Positron production, capture and acceleration until the damping ring

Iryna Chaikovska

Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab)
CNRS, Université Paris-Saclay

on behalf of the WP3 team (FCC-ee injector update studies)
F. Alharthi, R. Chehab, V. Mytrochenko (IJCLab), S. Doebert, J.-L. Grenard, B. Humann, A. Latina, A. Lechner,
R. Mena Andrade, A. Perillo Marcone, Y. Zhao (CERN), B. Auchmann, P. Craievich, M. Duda, J. Kosse, M. Schaer, N. Vallis, R. Zennaro (PSI),
L. Bandiera, M. Soldani, A. Sytov (INFN/Ferrara), A. Bacci, M. Rossetti Conti (INFN/Milano), Y. Enomoto (KEK), P. Martyshkin

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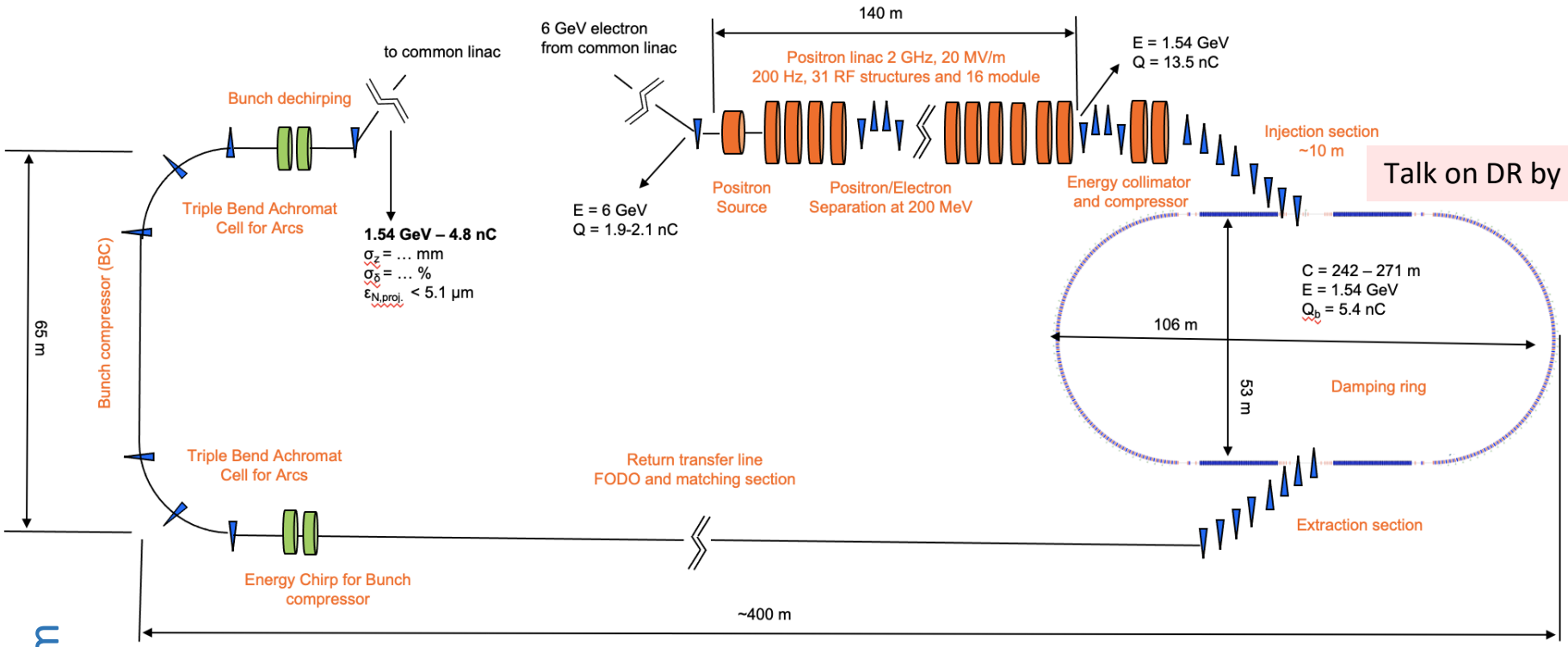
https://chart.ch - CHART Scientific Report 2022: https://chart.ch/reports/

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.'

FCC-ee pre-injector layout (positron source)



Talk on DR by C. Milardi (LNF)

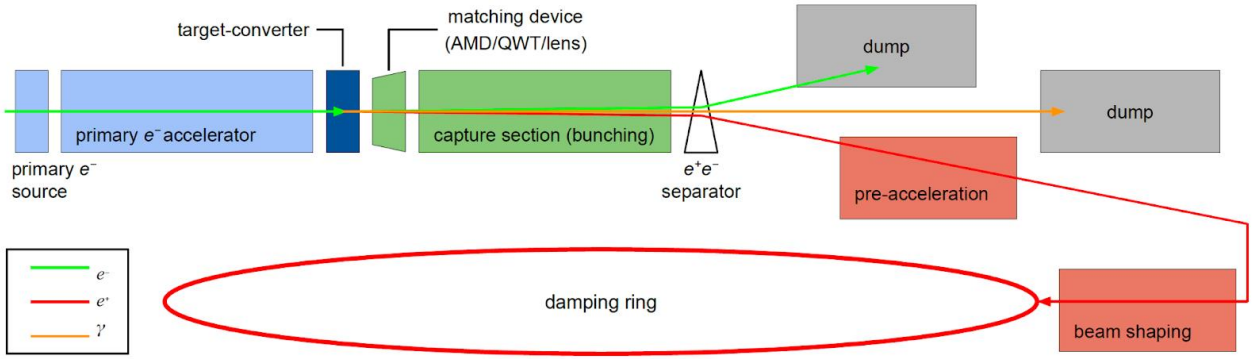
e⁻ drive beam

Beam energy	6 GeV
Bunch charge	~5.6 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

Nb of bunches per pulse	2
Bunch separation	25 ns
Repetition rate	200 Hz
Beam power	~13.3 kW (max)

FCC-ee positron source: requirements

Positron source basic scheme



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

To estimate the accepted yield:
energy window cut: (1540 ± 58.5) MeV → (±3.8% @ 1.54 GeV)
time window cut: 40° RF (~16.7 mm/c @2 GHz)

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

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

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

**A safety margin of 2.5 is currently applied for the whole studies.*

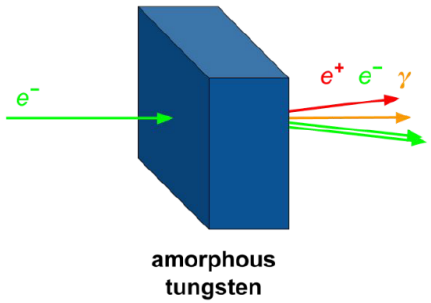
All the studies are focused on the operation scheme: 6 GeV, 2 bunches/pulse, 200 Hz rep. rate
→ positron flux of ~1.1×10^{13} e^+/s (×2.5). *Demonstrated at SLC (a world record for existing accelerators): ~6 ×10^{12} e+/s*

