Optimization study of a crystal-based positron source for FCC-ee

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Bando PRIN 2022
e+BOOST
PRIN2022-2022Y87K7X
Funded by the European Union
NextGenerationEU

Outlook

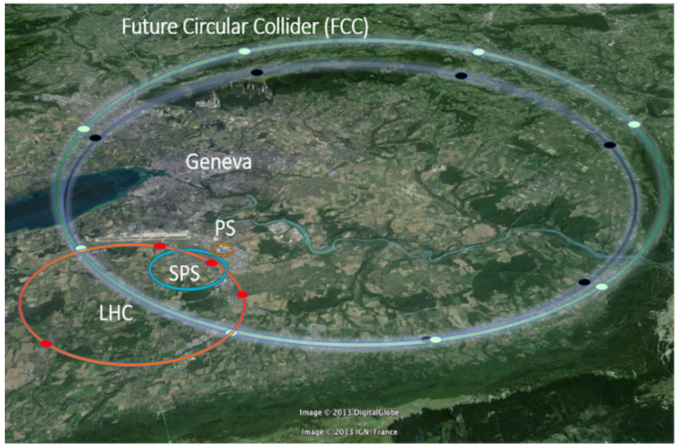
- Brief review of crystal-based positron sources schemes
- Novel optimization approach of a crystal-based positron source through an experimentally validated simulation framework
- Optimized solution for FCC-ee positron source

FCC / FCC-ee and Positron Sources

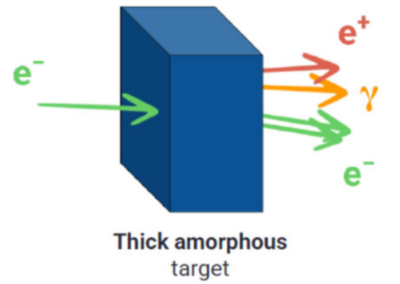
- Future CERN collider post LHC
  ~ 91 Km of circumference
- Stages: **FCC-ee**, Fcc-eh, FCC-hh
- High luminosity:
  up to $230 \times 10^{34} cm^{-2} s^{-1}$

FCC-ee Operation Mode	Final Energy [GeV]	Beam Current [mA]
Z	45	1270
W	80	137
H	120	26.7
ttbar	182.5	4.9

It is the most demaning for the positron source



Conventional scheme of a positron source



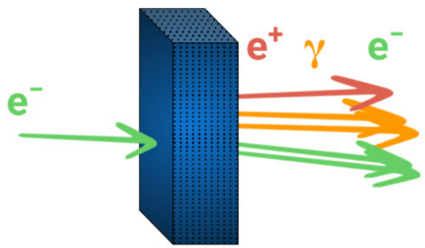
Positron source set a critical constraint for the peak and average current -> **Luminosity Constraint!** Expecially for future Linacs -> **crystal-based positrons sources**

FE activity in **crystal-based positron sources** born in past **INFN projects STORM** (2021-22) and **RD-MUCOL** (for LEMMA). Currently, we are in **RD-FCC, e+BOOST** (bando PRIN2022), **CHART PI**

Crystal-based positron source

Originally proposed by R. Chehab, A. Variola, V. Strakhovenko and X. Artru

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



oriented crystalline
target

Use of coherent effects in oriented crystals: **channeling** and **over barrier motion** (and **photon generation**) → **typical angular range of few mrad at few GeV for <111> axis in W** (axial potential is stronger and limits electron dechanneling, contrary to planar alignment)

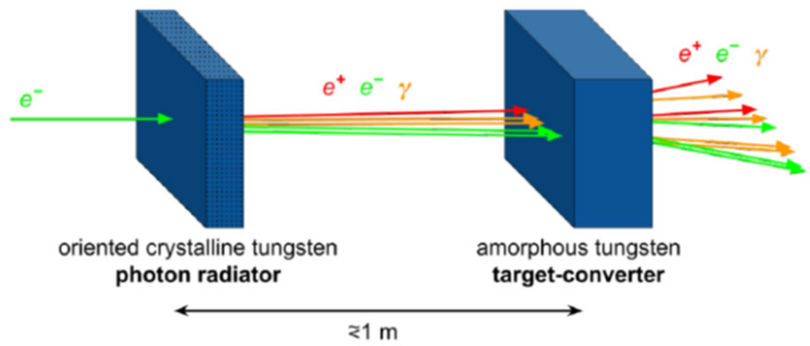
Novel production scheme for positron sources:

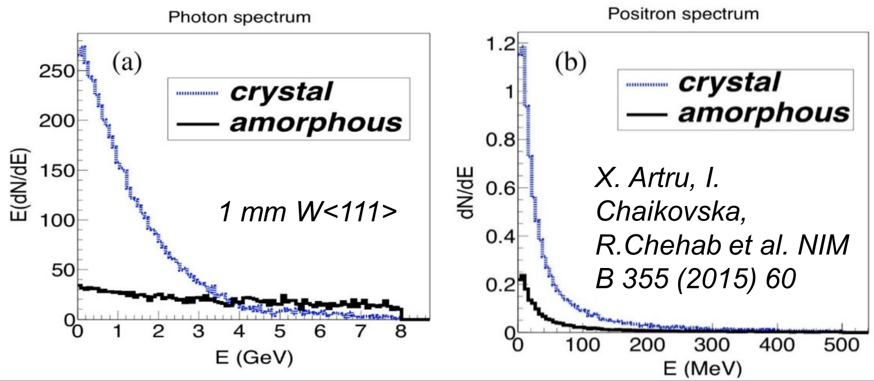
- Enhancement of (soft) photon generation in (high Z) oriented crystals → enhancement of pair production / positron charge
- Lower energy deposit and PEDD (**with hybrid scheme**) in target → lower heating and thermo-mechanical stress (target reliability)

Hybrid scheme

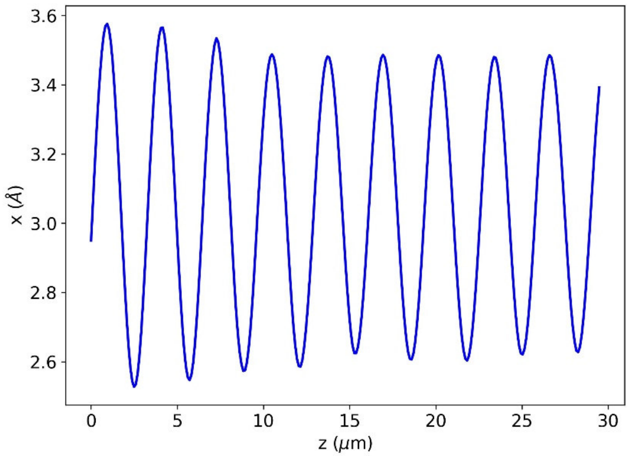
Idea of X. Artru et al., NIM B 266 (2008) 3868

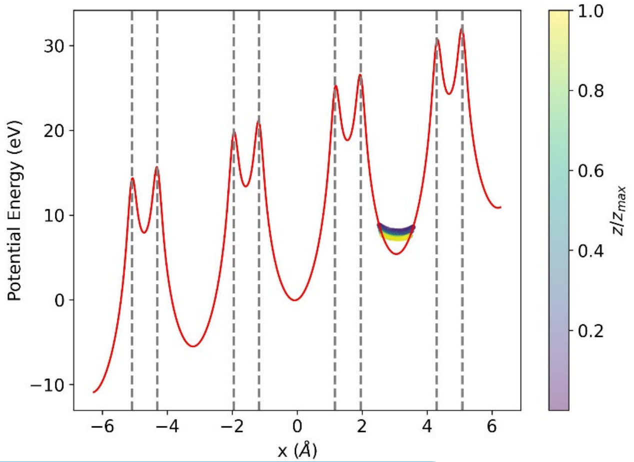
Test at KEK with a W crystal, NIM B 402 (2017) 58



