Crystal-based positron source for the lepton colliders

ICHEP 2022, July 7th

Iryna Chaikovska

on behalf of L. Bandiera, L. Bomben, R. Camattari, G. Cavoto, R. Chehab, D. De Salvador, V. Guidi, V. Haurylavets, E. Lutsenko, V. Mascagna, A. Mazzolari, M. Prest, M. Romagnoni, F. Ronchetti, F. Sgarbossa, M. Soldani, A. Sytov, M. Tamisari, V. Tikhomirov and E. Vallazza

Université Paris-Saclay

CNRS/IN2P3 Laboratoire de Physique des 2 Infinis Irene Joliot-Curie (IJCLab)

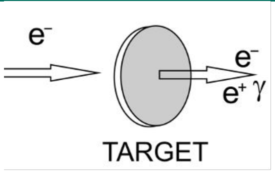
iryna.chaikovska@ijclab.in2p3.fr

Why e+ sources are critical components of the future colliders

$$L = \frac{N_1 N_2 f\, n_b}{4\pi\, \sigma_x \sigma_y}$$

High luminosity at the future machines => needs **high average and peak e- and e+ currents and small emittances**.

e+ are produced within large 6D phase space (e+/e- pairs produced in a target-converter)



Current => limited in conventional way by the target characteristics

- Average energy deposition => target heating/melting
- Peak Energy Deposition Density (PEDD): inhomogeneous and instantaneous energy deposition => thermo-mechanical stresses due to temperature gradient

Thermal dynamics and shock waves. Fatigue limit resulting from cycling loading. Material damages. Activation (handling)

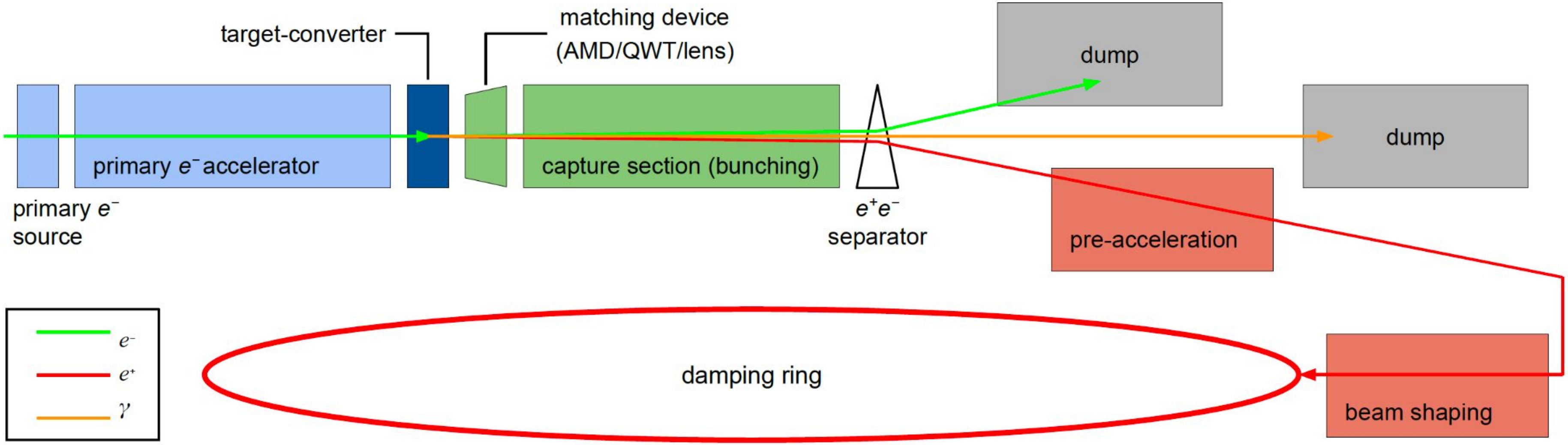
Emittance => at the production 6D phase space is very large

- After defined by the e+ capture system acceptance.

e+ source fixes the constraints for the peak and average current, the emittance, the damping time, the repetition frequency => Luminosity!

