Crystalline Undulators: A Gamma-Ray Source at the FCC-ee Linac e+ Beam

Other Science opportunities at the FCC-ee

CERN, 28 November 2024

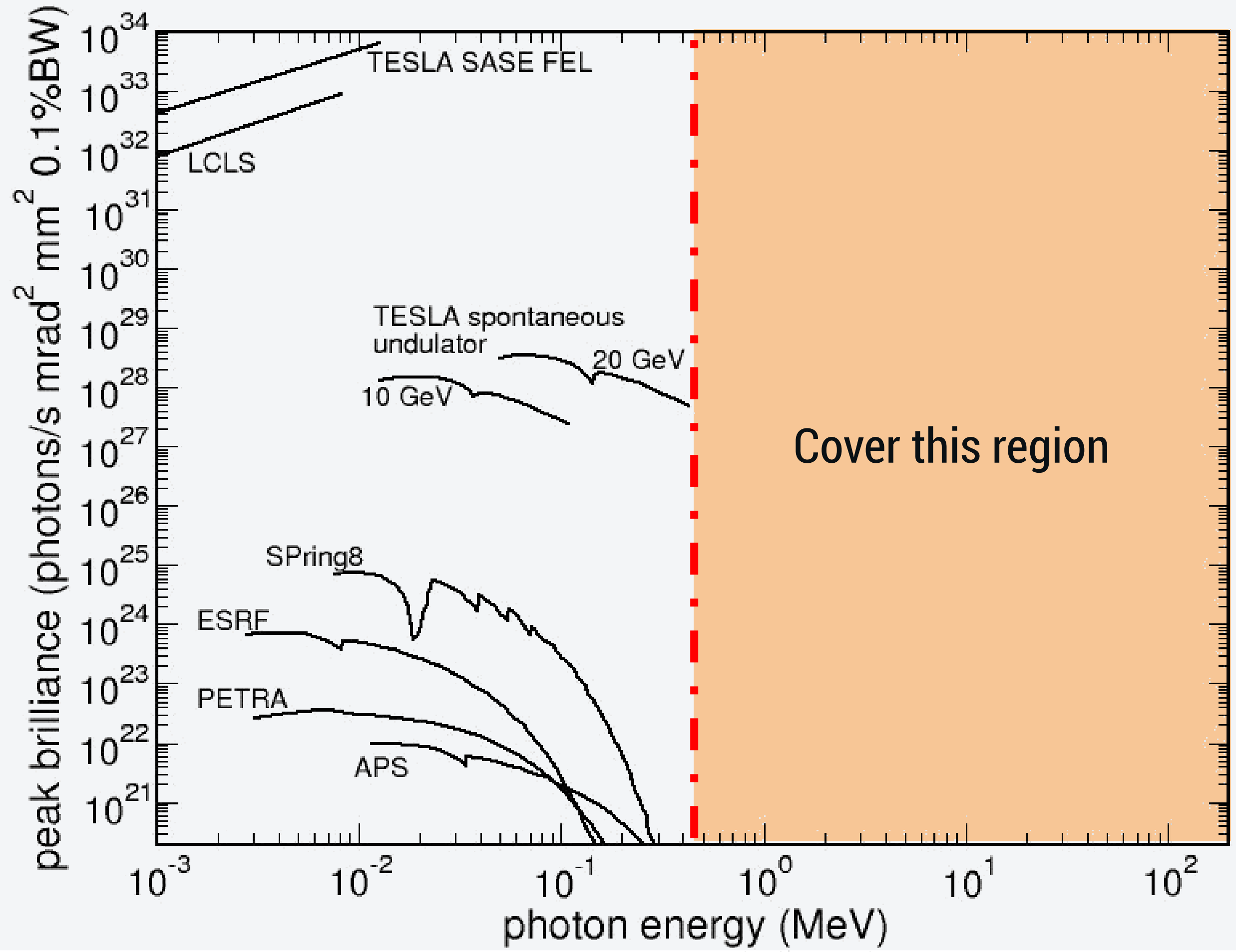
Riccardo Negrello, PhD student

Ferrara University
INFN Ferrara

riccardo.negrello@unife.it

G.A. 101046458

Radiation Sources: State of the Art



Which are the alternatives?

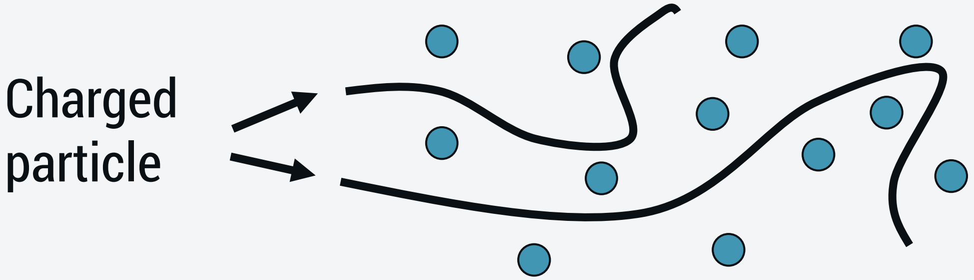
- **Inverse Compton Scattering & Gamma factory**
  Requires an high intensity laser

- **Crystalline Undulator**:
  - Crystals are **passive elements**
  - Better results with **positrons**

