FCC-ee Positron Source Design

I. Chaikovska*, R. Chehab, Y. Han (LAL), P. Martyshkin (BINP), L. Rinolfi, P. Sievers (CERN),
Y. Enomoto, K. Furukawa, T. Kamitani, F. Miyahara, M. Satoh, Y. Seimiya, T. Suwada (KEK)
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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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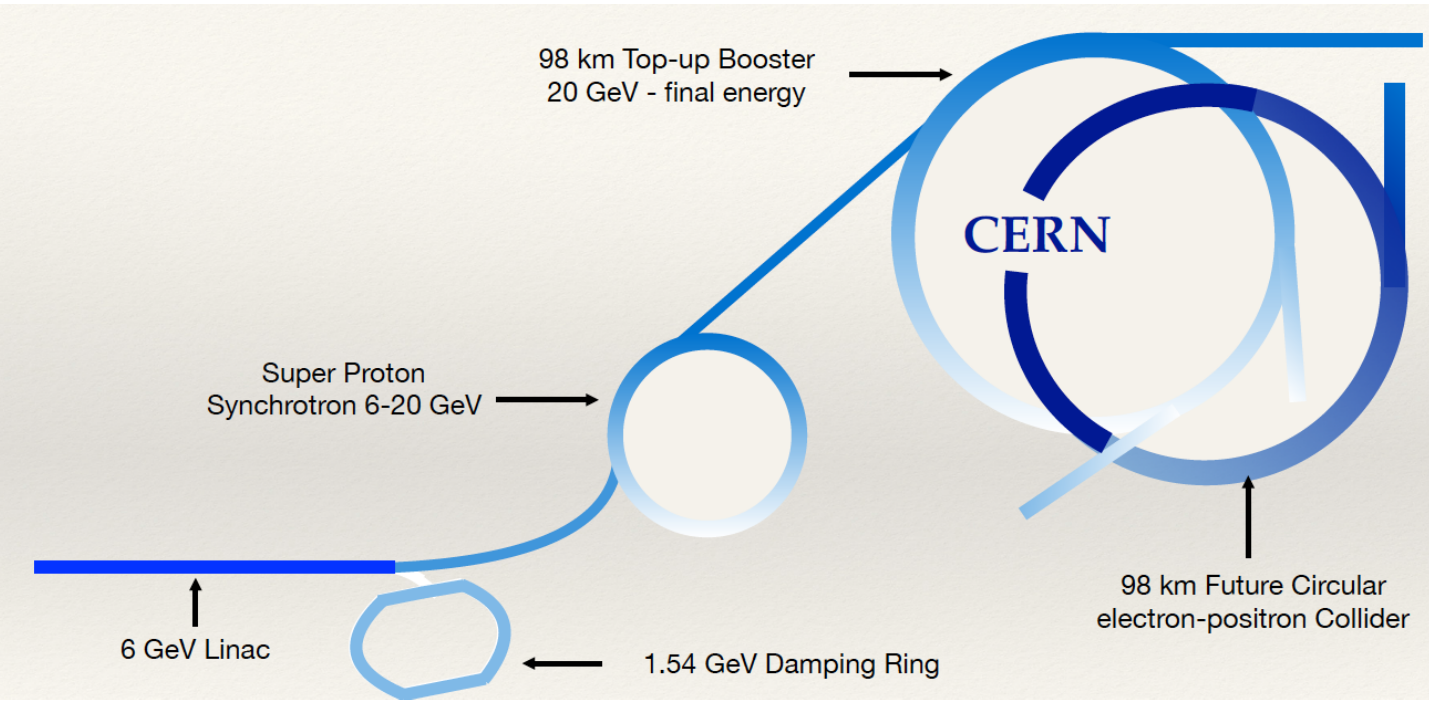
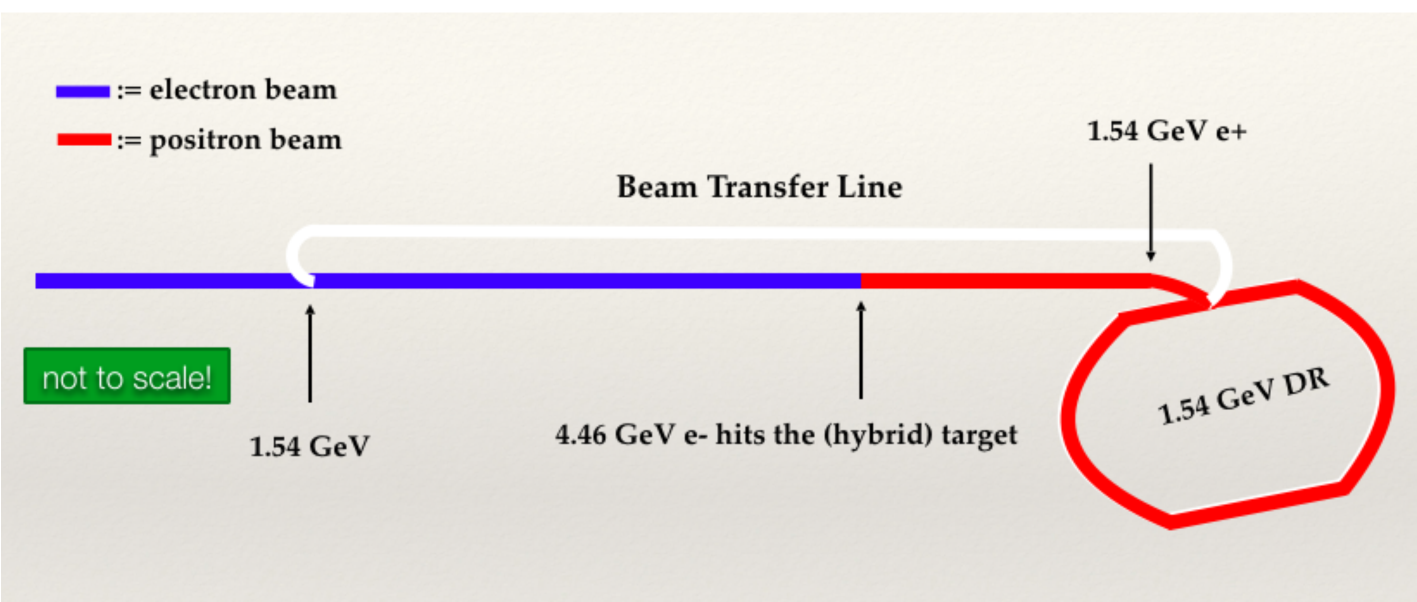
FCC-ee Injector Complex





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

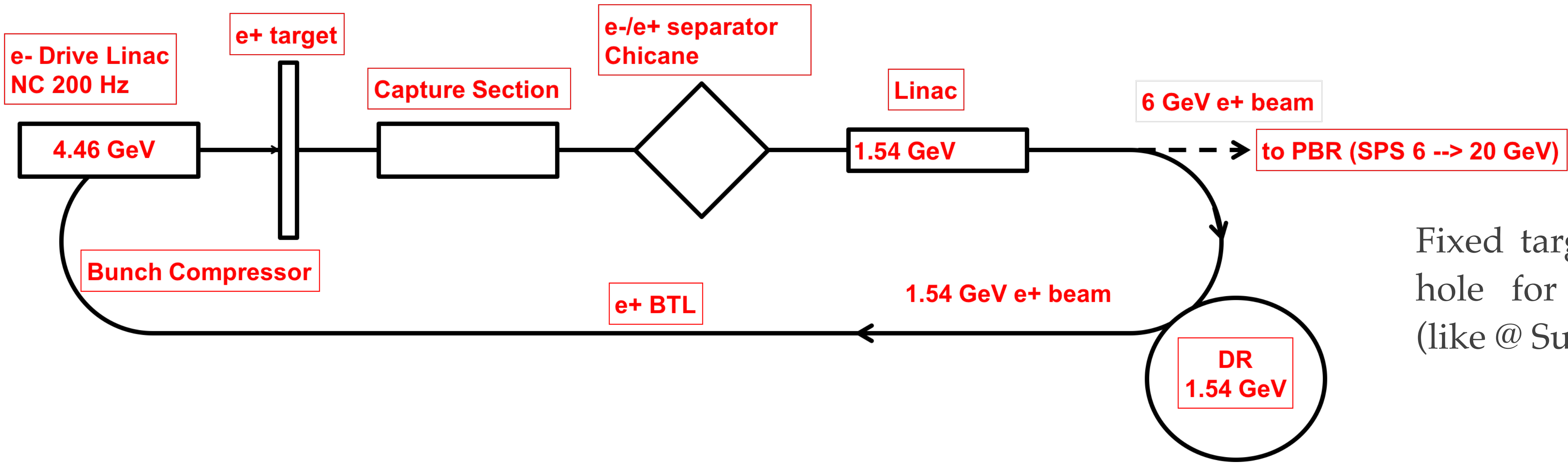
Injection to main Booster @ **20 GeV** and interleaved filling of e+/e- (**<20 min for full filling**) and continuous top-up

