Positron source and capture system (HTS-solenoid vs. Flux Concentrator options)

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on behalf of the CHART/FCC-ee Injector design collaboration (WP3)

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

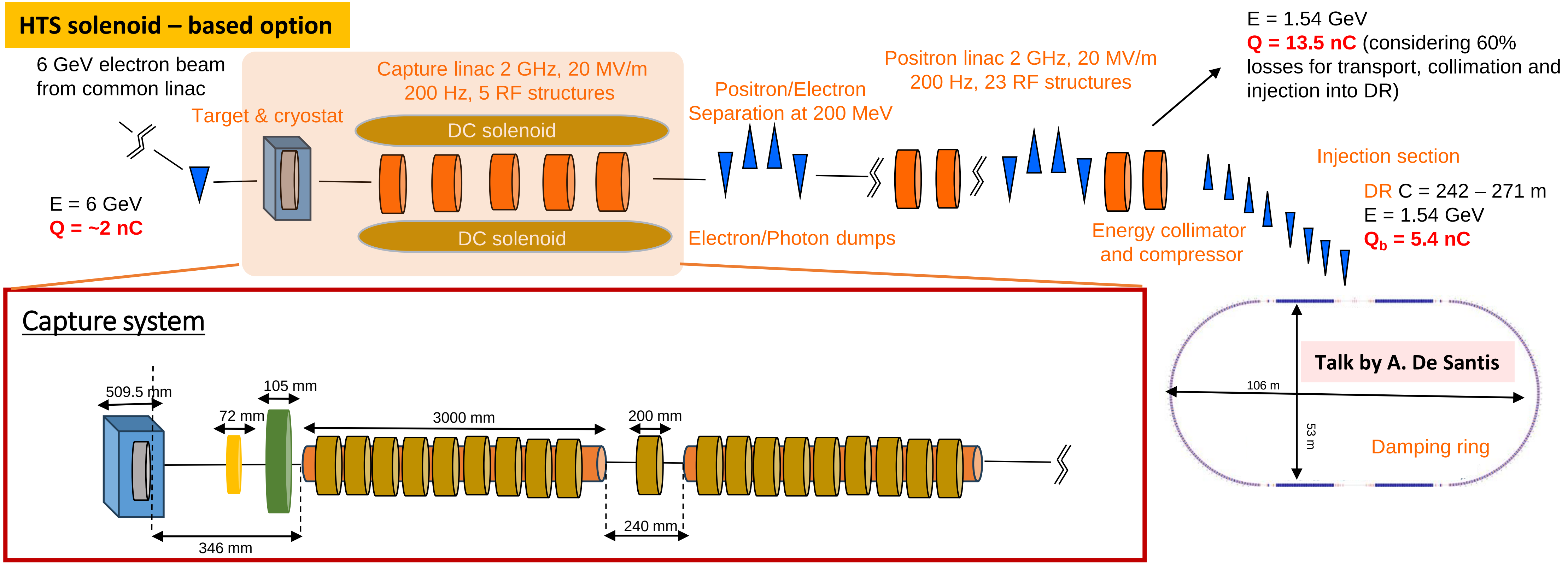
e^- drive beam

Beam energy	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)

→ 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*

Positron source physics design (current baseline)



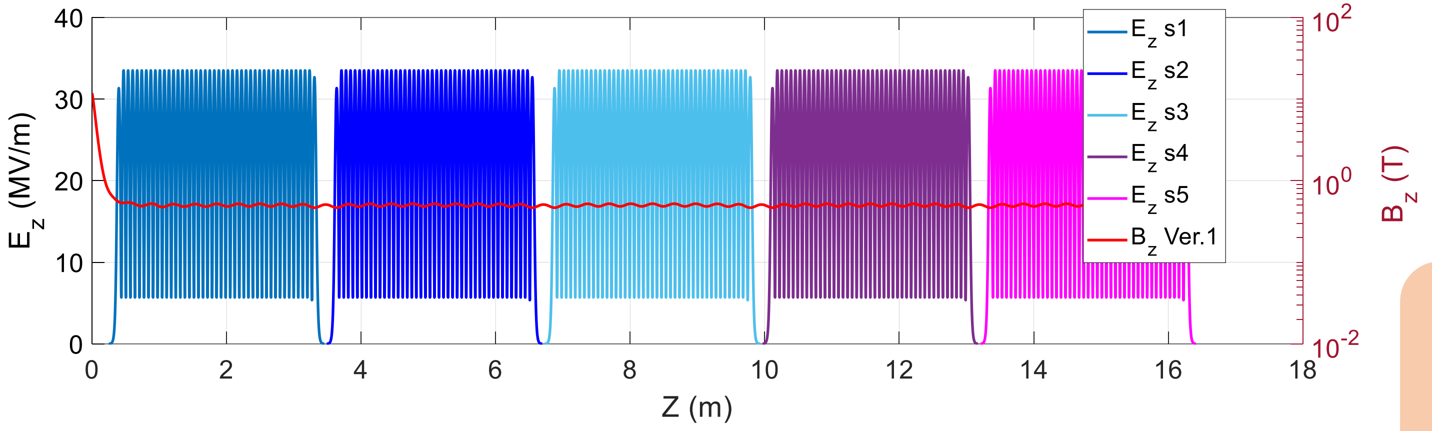
Positron production : conventional scheme (e- beam size on target = 1 mm rms). Target exit located at 40 mm w.r.t. HTS solenoid peak field.

Matching device is based on the SC solenoid (5 HTS coils, ∅ 60 mm 72 mm bore, ∅ 60 mm including shielding)

Capture linac is based on the L-band TW RF structures (2 GHz, ∅ 60 mm, 3-m long)