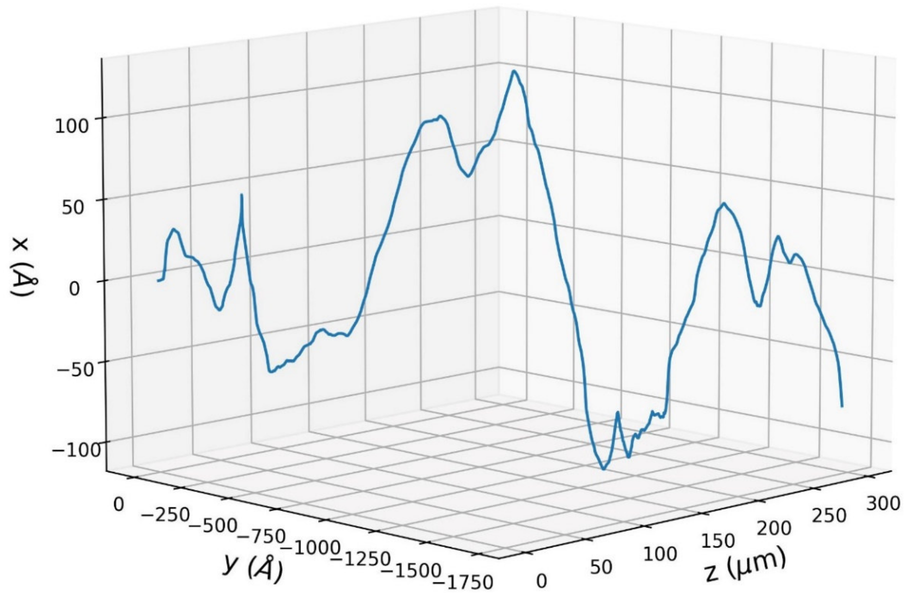


Planar vs Axial Channeling





Trajectory of one **530 MeV/c positron** interacting with a **0.03 mm bent (97 μrad) Si** crystal oriented along **(111) planes**



Trajectory of one **2.86 GeV/c electron** interacting with a **0.3 mm W** crystal oriented along **<111> axis**

Electrons impinging at a small-angle w.r.t. **an axis of a high-Z crystal** (**higher U_0** (~ 1 keV) -> stronger lattice effects and **θ_L** (~ 1 mrad @ 1 GeV) -> higher acceptance w.r.t. planes), are **mostly over-barrier** -> the motion is not periodic, but there are high field gradients -> high local deflection -> **sinchrotron-like radiation**, with enanchement of **soft photons emission**.

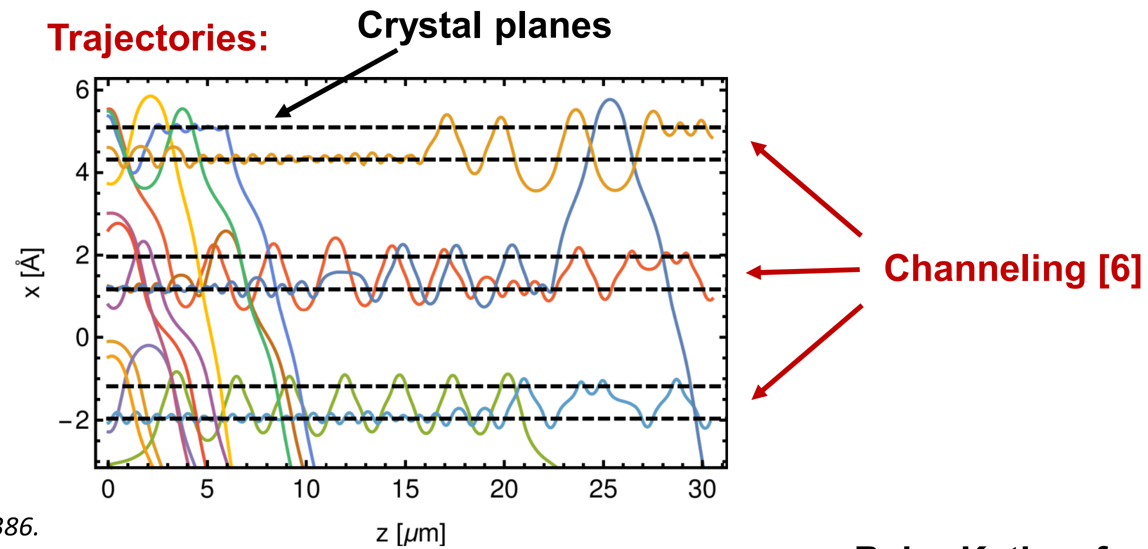
It is important to have a reliable simulation tool of particle interactions in oriented crystals.

Channeling simulation in Geant4: novel ***G4ChannelingFastSimModel*** and ***G4BaierKatkov*** classes were developed and embedded in Geant4 (since 11.2.0 version). These models are based on CRYSTALRAD (by A Sytov)

Main conception: simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes [1]. Multiple and single scattering, as well as ionization, simulation at every step. Photon emission simulated through MC integration of Baier-Katkov formula [2-5].

This model together with standard or pre-calculated (through B-K) pair-production model, allows us to simulate a wide **variety of applications**

coherent pair production model (from Geant4.11.3?)



European Commission

Trillion

GEANT4 A SIMULATION TOOLKIT

[1] A. Sytov, V. V. Tikhomirov. NIM B 355 (2015) 383–386.

[2] V. Guidi, L. Bandiera, V. Tikhomirov PRA 86 (2012) 042903

[3] L. Bandiera, et al., NIM B 355, (2015) 44

[4] L. Bandiera et al., NIM A 936 (2019) 124

[5] A. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

[6] A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)

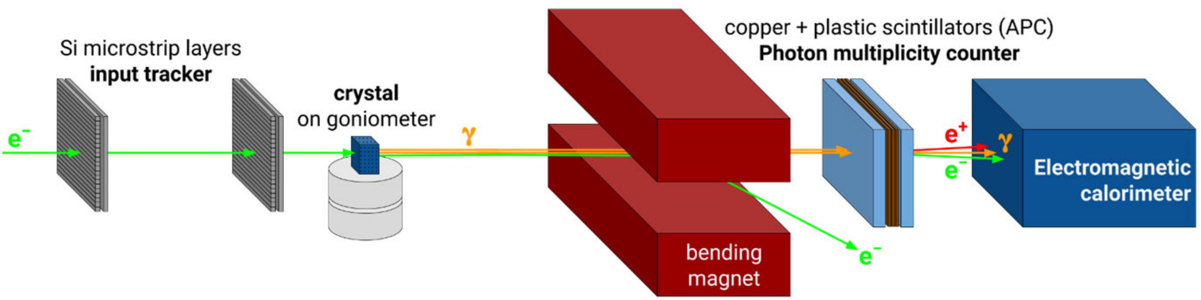
Baier-Katkov formula:

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

Validation of Geant4 channeling model against experimental data

EIC-PATHFINDER-OPEN
TECHNO-CLS
(GA 101046458)

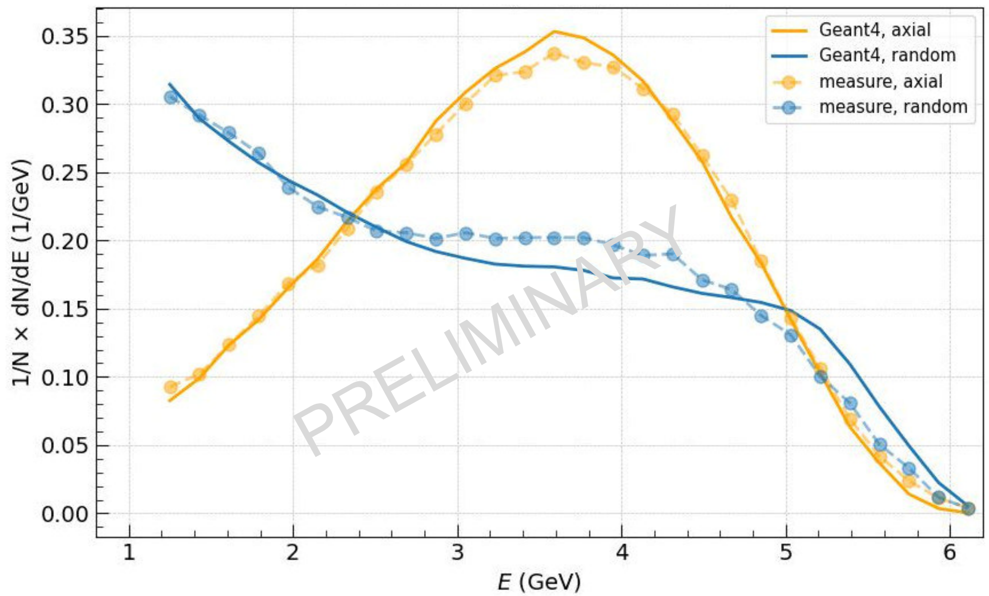
Setup @ CERN PS T9 beamline



Electron beam energy: 6 GeV
Crystal target: W <111>, 2 mm long

***Set-up similar to the one desribed in**: L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), where there is a also compoarison with simulations in which coherent interactions of e- in the W crystal were **simulated with CRYSTAL code** (by V. Tikhomirov).*

