Crystal-based pair production for a positron driven muon collider positron

MUON Collider Collaboration - Annual Meeting 2022, October 12th

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Positron driven muon source

Idea proposed in LEMMA:

direct production of muons from 45 GeV positron interaction with electrons in a target

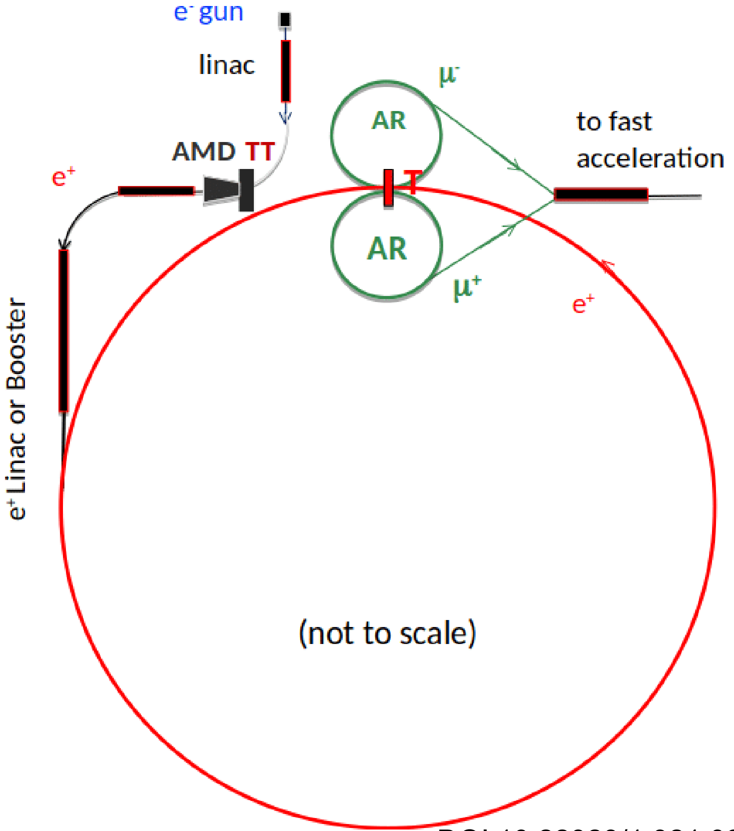
PRO:

- ✓ Production of low emittance μ beam
- ✓ Small energy spread
- ✓ Low background
- ✓ Reduced loss from decay

CONS:

- x Rate is much smaller than w proton-based source

Intense e+ beam → better e+ sources



Adapted from :
https://agenda.infn.it/event/20458/contributions/102936/attachments/67937/83660/muons.pdf

DOI 10.22323/1.321.0256

Positrons sources: ‘novel’ schemes

Positron sources are critical for several proposed accelerators such as CLIC, ILC and FCC
Such schemes are useful research for a positron driven muon collider

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

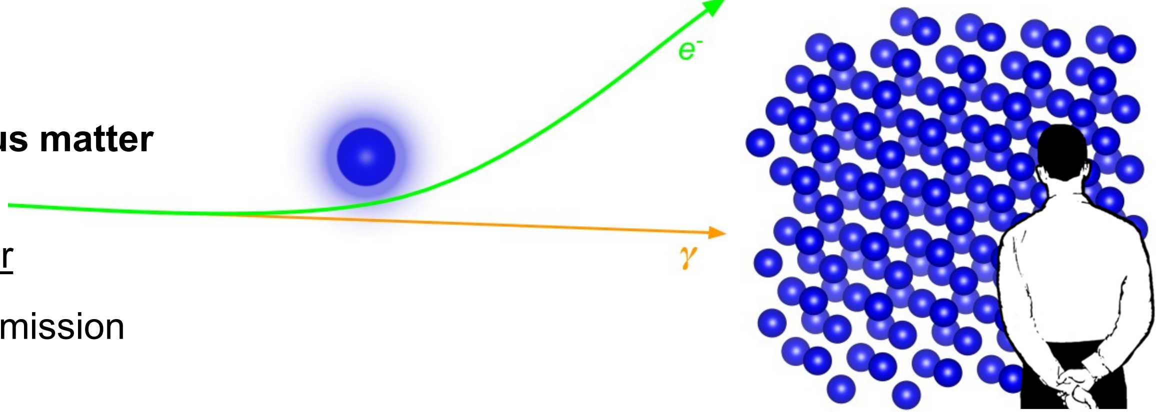
- Photons produced by channeling effect in the axially oriented crystals can be used for **the unpolarised positron source**
- **Polarized positrons** can be obtained by using polarized photons produced in helical undulator or in Compton scattering

