# FCC-ee positron source:
# *from convectional to crystal based.*

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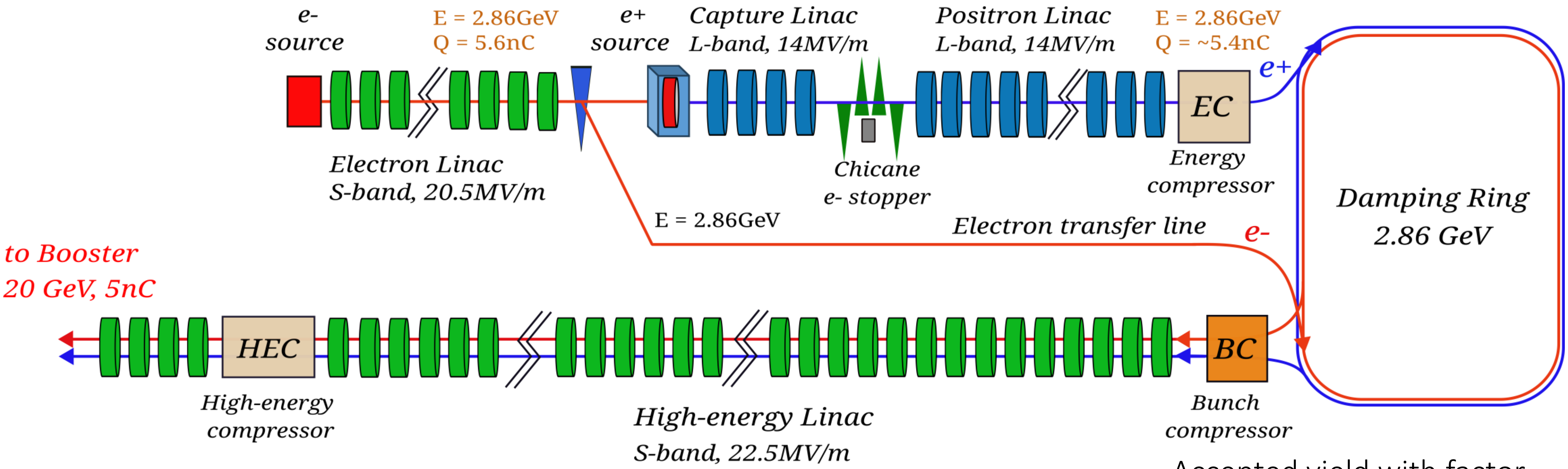
# Outline

- FCC-ee pre-injector latest layout.
- Conventional positron source (Target , Matching device , Capture linac)
- Beam dynamics and tracking.
- Crystal based positron source (Innovative, alternative to the conventional scheme).
- Summary and conclusion.

# Pre-injector layout (Current baseline)



## Electron drive beam:[1]

| | |
|---|---|
| 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 |

Accepted yield with factor 2.5 safety margin*

$$\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$$

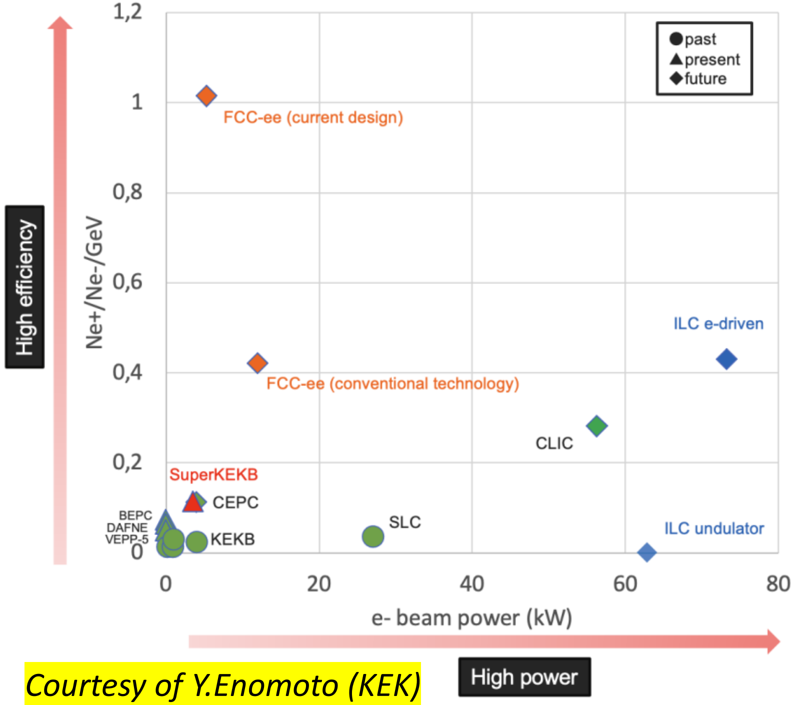
**50% losses for injection in the DR + 20 % losses from target up to the end of the e+ linac*

# Positron sources performance

- Key factors for high e+ yield at DR:
  - 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 ~ 12. T around the target can substantially increase state-of-the-art e+ yield, by one order of magnitude.

| [2] | SLC<br>1989 - 1998 | SuperKEKB<br>2014 - Present | FCC-ee (HTS Option)<br>2040s – 2060s |
|---|---|---|---|
| Primary e- energy [GeV] | 27 - 33 | 3.5 | 2.86 |
| Transverse aperture [mm] | 18 | 30 | 60 |
| Max. Solenoid Strength at target | 5.5 | 3.5 | 12.7 |
| Avg. Solenoid Strength along linac | 0.5 | 0.4 | 0.5 |
| e+ Yield at target | ~30 | ~8 | ~7 |
| e+ Yield at DR | 2.5 | 0.63 | ~3 |
| Yield at DR / e- Energy [GeV $^{-1}$] | 0.079 | 0.180 | 1.014 |

