FCC-ee Positron Source

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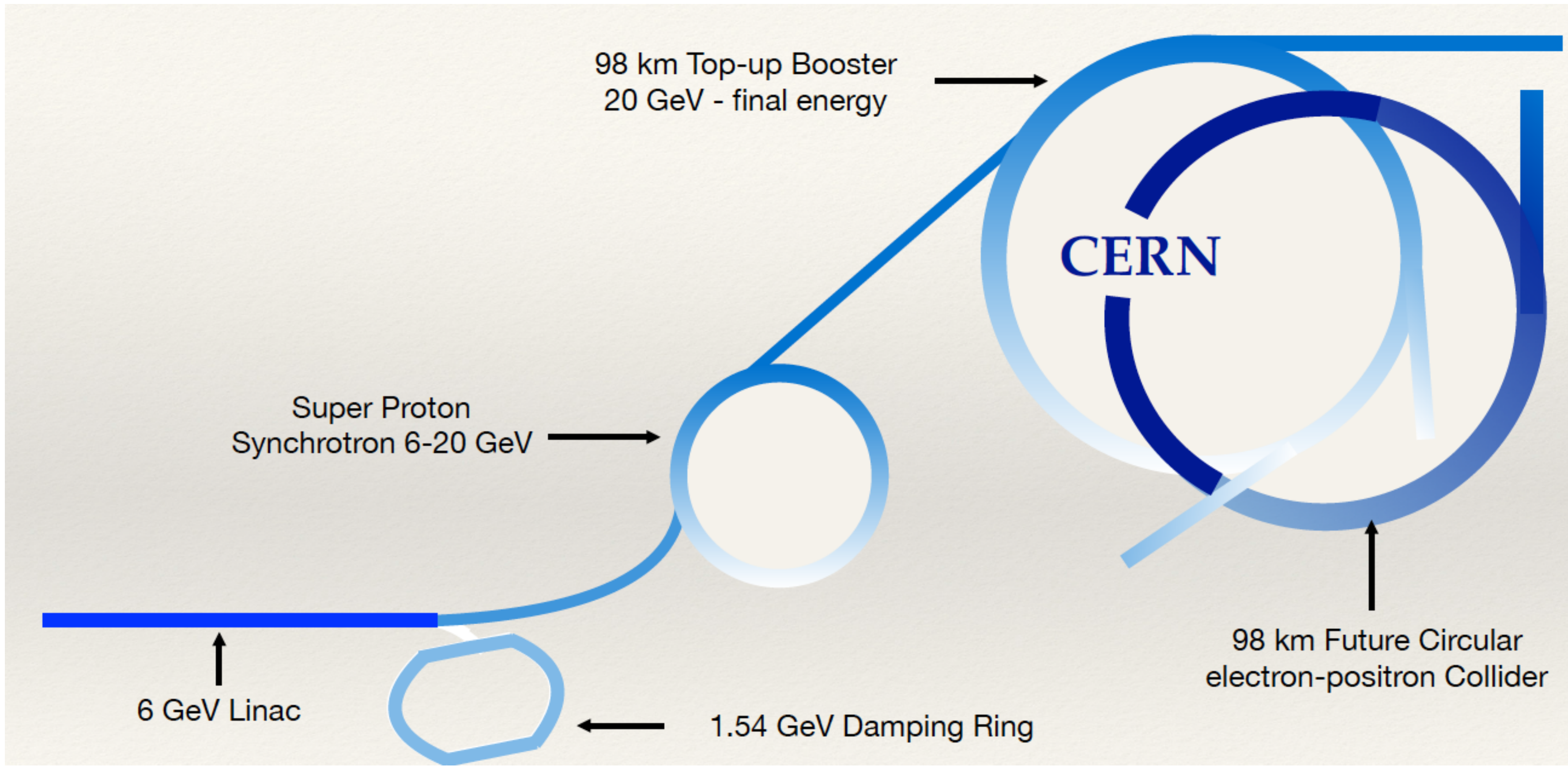
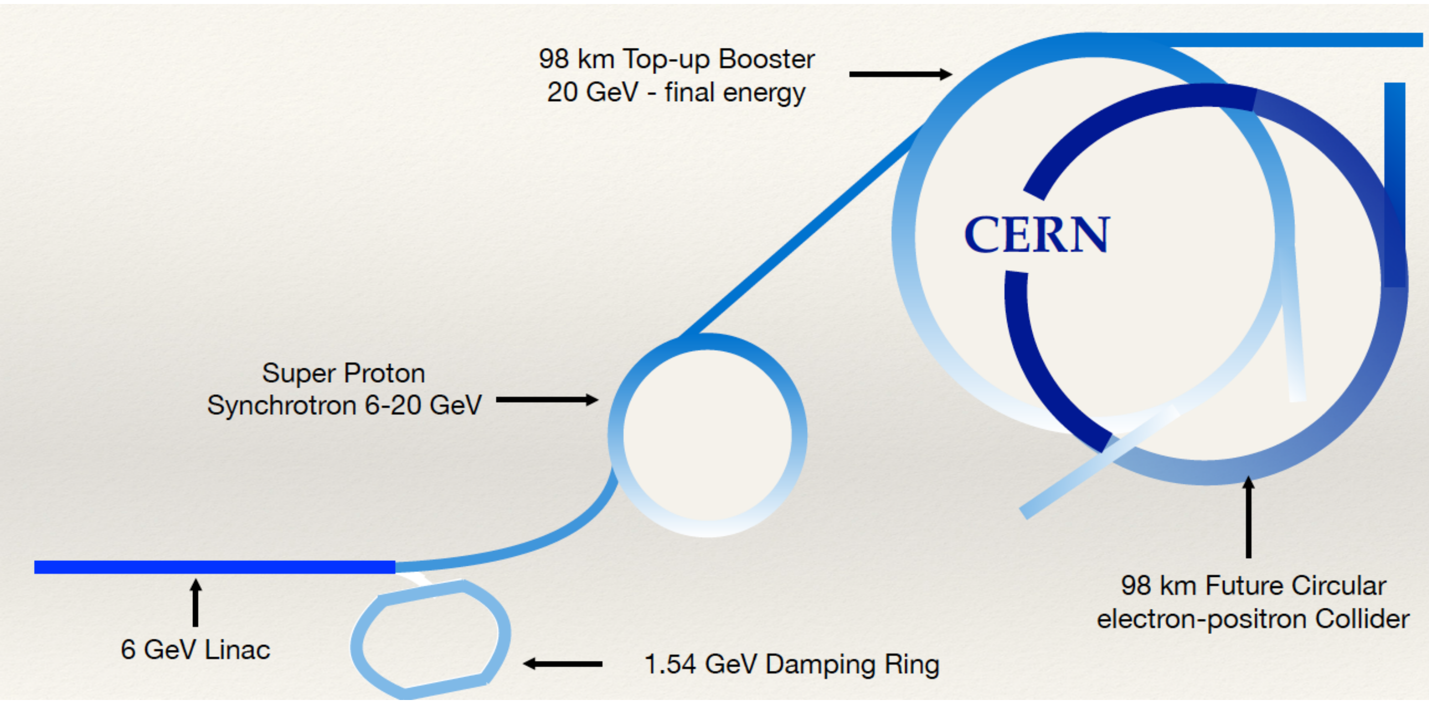
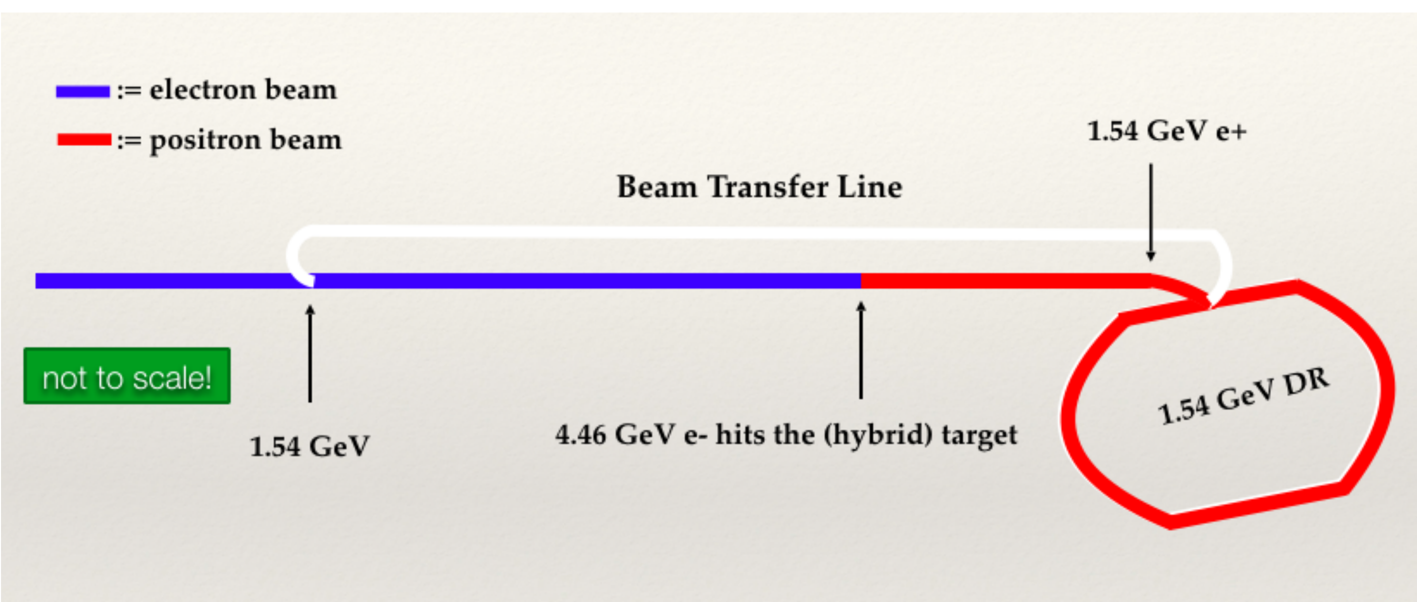
Future Circular Collider e^-e^+