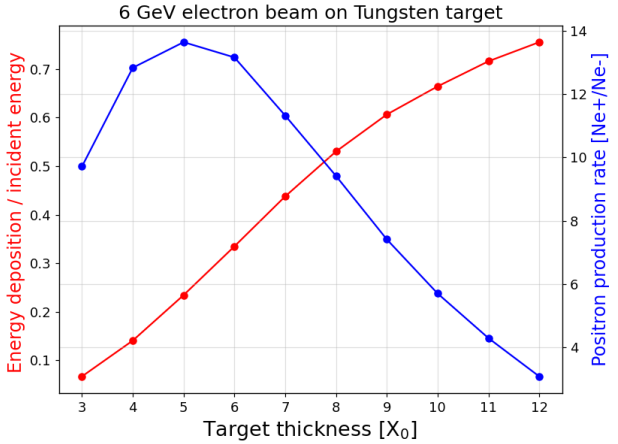
FCC-ee positron source: positron production

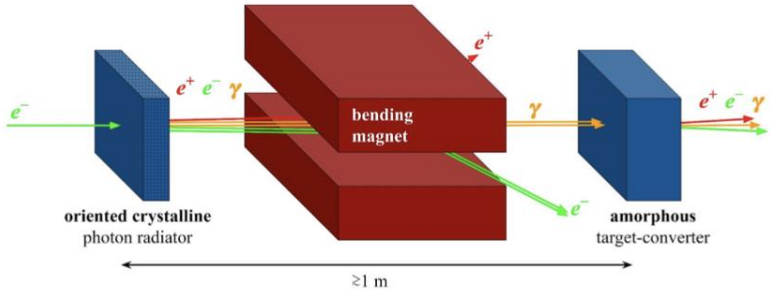
Schemes under consideration now

- Conventional scheme: bremsstrahlung and pair conversion (mainly studied until now)
- Hybrid scheme (crystal-based positron source) use the intense radiation emitted by high-energy (some GeV) electrons channeled along a crystal axis => channeling radiation.

Conventional target







Crystal-based target
Hybrid scheme

Target thickness	5 X0 17.5 mm
Production rate	~14 Ne^+/Ne^-
PEDD*	f(e^- beam)
Deposited power	f(e^- beam)

The final choice will be done based on the simulated performances

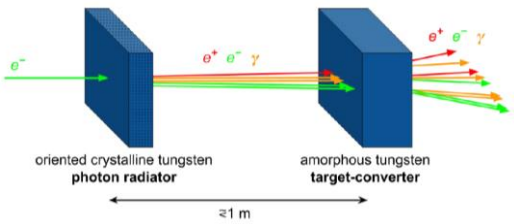
Studies on the target-converter shape in progress (tapered target, rod target, granular target)

According to SLC experience, $W_{74}Re_{26}$ material has a PEDD limit of **35 J/g (safe value to avoid target failure)*

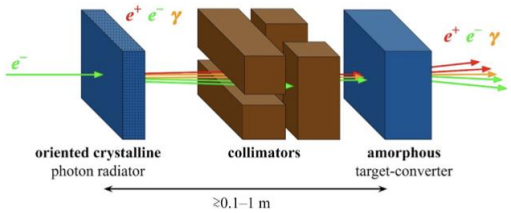
Hybrid scheme: positron production optimization for FCC-ee (in progress)

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

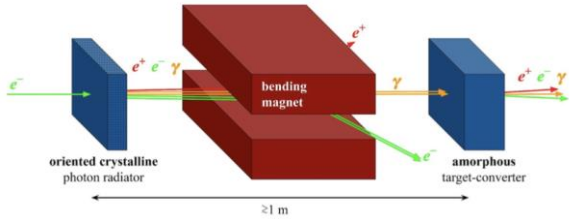
towards conceptual design



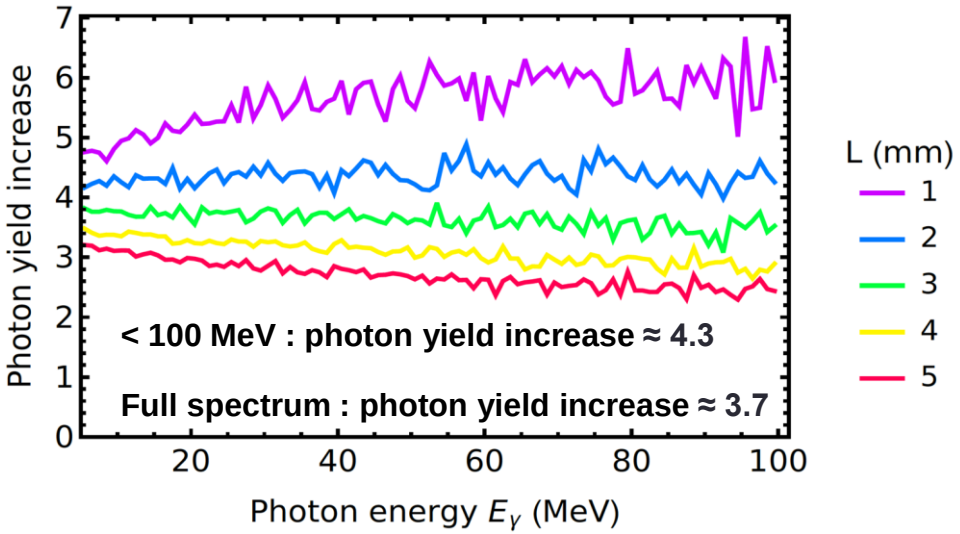
…with collimator



…with magnet



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



L. Bandiera et al., Eur. Phys. J. C (2022) 82:699

conventional (amorphous)
collimator
magnet

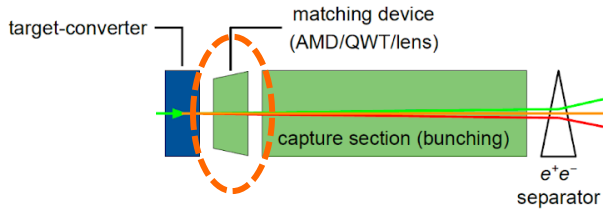
Scheme	conv.	hybrid						
L_{crys} [mm]	–				2			
D [m]	–	0.6		1			2	
L [mm]	17.6				11.6			
a = 5.5 mm Collimator?	no	no	no	yes	no	no	yes	no
Magnet?	no	no	no	no	yes	no	no	yes
E_{dep} [GeV/e^-]	1.46	1.34	1.32	1.13	1.32	1.27	1.11	1.27
PEDD [MeV/(mm³ · e^-)]	38.3	12.8	8.4	8.2	8.4	4.1	3.8	3.9
Out. e^+/e^-	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

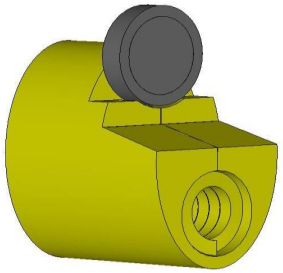
→ Comparable e^+ production rate but lower thermal load

