FCC-ee Positron Source Design

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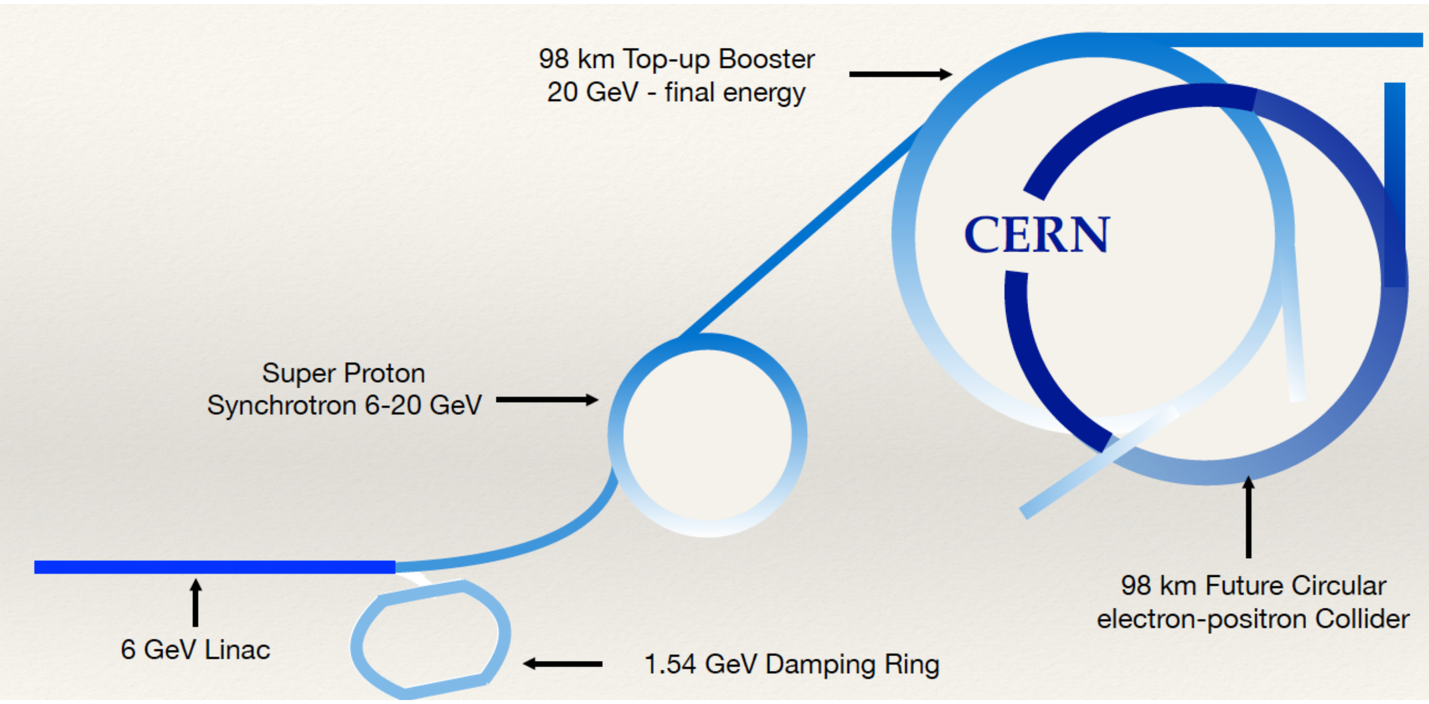
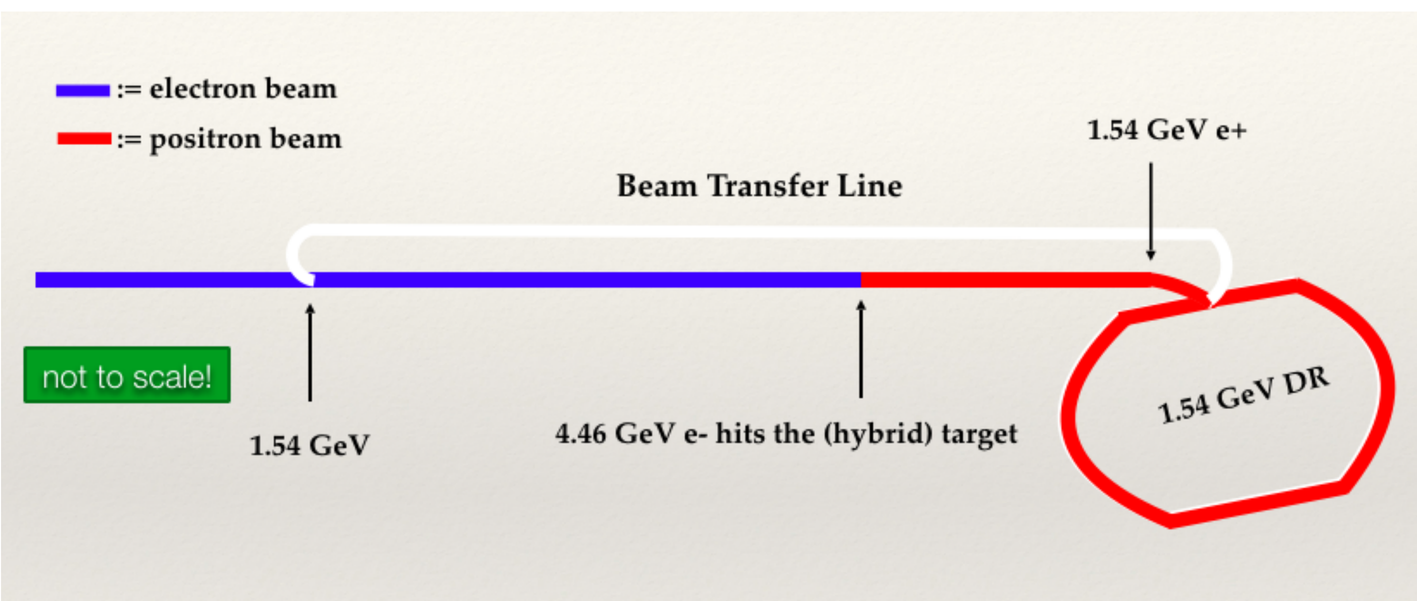
Thanks to: O. Dadoun (LPNHE), A. Faus-Golfe (LAL), S. Oğur, K. Oide, Y. Papaphilippou, F. Zimmermann (CERN)

FCC-ee Injector Complex





SLC/SuperKEKB-like 6 GeV S-band linac accelerating **1** or **2** bunches (2e10/bunch), with repetition rate **100-200 Hz**

Same linac used for e+ production @ **4.46 GeV**
e+ beam emittances reduced in DR @ **1.54 GeV**

Injection @ **6 GeV** into pre-booster Ring (SPS or new ring) & acceleration to 20 GeV or 20 GeV linac

Injection to main Booster @ **20 GeV** and interleaved filling of e+/e- (**<20 min for full filling**) and continuous top-up

The main 6(20) GeV linac hosts the e+ source. The positrons are produced with 4.46(18.46) GeV e- beam.

M. Benedikt
F. Zimmermann

Positron source performances

Demonstrated (a world record for the existing accelerators):

SLC e+ source: ~ 3.5e10 e+/bunch & 1 bunch/train & 120 Hz => ~0.042e14 e+/s

Required for the next collider project:

- CLIC (380 GeV) e+ source: ~ 5.9e9 e+/bunch & 352 bunch/train & 50 Hz => ~0.92e14 e+/s
- ILC (250 GeV) e+ source: ~ 2e10 e+/bunch & 1312 bunch/train & 5 Hz => ~1.3e14 e+/s
- LHeC (ERL) e+ source: ~ 2e9 e+/bunch & 2e7 bunches/s (CW operation) => ~440e14 e+/s
- **FCC-ee e+ source: ~17e10 e+/bunch in the collider & 3 kHz => ~5e14 e+/s (only ~0.06e14 e+/s @ Injector)**

FCC-ee Positron Injector

Current scheme

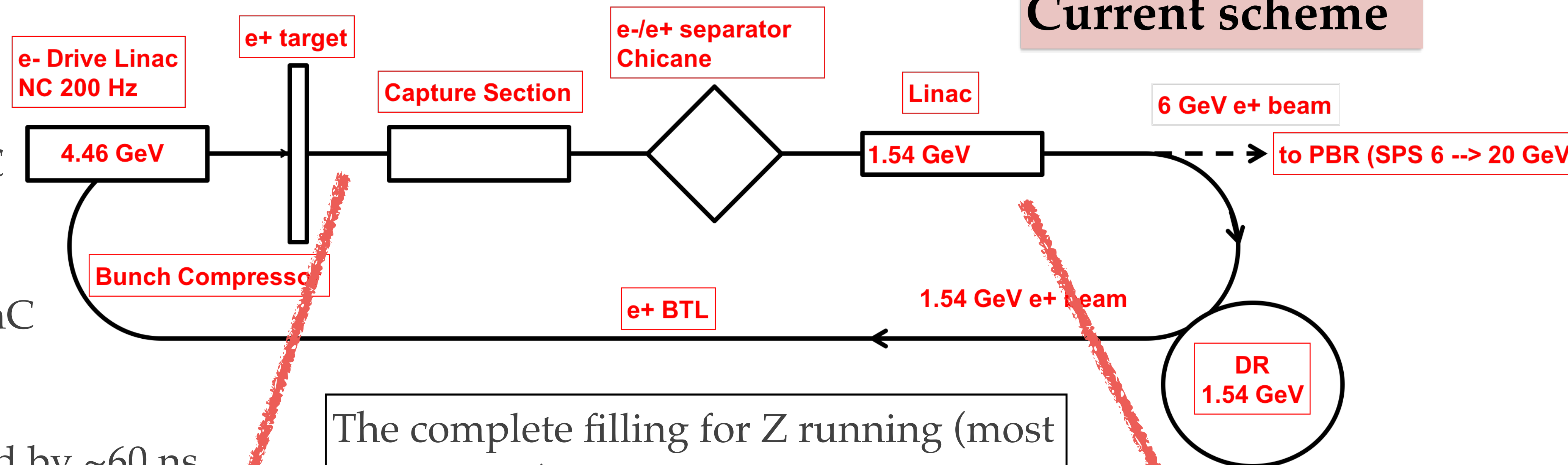
Primary e- beam

4.46 GeV

3 × 10^{10} e-/bunch ~ 5 nC (main e- beam)

4.2 × 10^{10} e-/bunch ~ 7 nC (for e+ production)

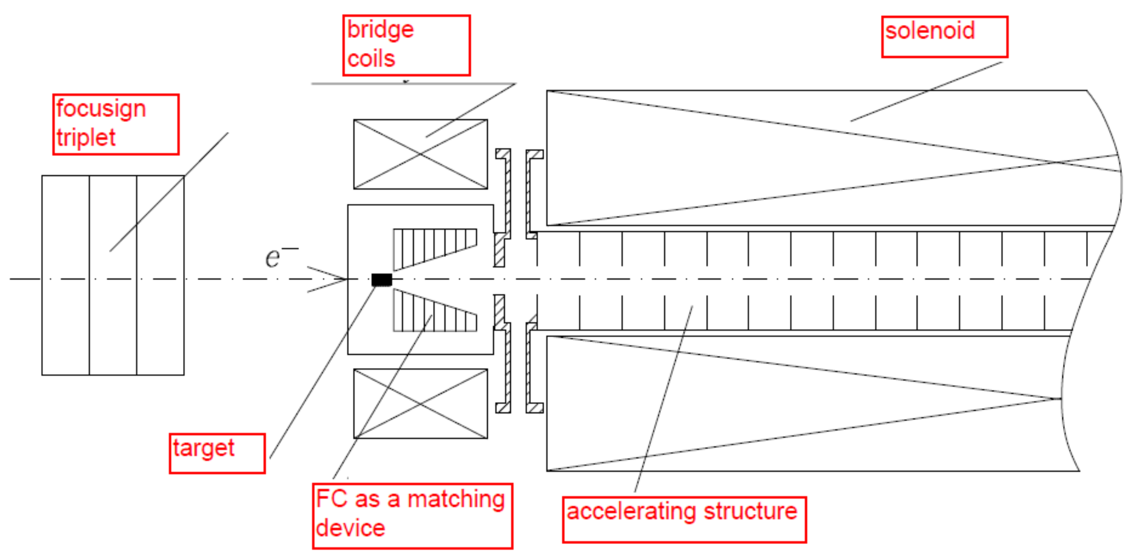
2 bunches/pulse spaced by ~60 ns



The complete filling for Z running (most demanding) => Requirement @ DR:
~2.1 × 10^{10} e+/bunch (4.3 nC)
~0.5 e+/e- without safety factor