Positron source basic scheme

High production e+ divergence => appropriate capture, focusing and post acceleration sections need to be integrated immediately after the target



Accepted e+ yield is a function of **primary beam characteristics** + **target** + **capture system** + **DR acceptance**

Positron source performances

I. Chaikovska et al 2022 JINST 17 P05015

Demonstrated (a world record for existing accelerators): SLC e+ source ~6e12 e+/s

Facility	SLC	SuperKEKB	DAFNE	BEPCII	LIL	CESR	VEPP-5	DCI
Research center	SLAC	KEK	LNF	IHEP	CERN	Cornell	BINP	LAL
Repetition frequency, Hz	120	50	50	50	100	60	50	50
Primary beam energy, GeV	30–33	3.5	0.19	0.21	0.2	0.15	0.27	1
Number of e^- per bunch	5×10^{10}	6.25×10^{10}	$\sim 1 \times 10^{10}$	5.4×10^{9}	2×10^{11}	3×10^{10}	2×10^{10}	–
Number of e^- bunches /pulse	1	2	1	1	1	7-21	1	1
Incident e^- beam size, mm	0.6	~ 0.5	1	1.5	~ 0.5	2	~ 0.7	–
Target material	W-26Re	W	W-26Re	W	W	W	Ta	W
Target motion	Moving	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Target thickness/size, mm	20, r=32	14, r=2	-	8, r=5	7, r= 8	7, r=10	12, r=(~ 10–>2.5)	10.5, r= –
Matching device	AMD (FC)	AMD (FC)	AMD (FC)	AMD (FC)	QWT	QWT	AMD (FC)	AMD (Sol.)
Matching device field, T	5.5	3.5	5	4.5	0.83	0.95	8.5 (10 max.)	1.25
Field in solenoid, T	0.5	0.4	0.5	0.5	0.36	0.24	0.5	0.18
Capture section RF band	S-band	S-band	S-band	S-band	S-band	S-band	S-band	S-band
e^+ yield, N_{e^+}/N_{e^-}	0.8-1.2 (@DR)	0.4 (@DR)	0.012(@LE)	0.015(@LE)	0.006 (@DR)	0.002(@LE)	$\sim$ 0.014 (@DR)	0.02 (@LE)
e^+ yield, $N_{e^+}/(N_{e^-} E)$ 1/GeV	0.036	0.114	0.063	0.073	0.030	0.013	0.05 (@DR)	0.02 (@LE)
Positron flux,* e^+/s	$\sim 6 \times 10^{12}$	2.5×10^{12}	$\sim 1 \times 10^{10}$	4.1×10^{9}	1.2×10^{11}	7.6×10^{10}	1.4×10^{10}	–
Damping Ring energy, GeV	1.19	1.1	0.510	No	0.5	No	0.51	No
DR energy acceptance $\frac{\Delta E}{E}$, %	±1	±1.5	±1.5	No	±1	No	±1.2	No

What are the main challenges?

High intensity

Polarization

Emittance

Reliability and radiation environment

Future collider project challenges

I. Chaikovska et al 2022 JINST 17 P05015

Demonstrated (a world record for existing accelerators): SLC e+ source ~6e12 e+/s

Project	CLIC	ILC	LHeC (pulsed)	LEMMA	CEPC	FCC-ee
Final e^+ energy [GeV]	190	125	140	45	45	45.6
Primary e^- energy [GeV]	5	128** (3*)	10	–	4	6
Number of bunches per pulse	352	1312 (66*)	10^5	1000	1	2
Required charge [10^{10} e^+/bunch]	0.4	3	0.18	50	0.6	2.1
Horizontal emittance $\gamma\epsilon_x$ [μm]	0.9	5	100	–	16	24
Vertical emittance $\gamma\epsilon_y$ [μm]	0.03	0.035	100	–	0.14	0.09
Repetition rate [Hz]	50	5 (300*)	10	20	50	200
e^+ flux [10^{14} e^+/second]	1	2	18	10–100	0.003	0.06
Polarization	No/Yes***	Yes/(No*)	Yes	No	No	No

* The parameters are given for the electron-driven positron source being under consideration.

** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.

*** Polarization is considered as an upgrade option.

Linear Collider projects: high request for polarization, requested intensity should be produced in "one shot".

Circular Collider projects: polarization is under discussion, requirements are relaxed due to stacking and top-up injection

Positrons sources: ‘novel’ schemes (production)

Target PEDD and heating/melting → separate the photon production and the pair conversion

First stage: photon generation

Second stage: e-/e+ and photon beams are separated and the latter is sent to the target-converter

(charged particles are swept off => the deposited power and PEDD are strongly reduced)

For the photon generation:

Radiation from helical undulator

Channeling radiation

Compton scattering

- Photons produced by channeling effect in the axially oriented crystals can be used for **the unpolarised positron source**
- **Polarized positrons** can be obtained by using polarized photons produced in helical undulator or in Compton scattering

ILC → Undulator scheme (conventional scheme as a back-up)

CLIC → Hybrid scheme based on use of channeling radiation (alternative: Compton scheme for polarization upgrade)

