Performance of the pre-injector with a crystal-based positron source

Gianfranco Paternò (INFN- Ferrara)

Based on the F. Alharthi's presentation at AHIPS-2024 workshop
(https://indico.ijclab.in2p3.fr/event/10644/timetable/#20241016.detailed)

On Behalf of L. Bandiera, A. Sytov, N. Canale, M. Romagnoni, A. Mazzolari, R. Negrello, L. Malagutti, V. Guidi, **F. Alharthi**, I. Chaikovska, V. Mytrochenko, R. Chehab, Y. Wang, D. Boccanfuso, O. M. Iorio, D. De Salvador, F. Sgarbossa, D. Valzani, M. Soldani, S. Bertelli, M. Prest, E. Vallazza, S. Carsi, A. Selmi, S. Mangiacavalli, G. Saibene, G. Zuccalà, P. Monti-Guarnieri, V. Tikhomirov, V. Haurylavets, and **FCC-ee injector study collaboration**

e+BOOST
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Outlook

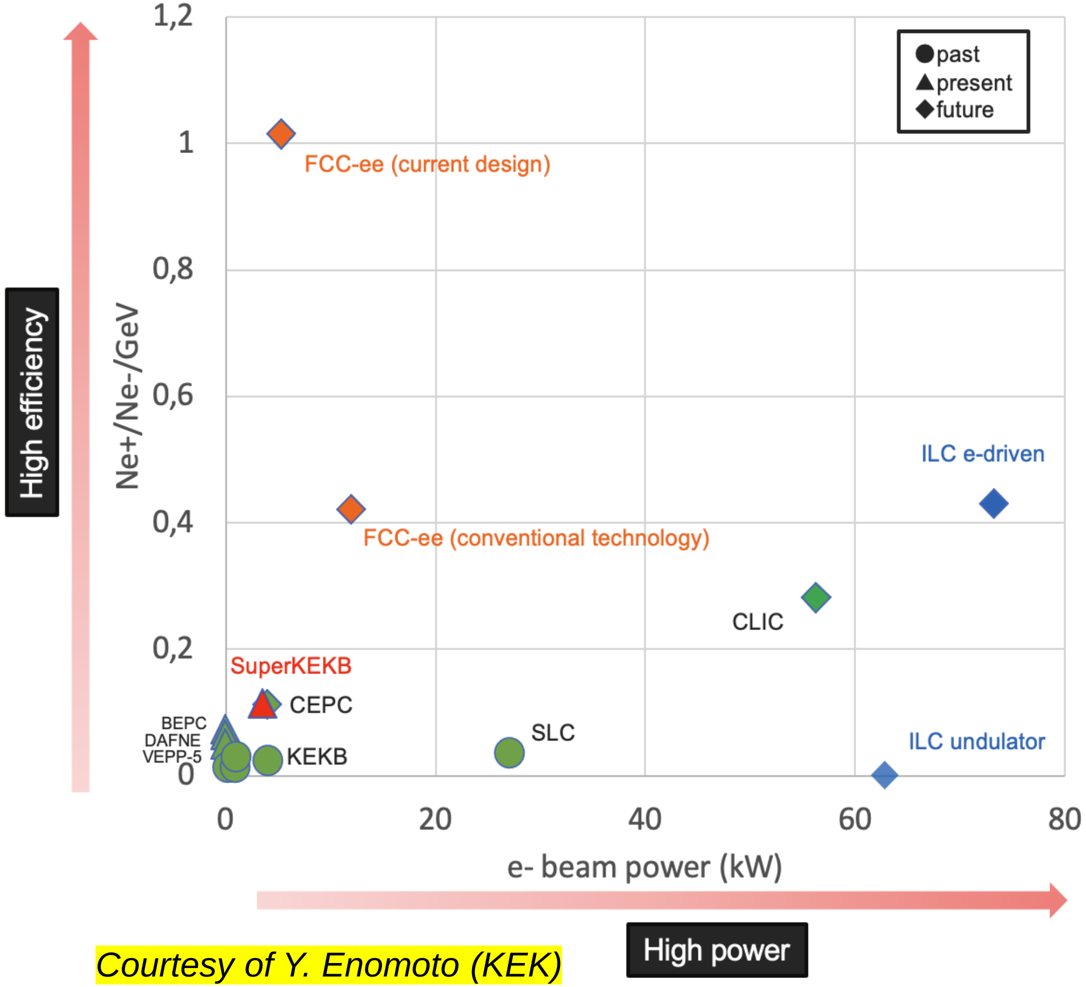
- Review of and FCC-ee and the scheme of the injector
- Optimization approach of a crystal-based positron source through an experimentally validated simulation framework
- Optimized solution for FCC-ee positron source

Performance of FCC-ee and other positron sources

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

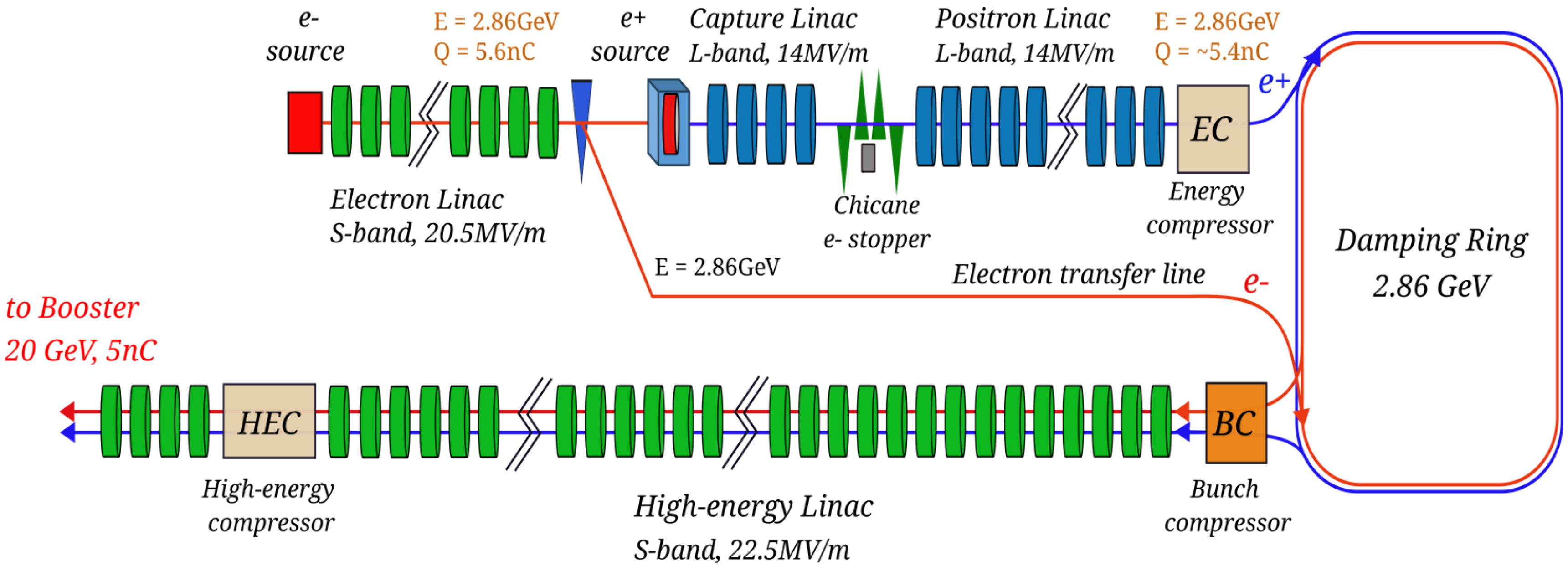
It is the most demaning for the positron source

- Key factors for **high positron yield**: $\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$
  - Primary e- energy
  - Target design
  - Magnetic strength around the target and capture linac
  - Transverse aperture of the capture linac.
- The use of an **HTS solenoid** with a peak field of **~12T** around the target can substantially increase state-of-the-art e+ yield, by one order of magnitude.



Courtesy of Y. Enomoto (KEK)

FCC-ee 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**

- Latest proposal: injector complex on the Prévessin site with damping ring next to the “decheterie”
- High-energy linac next to North Area and Beam Dump Facility

e^- drive beam

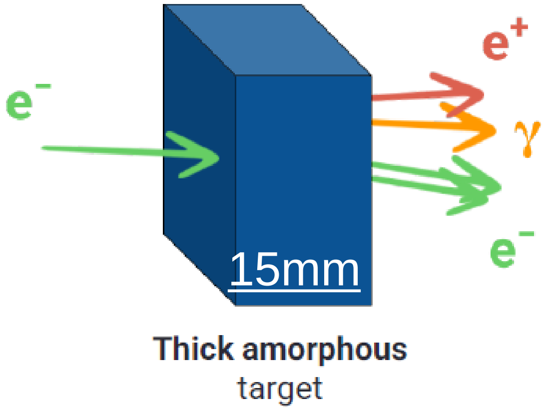
Beam energy	2.86 GeV
Bunch charge	~5.6 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

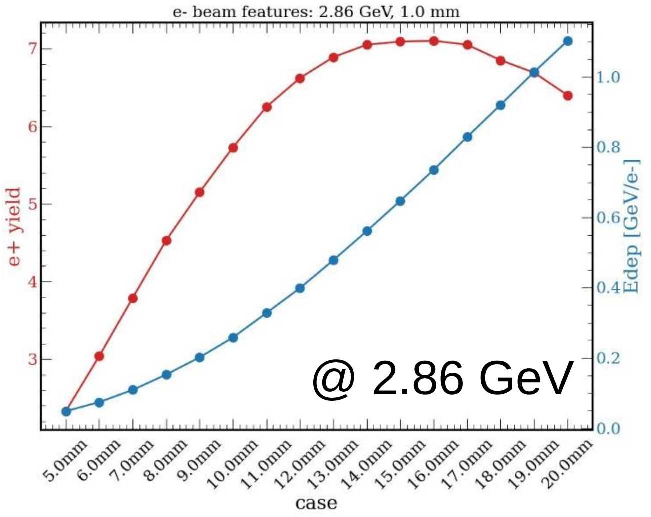
Nb of bunches per pulse	4
Bunch separation	25 ns
Repetition rate	100 Hz
Beam power	~6.4 kW (max)