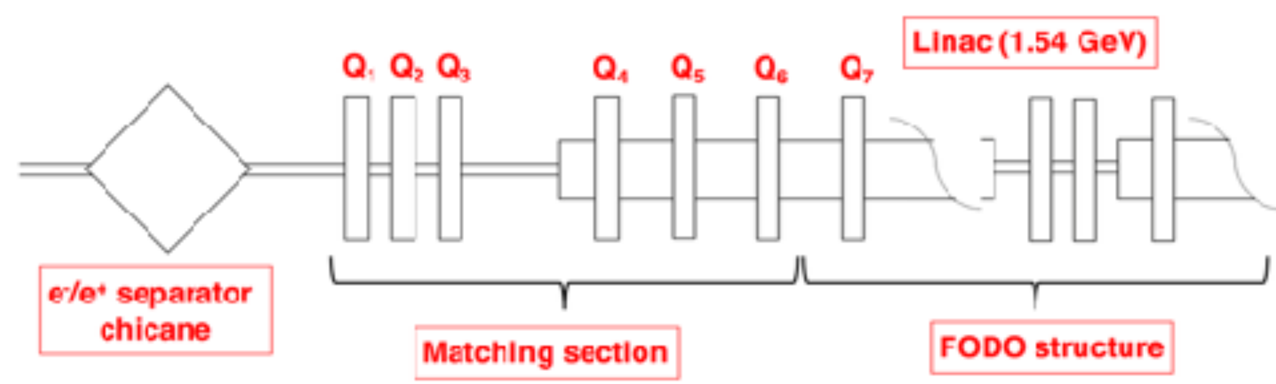
A safety factor of at least 2 should be considered

e+ production and capture section



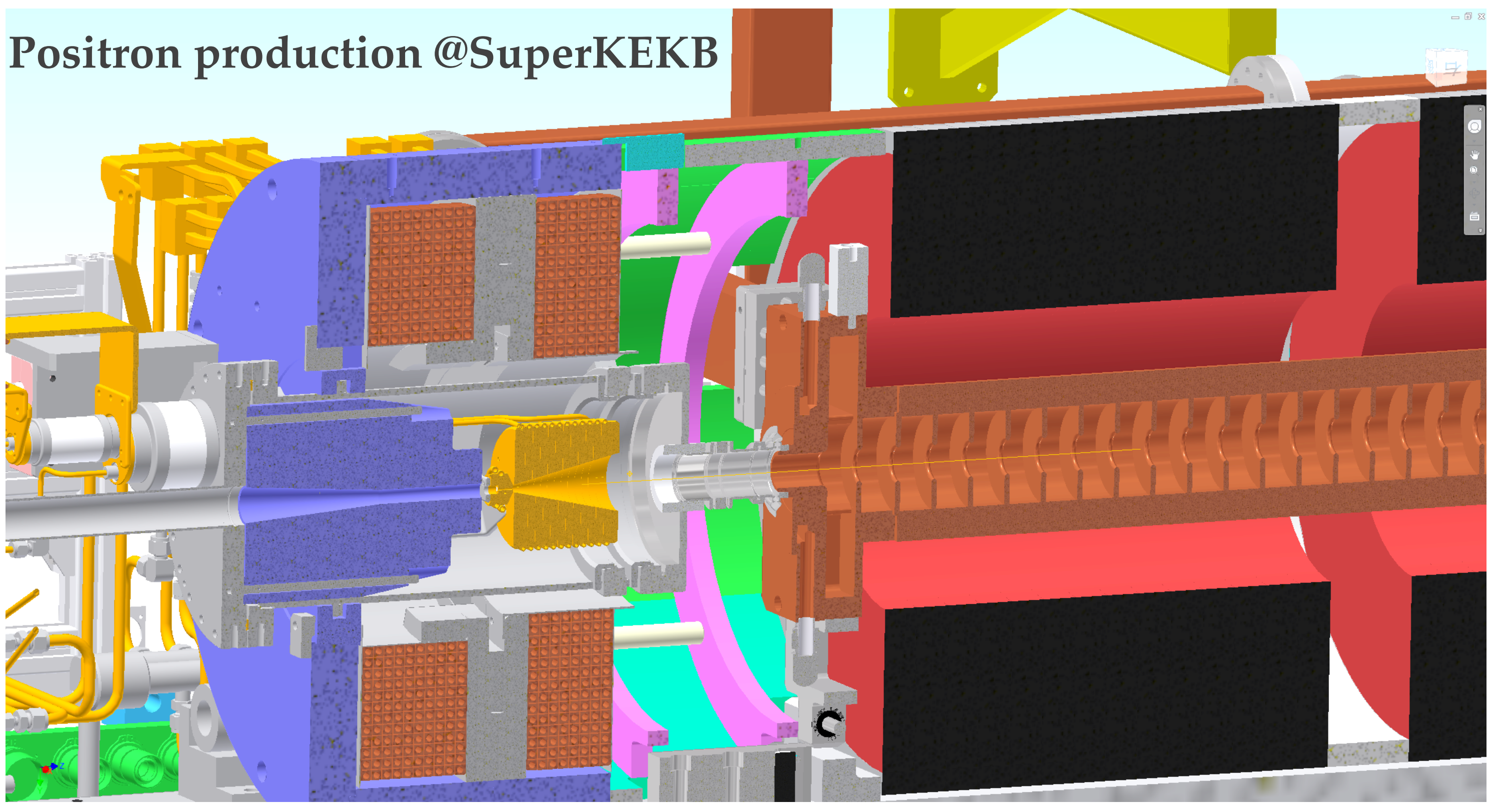
Fixed target-converter
(like @ SuperKEKB)

e+ acceleration up to 1.54 GeV

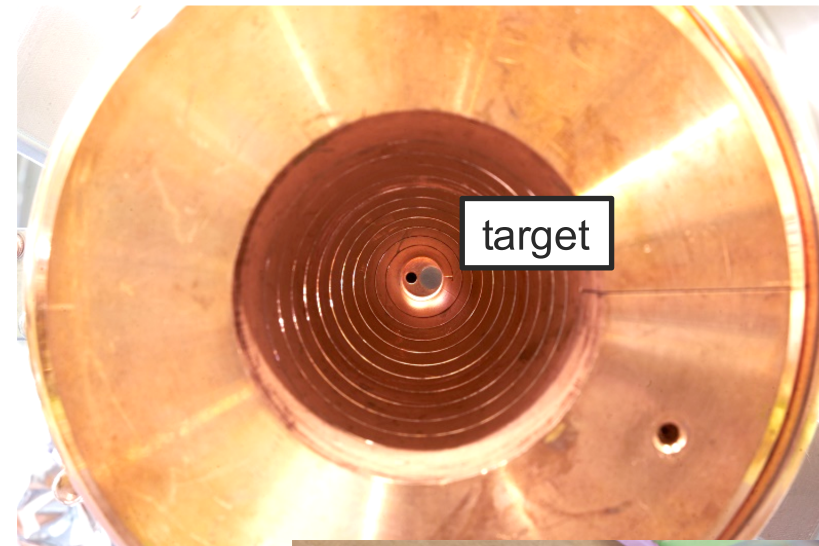


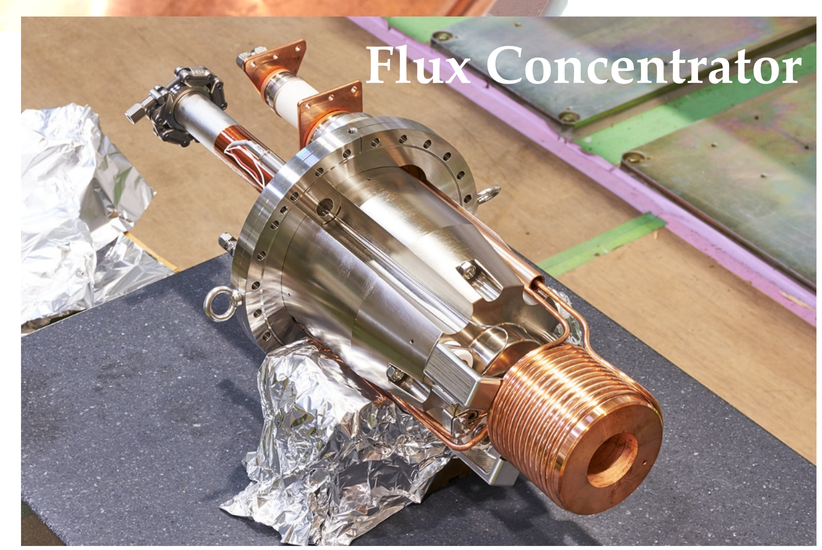
FCC-ee Positron Injector

- <u>SuperKEKB-like scheme:</u> **fixed target** (has a hole for e- beam passage), the positrons from the target share the same linac with electrons => additional degradation of the positron yield.



Y. Enomoto



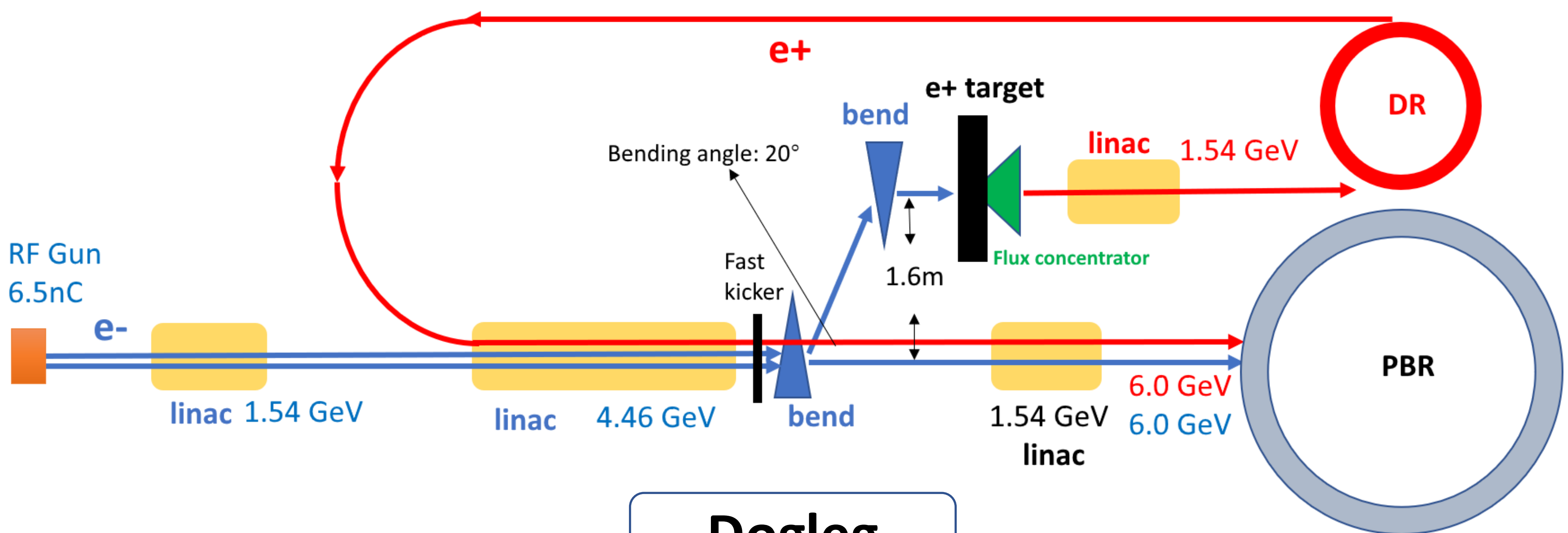


- <u>FCC-ee scheme:</u> **moving target** => design a bypass to separate e-/e+ beams.