- The FCC-ee is a high-luminosity, high-precision circular collider to be constructed in a new 100 km tunnel in the Geneva area. Double ring e+ e- collider ~100 km.
- It is part of the Future Circular Collider design study at CERN, and would be the first step towards the long-term goal of a 100 TeV proton-proton collider. Common footprint with FCC-hh, except around IPs.

FCC-ee Injector Complex





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

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

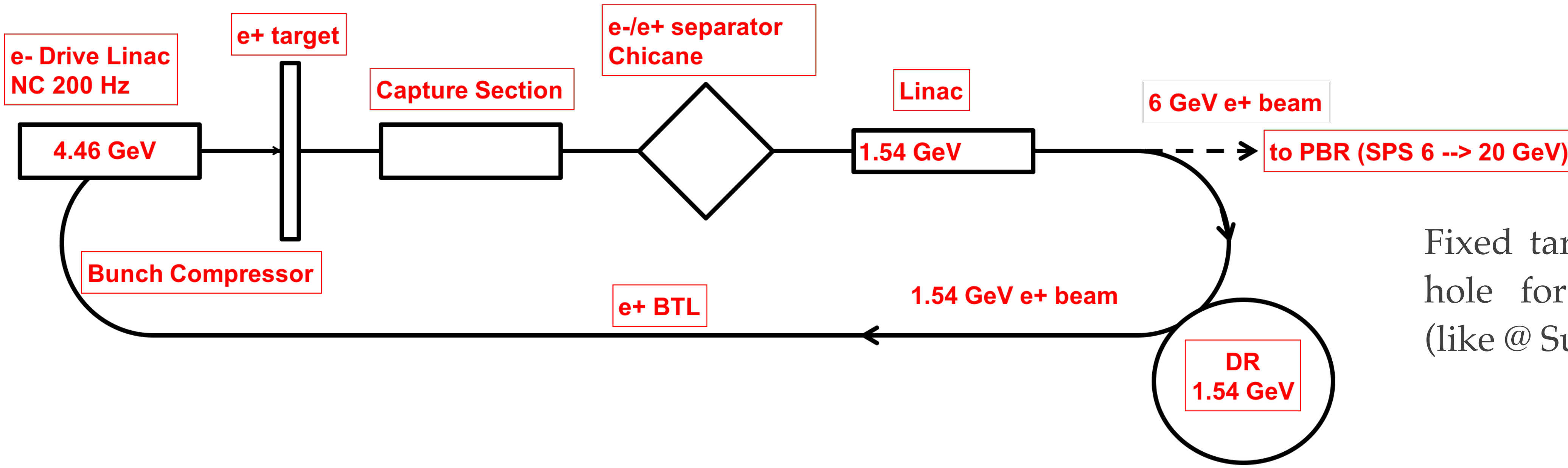
Injection @ **6 GeV** into pre-booster Ring (SPS or new ring) & accel. to 20 GeV, or 20 GeV linac

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.