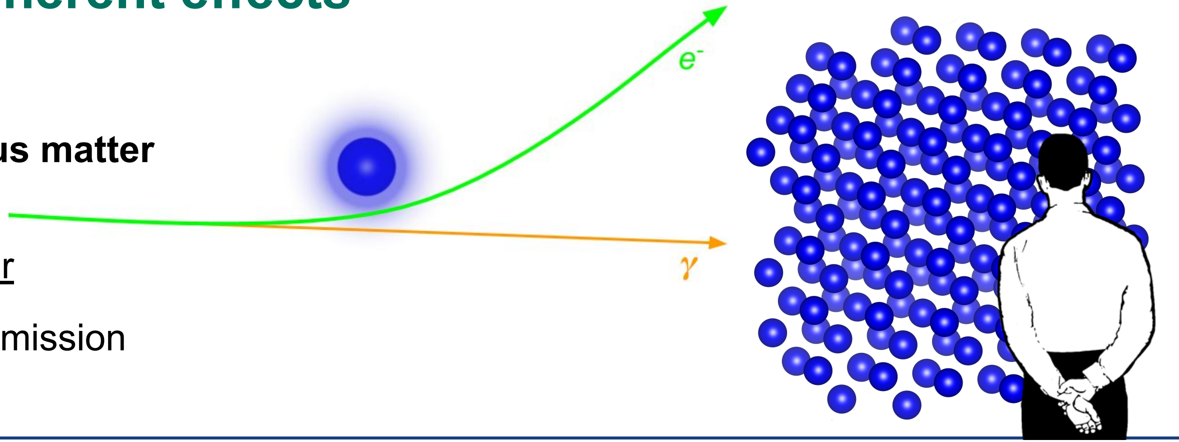
FCC-ee → Hybrid or conventional scheme

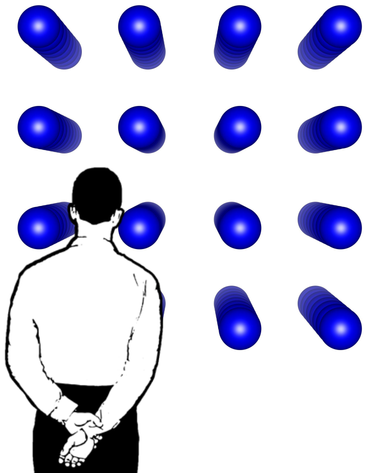
Crystal radiator lattice coherent effects

Passage of **electrons through amorphous matter**

random interactions with single-nucleus Coulomb fields, <u>independent on each other</u>

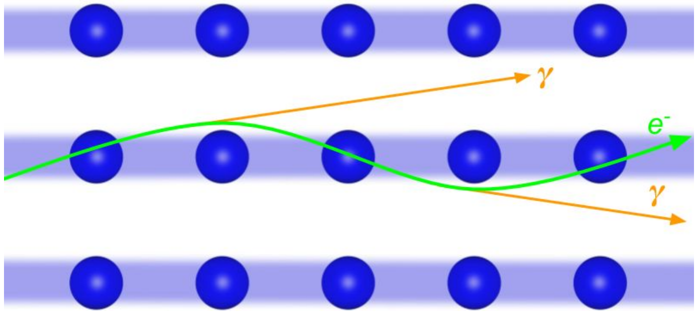
→ standard Bremsstrahlung radiation emission





At *small* angle between the particle trajectory and the nuclear strings, **axial condition**:

→ continuous potential along the axes (Lindhard)



→ <u>oscillatory dynamics</u> (**channeling**)

→ angular range: Lindhard's angle

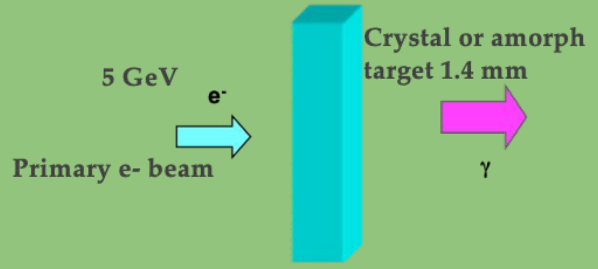
$$< \theta_c = \sqrt{\frac{2U_0}{\varepsilon}}$$

or <u>over-barrier motion</u>

→ θc is equal to <u>4.5 mrad (140 μrad) at 100 MeV (100 GeV)</u> for <111> axis in W