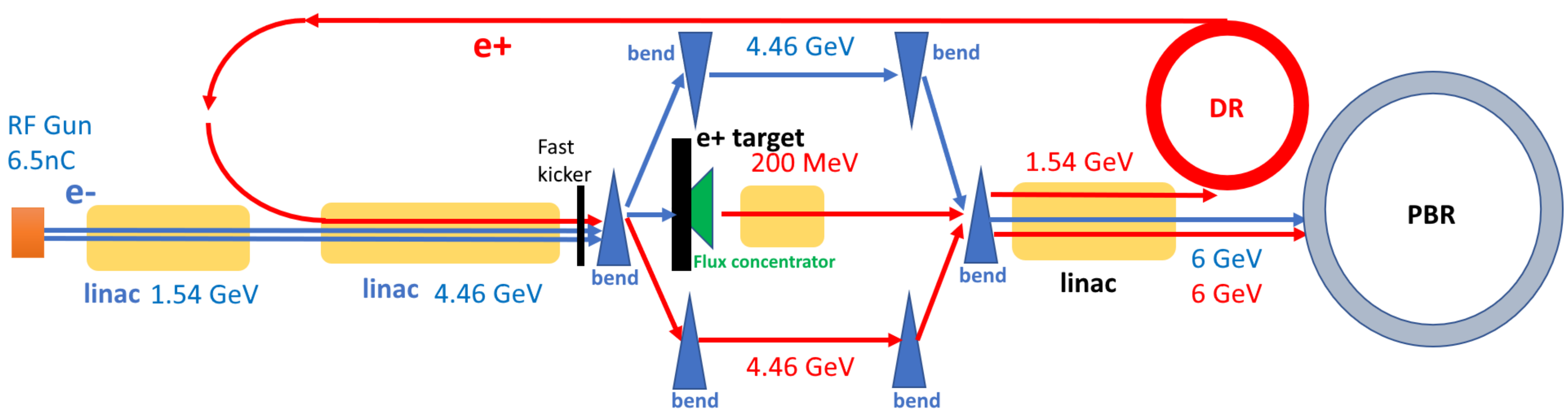
FCC-ee Positron Injector (bypass)

Schemes with the bypass under consideration

Preliminary



Dogleg



Chicane

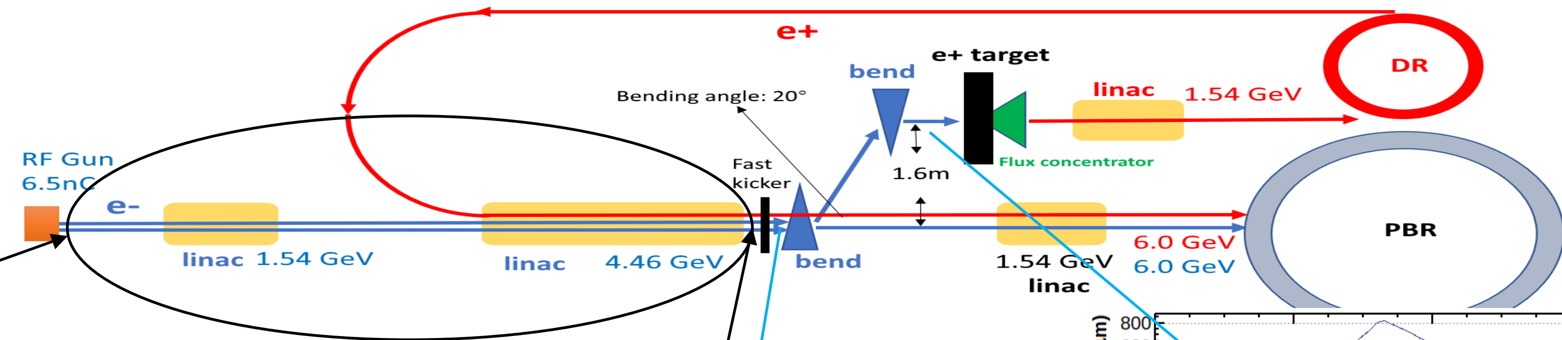
B. Bai

FCC-ee Positron Injector (bypass)

First results for the dogleg option

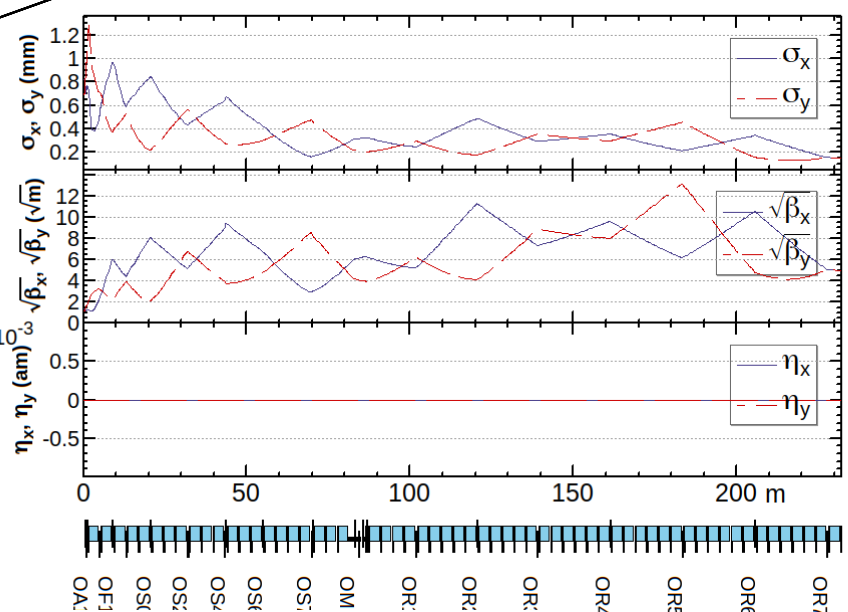
B. Bai CAS PhD @ LAL

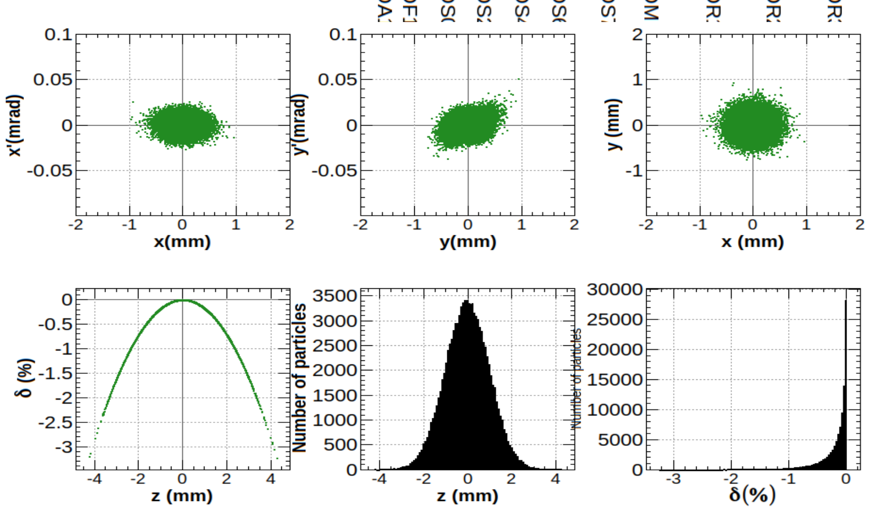
Dogleg bypass



Simulation with SAD

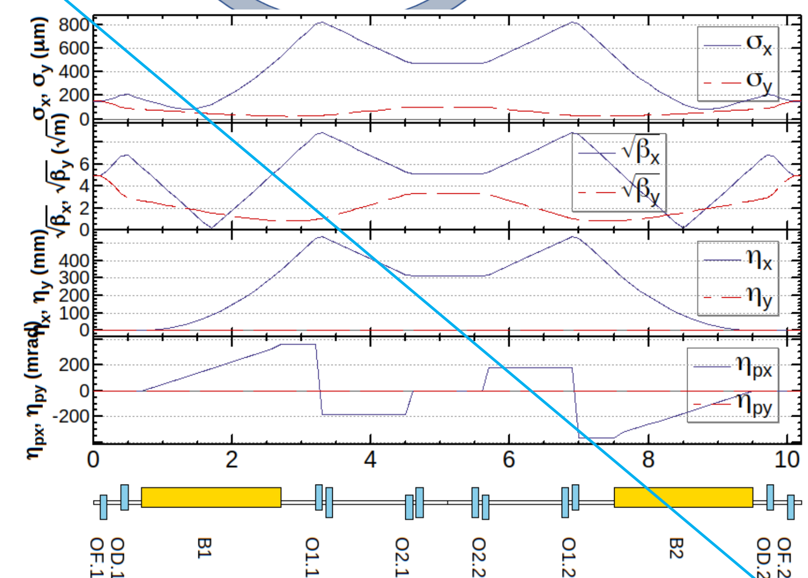
e-
Start point:
E = 11 MeV
δE = 1%
Q = 3.5 nC
σ_z = 1mm
$\varepsilon_{x,y}$ = 0.35 um



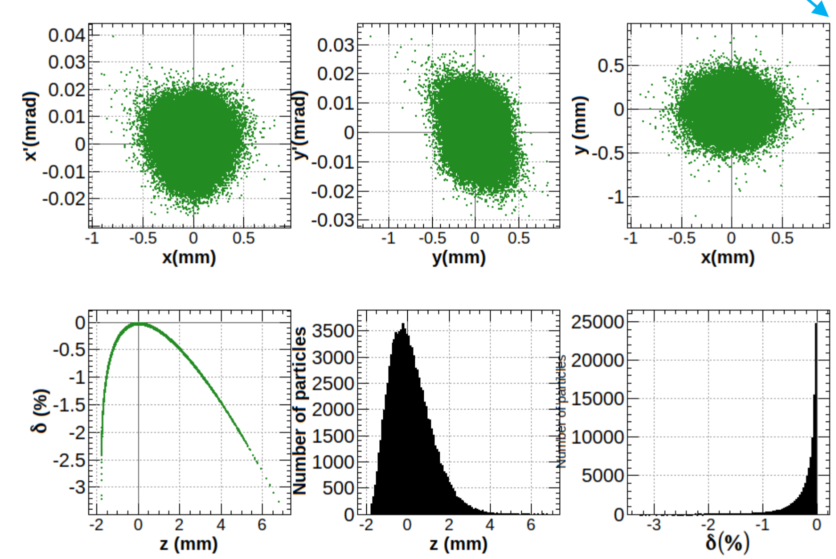


e-
End point:
E = 4.46 GeV
δE = 0.25%
Q = 3.5 nC
σ_z = 1mm
$\varepsilon_{x,y}$ = 9.4e − 10 m
σ_x = 152um
σ_z = 156um

e-
Start point:
E = 4.46 GeV
δE = 0.25%
Q = 3.5 nC
σ_z = 1mm
$\varepsilon_{x,y}$ = 9.4e − 10 m
σ_x = 152um
σ_z = 156um

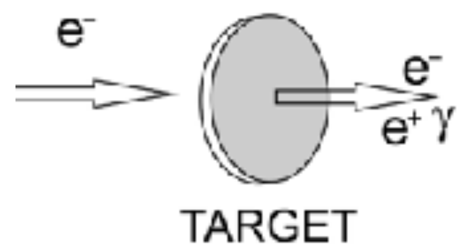


e-
End point:
E = 4.46 GeV
δE = 0.25%
Q = 3.5 nC
σ_z = 1mm
ε_x = 10.3e − 10 m
ε_y = 9.47e − 10 m
σ_x = 152 um
σ_z = 151 um



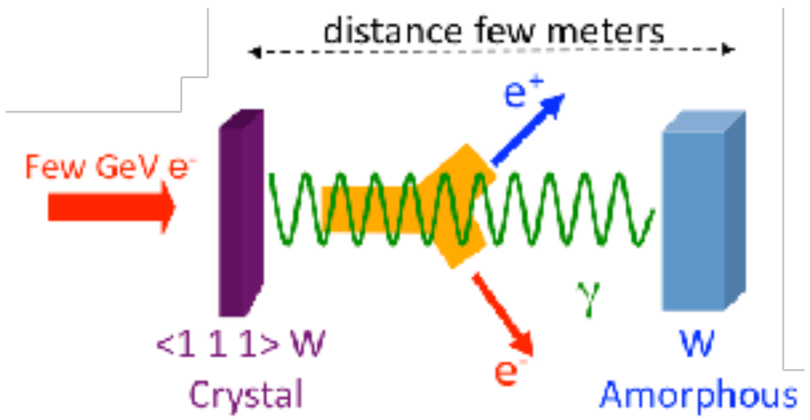
Two schemes of e+ production

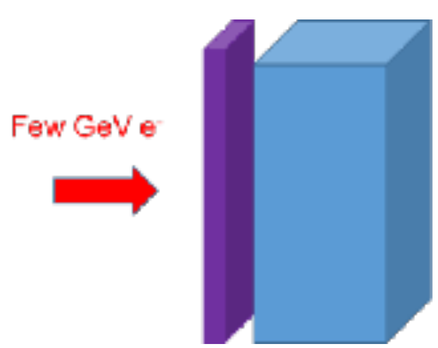
1) **Conventional positron target:** bremsstrahlung and pair conversion



- Classical e+ source.
- It was employed to produce e+ beam at the existing machines (ACO, DCI, SLC, LEP, KEKB…).