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

Conventional vs Crystal-based e+ source schemes

Conventional scheme: Bremsstrahlung -> Pair production (well understood and used in current and previous positron sources)

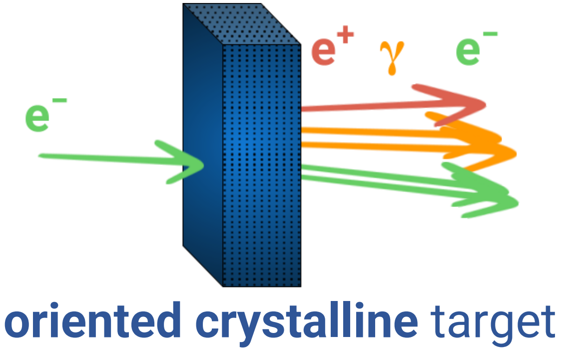




Considered parameters for positron source target:

- Positron production (*high Z-material*)
- Energy deposition (*target heating, cooling requirements*)
- Peak Energy deposition density “PEDD” (*Instantaneous, thermomechanical stress due to temperature gradient*.)
- Radiation around the target (*shielding requirements*)
- Huge emittance/angular divergence (*immediate matching*)

Crystal-based scheme: Use of coherent effects in oriented crystals: **channeling** and **over barrier motion** to **enhance the production of (“soft”) photons and positrons** and reduce the deposited power (and the PEDD with hybrid scheme)



See A. Sytov’s presentation

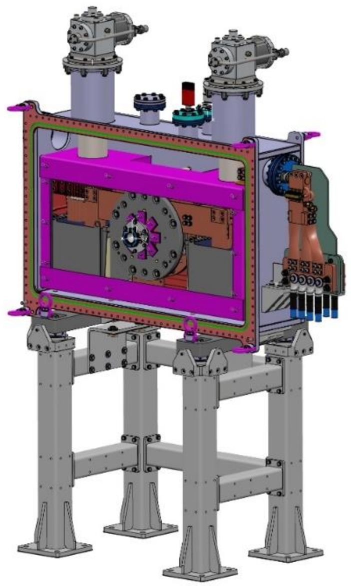
Positron source set a critical constraint for the peak and average current -> **Luminosity Constraint!** Especially for future Linacs -> **crystal-based positrons sources**

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 P^3**

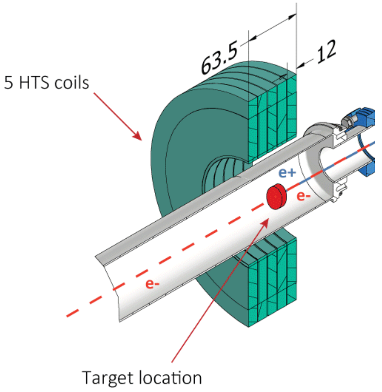
Positron source (adiabatic) matching device

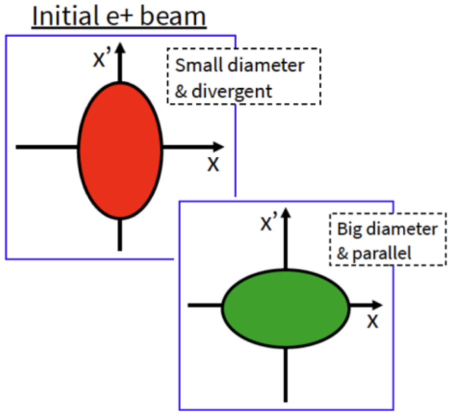
Matching device => a fast phase space rotation to transform the small size/high divergence in big sizes/low divergence beam

HTS solenoid integrated in the cryostat

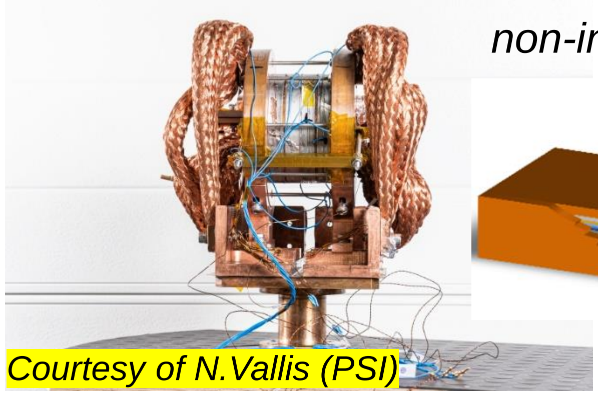


The same HTS solenoid design and cryostat aperture as for P^3 experiment (72 mm).



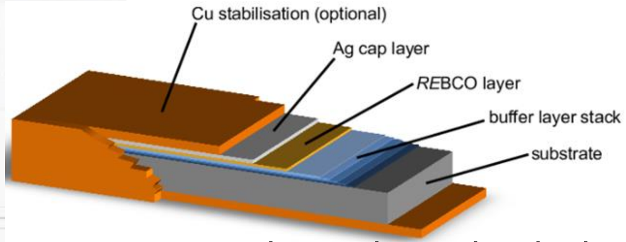


innovative in application for e^+ capture

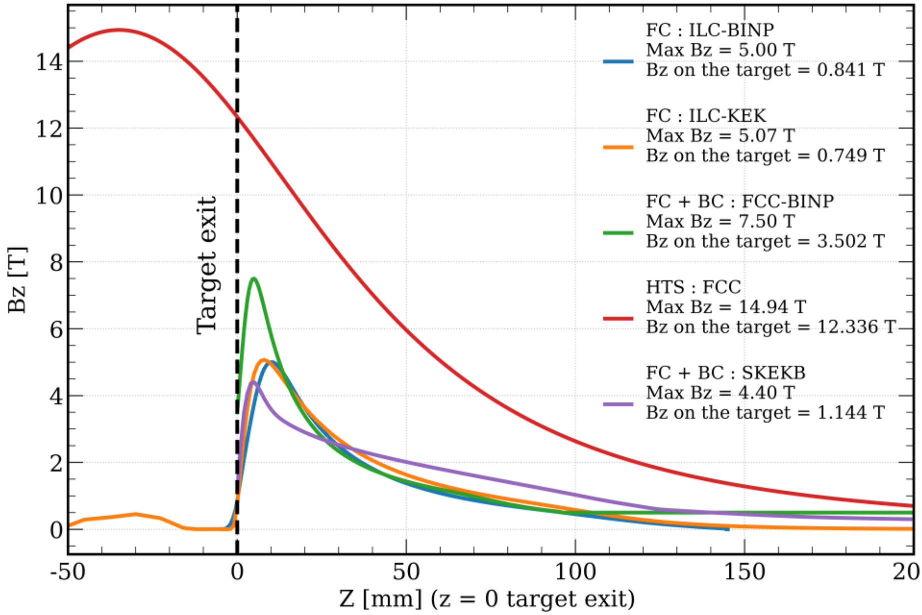


Courtesy of N.Vallis (PSI)

non-insulated coil technology



Better thermal, mechanical, magnetic features



Compared with classical AMD (flux concentrator FC):

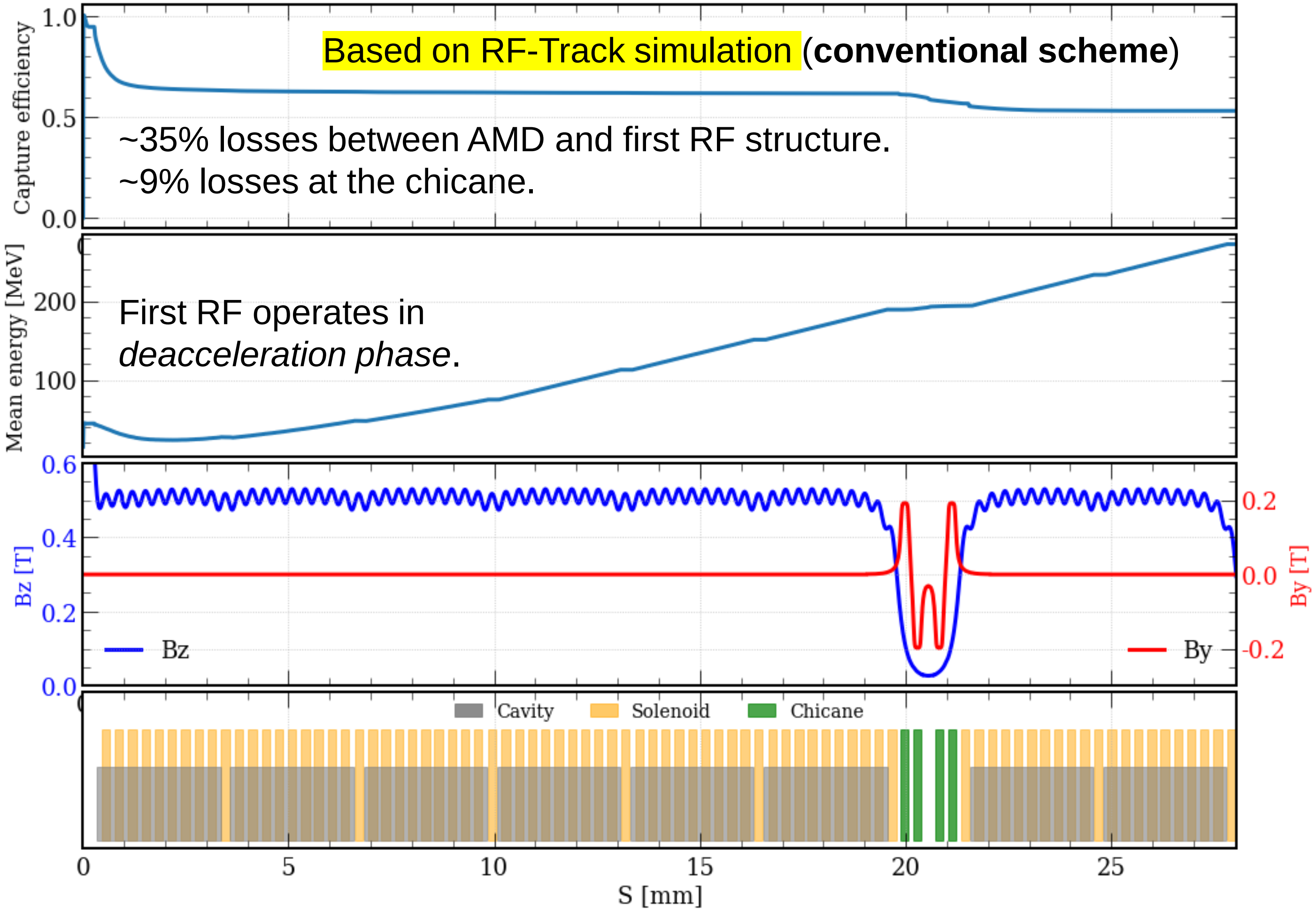
- Higher peak field (~15 T -> ~12 T @Target)
- Larger aperture (∅ = 30-60 mm)
- Flexible target position and field profile
- Axially symmetric solenoid field
- DC operation

Positron source capture LINAC

- **RF structures**: 2GHz L-band with aperture (2a) = 60mm, 3m long and 14MV/m.