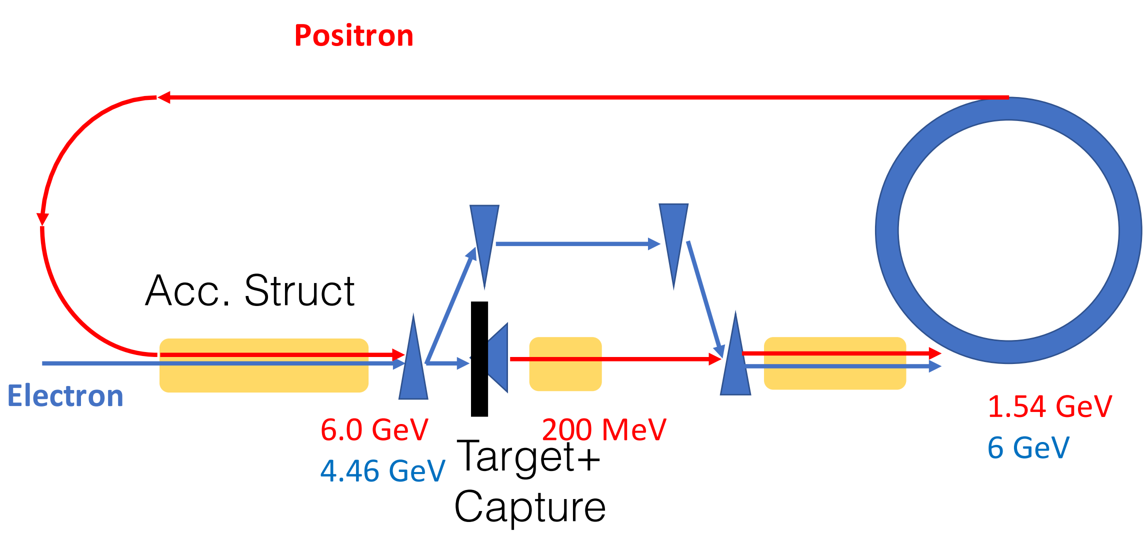
FCC-ee Positron Injector options

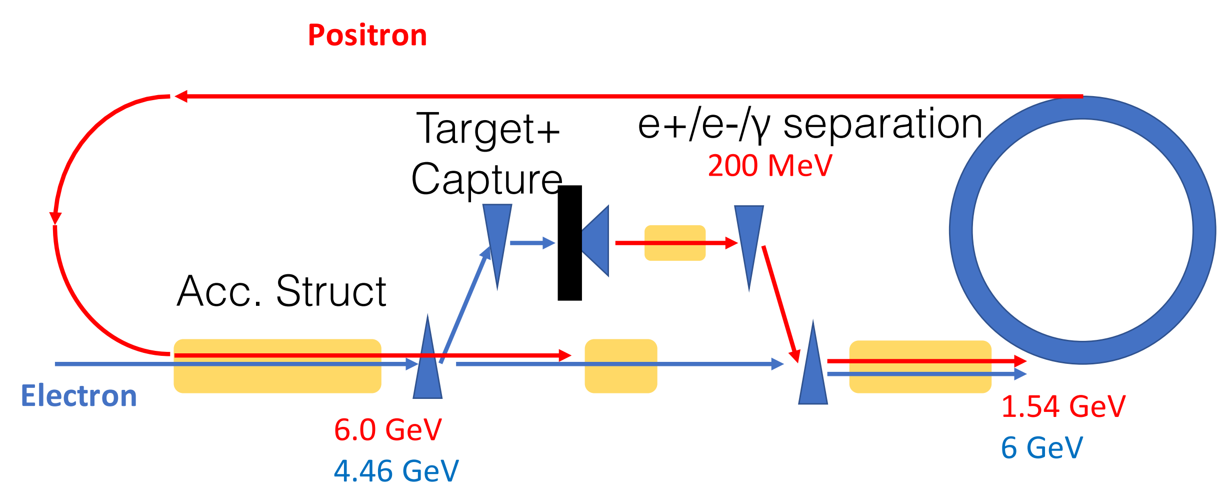
Current scheme



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

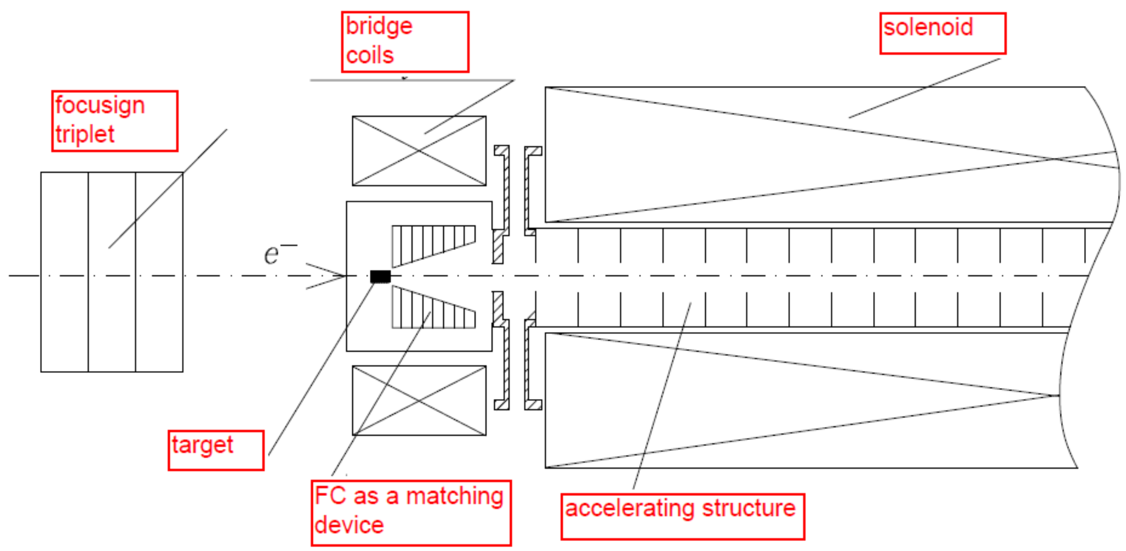
Schemes with the bypass under consideration (very preliminary)



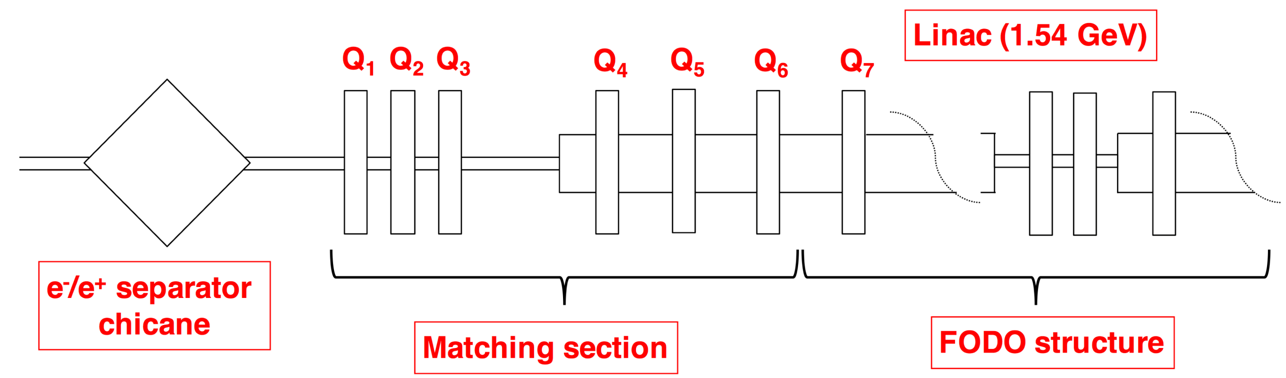


FCC-ee Positron Source and parameters

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)

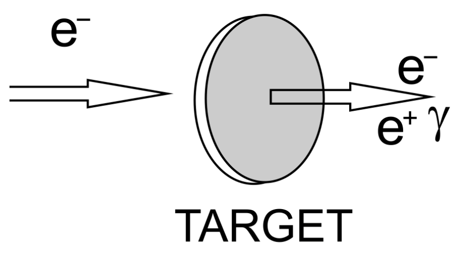
2 bunches/pulse spaced by ~60 ns

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

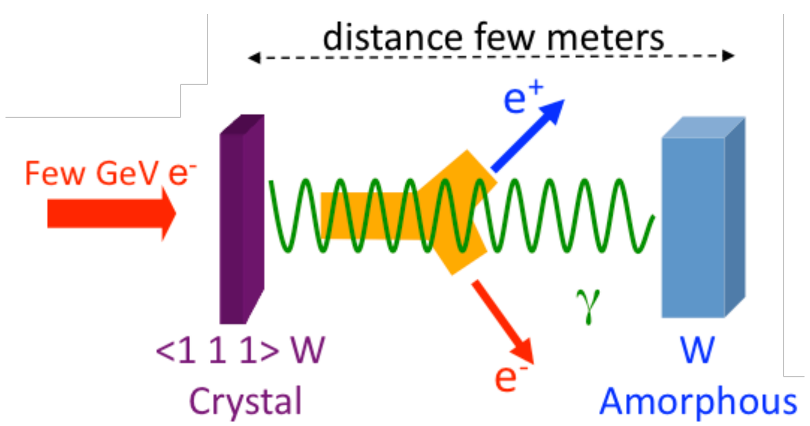
A safety factor of at least 2 should be considered