→ Capture simulations in progress

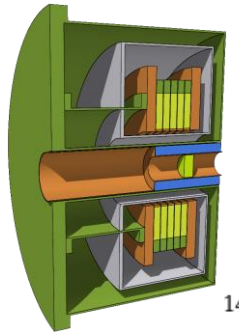
Positron capture: matching device

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

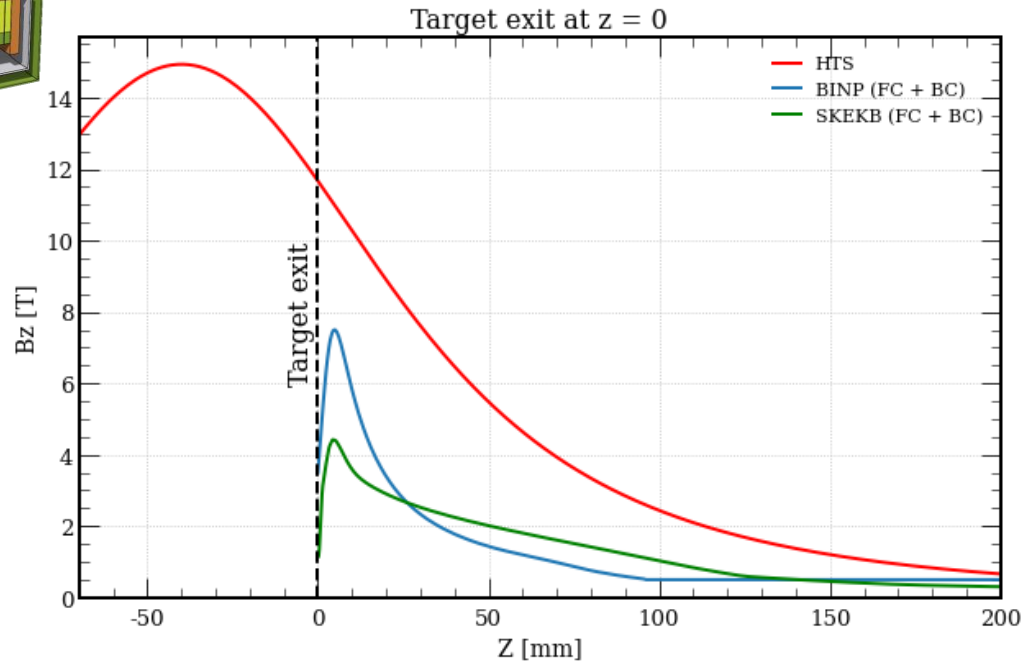




Flux Concentrator (FC)
Originally designed by BINP (P. Martyshkin). Starting collaboration with KEK and CERN.



High-Temperature Superconducting (HTS) solenoid designed by PSI (J. Kosse, B. Auchmann and M. Duda)

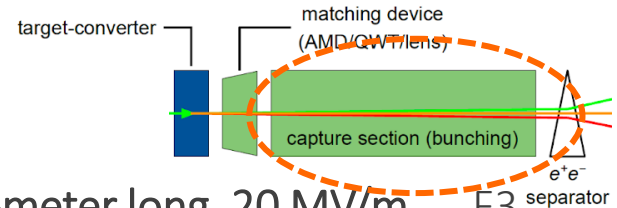


FC: lower peak field and aperture, fixed target position, challenging power source working at 200 Hz, ***robust and reliable solution****…*

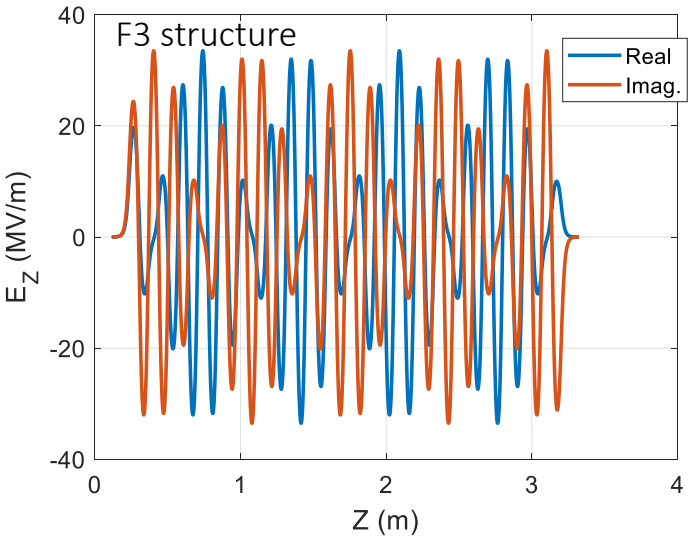
HTS solenoid: higher peak field and aperture, flexibility on the field profile and target position, DC operation, ***innovative solution in application for e⁺ capture****…*

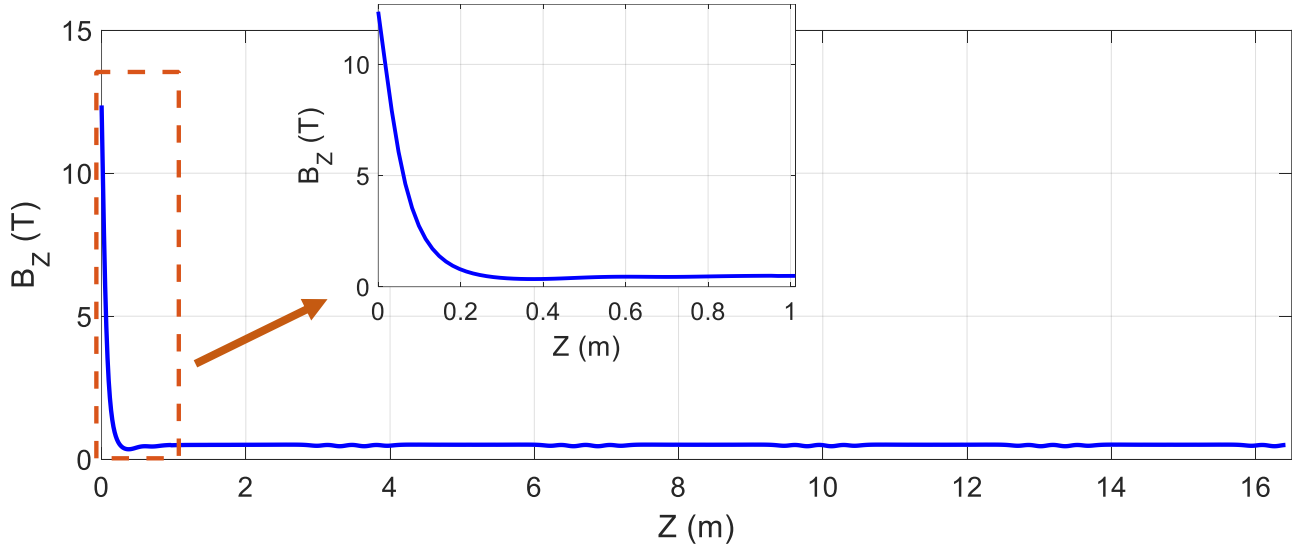
Positron capture: capture linac

The capture linac is encapsulated inside a solenoid with the axial magnetic field of ~0.5 T



- <u>Baseline structure: large-aperture (Φ = 60 mm) TW L-band @ 2 GHz, 9π/10, 3-meter long, 20 MV/m.</u> F3 structure designed by H. Pommerenke and A. Grudiev (CERN). 5 RF structures are used to accelerate the e^+ beam up to ~200 MeV.
- <u>Baseline solenoid configuration: 0.5 T NC solenoid.</u> Configuration designed by M. Schaer, R. Zennaro (PSI). For simplification, 0.5 T uniform NC field used (as the difference in final results was found to be small).





