Positron generation, capture, damping for FCC-ee

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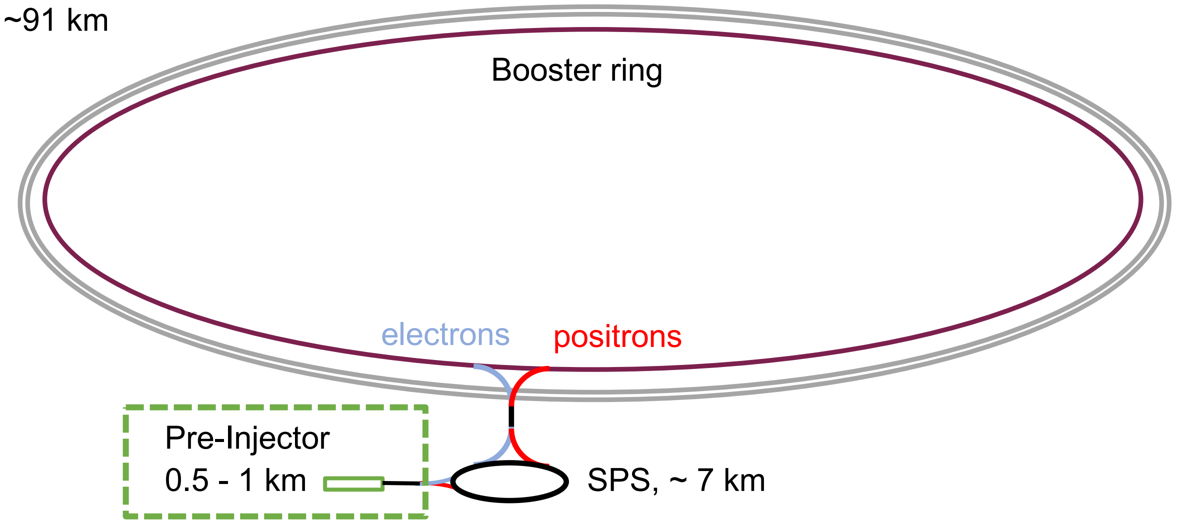
Many thanks to P. Craievich, M. Schaer, N. Vallis, R. Zennaro (PSI), F. Alharthi, R. Chehab, V. Mytrochenko (IJCLab), A. Grudiev, B. Humann, A. Latina, A. Lechner, H. Pommerenke , Y. Zhao (CERN), A. De Santis (LNF) and all memebers of the FCC-ee Injector Studies (CHART)

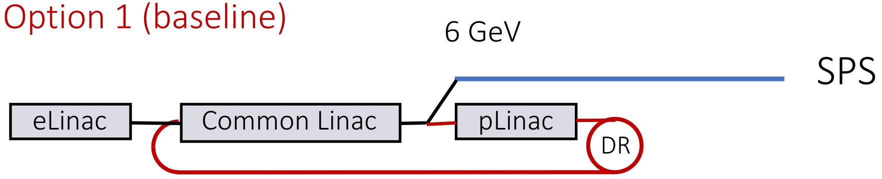
FCC-ee injector complex

Electron-Positron collider
~91 km

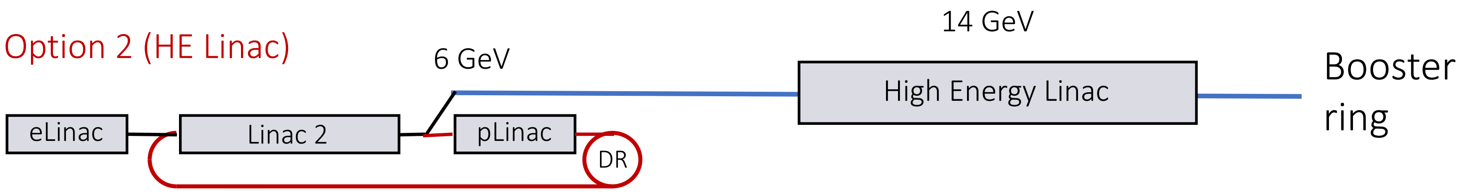


- Pre-injector: e-/e+ linacs up to 6 (20) GeV, 1.54 GeV Damping Ring
- Pre-Booster Ring (SPS or new ring) (6 - 20GeV)
- Booster Ring (20 → 45 GeV)
- The main 6 GeV linac feeds the positron source. The positrons are produced with 6 GeV e- beam.

Option 1 (baseline)

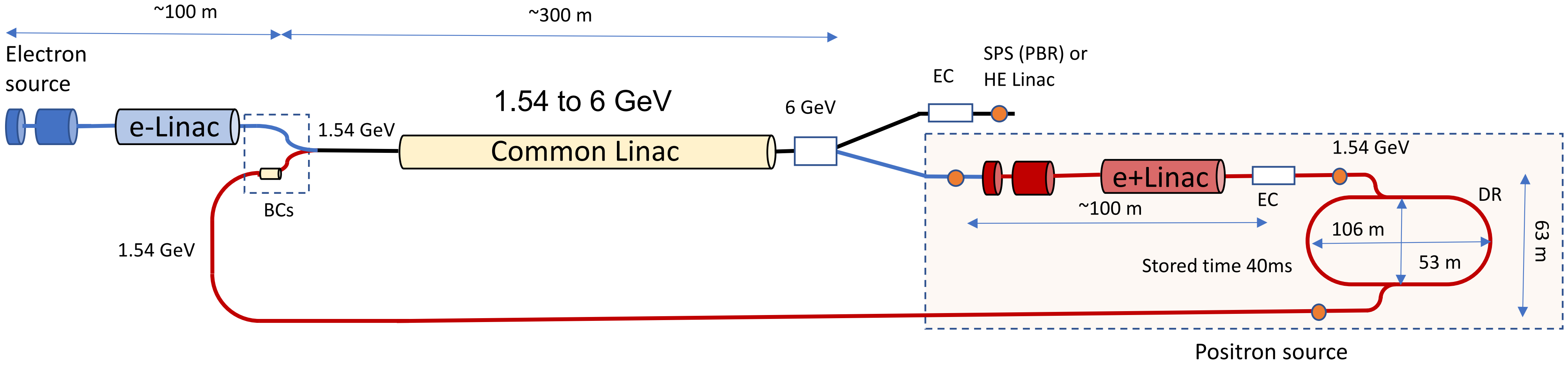


Option 2 (HE Linac)



FCC-ee pre-injector layout (6 GeV option)

More details: talk on linac studies by Simona Bettoni



- Linac efficiencies optimized: electron/positron beam with same energy, main and drive electron beam with same final energy
- Specifications are fulfilled for the electron bunch (beam dynamics simulations for the e- linac and common linac well advanced)
- e+ Linac: several options of the capture section, RF design well advanced 2 GHz, 200 Hz, large iris aperture, beam dynamics on-going.
- DR provides the damping of the positron beam and delays extraction to allow single species operation for the common linac.

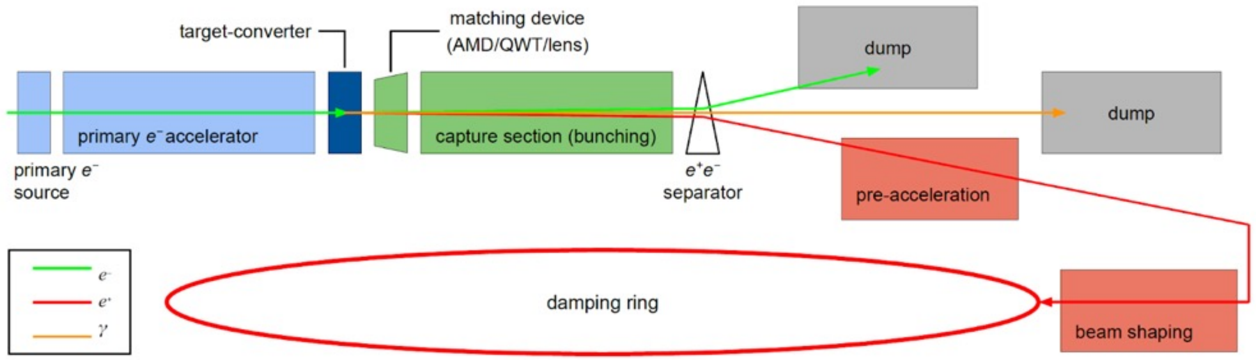
Injector parameters for the Z-mode

	Baseline	HE Linac	Unit
Ring for injection	SPS/PBR	BR	
Injection energy	6	20	GeV
Bunch population both species	3.47 (5.55)	3.12 (5.0)	1E10 (nC)
Repetition rate	200	200	Hz
Number of bunches	2	2	
Bunch spacing	17.5-50	17.5-50	ns
Normalized emittance (x, y) (rms)	50, 50	50, 50	mm.mrad
Bunch length (rms)	~1	~1	mm
Energy spread (rms)	<0.1	<0.1	%