Two schemes of e+ production



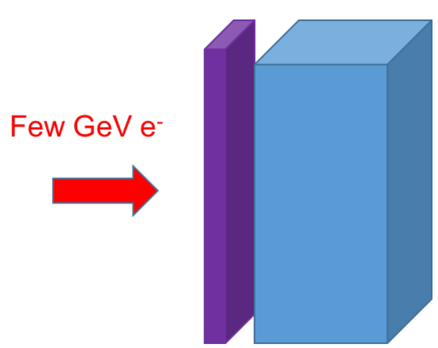
1) <u>Conventional positron target:</u> bremsstrahlung and pair conversion

- 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)

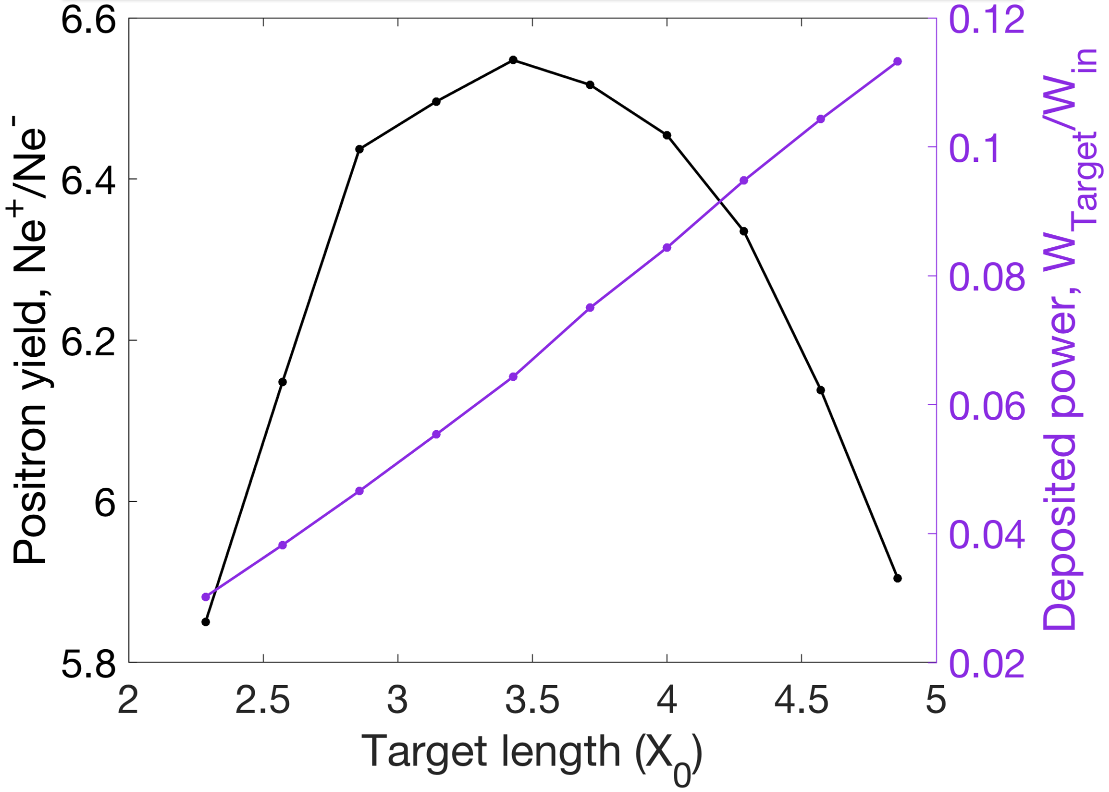
- Use the intense radiation emitted by high energy (some GeV) electrons channeled along a crystal axis => *channeling radiation*.
- <u>Hybrid scheme:</u> charged particles are swept off after the crystal target => the deposited power and PEDD (Peak Energy Deposition Density) are strongly reduced.
- 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

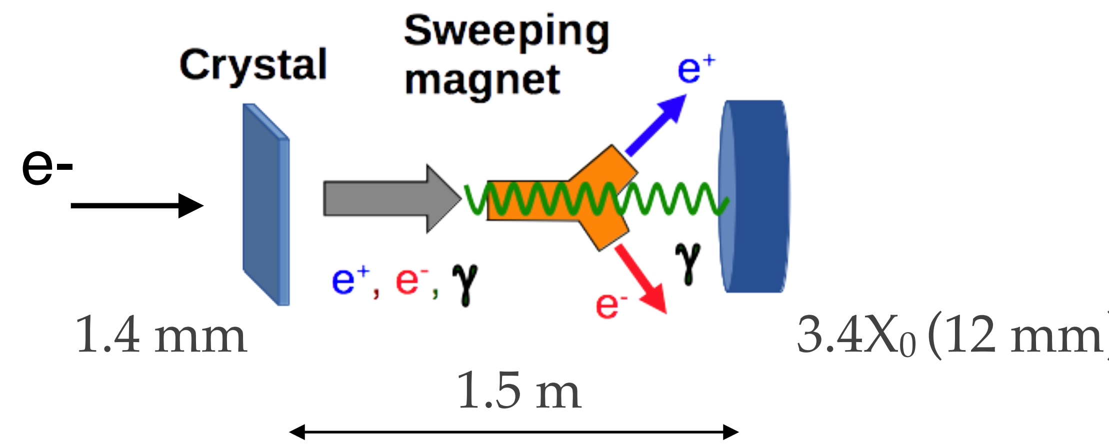


Several experiments had been conducted to study the hybrid e+ source (proof-of-principle experiment in Orsay, experiment @ SLAC, experiment WA 103 @ CERN and experiments @ KEK).