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

M. Benedikt

FCC-ee Positron Injector options

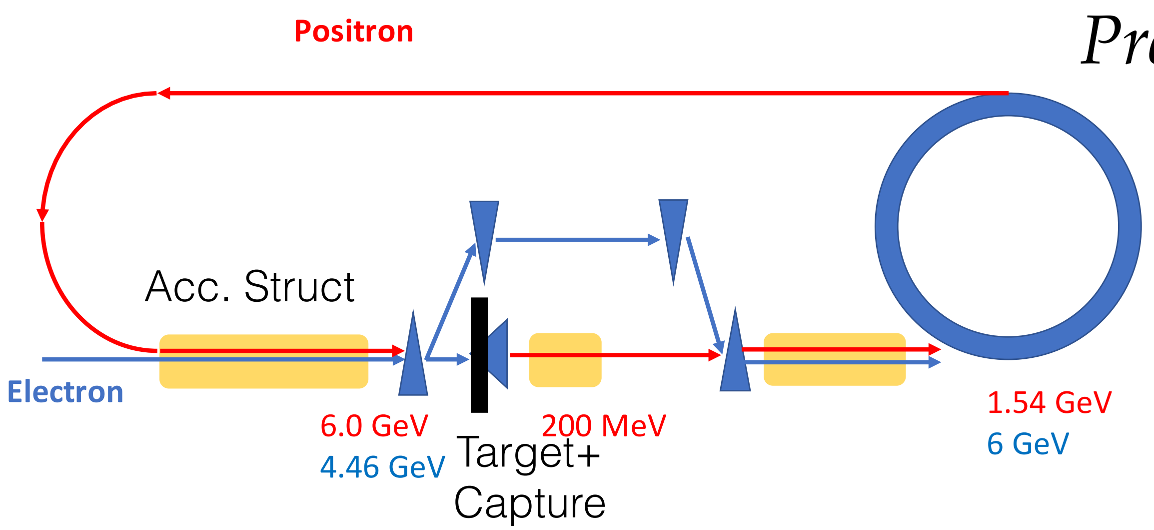
Current scheme

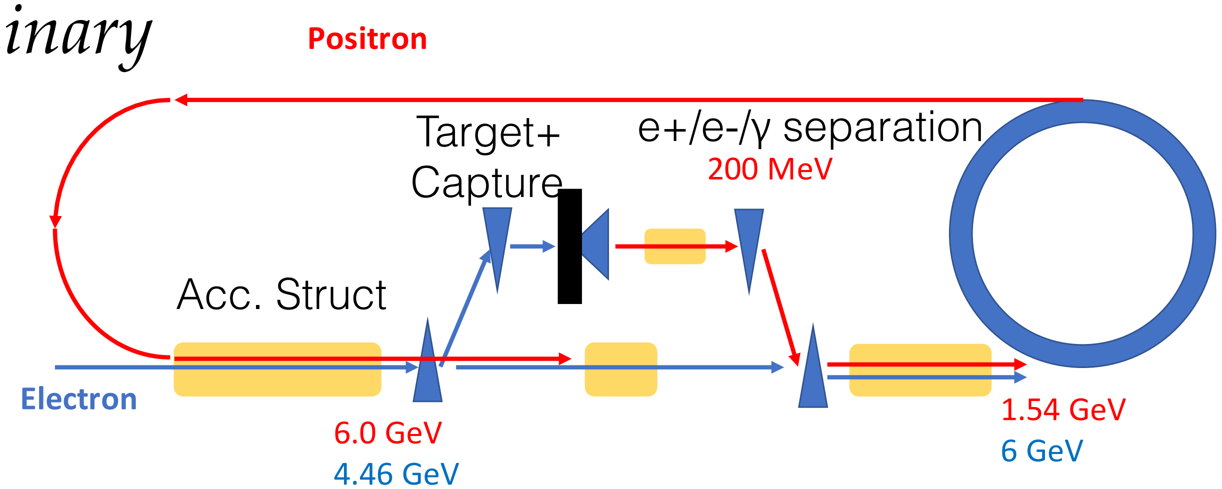


Fixed target-converter has a hole for e- beam passage (like @ SuperKEKB)

Schemes with the bypass under consideration

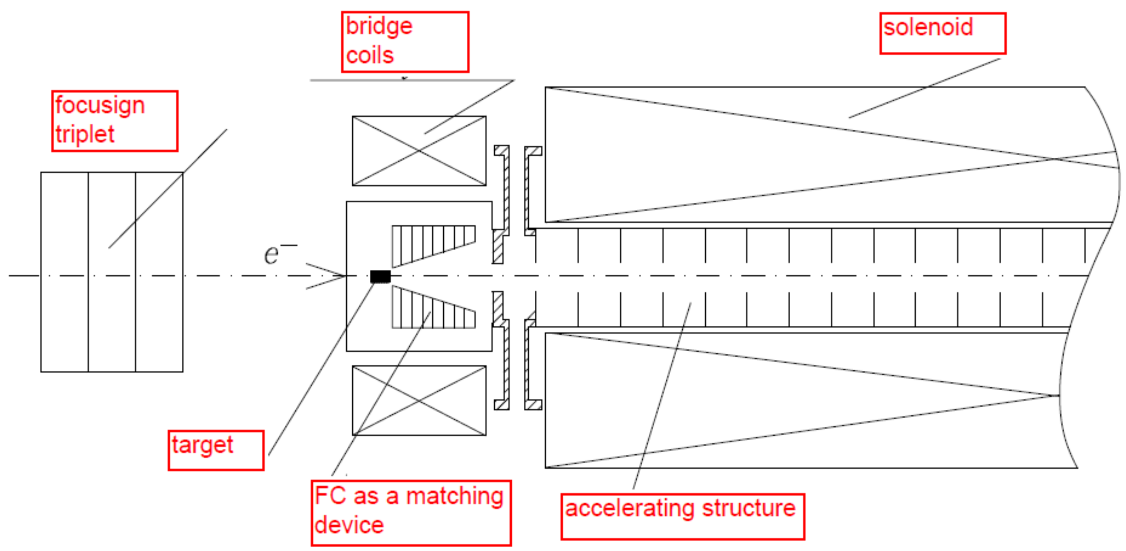
Preliminary



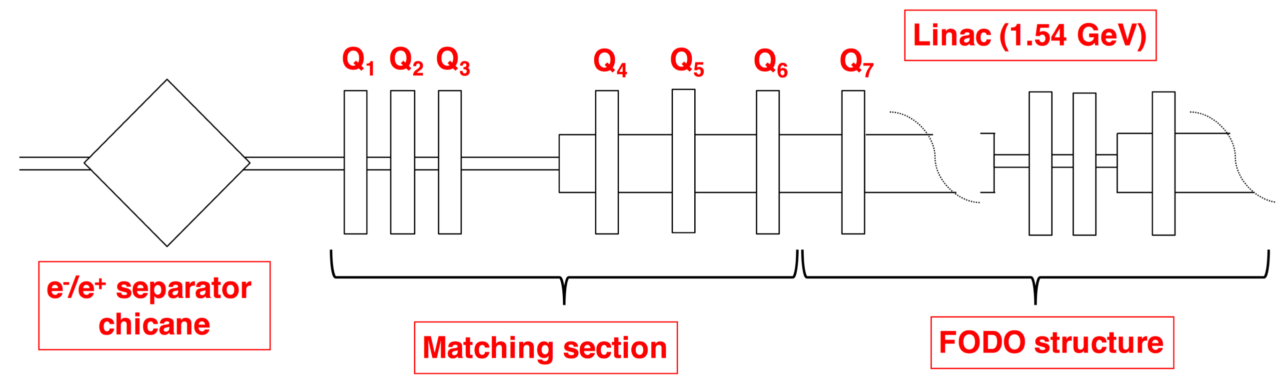


Beam parameters

e+ production and capture section



e+ acceleration up to 1.54 GeV



<u>Primary e- beam</u>

4.46 GeV

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

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

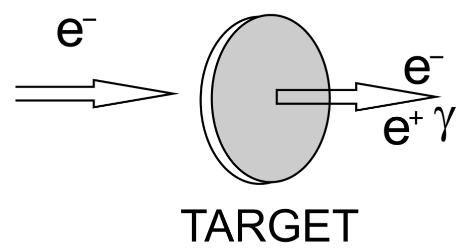
2 bunches/pulse spaced by ~60 ns

The complete filling for Z running (most demanding) => requires a linac bunch intensity of 2.1×10^{10} particles for both species

Requirement @ DR:
2.1×10^{10} e+/bunch (4.3 nC)
~0.5 e+/e- without safety factor

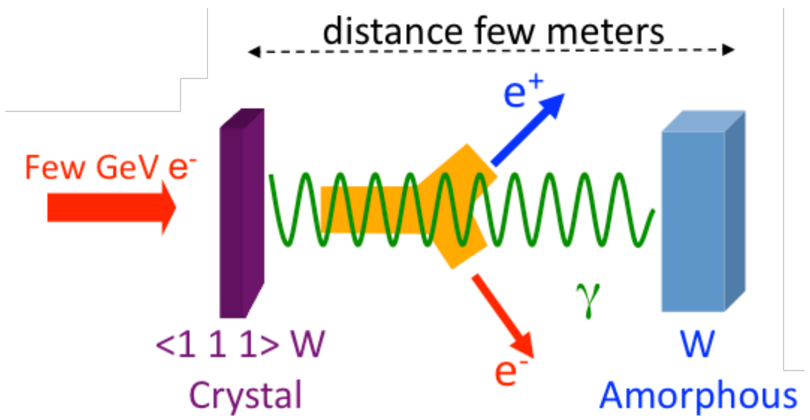
A safety factor of at least 2 should be considered