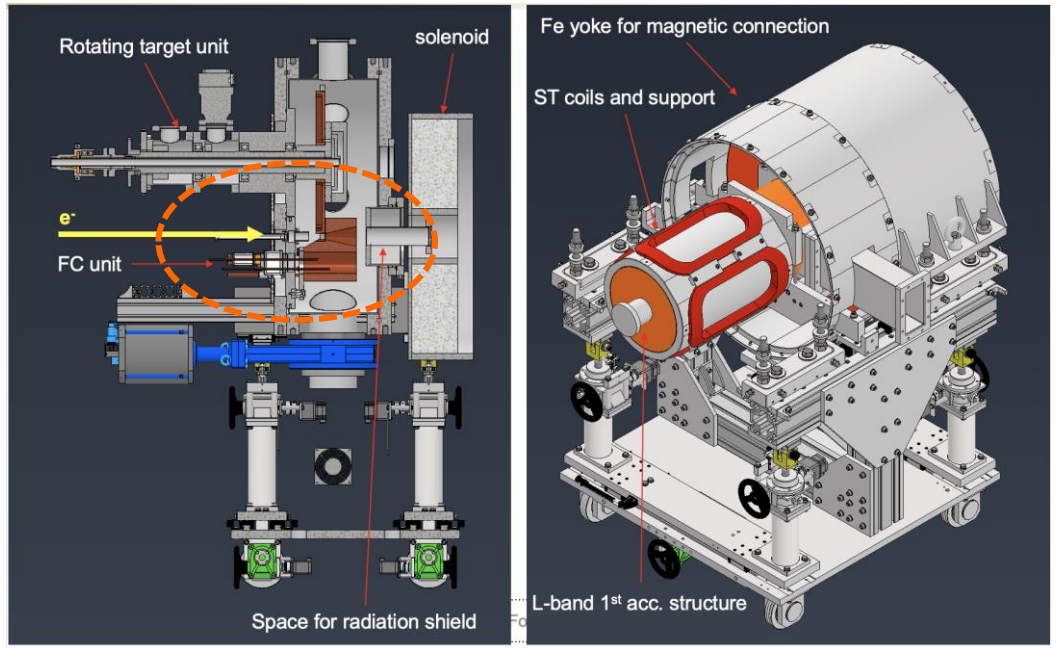
FC-based positron capture system (I)

- FCC-ee FC original design is made by BINP. *Very simple model (not realistic in terms of ohmic loss and high-power requirement for the pulsed power supply).* **Needs more realistic simulations.**
- FC-based capture system successfully works at SuperKEKB → starting point for the FCC-ee capture system studies. **FC is currently considered as a baseline for the ILC e^--driven and CLIC positron sources.**

Compared to SuperKEKB FC, high rep. rate (up to 300 Hz) and ideally higher max. field value/aperture are requested for the future collider projects.

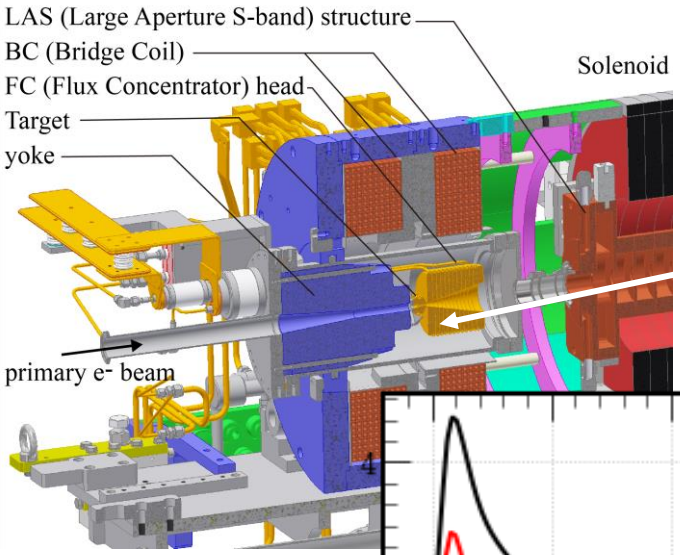
Make use of the SuperKEKB experiences and join the effort on the FC design between FCC/ILC/CLIC collaborations to arrive to a more realistic model.

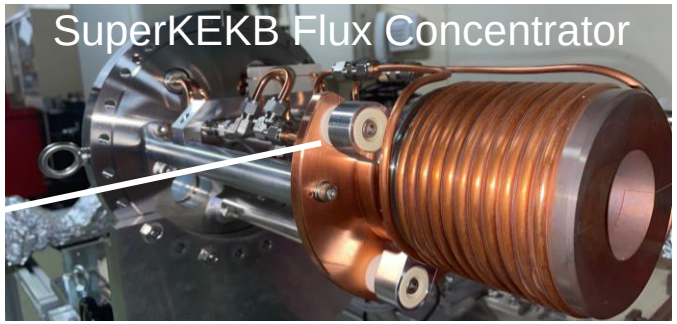
Prototype of the positron source for ILC

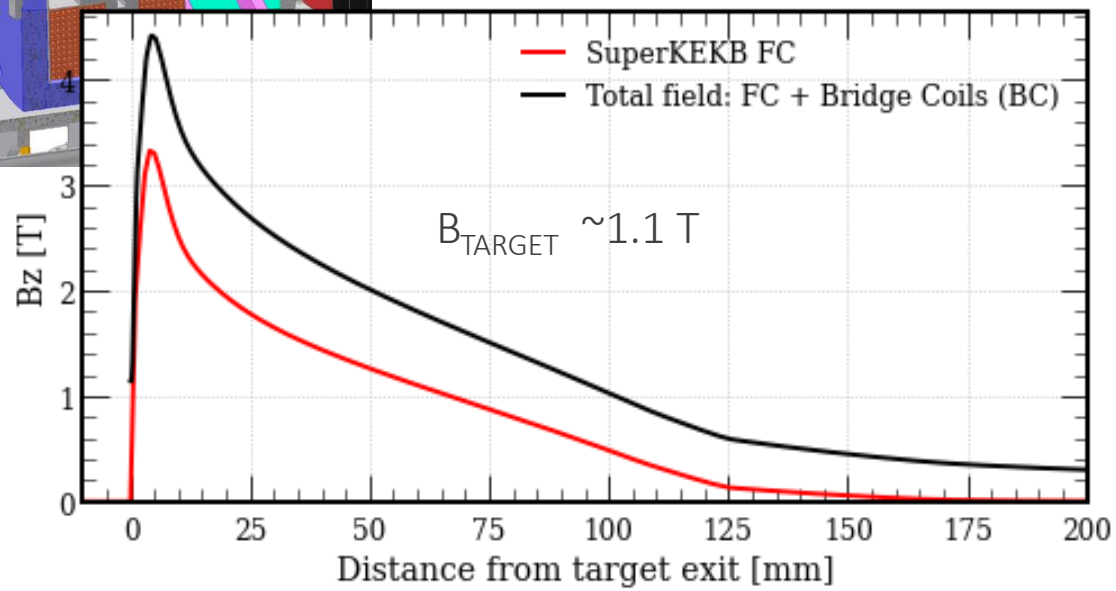


FC-based positron capture system (II)

