIAL @CERN: Si & Ge crystals e^- @120 GeV/c – **radiation generation under axial alignment**



Silicon crystal (2 mm long)
<110> crystal axis



Germanium crystal (2.8 mm long)
<110> crystal axis

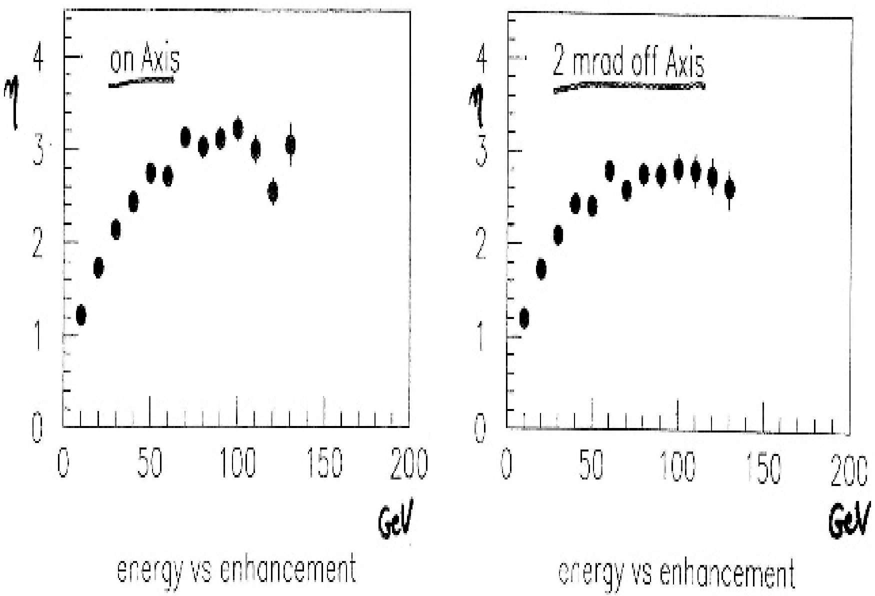
Energy loss spectrum

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

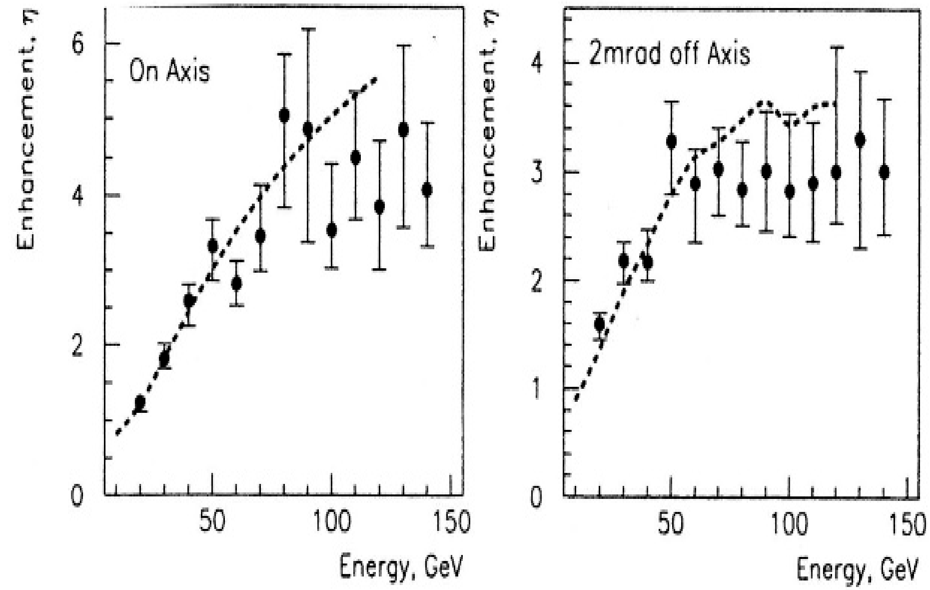
… and also for Pair Production

NA43 and NA48 experiments at CERN

Iridium



Tungsten



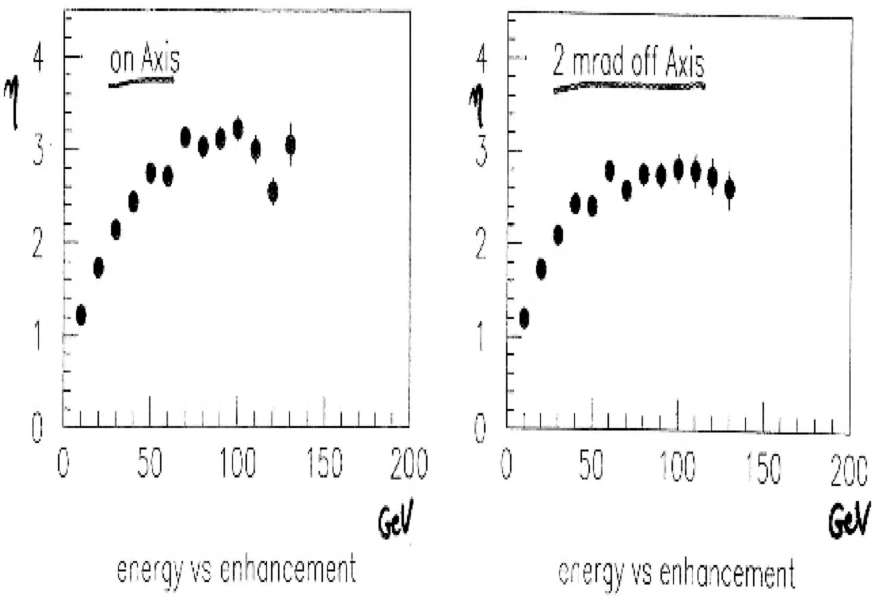
The NA48 experiment at CERN used **Ir crystal of 3mm thickness, corresponding to 0.98 X0 which became 1.79 X0 for the aligned crystal**, as a high energy photon converter.

A **30% reduction of multiple scattering occurred**, when **compared to** a lead converter with a thickness of **1.33 X0**.

From C. Biino, MiniWorkshop on Crystal Collimation @CERN, 2005

NA43 and NA48 experiments at CERN

Iridium



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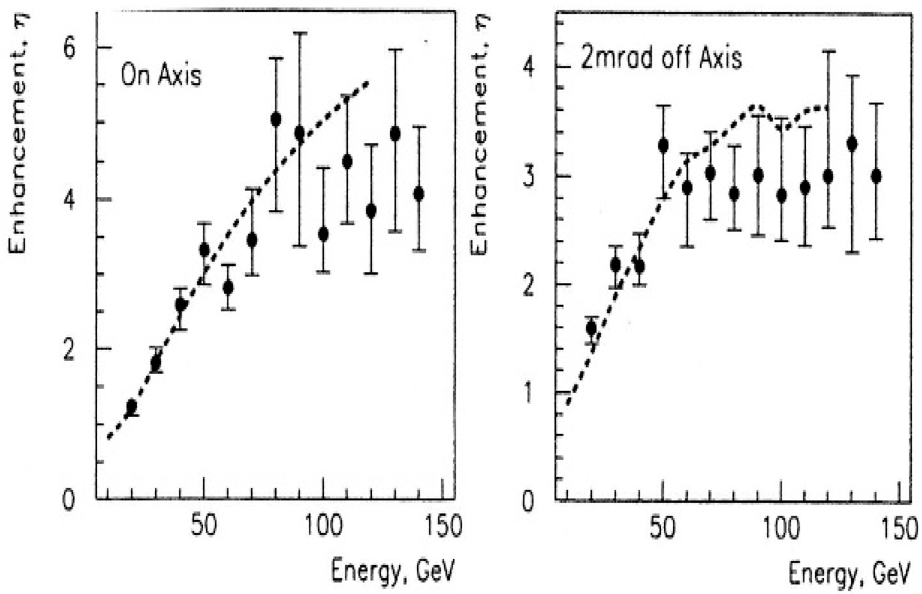


Possibility under evaluation for the KLEVER proposal -> possible successor of NA62 for Run4 (M. Moulson – INFN LNF)

NEW IDEA….

Can these orientational effects be important also for <u>inorganic scintillators</u> used in HEP electromagnetic calorimeters?