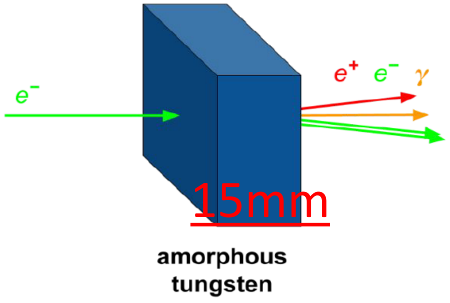


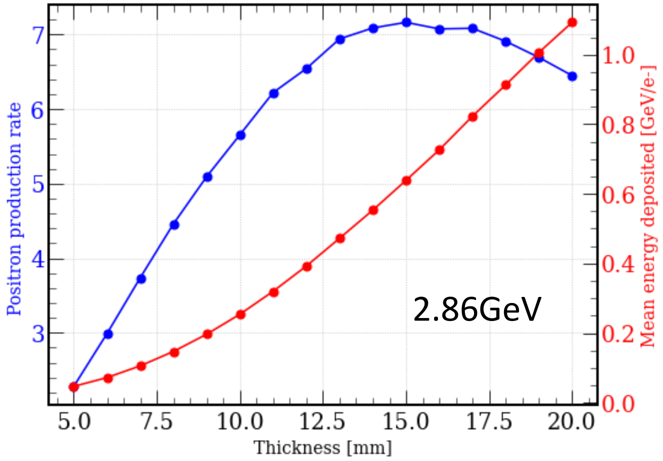
*Courtesy of Y.Enomoto (KEK)*

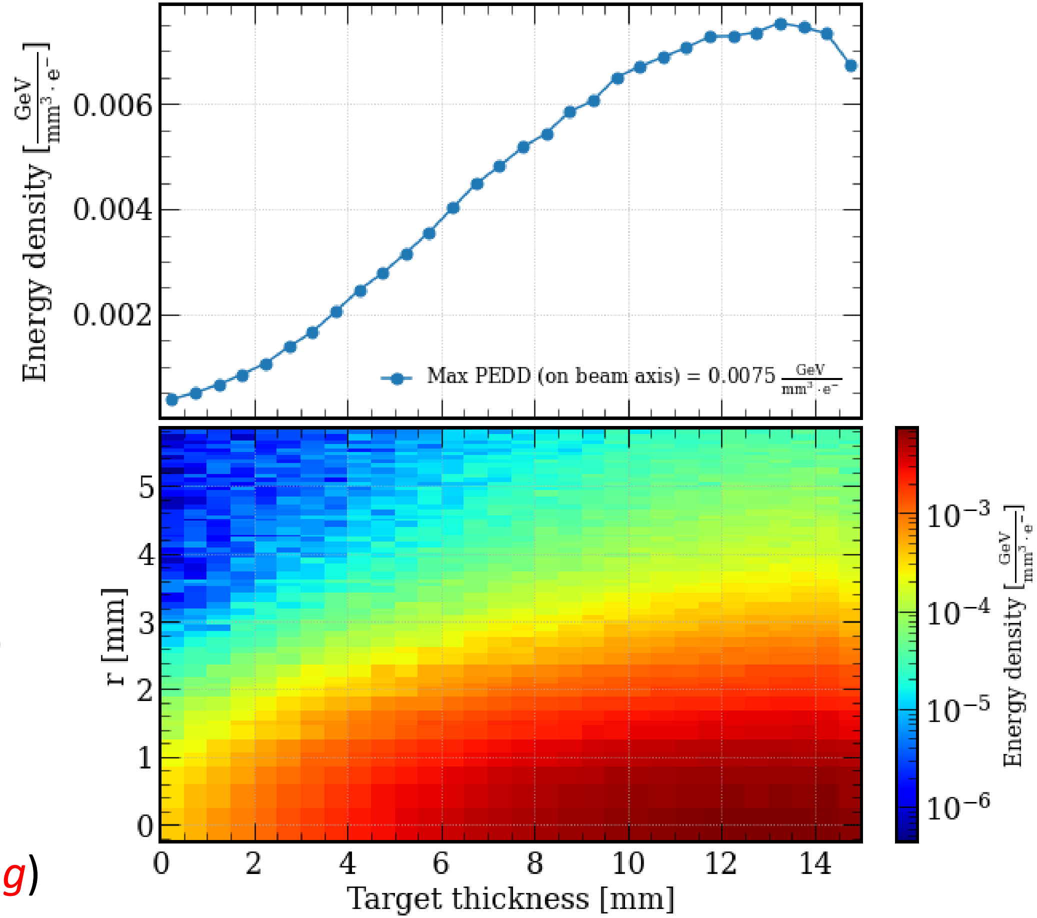
# Positron source : Target design

- **Conventional scheme (**Well understood and used in current and previous positron sources**)**

Bremsstrahlung -> *Pair production*







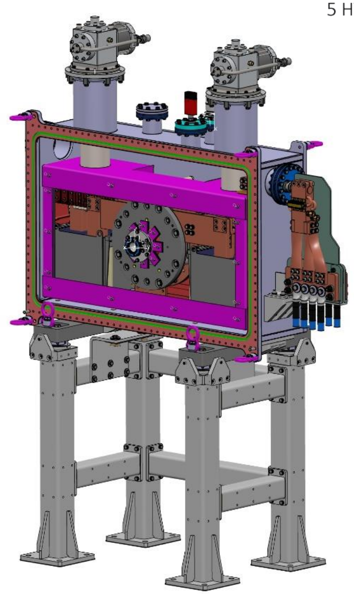
Considered parameters for Positron source target:

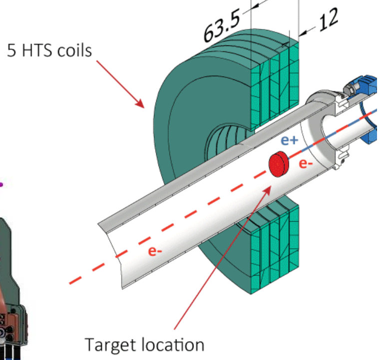
- Positron production (*high Z-material*)
- Energy deposition (*target heating , cooling requirements*)
- Peak Energy deposition density "PEDD" (*Instantaneous, thermomechanical stress due to temperature gradient.*)
- Radiation around the target (*shielding requirements*)
- Huge emittance /angular divergence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

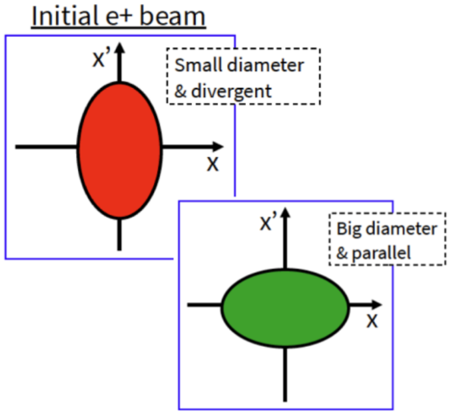
# Positron source : Matching Device (Adiabatic matching device )