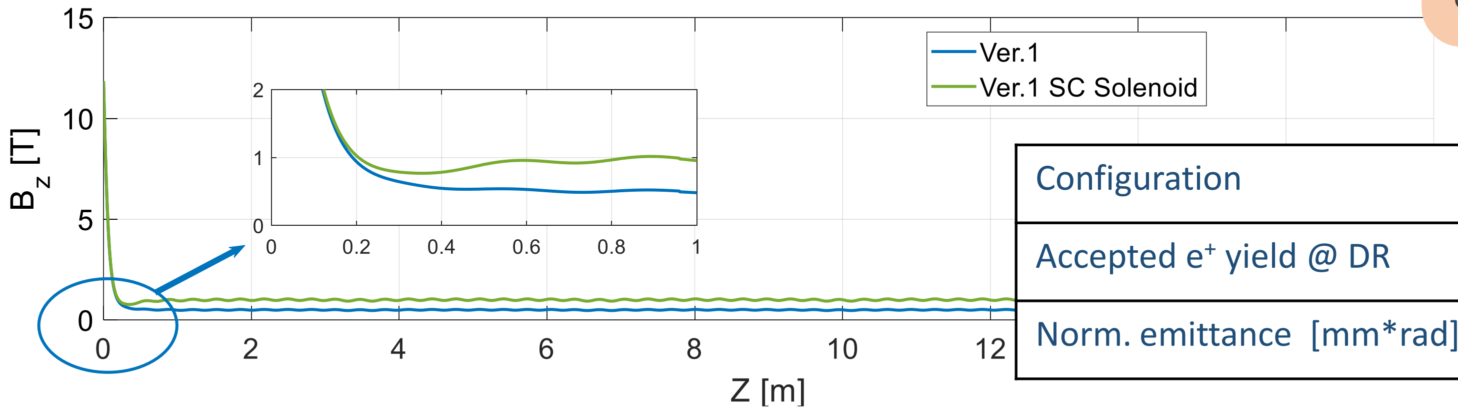
NC solenoid B = 0.5 T (realistic conventional design based on the short coils B = 0.31 T) + short “tuning” solenoid B = 0.248 T before the 1st RF structure

Positron capture system : toward better performance



Fieldmap for capture system (HTS solenoid – based option)

Assuming the SC solenoid after the cryostat (~1T) and decreasing the aperture of the RF structures (∅40 mm) can provide similar positron yield

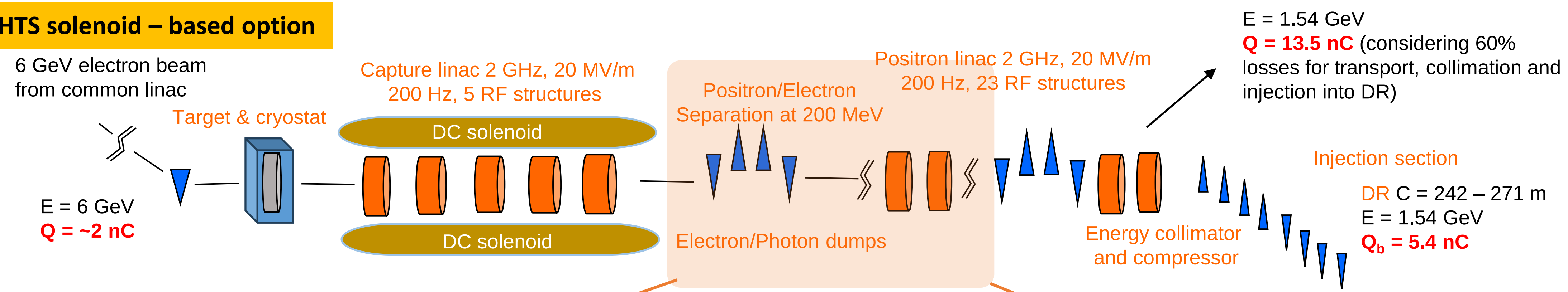


Configuration	∅60, NC Solenoid	∅40, SC Solenoid
Accepted e^+ yield @ DR	7.6	7
Norm. emittance [mm*rad]	11	9.5

Proposed solution could potentially decrease the power consumption of the solenoid and make more efficient the capture section RF system (smaller aperture)

work in progress

HTS solenoid – based option



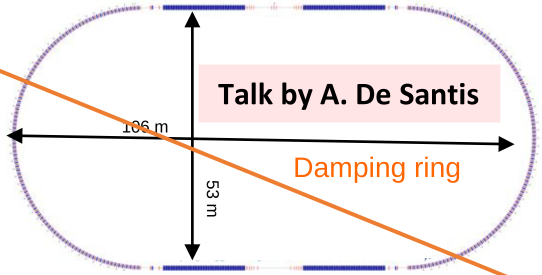
Positron linac

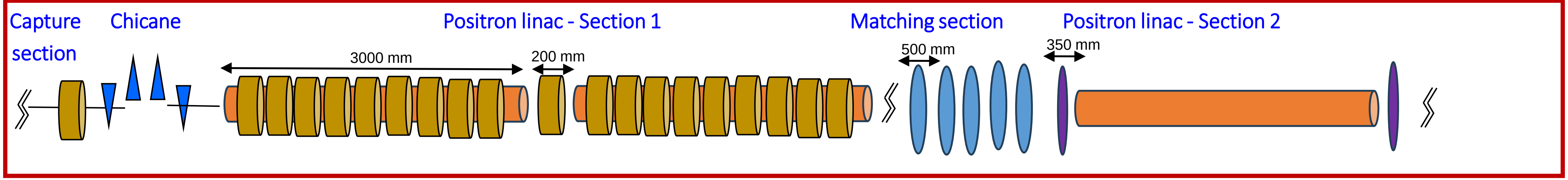
Separator chicane : Rectangular beampipe and hor./vert. collimators, Dipole peak field: ~0.2 T

Section 1 : up to ~730 MeV. Same RF structure with Capture Linac (CL). 9 structures. G = 20 MV/m

Matching section : 5 quadrupoles. Quadrupole (0.5 m long) distance fixed to 2 m

Section 2 : up to 1.54 GeV. Same RF structure with CL. 14 structures in 7 FODO cells. Quadrupole (0.35 m long) distance fixed to ~4 m. G = 20 MV/m