- **Solenoids**: 10 NC short solenoids surrounding each RF structure to create 0.5T magnetic channel.

- **Chicane**: 4 dipoles (0.2T) to separate e- and e+, with electron stopper at the middle (to be updated).


Based on RF-Track simulation (**conventional scheme**)

~35% losses between AMD and first RF structure.
~9% losses at the chicane.

First RF operates in *deacceleration phase*.

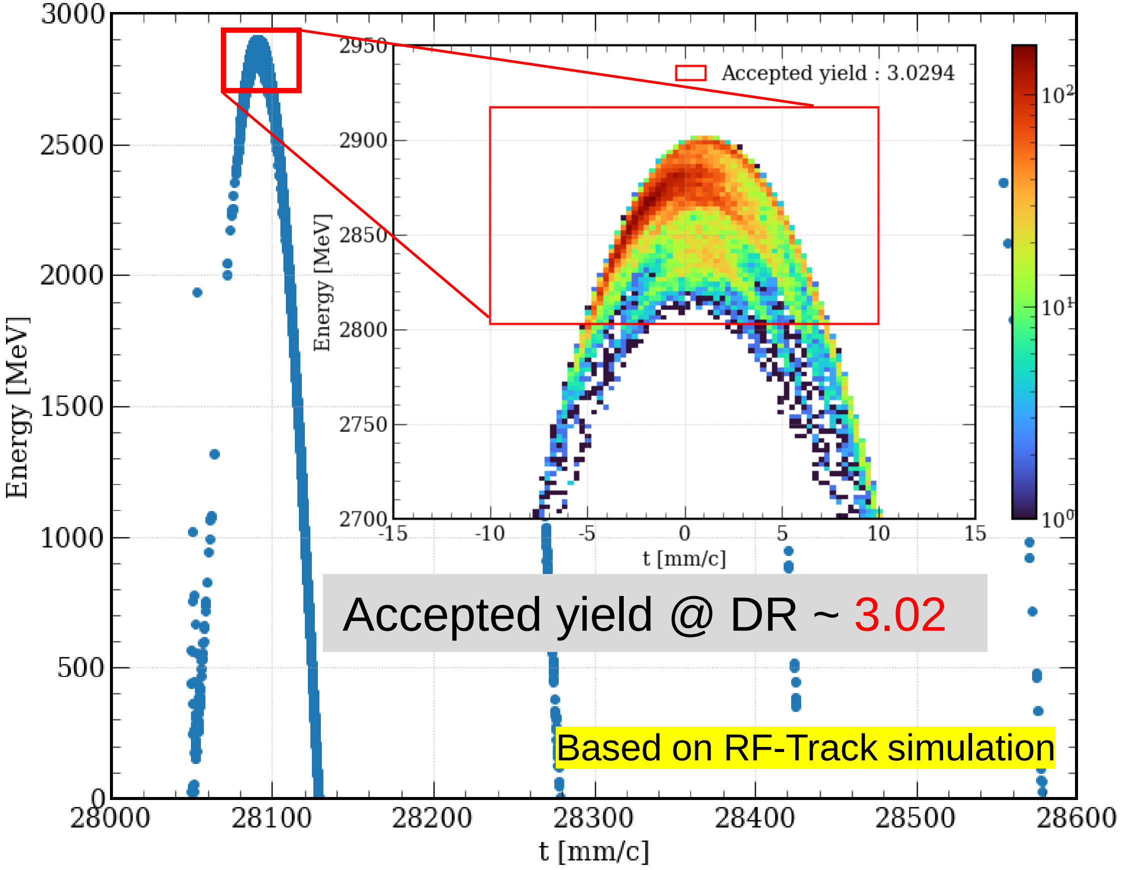
Positron linac + Damping Ring (DR)

- Positron linac (PL) is **under optimization**, composed of two sections with one matching sections:

- PL section 1: **16** RF structures, with solenoids → **~0.821GeV.**
- PL section 2: **52** RF structures, with 2 RF structures per FODO cell → **~2.86 GeV.**

- **New DR is under design and optimization**.
- Energy/time window is used to estimate the accepted yield: (ΔE: ±2%, Δt: 20 mm/c)

Longitudinal phase space and window acceptance*

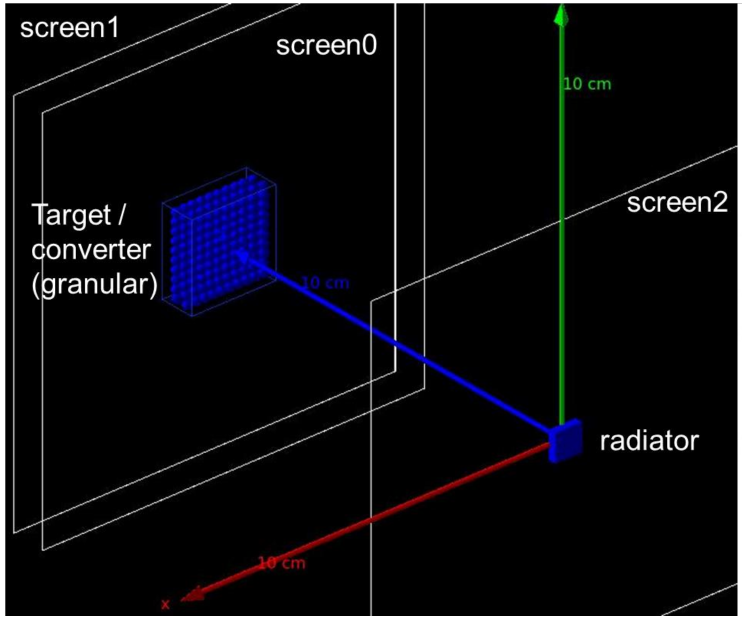


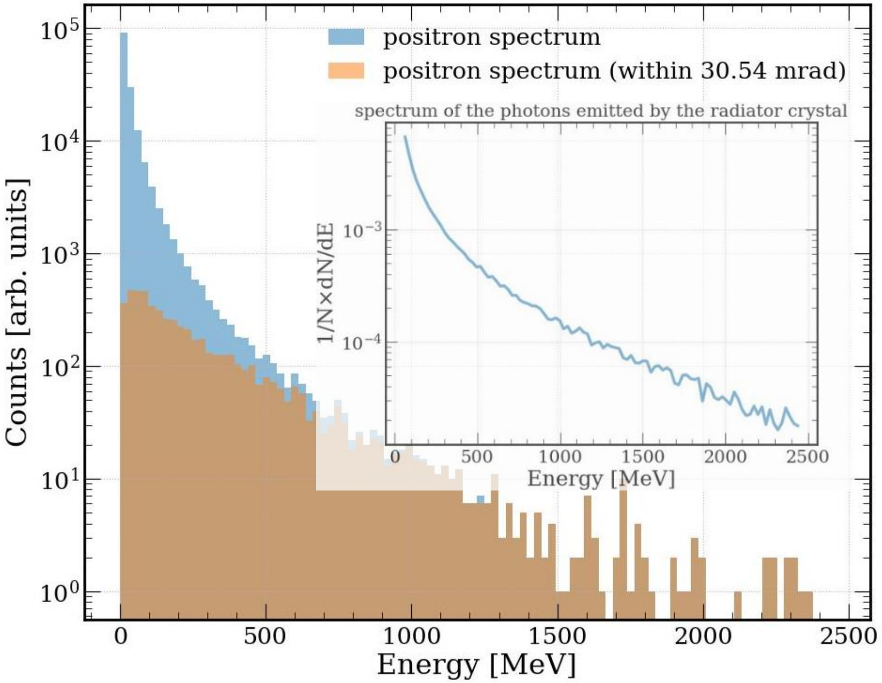
Accepted yield @ DR ~ 3.02

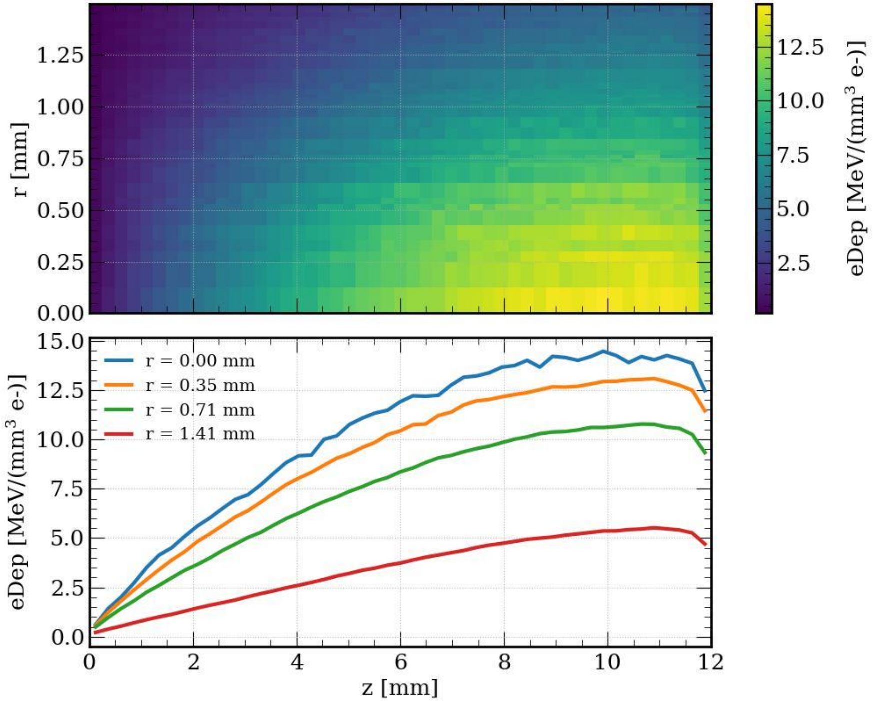
Based on RF-Track simulation

* Simplified longitudinal analytical formula used to track the particles in the positron linac