2) **Hybrid positron target:** Two-stage process to generate positron beam. Channeling (crystal target) and pair conversion (amorphous target)

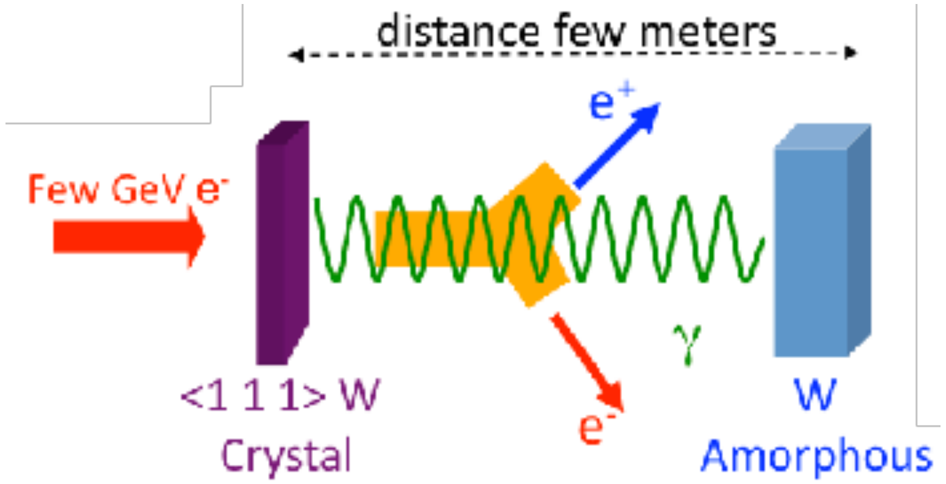


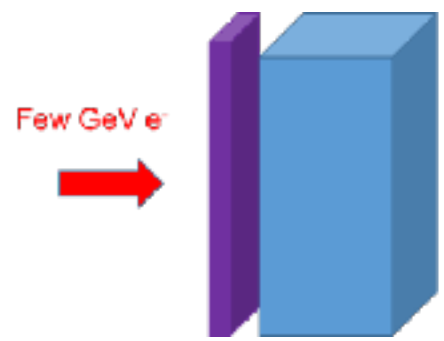


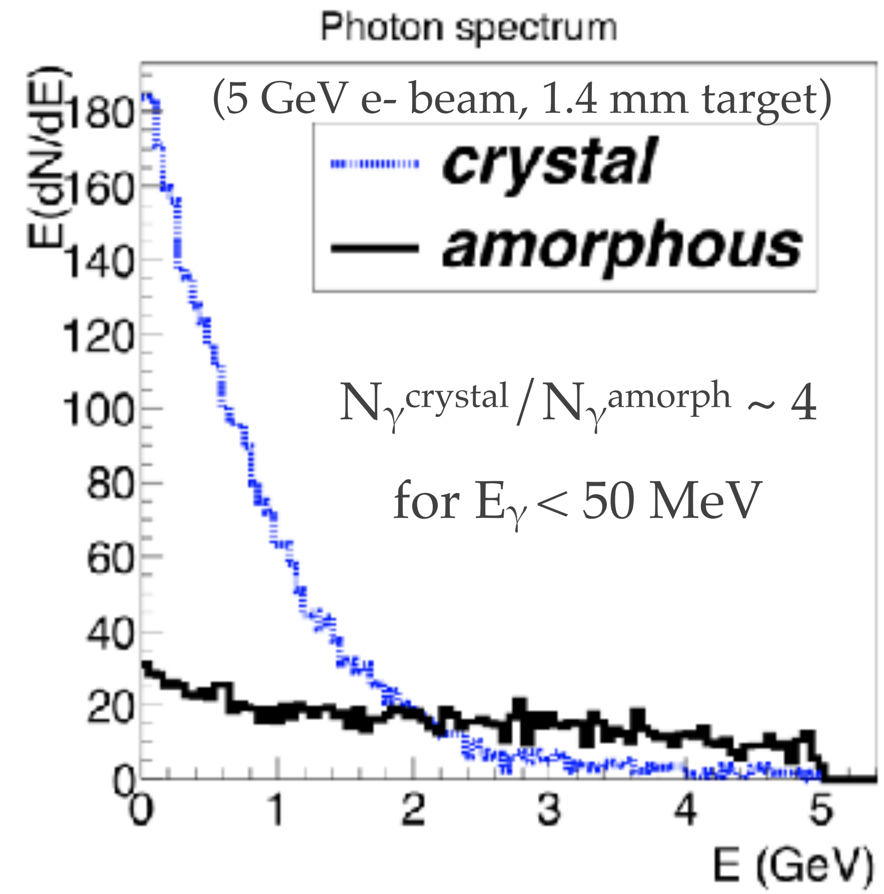
- Use the intense radiation emitted by high energy (some GeV) electrons channeled along a crystal axis => *channeling radiation*.
- Hybrid scheme 1: charged particles are swept off after the crystal target => the deposited power and PEDD (Peak Energy Deposition Density) are strongly reduced.
- Hybrid scheme 2: crystal target is installed closer to the target-converter (smaller beam size on the target)

Several experiments had been conducted to study the hybrid e+ source (proof-of-principle experiment in Orsay, experiment @ SLAC, experiment WA 103 @ CERN and experiments @ KEK).

Hybrid positron source







Energy spectrum: bigger number of the soft photons => more soft positrons are produced => easier capture by matching devices

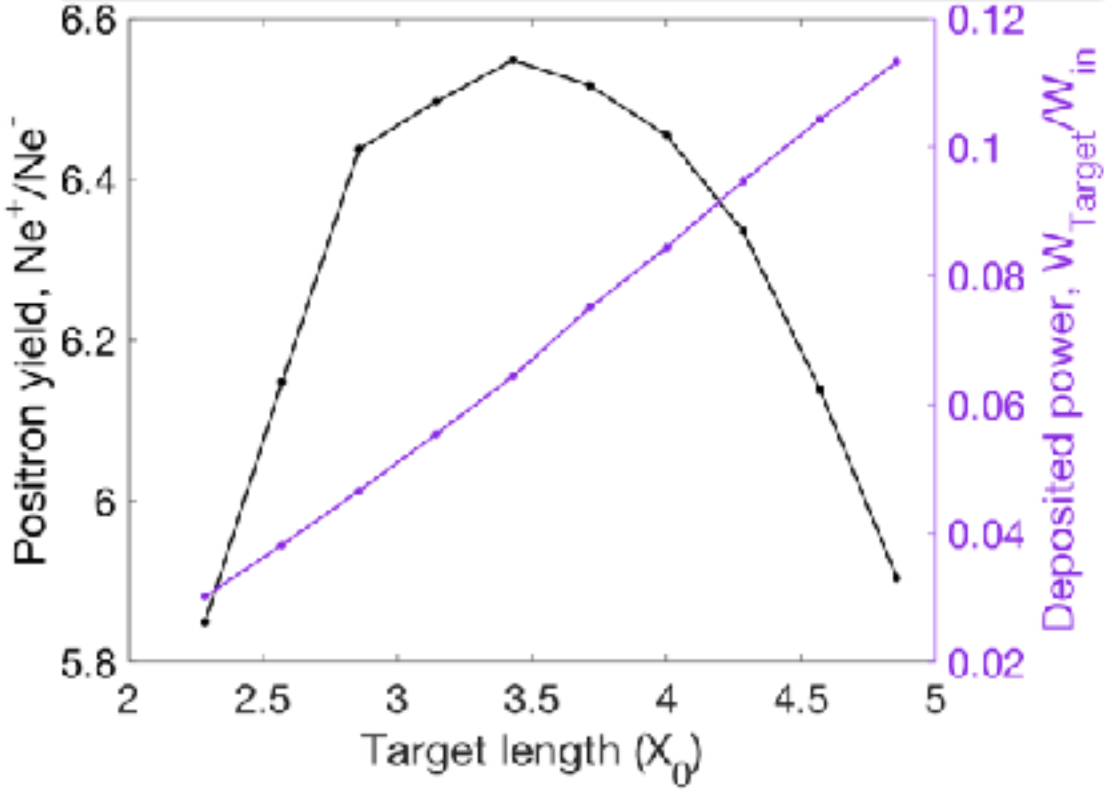
Typical parameters of the hybrid e+ sources:

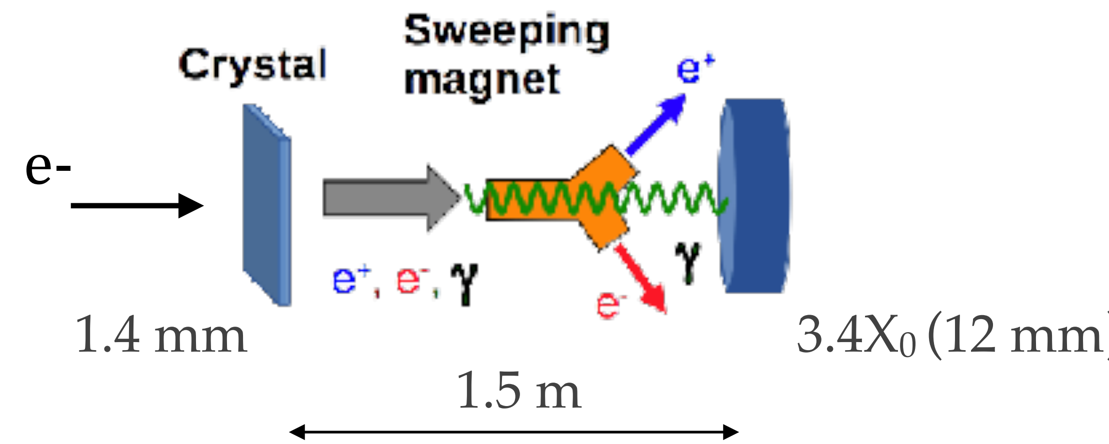
- **Thickness of the crystal:** optimum thickness is between 1-2 mm for E ≤ 10 GeV.
- **Thickness of the amorphous target (high Z material):** compromise between the requested yield and the amount of deposited energy => what is essential is **the accepted yield.**
- **Distance between the radiator and converter:** 1) installation of a sweeping magnet 2) increase the size of the photon beam => contribute to lower the deposited energy and its density.
- **Incident e- energy:** some GeV (to get $U_{ch} >> U_{bremss}$), U is the energy radiated. The radiated energy and the photon yield are increasing with the incident electron energy.
- **Crystal kind and orientation:** Tungsten W => high atomic potential (1 keV) at <111> orientation.