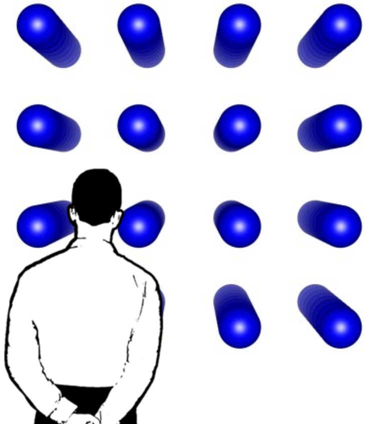
Crystal radiator → **lattice coherent effects**

Passage of **electrons through amorphous matter**

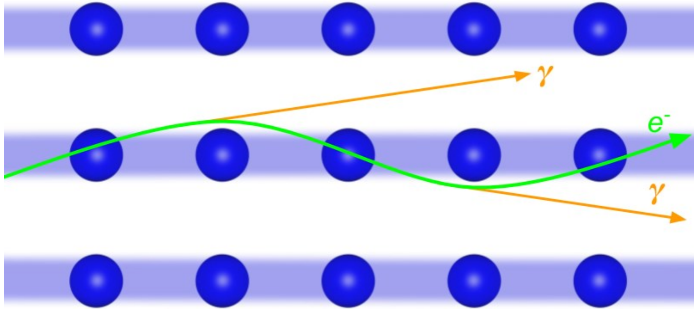
random interactions with single-nucleus Coulomb fields, <u>independent on each other</u>

→ standard Bremsstrahlung radiation emission





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



All atoms along a string interact coherently with projectile particle

Photon emission is strongly enhanced

lattice effects **the strong crystalline field**

***small* particle-to-axis angle** (within few mrad)

$$< \Theta_0 = \frac{U_0}{mc^2}$$

CB/CPP: less pronounced effects attained within 1°

+

high energy (≳10 GeV) → **Lorentz contraction**

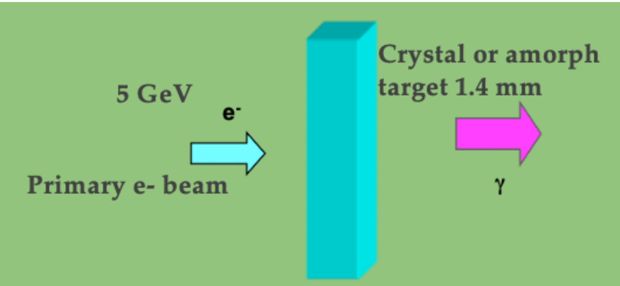
$$\chi = \frac{\gamma E}{E_0} > 1 \qquad E_0 = \frac{m^2 c^3}{e\hbar} = 1.32 \cdot 10^{18} \frac{\mathrm{V}}{\mathrm{m}}$$

= Strong Field

(U_0 and E being the axis potential and the corresponding field in the lab frame → crystal-dependent)

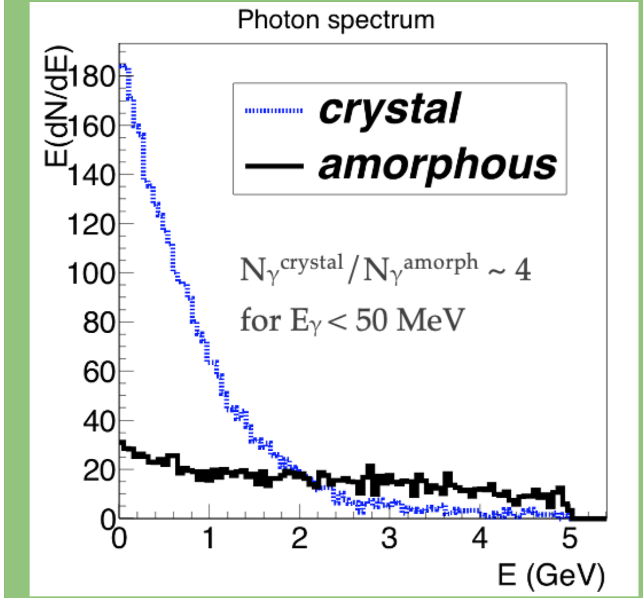
Channeling vs. Bremsstrahlung for positron sources

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

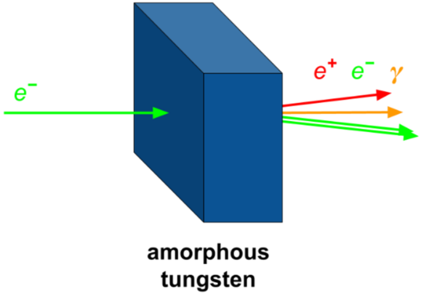


<u>Proof-of-principle experiment in Orsay (1992-1993):</u> observing radiation enhancement in a W crystal oriented along the〈111〉axis submitted to a 2 GeV e- beam.