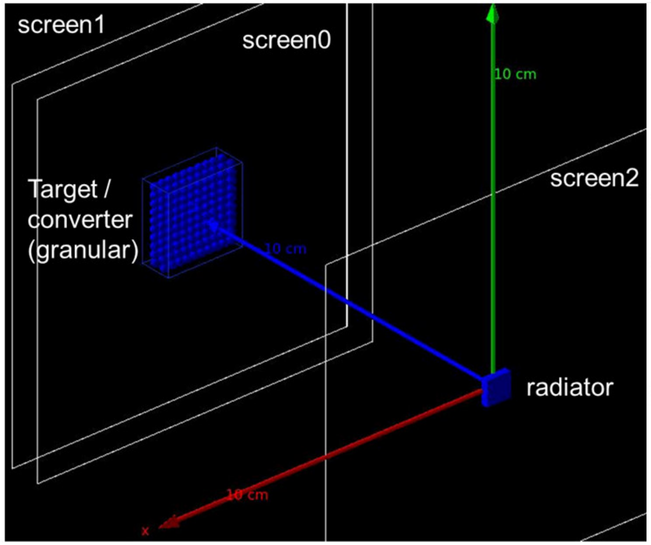
Radiative energy loss measured by the Ecal

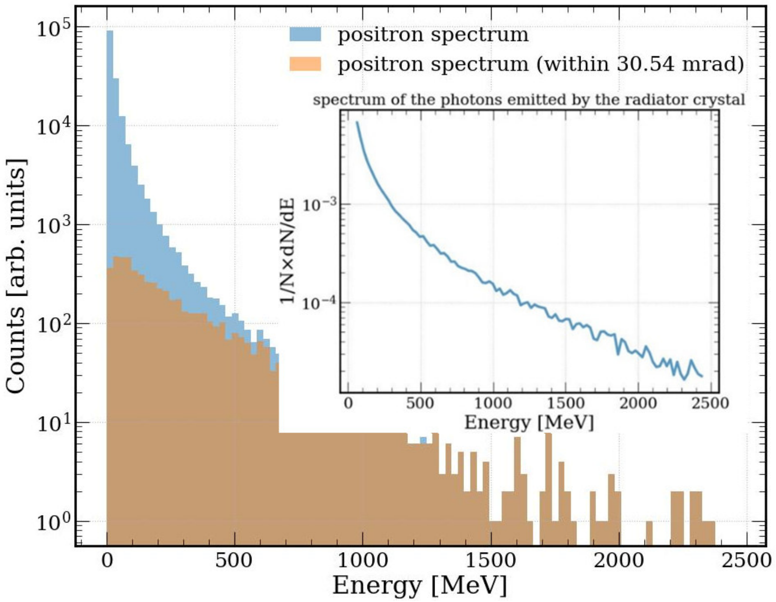


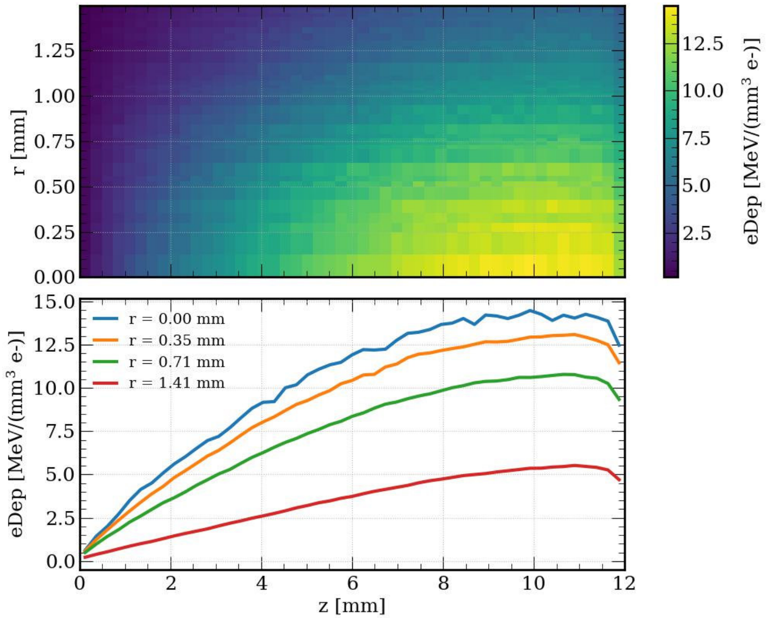
Simulation performed with Geant4 taking advantage of the novel ***G4BaierKatkov*** and ***G4ChannelingFastSimModel***.

Validation of our Geant4 models at an energy significant for FCC-ee positron source.

Simulation of the e+ production stage: **PositronSource** application (now it is on GitHub and will be an extended example of Geant4)

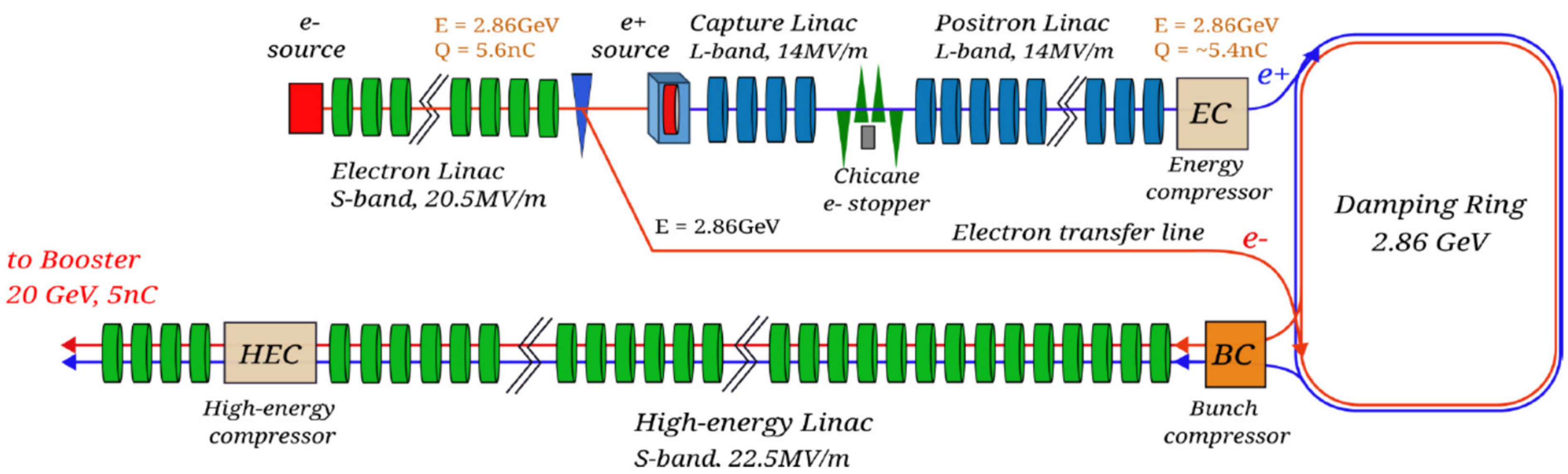






- It allow us to simulate both a **conventional** and a **crystal-based positron source**.
- The code relies on ***G4ChannelingFastSimModel***. Alternatively, a phase-space (e.g. from CRYSTAL code) can be imported.
- A **collimator** or a **magnetic field** can be included in the simulation (**improved hybrid scheme**).
- Scoring of particle phase space at exit of crystals and of energy distribution inside them (**BoxMesh** or custom VoxelScorer).
- The application is fully compatible with **multi-threading** and everything can be controlled via **macro commands**.
- A set of **python scripts** are available for output **analysis** and **positron phase-space export for tracking in the pre-injector**.