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

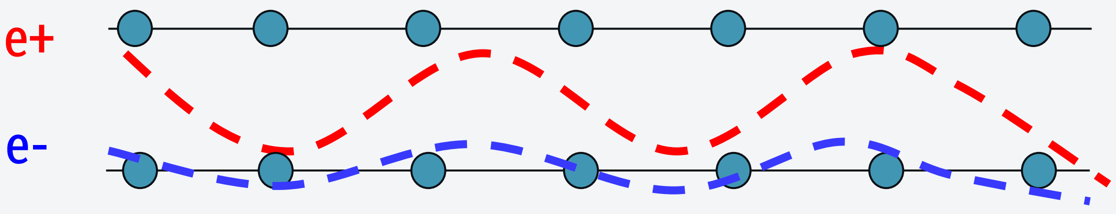
Channeling

Amorphous material



Incoherent scattering

Oriented material



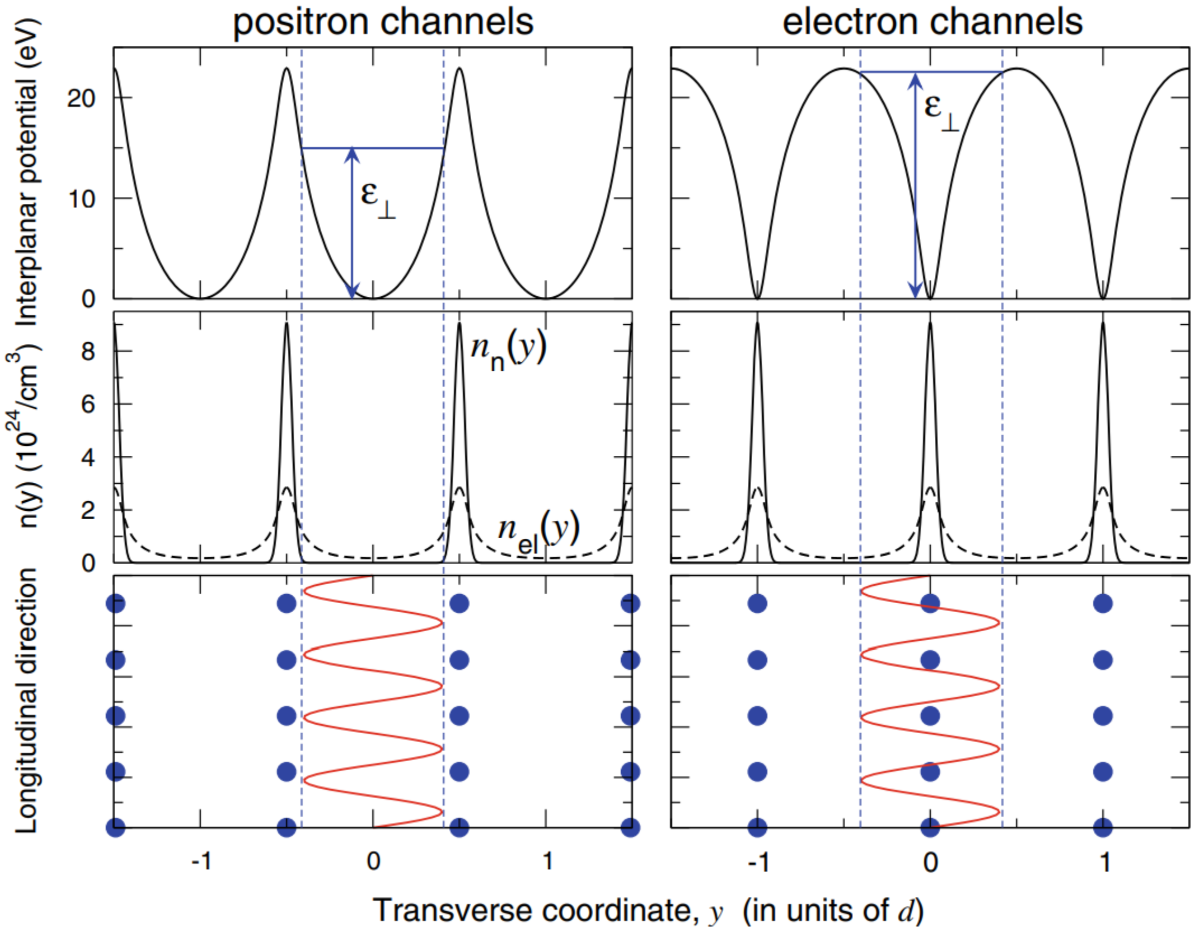
If the incidence angle < **critical angle** $\theta_c = \sqrt{\frac{2U_0}{pv}}$

$$U_0 \approx 20 \text{ eV}, \text{E} \approx 20 \text{ GeV} \rightarrow \theta_c \approx 50\ \mu rad$$

Particles feels the interaction with the atoms of the plane as a whole and start to oscillate in channeling.

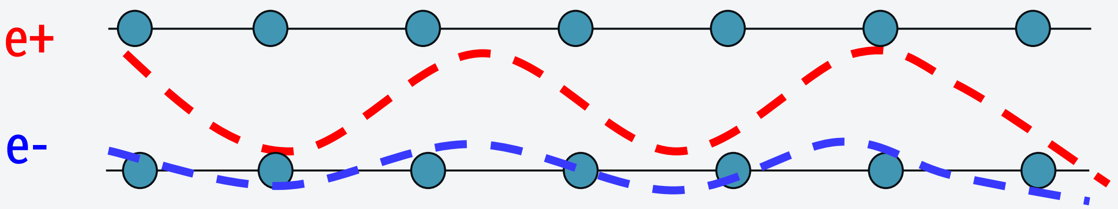
Dechannelig affects electrons more than positrons.

Comparison between e+ and e-



A. V. Korol & A. V. Solov'yov, Novel Lights Sources Beyond Free Electron Lasers,Springer, 2022

Oriented material



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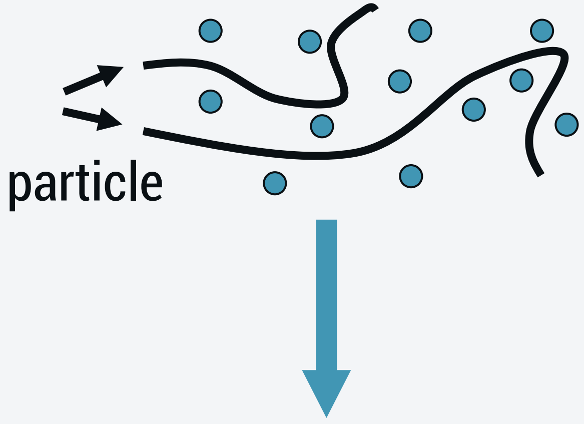
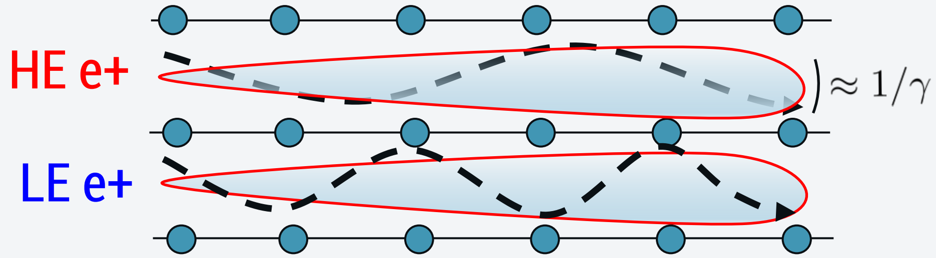
Radiation effects in crystals

Amorphous medium



Crystalline plane/axis



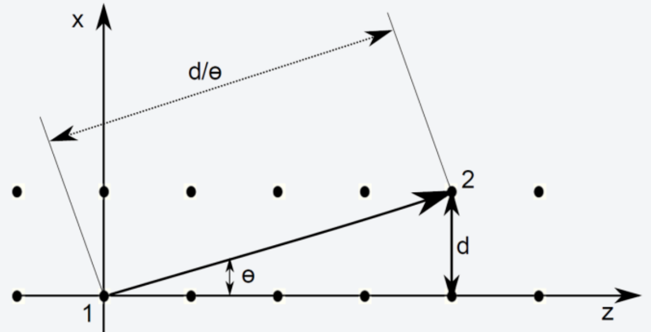
$$\theta_c = \sqrt{\frac{2U_0}{pv}}$$

Channeling Radiation

Low Energy (<GeV) → **dipole radiation** (undulator)

High Energy (≫GeV) → **synchrotron radiation** (wiggler)

Coherent Bremmstrahlung



Constructive interference condition:

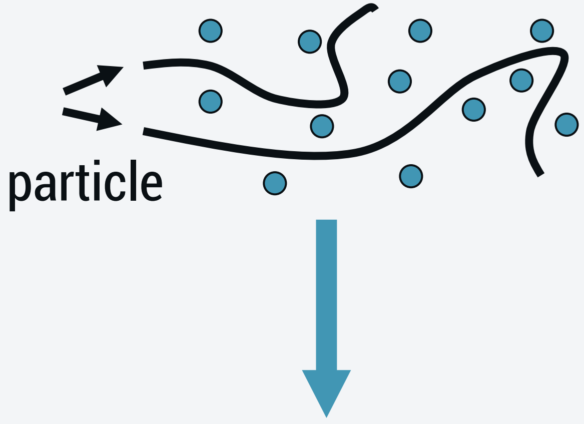
$$\frac{\delta}{\theta} = n\frac{2\pi}{d}$$