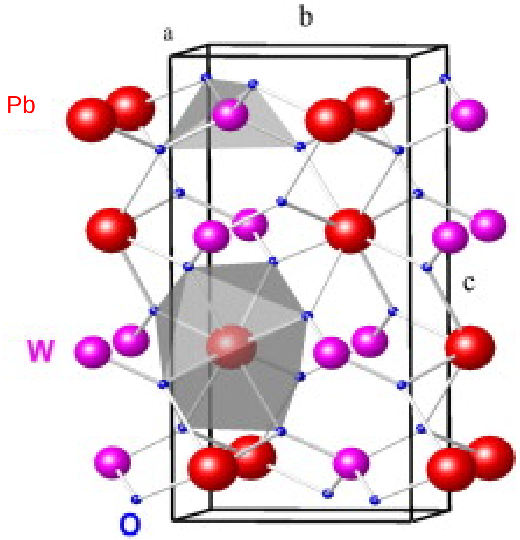
<u>The modern electromagnetic calorimeters are designed for experiments at energies of hundreds of GeV/TeV and these enhancement effects are expected to be quite important in this energy range.</u>

We performed an experiment to study the energy loss of hundreds GeV electrons in a lead tungstate at CERN

L. Bandiera et al, ArXiv: 1803.10005, under minor revision on Phys. Rev. Lett

PWO as high-Z scintillator

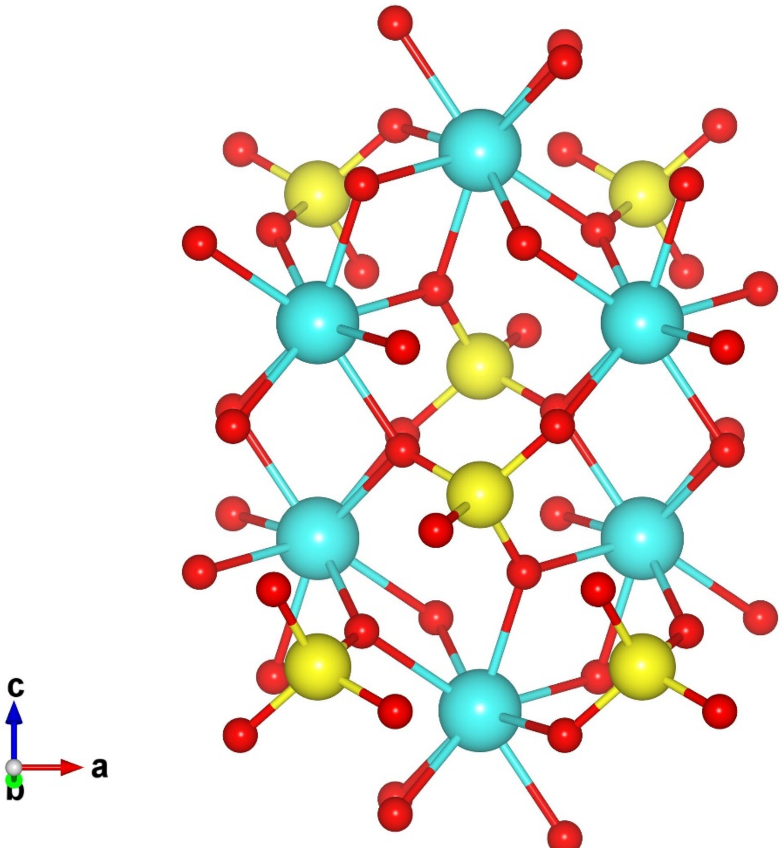
- $PbWO_4$ (PWO) scintillation crystals introduced by INP team in 1994 are currently used by CMS, ALICE, PANDA collaborations in EM calorimeters, about 100000 crystals in total has been produced.
- **PWO propreties:**
  - **Short radiation length (8.9 mm);**
  - **small Moliere Radius;**
  - **emission in visible;**
  - **cheap;**
  - **low light yield;**
  - **temperature dependent.**

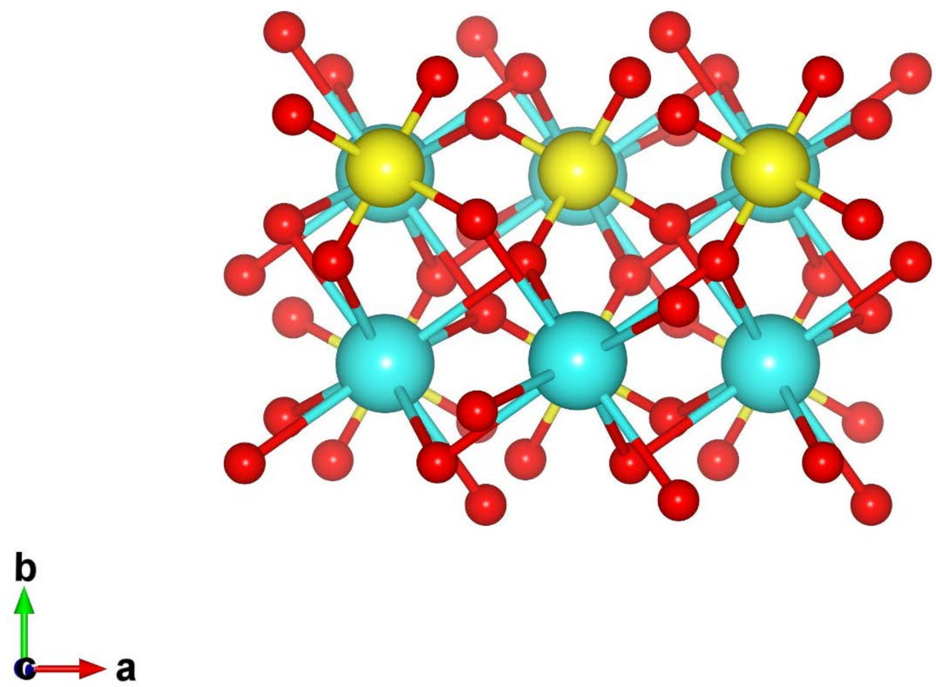


PWO crystralline structure

Structural characterization of PWO single crystal by x-ray diffraction showed scheelite type structure

(tetragonal, a=5.456, c=12.020 Å).





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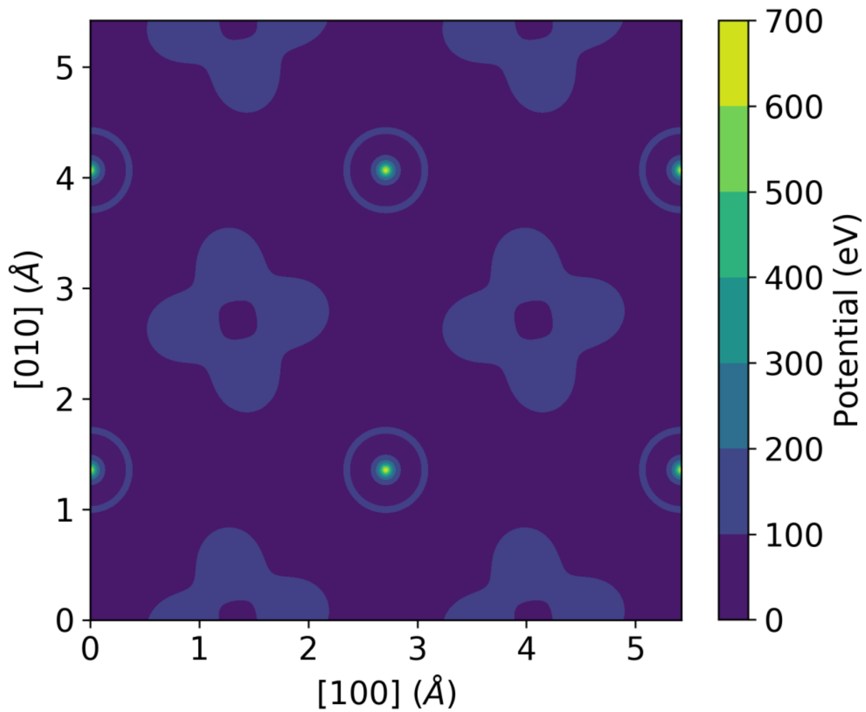
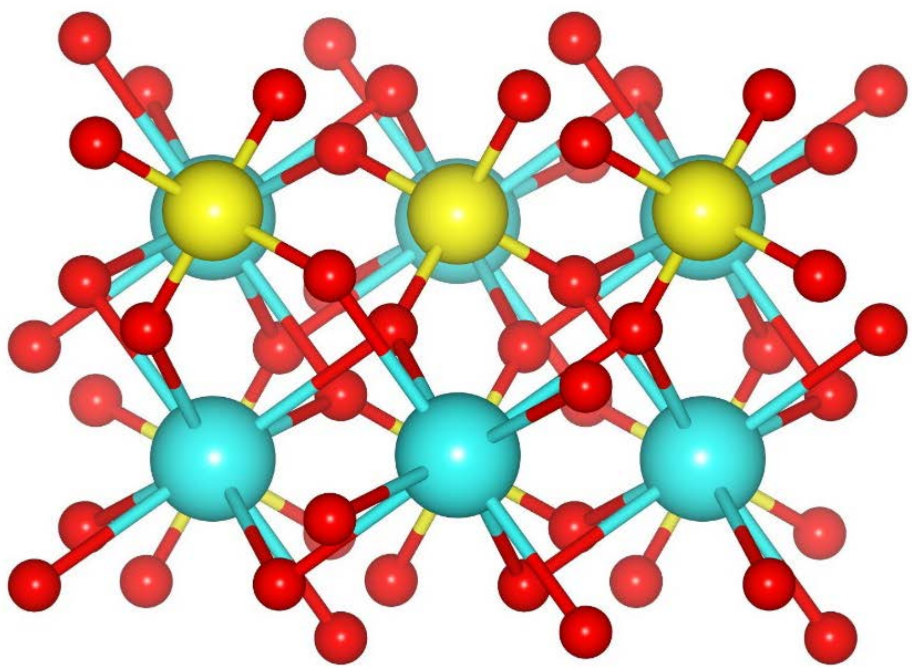




Experimental test at CERN SPS

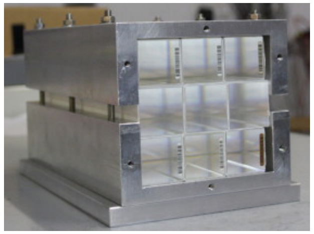
On the extracted beamline H4 from the Super Proton Synchrotron, tertiary “clean” beams of electrons and positrons are available up to 200 GeV/c.