FCC-ee positron source requirement and injector layout (current baseline)



To fulfil the requirements for the Z mode → **5.4 nC e+/bunch at the DR*** → **13.5 nC e+/bunch at the exit of the Positron Linac**, considering **60% of losses** due to transport, collimation and injection in the DR (**safety margin of 2.5**). This e+ charge has to be obtained from the following **e- drive beam**

e^- drive beam

Beam energy	2.86 GeV
Bunch charge	~5.6 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

Nb of bunches per pulse	4
Bunch separation	25 ns
Repetition rate	100 Hz
Beam power	~6.4 kW (max)

*positron flux of **~1.35×10^{13} e^+/s.** *Demonstrated at SLC (a world record for existing accelerators):* **~6 $\times10^{12}$ e+/s**

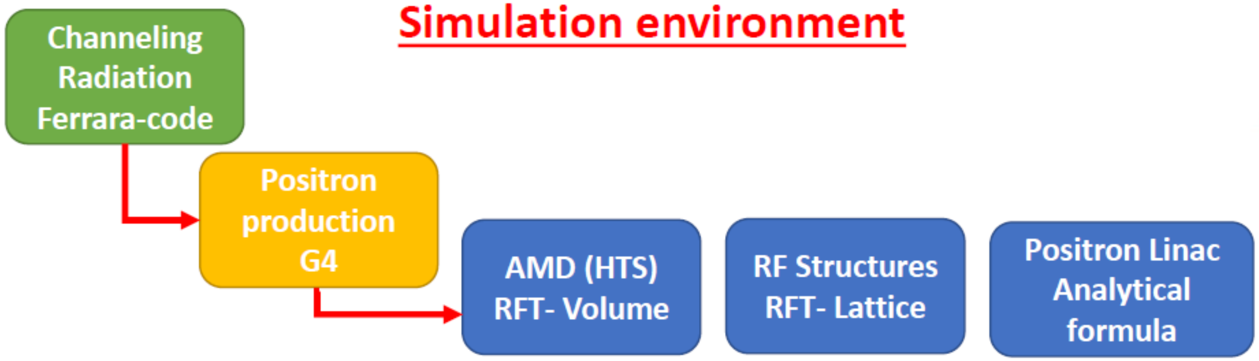
Simulation of the capture / pre-acceleration stages

- After the production, the pair is captured in the pre-injector system.
- The main stages of the pre-injector are simulated through a set of dedicated ***RF-Track**** scripts.

*https://doi.org/10.5281/zenodo.4580369

Collaboration with **FCC-ee Injection Group** - positron source task (leader I. Chaikovska (IJCLab)). MoU signed between in INFN Ferrara and **IJCLab** in Sept. 2022

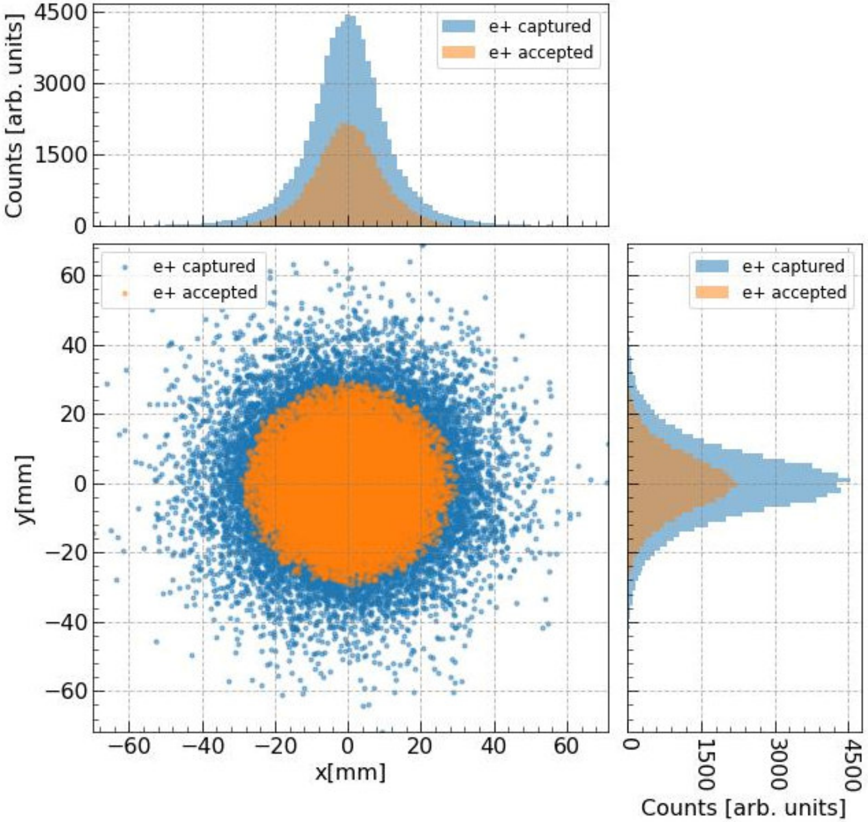
Simulation environment

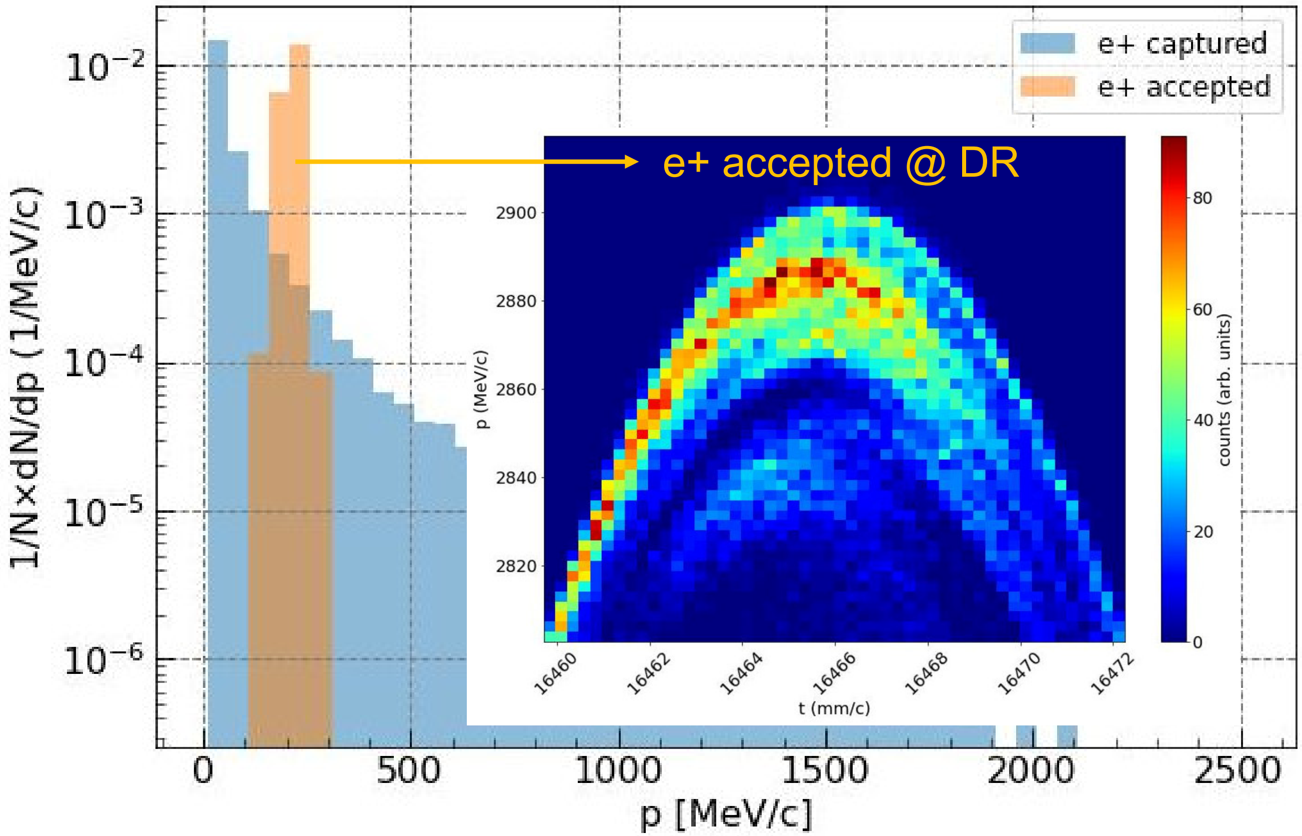


(See **F. Alharthi's presentation** for details)