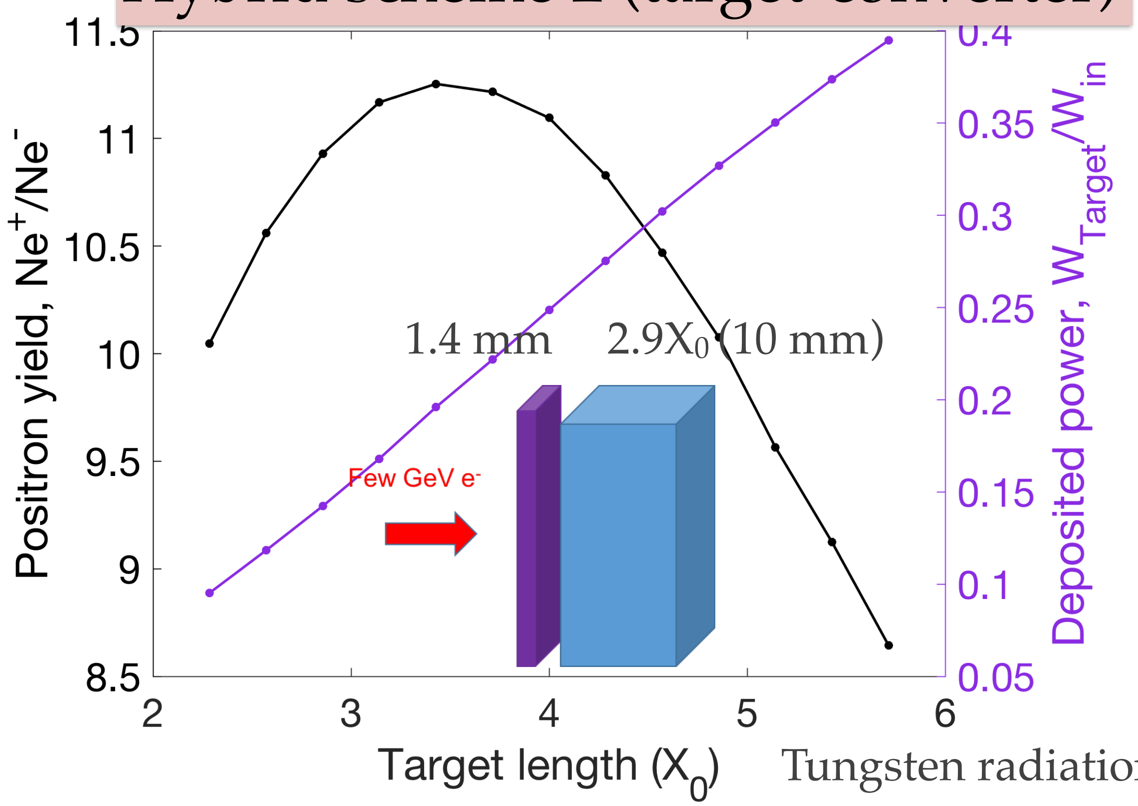
Production Target

Hybrid scheme (target-converter)

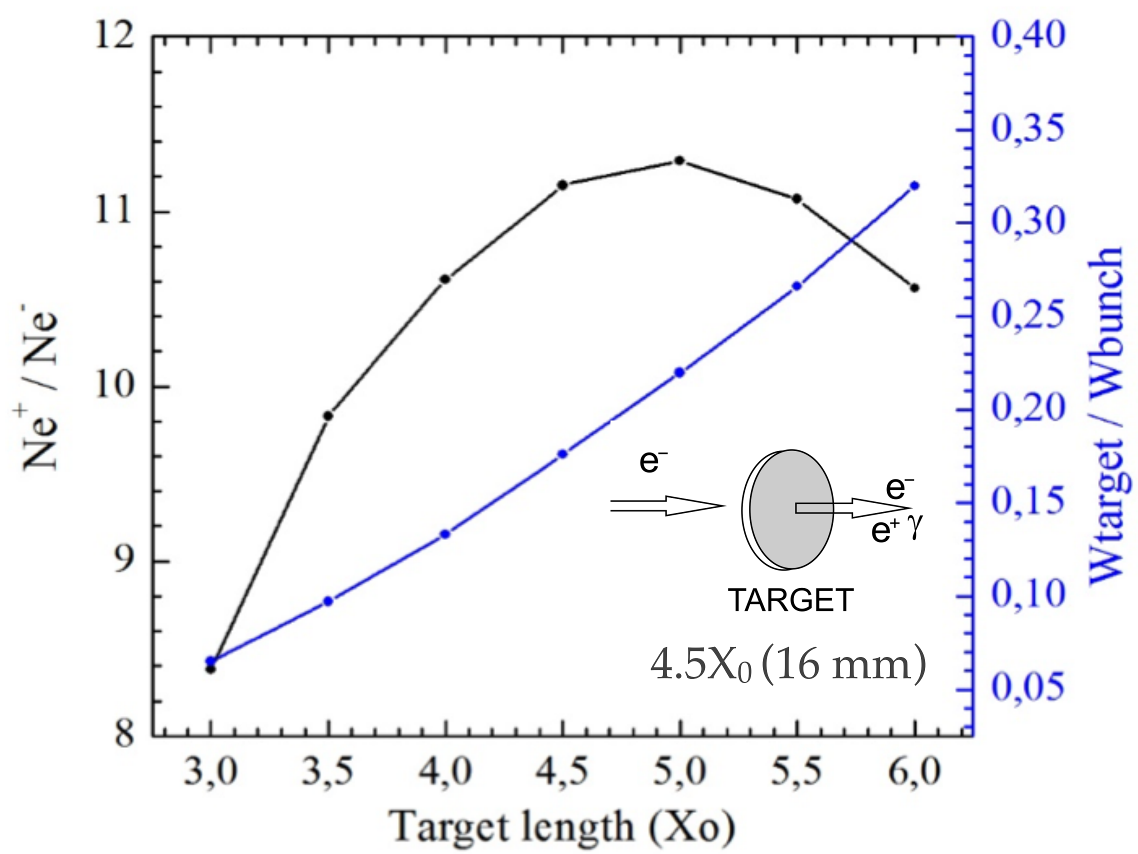




Hybrid scheme 2 (target-converter)



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*

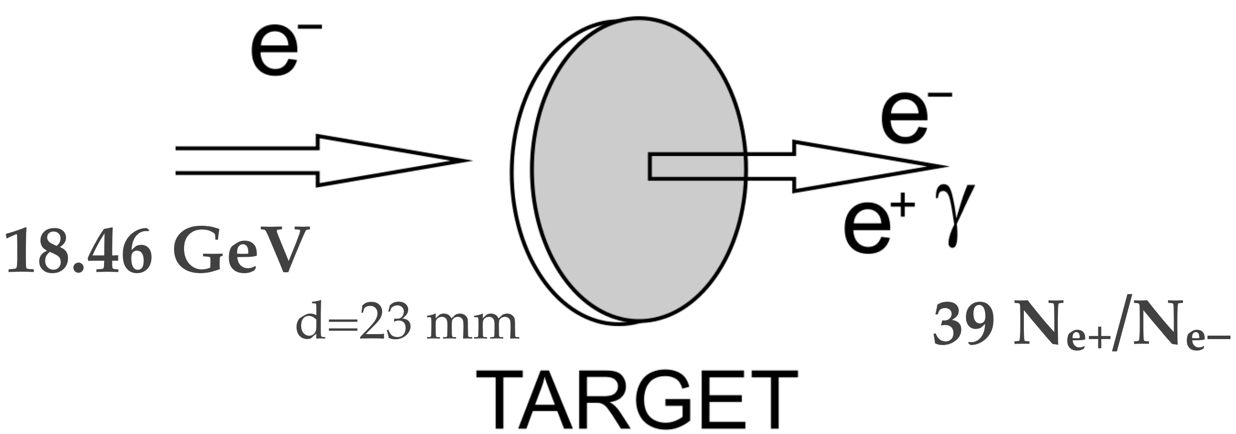
- PEDD (Peak Energy Deposition Density, [$GeV/cm^3/e^-$] or [J/g]) ~ beam and target parameters (beam energy, spot size and target thickness) => thermo-mechanical stresses.
- According to SLC experience, $W_{74}Re_{26}$ material has a PEDD limit of **35 J/g** (safe value to avoid target failure).