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**

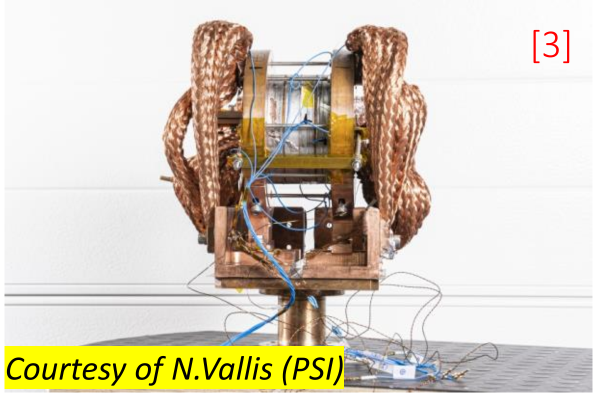






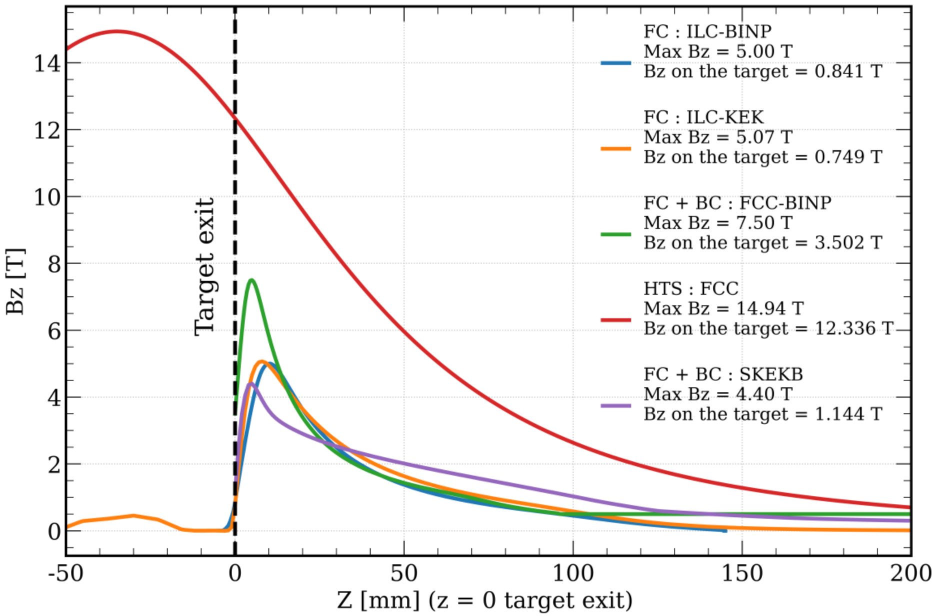
*innovative in application for e$^+$ capture*

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



[3]

*Courtesy of N.Vallis (PSI)*



Compared with classical AMD:

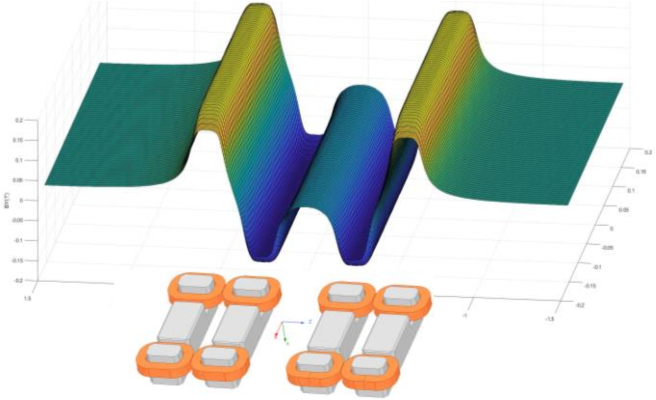
- Higher peak field (~15 T, ~12 T @Target)
- Larger aperture (∅ = 30-60 mm)
- Flexible target position and field profile
- Axially symmetric solenoid field
- DC operation

# Positron source: Capture LINAC

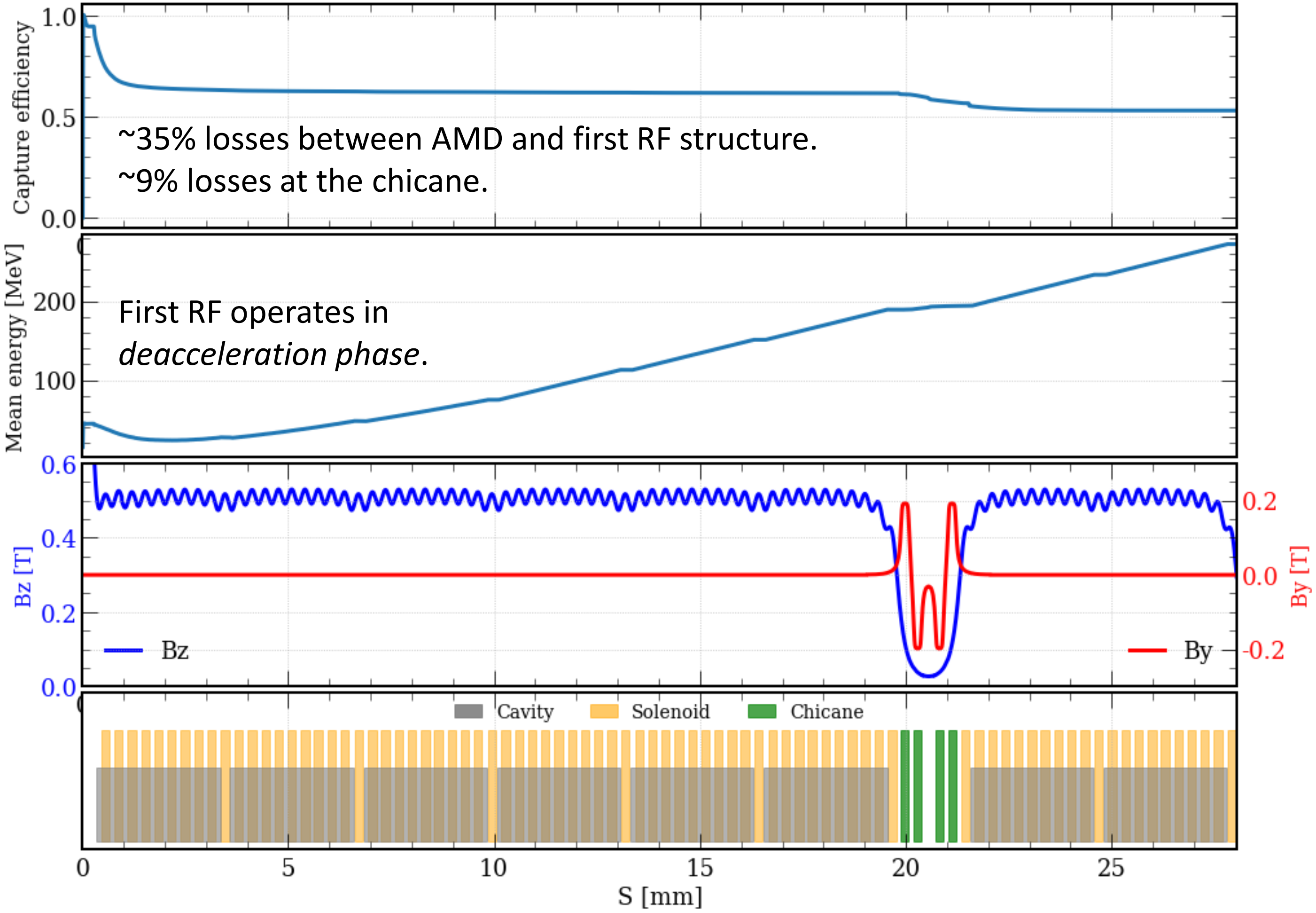
- **RF structures**: 2GHz L-band with aperture (2a) = 60mm , 3m long and 14MV/m.

- **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.



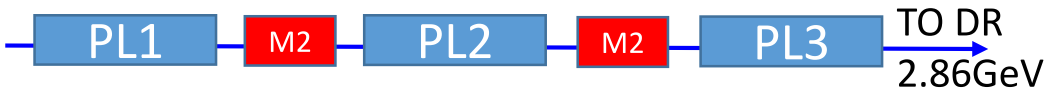
Based on RF-Track simulation



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

First RF operates in *deacceleration phase*.