Hybrid source is a baseline design for the CLIC positron source

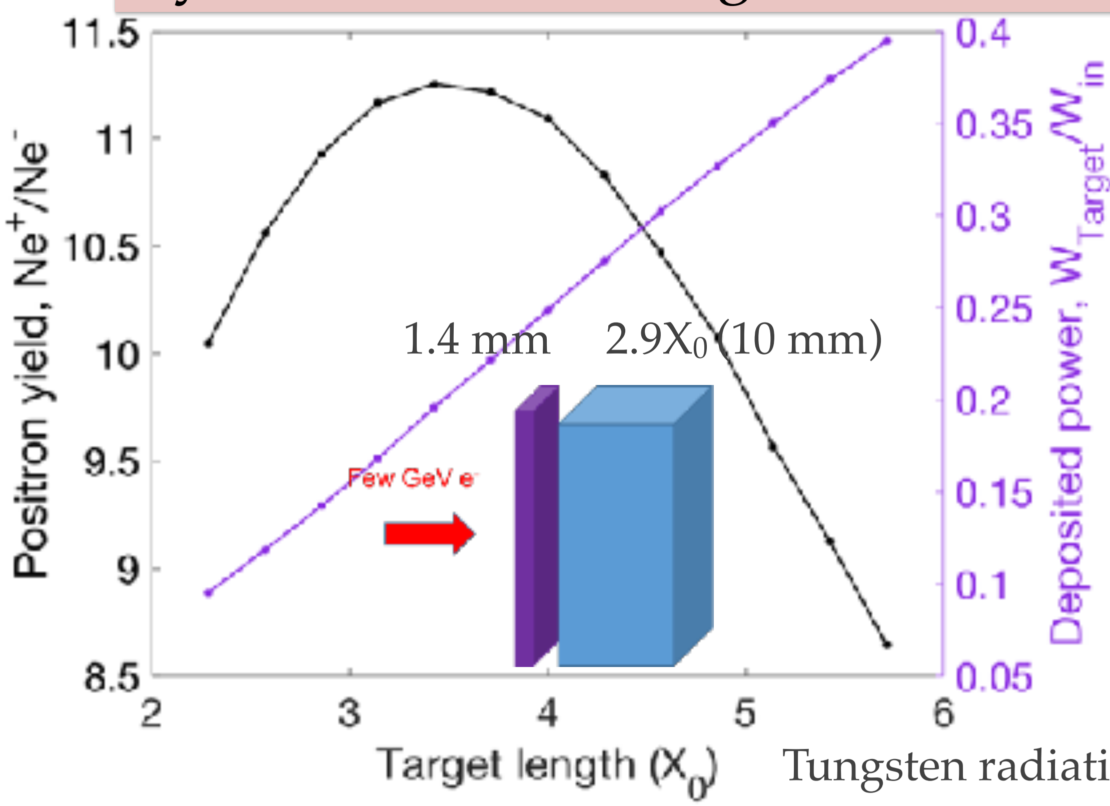
Production Target

Hybrid scheme 1 (target-converter)

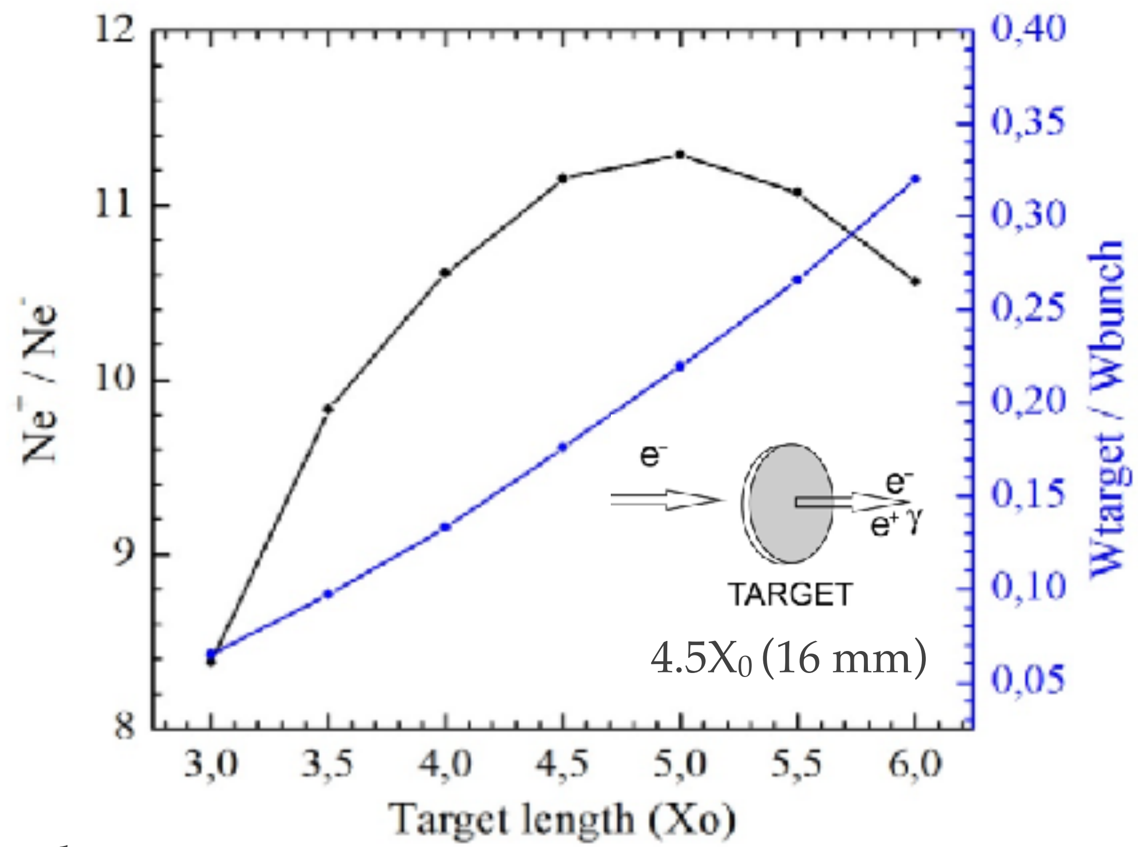




Hybrid scheme 2 (target-converter)



Conventional scheme



Tungsten radiation length X_0 is 0.35 cm.

Production Target

Primary e^- beam for e^+ production	
Beam energy	4.46 GeV
Bunch charge	4.2×10^{10}
Bunch length (rms)	**1** mm
Bunch transv. size (rms)	**0.5** mm
Bunch separation	60 ns
Nb of bunches per pulse	2
Repetition rate	100-**200** Hz
Beam power	12 kW

Beam Parameter	Convention	Hybrid 1	Hybrid 2*
Target thickness	$4.5X_0$	$0.4\ X_0/\ 3.4X_0$	$0.4\ X_0/\ 2.9X_0$
e+ yield @ Target	~11 e+/e-	~7 e+/e-	~11 e+/e-
PEDD	17 J/g	3 J/g	22 J/g
Deposited power	18 % (2.1 kW)	7 % (0.8 kW)	14 % (1.7kW)

**Hybrid 2 scheme should be optimized*

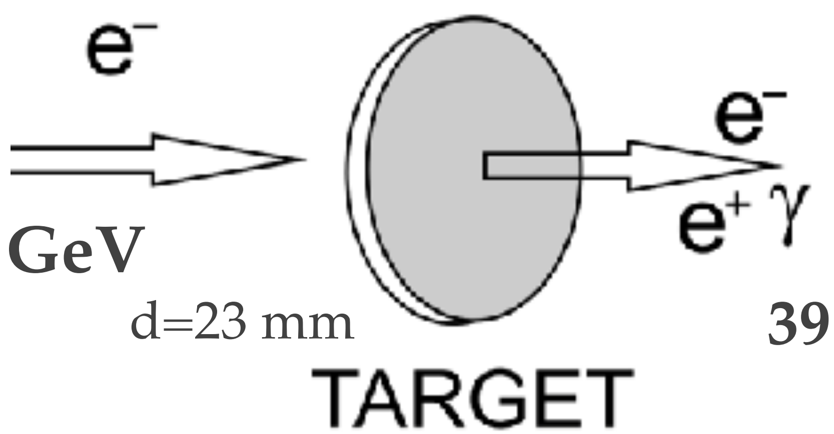
- PEDD (Peak Energy Deposition Density, [GeV/cm^3/e$^-$] or [J/g]) ~ beam and target parameters (beam energy, spot size and target thickness) => thermo-mechanical stresses.
- According to SLC experience, $W_{74}Re_{26}$ material has a PEDD limit of **35 J/g** (safe value to avoid target failure).

Positron Production (alternative options)

20 GeV linac as the FCC-ee injector:

- The higher-energy incident beam for positron production (18.46 GeV instead of 4.46 GeV)
- A real advantage as *the positron yield is increasing with the incident energy.*
- *Channeling process* in the crystal becomes *more effective* (more photons produced)

Conventional scheme



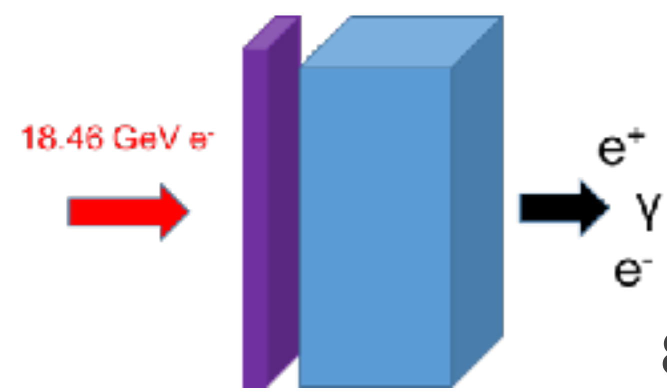
18.46 GeV

d=23 mm

39 N_{e+}/N_{e-}

Thickness is chosen to maximize the positron production

Hybrid scheme 2



38 N_{e+}/N_{e-} @Target

8 N_{e+}/N_{e-} @200 MeV

1.4 mm 12 mm

After the crystal: 26 γ/e- due to channeling compared to 4 γ/e- without channeling

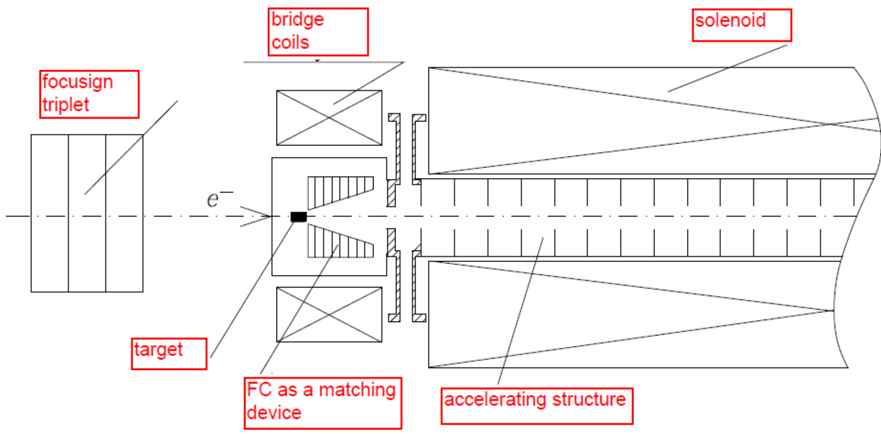
(16 γ/e- compared to 4 γ/e- @4.46 GeV)

☞ The full optimization of the production should be performed including the deposited power in the target, PEDD and the captured positron yield.

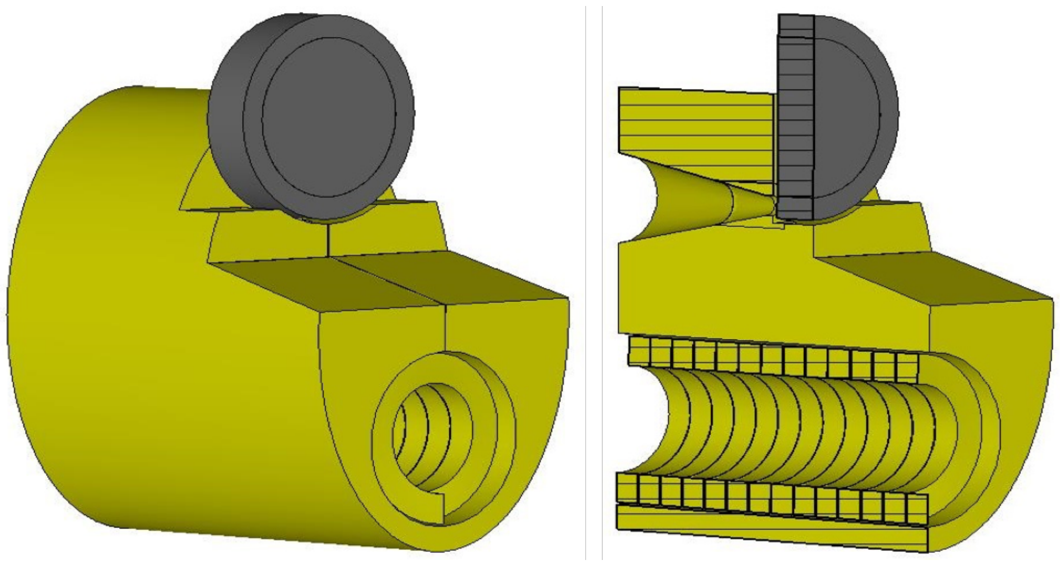
Capture and Primary Acceleration

The capture section design for both schemes is based on an Adiabatic Matching Device (AMD).