→ Dimension of reciprocal lattice vector

δ: parallel momentum transferred from particle to atom

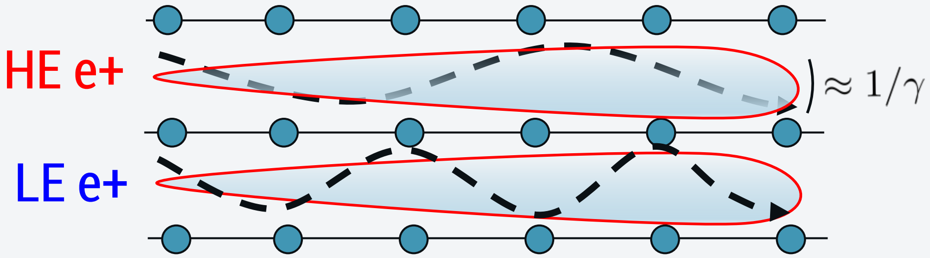
Radiation phenomena in crystals

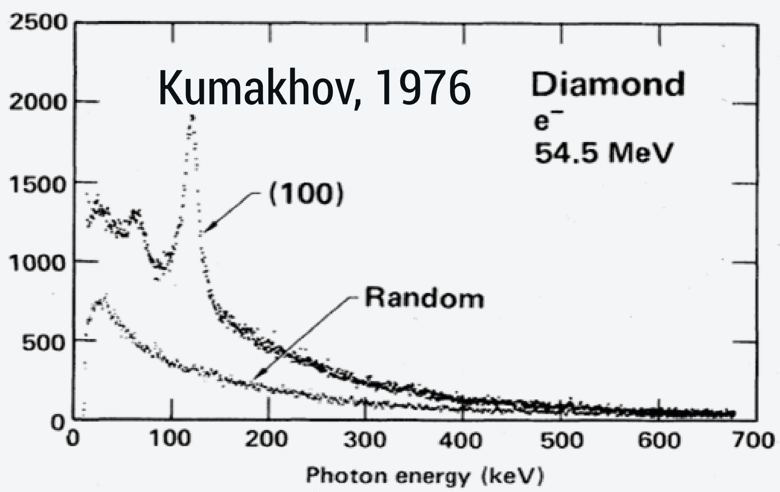
Amorphous medium



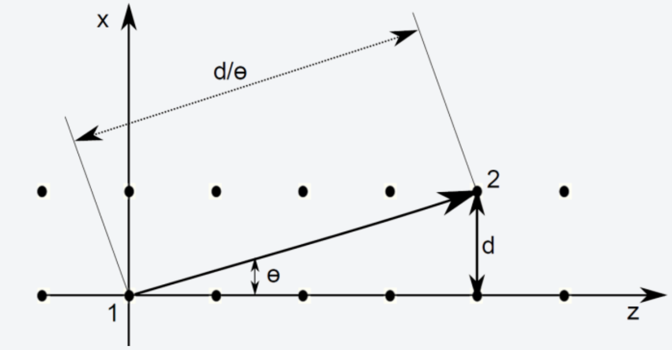
Bremsstrahlung

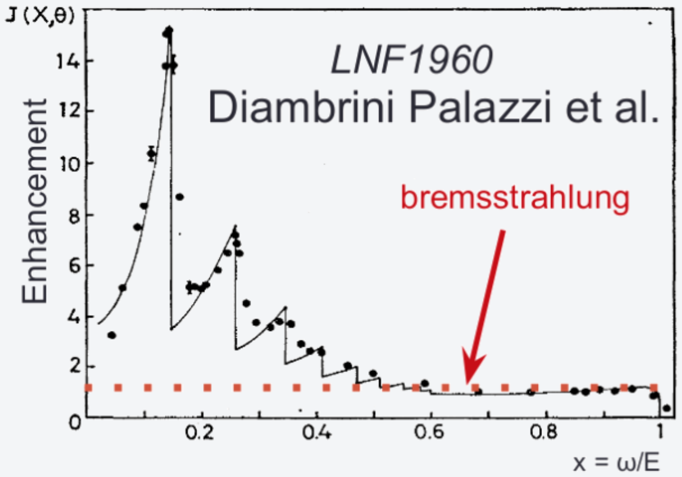
Crystalline plane/axis





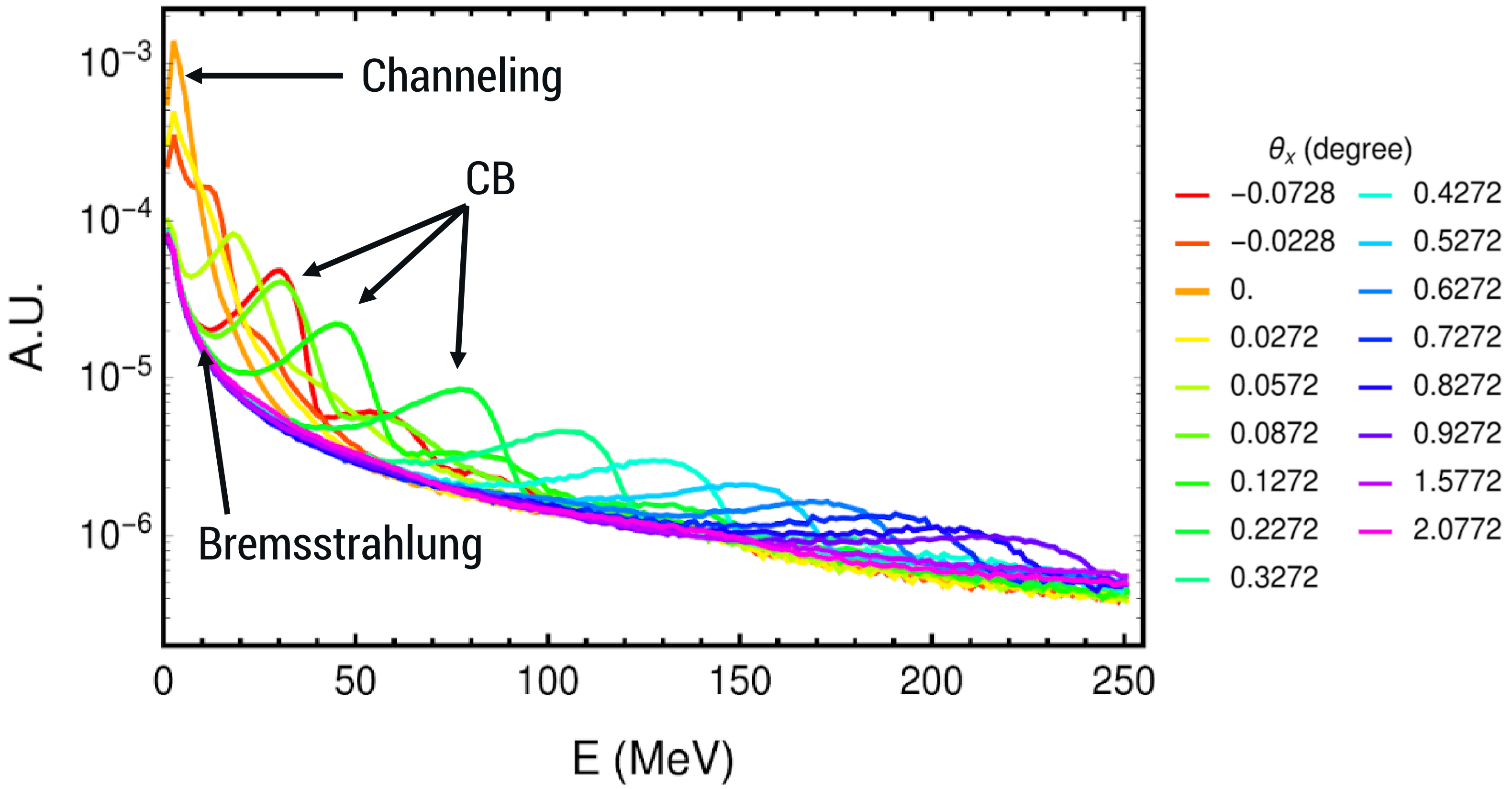
Coherent Bremmstrahlung





Radiation emission comparison

600 MeV e- interacting with a diamond crystal of 0.31 mm thickess along (110) planes



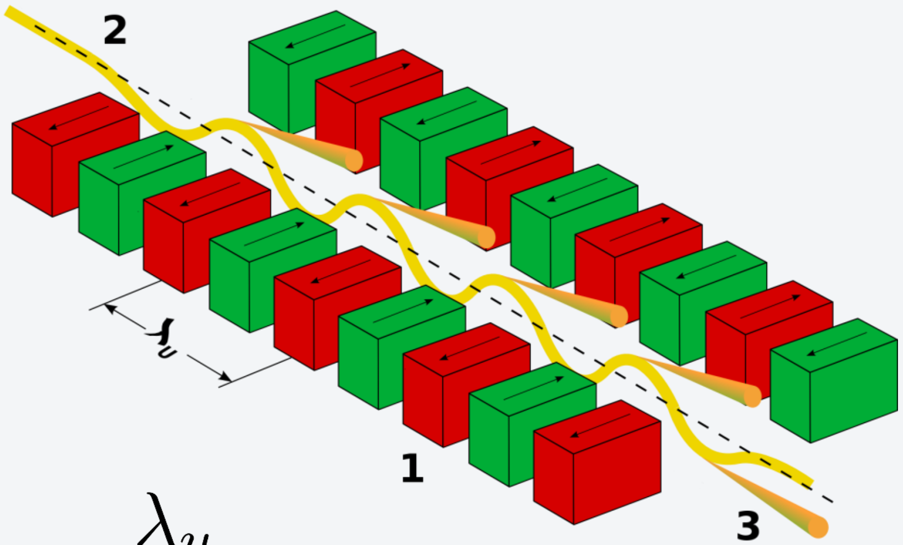
Intensities even higher than **Channeling Radiation** can be achieved with **Crystalline Undulators** if some conditions are matched

R. Negrello et al, *NOVEL HIGH-INTENSITY AND GAMMA-RAYS SOURCES USING CRYSTALS,* JACoW (2024)

Crystalline Undulator

Magnetic undulator

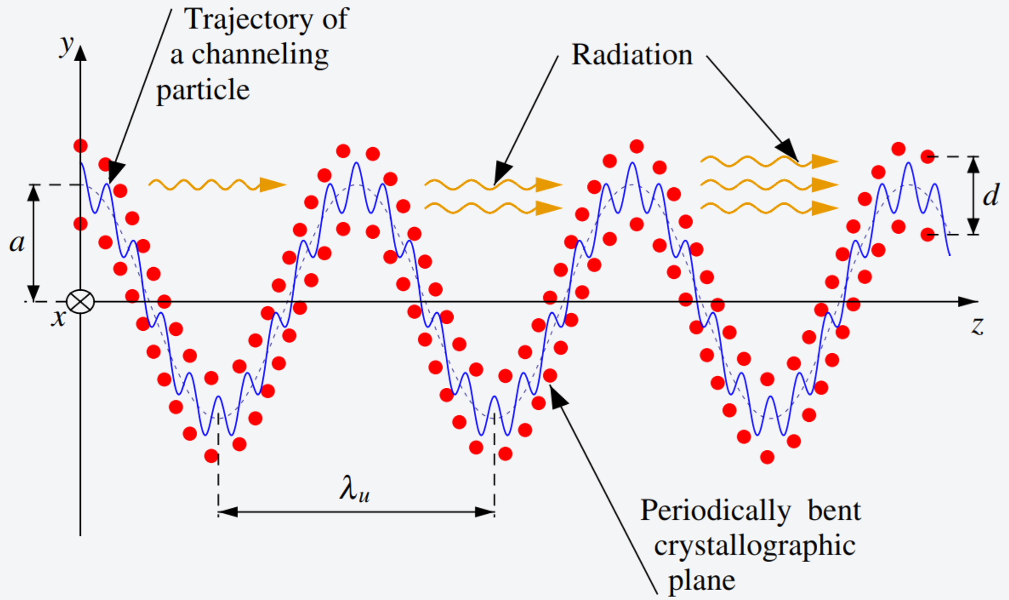