Simulation of the e+ production stage: **PositronSource** application (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*** (see **A. Sytov's talk**). Alternatively, a phase-space 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**.
- The model has been **validated** at the energy of interest (see **N. Canale's talk**).

Simulation of the e+ capture / pre-acceleration system for the optimization of the crystal target

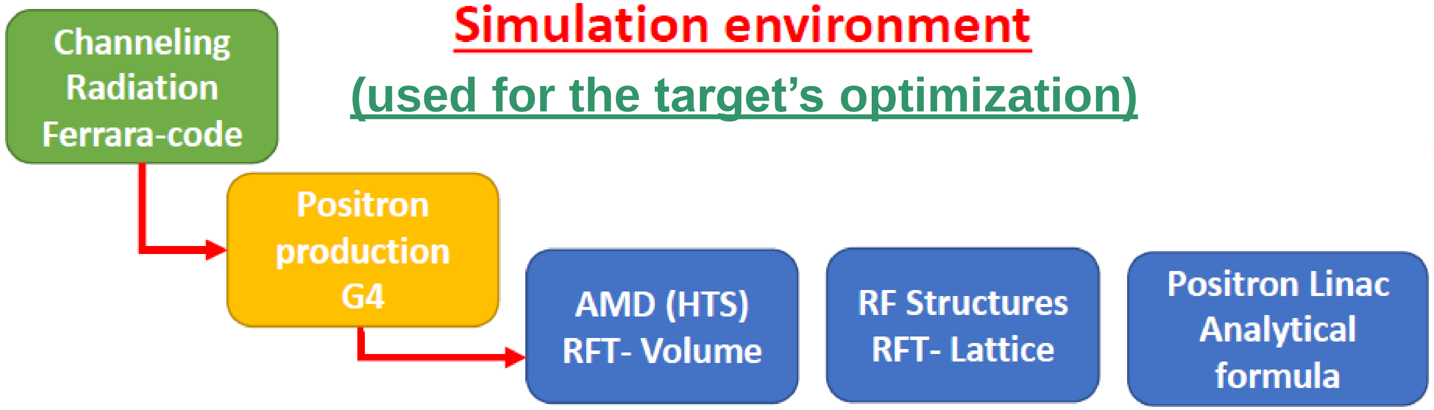
The main stages of the capture / pre-acceleration are simulated through a set of dedicated ***RF-Track***[*] scripts.

[*] *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

(used for the target's optimization)



Channeling Radiation Ferrara-code

Positron production G4

AMD (HTS) RFT- Volume

RF Structures RFT- Lattice

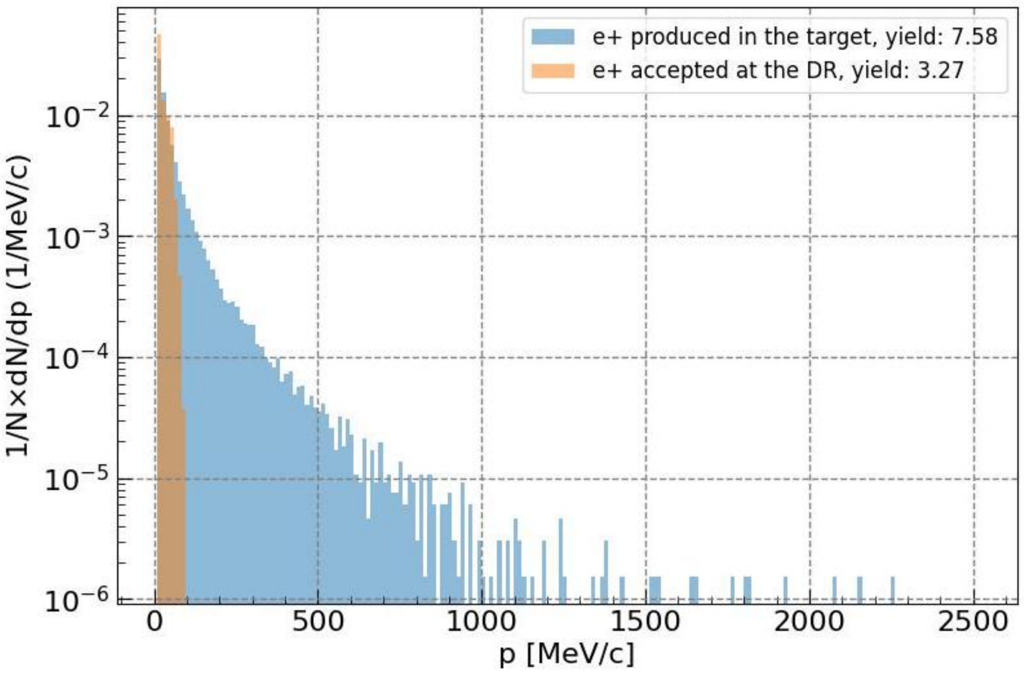
Positron Linac Analytical formula

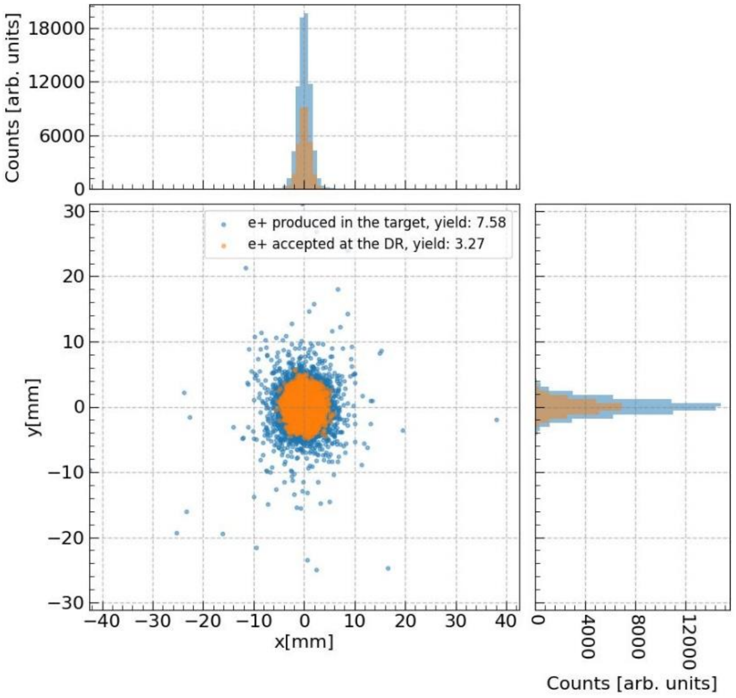
We measure the performances of e^+ sources **before the damping ring** where cooling occurs (2.5 safety factor)

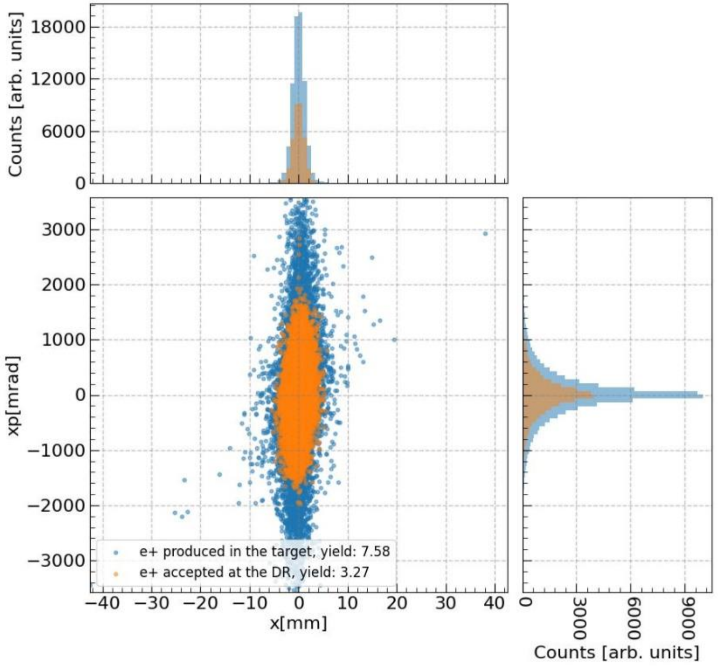
Which positrons are accepted by the DR ?

- Momentum: accepted positrons ≤ 100 MeV/c
  Primary factor

- Transverse beam size and divergence:
  Secondary factors.