- The bunch by bunch intensity will randomly vary from 0 to 100%, depending on the intensity balance between the collider rings
- Electron source: an injector based on a photocathode RF gun can provide electrons for both ring injection and positron production and the laser system can provide the bunch-to-bunch intensity modulation and stability required
- Position source: target-converter + capture system + 1.54 GeV linac + DR

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 ~3.5 × 10^{10} e^+/bunch (5.6 nC)

$$N_{e-}/\text{bunch} \times \eta^{e+}_{Accepted} \geq 5.6 \text{ nC/bunch} \times 2$$

**A safety margin of 2 is currently applied for the whole studies.*

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

All the studies are focused on the operation scheme: 6 GeV, 2 bunches/pulse, 200 Hz rep. rate, the max e- bunch charge is 5.6 nC → ~ 1.4 × 10^{13} e^+/s

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=($\sim$ 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)	$\sim$ 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	~3.5
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.

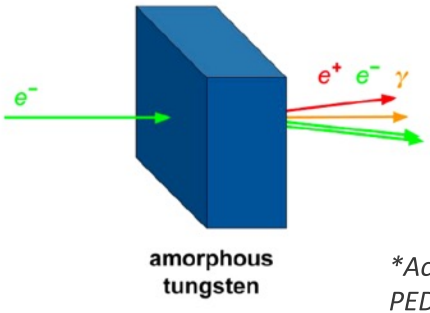
Linear Collider projects: high request for polarization, requested intensity should be produced in "one shot".
Circular Collider projects: polarization is under discussion, requirements are relaxed due to stacking and top-up injection

FCC-ee: positron production

Schemes under consideration now

- Conventional scheme: bremsstrahlung and pair conversion (mainly studied until now)
- Hybrid scheme: two-stage process to generate positron beam. Channeling (crystal target) and pair conversion (amorphous target). Benchmark of simulation codes and first simulation/optimization studies => in progress

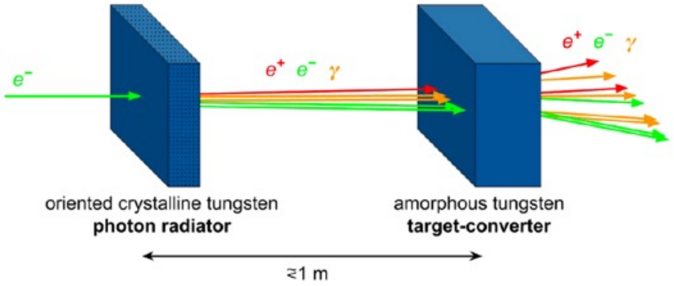
Conventional target

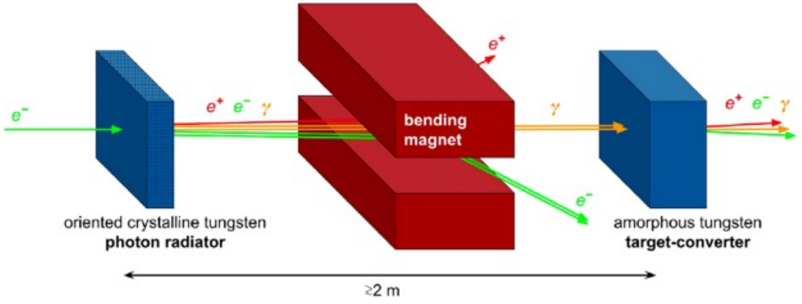


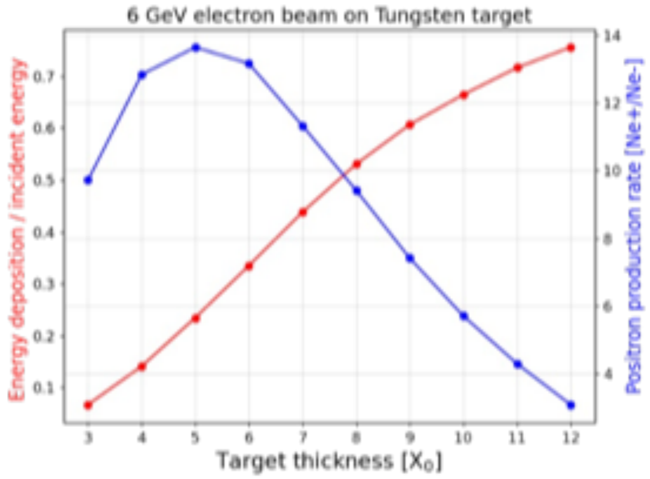
Target thickness	5 X_0 17.5 mm
Production rate	~14 Ne+/Ne-
PEDD*	f(e- beam)
Deposited power	f(e- beam)

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

Crystal-based target
Hybrid scheme





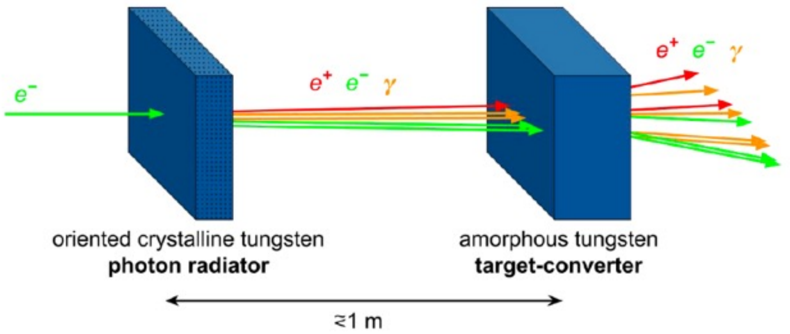


The final choice will be done based on the simulated performances

Hybrid scheme: preliminary simulations for the FCC-ee

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

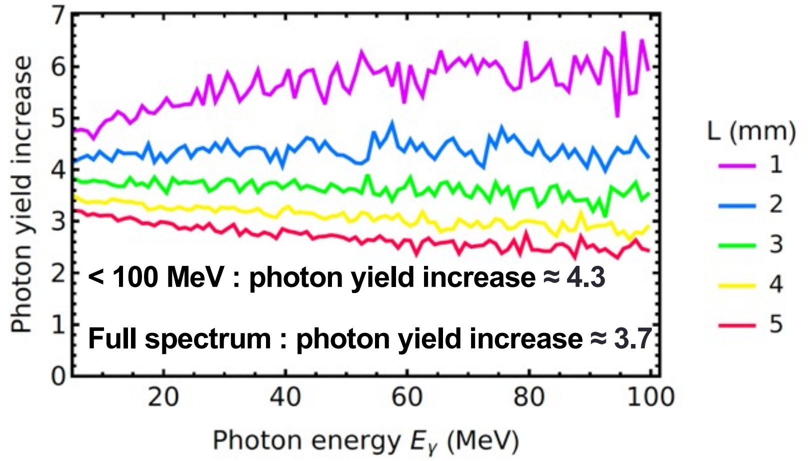
e- beam energy = 6 GeV, angular divergence 0.1 mrad and with the r.m.s. transverse beam size of 0.5 mm. W crystal oriented in <111> (θc ≈ 0.6 mrad).



A 2 mm thick crystal has been selected to be used as a radiator for the hybrid positron source.

→ good photon yield, moderate values of photon divergence and energy deposition in the crystal.