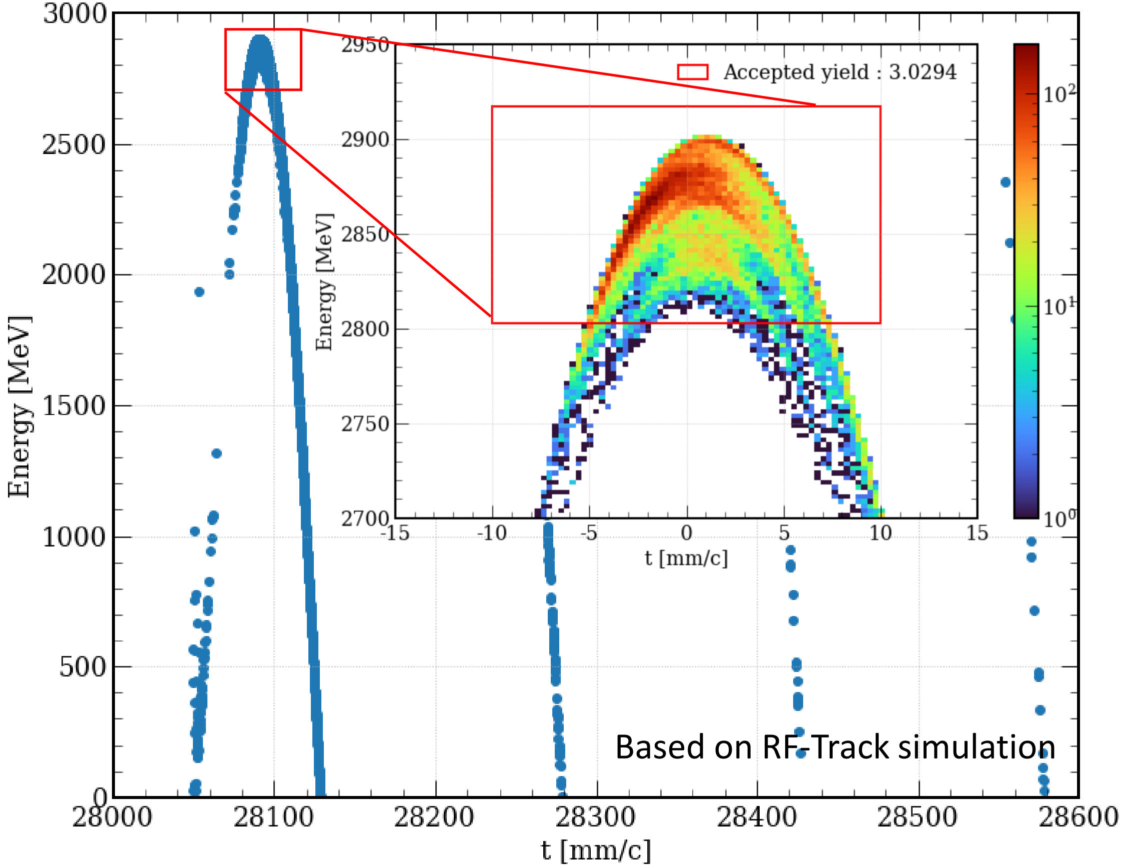
# Positron linac + Damping Ring



- Positron linac (PL) under optimization, composed of three sections with two matching sections :
  - PL section 1: 20 RF structures, → ~1GeV.
  - PL section 2: 20 RF structures, → ~1.9 GeV.
  - PL section 3: 24 RF structures, → ~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)
- Accepted yield @ DR ~ 3.02