We measure the performances of e^+ sources **before the damping ring** where cooling occurs (2.5 safety factor)

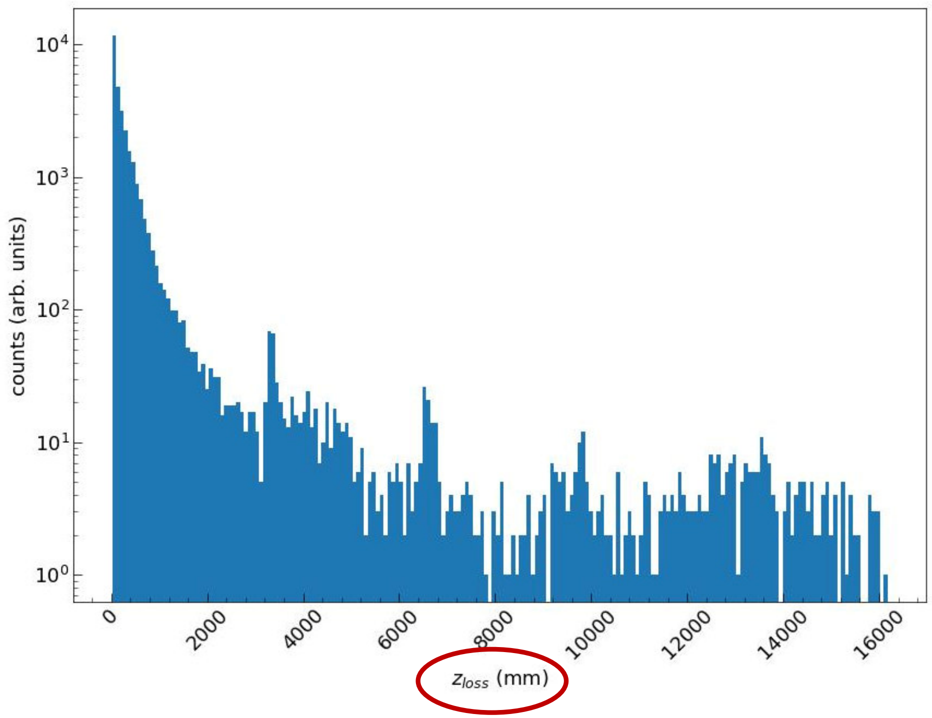
Simulation of the capture / pre-acceleration stages

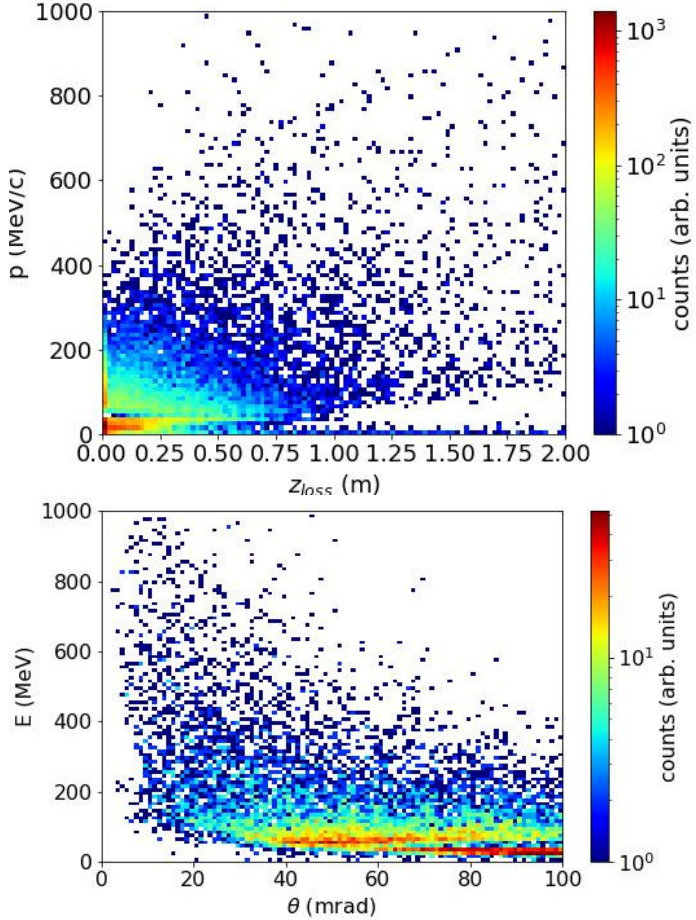




Simulation of the capture / pre-acceleration stages

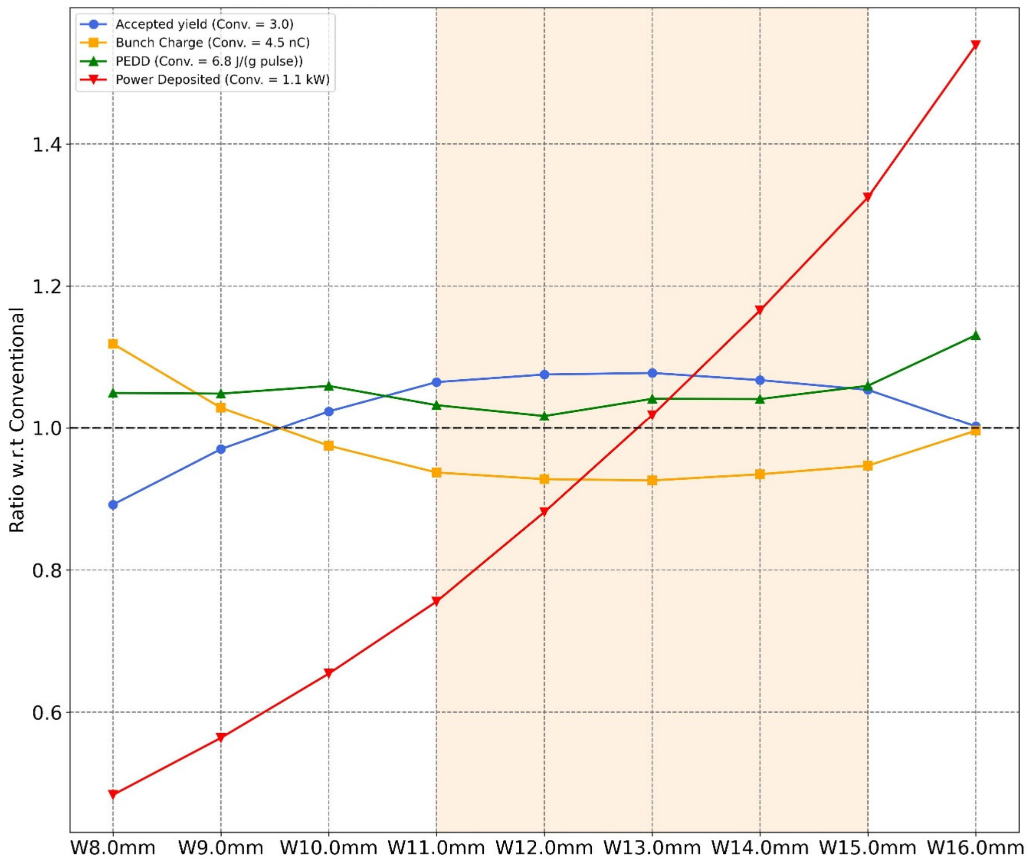
e+ lost within the CS

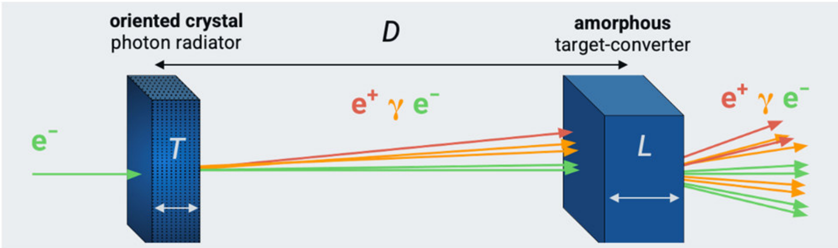




Simulation (Geant4 + RF-Track) results for 2.86 GeV FCC-ee positron source (aftet the positron linac)

Sigle W<111> oriented crystal of **varing T (room temp)**





Simulation studies converge to a **total W thickness of about 12 mm** (~3.4 X_0) → need **D~0** (2 targets) or **a one thick single-crystal**.