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



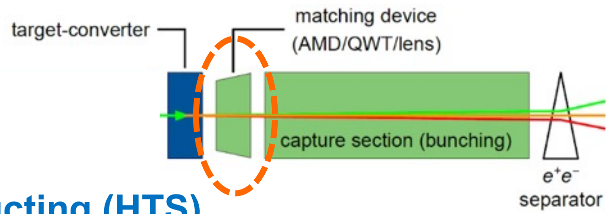
Results for the positron production simulations

scheme	conventional	hybrid[1]
target thickness [mm]	17.6	2 + 10
e^+ production rate [N_{e^+}/N_{e^-}]	14.4	15.1
target deposited energy [GeV/e^-]	1.44	0.946
PEDD [GeV/mm^3/e^-]	0.0416	0.0156

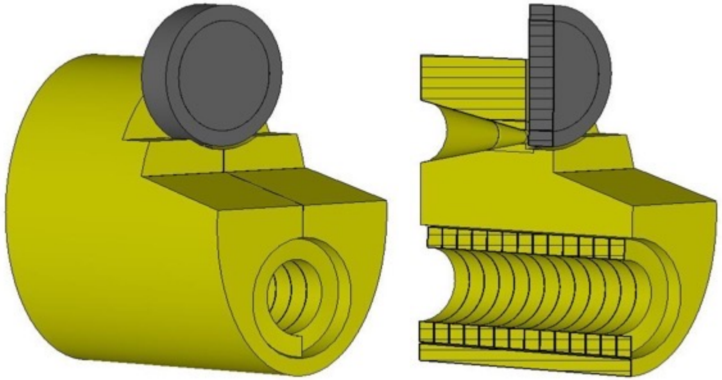
[1] The values are given for the amorphous target-converter installed after the crystal target.

FCC-ee: positron capture system (matching device)

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



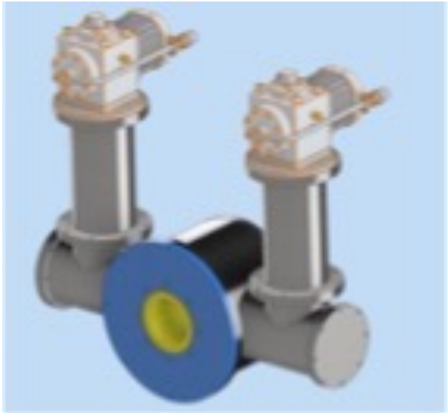
Flux Concentrator (FC)
designed by P. Martyshkin (BINP)



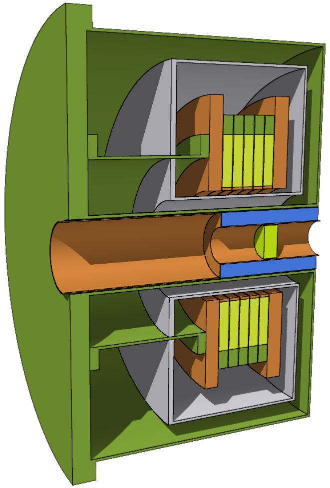
Compared with HTS solenoid:
- **Low peak field (5−7 T, ~1.5−3 T at target exit)**
- **Small entrance aperture (Φ = 8−16 mm)**
- **Fixed target position (2−5 mm upstream)**

Therefore, lower e+ yield

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



5 coils ReBCO tape

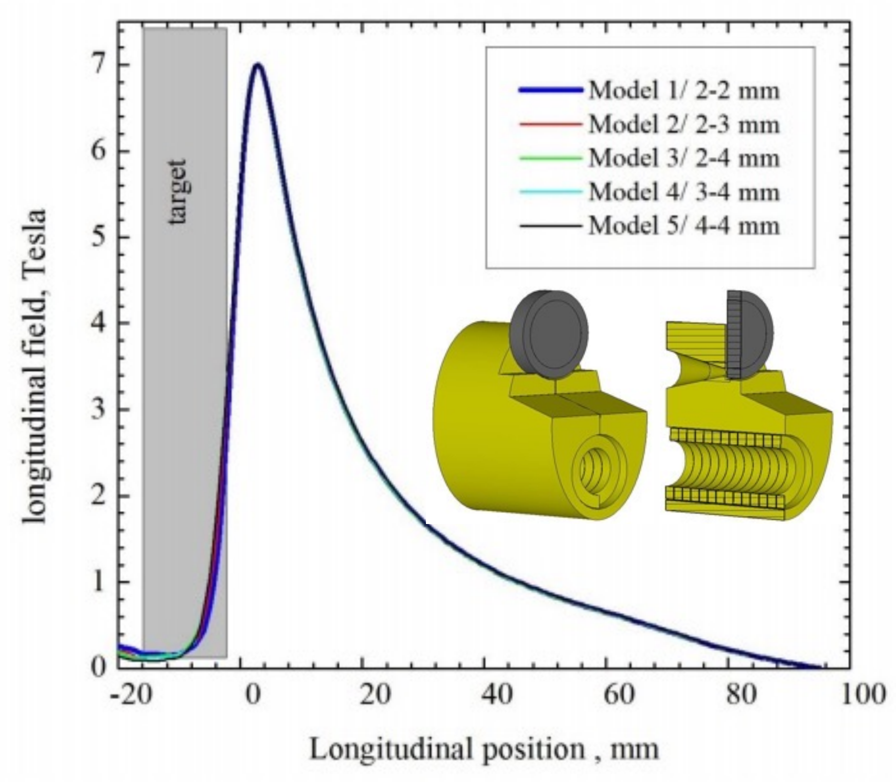


Compared with FC:
- **High peak field (~15 T, ~12 T at target exit)**
- **Large aperture (Φ = ~40 mm)**
- **Flexible target position (can be placed inside the bore)**

Therefore, higher e+ yield

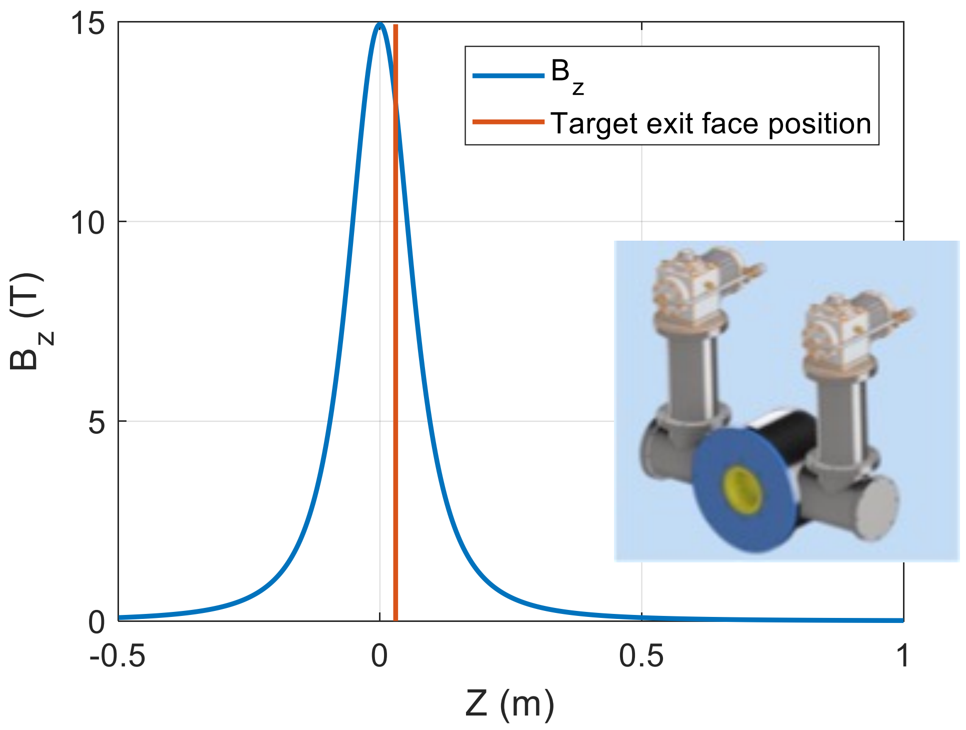
FCC-ee: positron capture system (matching device)

Flux Concentrator (FC)