Longitudinal phase space and window acceptance*

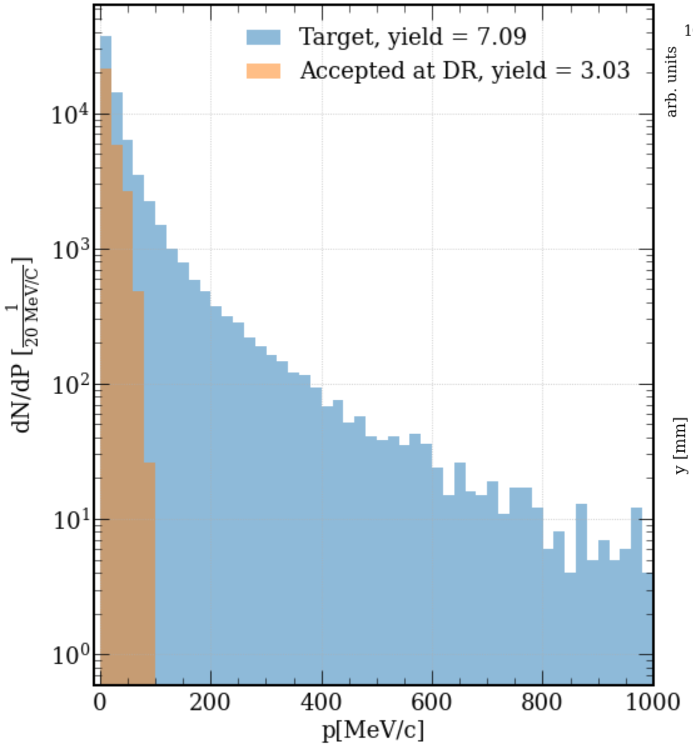


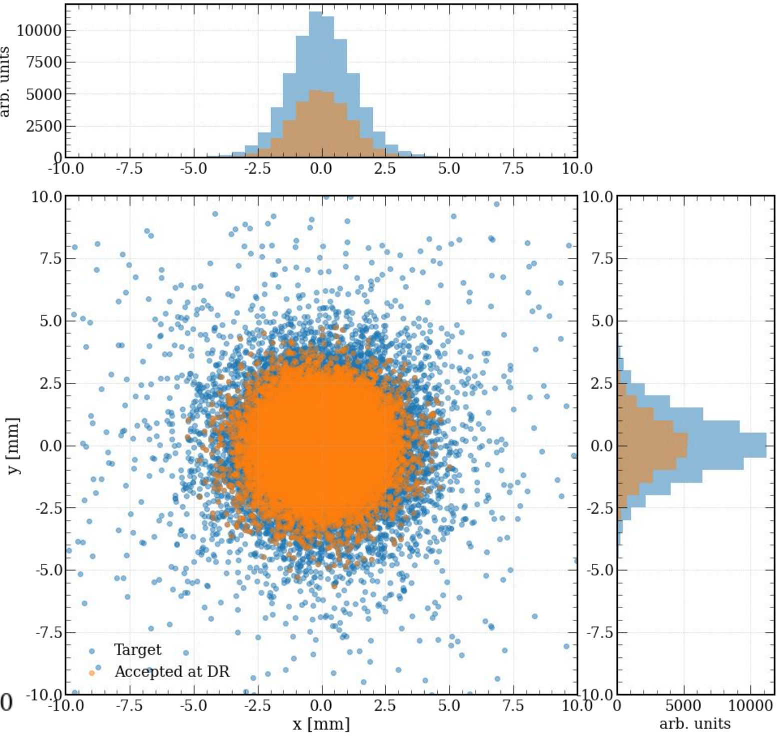
Based on RF-Track simulation

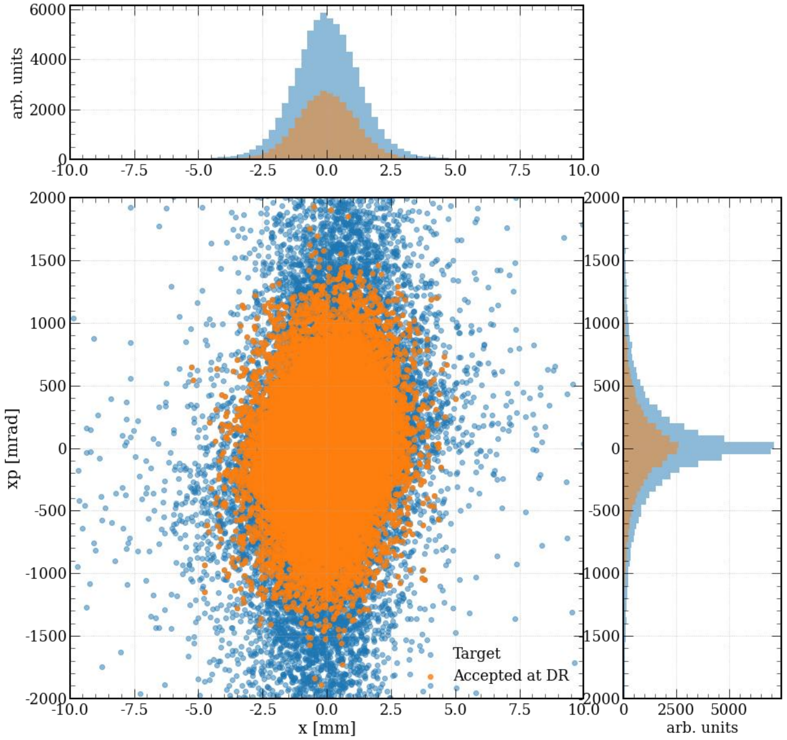
* Simplified longitudinal analytical formula used to track the particles in the positron linac

# Accepted positrons criteria

- Momentum : accepted positrons $\leq$ 100 MeV/c
  Primary factor
- Transverse aperture and divergence:
  Secondary factor.



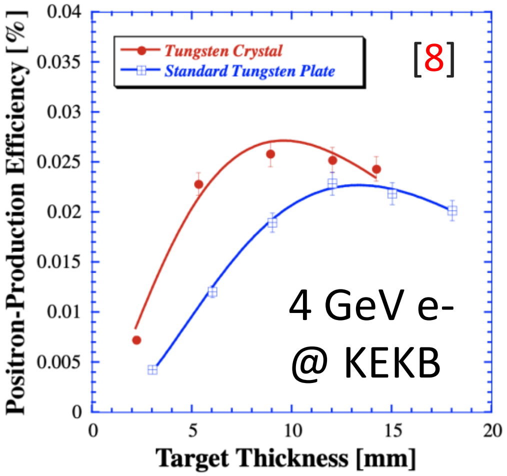


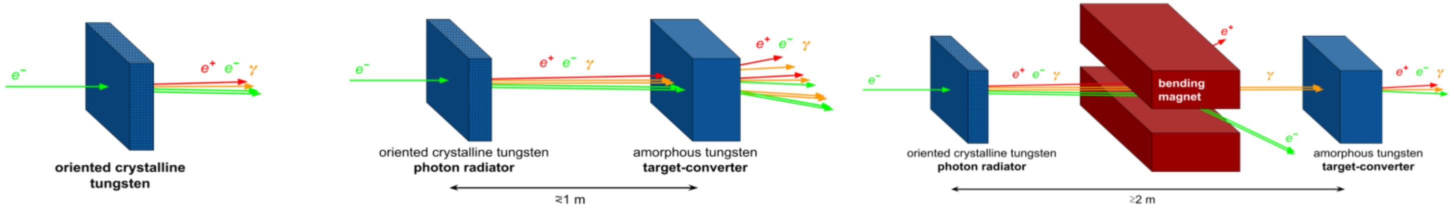


<u>More positrons in the low energy spectrum with lower divergence => increase the accepted yield.</u>

# Crystal based positron source

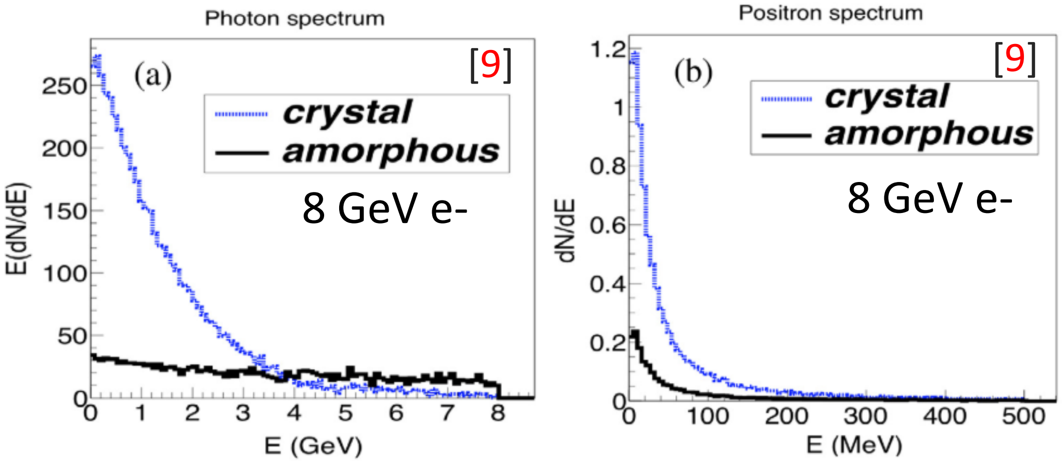
- Originally proposed by R. Chehab, A. Variola, V. Strakhovenko and X. Artru [4].
- Several experiments performed: ( Orsay[5], WA103@CERN[6] and KEK[7]) in the 1 – 10 GeV region.
- Three approaches have been studied experimentally.





**Use of lattice coherent effects in oriented crystals <111> : channeling and over barrier motion**

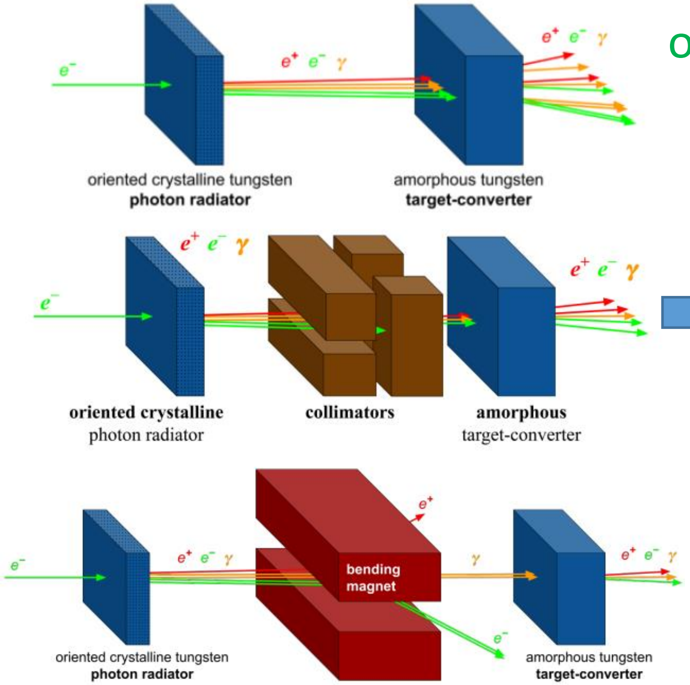
- Enhancement of photon generation in oriented crystals
- Soft photons will generate the soft positrons → easier to capture by matching devices.
- Lower energy deposit and PEDD in target → lower heating and thermo-mechanical stress (target reliability)