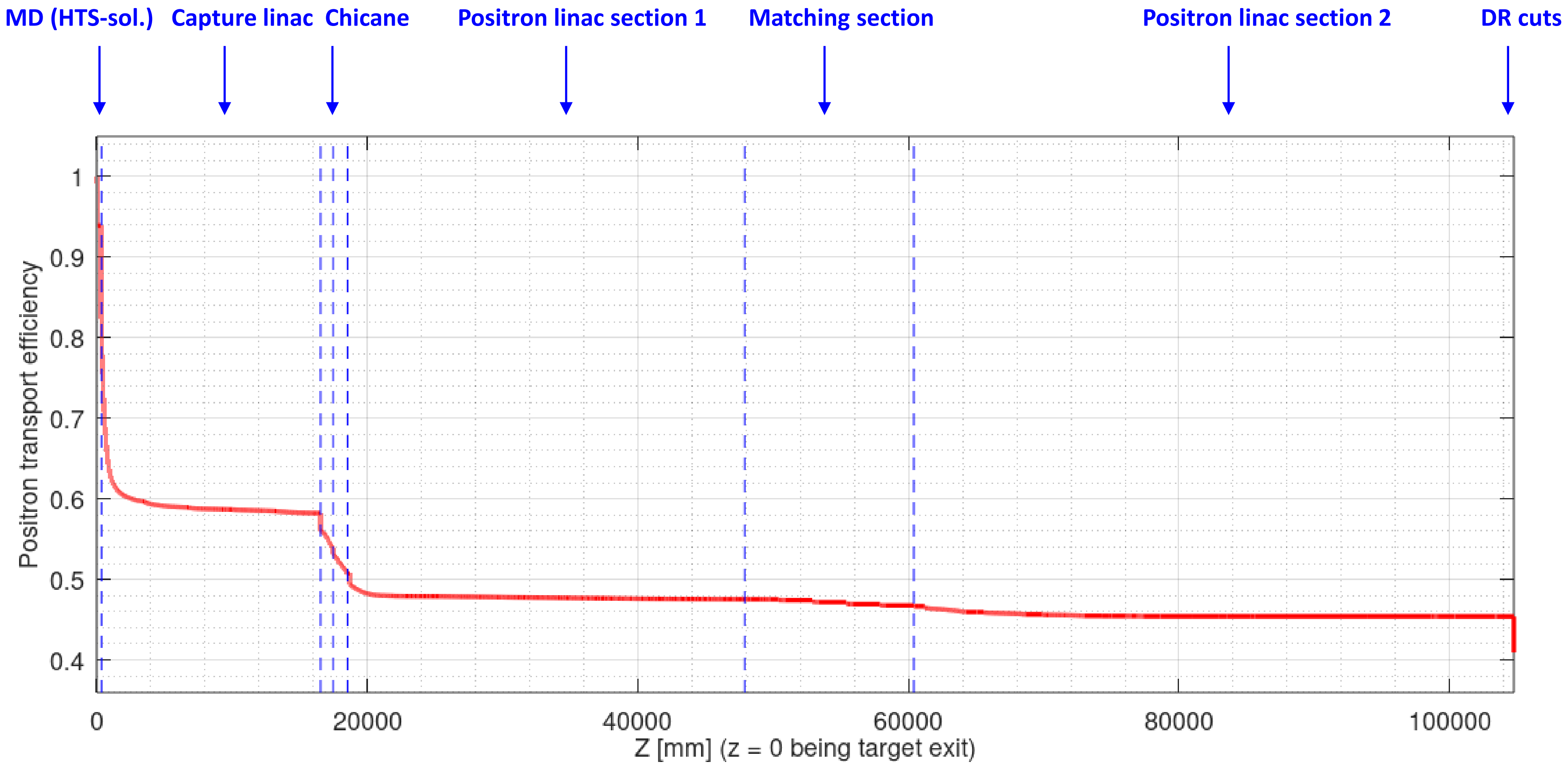




Start-to-end simulation environment (from target to the DR) is under development

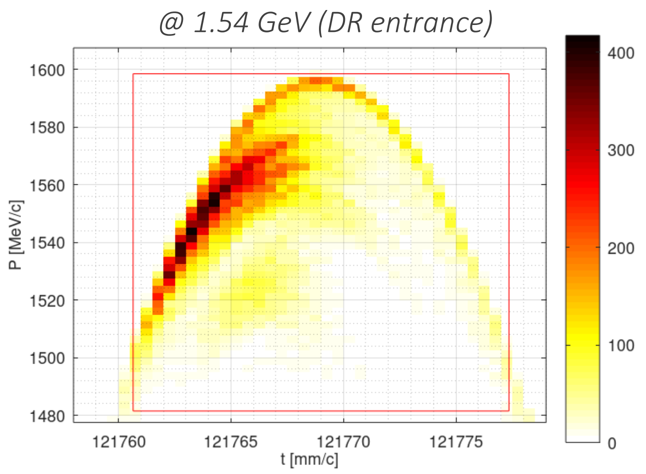
work in progress

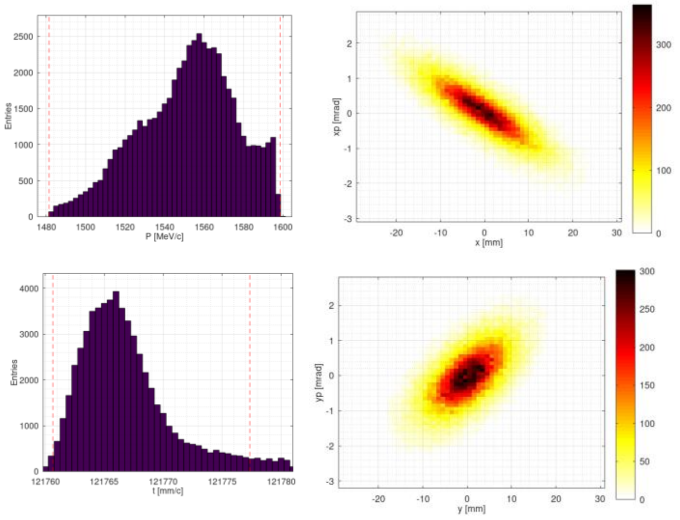
Positron source overall efficiency (current baseline)



DR acceptance window: (Energy : 1.54 GeV ± **3.8% ;** Time : **16.7 mm/c**)

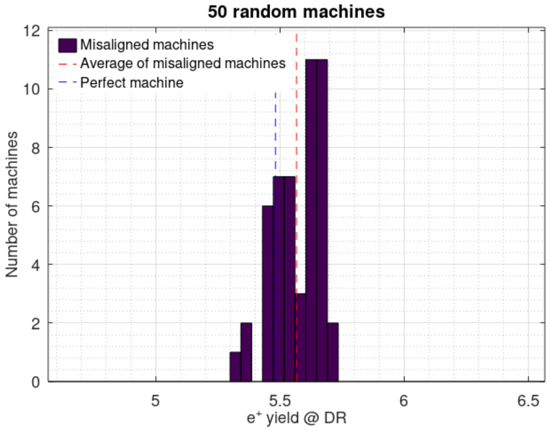
Simulation results and error studies (HTS solenoid – based option)

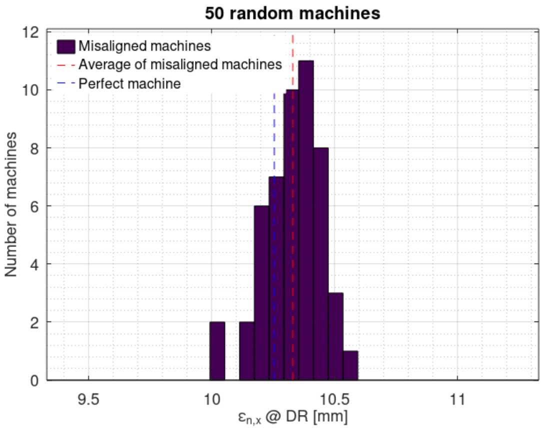




e^+ yield @ Target	13.9
e^+ yield @ Capture Section	8.1 (8.0*)
e^+ yield @ Positron Linac	6.3 (6.2*)
Accepted e^+ yield @ DR	5.7 (5.6*)
ε_n x/y after DR cuts [mm.rad]	10.3/10.9