FC on-axis field, with fixed target position

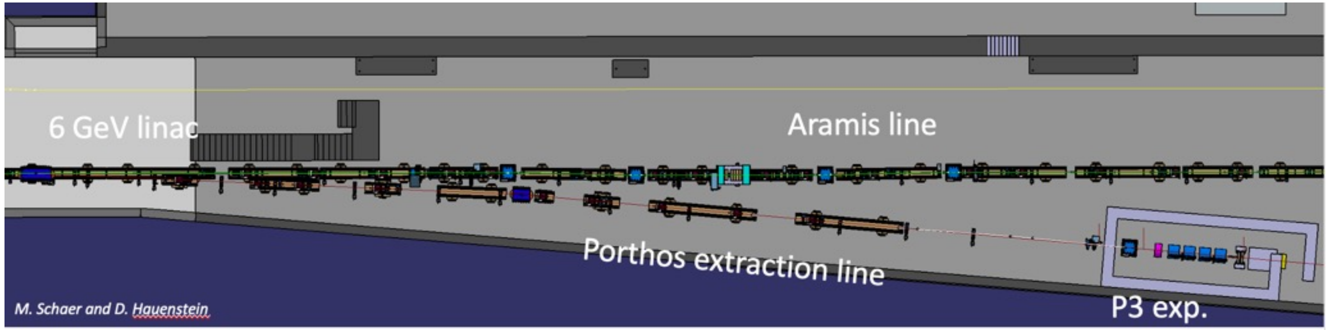
High-Temperature Superconducting (HTS) solenoid

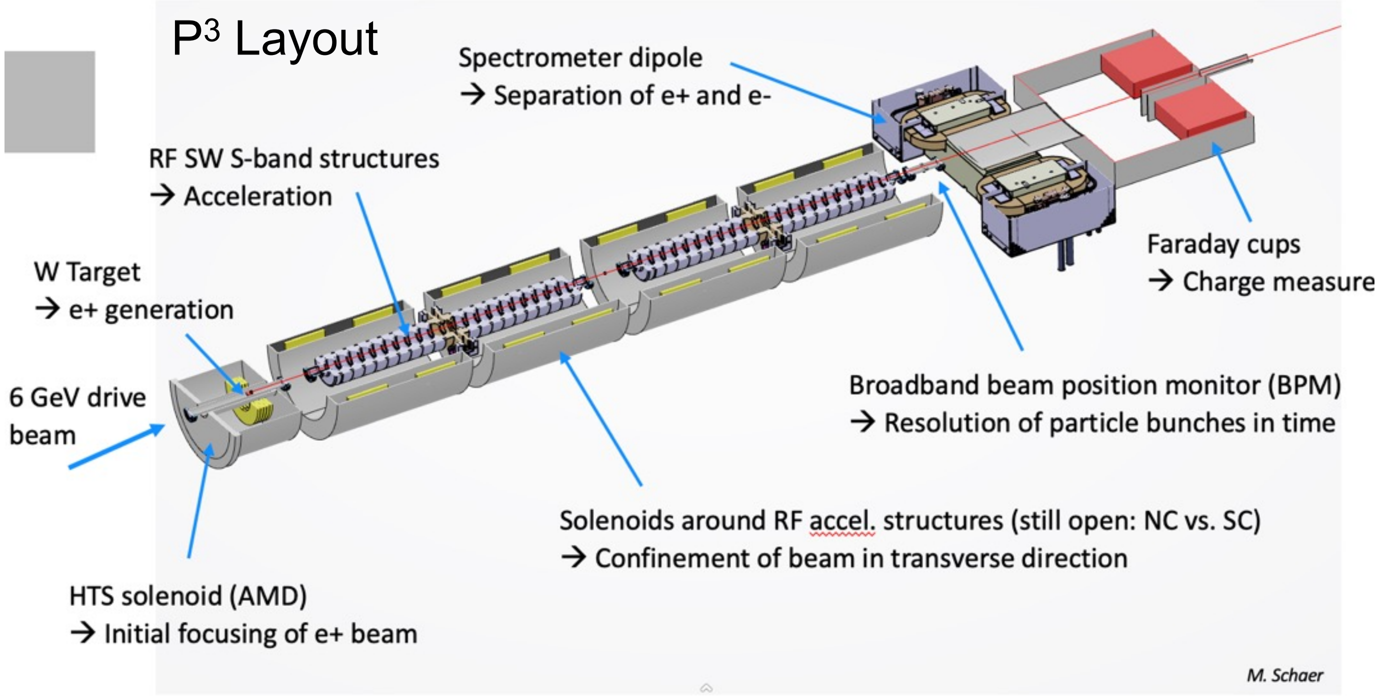


HTS solenoid field, with optimised target position

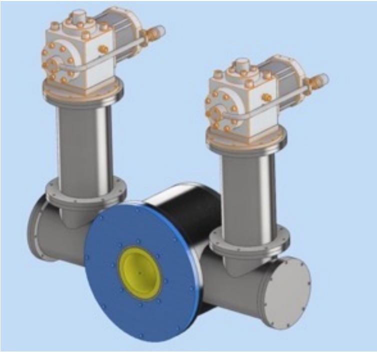
Peak of the FC field is at 5 mm from the target => ~40 % drop in capture efficiency

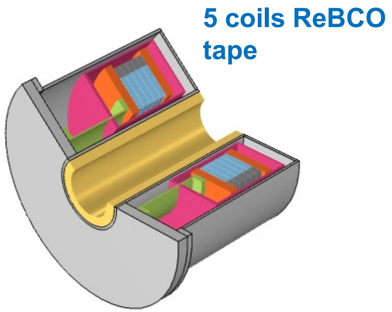
SC-solenoid and PSI Positron Source Experiment at PSI (P^3 project)





More details: talk on P^3 project by Nicolas Vallis





HTS solenoid integrated in the cryostat (M. Duda et al.)
Peak magnetic field: 12 T (test up to 18 T)

- ✓ Positron yield with conventional scheme (simulation vs measurement)
- ✓ MD: SC Solenoid with HTS technology including mech. and thermal (cryostat) concept
- ✓ RF structures: large iris aperture
- ✓ NC versus SC solenoids around the RF structures
- ✓ Phase 2: hydride scheme with crystal

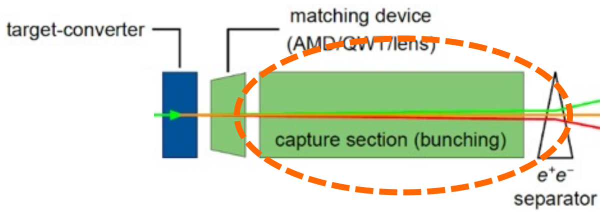
P. Craievich, M. Schaer, N. Vallis, R. Zennaro et al. (PSI)

FCC-ee: positron capture system (capture linac)

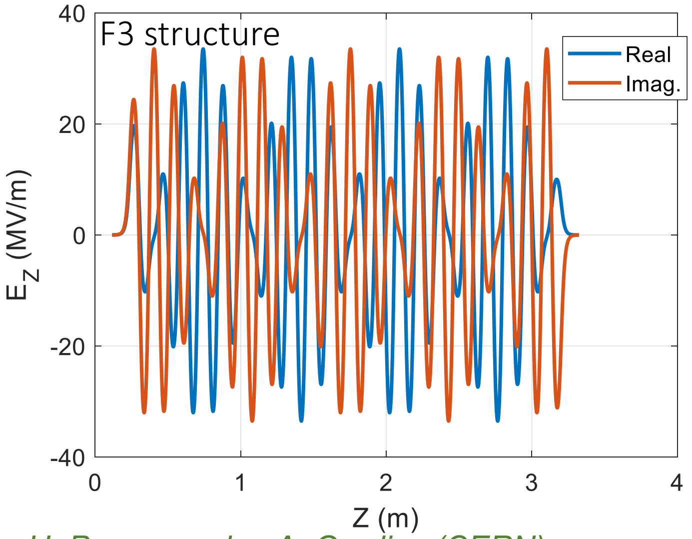
The capture linac is encapsulated inside a solenoid with the axial magnetic field of ~0.5 T (NC)

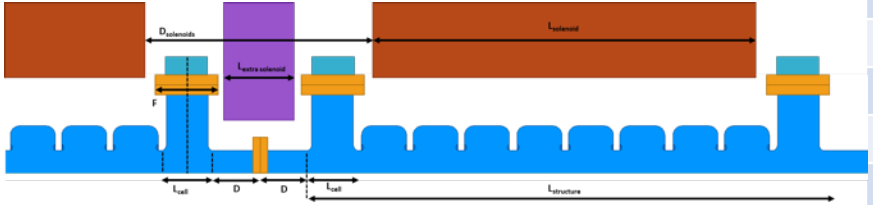
(usually with constant solenoid field and recently, more realistic field profiles started to be used)