period ~ cm
X-ray production of ~10 keV



$$\lambda \approx \frac{\lambda_u}{2\gamma^2}$$

Crystalline undulator

period < mm
Production of γ-rays of ~ MeV



A. V. Korol & A. V. Solov'yov, Novel Lights Sources Beyond Free Electron Lasers,Springer, 2022

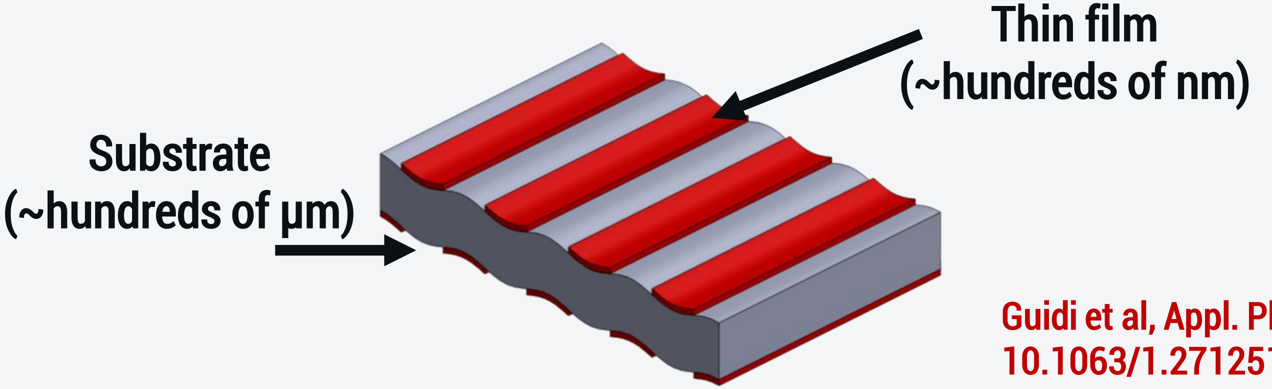
Manifacturing techniques

Principle:
Inducing a **periodic deformation** field in the surfaces that **transfers to the bulk** of the crystal

- **Grooving method**
  Camattari et al, PRAB (2019)
  10.1103/PhysRevAccelBeams.22.044701
- **Pulsed laser melting** (PLM)
  Di Russo et al, App. Surf. Sci.(2023)
  10.1016/j.apsusc.2022.155817
- **Ion Implantation**
  Bellucci et al, Appl. Phys. Lett (2015)
  10.1063/1.4928553
- **Si-Ge alternate concentration**
  Avakian et al, NIM A, (2002) /10.1016/S0168-9002(02)01316-5
- **Acoustically driven**
  Kaleris et al, ArXiv (2024)
  10.48550/arXiv.2410.11621