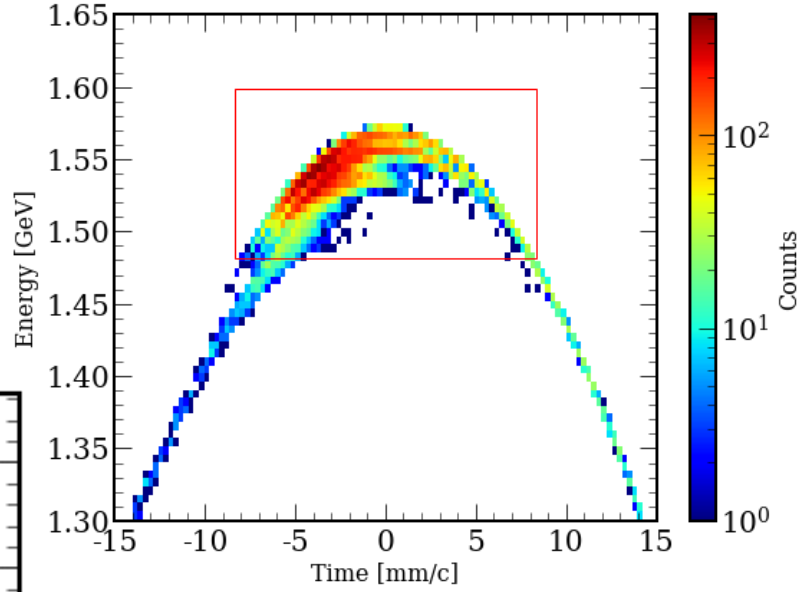
Application of the SuperKEKB FC to the FCC-ee positron source







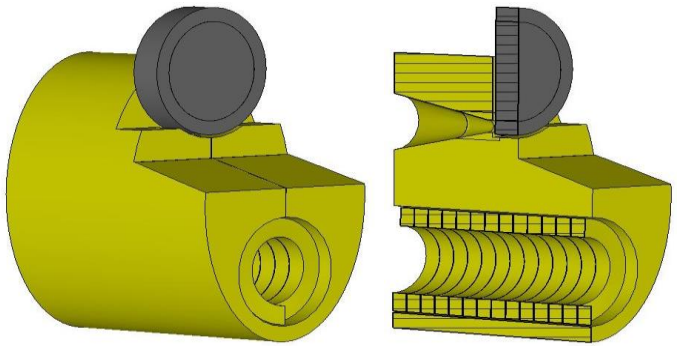
@ 1.54 GeV (DR entrance)



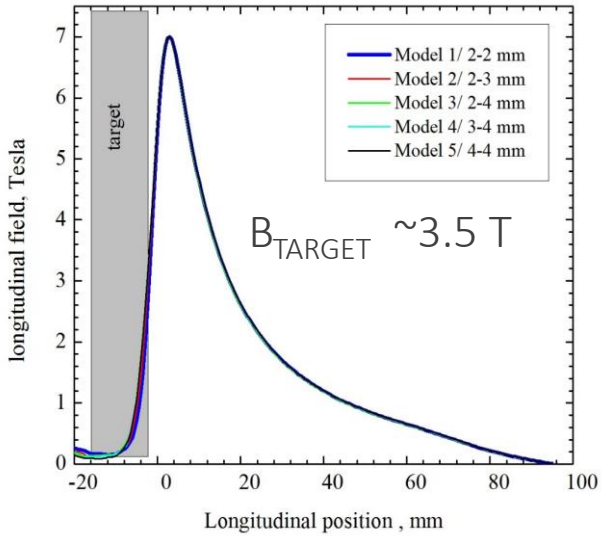
Accepted e^+ yield @ DR	2.7
Norm. emittance [mm*rad]	11.9
Energy spread (RMS) [%]	1.1
Bunch length (RMS) [mm]	2.6

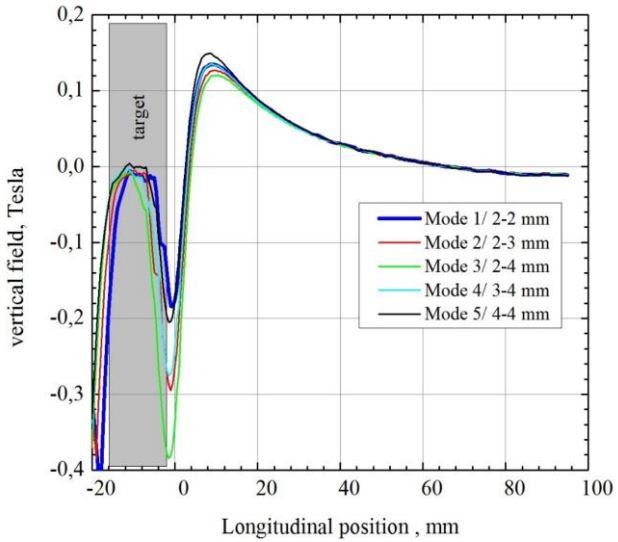
FC-based positron capture system (III)

In the FCC CDR, the baseline for the capture system is based on the BINP FC



Parameter [unit]	Value
Target diameter [mm]	90
Target thickness [mm]	15.8
Gap between target and FC [mm]	2
Grooving gap between target side face and FC body [mm]	2
Elliptical cylinder size [mm]	120×180
Total length [mm]	140
Conical part length [mm]	70
Min cone diameter [mm]	8
Maximm cone diameter [mm]	44
Cone angle [deg.]	25
Cylindrical hole diameter [mm]	70
Coil turns [-]	13
Current profile pulse length [μs]	25
Peak field [T]	7
Peak transverse field [mT]	135–157
Gap between coil turns [mm]	0.4
Gap between coil and FC body [mm]	1
Turns size	9.6×14 mm





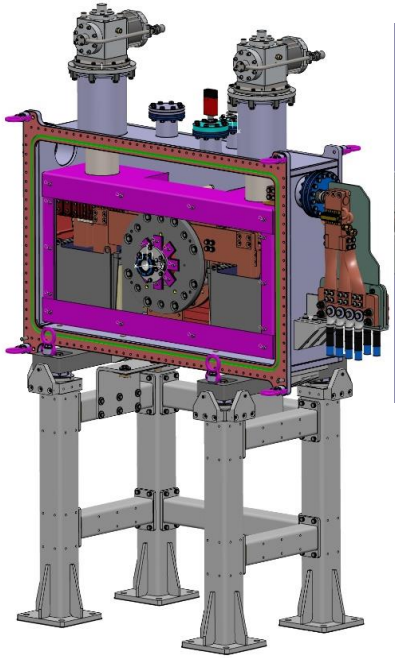
Simulation results update (capture linac)

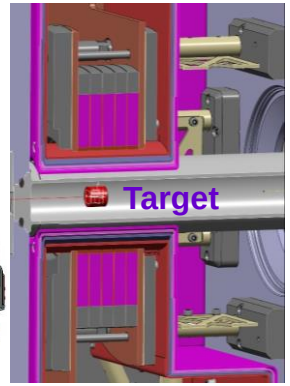
Accepted e^+ yield @ DR	4.4
Norm. emittance [mm*rad]	12.2
Energy spread (RMS) [%]	1.2
Bunch length (RMS) [mm]	2.9