Setup on H4 @CERN

Setup of MiB&UniInsubria
Prof. M. Prest

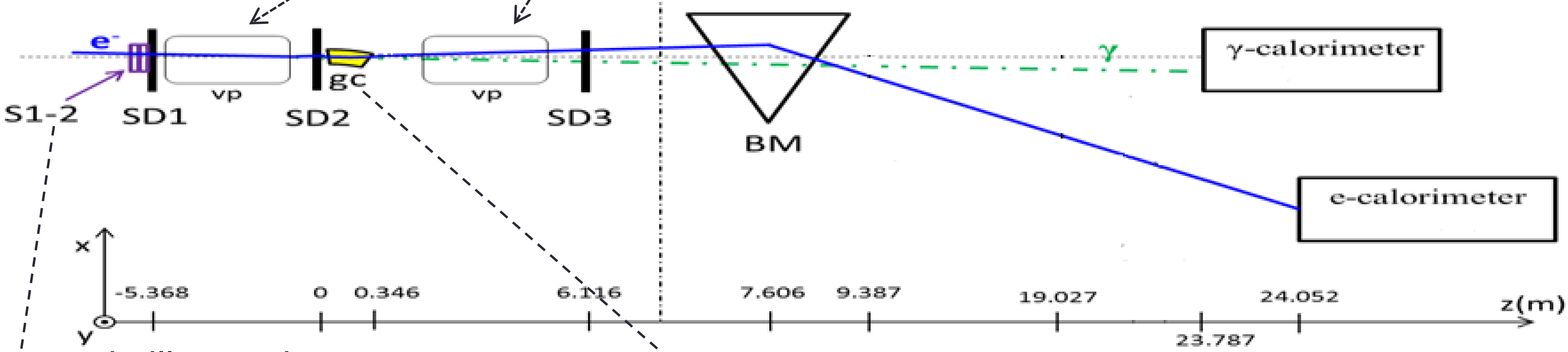
Double sided silicon detectors
1.92x1.92 cm^2 SDi
(300μm thick)
[6-11 μm spatial resolution]

vp = vacuum pipe

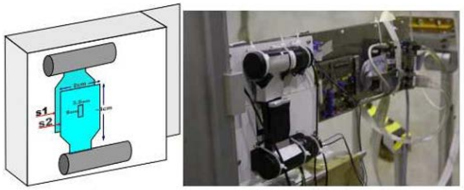


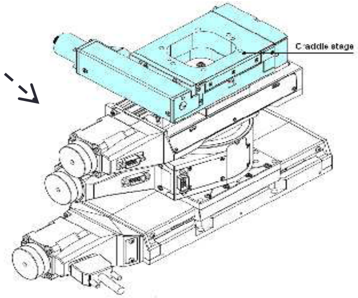
γ-beam (photo) and e-beam calorimeters to measure the emitted photons and to discriminate $e^{\pm}$ from impurities ($\mu^{\pm}$,$\pi^{\pm}$)

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



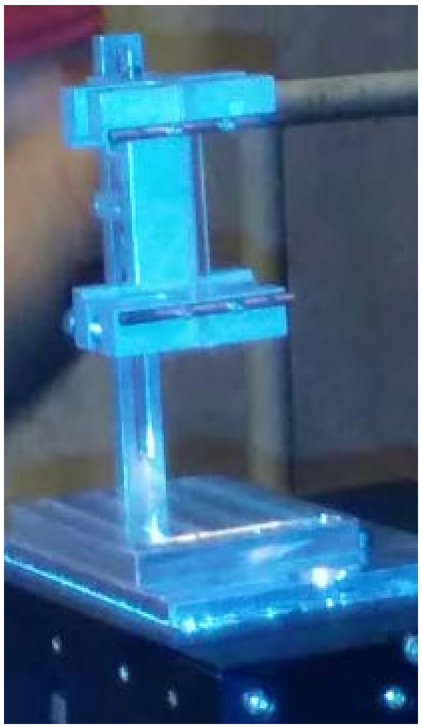
Scintillator Trigger: S2 has an hole (3x9mm^2)
Ainticoincidence

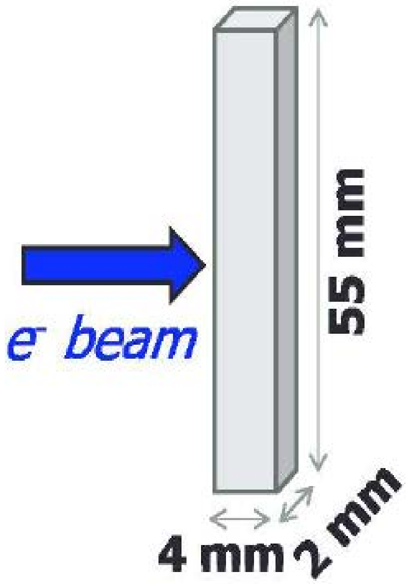


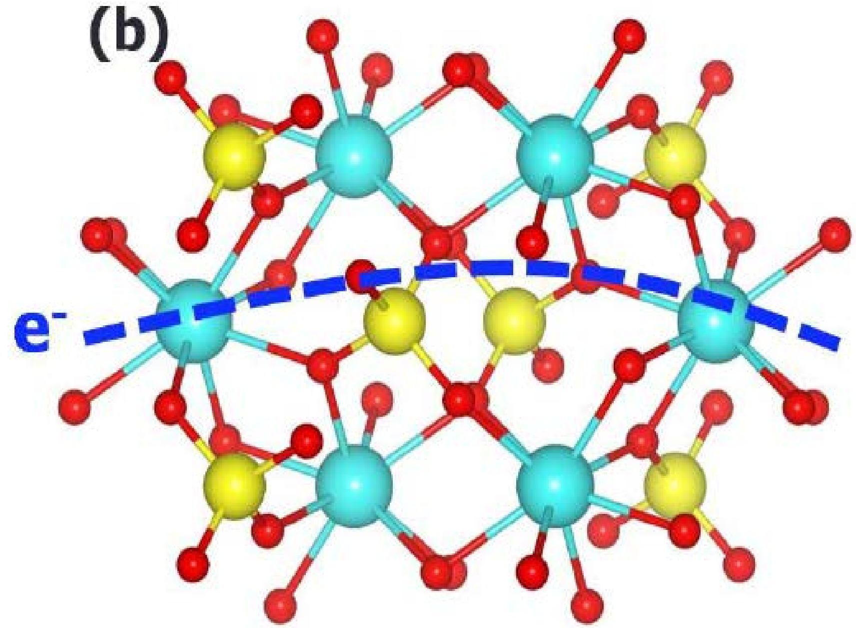


High precision goniometer to align the crystals on the beam.
[Few μrad of resolution]