Positron Production (alternative options)

20 GeV linac as the FCC-ee injector:

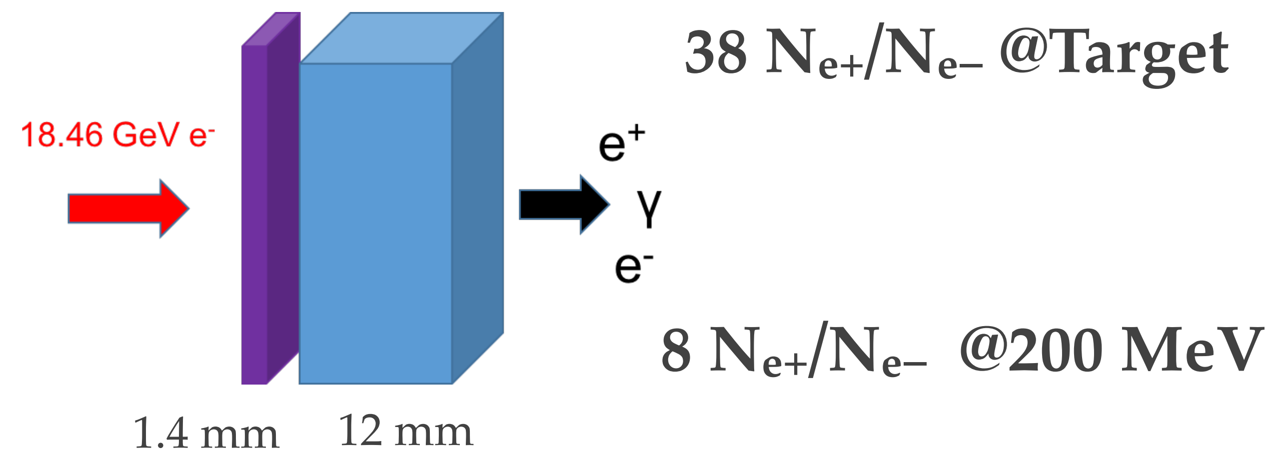
- The higher-energy incident beam for positron production (18.46 GeV instead of 4.46 GeV)
- A real advantage as *the positron yield is increasing with the incident energy.*
- *Channeling process* in the crystal becomes *more effective* (more photons produced)

Conventional scheme



Thickness is chosen to maximize the positron production

Hybrid scheme 2



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

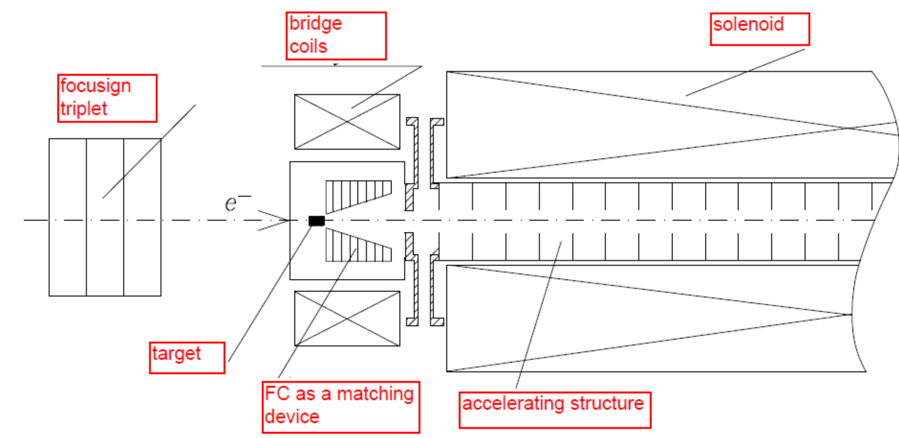
(16 γ/e- compared to 4 γ/e- @4.46 GeV)

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

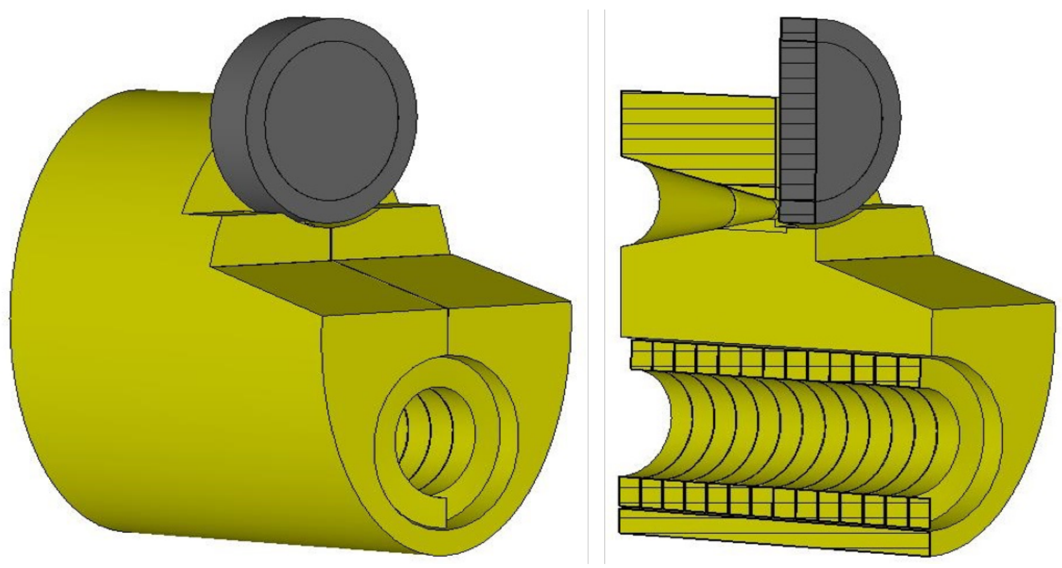
Capture and Primary Acceleration

The capture section design for both schemes is based on an Adiabatic Matching Device (AMD). The AMD may use a pulsed Flux Concentrator or SC magnet to form adiabatically decreasing magnetic field.