Bagli et al, EPJC (2014) 10.1140/epjc/s10052-014-3114-x

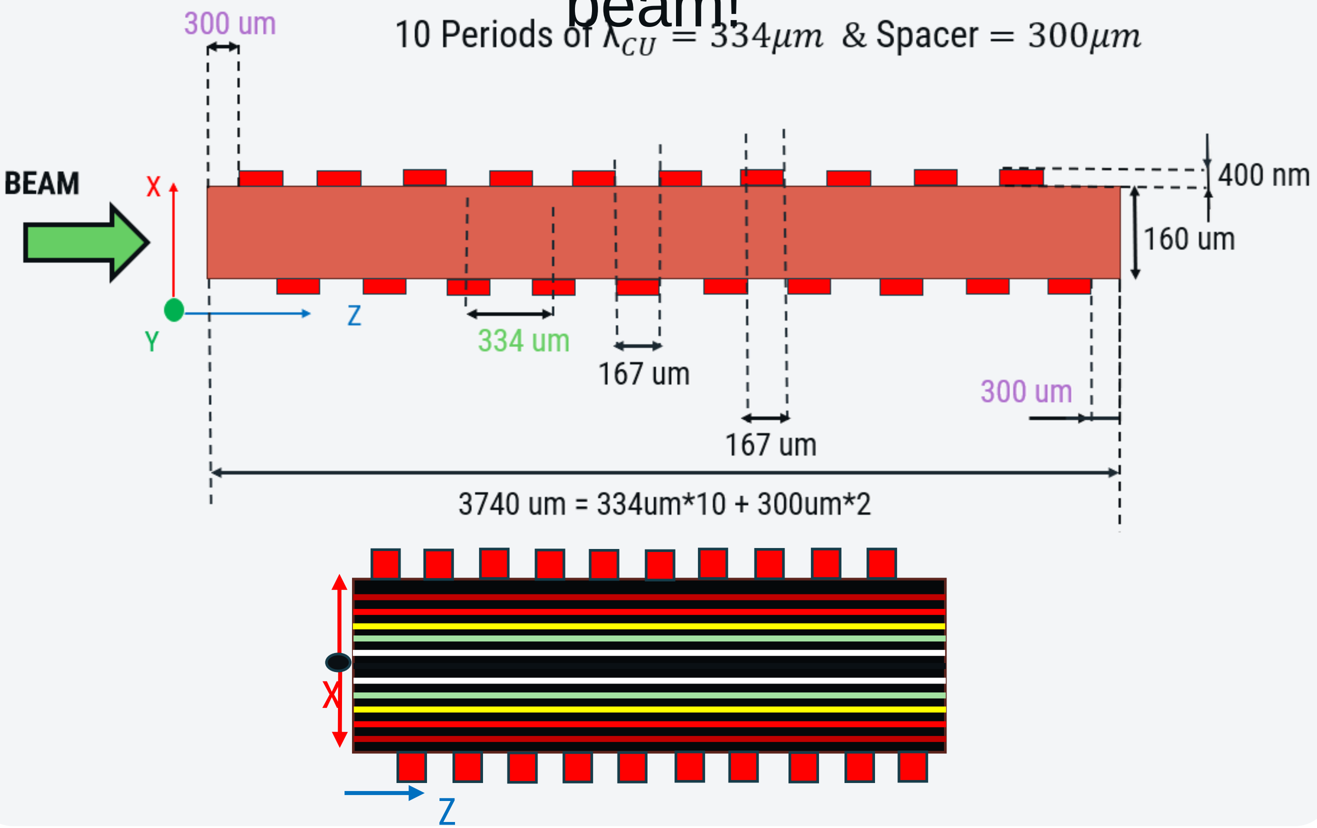
Low-pressure chemical vapour deposition (LPCVD):
Alternate pattern of silicon nitride on a **Si** wafer at high temperature (800°).
Thermal stress arises when the wafer is being cooled, due to the **difference in thermal expansion** coefficients between film and substrate



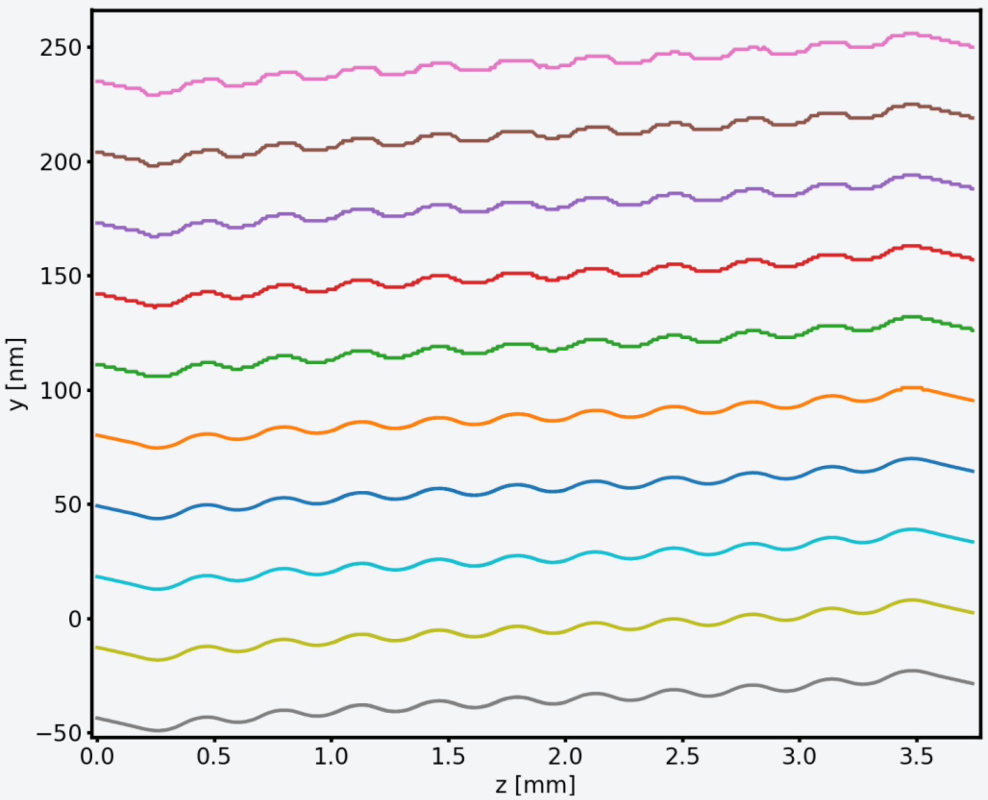
Guidi et al, Appl. Phys. Lett. (2007)
10.1063/1.2712510

CU Modelling

CU specifically developed for 10-20GeV e+ beam!



Deformation profiles (FEM) Ansys



Our sample will be studied at Diamond/ESRF

Crystalline Undulator Spectrum

A. V. Korol and A. V. Solov'yov, Novel Lights Sources Beyond Free Electron Lasers, Springer Cham, 2022

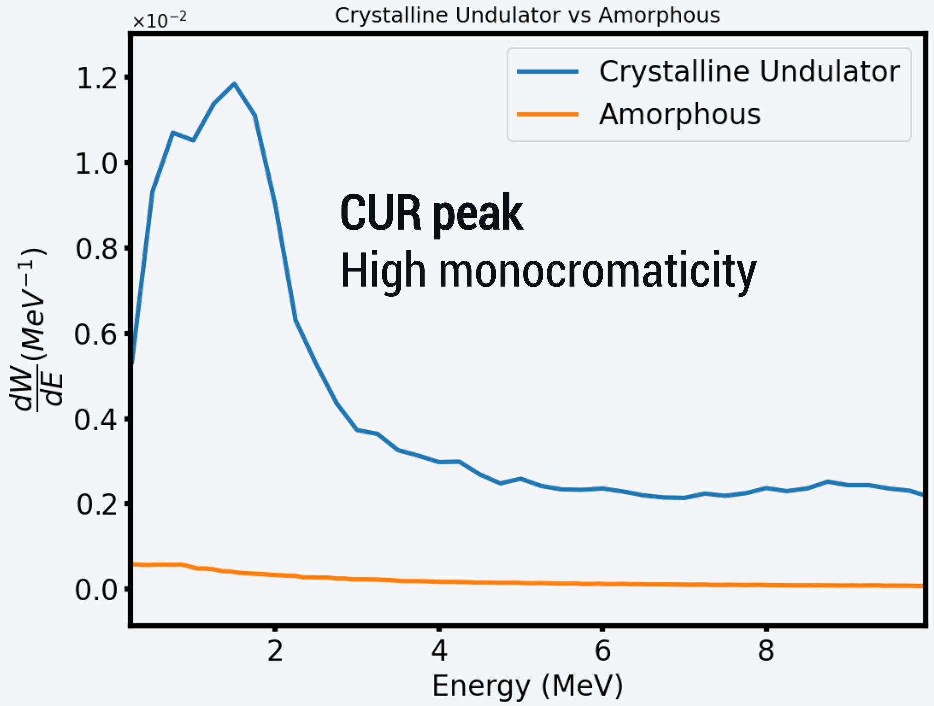
Channeling and Undulator oscillations Ω_{ch}, Ω_u
To separate the peaks and suppress Ω_{ch}

Large Amplitude Long Period (LALP) $\Omega_{ch} \gg \Omega_u \rightarrow a_u \gg d$