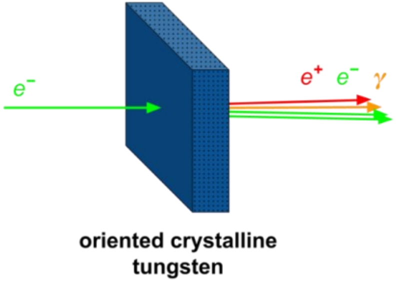
X. Artru et al., NIM Section B, 119.1 (1996): 246-252

Crystal-based positron source for future colliders

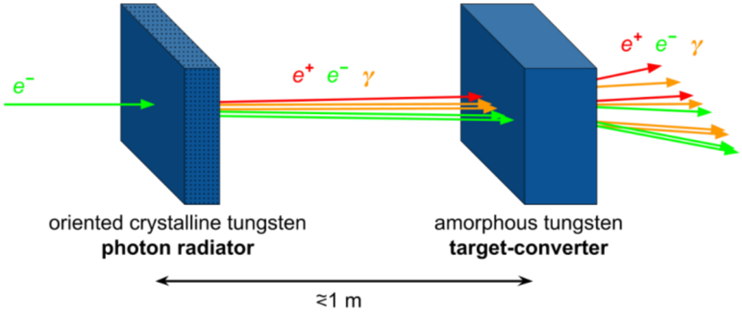
Conventional target



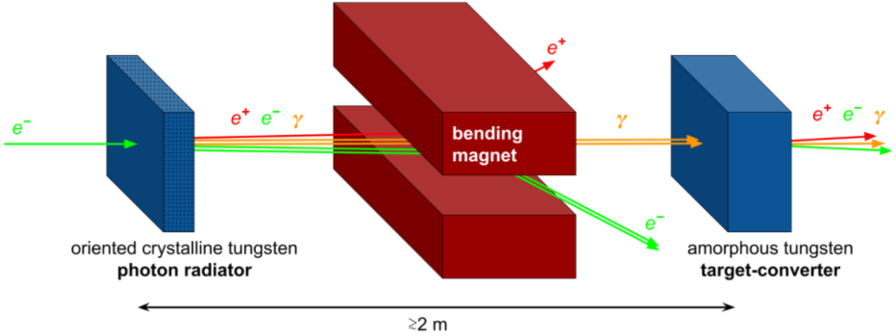
1) Crystal target: radiation and conversion in the same target



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

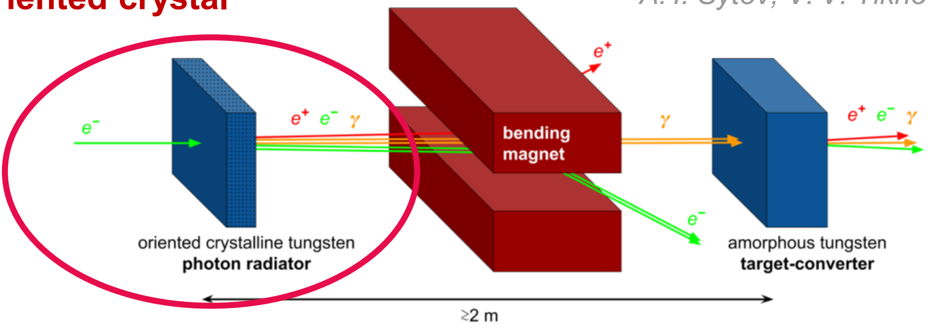
Originally proposed by R. Chehab and A. Variola (LAL, Orsay), V. Strakhovenko (BINP) and X. Artru (IPNL, Lyon)

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)