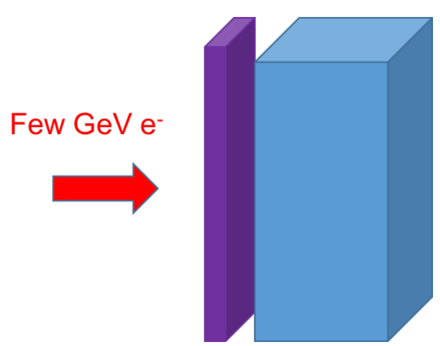
Two schemes of e+ production



1) <u>Conventional positron target:</u> bremsstrahlung and pair conversion

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





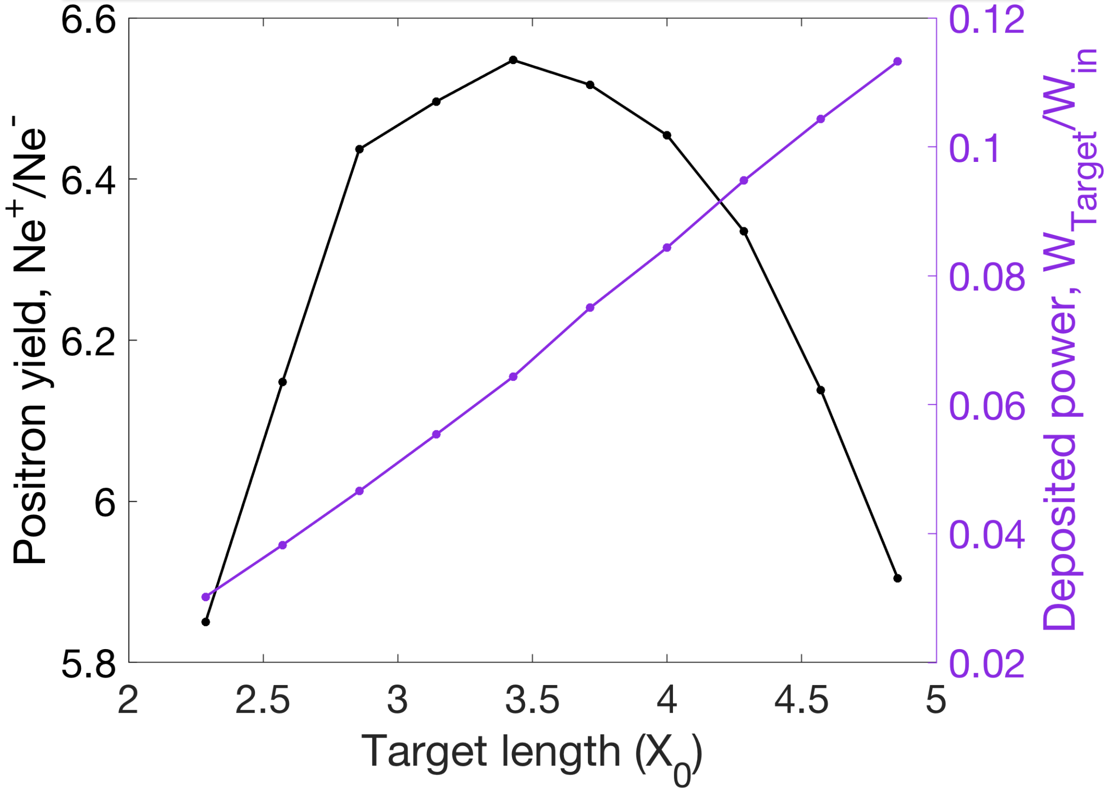
2) <u>Hybrid positron target:</u> Two-stage process to generate positron beam. Channeling (crystal target) and pair conversion (amorphous target)

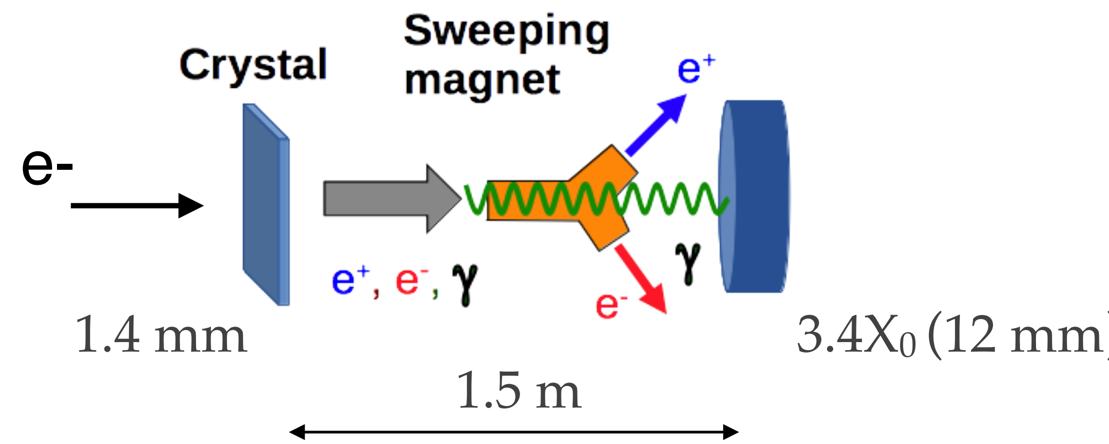
- Use the intense radiation emitted by high energy (some GeV) electrons channeled along a crystal axis => *channeling radiation*.
- <u>Hybrid scheme:</u> charged particles are swept off after the crystal target => the deposited power and PEDD (Peak Energy Deposition Density) are strongly reduced.
- <u>Hybrid scheme 2</u>: 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).

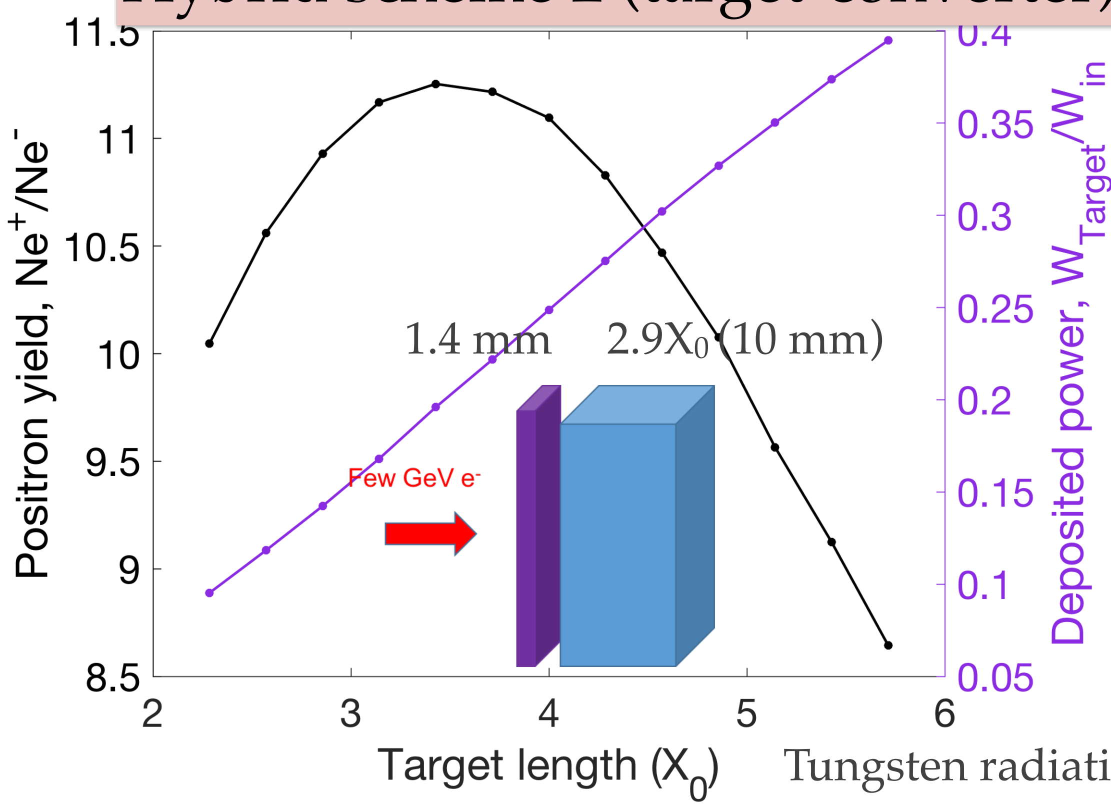
Production Target

Hybrid scheme (target-converter)

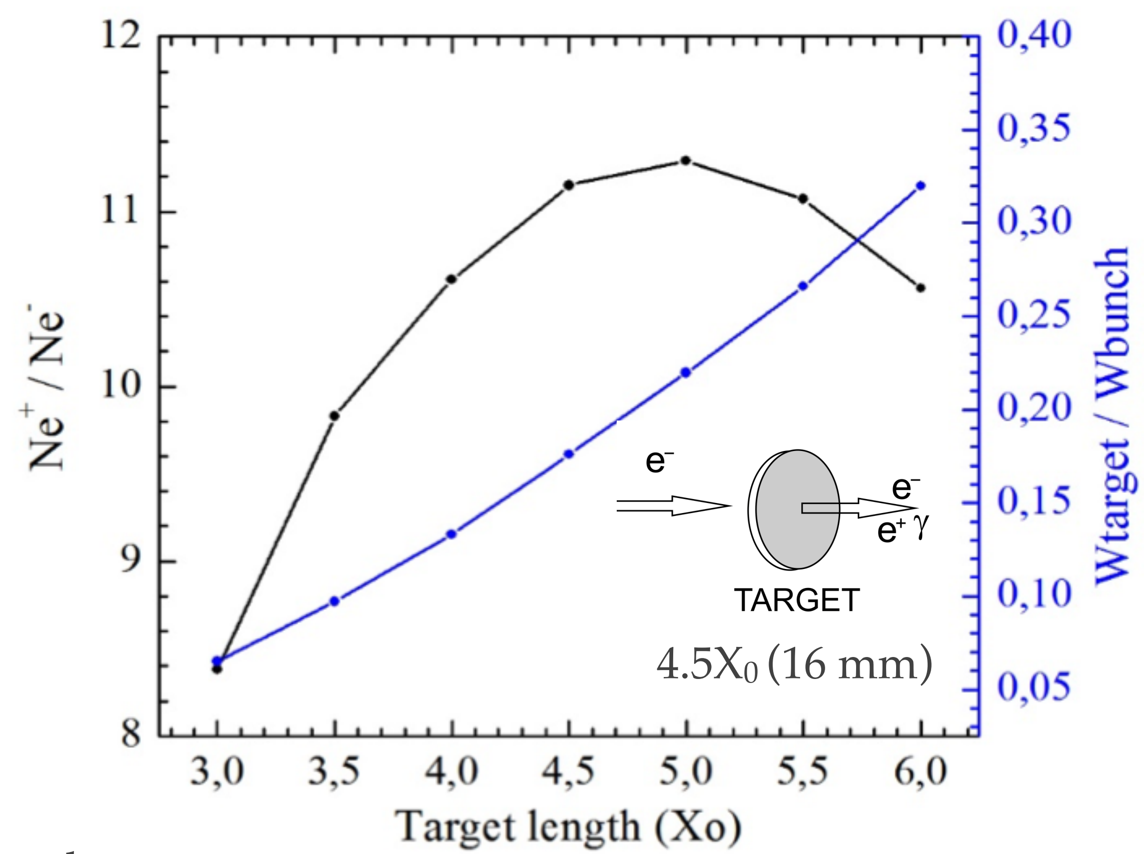




Hybrid scheme 2 (target-converter)