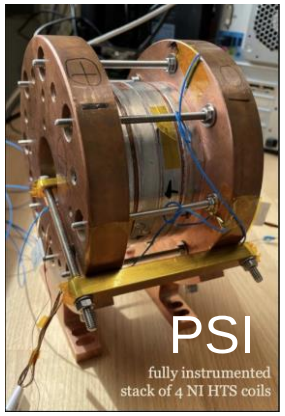
HTS-based positron capture system

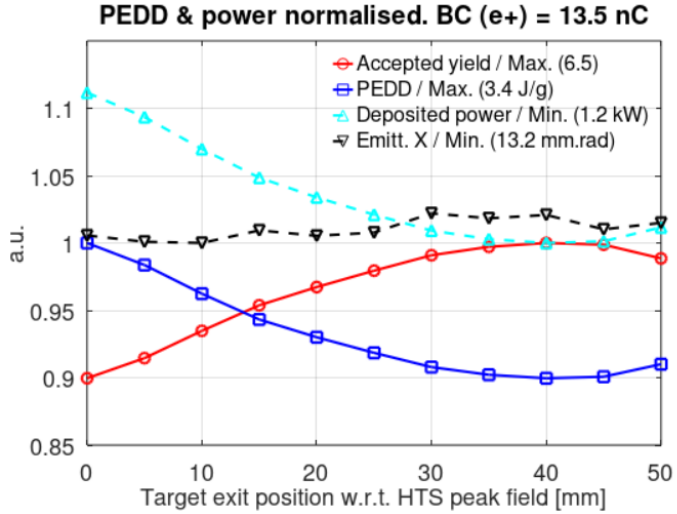
We consider the same HTS solenoid design and cryostat aperture as for P³ e⁺ production experiment at PSI (72 mm)

HTS solenoid integrated in the cryostat



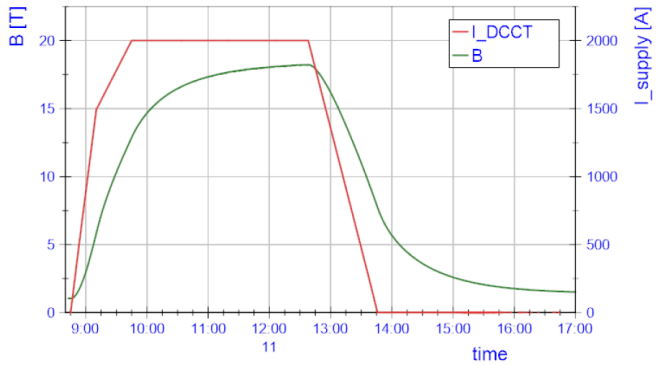


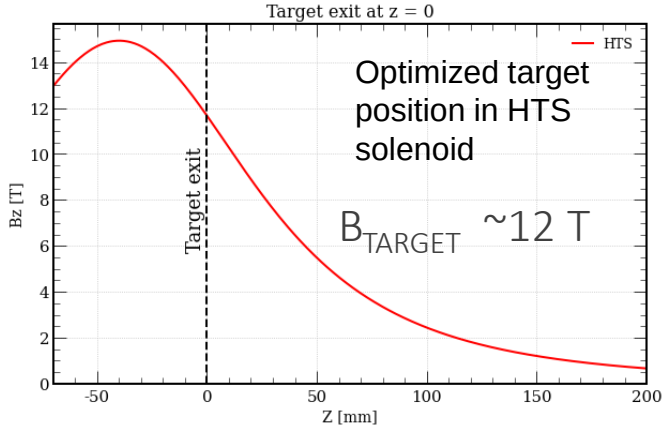




18.2 T @15K@2kA reached for stack of 4 coils

- **High peak field (~15 T, ~12 T at target exit)**
- **Large aperture (Φ = 30-40 mm)**
- **Flexible target position (can be placed inside the bore)**
- **DC operation**

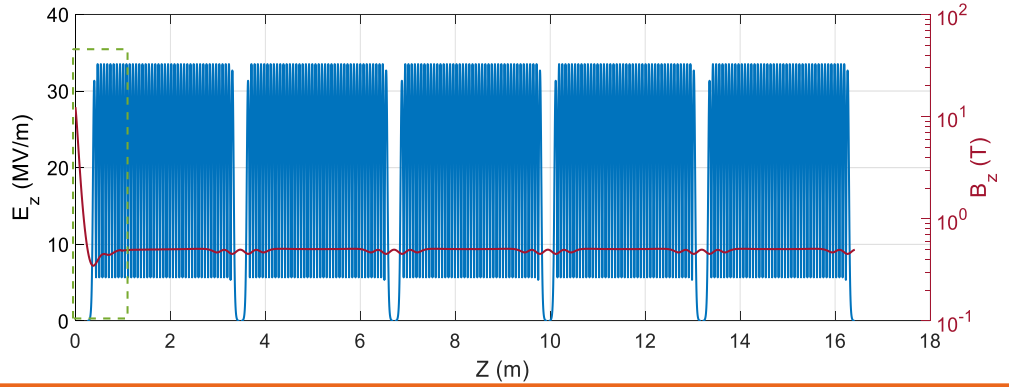




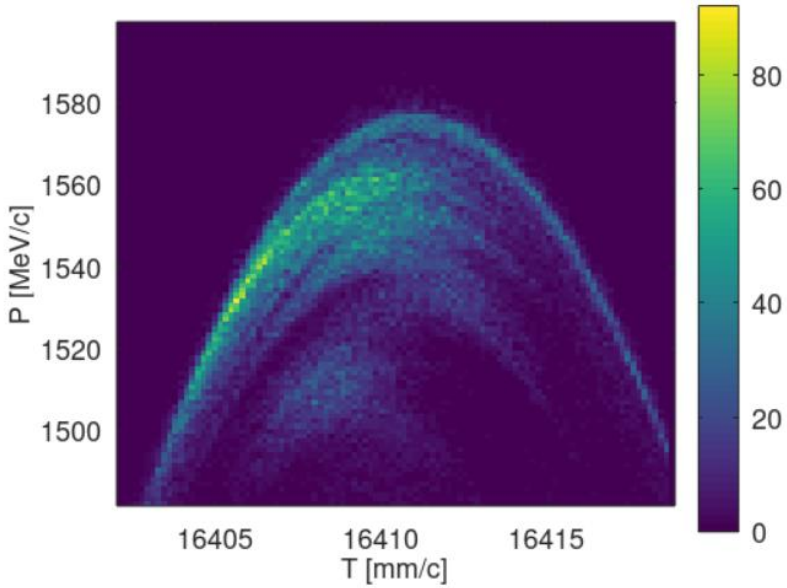
Current baseline: positron capture system –version 1

Capture system -version 1

- Positron production: conventional scheme (e^- beam size on target = 1 mm rms)
- Matching device is based on the SC solenoid (5 HTS coils, 72 mm bore including shielding). Min beam aperture (w/o significant yield loss): 30- 32 mm (Maximum shielding thickness: ~21 mm)
- Capture linac is based on the F3 RF structures
- NC long solenoid B = 0.5 T (realistic conventional design based on short coils)



@ 1.54 GeV (DR entrance)



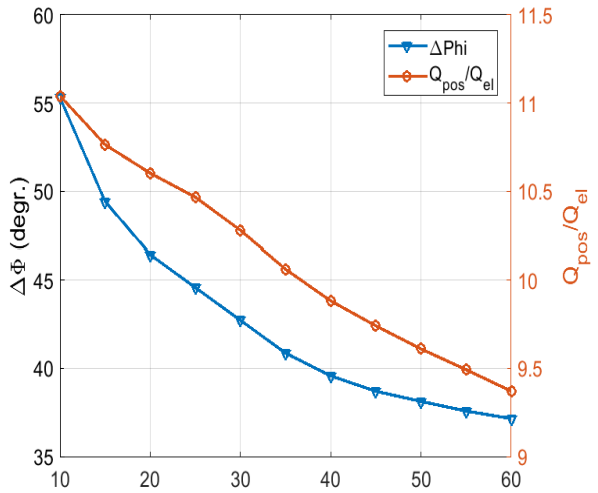
Accepted e^+ yield @ DR	6.5
Norm. emittance [mm*rad]	13.7
Energy spread (RMS) [%]	1.4
Bunch length (RMS) [mm]	2.9