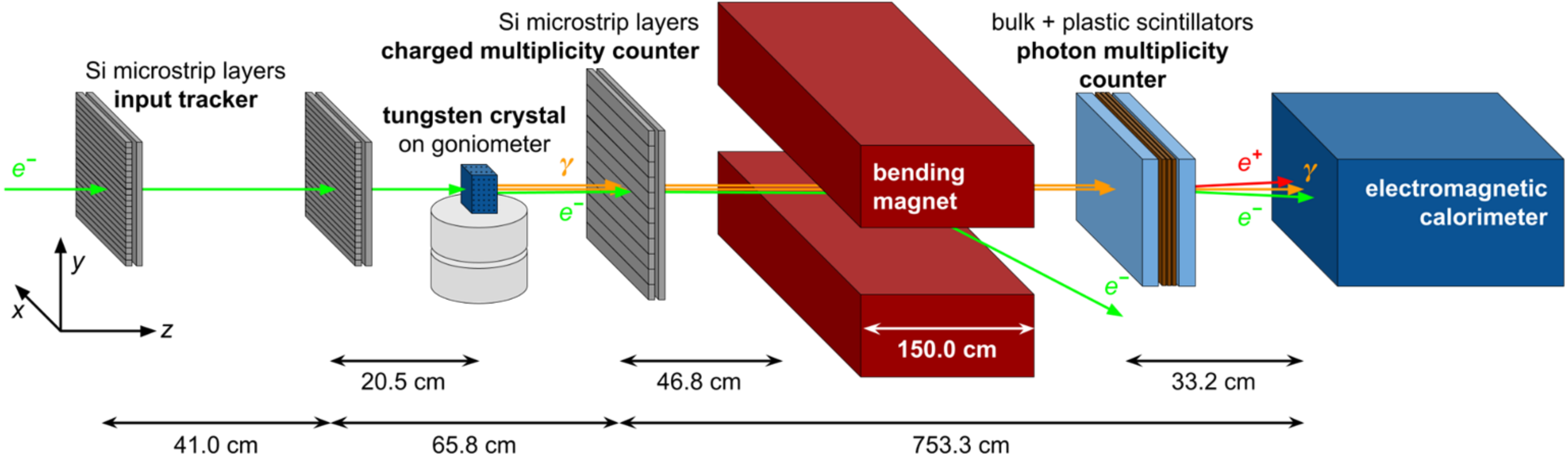
X. Artru et al., NIM B 48(1),278–282 (1990)
(FOT code by X. Artru)

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.

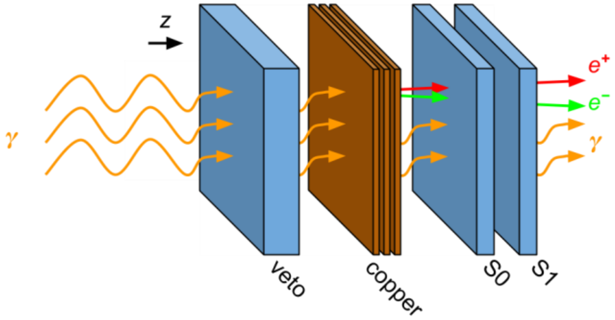


Eur. Phys. J. C (2022) 82:699 https://doi.org/10.1140/epjc/s10052-022-10666-6

Special thanks to DESY beamline staff for the assistance provided, testbeam financed by STORM project of INFN

Results on photon emission enhancement

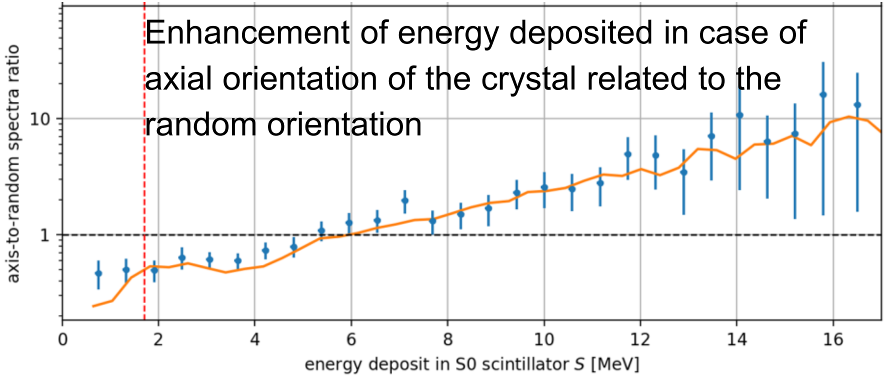
An estimate of the number of photons that emerge from the crystal was obtained via a preshower.



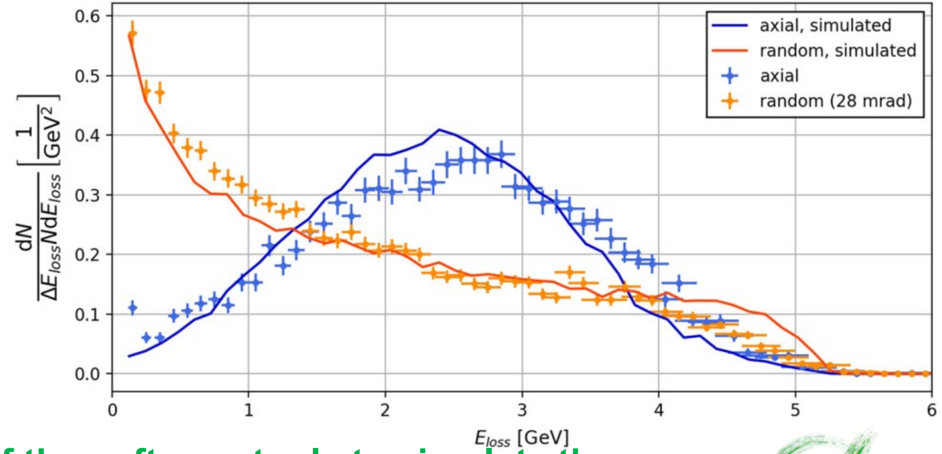
Increase in the average number of high-energy deposit events (i.e. number of events featuring many output photons) when close to the axial alignment condition.