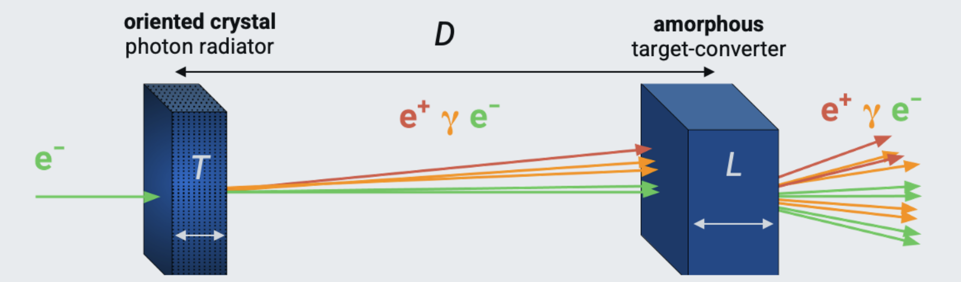






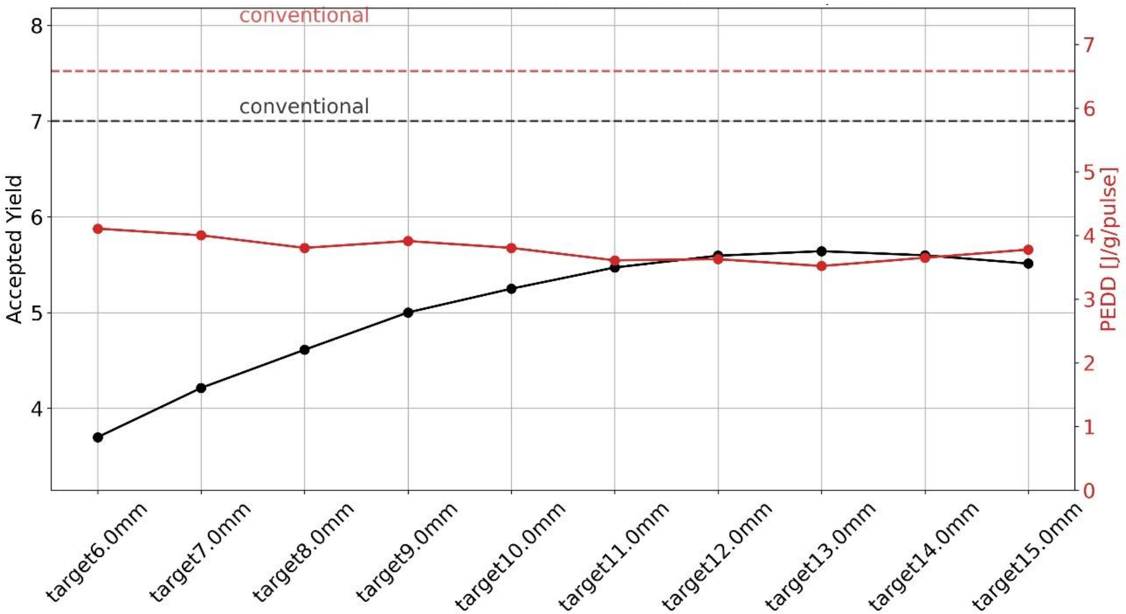
More positrons in the low energy spectrum with lower divergence => increase the accepted yield.

Simulation (Geant4 + RF-Track) results for **6 GeV** FCC-ee positron source (after the positron linac)

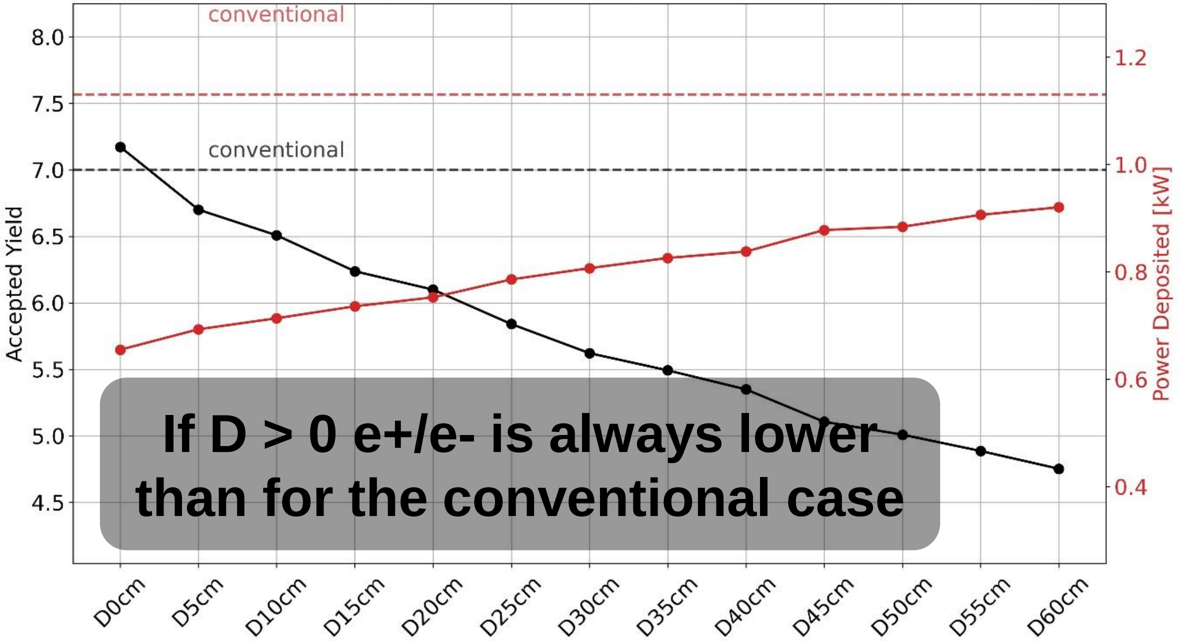


Positron yield, energy deposit and PEDD can be reduced tuning radiator *thickness (T), amorphous thickness (L)* and the distance between them (*D)*

Fixed **T=2 mm** and **D=50 cm**, **varing L**



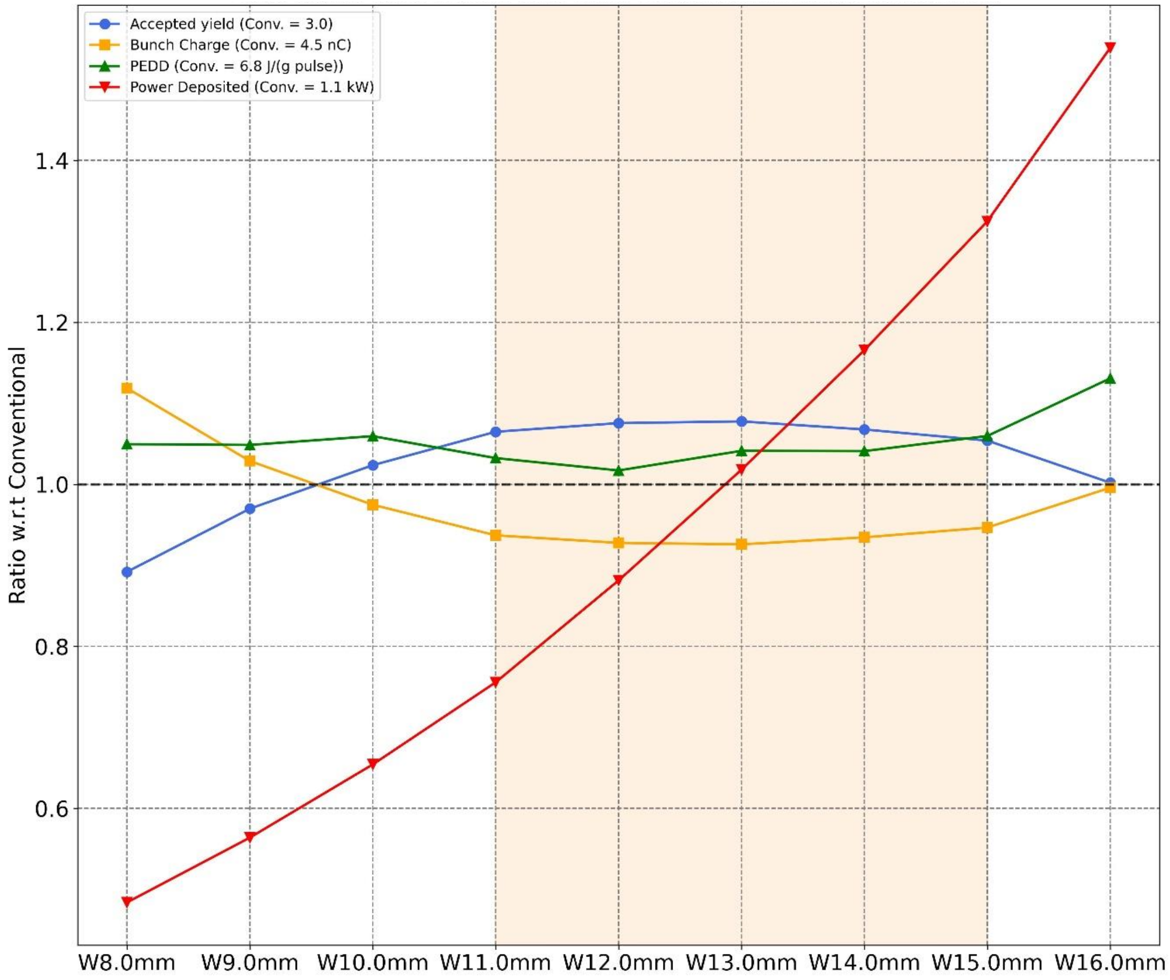
Fixed **T=2 mm** and **L=9 mm**, **varing D**

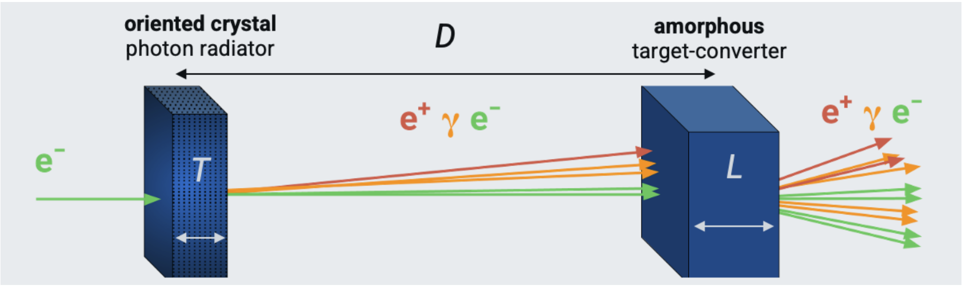


If D > 0 e+/e- is always lower than for the conventional case

Simulation (Geant4 + RF-Track) results for **2.86 GeV** FCC-ee positron source (after 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**.