Experiment @120 GeV electrons

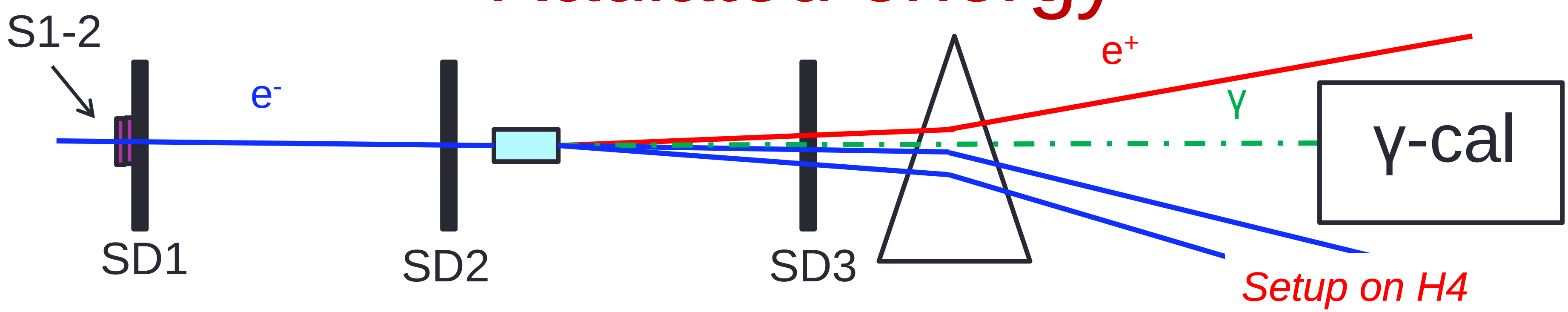




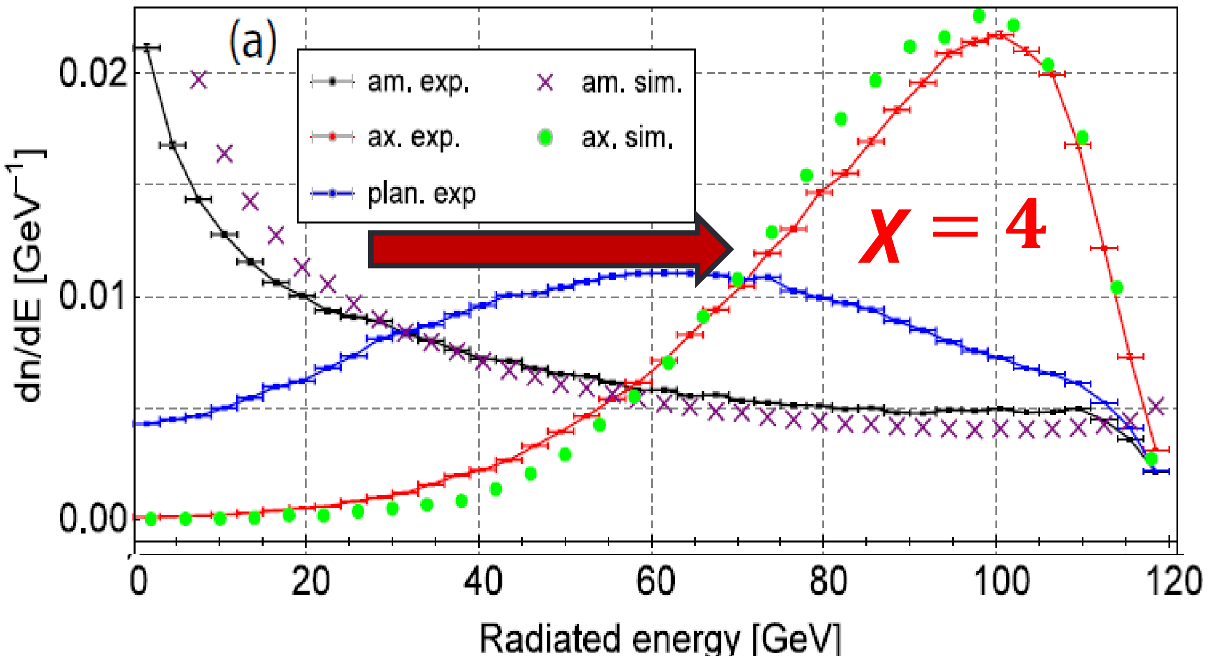


A 2x55x4 mm^3 strip-like PWO crystal with the largest faces oriented parallel to the (100) planes was selected for the experiment. **4 mm length** along the beam direction corresponds to about **0.45 X_0**.

Radiated energy



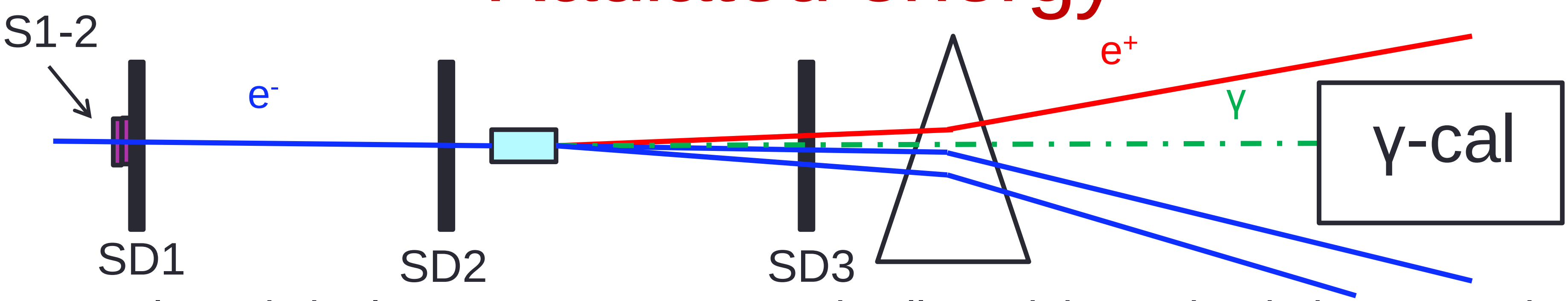
We selected single events on SD1-2 and collected the emitted photons at the gamma-calorimeter.



Peak at 100 GeV!

Strong reduction of X_0 in the oriented cases.

Radiated energy



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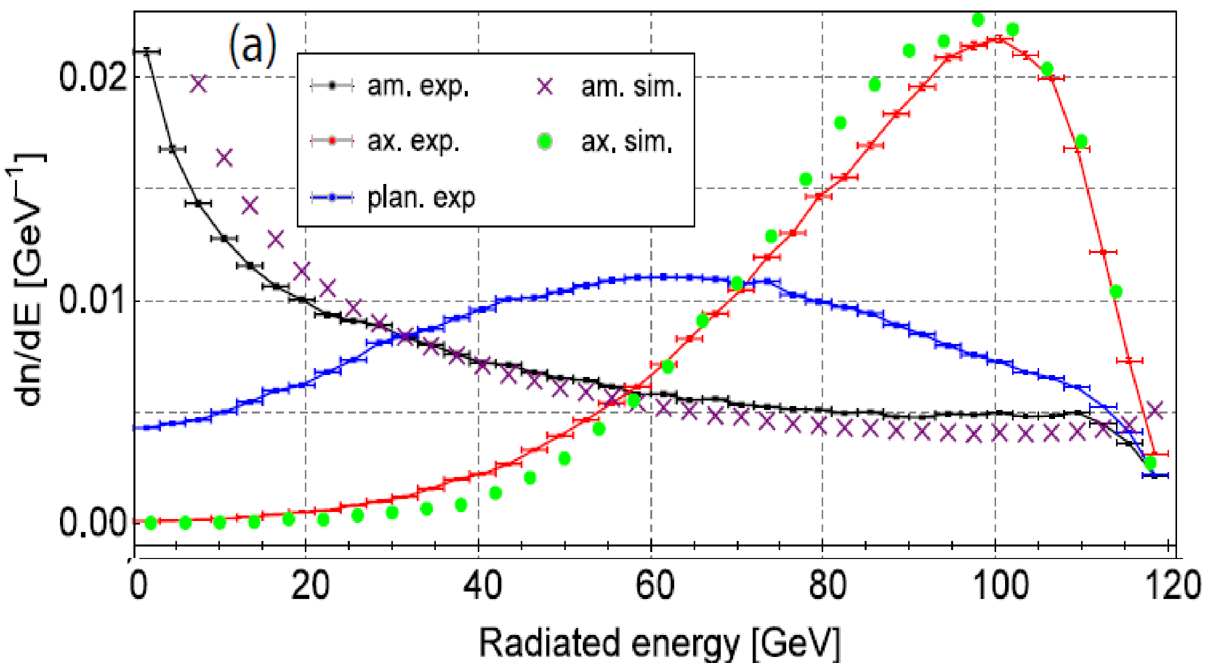
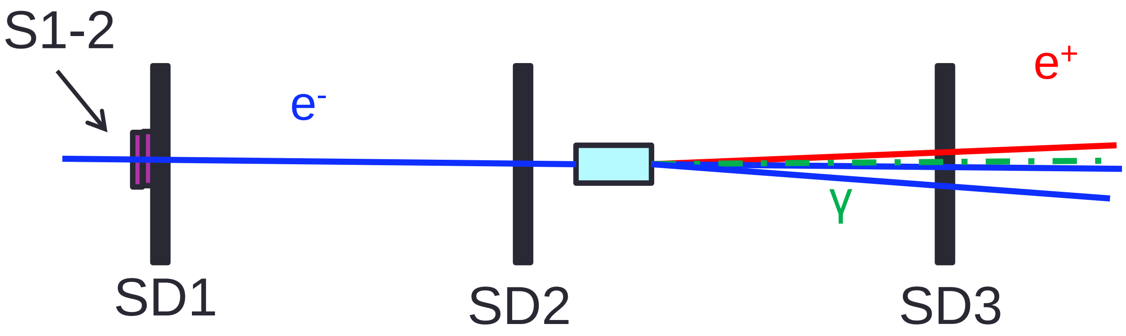
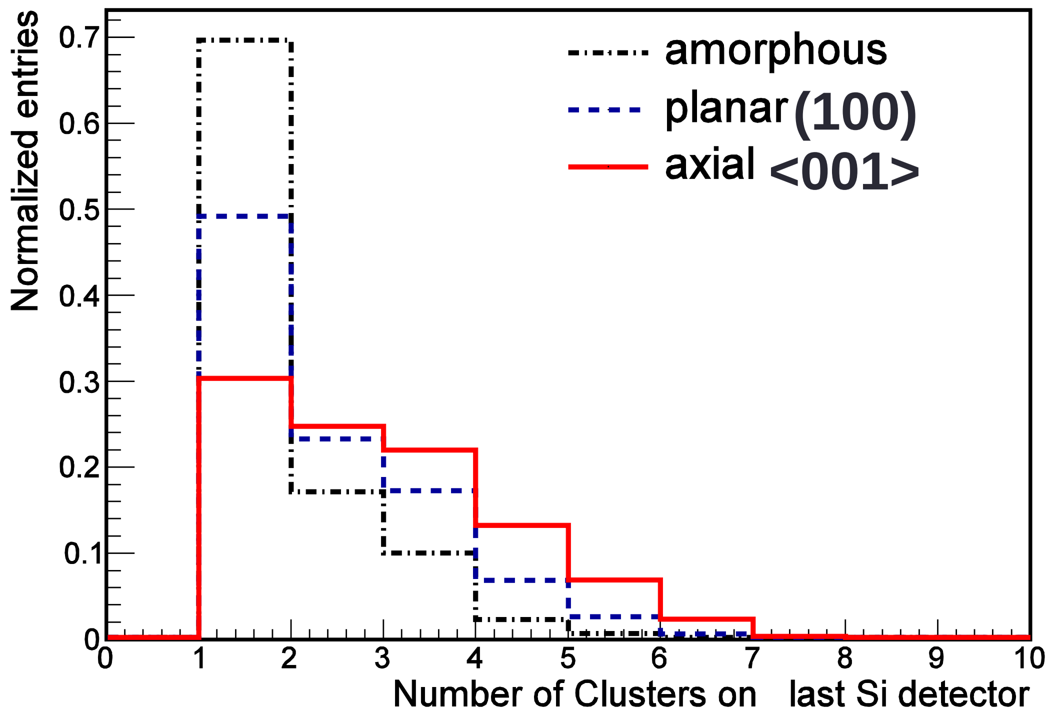