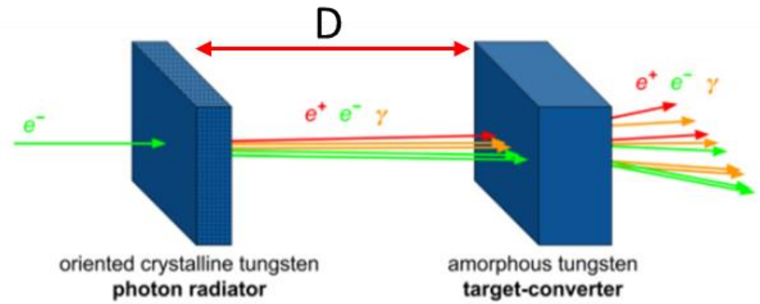
# Crystal based positron source: simulation

The whole setup was simulated through Geant4 toolkit taking advantage of GeantG4ChannelingFastSimModel [10] (*talk by A.Sytov & by G. Paternò*)

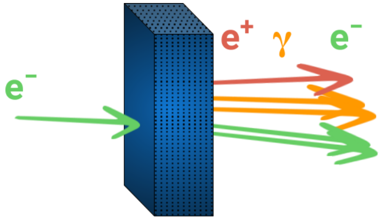
- The simulation environment was benchmarked/validated with experiments at energies of interest for positron sources of future colliders → optimization studies for the FCC-ee [11]



[12]



Thin crystal as a radiator + amorphous target as converter with D optimization



Single thick crystal act as radiator and converter

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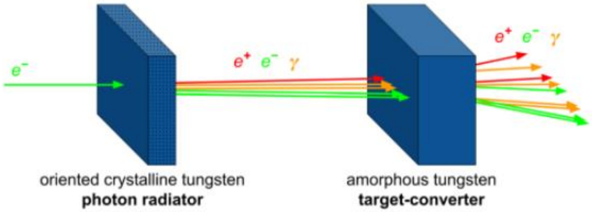
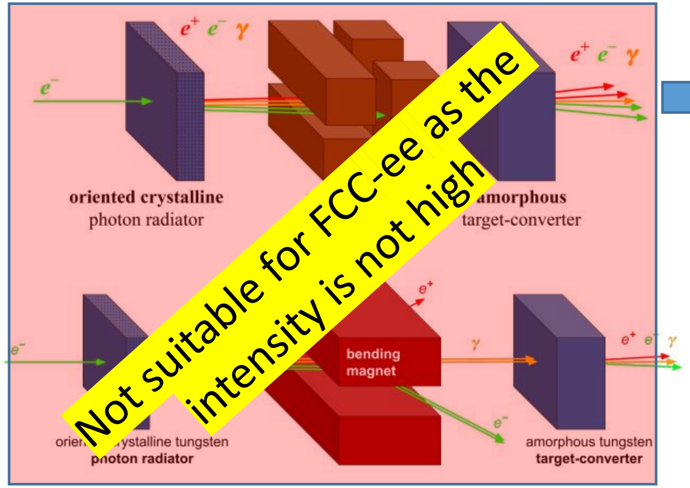
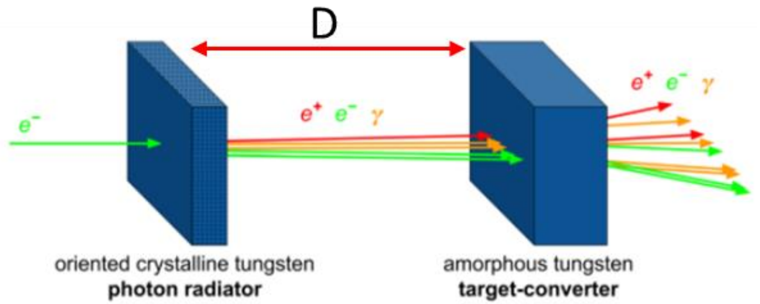


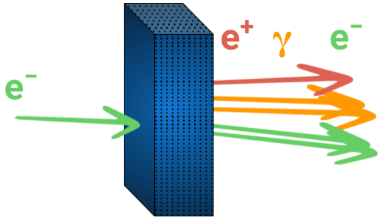


Not suitable for FCC-ee as the intensity is not high

[12]



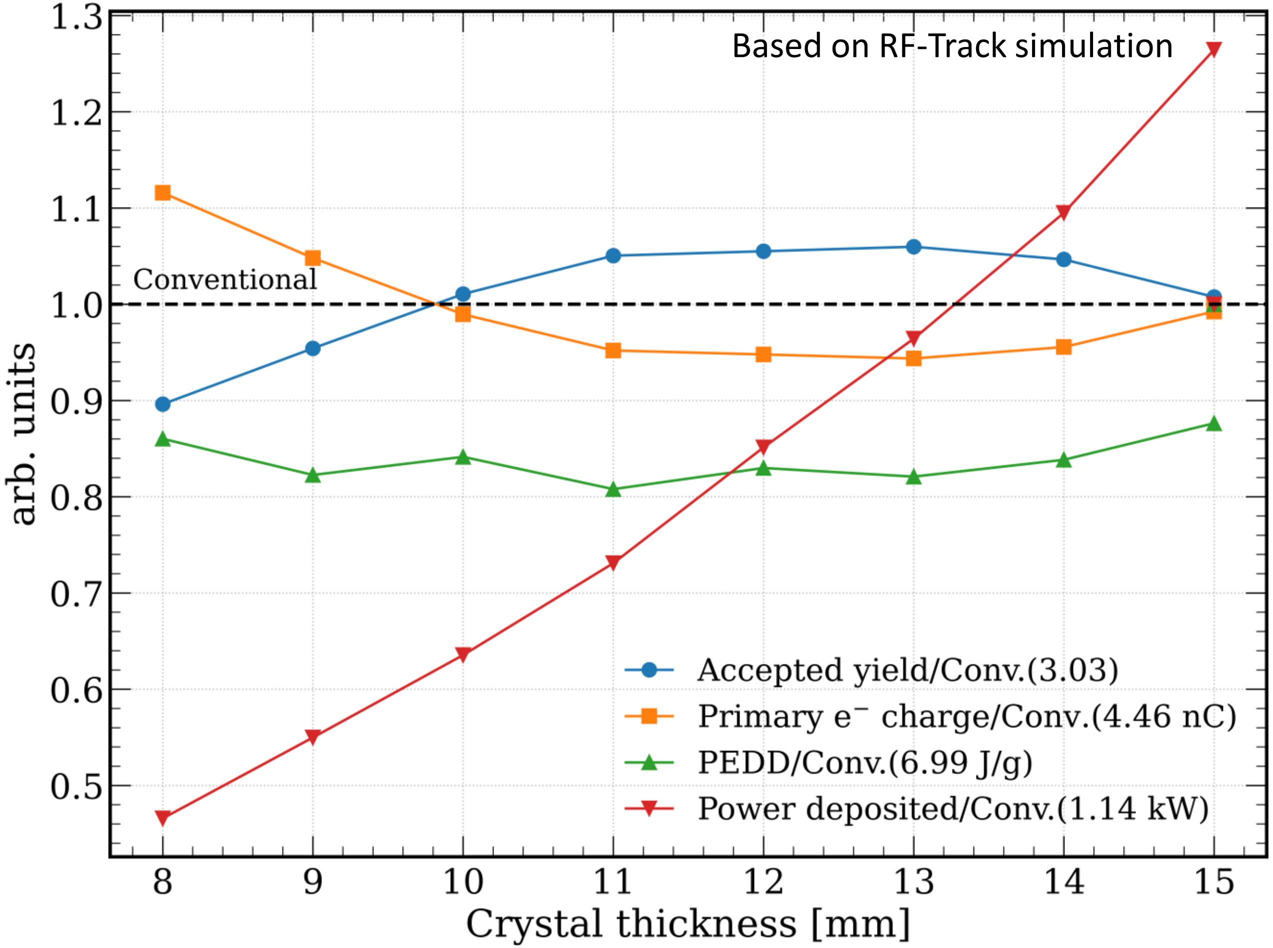
Thin crystal as a radiator + amorphous target as converter with D optimization