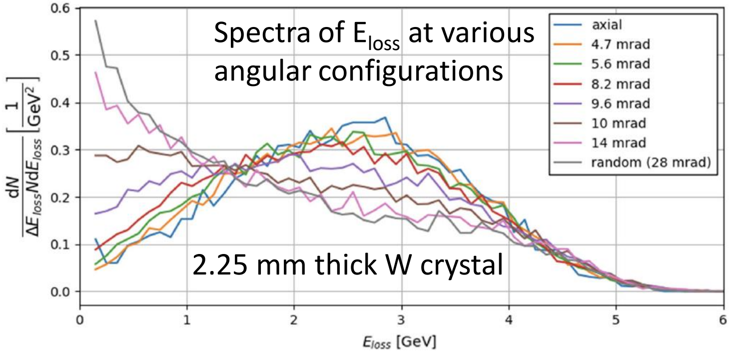
The Single Crystal **PEDD** is **acceptable** considering FCC-ee parameters [max safe value for W is 35 J/g/pulse].

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

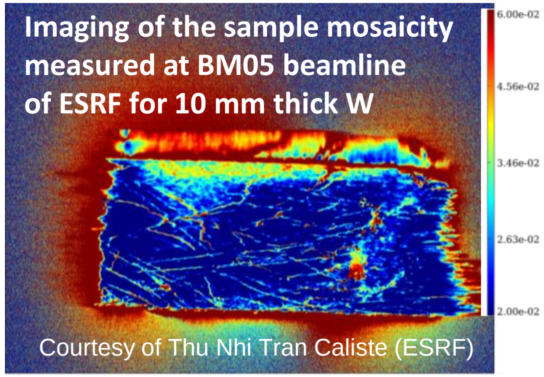
Integration and operation of the crystal target: effect of misalignments and high temperature

- **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

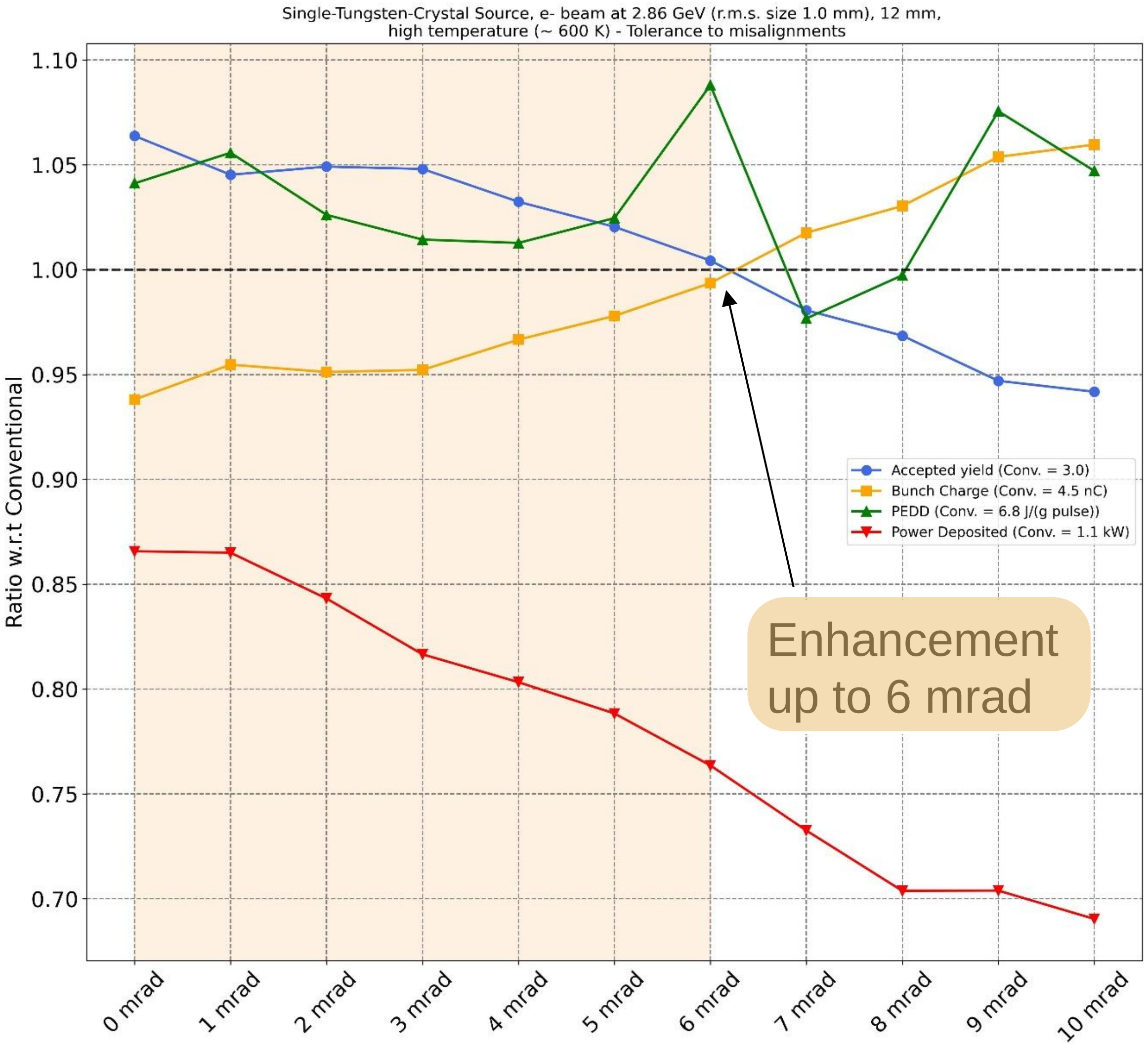

Spectra of E_{loss} at various angular configurations

2.25 mm thick W crystal


Imaging of the sample mosaicity measured at BM05 beamline of ESRF for 10 mm thick W

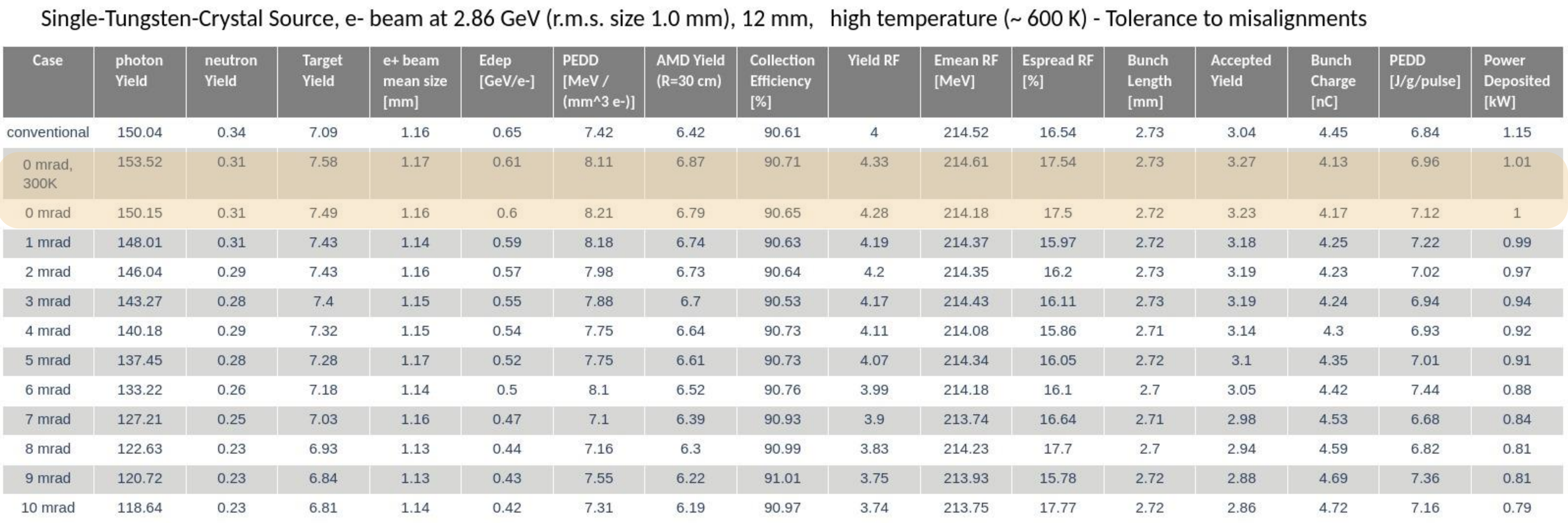
Courtesy of Thu Nhi Tran Caliste (ESRF)

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**)


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

Enhancement up to 6 mrad

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

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 (optimization of the capture section of pre-injector still ongoing).
- **Next steps**: **integration studies** with potential **proof-of-principle** at **P³** experiment @ PSI (and future CHART projects).
- **Missing**: test of positron production with single crystal without goniometer and of radiation resistance.