The energy lost into pairs cannot be measured, since the magnet swiped away not only the primary particles but also the secondary electrons and positrons.

Increase of secondaries in oriented crystal



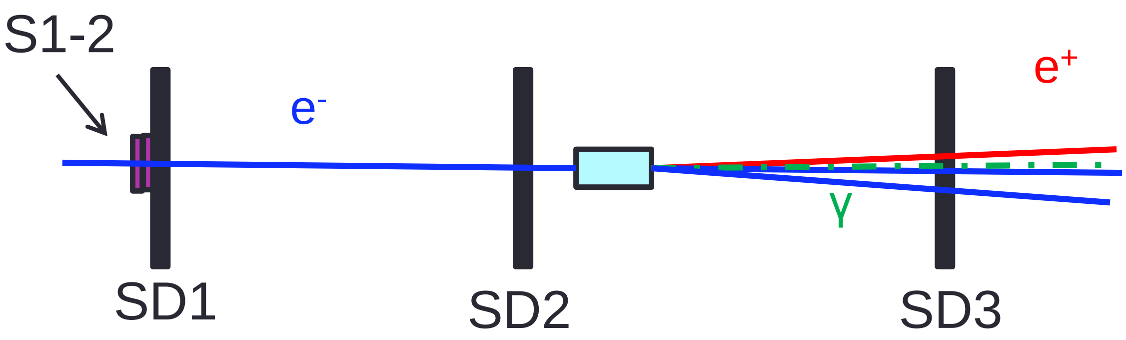


Multiple Tracks

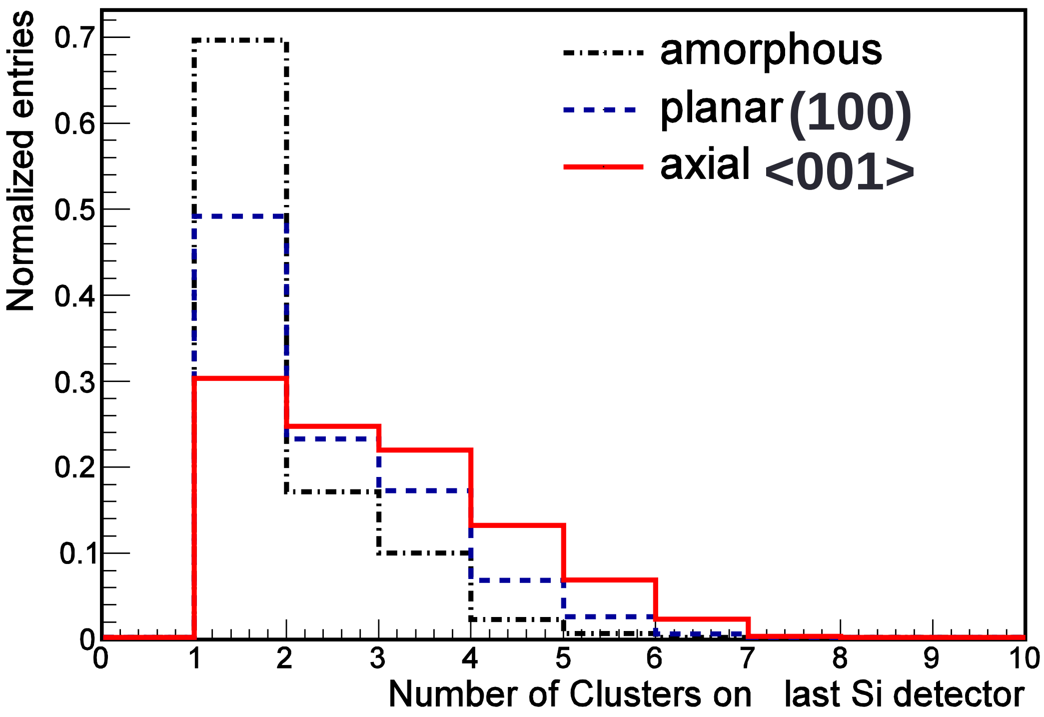
Scintillators S1-S2 are used for the trigger.
We selected single events on SD1-2 and measured the hits at the SD3 detector.

We measured a strong increment of multi-hits at the third detector, depending on crystal-to-beam orientation

Increase of secondaries in oriented crystal



Multiple Tracks



An electromagnetic shower has been initiated

Effective reduction of the radiation length in the oriented cases.

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: 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 quasi-classical Baier-Katkov formula

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

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where the integration is made over the classical trajectory.

SMALL ANGLE APPROXIMATION:

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

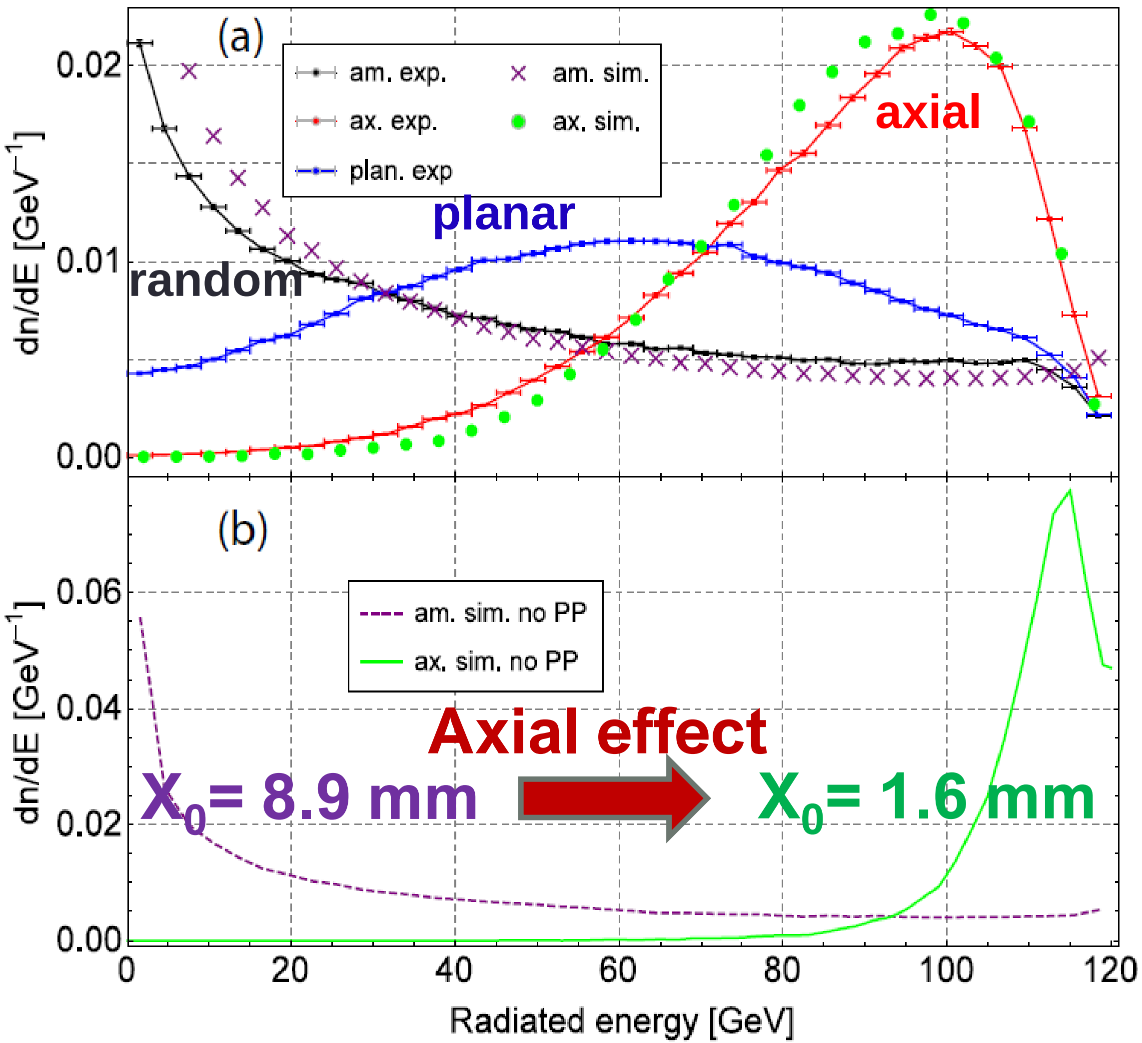
where

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

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

L. Bandiera et al., Phys. Rev. Lett. 111(2013) 255502 – past experiment with Si crystal

Simulation results for PWO

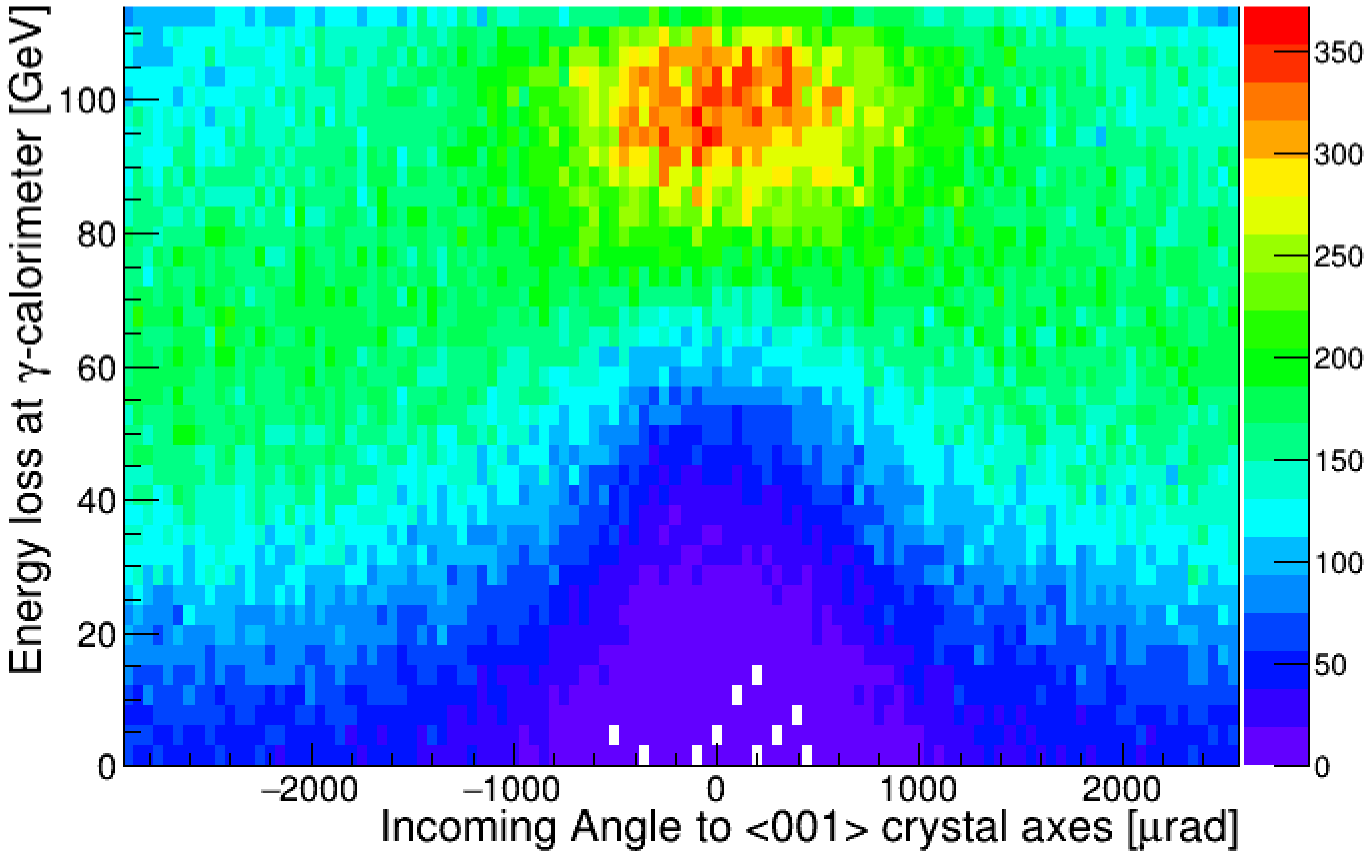


Simulation for **bremsstrahlung + pair production** in agreement with experimental results for:
Random orientation
Axial orientation

Simulation for **pure bremsstrahlung** .
In axial case, X_0 is decreased from 8.9 to 1.6 mm

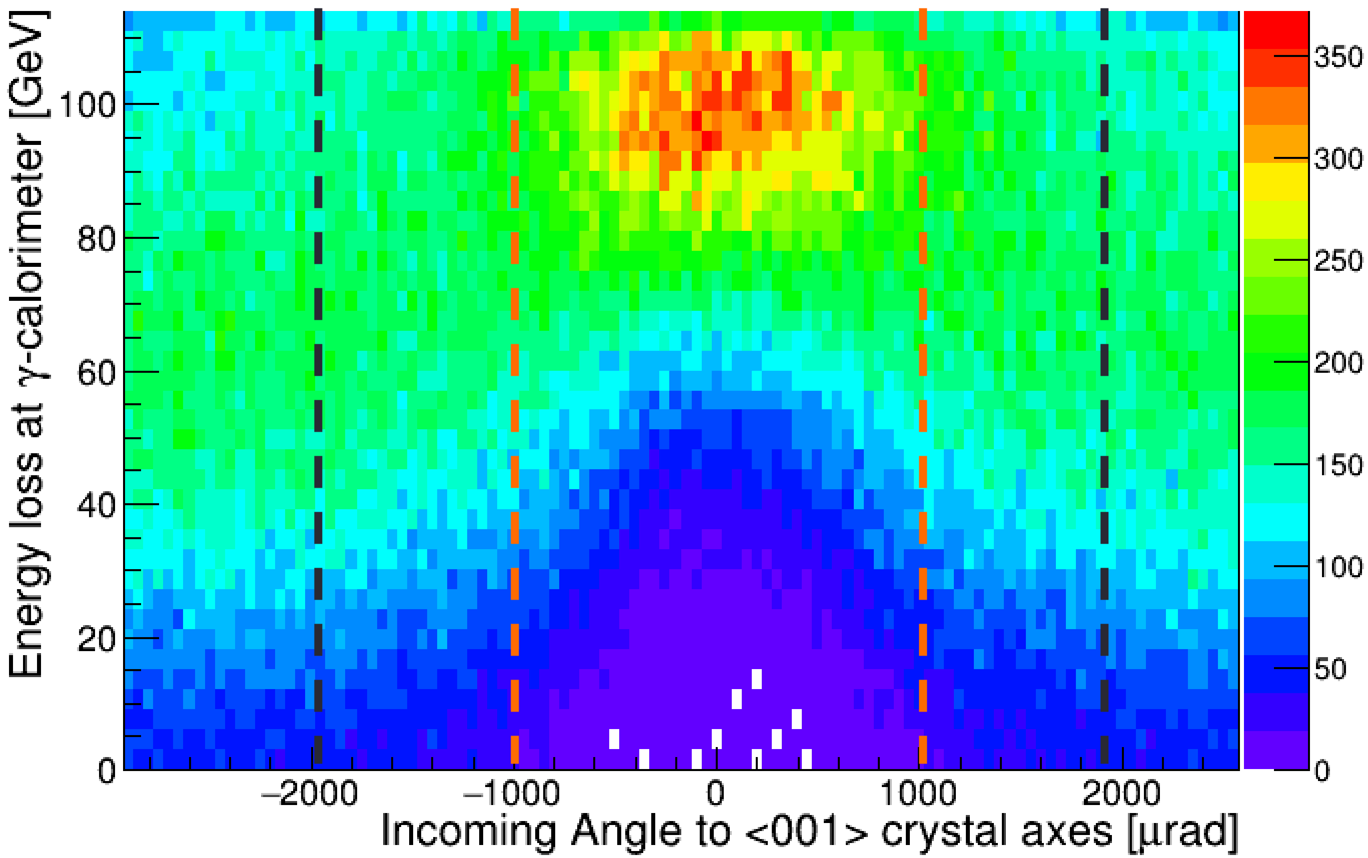
L. Bandiera et al, ArXiv: 1803.10005, under minor revision on Phys. Rev. Lett.