Very good agreement with Monte-Carlo simulations.

Eur. Phys. J. C (2022) 82:699 https://doi.org/10.1140/epjc/s10052-022-10666-6



Enhancement of energy deposited in case of axial orientation of the crystal related to the random orientation



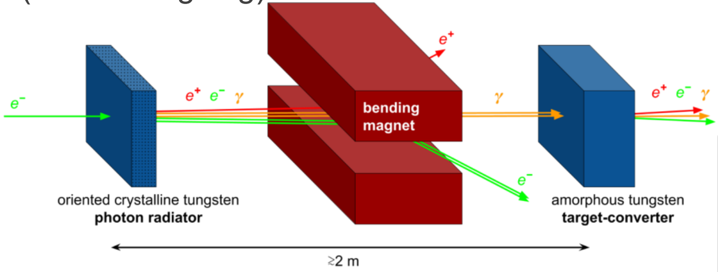
→ validation of the software tools to simulate the e.m. interactions in oriented crystals → e+ source design!

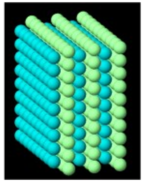
Hybrid e+ Source Applications:

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)

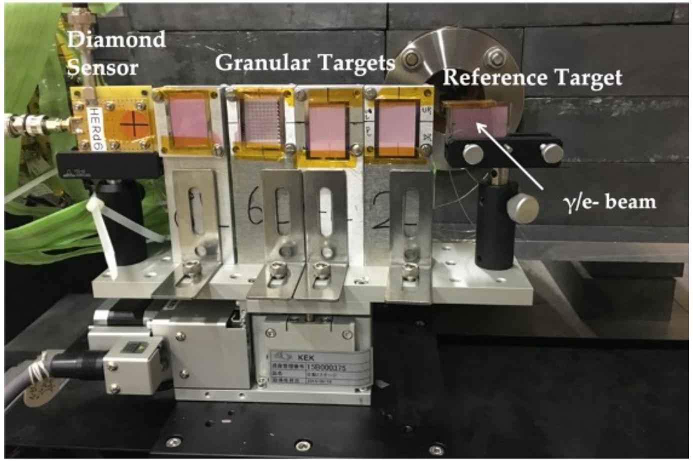
CLIC → Hybrid scheme is a baseline design *CLIC Conceptual Design Report*
FCC-ee → Hybrid or conventional scheme *I. Chaikovska Proceedings of the IPAC'19, p. 424 (2019)*

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)*





A past test at SLAC with a 0.3mm W crystal showed no damages from 2x10^{20} e⁻/cm^2 dose. We plan to determine the damage threshold)



Hybrid e+ source R&D at KEK

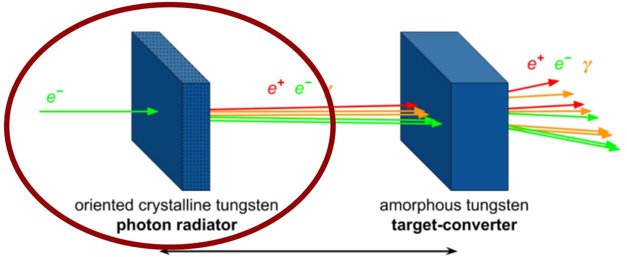
Crystal target optimization

Simulation input:

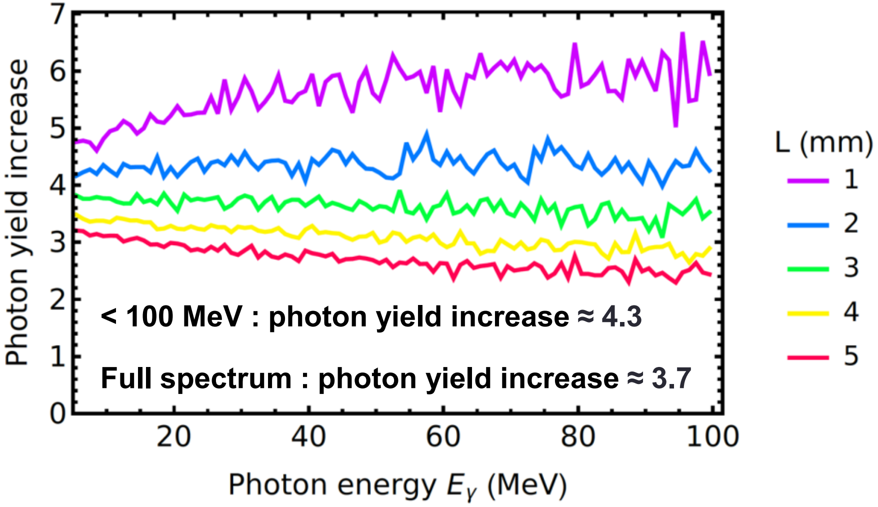
- e- beam energy = 6 GeV
- angular divergence 0.1 mrad
- r.m.s. transverse beam size of 0.5 mm.
- W crystal oriented in <111> (θc ≈ 0.6 mrad)