*Simulations include collective effects (space charge and short-range wakefield)

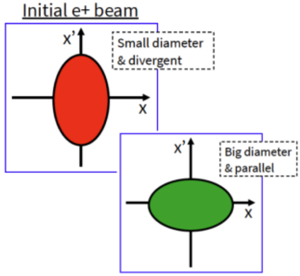




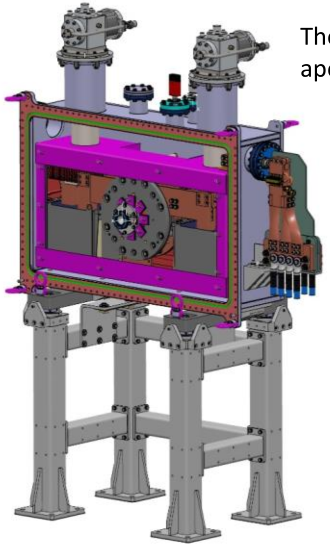
Position error (x, y): σ = 100 µm for all elements
Angular error σ = 100 µrad for all elements, except that σ = 200 µrad for all NC solenoids and dipoles
Magnetic **strength** error: σ = 0.1% for all magnets
RF **gradient** error: σ = 1% for all RF structures
RF **phase** error: σ = 0.1° for all RF structures
Beam **position jitter** (x, y): σ = 100 µm for e^+ beam from target
Beam **angular jitter** (x’, y’): σ = 100 µrad for e^+ beam from target

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

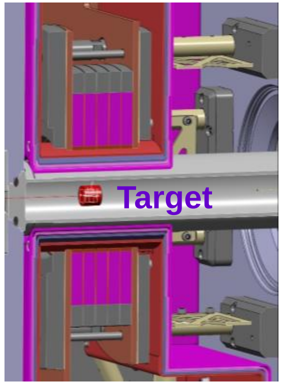
Matching device => a fast phase space rotation to transform the small size/high divergence in big sizes/low divergence beam



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

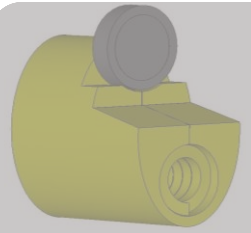
Compared with FC
- Higher peak field (~15 T, ~12 T @Target)
- Larger aperture (∅ = 30-40 mm)
- Flexible target position and field profile
- Axially symmetric solenoid field
- DC operation

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

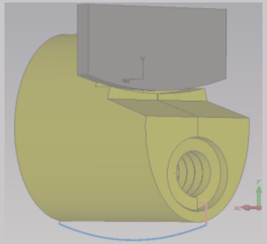
robust and reliable solution

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)

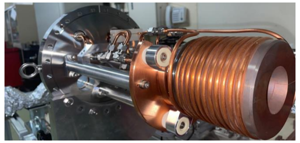
Positron capture: Flux Concentrator (FC) as a matching device



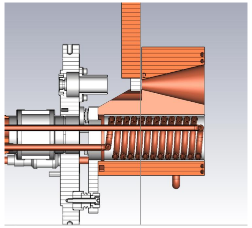
Originally designed by BINP for the FCC-ee (P. Martyshkin)
=> FC:FCC-BINP
Dropped as no info and further studies available



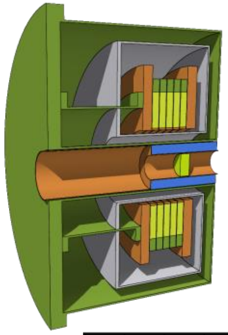
Originally designed by BINP for the ILC (P. Martyshkin) => FC:ILC-BINP
Dropped as no info and further studies available



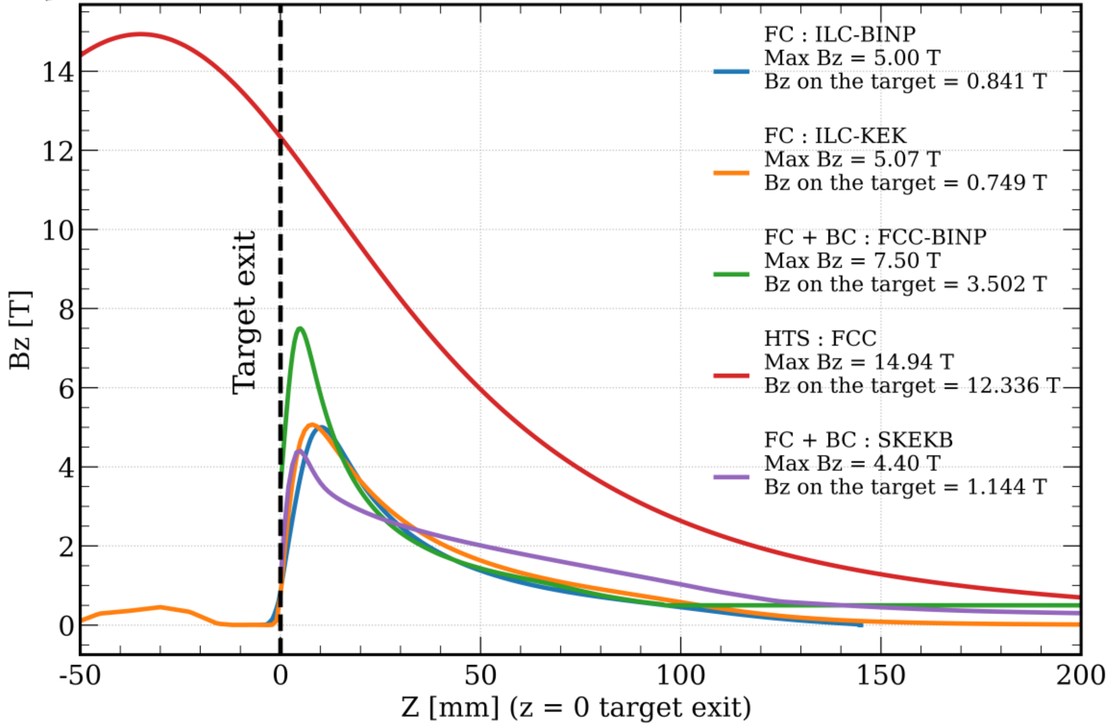
Originally designed by KEK for the SuperKEKB => FC:SKEKB-KEK
Under consideration for the FCC-ee (with and w/o Bridge Coils)