Angular acceptance of radiation enhancement



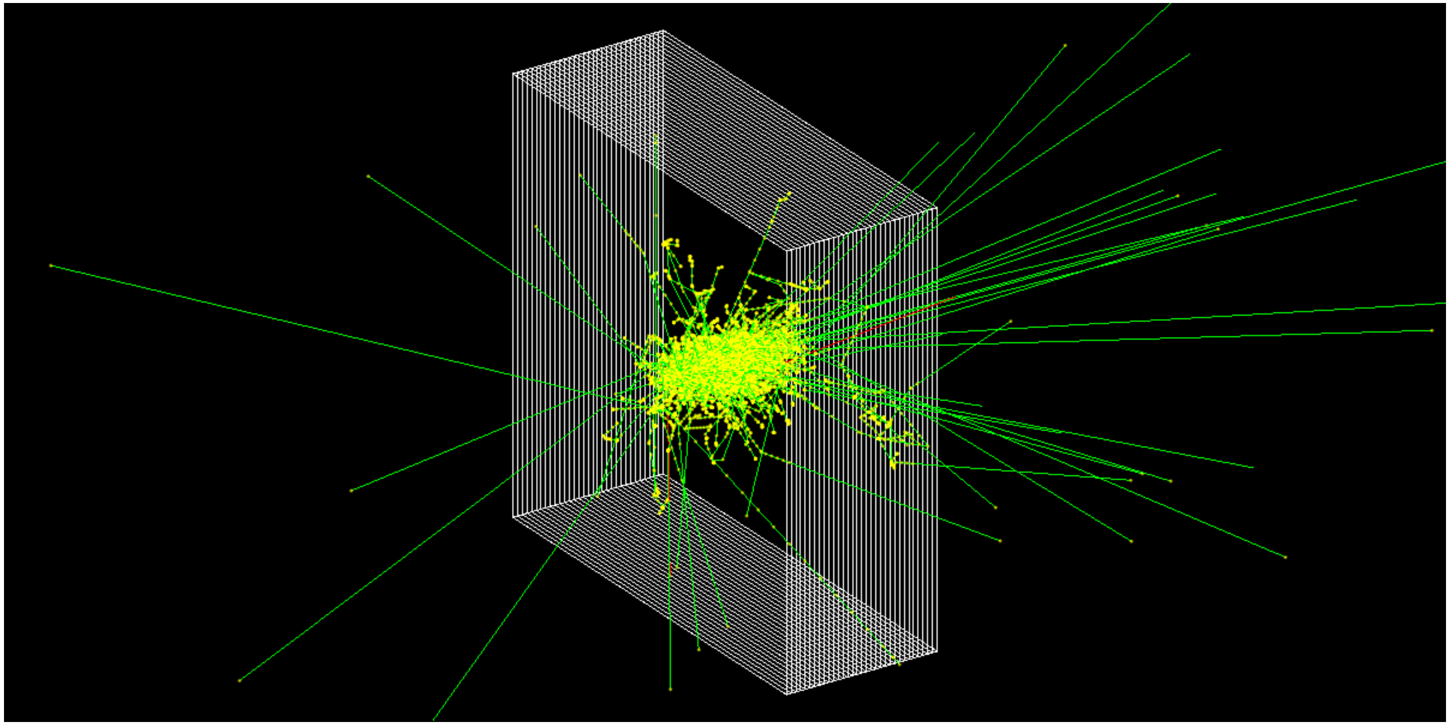
Rotational scan around the <001> axes – along the (100) planes

Angular acceptance of radiation enhancement



The axial influence is strong in **±1 mrad** angular range and it is maintained up to almost **±2 mrad** (±0.1 deg). *Due to Coherent PP, one expects a* ***contribution up to 0.5°-1°.***

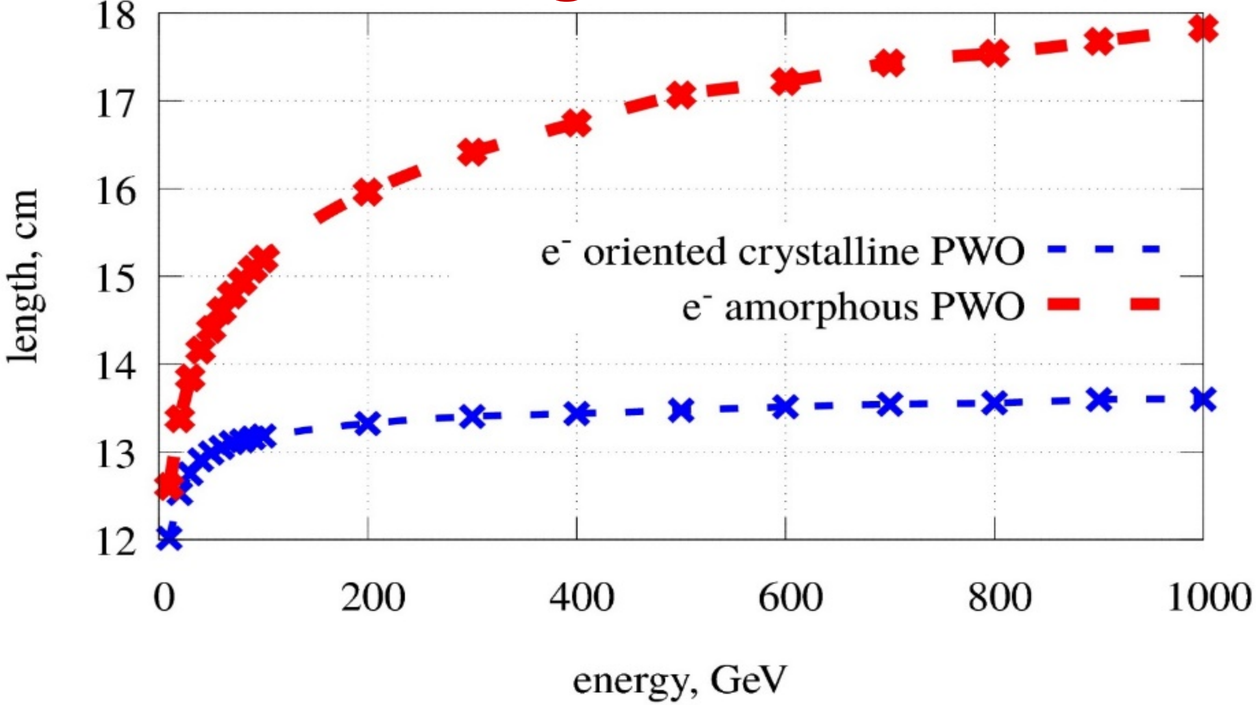
GEANT4 modified simulation for a PWO crystal with X_0 reduced



The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with full BK Monte Carlo.

V.G.Baryshevsky, **V.V.Haurylavets**, et al., Nucl. Instrum. Methods Phys. Res. B, 402 (2017) 35.

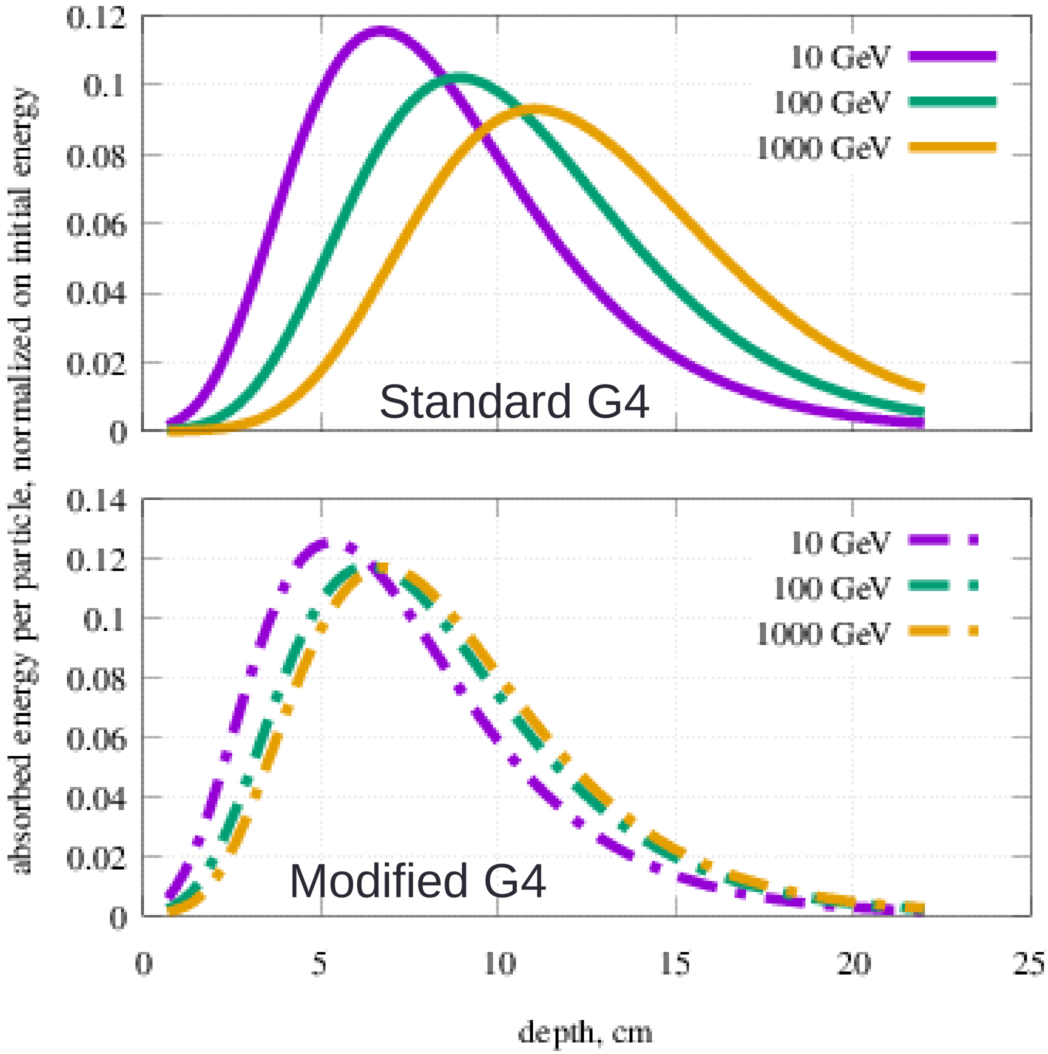
E.m. shower length vs. beam energy



Electromagnetic shower length (defined as 90% of energy deposited inside the crystal) vs. beam energy, for primary electrons. Since the crystalline strong field effect increases with beam energy with a consequent X_0 decreasing, the shower length is almost constant with energy.