Beam	**10 GeV e^+**
Beam divergence	30μrad
Material	Silicon
Channeling plane	(111)
CU width—x [mm]	2
CU length—y [mm]	3.34
CU thickness—z [mm]	0.2
Number of periods	10
Periods (λ_u) (μm)	334
Amplitude (a_u) [nm]	1.28
Collimator angle (μm)	$1/2\gamma$

Camattari et al, PRAB (2019) 10.1103/PhysRevAccelBeams.22.044701

Full Montecarlo simulation using Baier-Katkhov formula



Photon energy for 20 GeV e^+

Crystalline Undulators also offers:

- Possibility to **optimize amplitude** and **period** for specific applications
- **Control** over the harmonic oscillations
- More **monocromatic** spectrum compared to channeling radiation

$$E_\gamma = \frac{4\gamma^2\pi\hbar c}{1+\gamma^2\vartheta^2+\frac{K^2}{2}} \cdot \frac{1}{\lambda_u}, \quad (1)$$

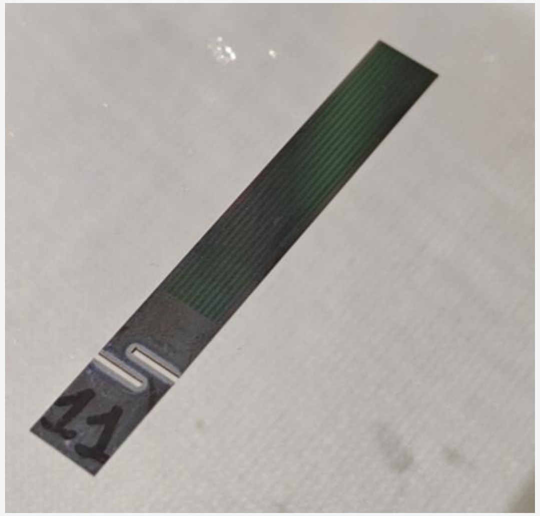
$$K = 2\pi \frac{A_u}{\lambda_u}. \quad (2)$$

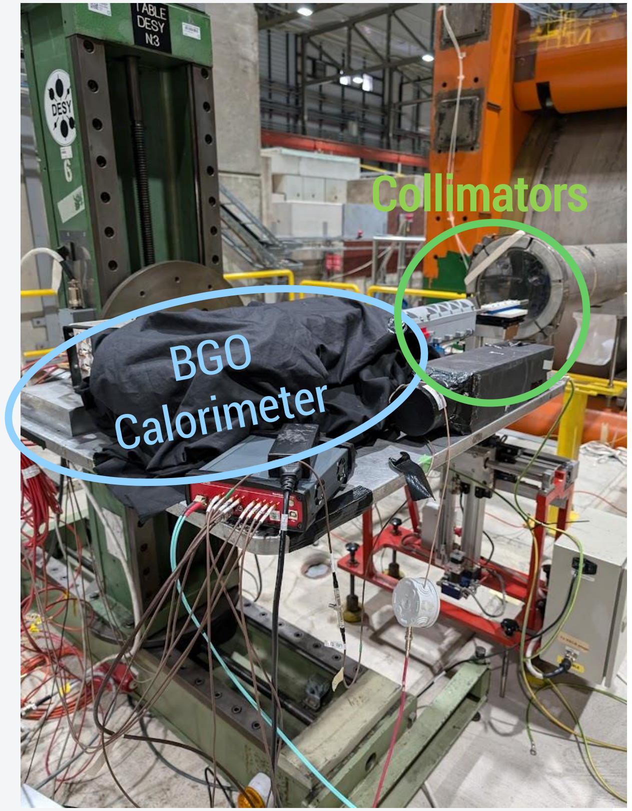
$$\lambda_u \approx 100 - 700\ \mu\text{m}$$
$$A_\text{u} \approx 1\text{-}2\ \text{nm}$$
$$E_\gamma \approx 5 - 50\ MeV$$

Undulator Test Beam @CERN

CERN SPS H2 Beamline,13-27 August

35 GeV e+ beam





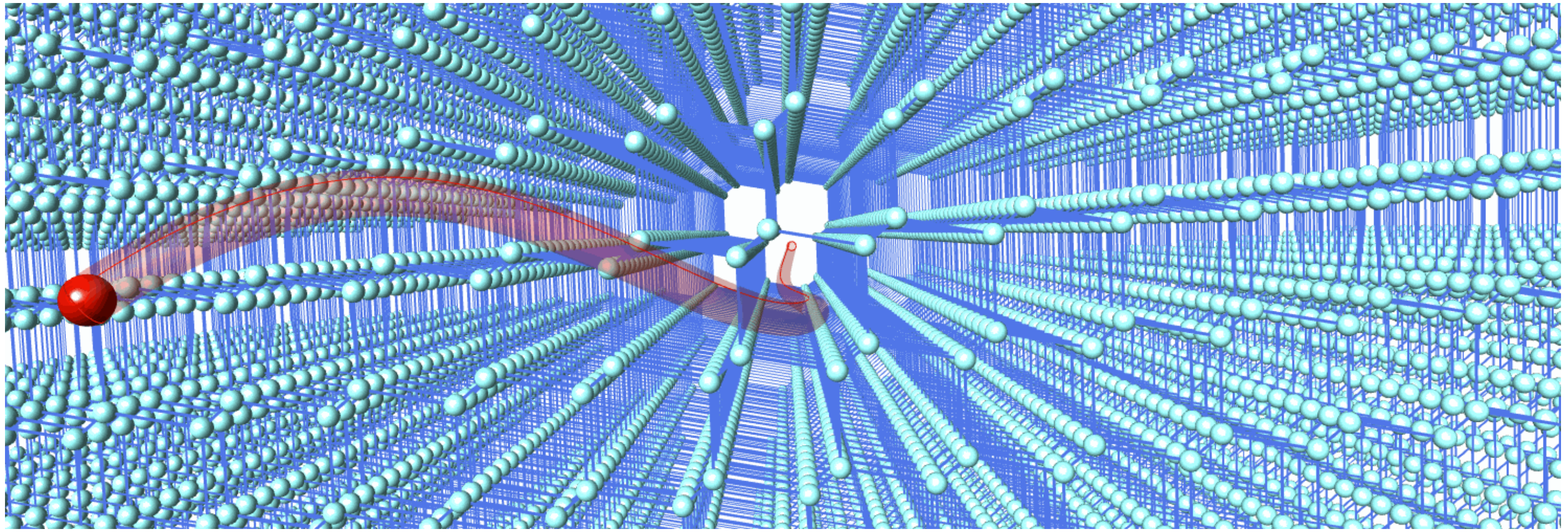
We are now analyzing the data, the results are preliminary but promising.
Non optimal condidtion, tertiary beam, purity, divergence and high radiation background

Applications

- Medical physics
- Nuclear interactions
- Industry and technology

Conclusions

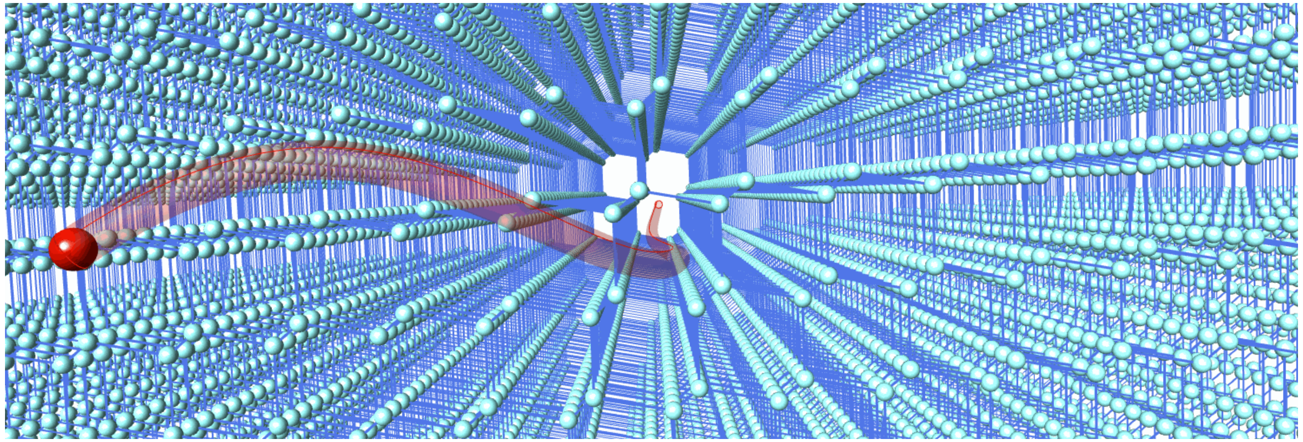
- CU are tunable for specific applications.
- Crystals function as passive elements.
- Some prototypes have been produced and under test.
- Perfectly applicable as a gamma-ray source at the FCC-ee injector LINAC