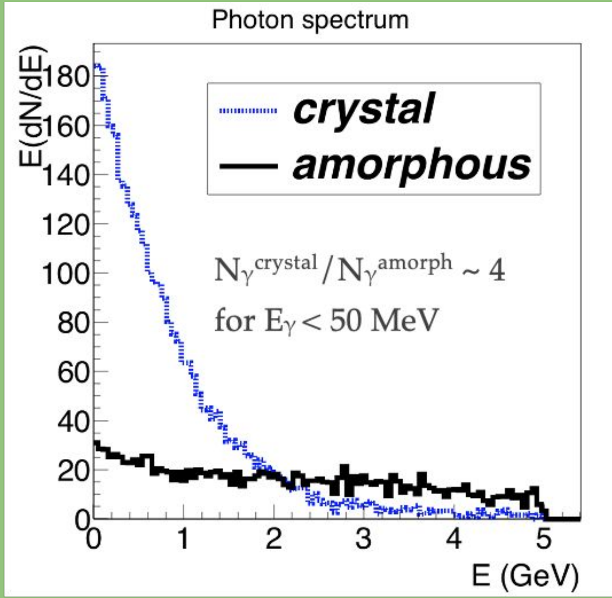
Channeling vs. Bremsstrahlung for positron sources

For targets of the same thickness → **enhancement of the soft photons production in the crystal** oriented on its <111> axis compared to the amorphous.



- Soft photons will generate the soft positrons → easier to capture by matching devices.
- There is a threshold in energy, for which the energy radiated by channeling becomes more important than that of bremsstrahlung. For W, E > 700 MeV. For other crystals (Si, Ge, C(d)…) the threshold is higher.

V N Baier, Katkov, V M Strakhovenko, 1986 Phys. Stat. Solidi B 133, 583

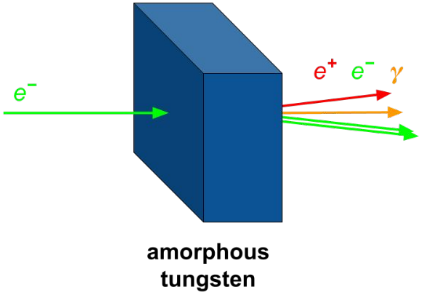


Proof-of-principle experiment in Orsay (1992-1993): observing radiation enhancement in a W crystal oriented along the〈111〉axis submitted to a 2 GeV e- beam.

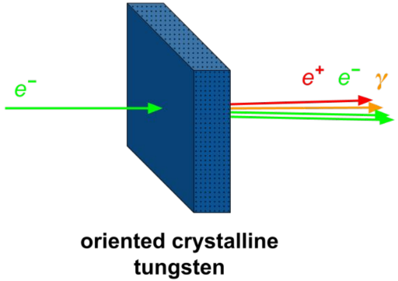
X. Artru et al., NIM Section B, 119.1 (1996): 246-252

Crystal-based positron source for future colliders

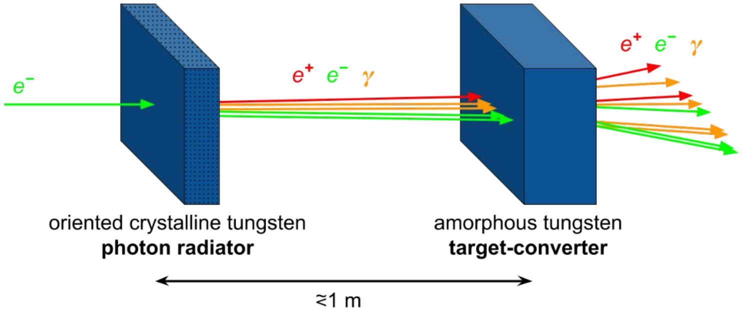
Conventional target



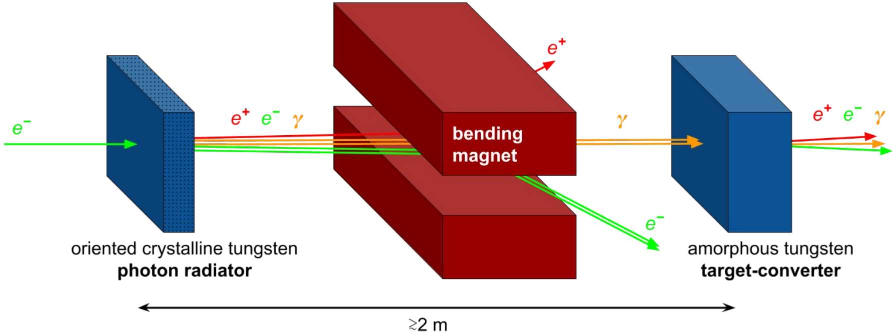
1) Crystal target: radiation and conversion in the same target



2) Hybrid scheme: thin crystal & thick amorphous converter



3) Optimized hybrid scheme: decrease of the deposited energy and PEDD by sweeping off the e+/e- (from crystal)



→ three approaches have been studied experimentally

Orsay, WA 103@CERN and KEK

Originally proposed by R. Chehab and A. Variola (LAL, Orsay), V. Strakhovenko (BINP) and X. Artru (IPNL, Lyon)