☞ *Flux Concentrator (FC) to form* adiabatically decreasing magnetic field

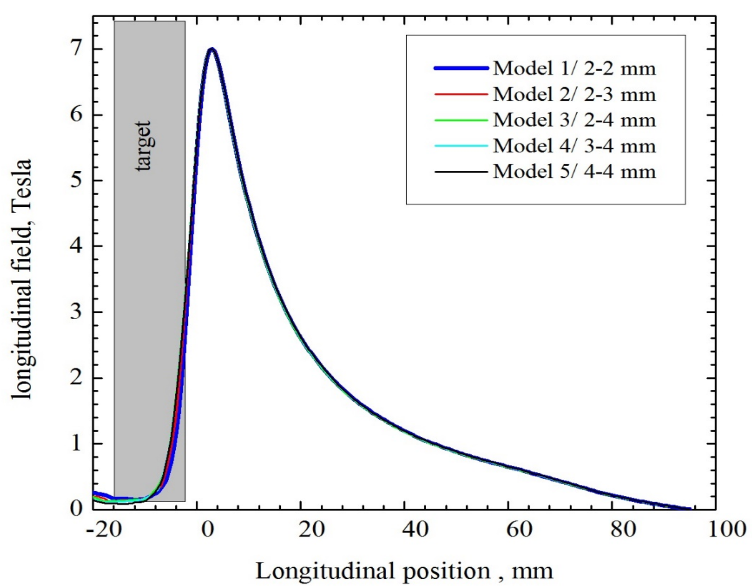


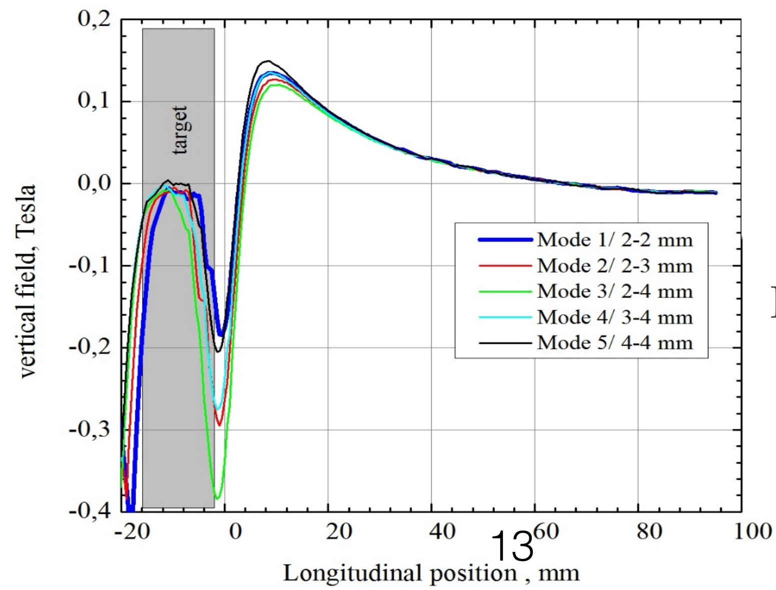
Matching the e+ beam (with very large transverse divergence) to the acceptance of the pre-injector linac.



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

Flux Concentrator field profile





Full 3D magnetic field map is used in the simulations.

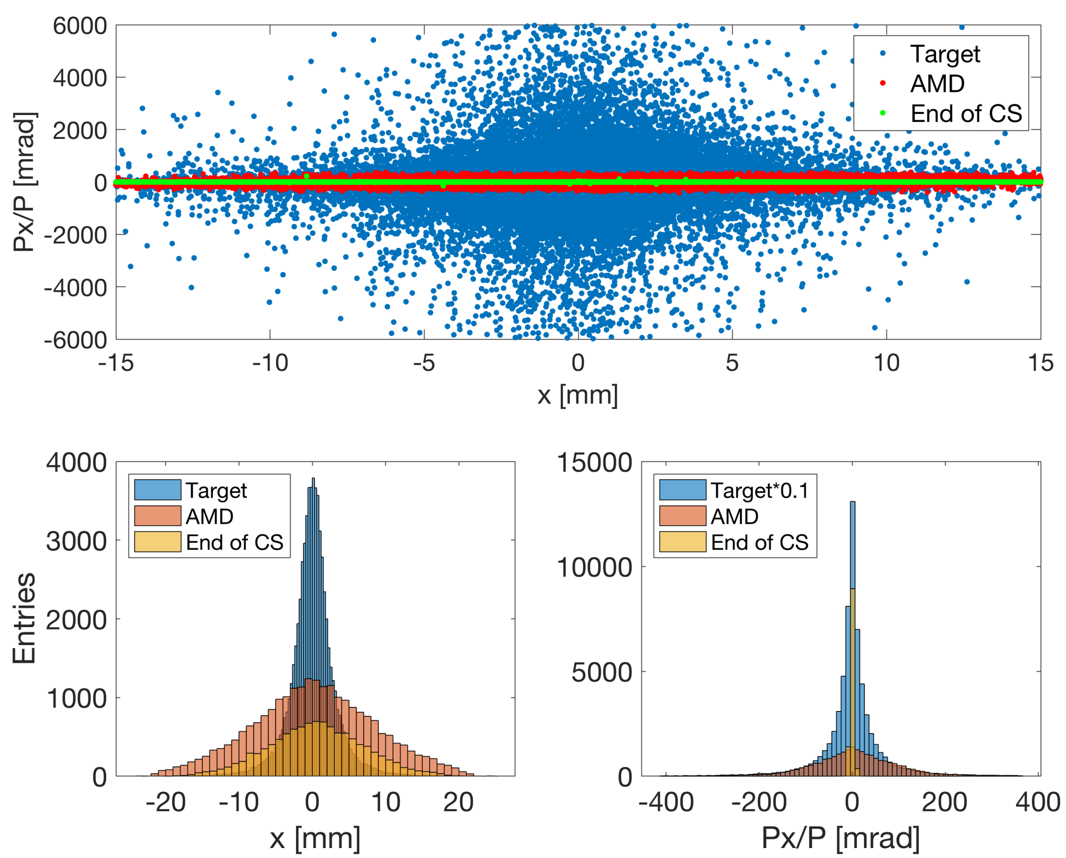
Peak of the magnetic field is at 5 mm from the target.

P. Martyshkin

Capture and Primary Acceleration

The capture linac is encapsulated inside a solenoid with the axial magnetic field of 0.5-0.7 T.
☞ **Hybrid scheme:** 1.5 meter long 17 MV / m, 2 GHz L-band structures.
☞ **Conventional scheme:** 3 meter long 20 MV / m 2856 MHz large aperture S-band structures.

Positron emittance at the exit of the target, the AMD and the capture section at 200 MeV (uniform DC solenoid field)

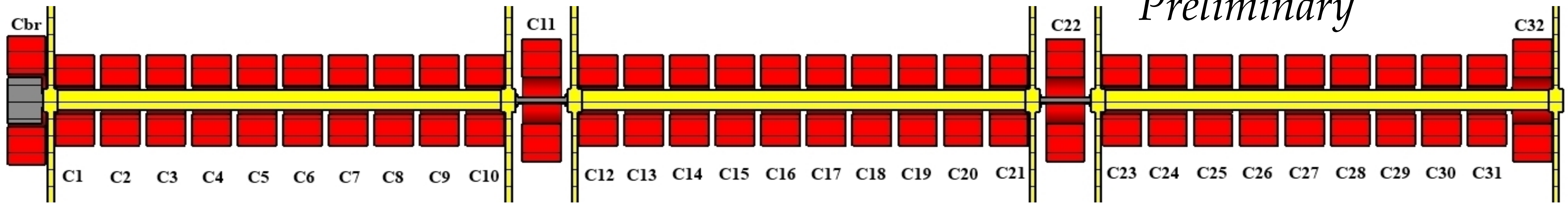


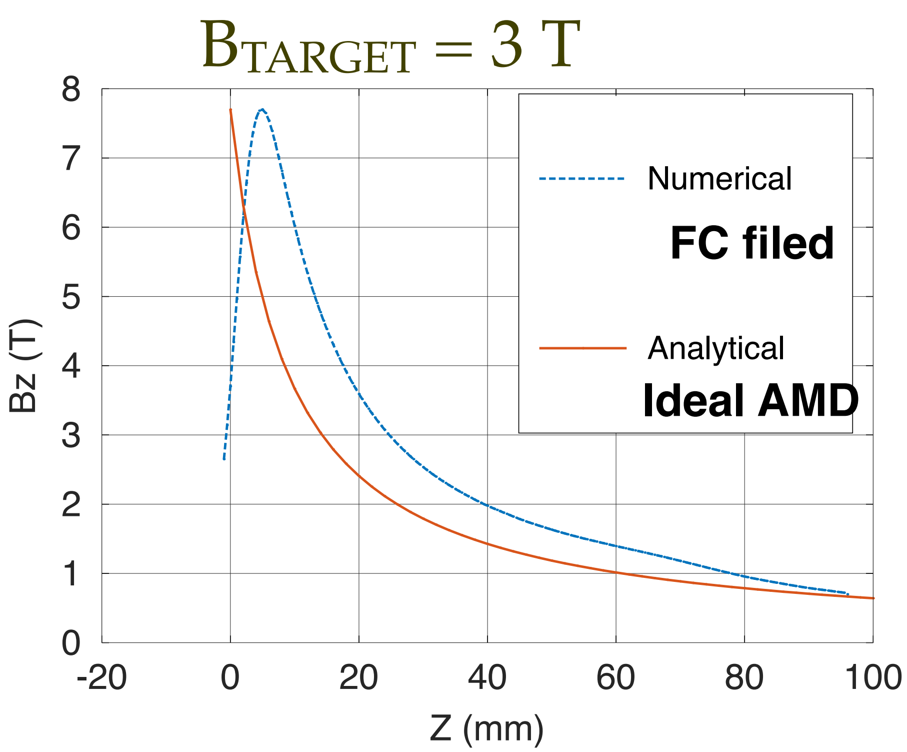
Beam Parameter	Convention	Hybrid 1	Hybrid 2
B_{max} = 5 T, B_{DC} = 0.5 T			
Mean Energy	190 MeV	197 MeV	235 MeV
Accepted yield	1.1 N_{e+}/N_{e-}	0.7 N_{e+}/N_{e-}	~1.4 N_{e+}/N_{e-}
Emittance h/v	17 μm (1σ)	14 μm (2σ)	10 μm (3σ)
B_{max} = 7 T, B_{DC} = 0.7 T			
Mean Energy	190 MeV	198 MeV	226 MeV
Accepted yield	1.3 N_{e+}/N_{e-}	~0.9 N_{e+}/N_{e-}	~2 N_{e+}/N_{e-}
Emittance h/v	21μm (1σ)	16 μm (2σ)	11 μm (3σ)