☞ *Flux Concentrator (FC)*

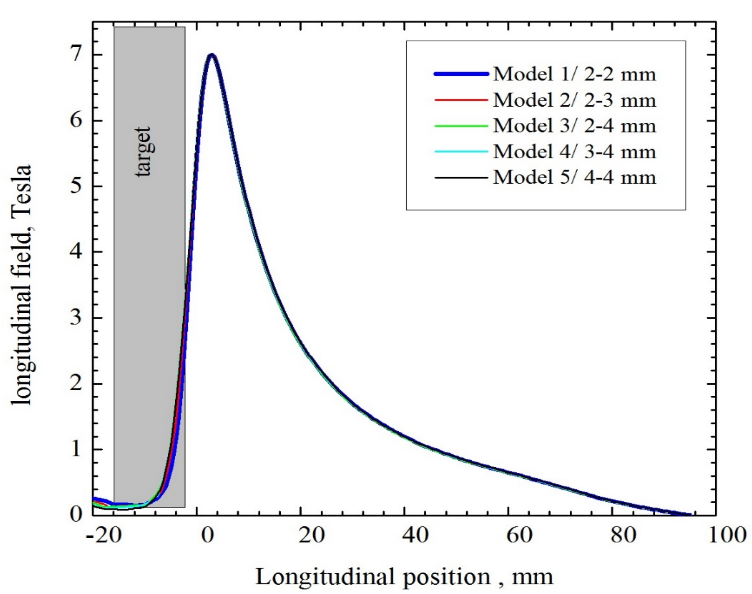


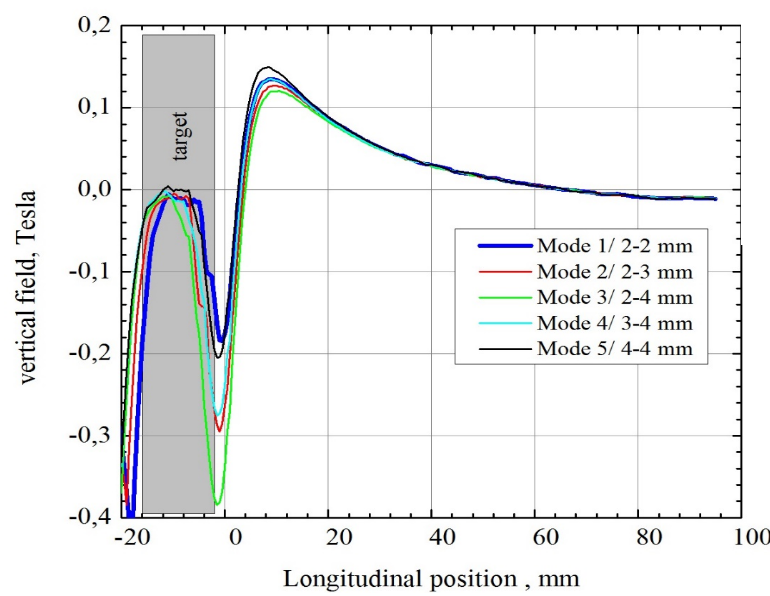
Matching the e+ beam (with very large transverse divergence) to the acceptance of the pre-injector linac.



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.

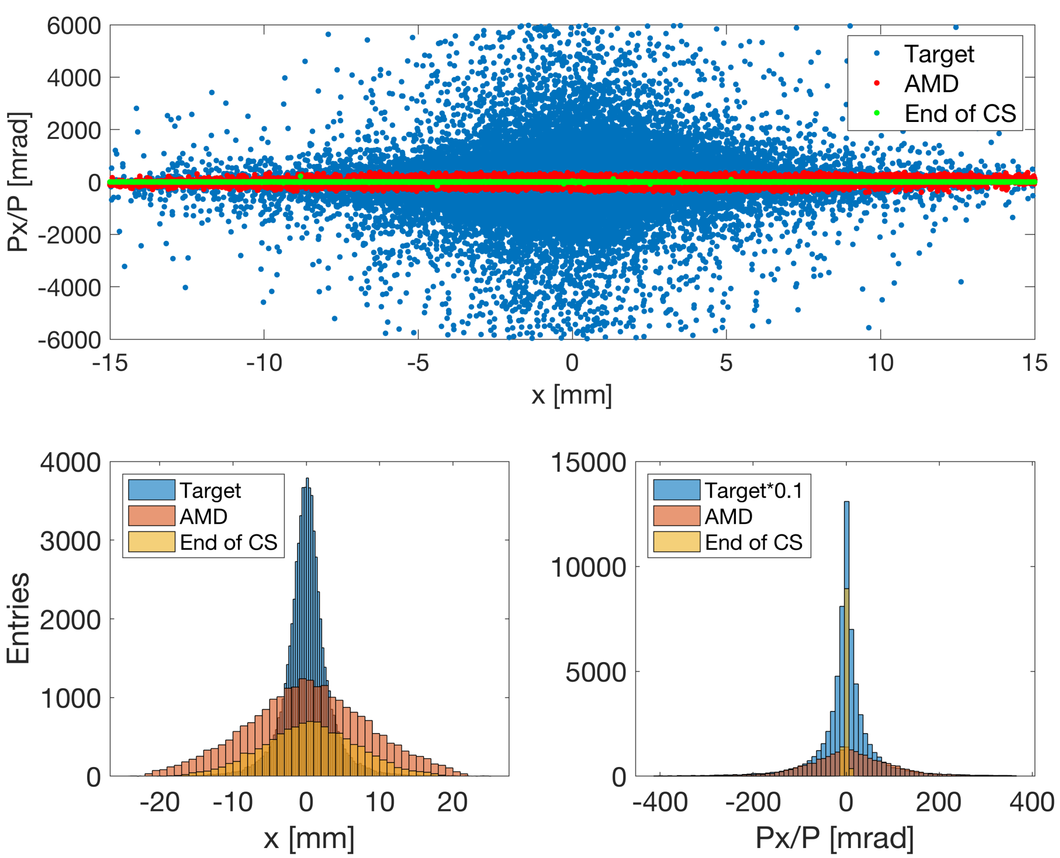
Capture and Primary Acceleration

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)