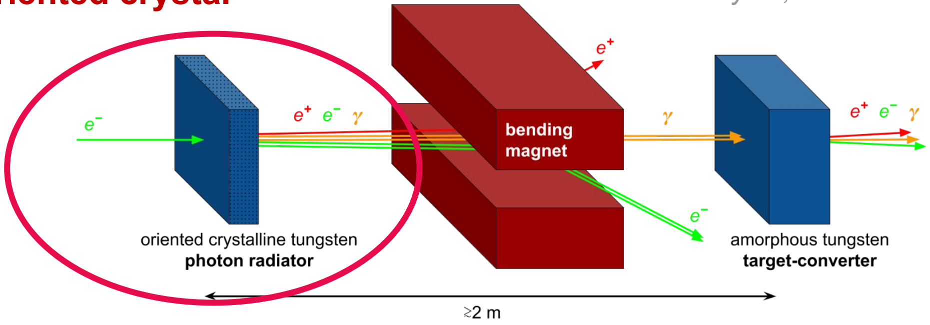
R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285

Crystal-based positron source for future colliders

Software tools to simulate the electromagnetic processes in oriented crystals are needed for the positron source design and optimization *

→ have to be benchmarked/validated with experiments at energies of interest for positron sources of future colliders

oriented crystal



** A. I. Sytov, V. V. Tikhomirov, and L. Bandiera, Phys. Rev. Accel. Beams 22, 064601 (2019)*
V.G. Baryshevsky et al., NIM B 402, 35–39 (2017)

X. Artru et al., NIM B 240.3, 762-776 (2005)
(CGS code by V. Strakhovenko)

X. Artru et al., NIM B 48(1),278–282 (1990)
(FOT code by X. Artru)

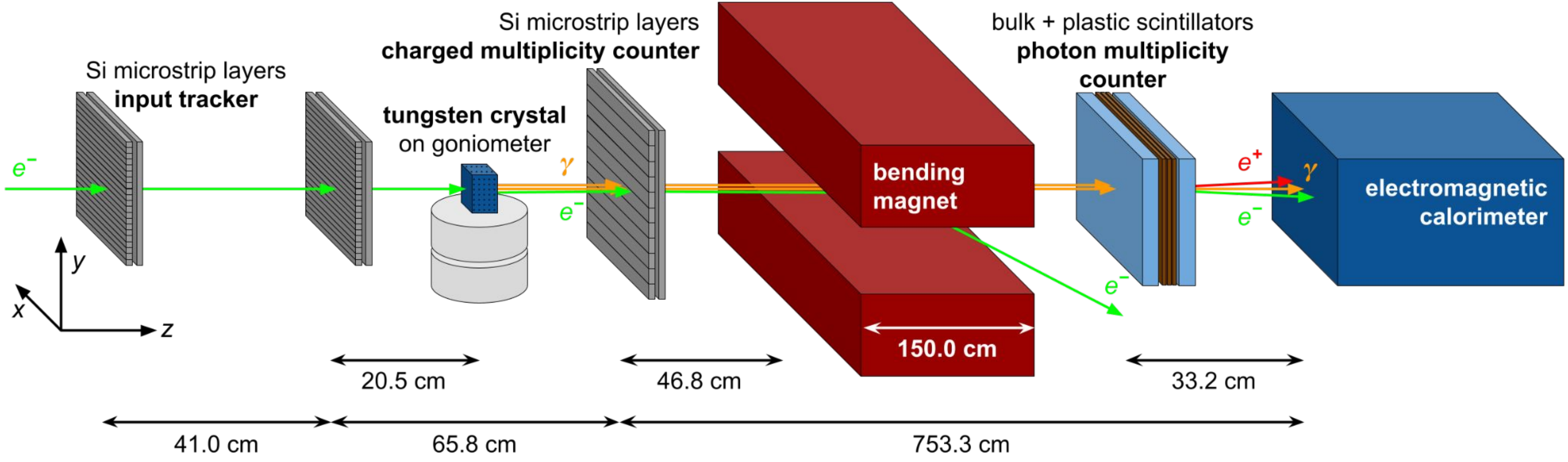
Several tests with electron beams were carried out and planned, in particular at

1.	CERN SPS	e^- at **6 and 10 GeV/*c***	**W <111>**	(experiment WA103)
2.	DESY	e^- at **5.6 GeV/*c***	**W <001>, C(d)**	
3.	CERN H2	e^- at **20 GeV/*c***	**W <111>, C(d)**	
4.	MAMI	e^- at **< 1 GeV/*c***	**W <111>, Ir**	

Experiment @DESY Test Beam Facility T21 (2019)