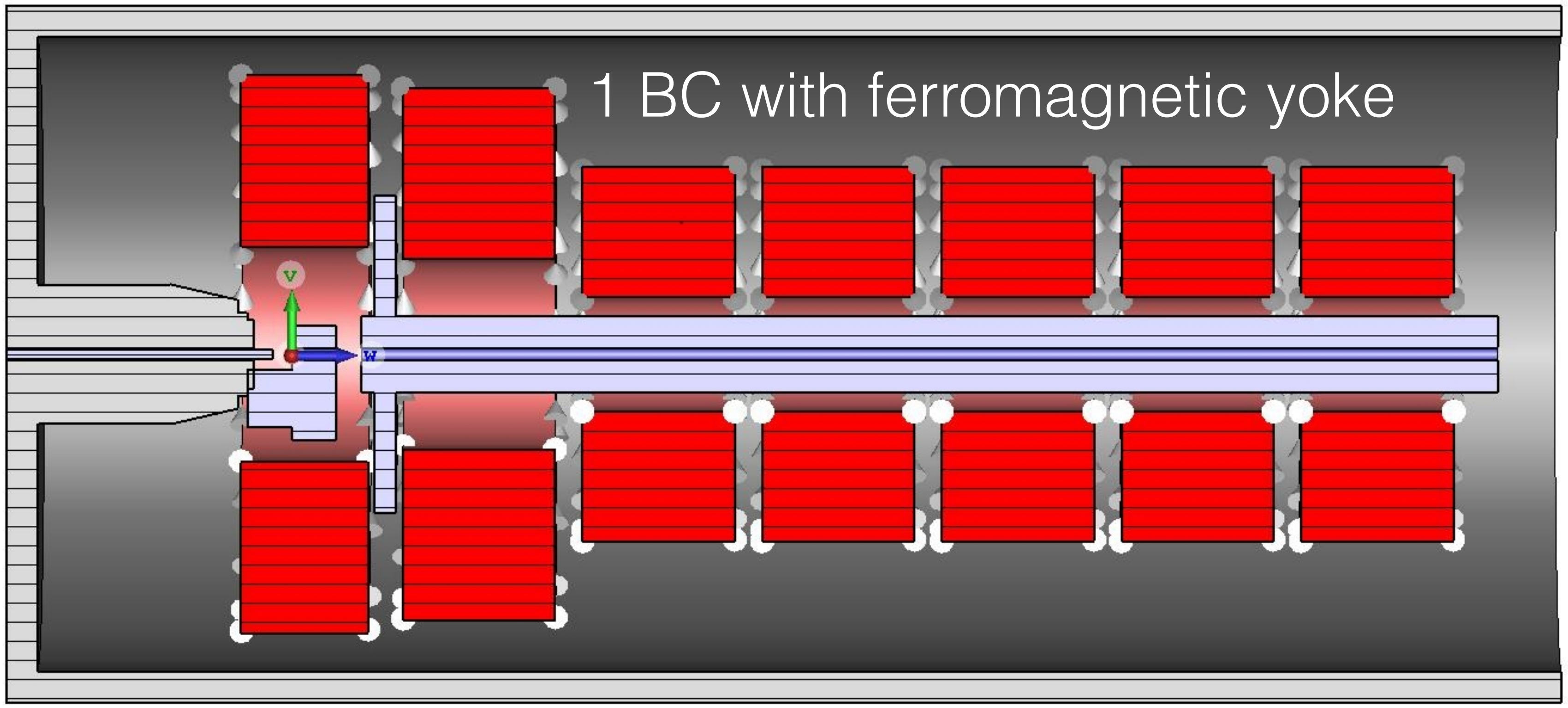
B_{DC} up to 0.7 - 0.8 T and FC B_{max} ~ 7-8 T

Assuming [optimization x transport until 1.54 GeV x DR injection efficiency] e+ yield ≳ 1 N_{e+}/N_{e-} but the realistic simulations are needed + safety factor.

Positron capture section design







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

Next steps: optimization of the magnetic field profile near/at the target (FC + Bridge Coils) and calculation of the realistic solenoid field distribution along the capture section (with steering coils).

SC solenoid as the AMD

The Adiabatic Matching Device (AMD) may use a pulsed Flux Concentrator or SC magnet
☞ *SC solenoid*

☞ Advantages => higher field value on the target, DC operation

☞ Promising results of the first tests at KEK. Possible continuation in collaboration with PSI => beam test of the positron production and capture @PSI.

In the early stage of the SuperKEKB positron source design studies, a possibility of using a SC solenoid as a positron focusing device was considered.

Beam tests in the KEKB linac (2009 - 2011):

- beam irradiation experiment directly into a superconducting solenoid to investigate a quench limit
- beam irradiation experiment of a dummy target installed inside a beam pipe which penetrate a cryostat of a SC solenoid at the beam dump at 1.7 GeV. The solenoid survived at least for 10 minutes at 3.2 Tesla field level with an irradiation of 7nC x 2 bunch 1.7 GeV beam at 49 Hz.

SC solenoid as the AMD

The Adiabatic Matching Device (AMD) may use a pulsed Flux Concentrator or **SC magnet**
☞ *SC solenoid*

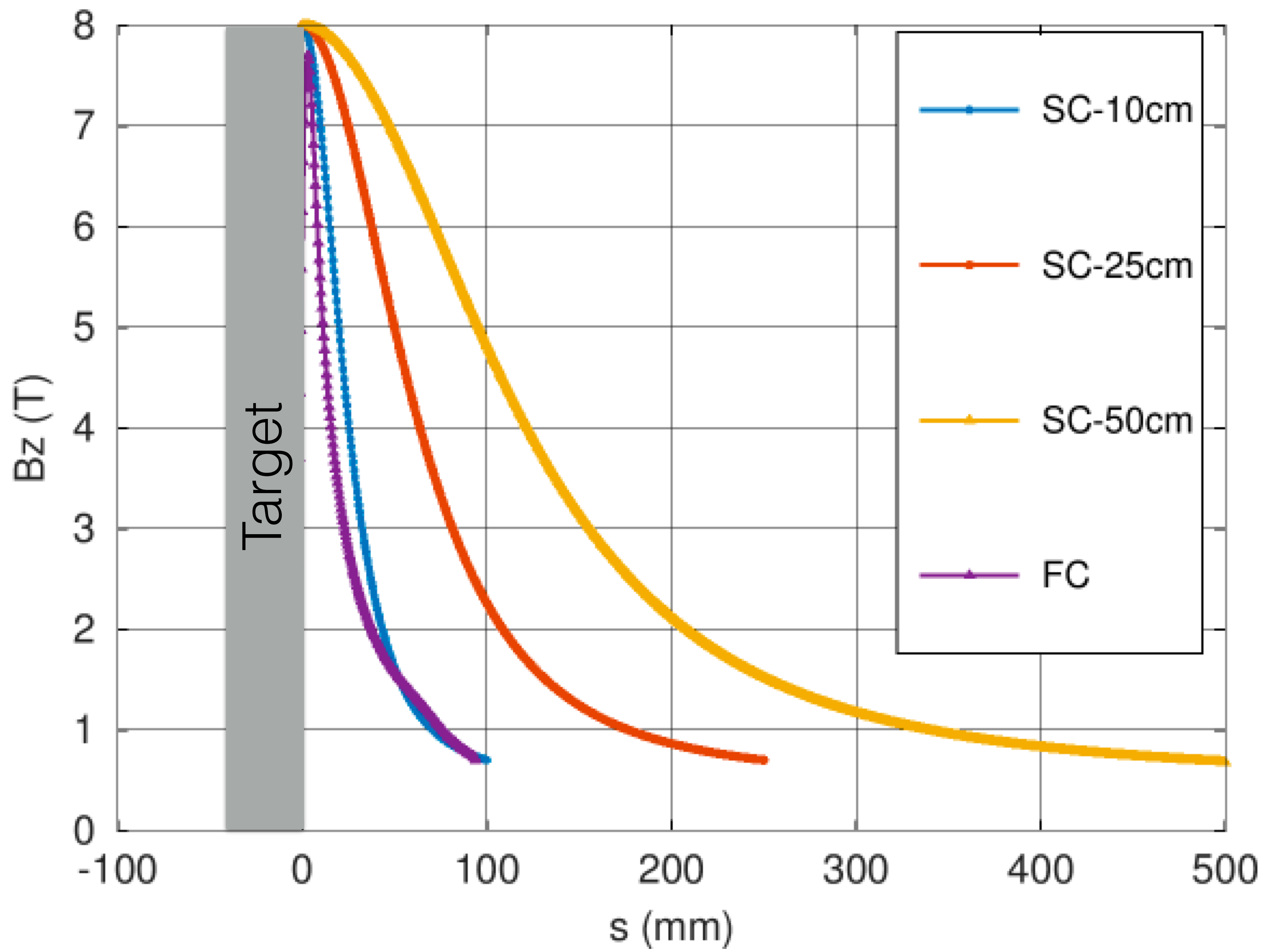
SC solenoid
B(z)=Bw+(Bt-Bw)*Rs^3/(Rs^2+z^2)^1.5

Bt=8 Tesla
Bw=0.7 Tesla

Rs=0.15 m => L=50 cm
Rs=0.08 m => L=25 cm
Rs=0.03 m => L=10 cm

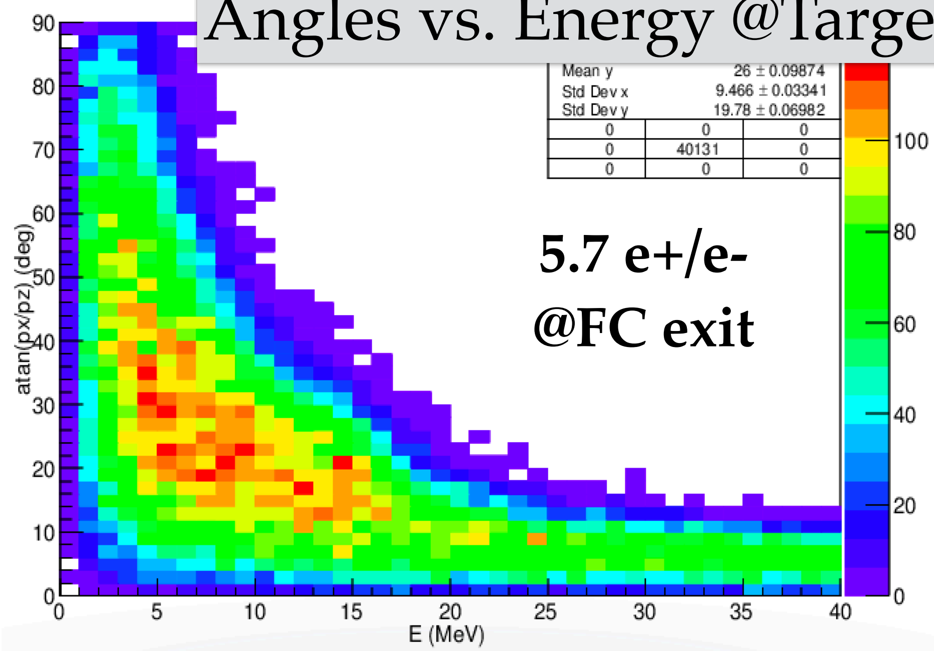
Flux Concentrator
FC => L = 10cm

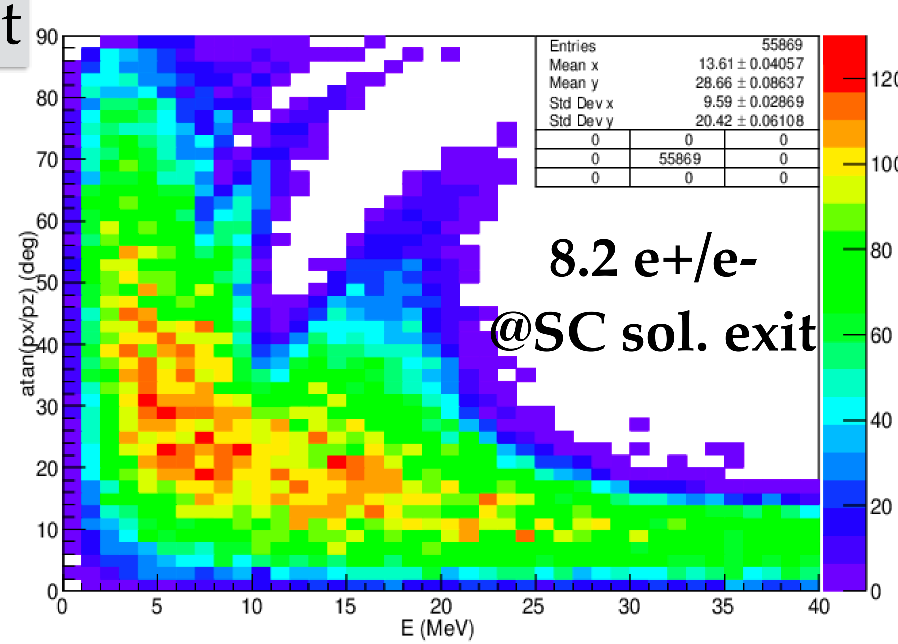
- The AMD length is different
- DC solenoid after AMD