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	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*

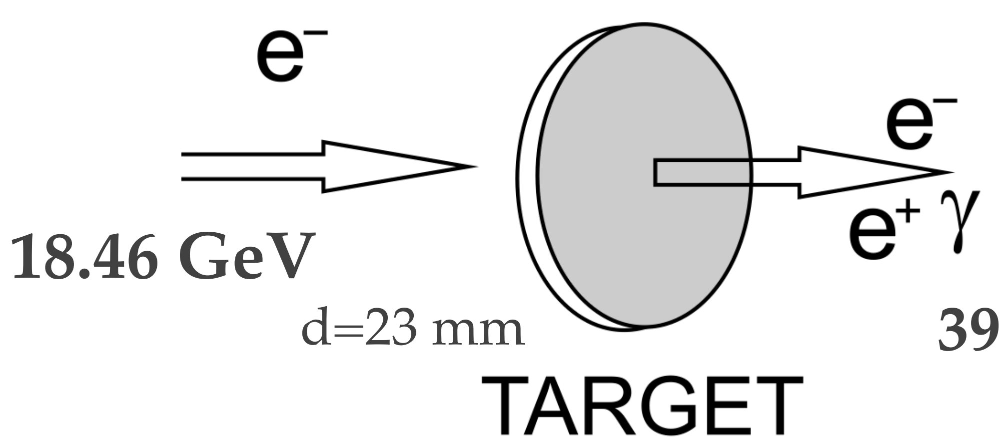
- PEDD (Peak Energy Deposition Density, [GeV/cm^3/e$^-$] or [J/g]) ~ beam and target parameters (beam energy, spot size and target thickness) => thermo-mechanical stresses.
- According to SLC experience, $W_{74}Re_{26}$ material has a PEDD limit of **35 J/g** (safe value to avoid target failure).

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)

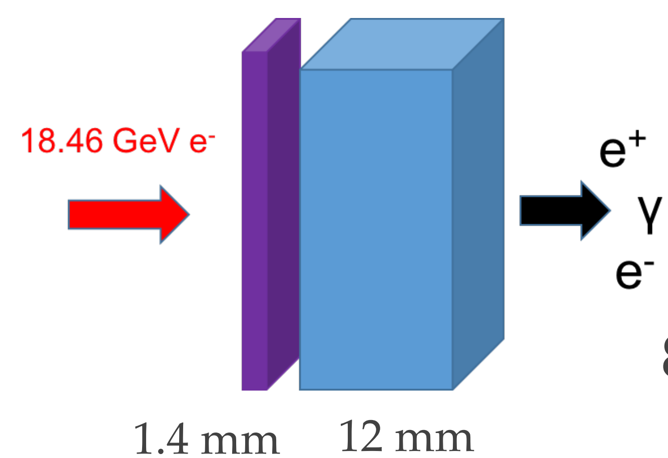
Conventional scheme



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

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)

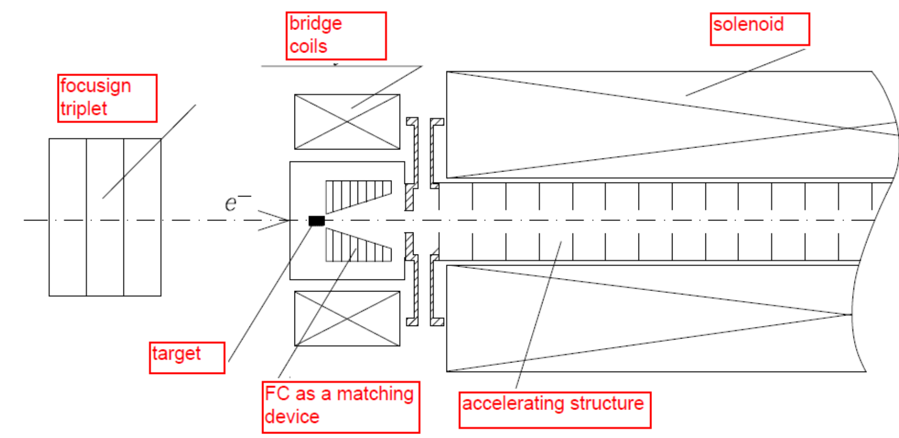
☞ The full optimization of the production should be performed including the deposited power in the target, PEDD and the captured positron yield.

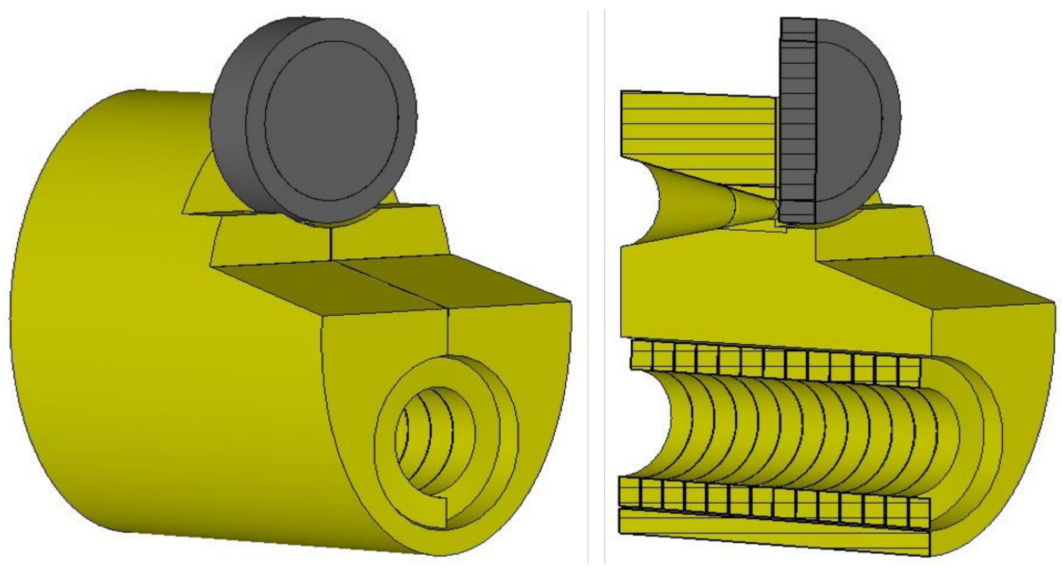
Capture and Primary Acceleration

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

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

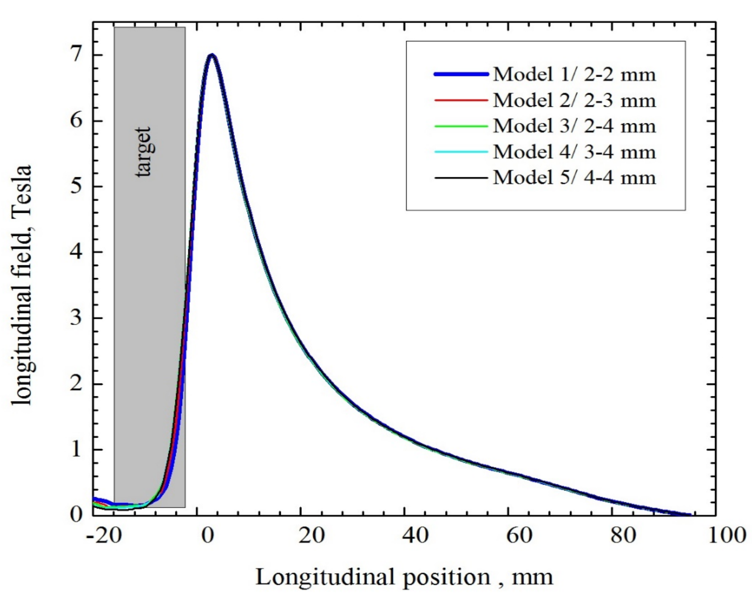
Matching the e+ beam (with very large transverse divergence) to the acceptance of the pre-injector linac.