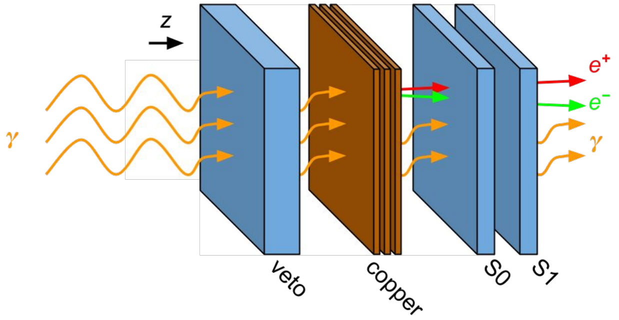
Investigation of radiation enhancement **in an axially oriented tungsten crystal**

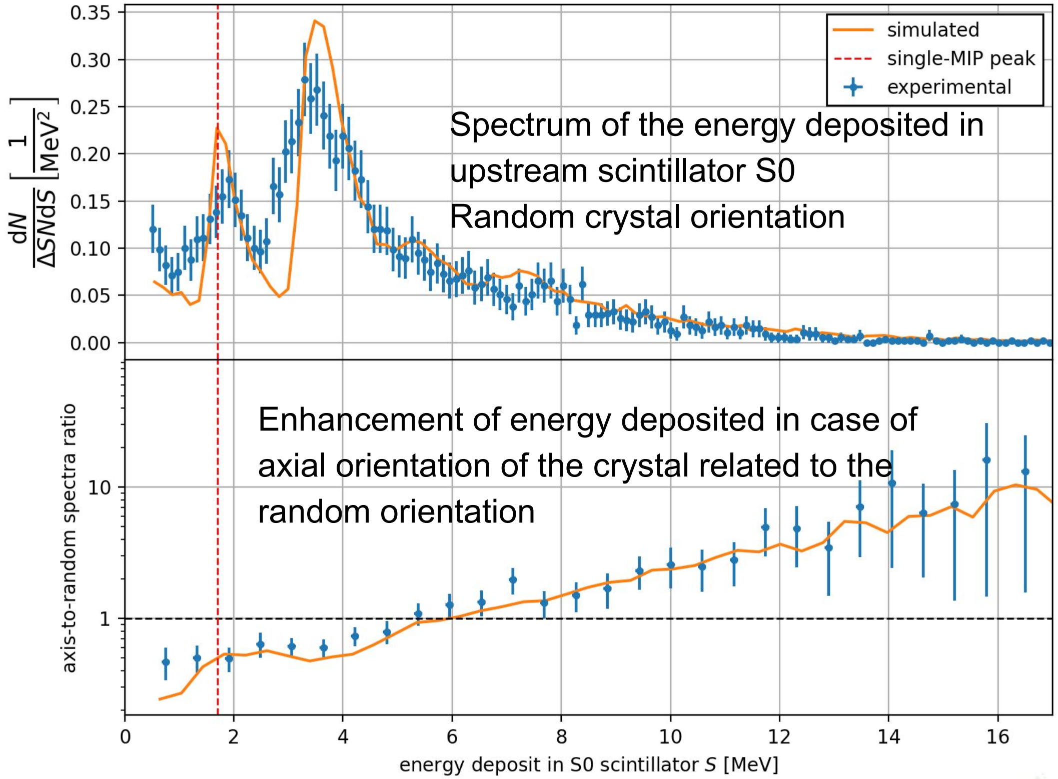
e- beam energy = 5.6 GeV, beam divergence ≈ 0.7 mrad, W crystal, <100> oriented, 2.25 mm thick (≈0.65 X0). For this axial orientation: θc ≈ 0.52 mrad. Mosaicity < 150 μrad.



Results on photon emission enhancement

An estimate of the number of photons that emerge from the crystal was obtained via a preshower.





Increase in the average number of high-energy deposit events (i.e. number of events featuring many output photons) when close to the axial alignment condition.

Very good agreement with Monte-Carlo simulations.

→ validation of the software tools to simulate the e.m. interactions in oriented crystals → e+ source design!

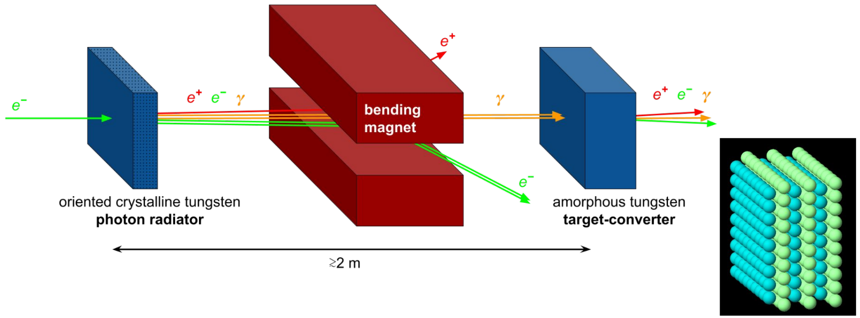
Hybrid e+ Source Applications:

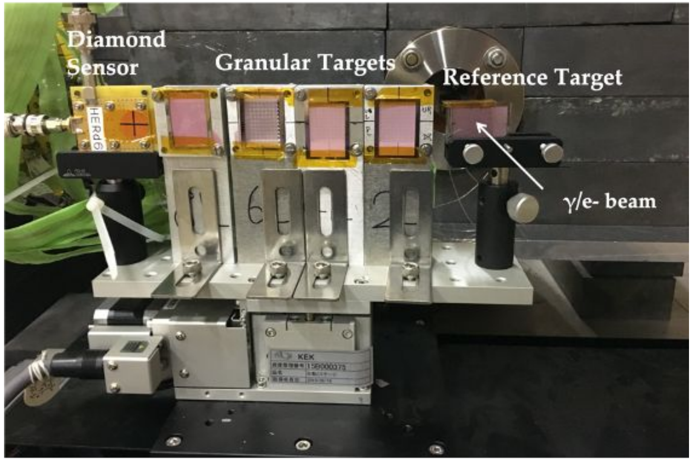
KEKB/SuperKEKB → W crystal target @KEKB during 1 year (2006) + experimental R&D program on hybrid scheme *T. Suwada et al. PRST-AB 10 (2007) 073501*
I. Chaikovska et al., Proceedings of the IPAC'17, 2910-2913 (2017)

CLIC → Hybrid scheme is a baseline design *CLIC Conceptual Design Report*
FCC-ee → Hybrid or conventional scheme *I. Chaikovska Proceedings of the IPAC'19, p. 424 (2019)*

Recent idea: to replace the bulk target-converter by a **granular** one made of **small spheres** → *new option for the amorphous converter* (studies ongoing)

Cheng-Hai Xu et al., Chinese Physics C 36.9, 871 (2012)

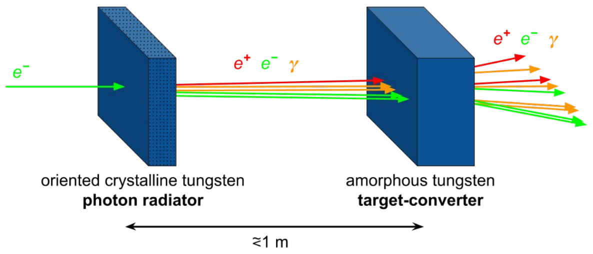




Hybrid e+ source R&D at KEK

Preliminary simulations for the FCC-ee

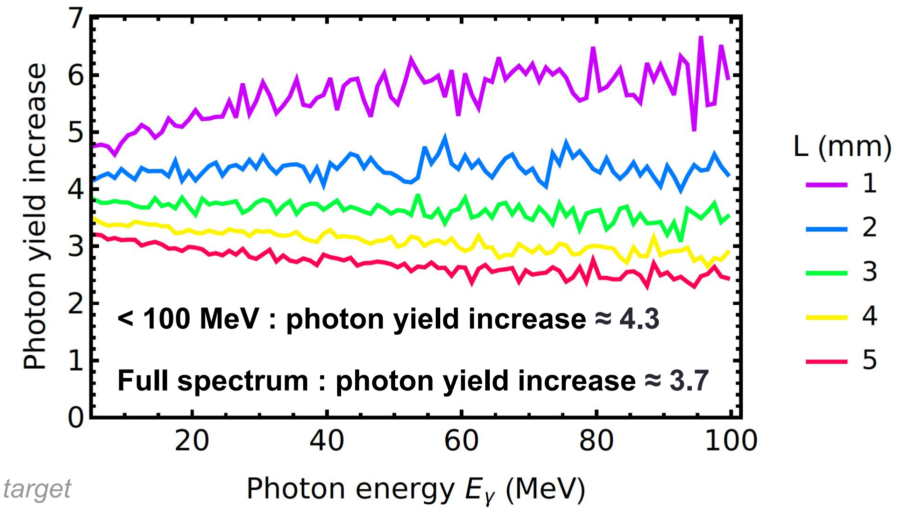
e- beam energy = 6 GeV, angular divergence 0.1 mrad and with the r.m.s. transverse beam size of 0.5 mm.
W crystal oriented in <111> (θc ≈ 0.6 mrad).



A 2 mm thick crystal has been selected to be used as a radiator for the hybrid positron source.

→ good photon yield, moderate values of photon divergence and energy deposition in the crystal.