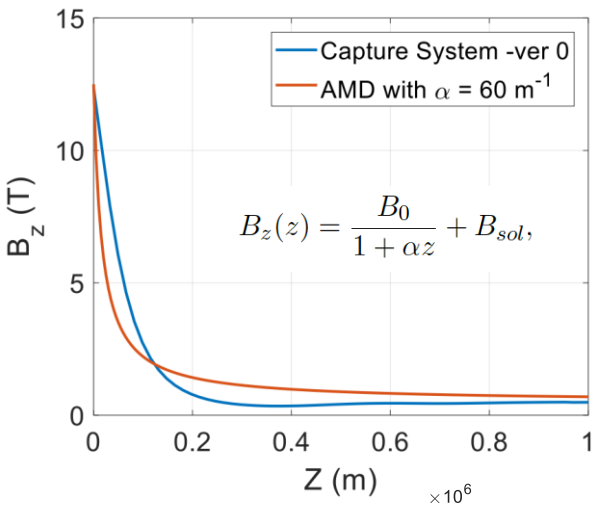
Optimization studies toward better performance

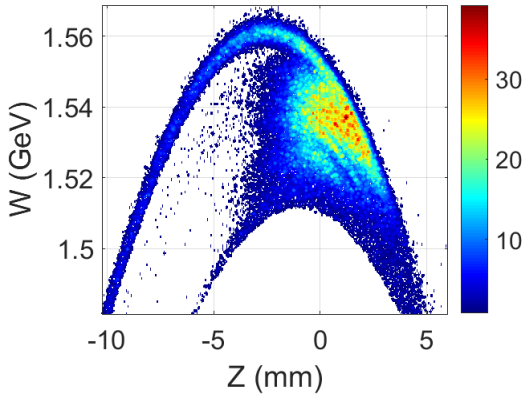
Target and capture system studies are in progress to provide the optimized positron bunch 6D phase space matched to the positron linac and DR

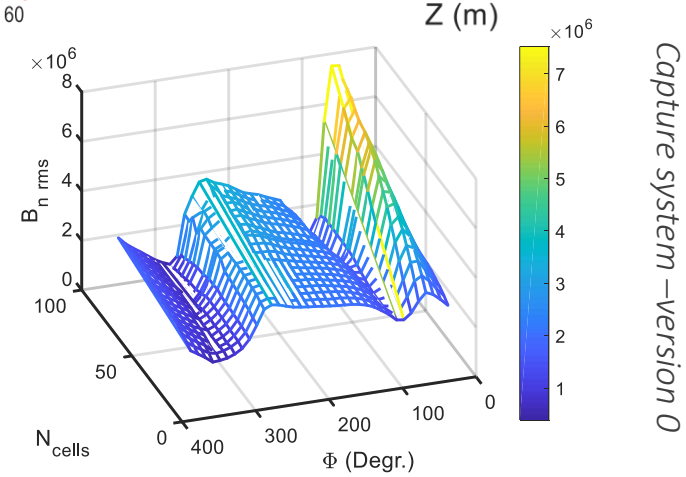
- Overall parameter scanning (target thickness, distances, etc.)
- Matching device field profile
- RF structure length
- Distance between the target and the first RF structure
- Overall optimization (GIOTTO, etc.)
- …

GIOTTO results:
Δ W/W (1σ) = 0.99 %,
Δ Z (1σ) = 2.4 mm
Beam size (1σ) = 8.7 mm
Acc. Yield = 7
$\varepsilon_{n\ rms\ x,y}$ = 9.6·10³ mm·mrad









Radiation load studies and status of target design

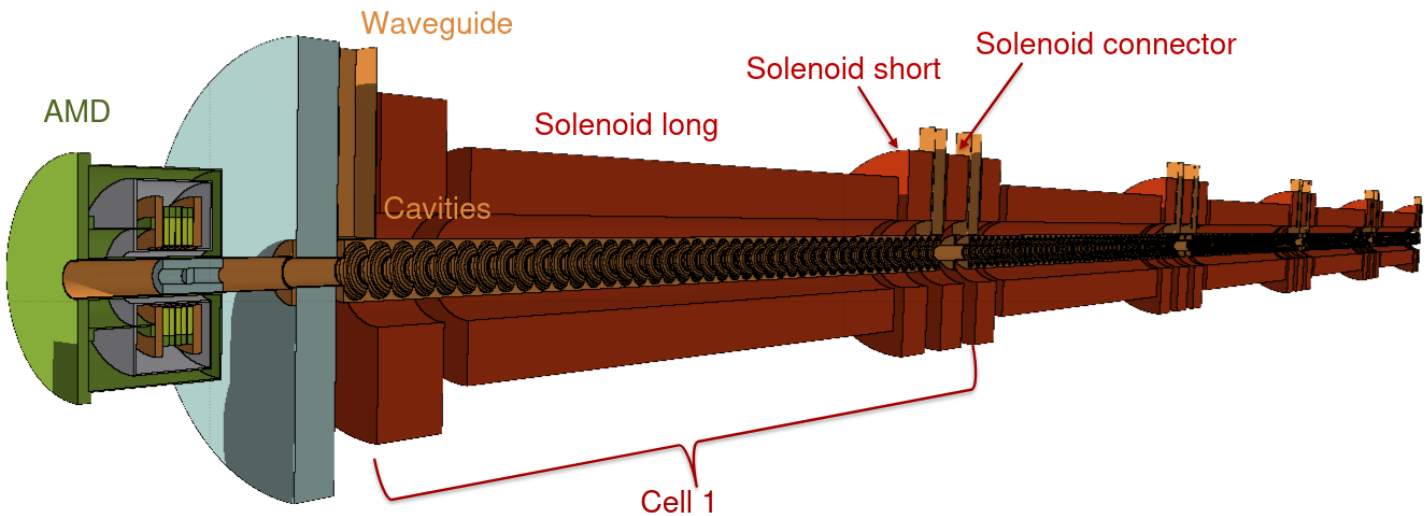
Currently, the radiation load and target design studies focused exclusively on the HTS solenoid-based system (capture system –version 1)

Dedicated talk by R. Mena Andrade (CERN)