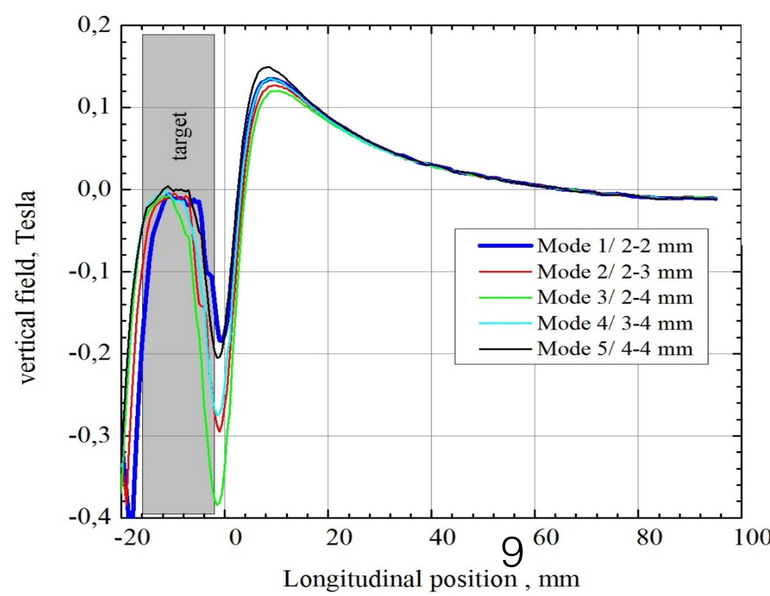




Parameter [unit]	Value
Target diameter [mm]	90
Target thickness [mm]	15.8
Gap between target and FC [mm]	2
Grooving gap between target side face and FC body [mm]	2
Elliptical cylinder size [mm]	120×180
Total length [mm]	140
Conical part length [mm]	70
Min cone diameter [mm]	8
Maximm cone diameter [mm]	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.

<u>Peak of the magnetic field is at 5 mm from the target.</u>

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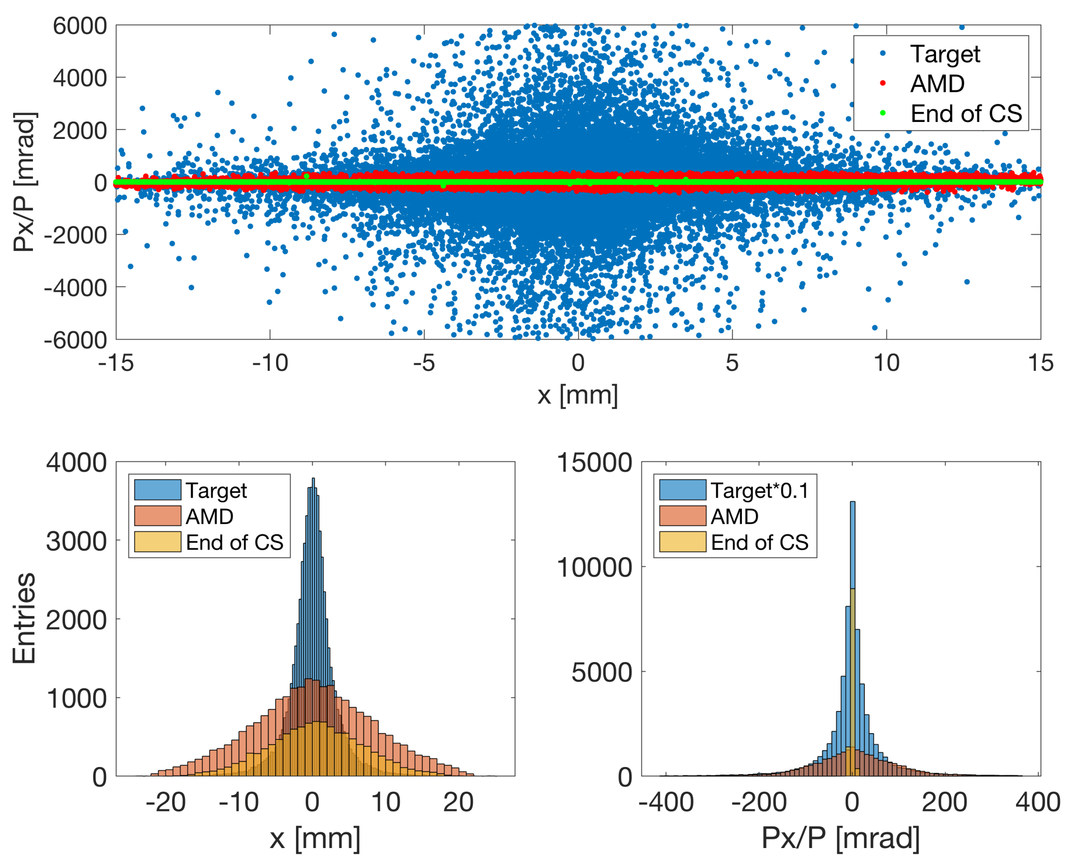
Capture and Primary Acceleration

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)

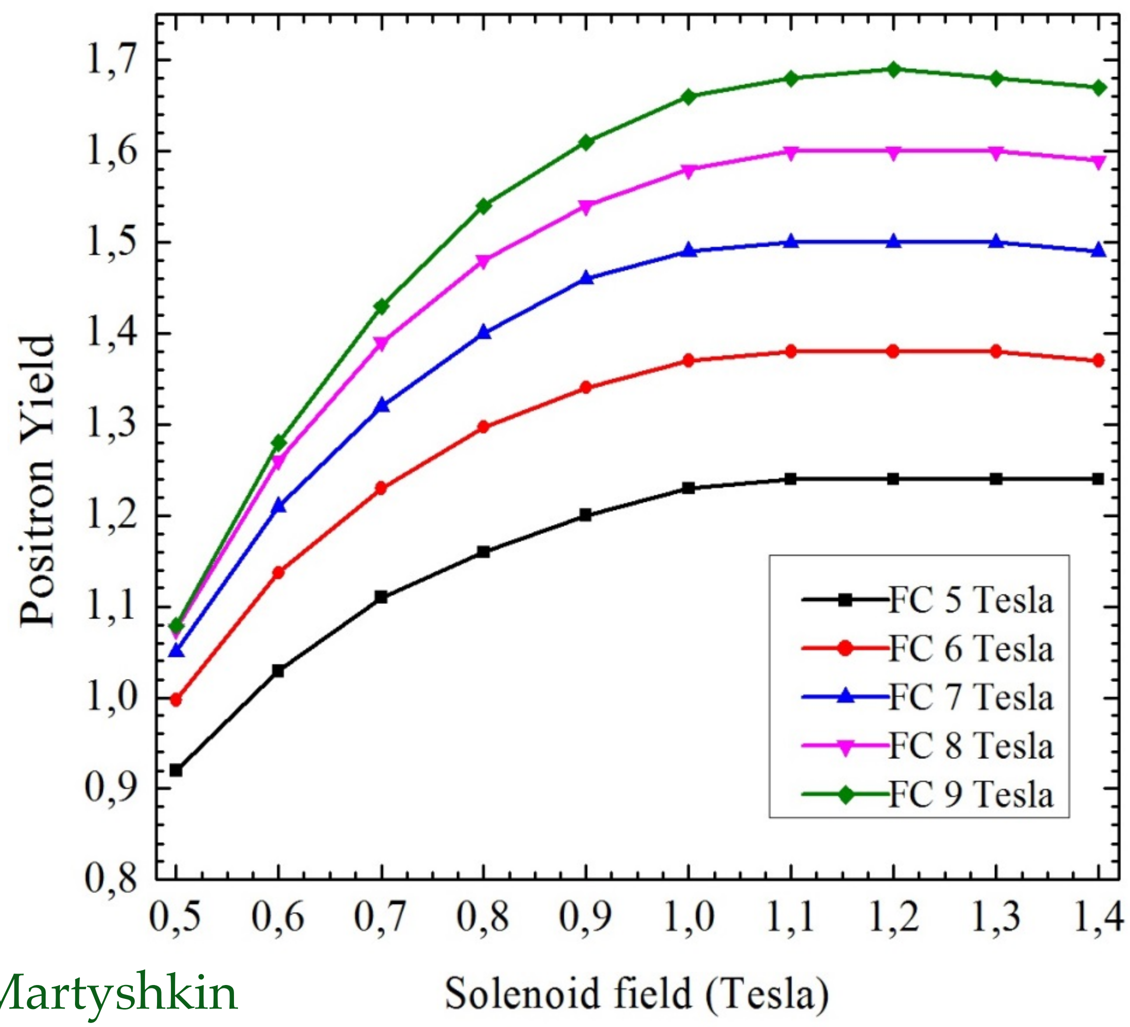


Beam Parameter	Conventional	Hybrid	Hybrid 2
B_{max} = 5 T, B_{DC} = 0.5 T			
Mean Energy	190 MeV	197 MeV	235 MeV
Total yield	XX N_{e+}/N_{e-}	0.9 N_{e+}/N_{e-}	1.7 N_{e+}/N_{e-}
Accepted yield	1.1 N_{e+}/N_{e-}	0.7 N_{e+}/N_{e-}	~1.4 N_{e+}/N_{e-}
Emittance hor./vert.	17 μm (1σ)	14 μm (2σ)	10 μm (3σ)
B_{max} = 7 T, B_{DC} = 0.7 T			
Mean Energy	190 MeV	198 MeV	226 MeV
Total yield	XX N_{e+}/N_{e-}	1.1 N_{e+}/N_{e-}	2.6 N_{e+}/N_{e-}
Accepted yield	1.3 N_{e+}/N_{e-}	~0.9 N_{e+}/N_{e-}	~2 N_{e+}/N_{e-}
Emittance hor./vert.	21μm (1σ)	16 μm (2σ)	11 μm (3σ)

Assuming [optimization x transport until 1.54 GeV x DR injection efficiency] ~ 0.7 - 0.8 => e+ yield Ne+/Ne- ≳ 0.5 but the realistic simulations are needed + safety factor.