Single thick crystal act as radiator and converter

# Single crystal thickness optimization

E = 2.86 GeV, spot size (rms) x/y = 1mm

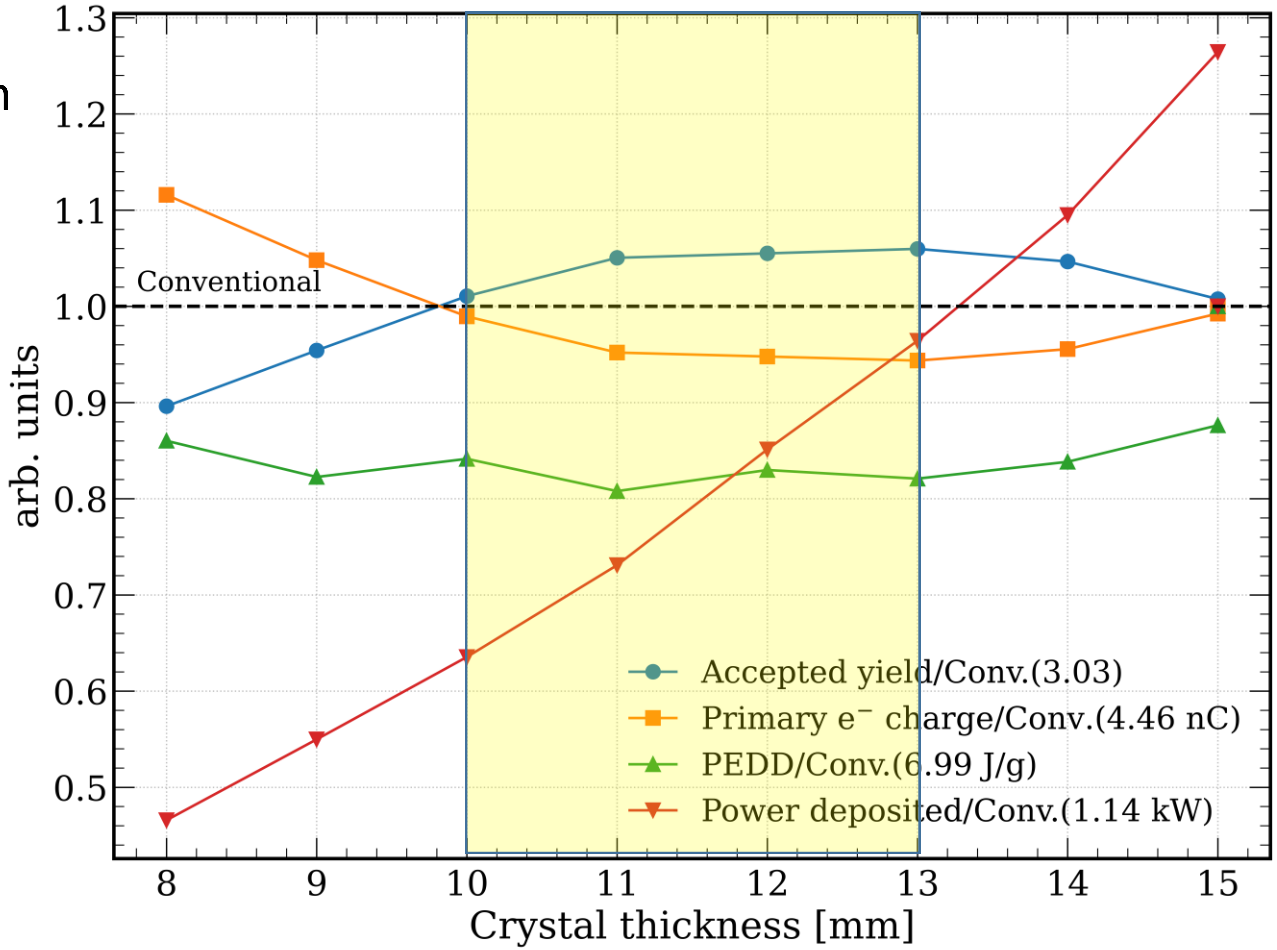


# Single crystal thickness optimization

Simulation results converge to 10 – 13mm thick crystal :

- Target thickness : thinner target => clean radioactive environment.
- Accepted yield: 2%↑– 7%↑ => lower e- bunch charge.
- Power deposited: 35%↓– 3%↓ => lower cooling requirements.
- PEDD: ~ 16% ↓ => increase target reliability.

E = 2.86 GeV, spot size (rms) x/y = 1mm



# Summary table

| Parameter | Unit | Conventional | Crystal based |
|---|---|---|---|
| Matching device peak magnetic field (@target) | T | HTS: 14.94 (11.77) T<br>2r = 30~60 | |
| Matching device aperture | mm | | |
| Target thickness | mm | 15 | 10 |
| Positron yield @ target | $N_{e+}/N_{e-}$ | 7.09 | 7.6 |
| Positron yield @ PL | $N_{e+}/N_{e-}$ | 3.7 | 3.7 |
| Accepted yield @ DR (ΔE: 2%, Δt: 20 mm/c) | $N_{e+}/N_{e-}$ | 3.03 | 3.1 |
| Primary bunch charge | nC | 4.46 | 4.41 |
| Target deposited power | Kw | 1.14 | 0.73 |
| PEDD | J/g | 6.99 | 5.9 |
| Emittance x/Emittance y (normalized) | mm.Rad | 9.6/10.1 | 9.7/10.2 |
| Energy spread @PL | % | 0.8 | 0.8 |
| Bunch length | mm | 2.6 | 2.6 |

*Work in progress*

# Conclusion

- The work is in progress to optimize the FCC-ee pre-injector and maximize the yield (***~3 Ne+/Ne-***)
- A start-to-end simulation based on the G4ChannelingFastSimModel and RF-Track code.
- Conceptual design of crystal based positron source: **several options were simulated and the results converges to single thick crystal (*35% lower Energy deposition, 16% lower PEDD*)**

- Challenges associated with single crystal scheme:
  - Quality of the thick crystal (thicker crystals => large mosaic spread)
  - Alignment and pre-alignment studies (*talk by G. Paternò*)
  - High temperature effects on the crystalline structure. (*talk by G. Paternò*)
  - Mechanical integration in the HTS.
  - Reliability and radiation induced damage.