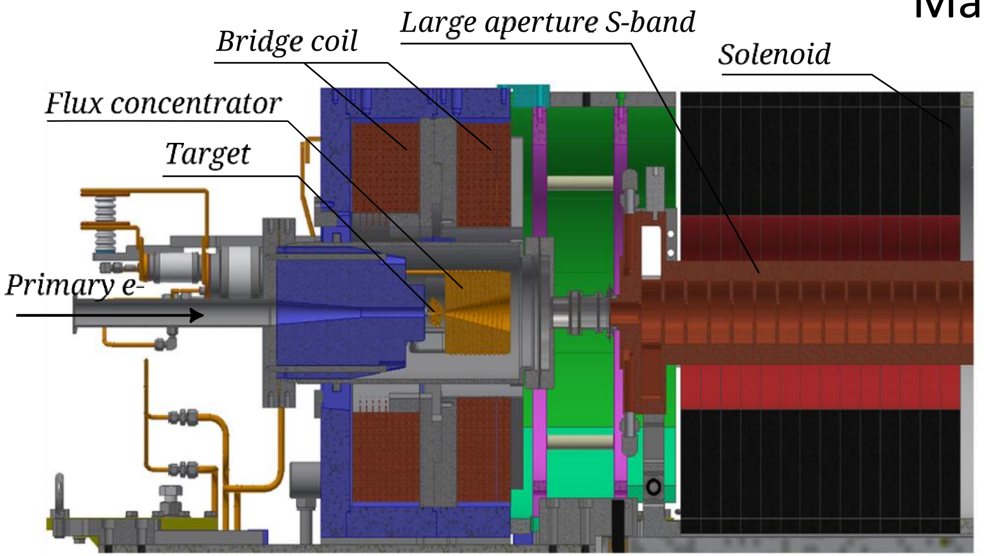
Designed by KEK for the ILC (Y. Enomoto) => FC:ILC-KEK
Under consideration for the FCC-ee

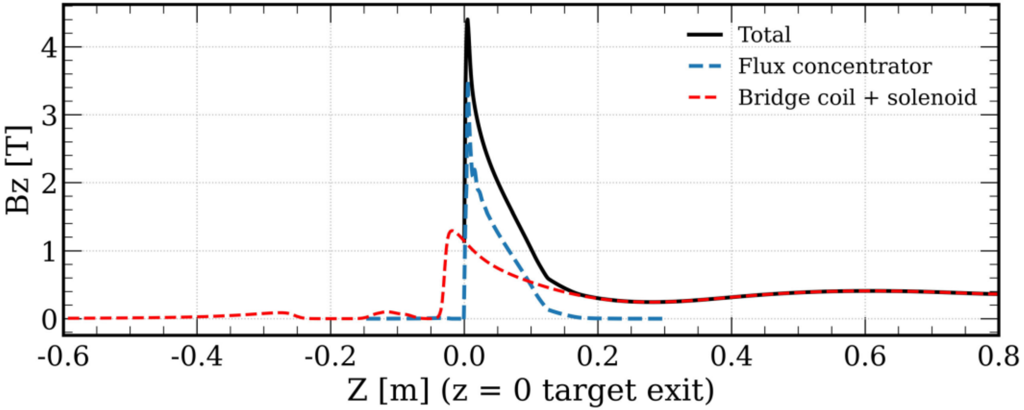


High-Temperature Superconducting (HTS) solenoid designed by PSI => HTS:FCC
Current baseline option



SuperKEKB FC designed by KEK in application to FCC-ee





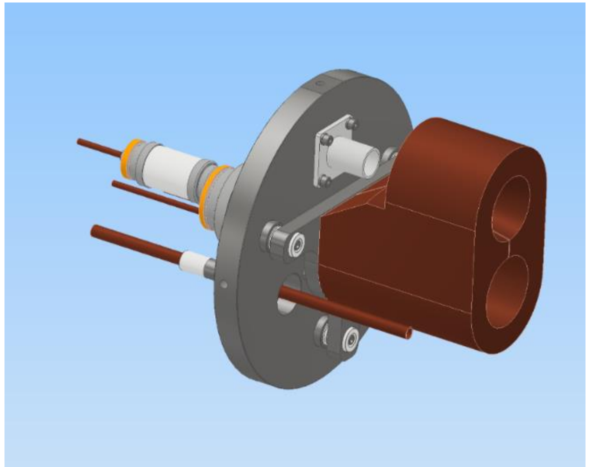
Matching device: Flux Concentrator (FC) + Bridge Coils (BC)

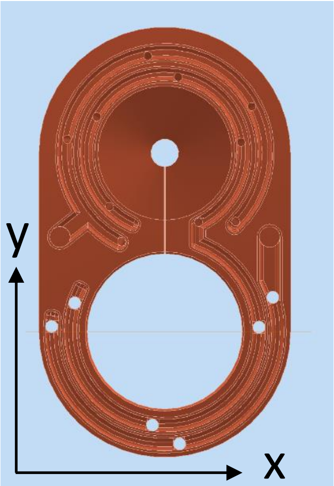
- FC field : 3.5 T at 12.5 kA
  (Pulsed, 50 Hz)

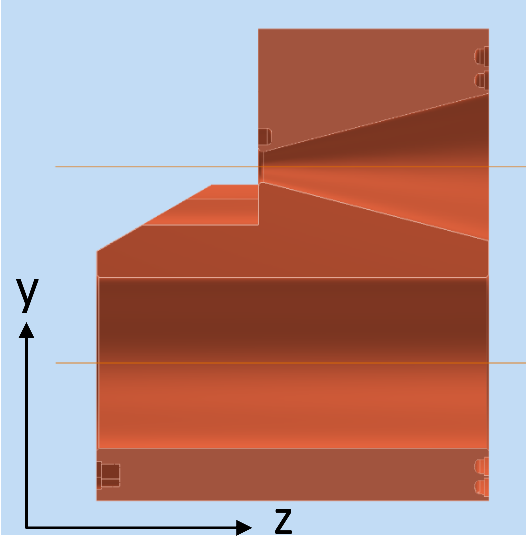
SKEKB FC	
Peak field (FC+BC)	4.4 T
2Ri	7 mm
2Ro	52 mm
Length	100 mm
Field on the target	1.14 T (with BC)

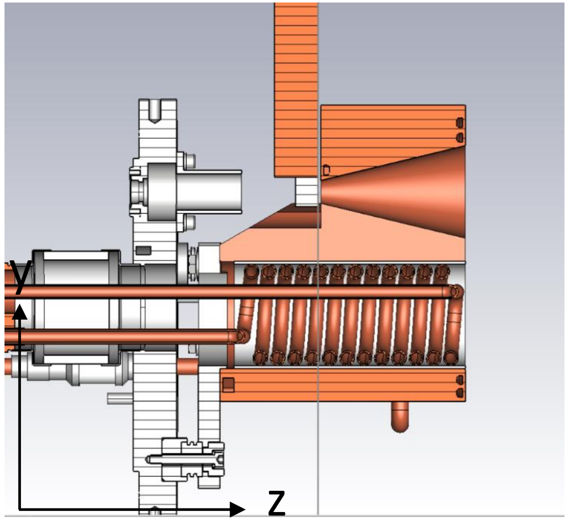
@FCC-ee
Simulations with the FC (w/o BC) and the nominal solenoid fieldmap.
Simulations for (FC + BC) in progress.