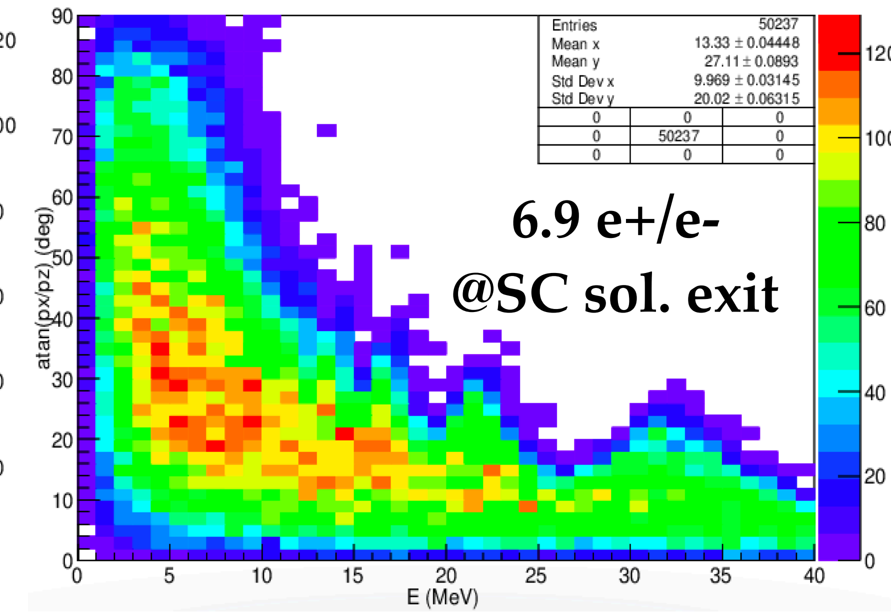


Positron capture @Target/AMD

Angles vs. Energy @Target





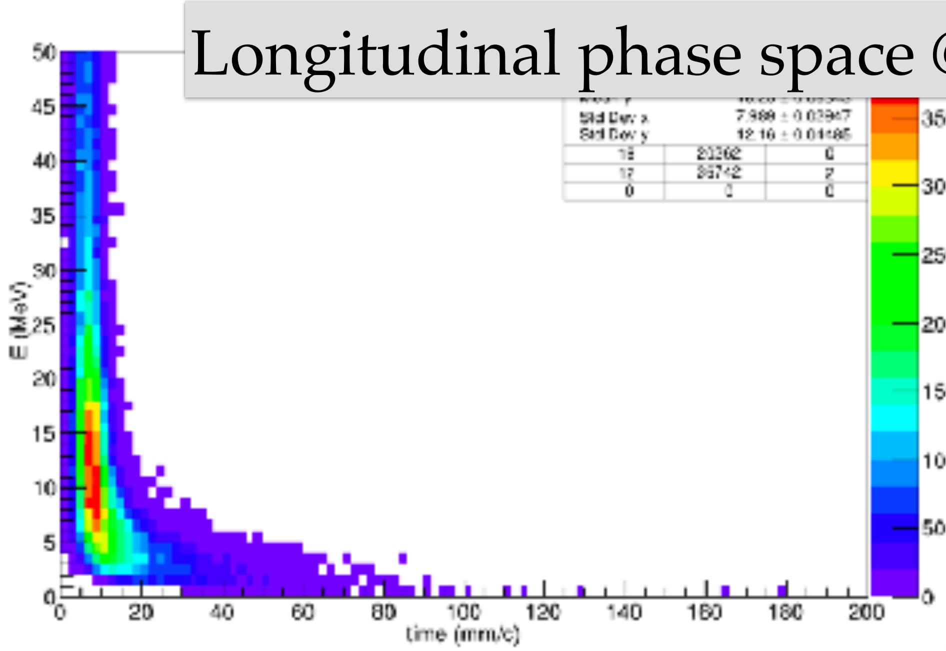


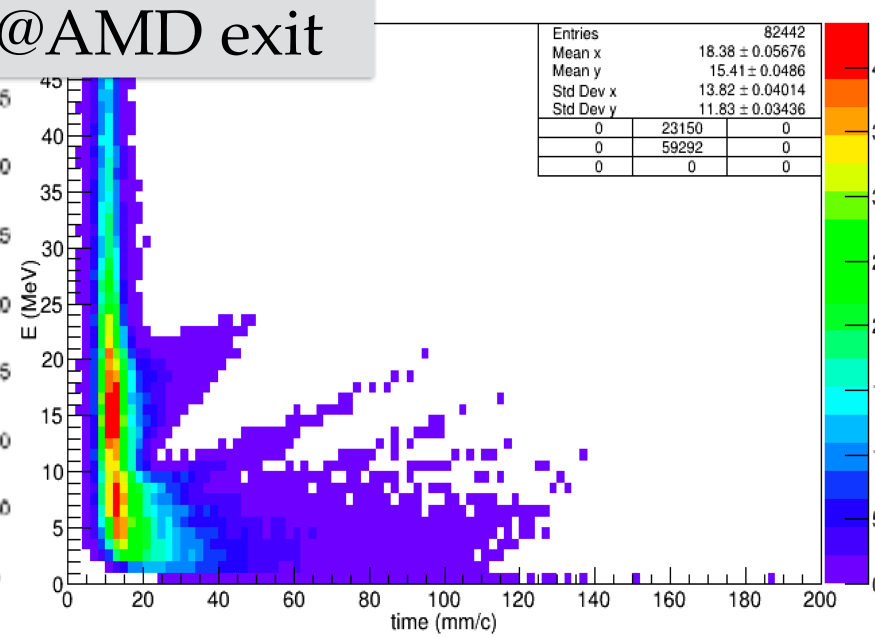
FC L = 10 cm

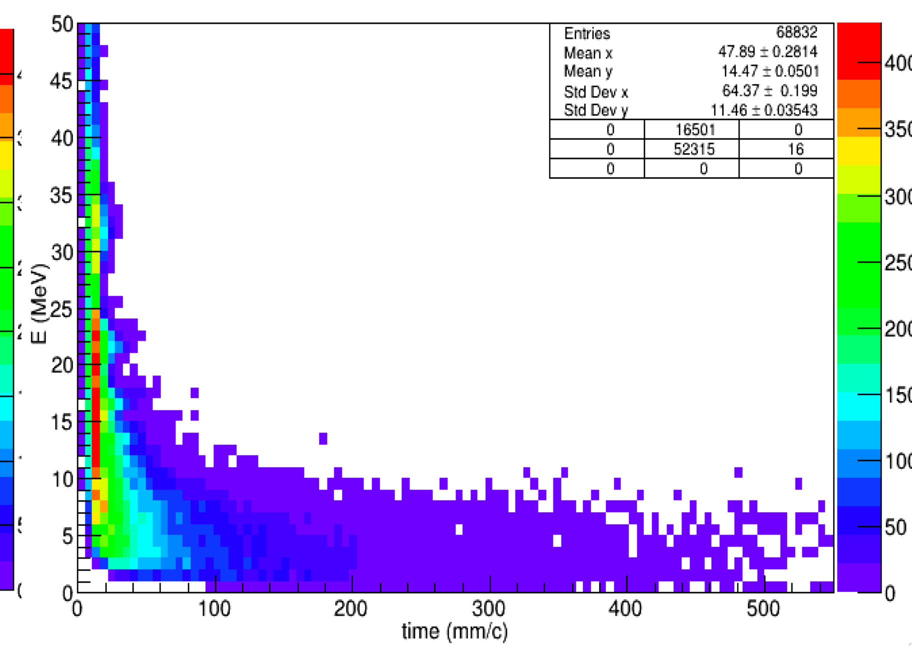
SC solenoid L = 10 cm

SC solenoid L = 50 cm

Longitudinal phase space @AMD exit







Primary Acceleration with SC solenoid

The simulations are done for the hybrid 2 scheme with the SC solenoid (B_{max} = 8 T, B_{end} = 0.7 T, different length) and FC (B_{max} = 7 T, B_{DC} = 0.7 T) as the AMD.

SC solenoid: B_{TARGET} = 8 T
FC: B_{TARGET} = 3 T

Preliminary

	Yield @ AMD	Total Yield @ 200 MeV	Acc. Yield @ 200 MeV (30 MeV & 40 degrees RF)
FC	5.7	2.3	1.5
SC – 10 cm	8.2	3.0	2.0
SC – 25 cm	7.5	3.4	1.8
SC – 50 cm	6.9	3.4	1.0

Positron capture to be optimized (RF phase, gradient) + global optimization of the capture section

Target Thermal Load

Beam Parameter	Convention	Hybrid 1	Hybrid 2
Target thickness	$4.5X_0$	$0.4\ X_0$/ $3.4X_0$	$0.4\ X_0$/ $2.9X_0$
e+ yield @ Target	~11 e+/e-	~7 e+/e-	~11 e+/e-
PEDD	17 J/g	3 J/g	22 J/g
Deposited power	18 % (2.1 kW)	7 % (0.8 kW)	14 % (1.7kW)

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

- The target life time will suffer from the cyclic thermal loads and stresses from the beam pulses. Also the evacuation of the average power from the target at 200 Hz can be difficult
- A stationary target will not be sufficiently robust => rotating/trolling target (pendulum ?)
- The effects of eddy currents and the additional power, injected by the pulsed Flux Concentrator into the target, should be investigated
- **Evaluation of the thermal load in the target (peak stress and fatigue limit) and design of the cooling system to be addressed => reliability of the target.**

Summary

- FCC-ee can employ the conventional/hybrid positron source. *No showstopper identified* => studies ongoing.
- Current studies: both schemes can provide *the comparable e+ yield (> 1 N_{e+}/N_{e-})* accepted by the DR.
- As far as reliability of the target is concerned, *the hybrid scheme is more attractive* allowing *lower deposited power and PEDD* in the production target.
- Design studies of the FC, BC + DC solenoid have been started. SC solenoid as the AMD ?
- Evaluation of the thermal load in the target => target design and cooling system.
- Design of e+ linac from 200 MeV to 1.54 GeV. Start-to-end simulations to the DR and full optimisation are underway .
- Design of the bypass line for e+ generation/capture:
    - dogleg: different angles studies to cope with target hardware, chromaticity correction and Coherent SR mitigation
    - chicane: to be designed following a scheme similar to CEPC, but shorter length.

Positron source performances

	SLC	LEP (LIL)	KEKB/SKEKB	FCC-ee*
Incident e- beam	33 GeV	200 MeV	4.3/3.5 GeV	4.46 GeV
e-/bunch [10^{10}]	3-5	0.5 - 30 (20 ns)	6.25/6.25	4.2
Bunch/pulse	1	1	2/2	2
Rep. rate	120 Hz	100 Hz	50 Hz/50 Hz	100-200 Hz
Incident Beam power	~20 kW	1 kW (max)	4.3 kW/3.3 kW	12 kW
Beam size @ target	0.6 - 0.8 mm	< 2 mm	/>0.7 mm	
Target thickness	$6X_0$	$2X_0$	/$4X_0$	
Target size	70 mm	5 mm	14 mm	
Target	Moving	Fixed	Fixed/Fixed	Moving
Deposited power	4.4 kW		/0.6 kW	
Capture system	AMD	λ/4 transformer	/AMD	AMD
Magnetic field	6.8T->0.5T	1 T->0.3T	/4.5T->0.4T	
Aperture of 1st cavity	18 mm	25mm/18 mm	/30 mm	
Gradient of 1st cavity	30-40 MV/m	~10 MV/m	/10 MV/m	
Linac frequency	2855.98 MHz	2998.55 MHz	2855.98 MHz	
e+ yield @ CS exit	~4 e+/e-	~3 $\times 10^{-3}$ e^+/e- (linac	~0.1/~0.5 e+/e-	
Positron yield @ DR	~1.2 e+/e-		NO/0.4 e+/e-	
DR energy acceptance	+/- 2.5 %	+/- 1 % (EPA)	+/- 1.5 % (1 σ)	+/- 4 %
Energy of the DR	1.15 GeV	500 MeV	NO/1.1 GeV	1.54 GeV

*FCC-ee under study