Thank you!

riccardo.negrello@unife.it
lbandiera@fe.infn.it

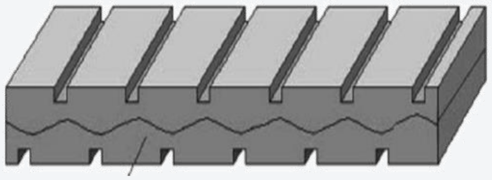
Backup slides



Manifacturing techniques

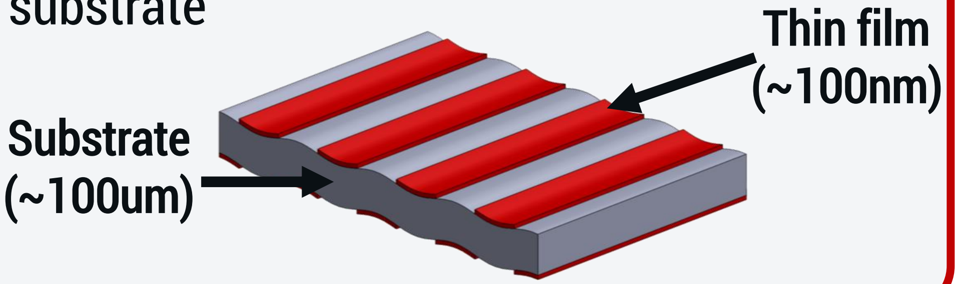
Principle:
Inducing a **periodic deformation** field in the surfaces that **transfers to the bulk** of the crystal

Grooving method:
The deformation is obtained by a series of **alternated parallel grooves** on the major surfaces of the crystal.
Cons: damages in the crystal

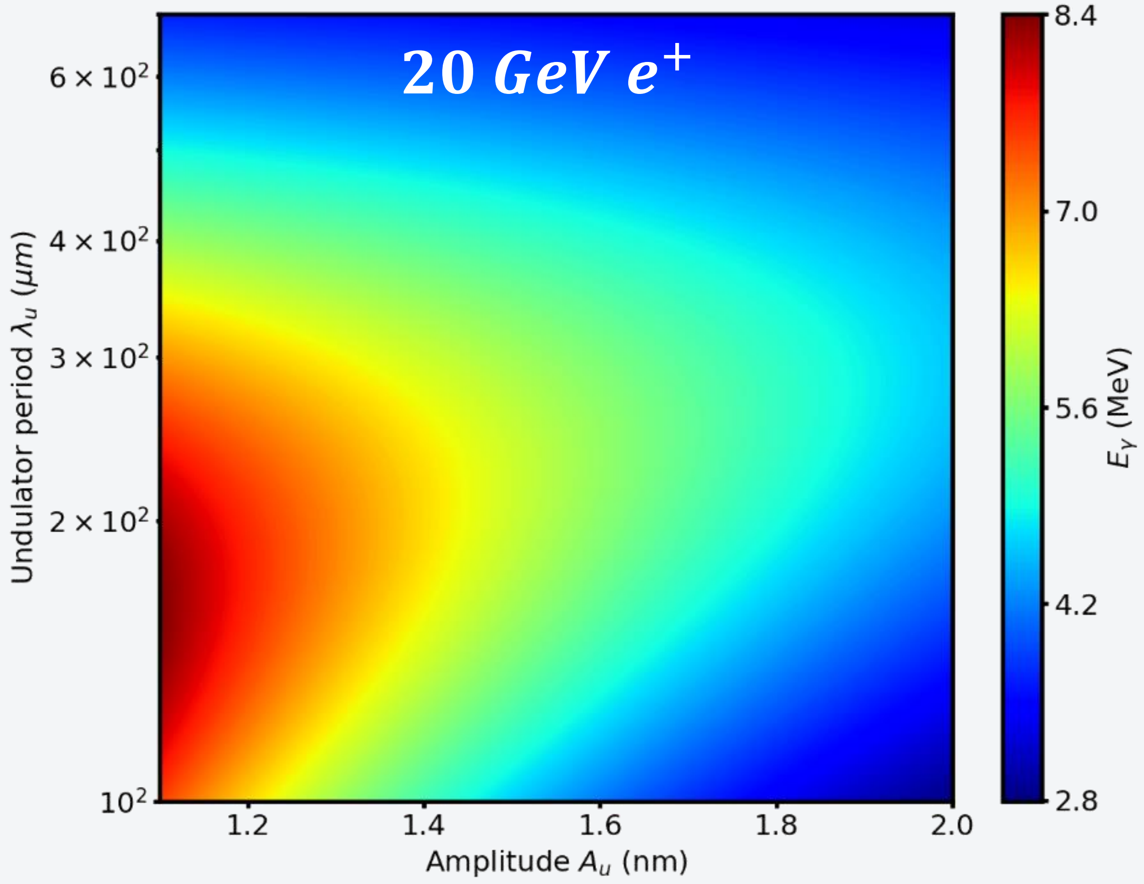


Pulsed laser melting:
Alternate deposition of Sb on the surface of **Ge** though spattering technique.
A **pulsed laser** as a heat source, allowing to **melt the substrate** with spatial and temporal control.
PLM allows to produce a strained layer of Sb-Ge alloy on Ge (111).
Cell parameter variation induces the bending of the planes

Low-pressure chemical vapour deposition:
Deposition of an **alternate pattern of silicon nitride** thin layer on both sides of the **Si** wafer at high temperature (800°). **Thermal stress** arises when the wafer is being cooled, due to the **difference in thermal expansion** coefficients of the film and the substrate



Photon energy for 20 GeV e^+



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$$E_\gamma = \frac{4\gamma^2 \pi \hbar c}{1 + \gamma^2 \vartheta^2 + (K^2/2 + K_{ch}^2/2)} \cdot \frac{1}{\lambda_u}$$

$$K = 2\pi \frac{A}{\lambda_u}; K_{ch} = 2\pi \frac{\langle a_{ch} \rangle}{\lambda_{ch}}, \langle a_{ch} \rangle \sim \frac{d_{ch}}{2}$$

$20\ GeV\ e^+$, $\lambda_u \approx 334$ μm, A ≈1.2nm, ϑ=0

$E_\gamma \approx 6\ MeV$

Study on the brilliance

Sushko et al, Eur. Phys. J. D (2022) 76:166
https://doi.org/10.1140/epjd/s10053-022-00502-7