ILC FC designed by KEK in application to FCC-ee









No Bridge Coils (BC) by design

Talk by Y. Enomoto

- FC is under construction now at KEK **(Pulsed, ~100 Hz)**

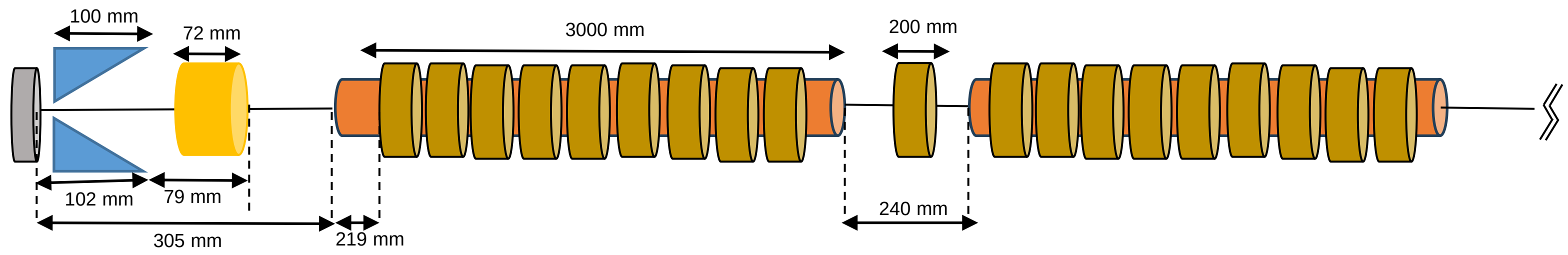
ILC FC	
Peak field	5.1 T
2Ri	12 mm
2Ro	64 mm
Length	100 mm
Field on the target FC	0.75 T

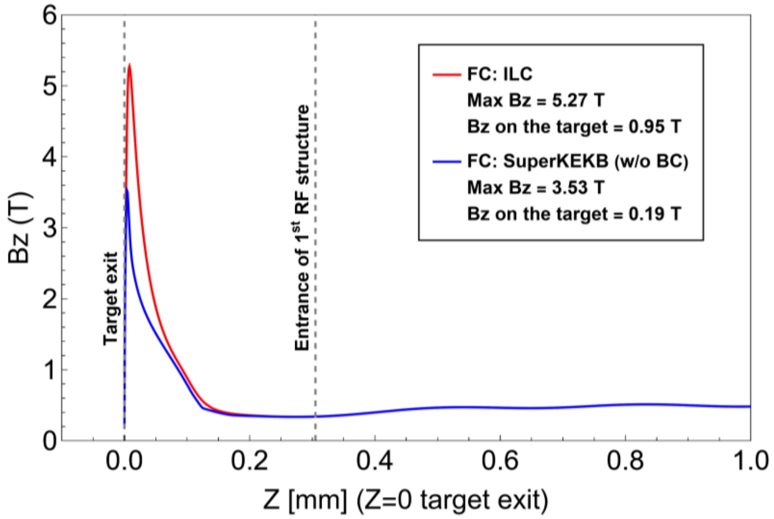
@FCC-ee
Simulations with the FC and the nominal solenoid fieldmap

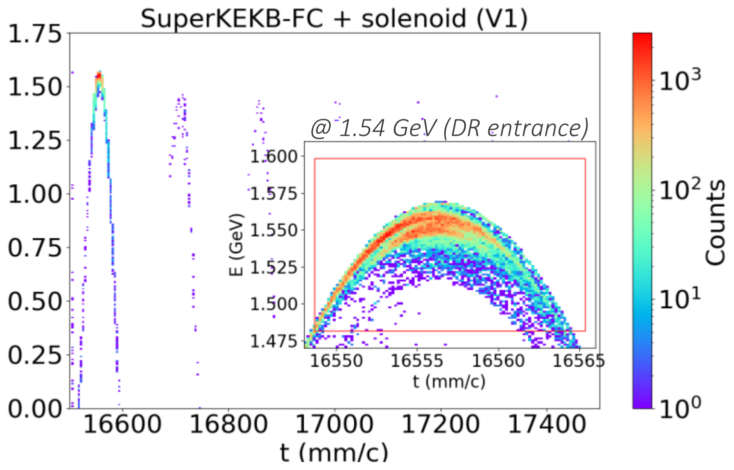
FCC-ee positron capture system based on the FC

Capture system (with FC)

SKEKB-FC (w/o BC)







Two FC are currently considered in application to FCC-ee

- ✓ Physics design
- ✓ Positron production and capture simulations → accepted e^+ yield
- ✓ No thermal and radiation load studies
- ✓ No integration studies

SuperKEKB FC option is now under investigation for target design

Talk by R. Mena Andrade

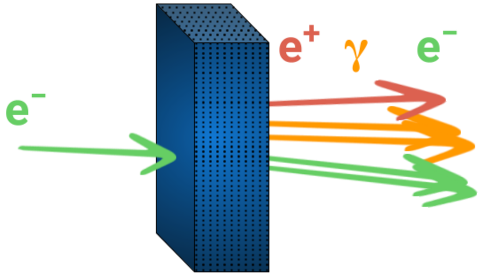
HTS solenoid vs. Flux Concentrator (FC) option for capture system

Drive beam parameters	FC-based capture system		HTS- sol. based capture system
Matching device	ILC-KEK FC	SuperKEKB FC	HTS solenoid
Matching device aperture	2a=12-64mm	2a=7-52mm	$2a_{min}$=60 mm
Matching device peak magnetic field (@Target) [T]	5.3 (0.95)	3.5 (0.19)	15 (12)
e- beam bunch charge [nC] / e- beam power [kW]	**5.3 / 12.7**	**6.2 / 14.8**	**2.0/4.8**
Target deposited power [kW] / PEDD [J/g]	3 / 7.5	3.5 / 8.8	1.1/2.8
Target deposited power [kW] / PEDD [J/g] **@100Hz/4 bunches**	3 / 15	3.5 / 17.6	1.1/5.6
Positron yield @Target / @CS [Ne^+/Ne^-]	13.9 / 3.2	13.9 /2.5	13.9/8.4
Positron yield @DR [Ne^+/Ne^-]	**2.5**	**2.2**	**6.8**
Normalized emittance x/y (rms) [mm.rad]	12.4/11.7	8.9/8.9	10.4/10.9
Energy spread (rms) [%]	0.7	0.7	1.7
e+ beam bunch charge [nC]		**13.5**	