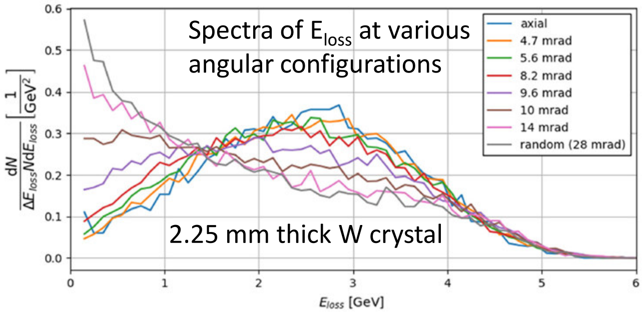
The Single Crystal **PEDD** is **acceptable** considering FCC-ee parameters [max 10.5 J/g/pulse].

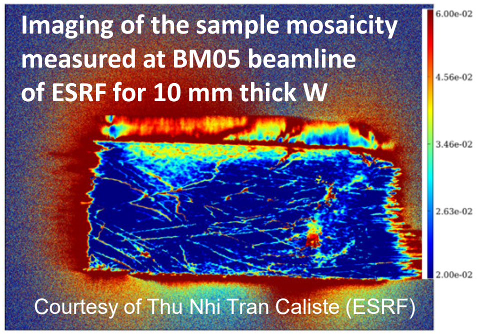
We can use **just one device** to obtain +8% e+ yield and -15% power at «**zero cost**».

Integration and operation of the crystal target: effect of misalignments and high temperature

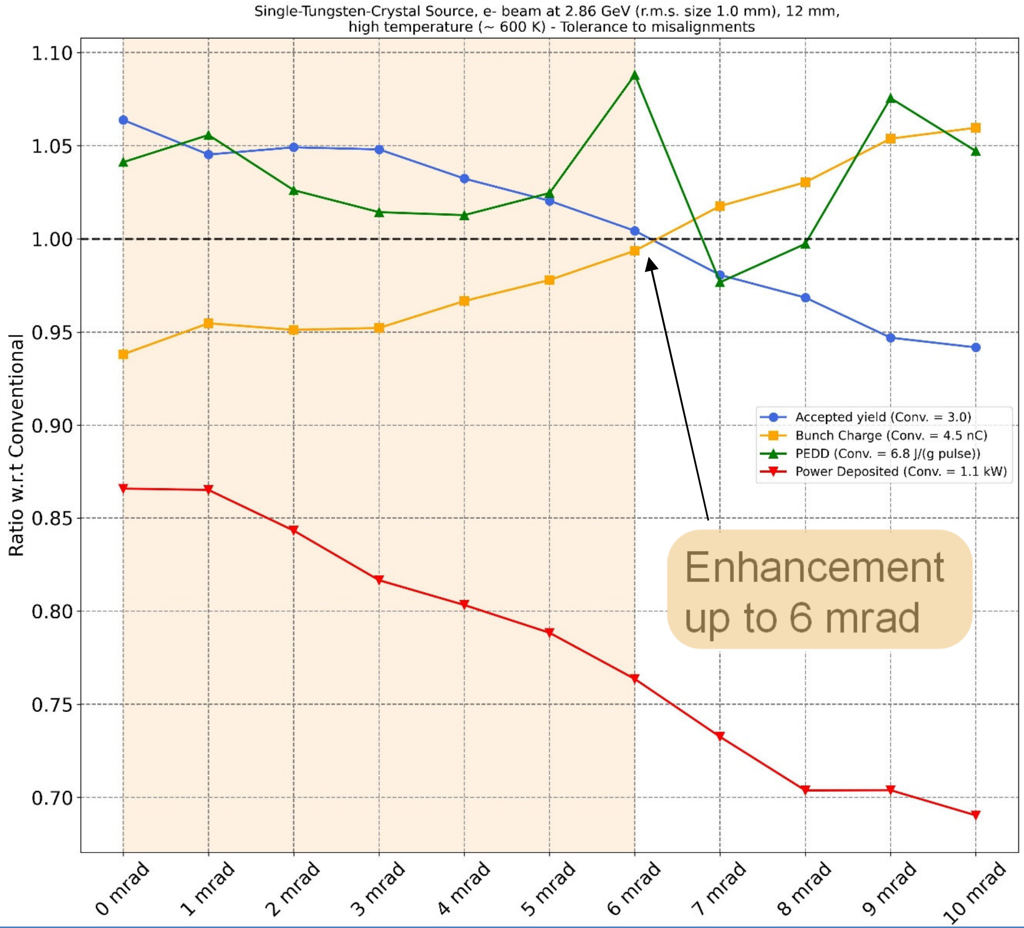
- **Crystal heating:** The photon yield drops insignificantly for temperatures ~ 600 K
- **Crystal alignment:** No goniometer inside the AMD-HTS. The typical precision of the pre-alignment procedure ~ 1 mrad (margins of improvement).
- **Crystal quality:** The crystalline quality of ~ 10 mm thick W sample is lower than for a thin sample → lower yield, but larger acceptance angles.

Beam test at the DESY TB 21 with 5.6 GeV





At local level: mosaicity is contained within 0.2 – 0.4 mrad
At larger scale: separate crystal domains (on 10x10x10 mm^3, total angular distribution of all the crystals domains is within 8.7 mrad)



And what about the other lepton colliders?

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

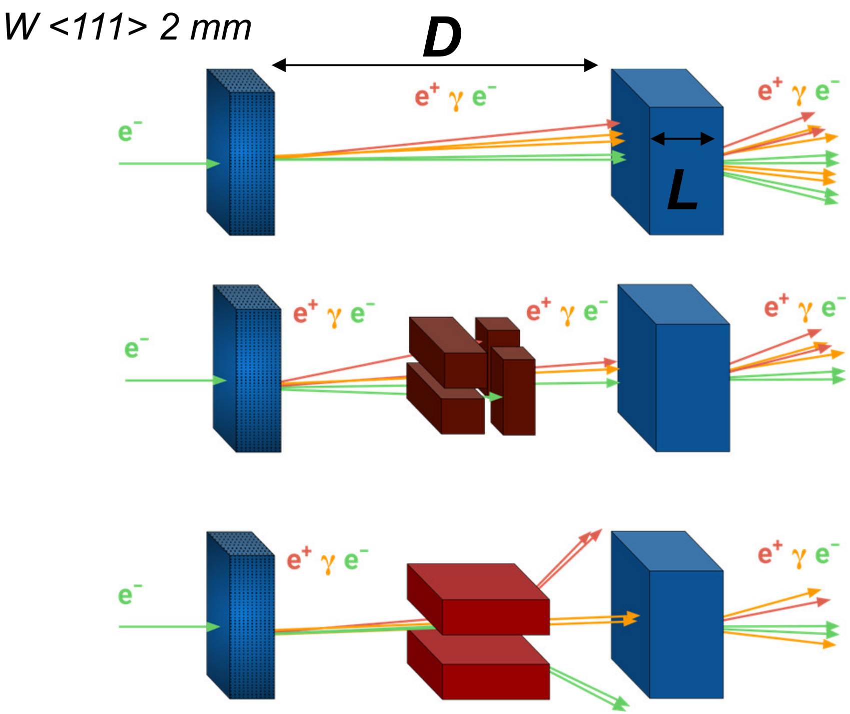
* The parameters are given for the electron-driven positron source being under consideration.
** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.
*** Polarization is considered as an upgrade option.