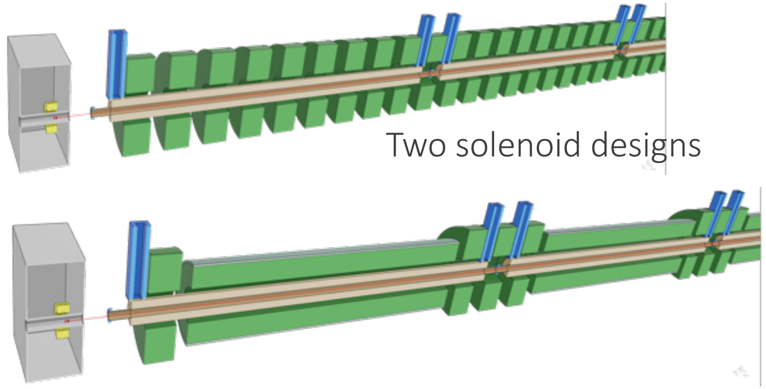
- 1.5 m long, ~21 MV/m, TW 2 GHz L-band structures, (Φ = 40 mm)
- 3 m long ~20 MV/m, TW 2856 MHz S-band structures (Φ = 30 mm),
- 1.5 m long ~18 MV/m, SW 2998 MHz S-band structures (Φ = 40 mm) -> P^3 project
- 3 meter long ~20 MV, TW 2 GHz large aperture structures (Φ = 60 mm)



	F3 („baseline“)
Frequency	**2.0 GHz**
Constant aperture	**30 mm = 0.2 λ**
Phase advance	**9π/10**
Length	**3.0 m = 44 cells**
Entr., exit iris thickness	14.3 mm, 20.0 mm
Transverse wake at 17.5 ns	0.13 V/pC/mm/m
Filling time	447 ns
Min. group velocity	1.9 % c
Largest cell radius	**61 mm**
SLED coupling	17
Eff. shunt impedance	**39 MΩ/m**
Average gradient	**15 MV/m**
E_{max} (instant.)	58 MV/m
$S_{c,max}$ (instant.)	329 mW/µm²
Klystron pulse length	5 µs
Klystron power per structure	17 MW



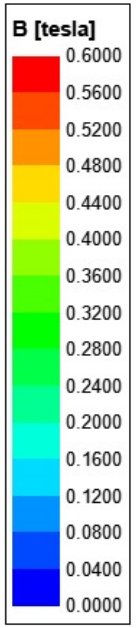


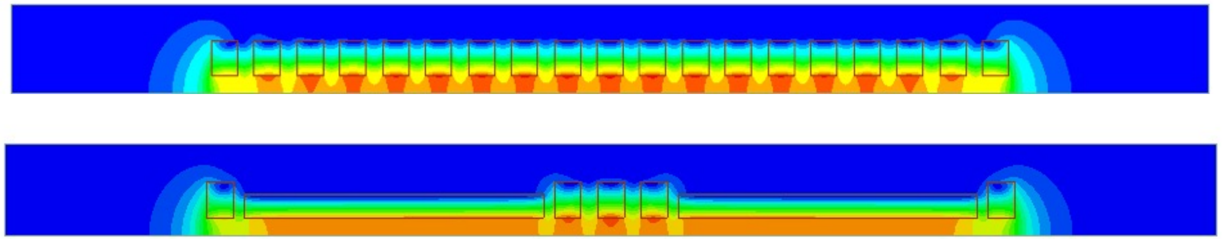


Two solenoid designs

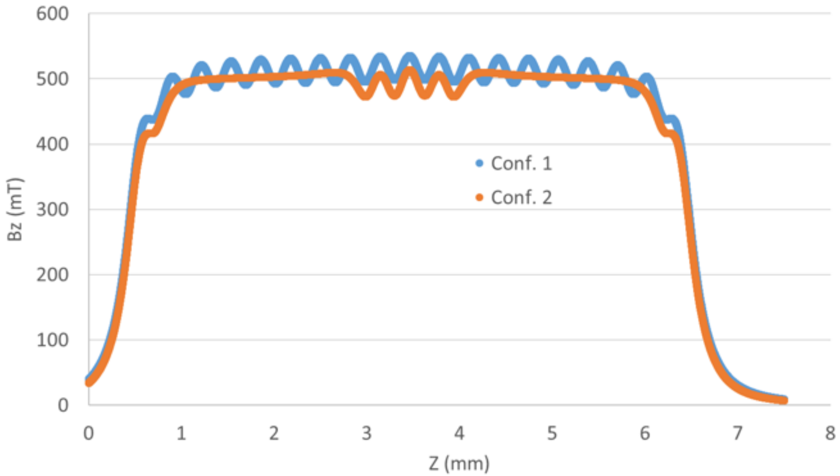
H. Pommerenke, A. Grudiev (CERN)
M. Schaer, R. Zennaro (PSI)

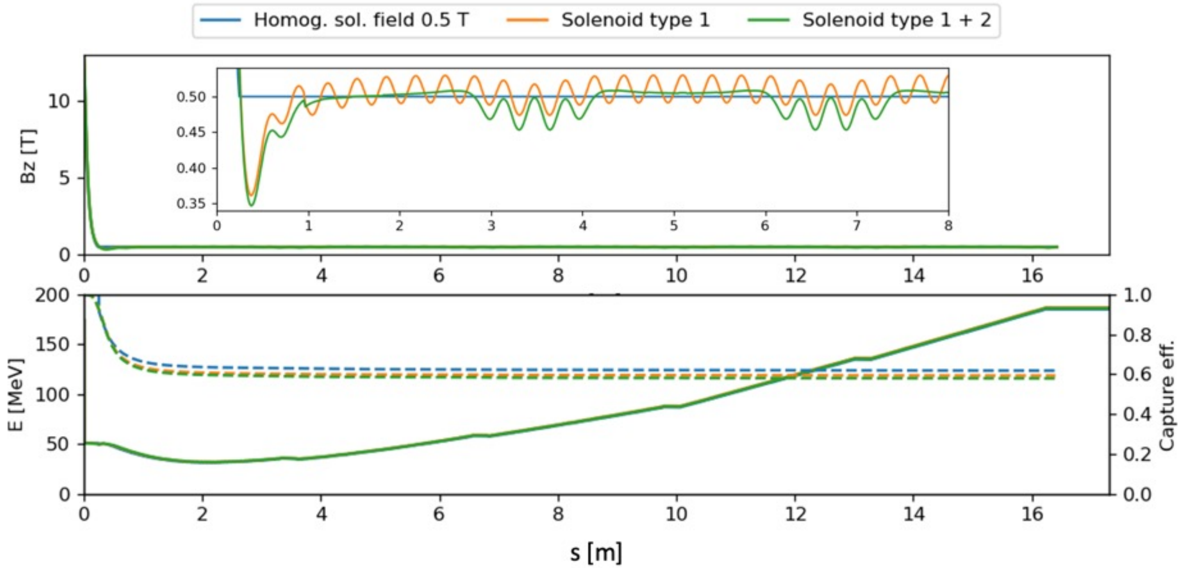
Maxwell 2D simulation for solenoid over 2 RF structures





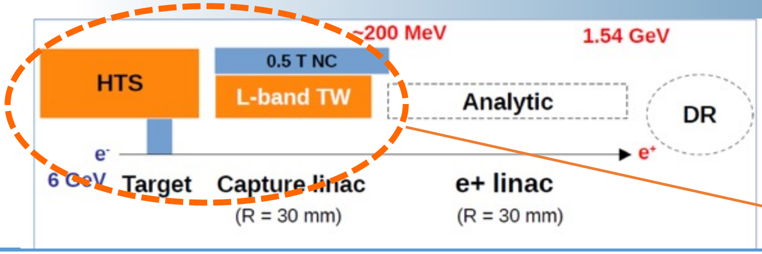
Minimal reduction in capture efficiency between homog. channel (0.618) and realistic solenoids (0.593 and 0.579)