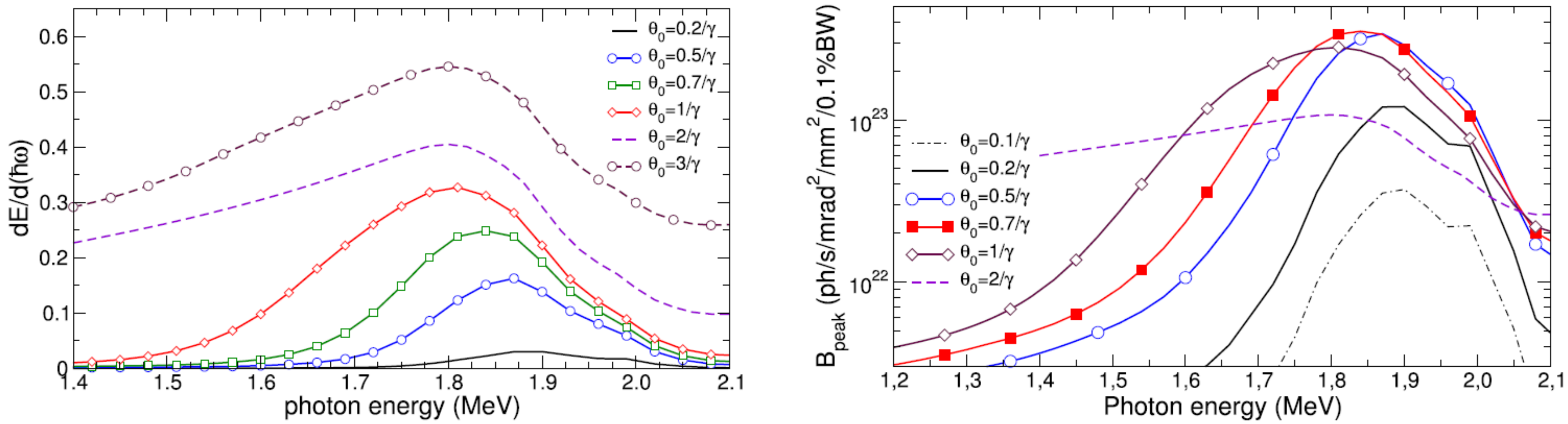
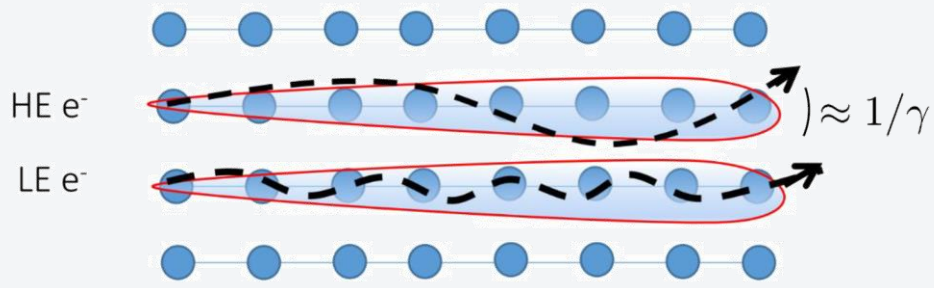


Fig. 3 Spectral distribution of radiation emitted (left) and peak brilliance of CU-LS (right) calculated for different emission cones θ_0 as indicated. Both panels refer to the CU with the parameters labeled as 'Set (I) in Table 2

$$\gamma\epsilon_{x,y} = 10 - 20\,\text{m-}\mu\text{rad},\, \sigma_{x,y} = 10 - 20\,(\mu\text{m}),\, I_{\text{peak}} = 6 - 15\,\text{kA}$$

Channeling Radiation

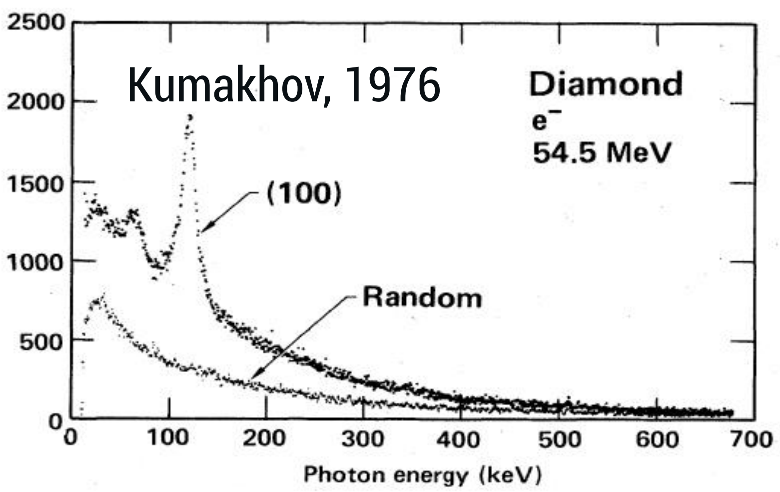
Oriented material



Channeling radiation (CR)

Low Energy (<GeV) → **dipole radiation** (undulator)
High Energy (≫GeV) → **synchrotron radiation** (wiggler)

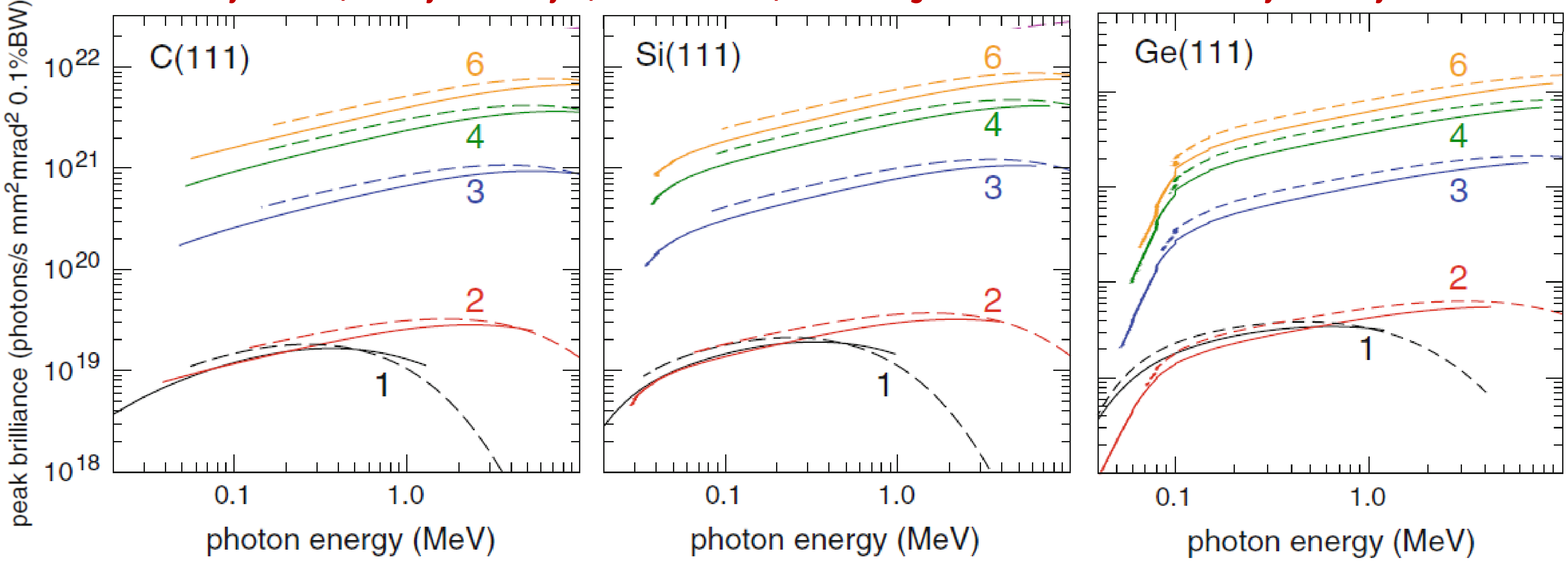
- Huge potential for a compact hard X-or γ-ray source
- Crystals are passive element →**no energy consumption**



What about the Brilliance?

With Channeling Radiation: photon fluxes on the order of 10^{12}/s in the primary peak, with reasonable values for the beam current (@ µA) and crystal lifetime.

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



Curve 1, estimates for DAΦNE beam