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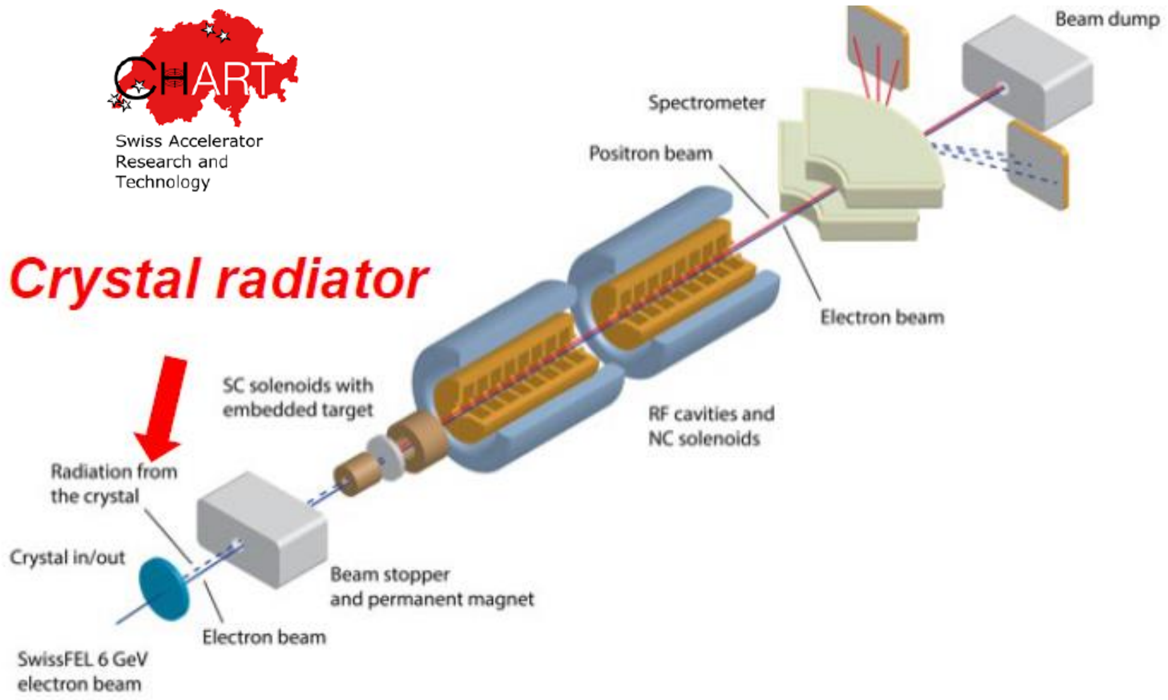

Credits

PSI	B. Auchmann, P. Craievich, M. Duda, J. Kosse, M. Schaer, N. Vallis, R. Zennaro
IJCLab	F. Alharthi, I. Chaikovska, R. Chehab, V. Mytrochenko, Y. Wang
CERN	S. Doebert, A. Grudiev, A. Latina, B. Humann, A. Lechner, R. Mena Andrade, J.L. Grenard, A. Perillo Marcone, P. Sievers, Y. Zhao
INFN - Ferrara	L. Bandiera, N. Canale, A. Mazzolari, R. Negrello, G. Paternò, M. Romagnoni, A. Sytov, L. Malagutti, V. Guidi
INFN – Napoli / INFN – LNF / INFN – Milano	D. Boccanfuso, O. Iorio / M. Soldani, S. Bertelli / A. Bacci, M. Rossetti Conti
INFN - LNL and University of Padova	D. De Salvador, F. Sgarbossa, D. Valzani
INFN Milano Bicocca and Universiy of Insubria	M. Prest, E. Vallazza, S. Carsi, A. Selmi, S. Mangiacavalli, G. Saibene, G. Zuccalà
INFN and University of Trieste	P. Monti-Guarnieri
	V. Tikhomirov, V. Haurylavets
KEK	Y. Enomoto

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e+BOOST
PRIN2022-
2022Y87K7X

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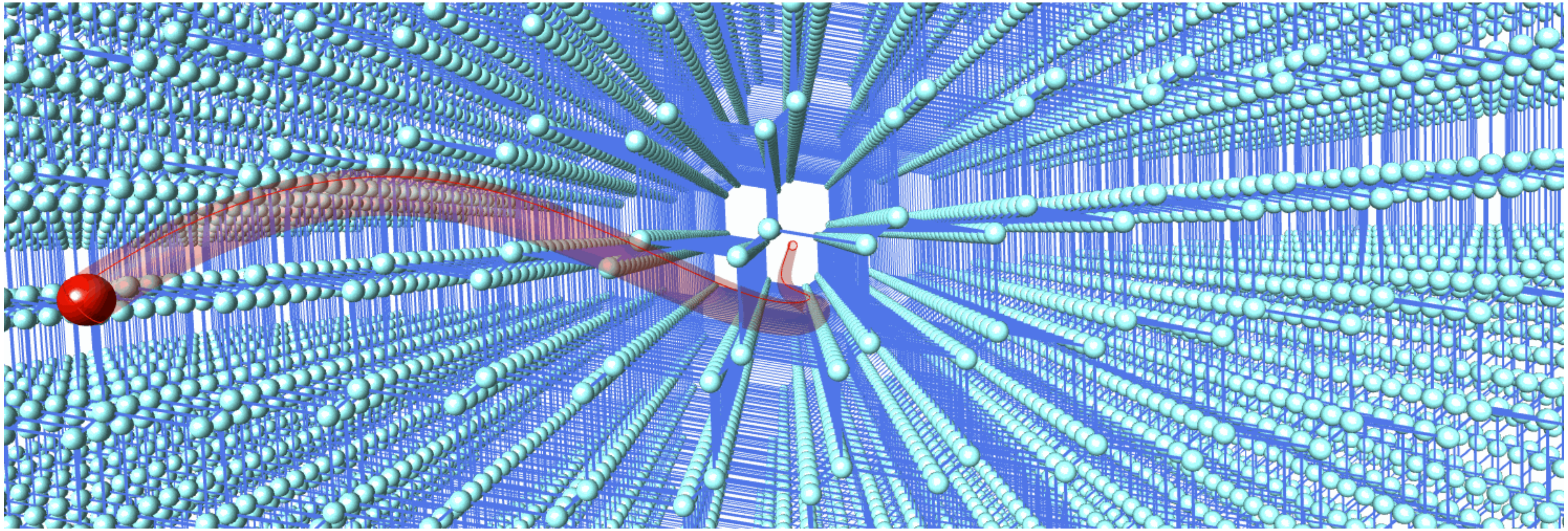
FCCIS: 'This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.'

Thank you for your attention!



My email address: paterno@fe.infn.it

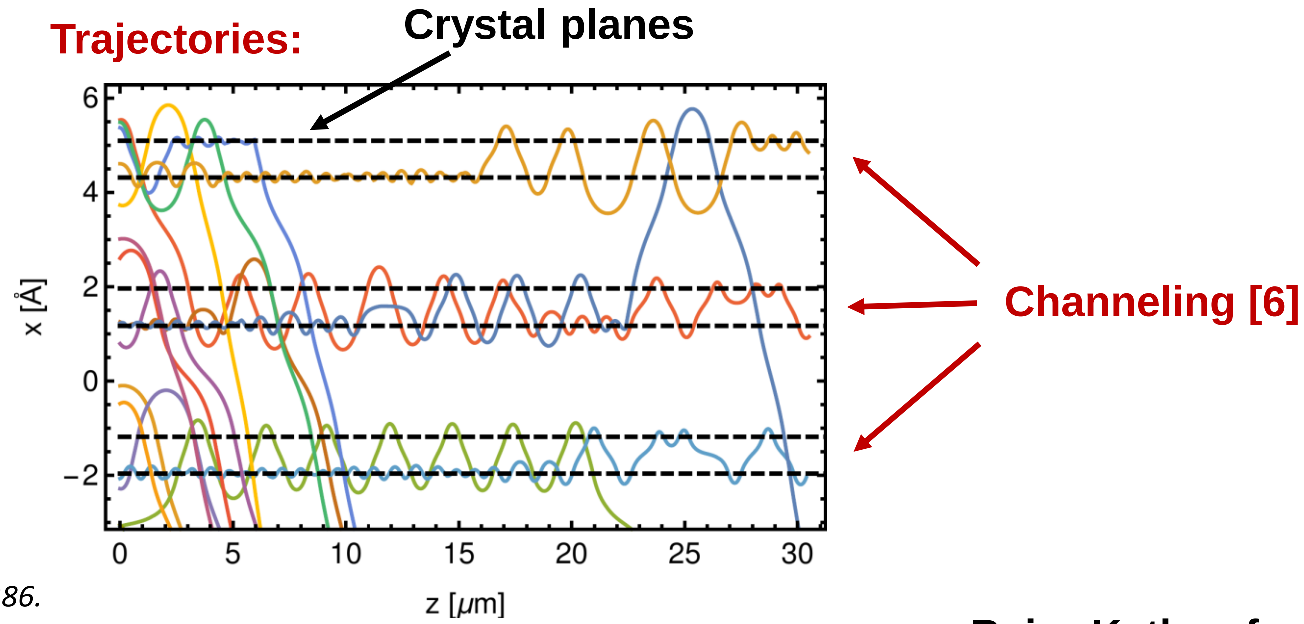
Back-up slides

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)