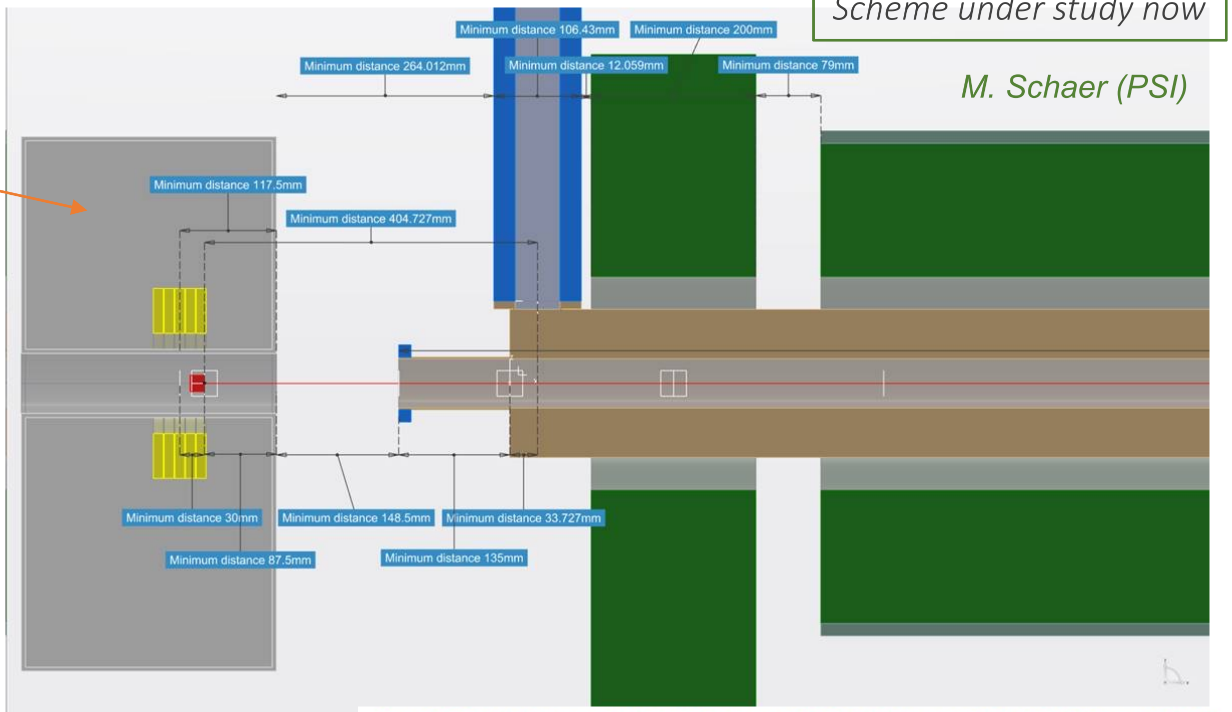
M. Schaer, R. Zennaro (PSI)

SC-solenoid-based capture system (work in progress)



Scheme under study now

M. Schaer (PSI)

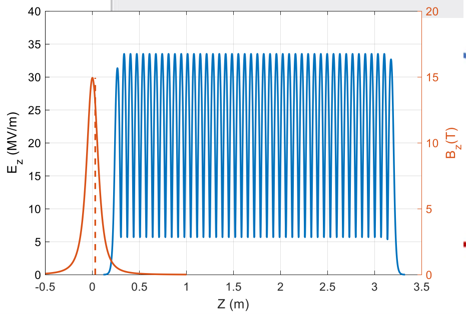


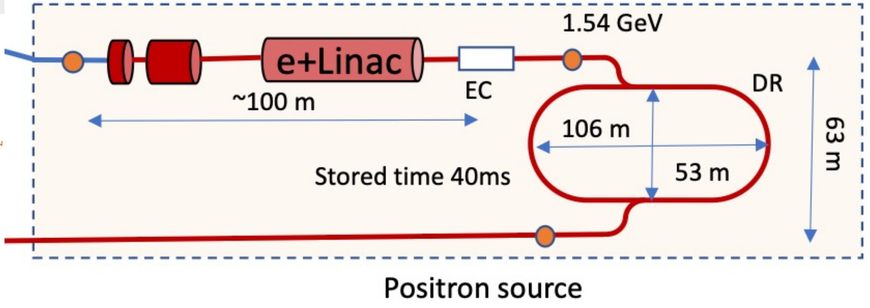
Capture system "-version 0"

- Positron production: conventional scheme
- Matching Device is based on the SC solenoid (5 HTS coils, 72 mm bore including shielding)
- Capture Linac is based on the L-band TW RF structures (2 GHz, 3-m long)
- NC long solenoid B = 0.5 T (realistic design conf. 2)

The first results (preliminary)

- Capture efficiency @ 200 MeV: ~0.6
- e+ yield @1.54 GeV: 6.4 Ne+/Ne-
- e+ norm. emittance: ~12 mm.rad

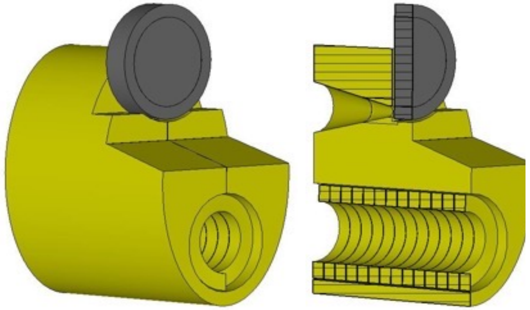


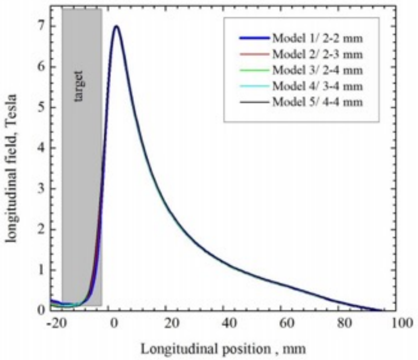


Flux Concentrator-based capture system (CDR baseline)

	Baseline AMD/FC		
Drive beam parameters	**Value**		**Unit**
Beam energy	6		GeV
Numebr of bunch	2		
Bunch charge	2,88	2,24	nC
Bunch length (rms)	1		mm
Beam size (rms)	0,5		mm
Bunch separation	>17.5		ns
Repetition rate	200		Hz
Normalized Emittance	<1		mm.rad
Energy spread (rms)	<1		%
Target parameters			
Tickness	17.5 (5X0)		mm
Beam power	6,9	5,4	kW
PEDD	10.4	8,46	J/g
Deposited power	1,48	1,32	kW
Capture linac parameters			
Frequency range	S-band (2a=30mm)	L-band (2a=40mm)	
Accelerating gradient	20	17.5/21	MV/m
Solenoid strenght	0,7	0,5	T
AMD peak magnetic field	7	7	T
Positron parameters			
Beam energy	198		MeV
Bunch charge	6,73		nC
Positron yield	2,3	3,0	
Bunch length (rms)		2,1	mm
Normalized emittance (rms)		7,1	mm.rad
Energy spread (rms)		7,8	%
Mean energy at DR		1,54	GeV
Energy Spread at DR (rms)		1,2	%