FLUKA model of the FCC-ee positron source to assess

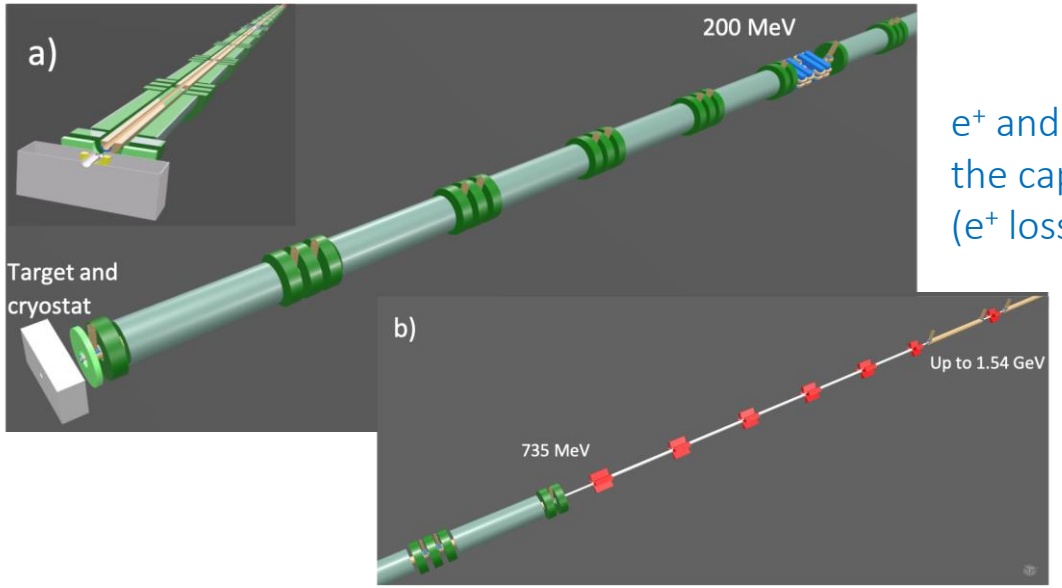
Heat load on the target/HTS solenoid/capture linac/solenoid
- Total deposited power
- Power density

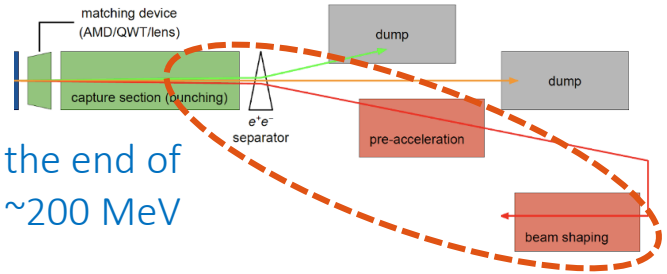
Long term radiation effects
- Dose
- Displacement per atom (DPA)



→ Design feasibility and mechanical integration
→ Reliability of the positron source system

Positron linac up to 1.54 GeV



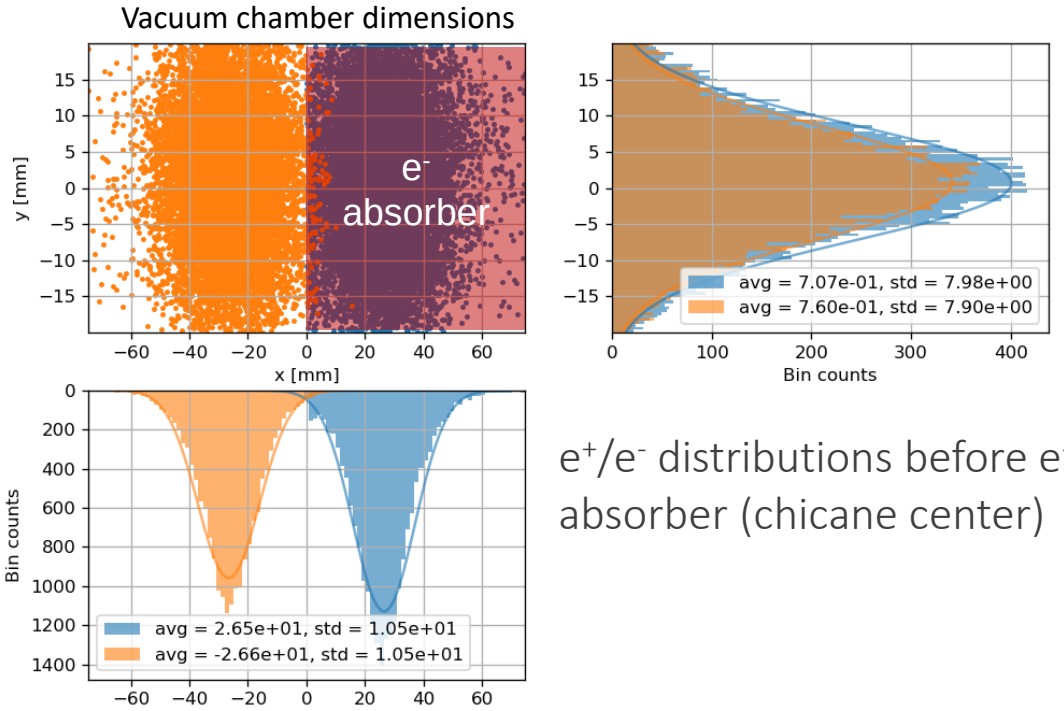


e^+ and e^- bunches are separated in the end of the capture system by a chicane at ~200 MeV (e^+ losses limited to ~ 15 %)

The solenoid focusing is used until ~735 MeV of e^+ beam energy.

After the matching section at ~735 MeV, the e^+ beam passes to a quadrupole focusing.

ECS is used to increase the number of e^+ within the DR energy acceptance (±3.8%).



e^+/e^- distributions before e^- absorber (chicane center)

Summary of the simulation results

Drive beam parameters	Alternative FC-based capture system		Capture system –v1
Matching device	BINP FC	SuperKEKB FC	HTS solenoid
Matching device aperture	2a=8-44mm	2a=7-52mm	$2a_{min}$=30 mm (bore 72mm)
Matching device peak magnetic field (@Target) [T]	7.5 (3.5)	4.4 (1.1)	15 (12)
e- beam bunch charge [nC] / e- beam power [kW]	**3.1 / 7.4**	**5 / 12**	**2.1 / 5**
Target deposited power [kW] / PEDD [J/g]	1.7 / 11.1	2.9 / 18.3	1.2 / 3.1
Positron yield @CS [Ne^+/Ne^-]	4.9	3.3	8
Positron yield @DR [Ne^+/Ne^-]	**4.4**	**2.7**	**6.5**
Normalized emittance (rms) [mm.rad]	12.2	11.9	13.7
Energy spread (rms) [%]	1.2	1.1	1.4
Bunch length (rms) [mm]	2.9	2.6	2.9
e+ beam bunch charge [nC]	**13.5**		

Conclusions and outlook

- The studies on the FCC-ee positron source are well advanced: positron production, HTS technology feasibility for matching device, capture linac (RF structures and solenoid). So far, no showstoppers found that prevent a SC solenoid matching device. Studies ongoing.

- FC-based capture system requires a realistic model capable to work at the FCC-ee operation parameters. Collaborative work is very essential.

- Two capture system layouts (based on the FC and SC solenoid) will be eventually compared in detail in terms of the performance and cost for the mid-term project review.

- Positron linac has a robust design with full tracking simulations from production target to damping ring using the realistic field maps.

- Thermal and radiation load studies: FLUKA model is available for capture system –version 1. Still to be developed for the FC-based capture system.

- Design and integration of the production target are under investigations and to be studied for both schemes.

Positron source performances

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)	~ 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

Emittance

Polarization

Reliability and radiation environment

Future collider project challenges

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	2	2
Required charge [10^{10} e^+/bunch]	0.4	3	0.18	50	1.88	~2.4
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	100	200
e^+ flux [10^{14} e^+/second]	1	2	18	10–100	0.04	~0.1
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