- Next steps: Integration studies and a potential of proof of principles experiments @ PSI (P3).

# 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, D. Boccanfuso (INFN Naple) , N. Canale, O. Iorio (INFN Naple), A. Mazzolari, R. Negrello, G. Papernò, M. Romagnoni, A. Sytov |
| INFN-Milano | A. Bacci, M. Rossetti Conti |
| KEK | Y. Enomoto |

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Horizon 2020
European Union funding
for Research & Innovation

Thank you for your attention!

# References

[1] P. Craievich, FCC Week 2024, 10-14 June
[2] I. Chaikovska et al 2022 JINST 17 P05015
[3] N. Vallis et al., Proof-of-principle e+ source for future colliders, Phys. Rev. Accel. Beams 27, 013401 – 2024
[4] R. Chehab, F. Couchot, A. R. Nyaiesh, F. Richard, and X. Artru, Proceedings of the 1989 IEEE Particle Accelerator Conference (PAC'89), Chicago, IL, USA, 1989, p. 283.
[5] X. Artru et al., Nucl. Instrum. Methods Phys. Res., Sect. B119, 246 (1996).
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[7] T. Suwada et al., in the 2006 International Linear Accelerator Conference (LINAC'06), Knoxville Convention Center, TN, USA, 2006.
[8] T. Suwada et al.,Phys. Rev. ST Accel. Beams 10, 073501 – Published 10 July 2007
[9] X. Artru, I. Chaikovska, R.Chehab et al. NIM B 355 (2015)
[10] A. Sytov et al. JKPS 83 (2023)
[11] L. Bandiera et al., Eur. Phys. J. C (2022) 82:699
[12] M. Soldani et al., Nucl. Instrum. Methods Phys. Res, A, vol. 1058, p. 168828, (2023)

# FCC-ee positron source: current requirements

The complete filling for Z running => Requirement ~2.75 × $10^{10}$ $e^+$/bunch (4.4 nC) at the linac end

or 5.4 nC accepted in the DR

$$\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$$

$$N_{e-}/\text{bunch} \times \eta^{e+}{}_{Accepted} \geq \underbrace{5.4\ \text{nC/bunch} \times 2.5}_{13.5\ \text{nC}}$$

******A safety margin of 2.5 is currently applied for the whole studies (50% losses for injection in the DR + 20 % losses from target up to the end of the e+ linac )*

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

$e^-$ drive beam

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

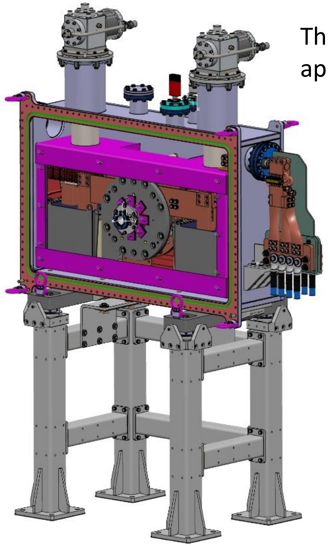
| | |
|---|---|
| Nb of bunches per pulse | 4 |
| Bunch separation | 25 ns |
| Repetition rate | 100 Hz |
| Beam power | ~6.9 kW (max) |

➜ positron flux of ~1.1×$10^{13}$ $e^+$/s (×2.5). *Demonstrated at SLC (a world record for existing accelerators): ~6 ×$10^{12}$ e+/s*

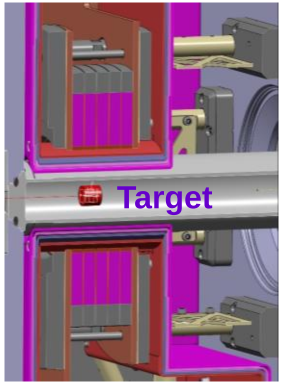
# HTS solenoid- and Flux Concentrator (FC)-based positron capture system

*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

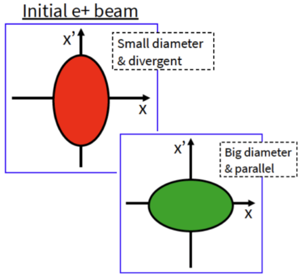


The same HTS solenoid design and cryostat aperture as for $P^3$ experiment (72 mm)



*innovative in application for $e^+$ capture*

## Flux Concentrator (FC)
## (SLAC, KEK, IHEP, LNF BINP)



*robust and reliable solution*

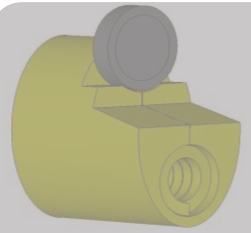
Compared with FC

- Higher peak field (~15 T, ~12 T @Target)
- Larger aperture (∅ = 30-40 mm)
- Flexible target position and field profile
- Axially symmetric solenoid field
- DC operation

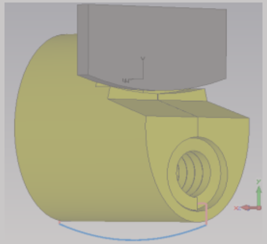
Compared with HTS solenoid

- Lower peak field (5−7 T, ≲1−3 T @Target)
- Smaller entrance aperture (∅ = 7−12 mm)
- Fixed target position (2−5 mm upstream the FC)
- Challenging pulsed power source working at high rep. rate (≳100 Hz)

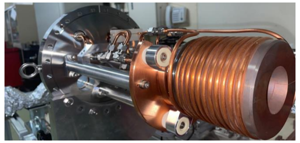
# Positron capture: Flux Concentrator (FC) as a matching device



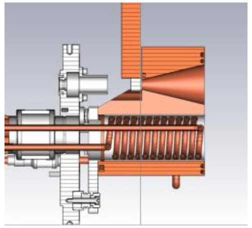
**Originally designed by BINP for the FCC-ee (P. Martyshkin)**
**=> FC:FCC-BINP**
*Dropped as no info and further studies available*



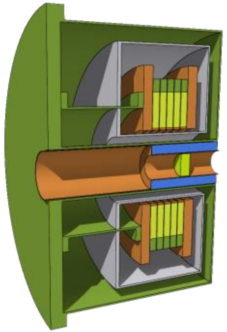
**Originally designed by BINP for the ILC (P. Martyshkin) => FC:ILC-BINP**
*Dropped as no info and further studies available*



**Originally designed by KEK for the SuperKEKB => FC:SKEKB-KEK**
*Under consideration for the FCC-ee (with and w/o Bridge Coils)*



**Designed by KEK for the ILC (Y. Enomoto) => FC:ILC-KEK**
*Under consideration for the FCC-ee*



**High-Temperature Superconducting (HTS) solenoid designed by PSI => HTS:FCC**
*Current baseline option*