Work in progress

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

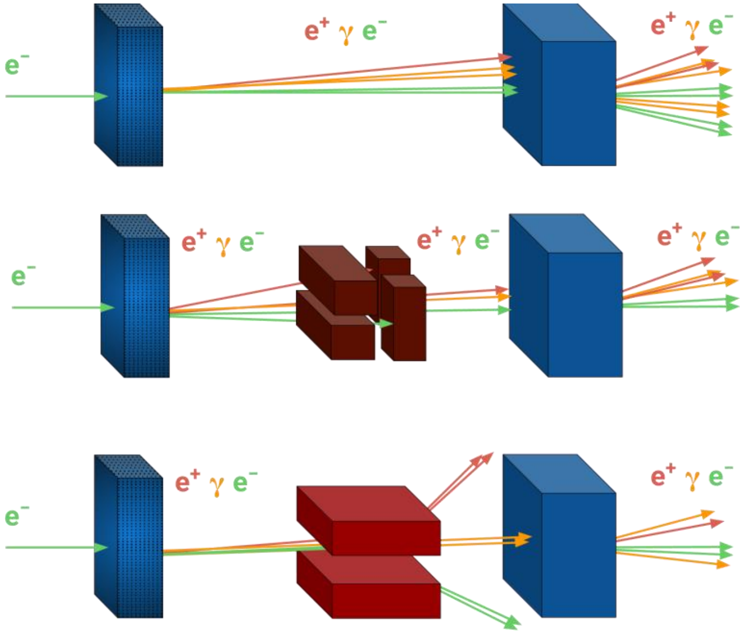
R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285



oriented crystalline
target

Use of lattice coherent effects in oriented crystals : channeling and over barrier motion

→ typical angular range ~a few mrad at 6 GeV for <111> axis in W

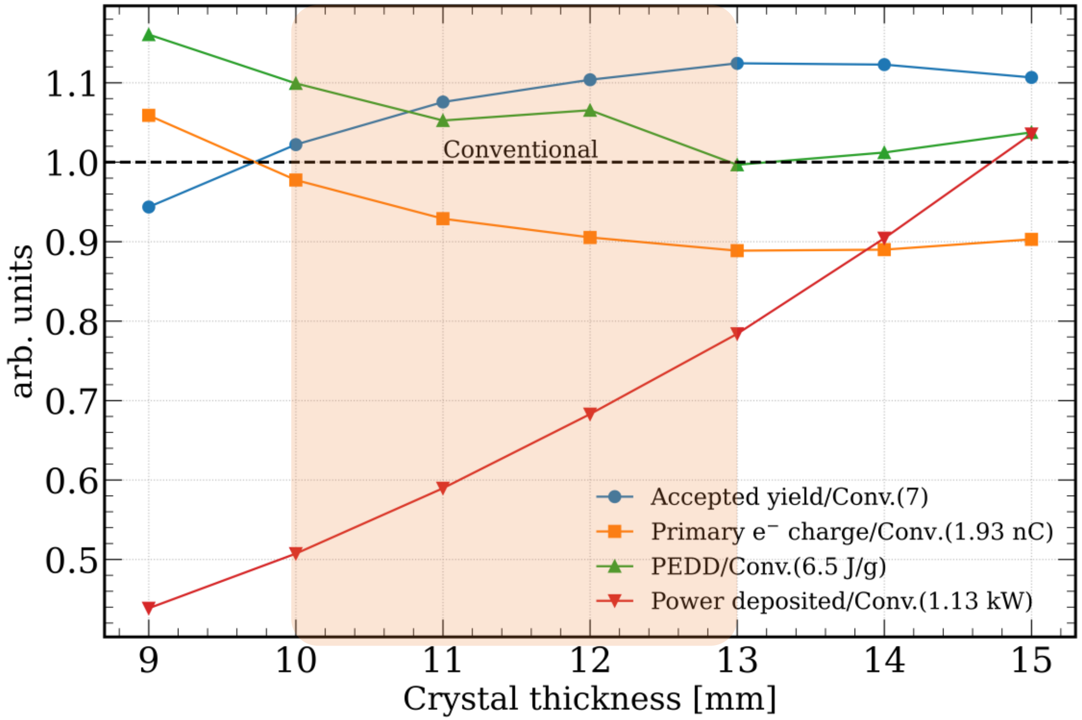


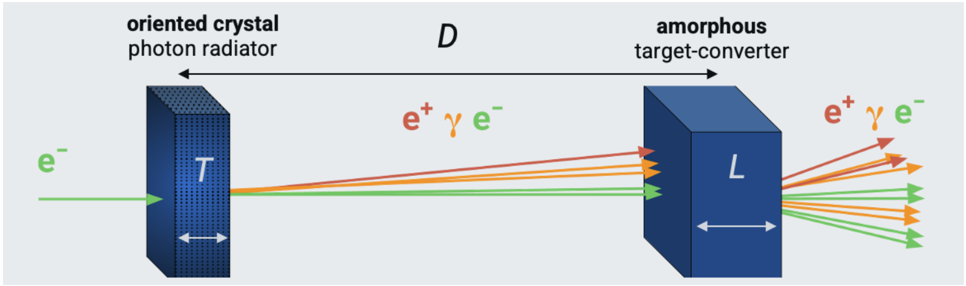
- Novel production scheme for positron sources
- Enhancement of photon generation in oriented crystals → enhancement of pair production / positron charge
- Lower energy deposit and PEDD in target → lower heating and thermo-mechanical stress (target reliability)

Crystal-based positron source for FCC-ee (towards conceptual design)

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

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





Simulation studies converge to a total W thickness of about **12 mm**
→ need D~0 (2 targets) or 1 thick single-crystal