L. Bandiera, V.V.Haurylavets, et al. Contribution at the Pisa Meeting for Frontier Detectors '18

Shower longitudinal development



Electromagnetic shower longitudinal development vs. e-beam energy.

In case of oriented PWO, the maximum is shifted to the entry surface of the crystal.

L. Bandiera, V.V.Haurylavets, et al. Contribution at the Pisa Meeting for Fronteer Detectors '18

Possible applications

In HEP:

- Realization of **forward calorimeters and preshowers with a reduced volume;**
- **Smart gamma-converters** for **fixed-target experiments** with reduced ratio X_0/λ_{int} (KLEVER proposal);
- **Light dark matter search** with fixed-target/beam dump experiments (*Idea of M. Raggi, UniSapienza*). If a dark photon is created during the shower generated by a primary electron, it can be detected only if survives after the remaining dump length. Shorter is such length, higher is the sensitivity.

PRIN2017 proposal under evaluation

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Further advantages of scintillators:

- Possibility to measure the cascade characteristics inside the crystal (e.g. NA64 active beam dump);
- Scintillators have better crystallographic quality than metals and the possibility to be produced in virtually any size.

PRIN2017 proposal under evaluation

Possible applications

In Astroparticle Physics: Production of **compact calorimeters** that contain the gamma e.m. showers at energies > 100 GeV **without increasing the weight** (and so the cost). With the birth of multimessenger astrophysics one can think of **pointing a telescope towards the source** (0.5°-1° acceptance) and exploit the X_0 reduction in oriented crystals.

PRIN2017 proposal under evaluation

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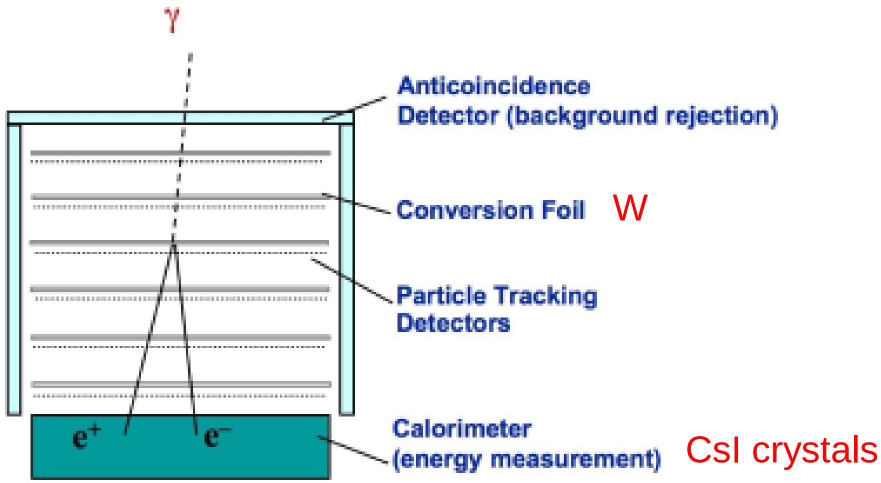
FERMI LAT-like telescope:

- reduce the thickness of the calorimeter (and so the weigth)
- **reduce the thickness of the photon converters in the tracker**, thus increasing the resolution.



Proposal under evaluation at PRIN2017-type B call – COLORS PROJECT

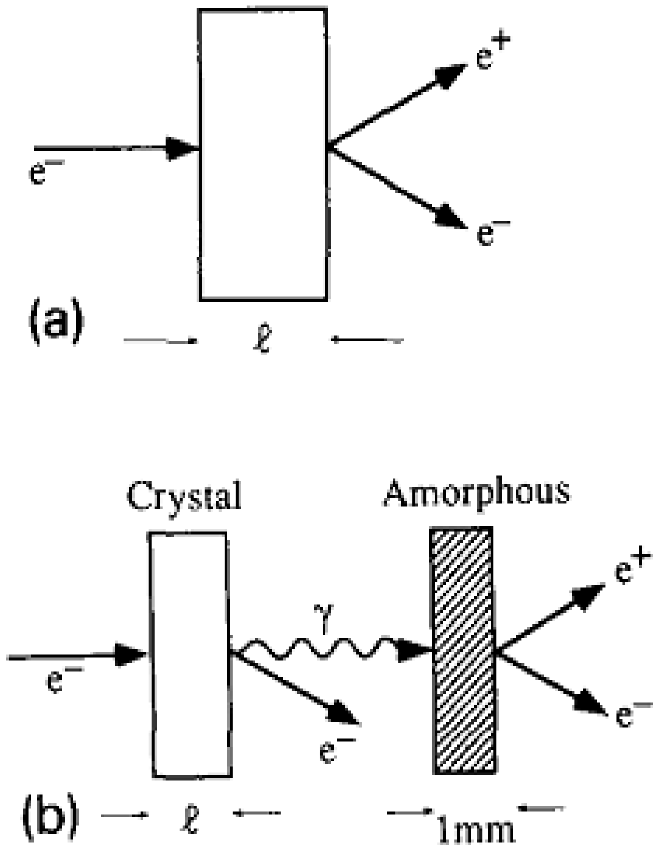
OTHER APPLICATION: INNOVATIVE POSITRON SOURCE

CLIC, ILC, Muon Collider

Innovative positron source

Positron source using channeling in a tungsten crystal

X. Artru [a], V.N. Baier [b], R. Chehab [c,*], A. Jejcic [d]



(a) Solution attractive because both processes, **intense channeling photon production** and pair creation, occur in the same medium.

(b) Hybrid source may be of interest since the amorphous target in which pairs are produced can be heated more.

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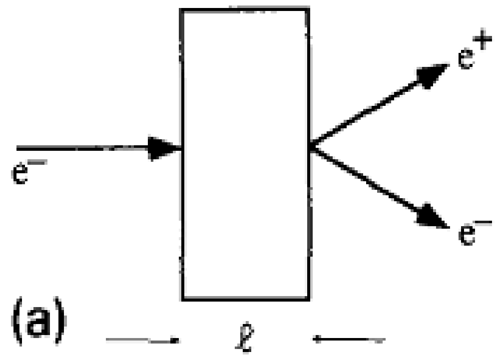

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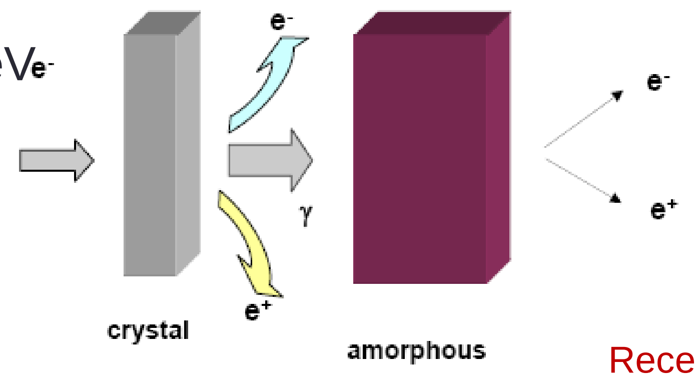
KEK 7 GeV e-



(b) Hybrid source may be of interest since the amorphous target in which pairs are produced can be heated more.

Recent test at KEK NIMB 402 (2017) 58 with a <111> W crystal

LAL people involved: I.Chaikovska and R.Chehab

Summary

- The modification of electromagnetic processes in oriented crystals is currently exploited in a medium energy range as a source of linearly polarized gamma beams;
- At higher energies, the strong crystalline e.m. field leads to a huge reduction of X_0 (exploited in the past by NA48 experiment for gamma conversion);
- Intense synchrotron-like radiation in an aligned W crystal can be used to increase the yield for a positron source for future colliders;
- **The recent results with a PWO scintillator crystal open the way to an investigation of compact calorimeters/preshowers for HEP and gamma-satellites**;

THANK YOU FOR THE ATTENTION!