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



< 100 MeV : photon yield increase ≈ 4.3

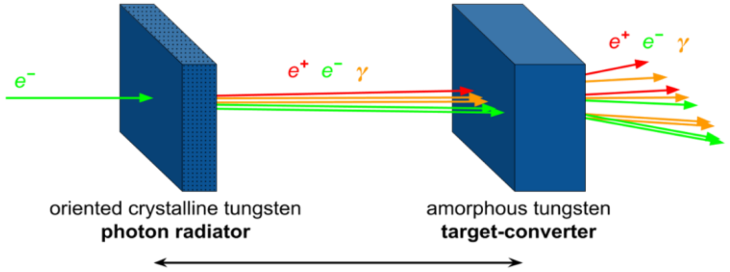
Full spectrum : photon yield increase ≈ 3.7

Hybrid source optimization

GEANT4 simulation of setup with different distance between crystal and amorphous target

Courtesy of M. Soldani

configuration	tgt. PEDD $\left[\frac{GeV}{e^{-}*mm^3}\right]$	e+ rate [e+/e-]	e+ beam size [mm]	e+ beam divergence [mrad]	e+ mean energy [MeV]
conventional, 17.6 mm	0.038	13.7	0.67	25.915	48.7
hybrid, 2mm+1000mm+11.6 mm	0.008	15.1	1.24	26.841	45.6
hybrid, 2mm+2000mm+11.6 mm	0.004	14.9	1.55	29.208	46.1
hybrid, 2mm+600mm+11.6 mm	0.013	15.1	1.05	27.392	46.2



Next step: simulation of 3rd scheme, with magnetic dipole between crystal and amorphous target

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!

Preliminary simulations for the FCC-ee

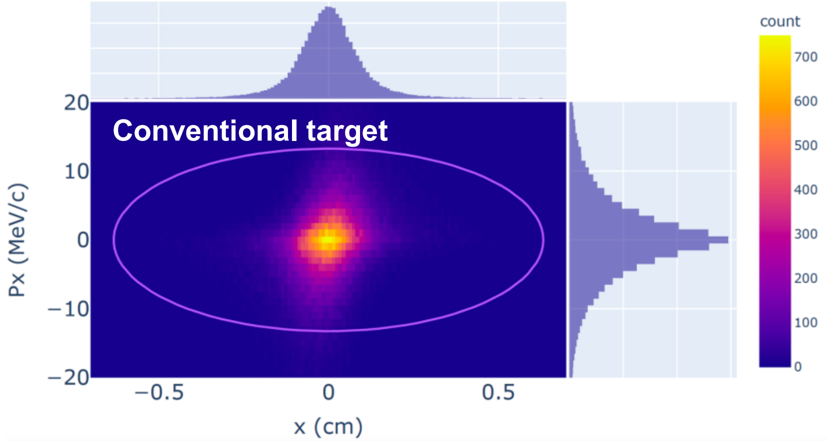
The created e+ are captured at the target exit by a magnetic matching device.

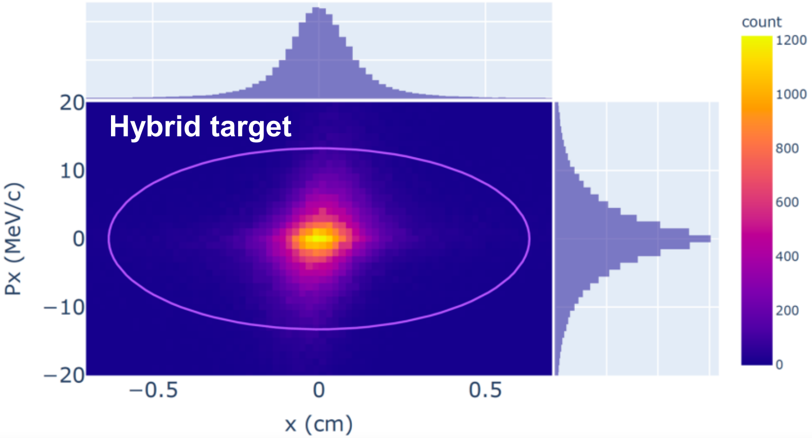
Studies ongoing

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

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

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).