Choice of the FC peak and DC solenoid field

- **Accepted positron yield** as a function of the DC solenoid field for different values of the FC peak magnetic field
- Conventional scheme with realistic FC model.



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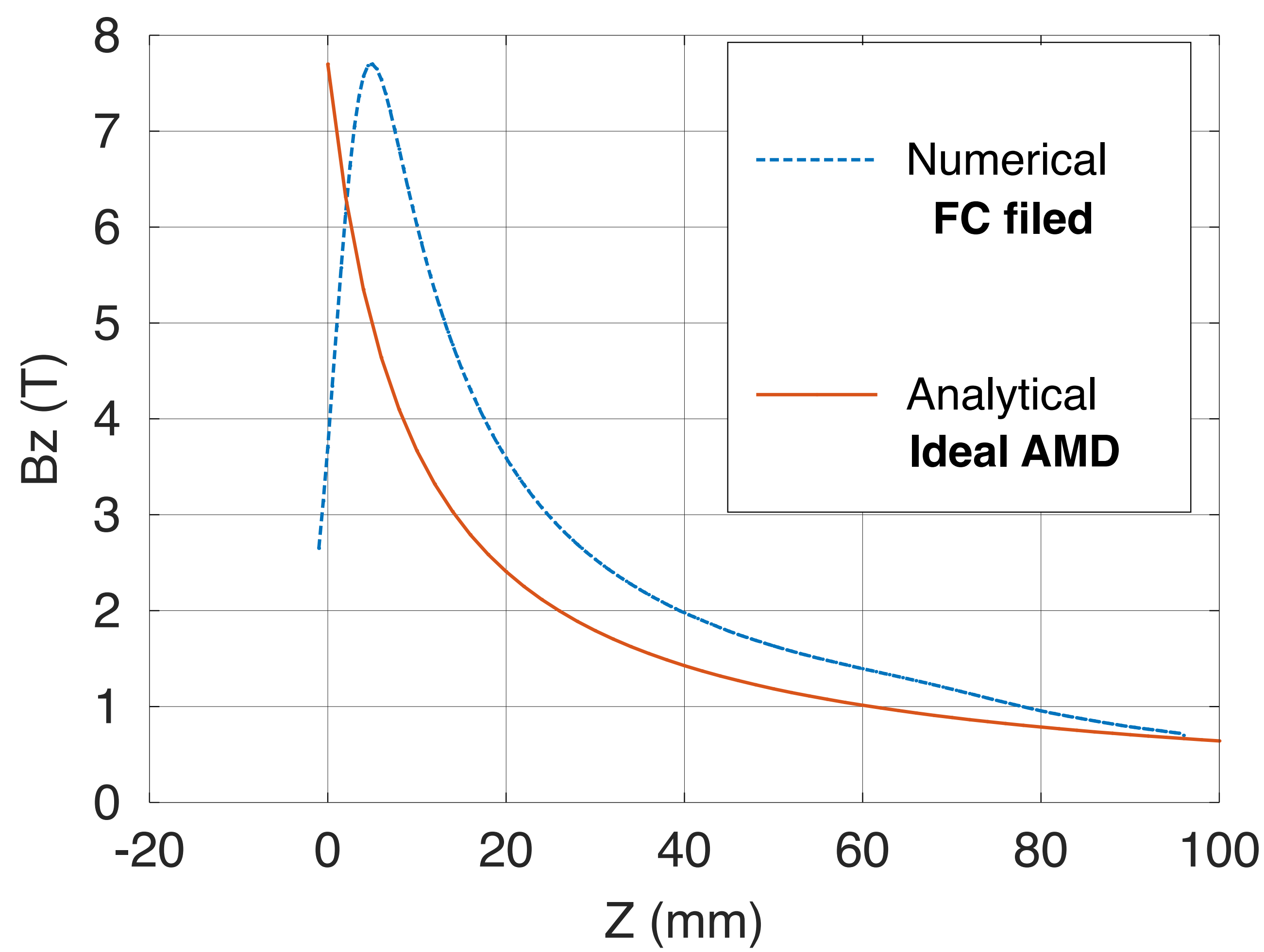
B_{DC} up to 0.7 - 0.8 T and FC B_{max} ~ 7-8 T

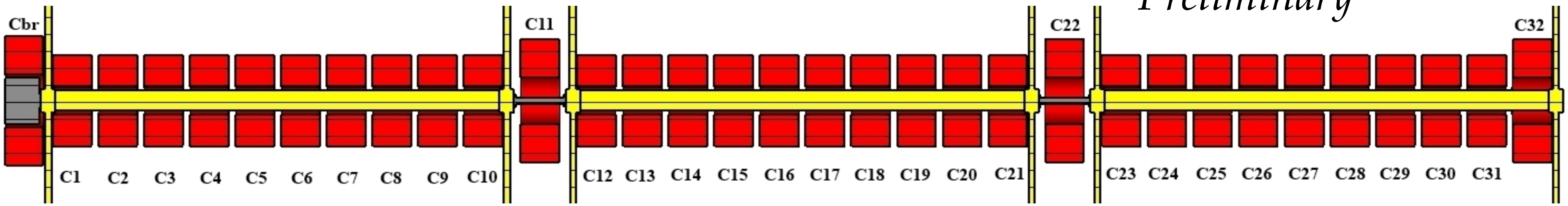
$B_{TARGET} = 3$ T

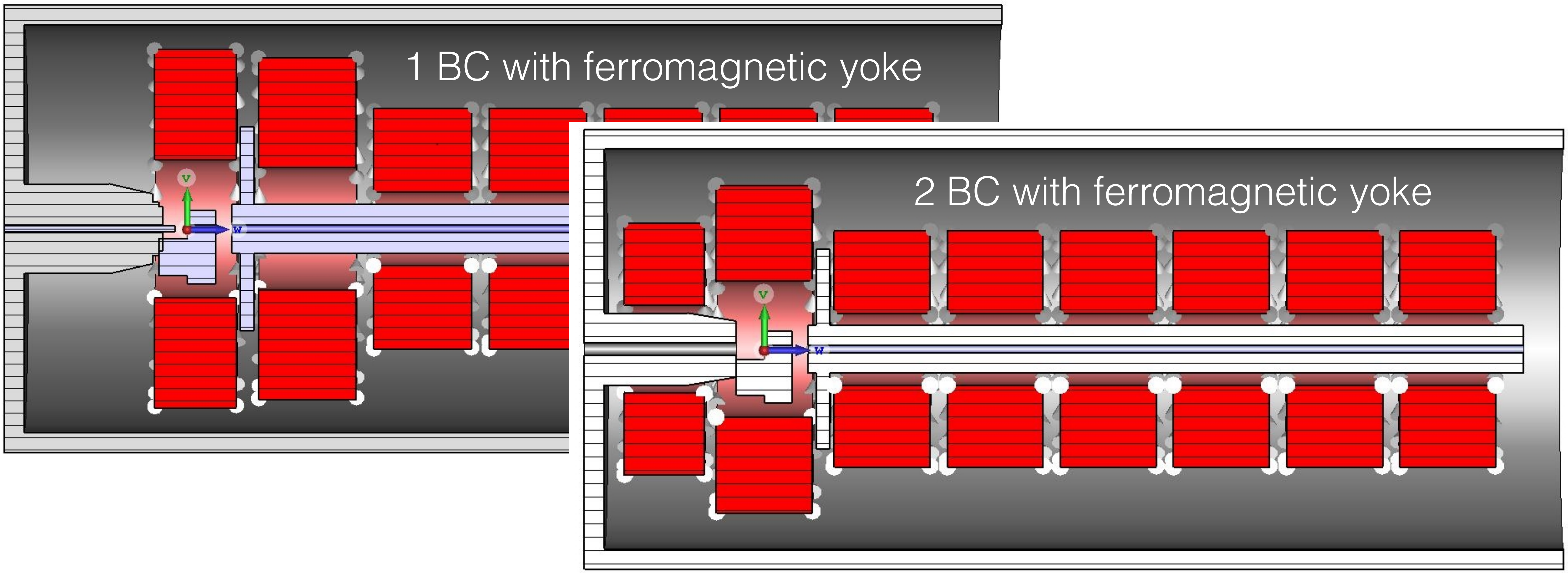


Peak of the magnetic field is at 5 mm from the target => 40 % drop in capture efficiency

Positron capture section design

Preliminary





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).