I. Chaikovska et al., Positron sources: from conventional to advanced accelerator concepts-based colliders 2022 JINST 17 P05015

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

- The future Linear Colliders **CLIC** and **ILC** designs foresee a positron rate higher than FCC-ee by a factor 20 ÷ 30;
- The **LHeC** and **LEMMA** proposals aim at extremely high rates, about two order of magnitude higher than CLIC and ILC.

Improved hybrid source…



Scheme	conv.	hybrid						
L_{crys} [mm]	–	2						
D [m]	–	0.6	1			2		
L [mm]	17.6	11.6						
Collimator?	no	no	no	yes	no	no	yes	no
Magnet?	no	no	no	no	yes	no	no	yes
E_{dep} [GeV/e^-]	1.46	1.34	1.32	1.13	1.32	1.27	1.11	1.27
PEDD [MeV/(mm$^3 \cdot e^-$)]	38.3	12.8	8.4	8.2	8.4	4.1	3.8	3.9
Out. e^+/e^-	13.7	15.1	15.1	13.6	15	14.9	13.7	14.9
Out. e^+ beam size [mm]	0.7	1	1.2	1.2	1.2	1.5	1.5	1.5
Out. e^+ beam div. [mrad]	25.9	27.4	26.8	27.7	28.9	29.2	25.6	27.1
Out. e^+ mean energy [MeV]	48.7	46.2	45.6	47.4	45.9	46.1	47.7	46.3
Out. n/e^-	0.37	0.31	0.31	0.27	0.29	0.29	0.26	0.3
Out. γ/e^-	299	310	308	270	307	301	268	301

***For FCC-ee @ 6 GeV**, M. Soldani et al., NIMA 1058 (2024) 168828*

PEDD decreased in case of hybrid, while yield was equal or higher w.r.t. conventional (even if more loss within CS).
The scheme with magnet is the baseline for CLIC and was proposed for LHeC/LEMMA (several hybrid targets in parallel with cooled, rotating/granular converter)

Conclusions

- A **reliable simulation framework** from the target to the positron linac **is available**.
- The **design** of a **crystal-based positron source** for the **FCC-ee @ 2.86 GeV** is well advanced (otpimization of the capture section of pre-injector still ongoing). The **goal** is to include the design in the next FCC CDR.
- **Next steps**: **integration studies** with potential **proof-of-principle** at **P^3** experiment @ PSI (and future CHART projects).
- **Missing**: test of positron production with single crystal without goniometer and of radiation resistance.
- The **PositornSource application** allow us to investigate also the improved hybrid scheme useful for very intense positron sources.

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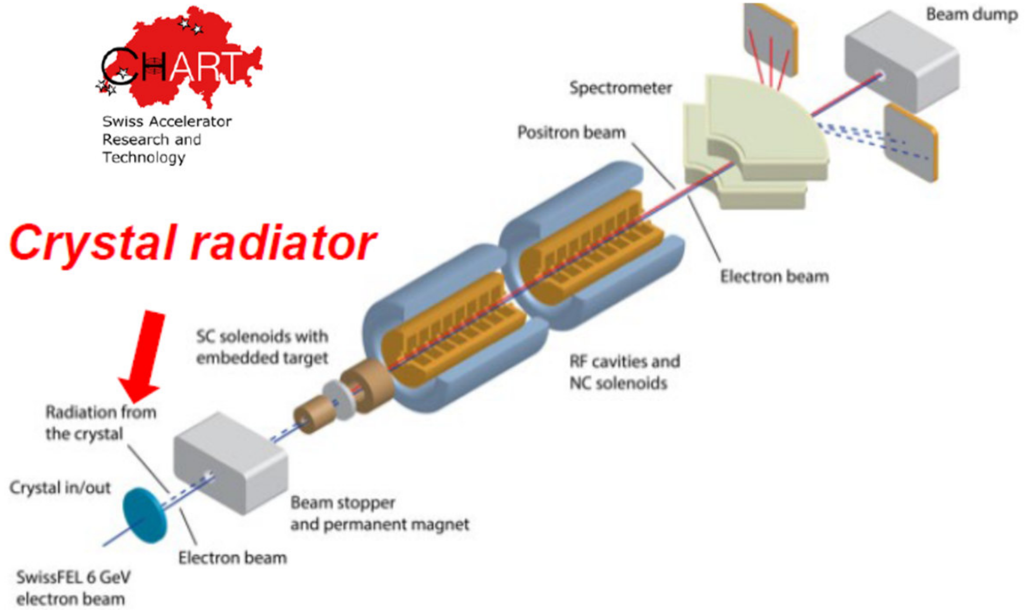

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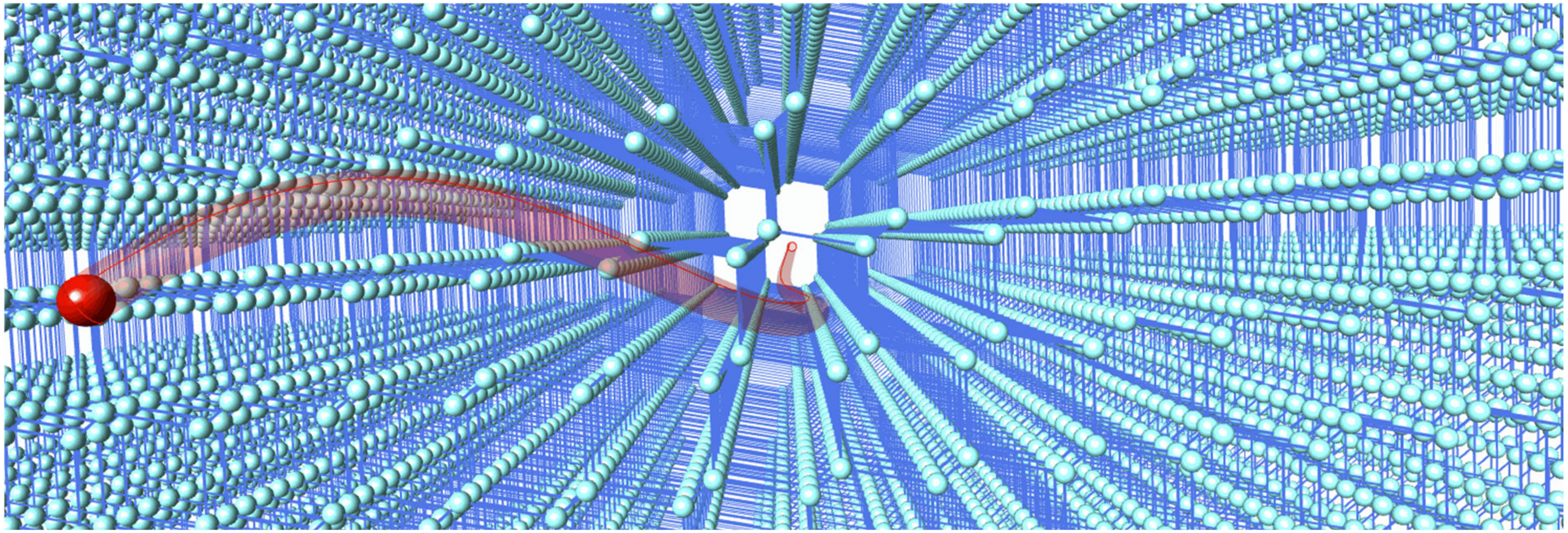