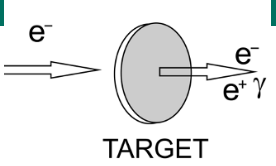
Advantages of the hybrid scheme are thus lower values of the **target deposited energy (34%) the PEDD (63%)**. A detailed analysis of thermal load in the target and positron tracking simulations are needed/ongoing.

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)

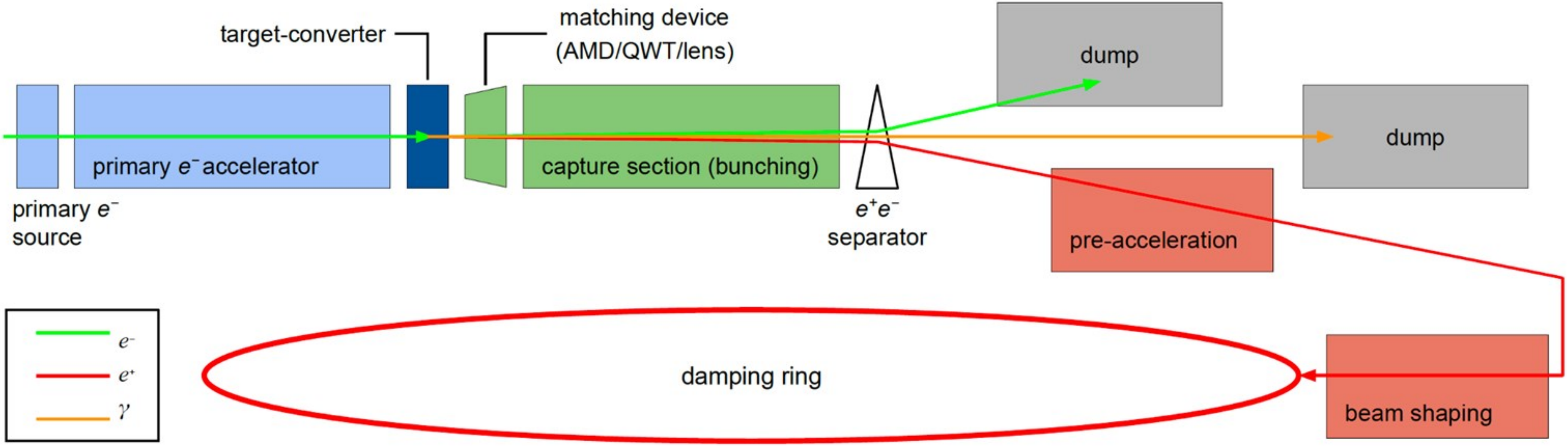
Emittance => at the production 6D phase space is very large