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SC solenoid as the AMD

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

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*

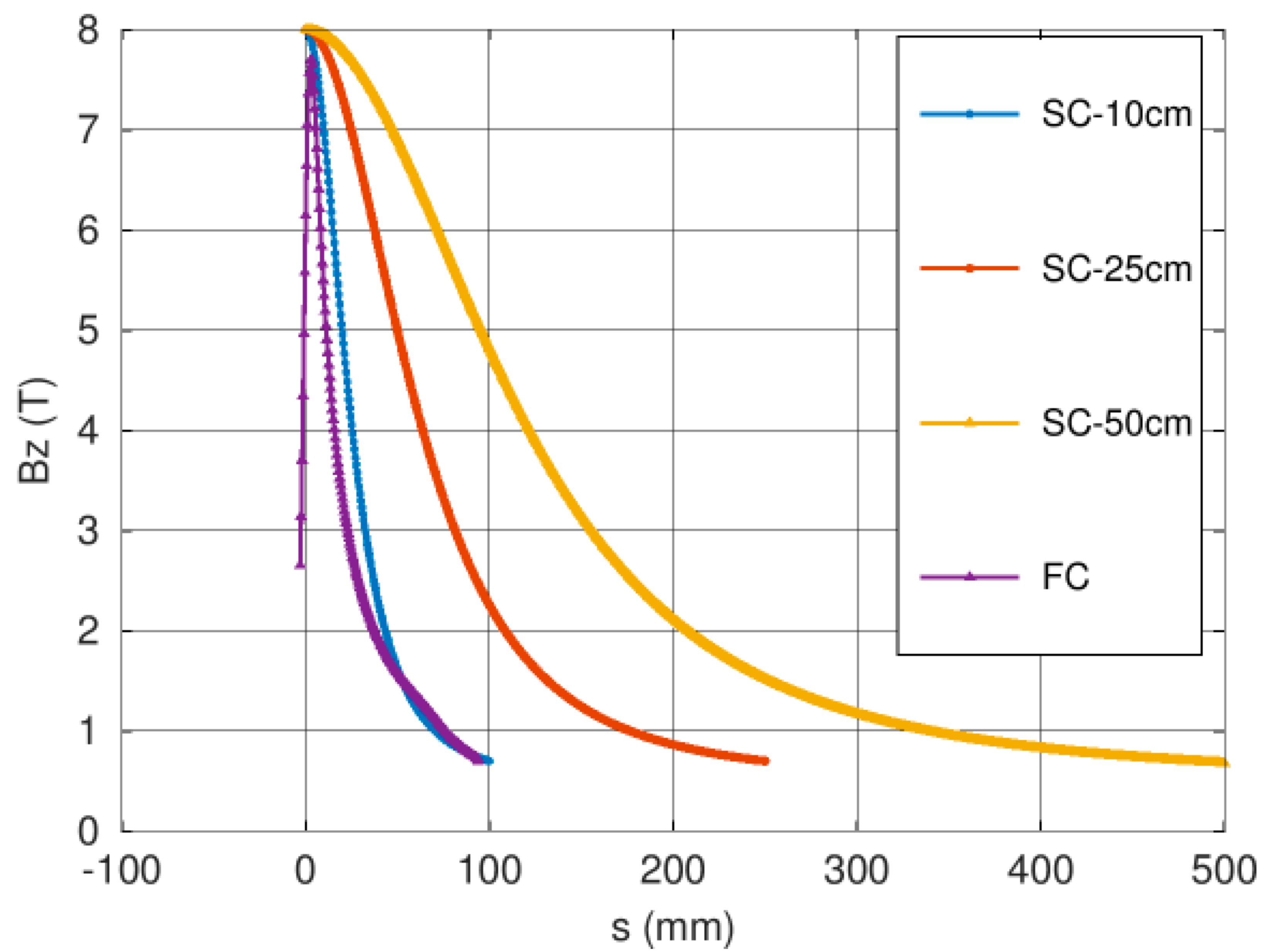
SC solenoid
B(z)=Bw+(Bt-Bw)*Rs^3/(Rs^2+z^2)^1.5

- The AMD length is different
- DC solenoid after AMD

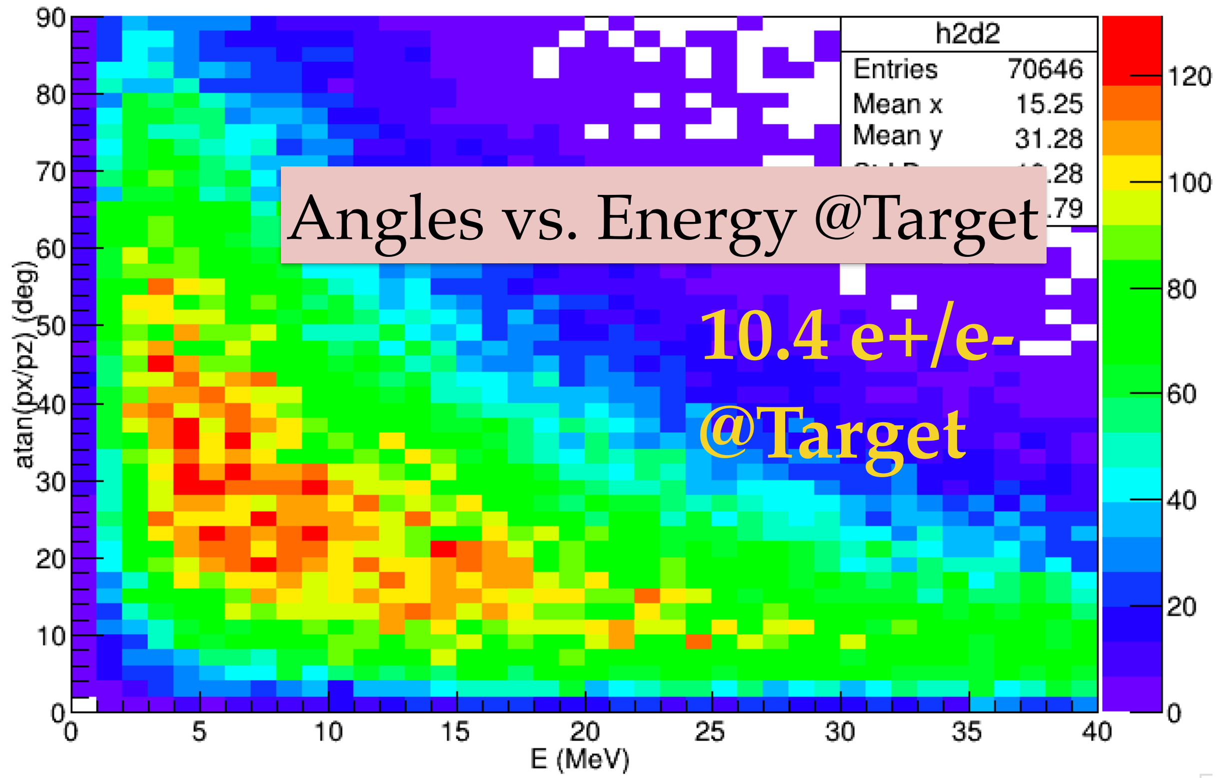
Bt=8 Tesla
Bw=0.7 Tesla

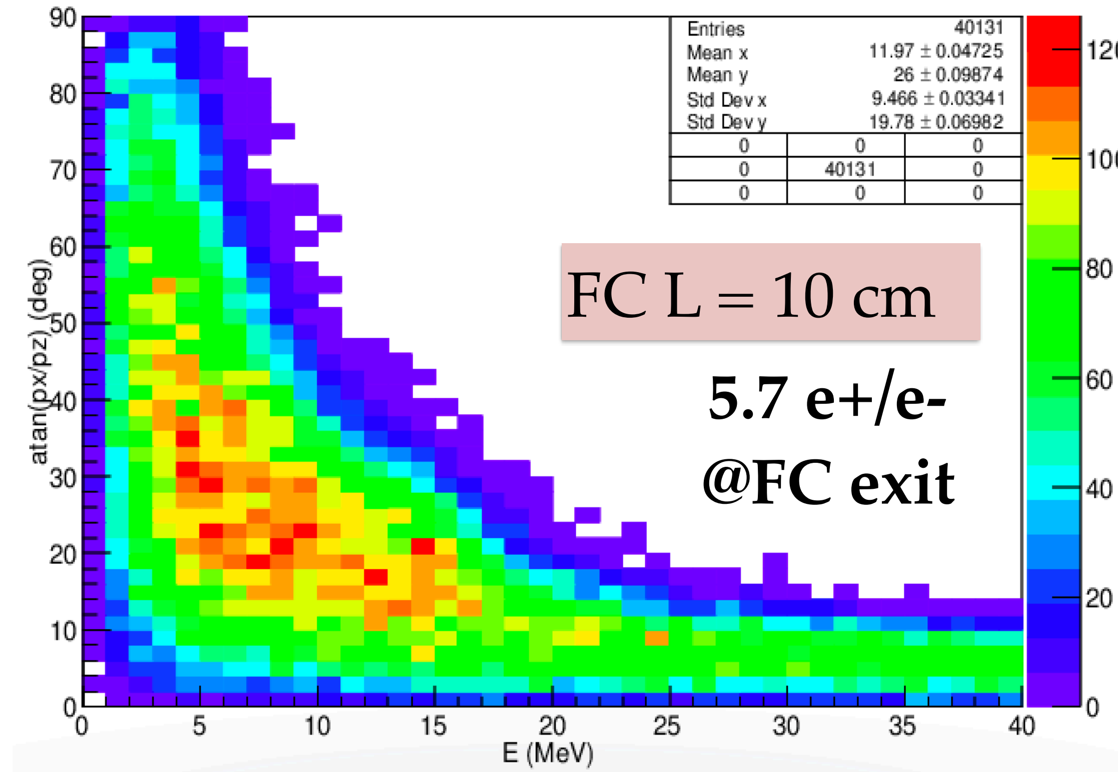
Rs=0.15 m => L=50 cm
Rs=0.08 m => L=25 cm
Rs=0.03 m => L=10 cm