P. Martyshkin (BINP), Y. Zhao (CERN)





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

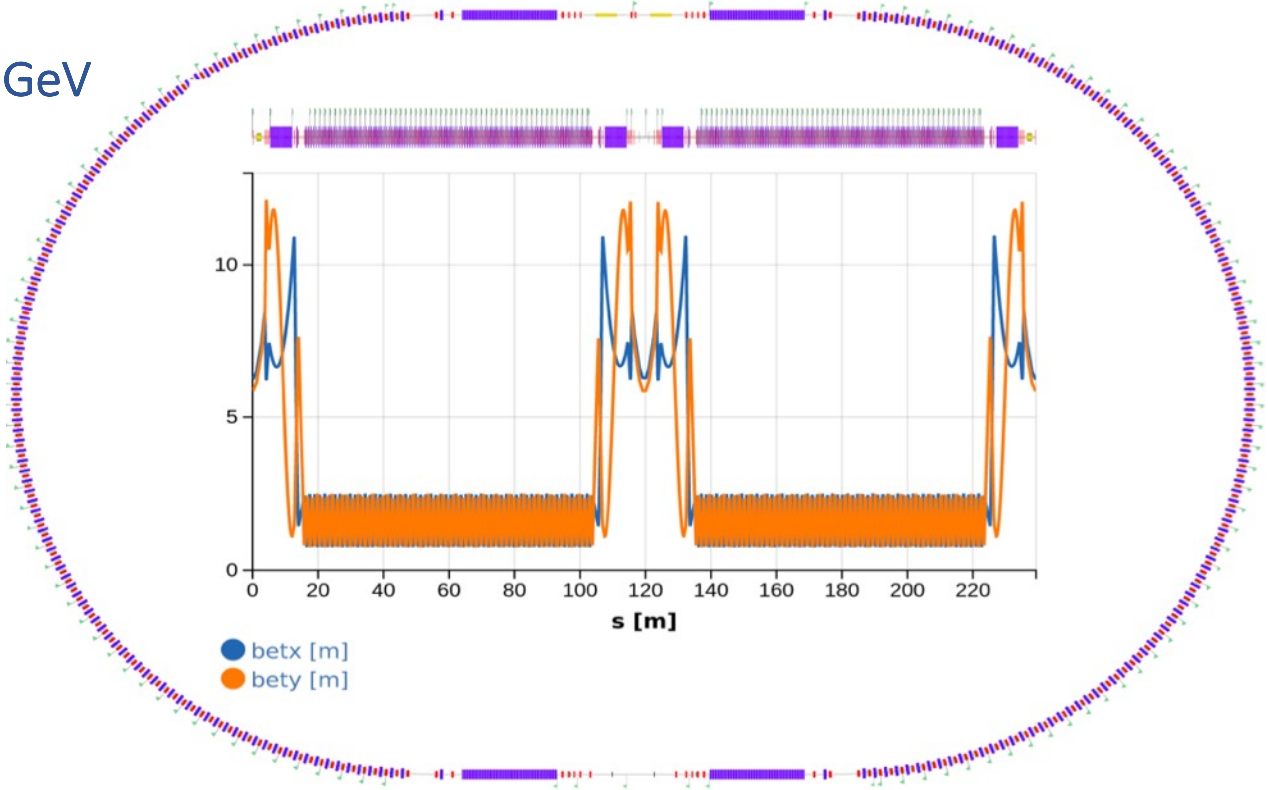
Perform radiation load studies, the first estimation for the target design. First mechanical integration.

Optimize the FC design if needed (rep. rate ?)

Damping Ring design studies

Studies of the DR dynamical aperture are in progress ➔ **start-to-end simulations for the positron source**

E = 1.54 GeV



2 wigglers each in straight sections
400 MHz LHC like 2 SC cavities

Parameter	FCC_ee DR
Circumference	239.2 m
Harmonic number	319
Eq. Emittance (x/y/z)	1.01 nm/ - / 1.46 μm
Dipole length, Field	0.21 m, 0.66 T
Wiggler #,Lenght, Field	4, 6.64 m, 1.8 T
Cavity #, Lenght, Voltage	2, 1.5 m, 4 MV
Bunch stored #, charge	18 , 4.0 nC
Damping Time (x/y/z)	10.8 / 10.8 / 5.4 ms
Store Time	42.5 ms
Energy loss per turn	0.227 MV
SR Power Loss (WGL)	15.7 kW

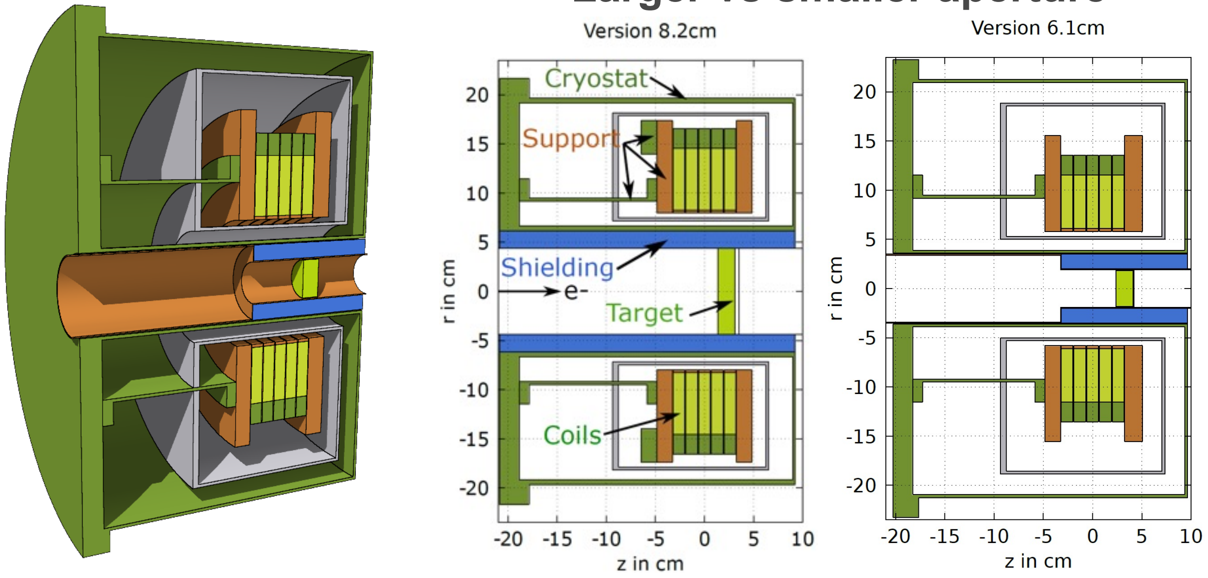
	V= 8MV	V= 6MV	V= 4MV	V= 2MV
U_0 [KeV]	227.1			
DE/E_s	0. 71 • 10^{-3}			
Ω_s [KHz]	25.313	21.918	17.888	12.618
T_0 [μsec]	0.79801			
ω_0 [s^{-1} rad]	7.87 10^6			
ν_s	0.003215	0.00278	0.002272	0.0016
L_{bunch}[m]	0.00207	0.00239	0.00293	0.00415
φ_s [rad]	0.0283967	0.0378663	0.0568164	0.113817
$(E - E_s)$ [GeV]	0.124	0.107	0.0862	0.058
$\Delta\varphi$ [unit of π]	1.8	1.7769	1.7269	1.6016
L_{bucket}[m]	0.6788	0.6664	0.6476	0.6006

A. De Santis et al. (LNF)

Radiation load studies for SC solenoid-based capture system

B. Humann, A. Lechner (CERN)

Larger vs smaller aperture



Radial Coil Position	8.2cm	6.1cm
Shielding thickness	1.8cm	1.4cm
Target radial size	4.4cm	1.8cm
Target position in z	3.1cm	2cm

Electron drive beam	6GeV
Beam size	0.5mm RMS
Repetition rate	200Hz
Bunches per pulse	2
e- charge per bunch	1.43nC
Beam Power	3.43kW
Target length	$5X_0$=17.5mm

Filling scheme of collider:
2.4% filling from scratch
97.6% at top-up injection with lower bunch charge

In the latest setup, the same cryostat aperture as for P^3 experiment (geometry –V6) is assumed

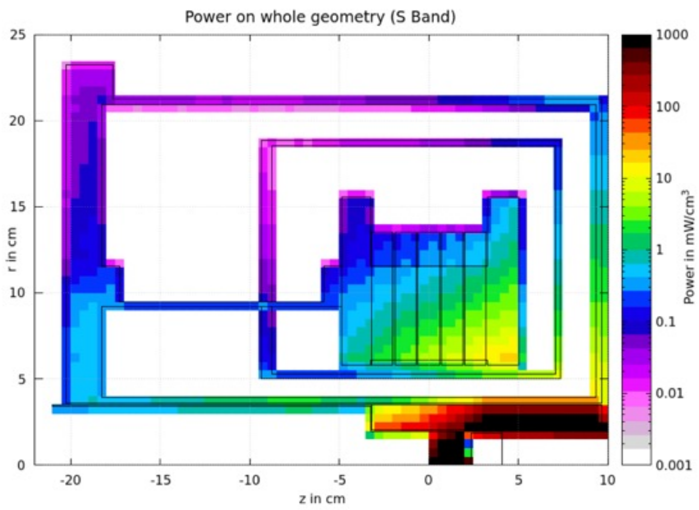
- For this option, two different longitudinal target positions are considered, reflecting the optimal position for S-band and L-band linacs