Radiation enhancement in the tungsten (W) crystals aligned along <111> axes



Results for the positron production simulations

scheme	conventional	hybrid[1]
target thickness [mm]	17.6	2 + 10
e^+ production rate $[N_{e^+}/N_{e^-}]$	14.4	15.1
target deposited energy $[\mathrm{GeV}/e^-]$	1.44	0.946
PEDD $[\mathrm{GeV/mm^3}/e^-]$	0.0416	0.0156

[1] *The values are given for the amorphous target-converter installed after the crystal target*

Preliminary simulations for the FCC-ee

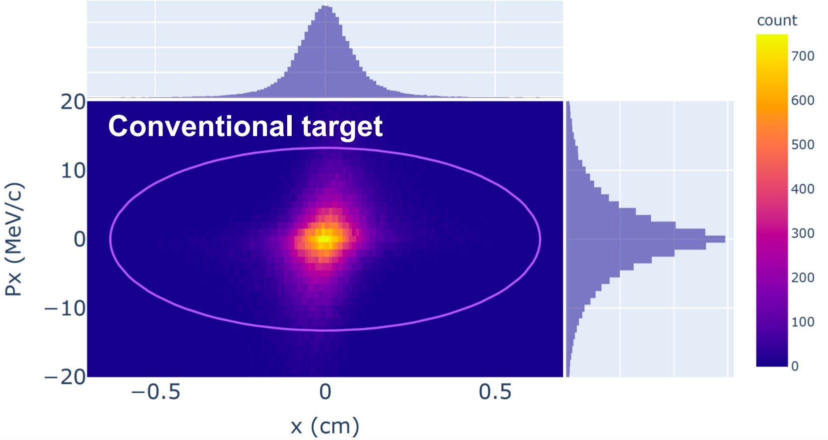
Studies ongoing

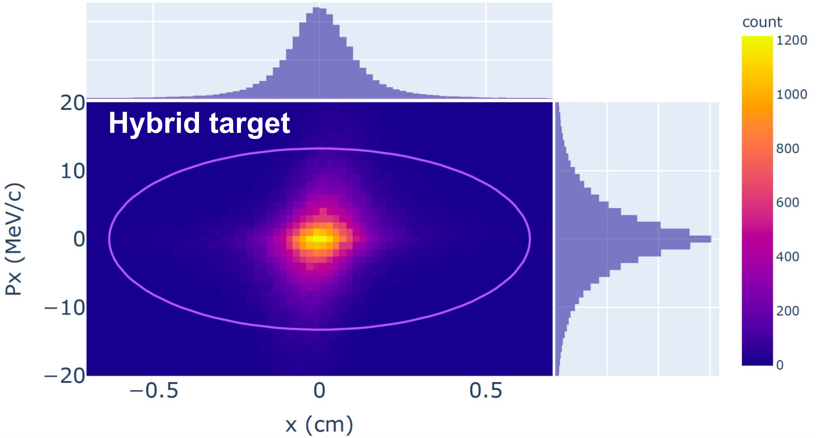
The created e+ are captured at the target exit by a magnetic matching device.

→ Adiabatic Matching Device (B0 = 7 Tesla, Bs = 0.7 Tesla and a = 20 mm) with the acceptance given by

$$\frac{B_0}{B_s}\left(\frac{r_0}{a}\right)^2+\left(\frac{p^*_{r0}}{\frac{1}{2}e\sqrt{B_0B_s}a}\right)^2+\left(\frac{p^*_{\phi 0}}{\frac{1}{2}eB_sa^2}\right)^2\left[\frac{B_s}{B_0\left[\frac{r_0}{a}\right]^2}-1\right]\leq 1.$$

R. Chehab, LAL-RT-89-02, 30p (1989)





The capture efficiency (part of the transverse and longitudinal accepted phase space) **is about 60%** for both schemes (taking into account the longitudinal acceptance Pz ≤ 34.9 MeV/c).

Advantages of the hybrid scheme are thus lower values of the **target deposited energy (34%) the PEDD (63%)**. A detailed analysis of thermal load in the target and positron tracking simulations are needed/ongoing.

Oriented crystals might represent an important milestone in the progress of high-intensity positron sources

Outlook

- Positron sources are a key element of past, present and future lepton colliders. The requirements of the future projects → physics, design and technological challenges (mainly driven by current and polarization).
- Different “novel” schemes have been suggested and preliminary tested. For the crystal-based positron source:
  - validation of a detailed simulation tool for radiation emission in channeling orientation due to the several beam tests.
  - in application to FCC-ee positron source, a start-to-end simulations/optimization are needed to make a real proposal for a future high-intensity positron source (ongoing).
- Experimental tests and extensive R&D are mandatory to study the reliability and final efficiency of the e+ sources.

See talk of Paolo Craievich “The FCC-ee Pre-injector and the PSI Positron Production at SwissFEL”

thank you!

any comments or questions? contact me at *iryna.chaikovska@ijclab.in2p3.fr*!