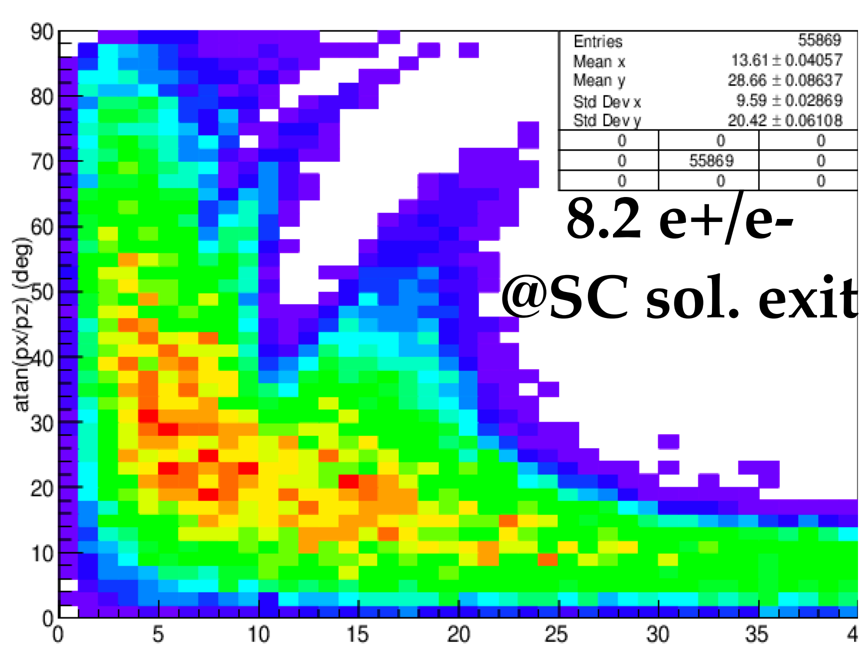
Flux Concentrator
FC => L = 10cm



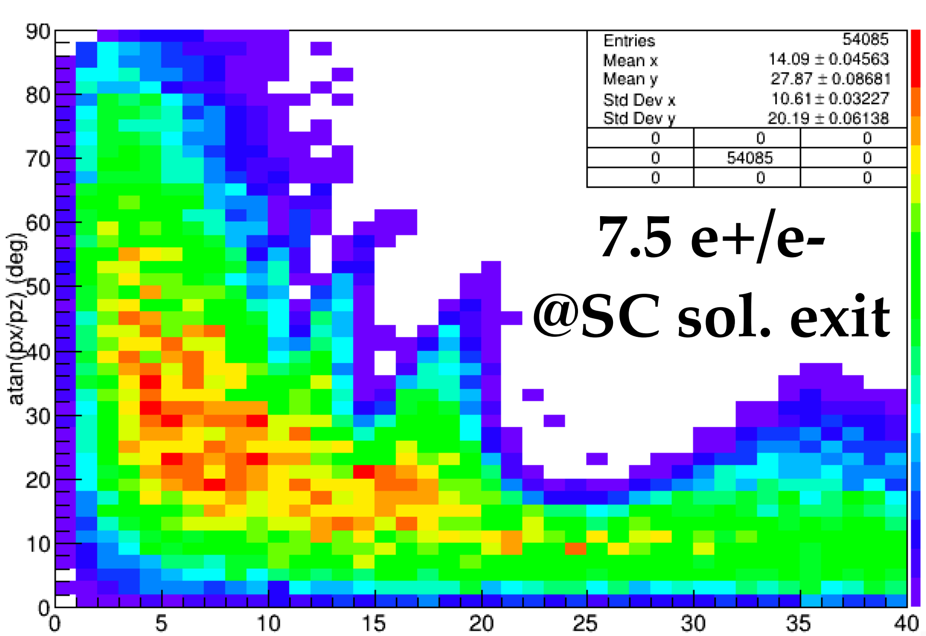
Positron capture @Target/AMD



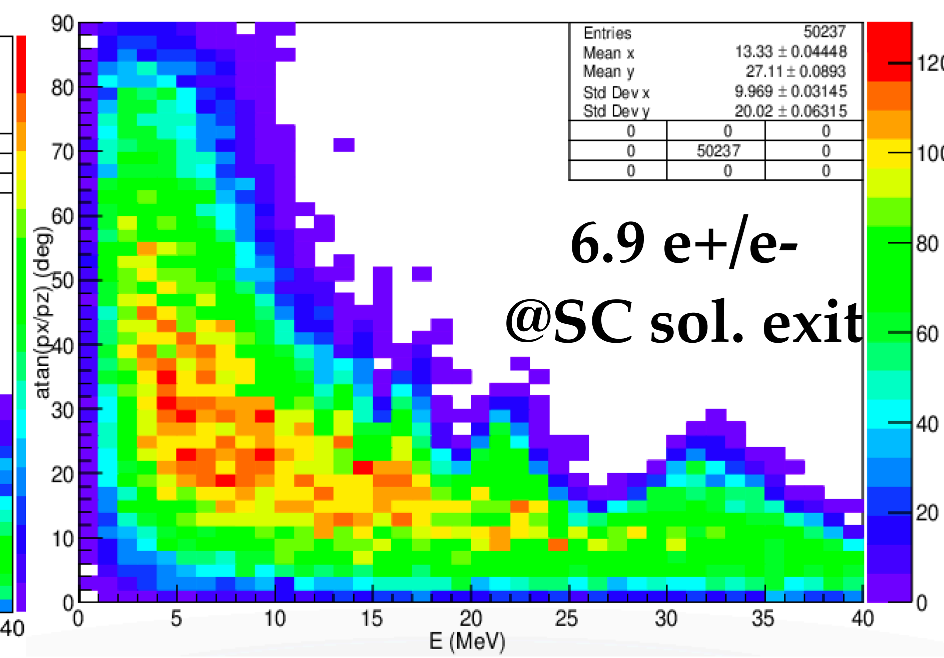




SC solenoid L = 10 cm



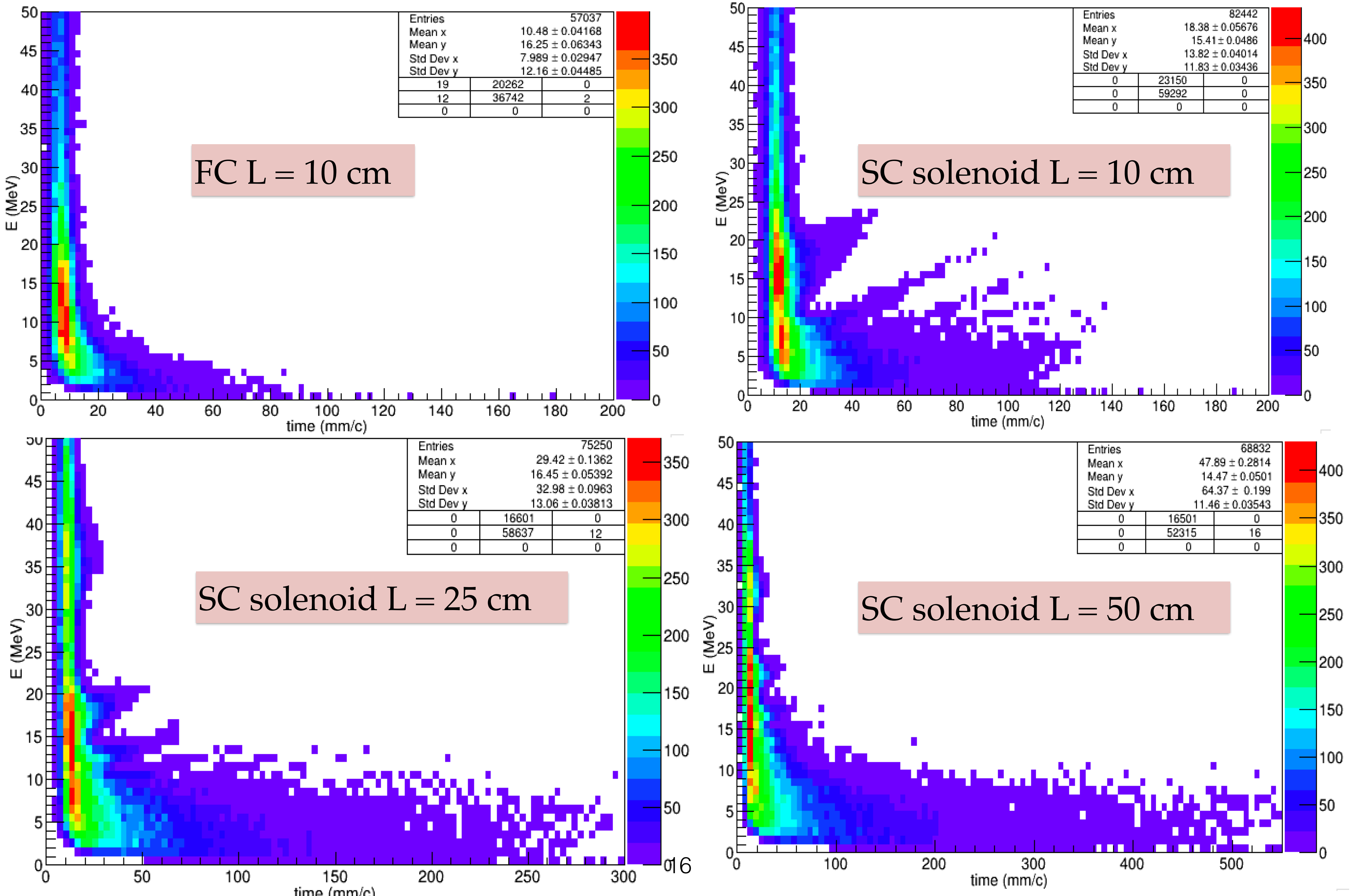
SC solenoid L = 25 cm



SC solenoid L = 50 cm

Positron capture @AMD

Longitudinal phase space



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 degree 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	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. Optimization to be done for the Hybrid scheme 2 (e.g. with 2.2X_0 target thickness => ~10 e+/e-, 20 J/g and 1.1 kW and 2.3 N_{e+}/N_{e-} @200 MeV).
- Design studies of the BC + DC solenoid have been started.
- Evaluation of the thermal load in the target => target design and cooling system.
- Start-to-end simulations to the DR and full optimisation are underway => *design of the bypass line for e+ generation/capture*.
- SC solenoid as the AMD ?

Positron source performances

	SLC	LEP (LIL)	KEKB/SKEKB	FCC-ee*
Incident e- beam energy	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	
Deposited power	4.4 kW		/0.6 kW	
Capture system	AMD	$\lambda/4$ 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