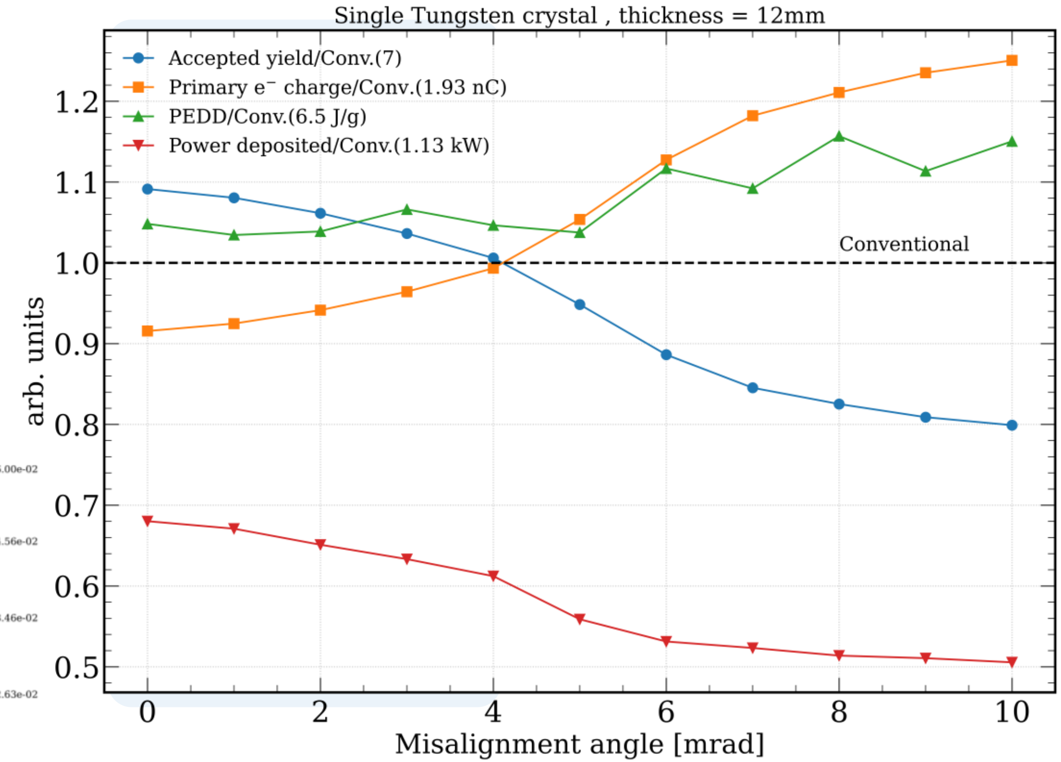
The whole setup was simulated through Geant4 toolkit taking advantage of GeantG4ChannelingFastSimModel, which is based on CRYSTALRAD code

A. Sytov et al. JKPS 83 (2023)

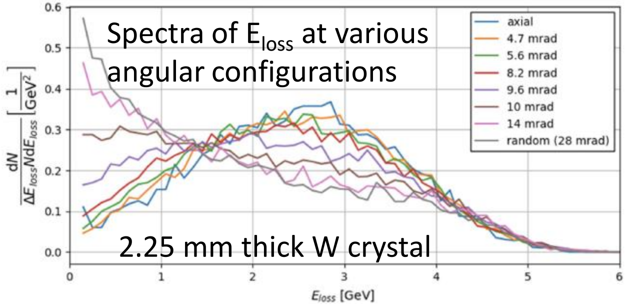
Integration and operation of the crystal target

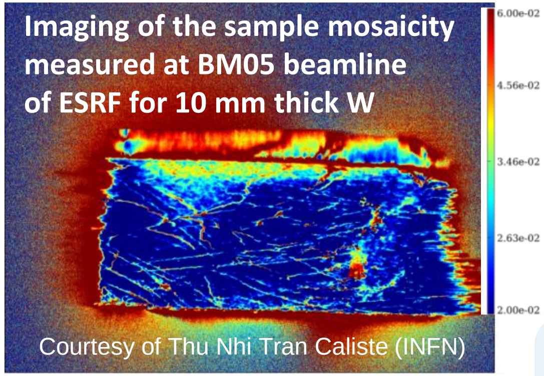
- **Crystal heating** The photon yield drops insignificantly for temperatures ~600 ⁰K
- **Crystal alignment** No goniometer. The typical precision of the pre-alignment procedure ~1 mrad Margins for improvement.
- **Crystal quality** The crystalline quality of 10 – 12 mm thick W sample is lower than for a thin sample → lower yield, but larger acceptance angles

Misalignment w.r.t. desired axis <111> of W crystal @590 ⁰K



Beam test at the DESY TB 21 with 5.6 GeV





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

Experimental studies and validation are needed ! (tests @MAMI, DESY, next week beam test @CERN, potential target design validation at P^3)

Summary of the simulation results: 6 GeV and 2.86 GeV injector options

Talk by P. Craievich

Parameter	Unit	For 13.5 nC e^+ bunch charge			
e^- beam energy	GeV	6		2.86	
Number of bunches		2	4	2	4
Repetition rate	Hz	200	100	200	100
e^- bunch charge	nC	2.4		6.1	
e^- beam power	kW	5.8		7	
Target thickness	mm	17.5		15	
Beam size, x/y	mm	1		1	
Positron yield @ Target	N_{e+}/N_{e-}	13.9		7.1	
Positron yield @ CS	N_{e+}/N_{e-}	8.1		4.1	
Positron yield @ PL	N_{e+}/N_{e-}	6.3		3.2	
Positron yield @ DR	N_{e+}/N_{e-}	5.7		2.2	
Target deposited power	kW	1.3	1.3	1.6	1.6
Target PEDD	J/g	3.6	7.1	4.8	9.6
e+ beam emittance, ε_n x/y	mm.rad	10.3/10.9		9.2/10.2	

Work in progress

Preliminary results

Conclusions and outlook

- The studies on the FCC-ee positron source are well advanced: baseline design is based on use of the HTS solenoid. The accepted e^+ yield is 5–6 N_{e+}/N_{e-}. So far, no showstoppers found that prevent a SC solenoid matching device (proof-of-principle with P^3 experiment @PSI in 2026).

- Flux Concentrator-based capture system has been investigated in application to the FCC-ee e^+ source
  - Use of a thermionic gun will probably be needed to provide the requested bunch charge of the e^- drive beam ($\gtrsim$ 5 nC), especially for 2.86 GeV injector option. Work in progress. The bunch-by-bunch intensity variation scheme to be developed.
  - FC operation at 200 Hz is very difficult (ohmic losses, power supply) ➜ 4 bunches scheme @100 Hz is preferred option.
  - More sophisticated target design should be considered due higher drive beam power.

- The start-to-end simulations from production target to the DR using the realistic fieldmaps are underway including collective effects and machine imperfections.

- For 2.86 GeV injector option, to fulfil the requirements for positron bunch charge, higher e^- drive beam charge will be needed. Work in progress.

- Conceptual design studies of the crystal-based positron source for the FCC-ee are well advanced. Next steps: integration studies and beam tests with potential proof-of-principle at P^3 experiment.

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. Lorio (INFN Naple), A. Mazzolari, R. Negrello, G. Paternò, M. Romagnoni, M. Soldani, A. Sytov
INFN-Milano	A. Bacci, M. Rossetti Conti
KEK	Y. Enomoto

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