- 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

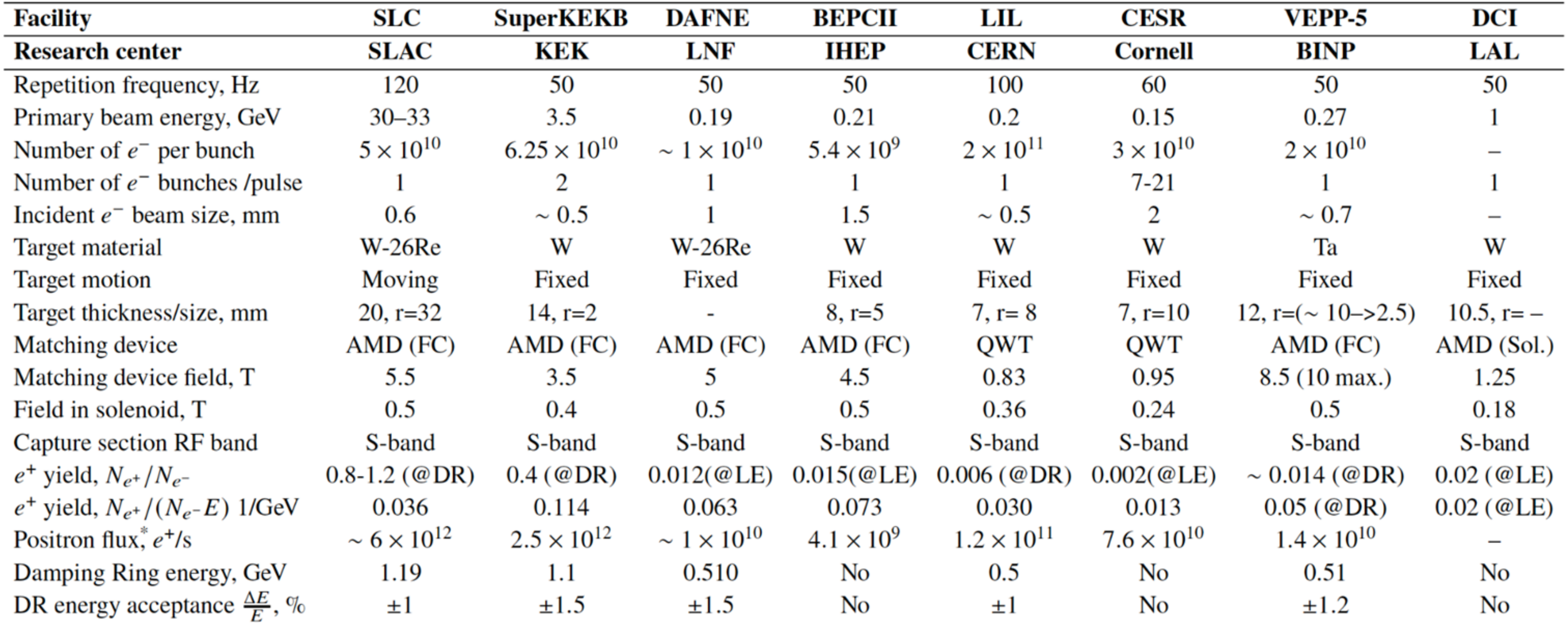


Accepted e+ yield is a function of **primary beam characteristics** + **target** + **capture system** + **DR acceptance**

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=($\sim$ 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

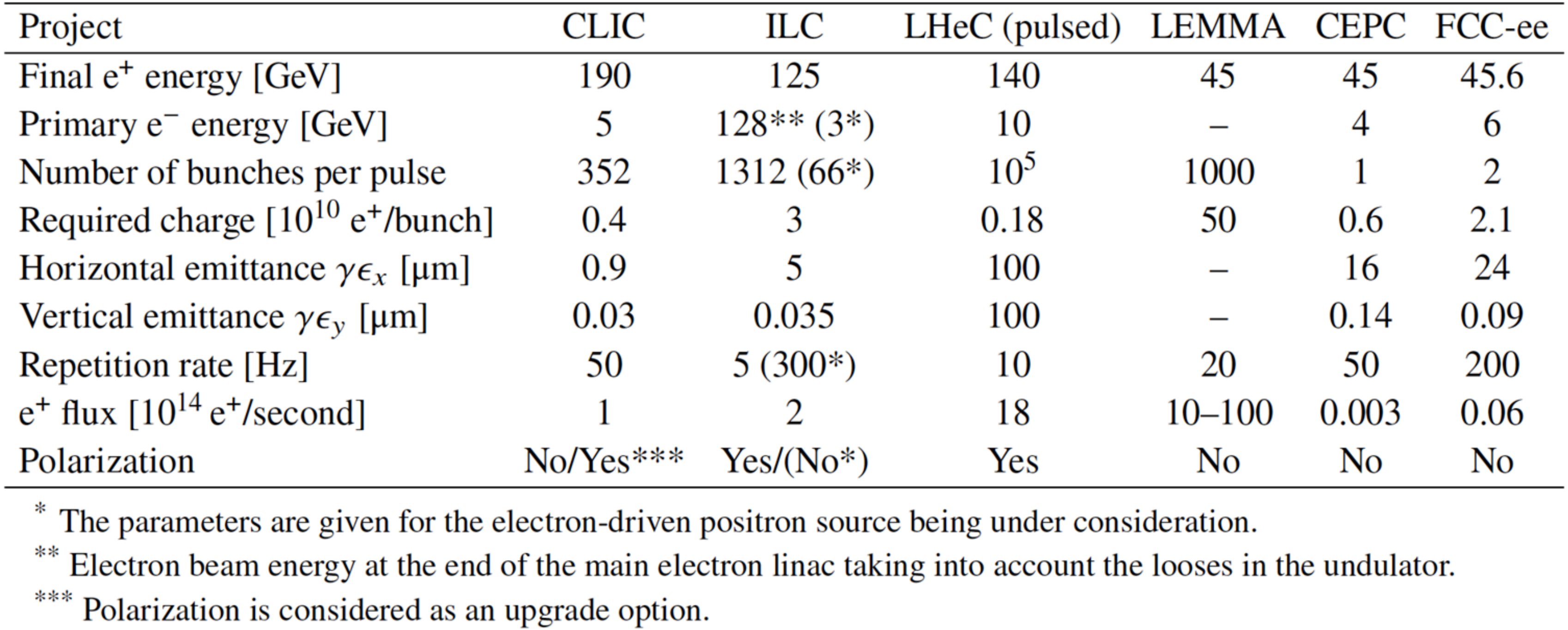
Emittance

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.

<u>Linear Collider projects:</u> high request for polarization, requested intensity should be produced in “one shot”.

<u>Circular Collider projects:</u> polarization is under discussion, requirements are relaxed due to stacking and top-up