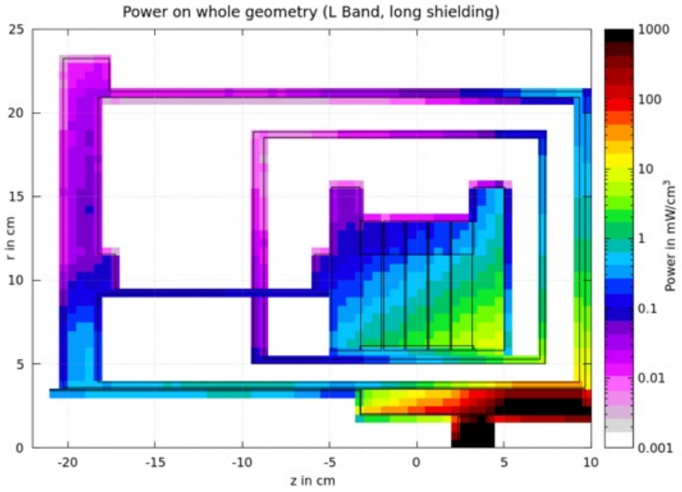
The FLUKA model to be updated wrt to capture system –version 0

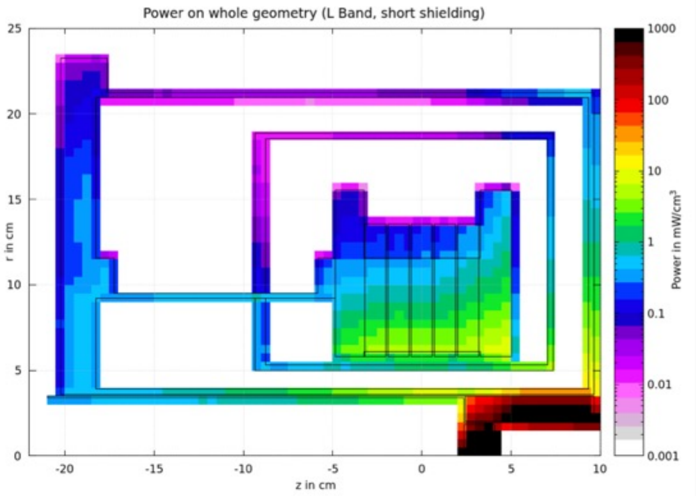
Z operation mode
400 bunches/s*3600s*24h*185 days*0.804 =
= 5.14×10^9 bunches/year

Radiation load studies for SC solenoid-based capture system

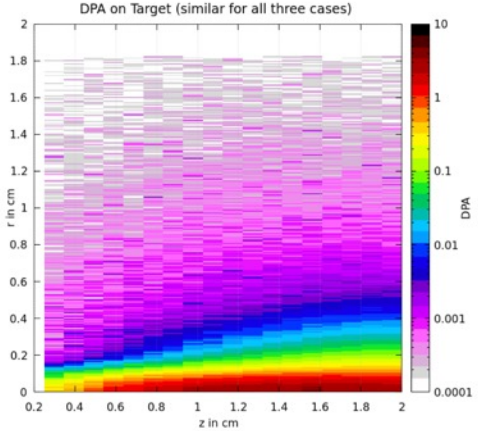
B. Humann, A. Lechner (CERN)



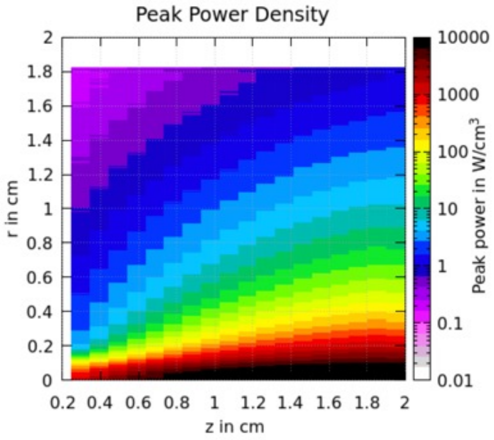




- Beam energy: 6GeV
- Beam power: 3.43kW
- Beam size: 0.5mm rms
- Bunches per pulse: 2
- e- charge per bunch: 1.43nC
- Repetition rate: 200Hz
- Target: 17.5mm



Up to 3DPA/year on target → high value considering em. beam



Up to 21kW/cm³ in centre of target

For a better estimate of the long-term dose need to establish the source operating conditions for higher collider energies (up to ttbar)!

Radiation load studies for SC solenoid-based capture system

B. Humann, A. Lechner (CERN)

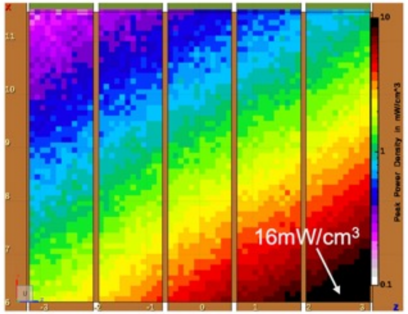
- Peak Power Density on coils seems to be OK

- DPA per year of Z operation on coils: Up to 1E-4 DPA per year => not negligible anymore

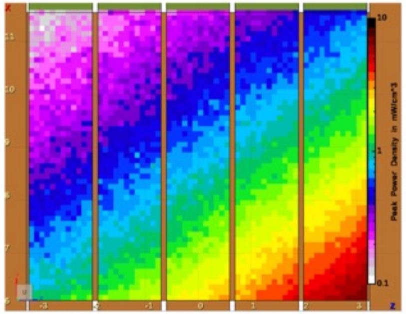
- Ionizing dose on coils per year of Z operation: S Band: up to 22MGy, L Band (long shielding): up to 9MGy, L Band (short shielding): up to 8MGy => should consider full running time and compare/study wrt HTS limits.

- Suggested shielding layout not sufficient ➜ try to make the in-bore shielding slightly thicker without compromising the yield OR/AND make the aperture slightly larger compared to P^3

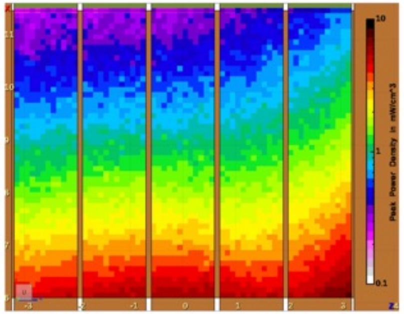
Peak Power Density seems OK



S Band

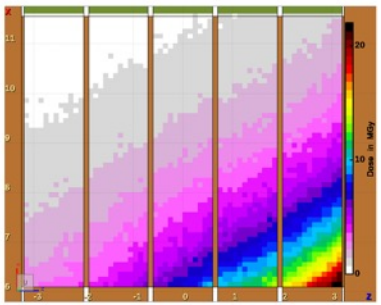


L Band (long shielding)

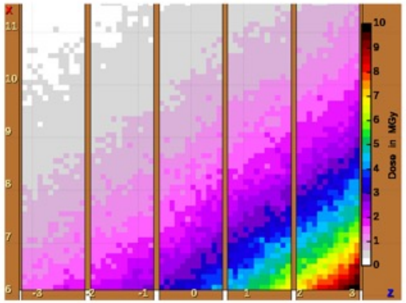


L Band (short shielding)

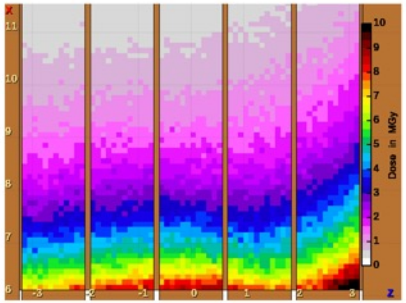
Dose seems to be limiting factor



S Band: up to 22MGy (shielding up to first coil)
Mostly double the dose of L Band



L Band (long shielding):
Last coil is impacted the most (up to 9MGy)



L Band (short shielding):
Last coil impacted similarly, but first coils receive much higher dose (8MGy instead of 2MGy)

Summary

- In the new version of the FCC-ee pre-injector layout, the positrons are produced by E = 6 GeV, 2 bunches/ pulse at 200 Hz electron beam (cf. CDR injector layout with E = 4.46 GeV).
- The studies on the FCC-ee positron source are well advanced : positron production, SC 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.
- e+ linac and DR designs are well-established and advanced. DR dynamic aperture to be optimized. DR filling schemes are under investigation.
- Radiation load studies: FLUKA model update (if needed, increase shielding and also the aperture), energy deposition in RF structures (evaluation if mask is needed).
- Design of the target mechanical system in on the way.
- A demonstrator for thee FCC-ee positron production and capture will be realized at SwissFEL facility at PSI.

Next deliverables (CHART and FCC FS): inputs for mid study costing exercise in summer 2023, final project cost update and feasibility study report in 2025