My email address: paterno@fe.infn.it

Back-up slides

Conventional, room temperature

W, e- beam at 2.86 GeV (r.m.s. size 1.0 mm), room temperature

Case	photon Yield	neutron Yield	Target Yield	e+ beam mean size [mm]	Edep [GeV/e-]	PEDD [MeV / (mm^3 e-)]	AMD Yield (R=30 cm)	Collection Efficiency [%]	Yield RF	Emean RF [MeV]	Espread RF [%]	Bunch Length [mm]	Accepted Yield	Bunch Charge [nC]	PEDD [J/g/pulse]	Power Deposited [kW]
conventional	150.04	0.34	7.09	1.16	0.65	7.42	6.42	90.61	4	214.52	16.54	2.73	3.04	4.45	6.84	1.15
W5.0mm	26.33	0.03	2.33	1.03	0.05	2.51	2.21	94.82	1.09	212.74	34.67	2.61	0.85	15.92	8.3	0.31
W6.0mm	35.8	0.04	3.04	1.03	0.07	3.44	2.86	94.05	1.45	212.7	30.33	2.62	1.12	12.11	8.65	0.36
W7.0mm	47.15	0.07	3.79	1.06	0.11	3.77	3.54	93.46	1.85	212.29	25.27	2.65	1.44	9.36	7.33	0.41
W8.0mm	59.92	0.09	4.53	1.07	0.15	4.58	4.2	92.76	2.27	212.32	22.64	2.68	1.76	7.66	7.29	0.47
W9.0mm	72.68	0.13	5.15	1.09	0.2	5.34	4.75	92.25	2.64	212.6	20.6	2.67	2.04	6.62	7.35	0.53
W10.0mm	86.14	0.14	5.73	1.08	0.26	6.22	5.27	91.87	3	212.3	19.19	2.69	2.31	5.85	7.57	0.6
W11.0mm	100.62	0.18	6.25	1.11	0.33	6.58	5.7	91.3	3.32	213.33	17.64	2.71	2.56	5.27	7.21	0.69
W12.0mm	113.86	0.21	6.62	1.1	0.4	6.9	6.03	91.15	3.58	213.63	18.16	2.71	2.76	4.89	7.01	0.78
W13.0mm	127.03	0.25	6.89	1.13	0.48	7.32	6.27	90.88	3.83	213.67	15.72	2.7	2.92	4.63	7.04	0.88
W14.0mm	139.18	0.28	7.05	1.14	0.56	7.65	6.4	90.7	3.96	214.15	15.89	2.73	3.01	4.49	7.14	1.01
W15.0mm	150.04	0.34	7.09	1.16	0.65	7.42	6.42	90.61	4	214.47	16.55	2.72	3.02	4.47	6.89	1.16
W16.0mm	160.18	0.39	7.1	1.19	0.74	7.53	6.41	90.36	4.07	214.92	15.58	2.73	3.07	4.4	6.88	1.29
W17.0mm	169.33	0.45	7.05	1.19	0.83	7.67	6.35	90.08	4.07	215.15	15.43	2.72	3.04	4.44	7.08	1.47
W18.0mm	177.16	0.45	6.85	1.21	0.92	7.89	6.16	89.9	3.97	215.45	15.49	2.76	2.96	4.56	7.48	1.68
W19.0mm	183.81	0.51	6.69	1.24	1.01	7.43	6.01	89.72	3.91	215.98	15.73	2.75	2.89	4.67	7.21	1.89
W20.0mm	188.43	0.57	6.4	1.23	1.1	7.69	5.73	89.41	3.76	215.83	15.44	2.77	2.79	4.84	7.73	2.13

Single Crystal, room temperature

Single-Tungsten-Crystal Source, e- beam at 2.86 GeV (r.m.s. size 1.0 mm), room temperature

Case	photon Yield	neutron Yield	Target Yield	e+ beam mean size [mm]	Edep [GeV/e-]	PEDD [MeV / (mm^3 e-)]	AMD Yield (R=30 cm)	Collection Efficiency [%]	Yield RF	Emean RF [MeV]	Espread RF [%]	Bunch Length [mm]	Accepted Yield	Bunch Charge [nC]	PEDD [J/g/pulse]	Power Deposited [kW]
conventional	150.04	0.34	7.09	1.16	0.65	7.42	6.42	90.61	4	214.52	16.54	2.73	3.04	4.45	6.84	1.15
W8.0mm	97.31	0.15	6.53	1.09	0.28	6.94	5.99	91.79	3.5	213.03	20.85	2.69	2.71	4.98	7.18	0.56
W9.0mm	112.33	0.2	7	1.1	0.35	7.54	6.41	91.53	3.85	213.45	19.41	2.69	2.95	4.58	7.17	0.65
W10.0mm	126.51	0.23	7.31	1.1	0.43	8.04	6.66	91.03	4.08	213.94	17.8	2.71	3.11	4.34	7.25	0.75
W11.0mm	140.35	0.27	7.52	1.13	0.52	8.15	6.84	90.93	4.26	214.09	16.71	2.71	3.24	4.17	7.06	0.87
W12.0mm	153.52	0.31	7.58	1.17	0.61	8.11	6.87	90.71	4.33	214.61	17.54	2.73	3.27	4.13	6.96	1.01
W13.0mm	164.75	0.37	7.5	1.16	0.71	8.32	6.79	90.52	4.35	214.61	15.69	2.73	3.28	4.12	7.12	1.17
W14.0mm	174.22	0.41	7.42	1.19	0.81	8.24	6.7	90.25	4.32	214.87	16.02	2.76	3.25	4.16	7.12	1.34
W15.0mm	182.76	0.47	7.27	1.2	0.9	8.28	6.55	90.04	4.29	215.5	15.3	2.78	3.2	4.21	7.25	1.52
W16.0mm	189.18	0.51	6.98	1.23	1	8.4	6.27	89.83	4.12	216.04	15.17	2.77	3.05	4.43	7.74	1.77

Single Crystal – HT, misalignment

Single-Tungsten-Crystal Source, e- beam at 2.86 GeV (r.m.s. size 1.0 mm), 12 mm, high temperature (~ 600 K) - Tolerance to misalignments

Case	photon Yield	neutron Yield	Target Yield	e+ beam mean size [mm]	Edep [GeV/e-]	PEDD [MeV / (mm^3 e-)]	AMD Yield (R=30 cm)	Collection Efficiency [%]	Yield RF	Emean RF [MeV]	Espread RF [%]	Bunch Length [mm]	Accepted Yield	Bunch Charge [nC]	PEDD [J/g/pulse]	Power Deposited [kW]
conventional	150.04	0.34	7.09	1.16	0.65	7.42	6.42	90.61	4	214.52	16.54	2.73	3.04	4.45	6.84	1.15
0 mrad, 300K	153.52	0.31	7.58	1.17	0.61	8.11	6.87	90.71	4.33	214.61	17.54	2.73	3.27	4.13	6.96	1.01
0 mrad	150.15	0.31	7.49	1.16	0.6	8.21	6.79	90.65	4.28	214.18	17.5	2.72	3.23	4.17	7.12	1
1 mrad	148.01	0.31	7.43	1.14	0.59	8.18	6.74	90.63	4.19	214.37	15.97	2.72	3.18	4.25	7.22	0.99
2 mrad	146.04	0.29	7.43	1.16	0.57	7.98	6.73	90.64	4.2	214.35	16.2	2.73	3.19	4.23	7.02	0.97
3 mrad	143.27	0.28	7.4	1.15	0.55	7.88	6.7	90.53	4.17	214.43	16.11	2.73	3.19	4.24	6.94	0.94
4 mrad	140.18	0.29	7.32	1.15	0.54	7.75	6.64	90.73	4.11	214.08	15.86	2.71	3.14	4.3	6.93	0.92
5 mrad	137.45	0.28	7.28	1.17	0.52	7.75	6.61	90.73	4.07	214.34	16.05	2.72	3.1	4.35	7.01	0.91
6 mrad	133.22	0.26	7.18	1.14	0.5	8.1	6.52	90.76	3.99	214.18	16.1	2.7	3.05	4.42	7.44	0.88
7 mrad	127.21	0.25	7.03	1.16	0.47	7.1	6.39	90.93	3.9	213.74	16.64	2.71	2.98	4.53	6.68	0.84
8 mrad	122.63	0.23	6.93	1.13	0.44	7.16	6.3	90.99	3.83	214.23	17.7	2.7	2.94	4.59	6.82	0.81
9 mrad	120.72	0.23	6.84	1.13	0.43	7.55	6.22	91.01	3.75	213.93	15.78	2.72	2.88	4.69	7.36	0.81
10 mrad	118.64	0.23	6.81	1.14	0.42	7.31	6.19	90.97	3.74	213.75	17.77	2.72	2.86	4.72	7.16	0.79