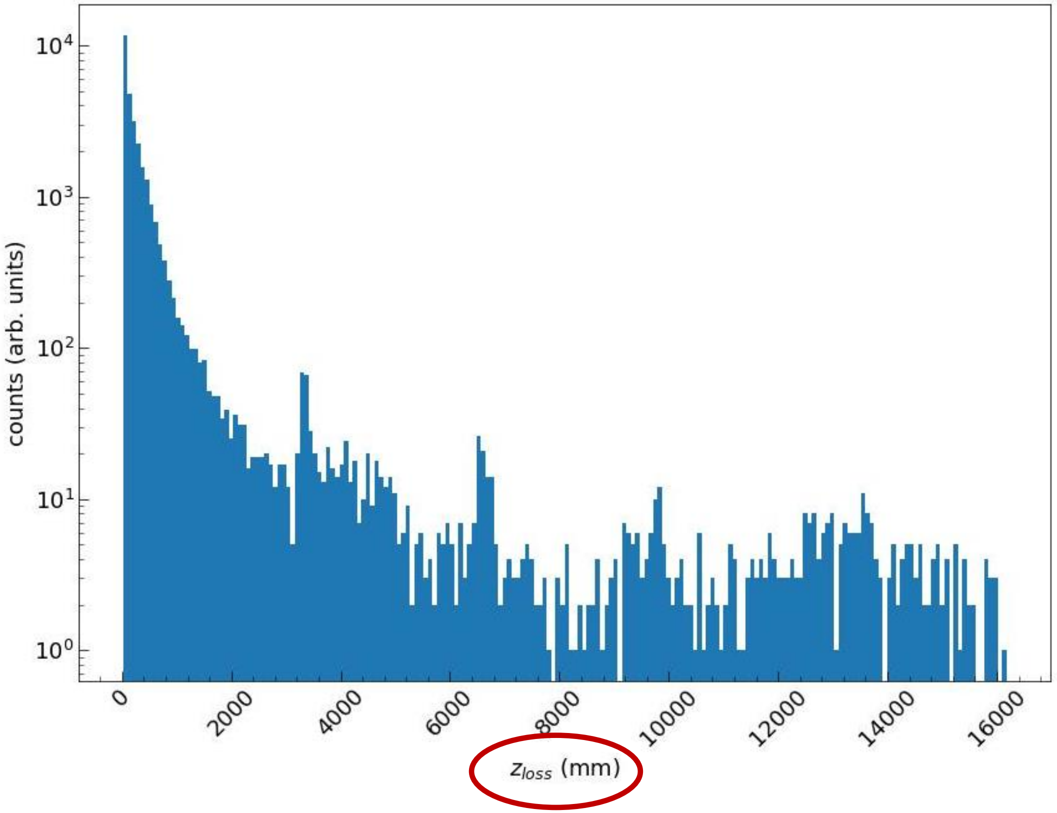
[1] A. Sytov, V. V. Tikhomirov. NIM B 355 (2015) 383–386.
[2] V. Guidi, L. Bandiera, V. Tikhomirov PRA 86 (2012) 042903
[3] L. Bandiera, et al., NIM B 355, (2015) 44
[4] L. Bandiera et al., NIM A 936 (2019) 124
[5] A. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)
[6] A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)

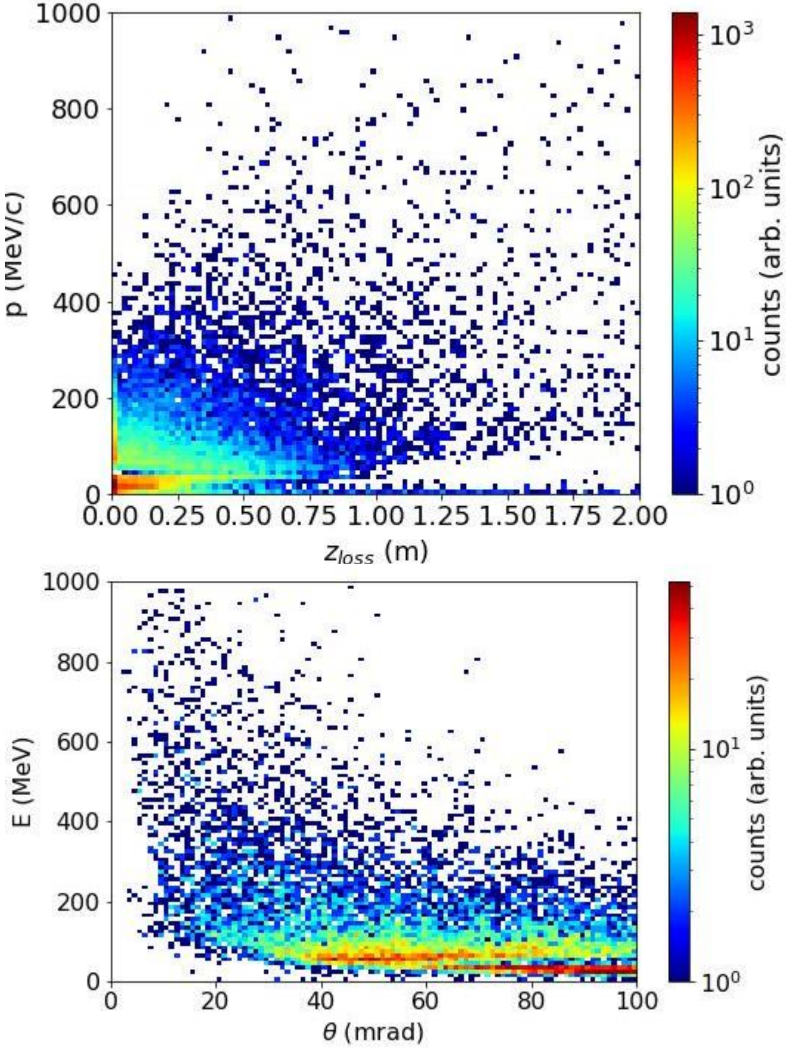
Baier-Katkov formula:

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

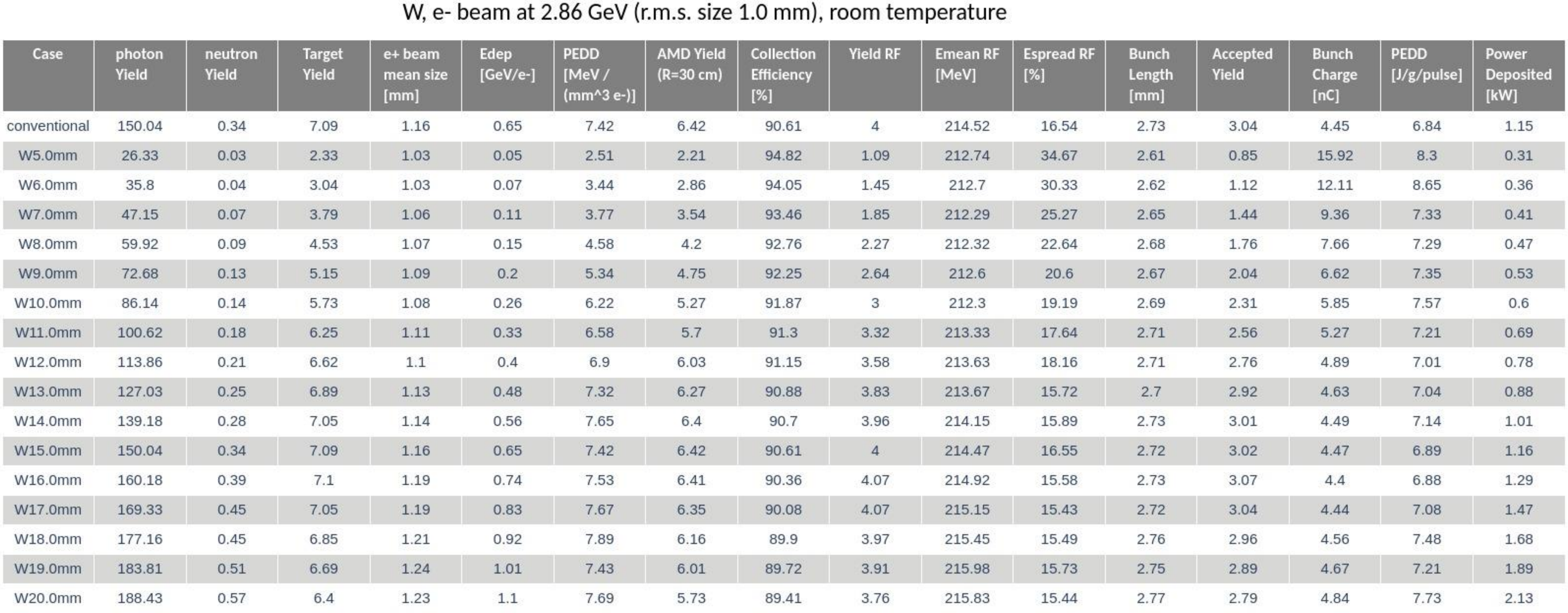
Which positrons are accepted by the DR ?

e+ lost within the CS





Single Crystal, room temperature

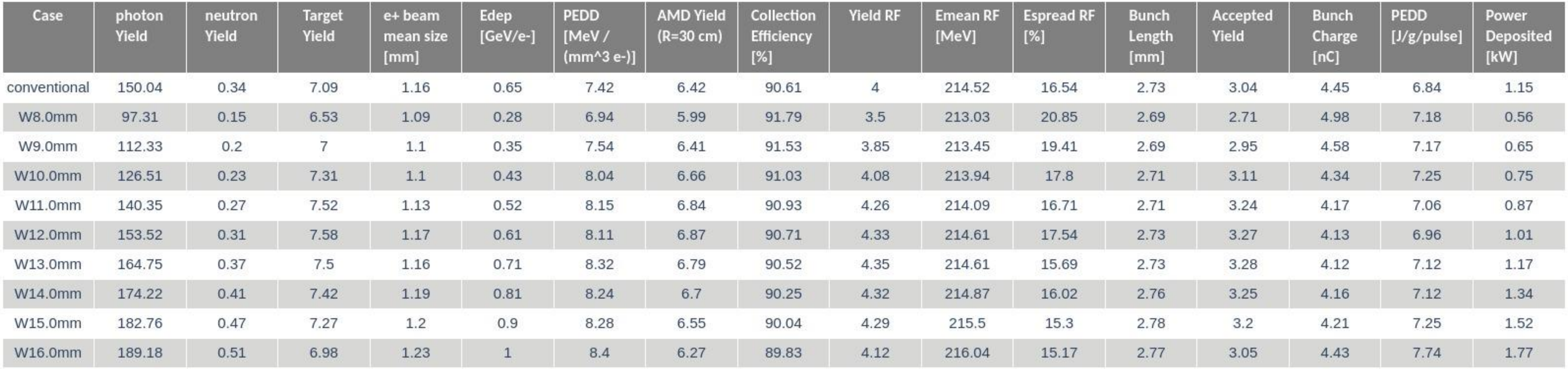


W, e- beam at 2.86 GeV (r.m.s. size 1.0 mm), room temperature

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