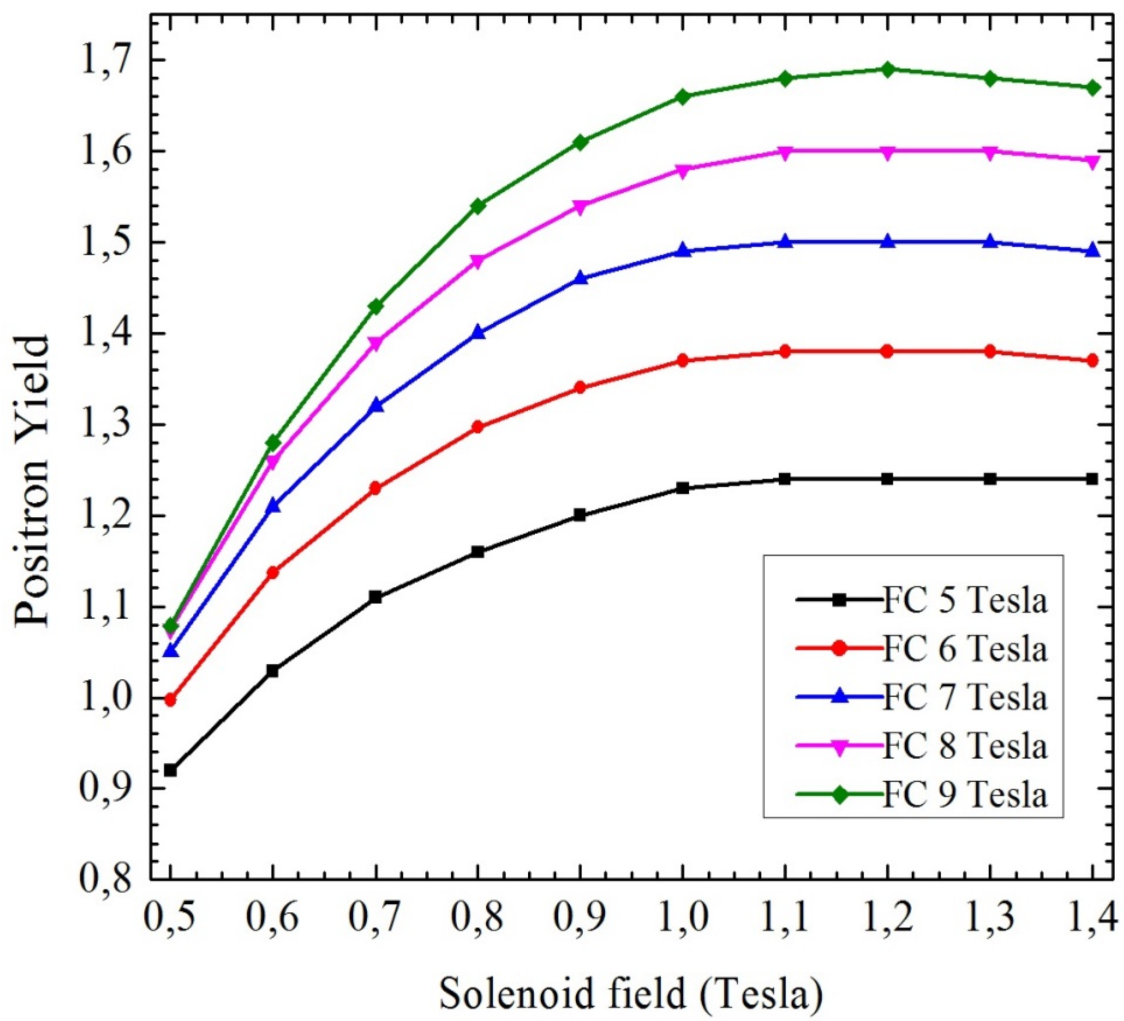


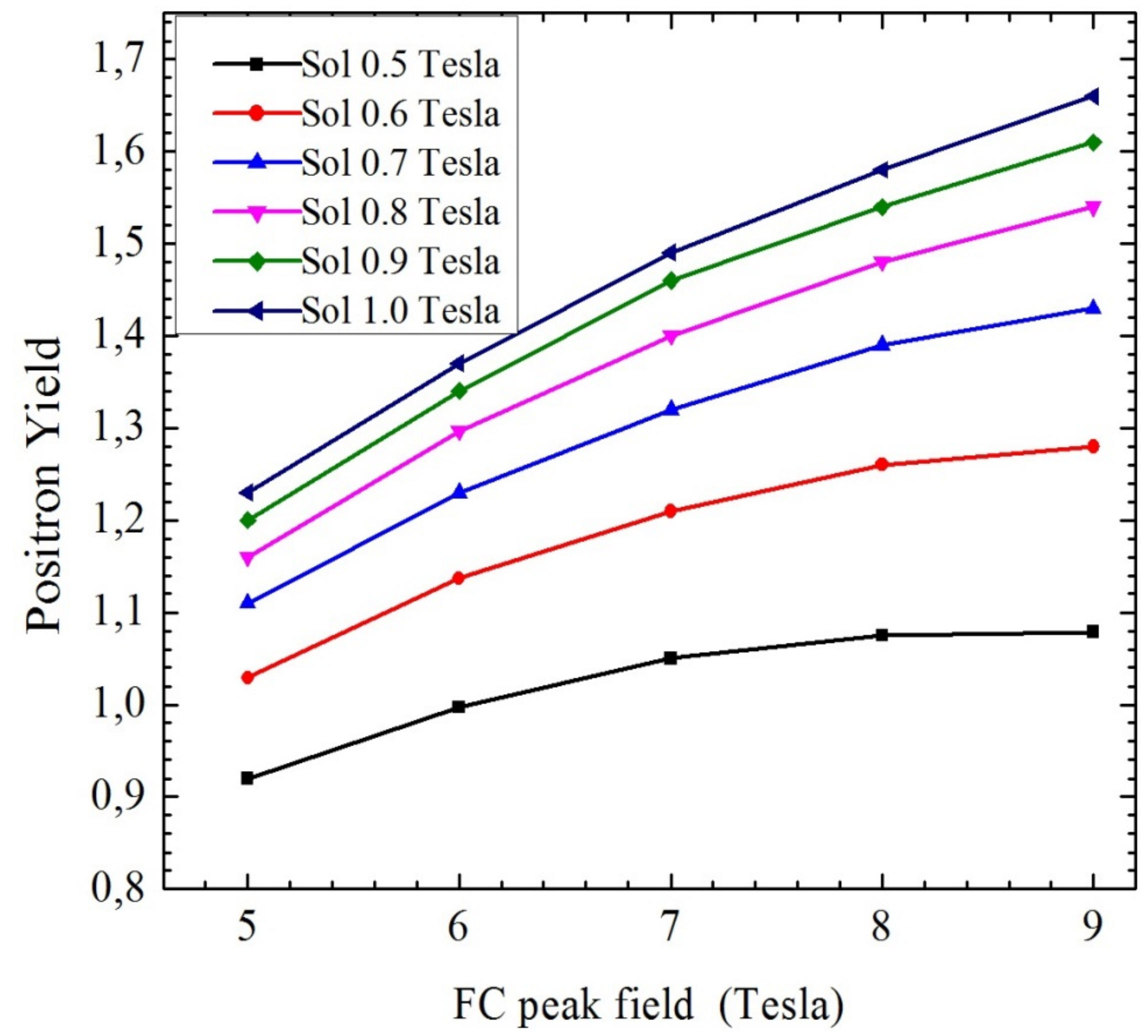
Beam Parameter	Conventional	Hybrid	Hybrid 2
B_{max} = 5 T, B_{DC} = 0.5 T			
Mean Energy	190 MeV	197 MeV	235 MeV
Total yield	XX N_{e+}/N_{e-}	0.9 N_{e+}/N_{e-}	1.7 N_{e+}/N_{e-}
Accepted yield	1.1 N_{e+}/N_{e-}	0.7 N_{e+}/N_{e-}	~1.4 N_{e+}/N_{e-}
Emittance hor./vert.	17 μm (1σ)	14 μm (2σ)	10 μm (3σ)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





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

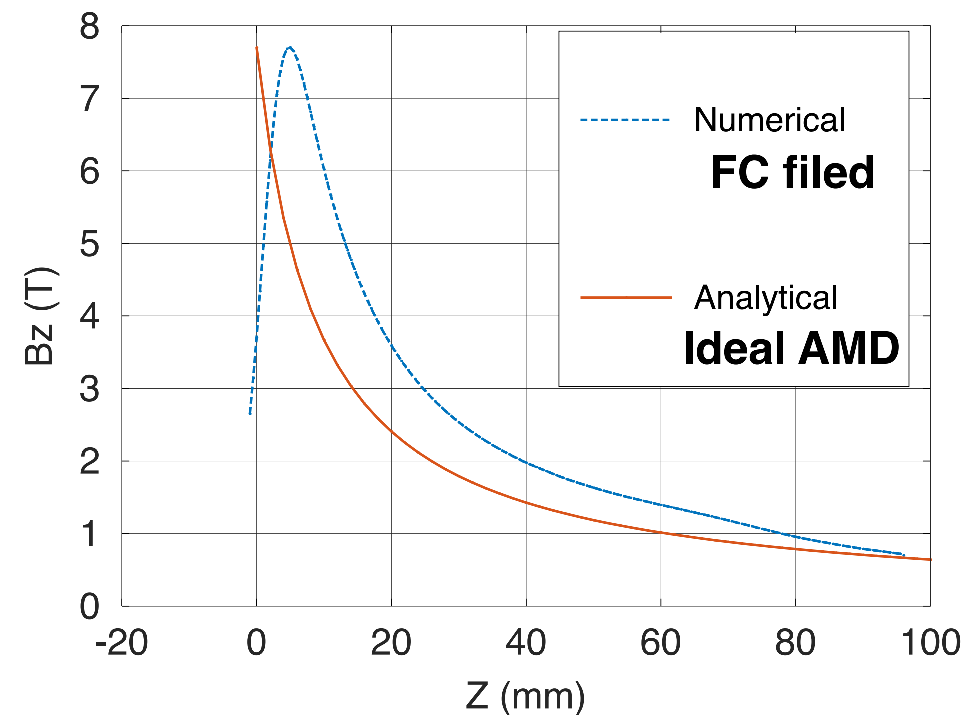
P. Martyshkin

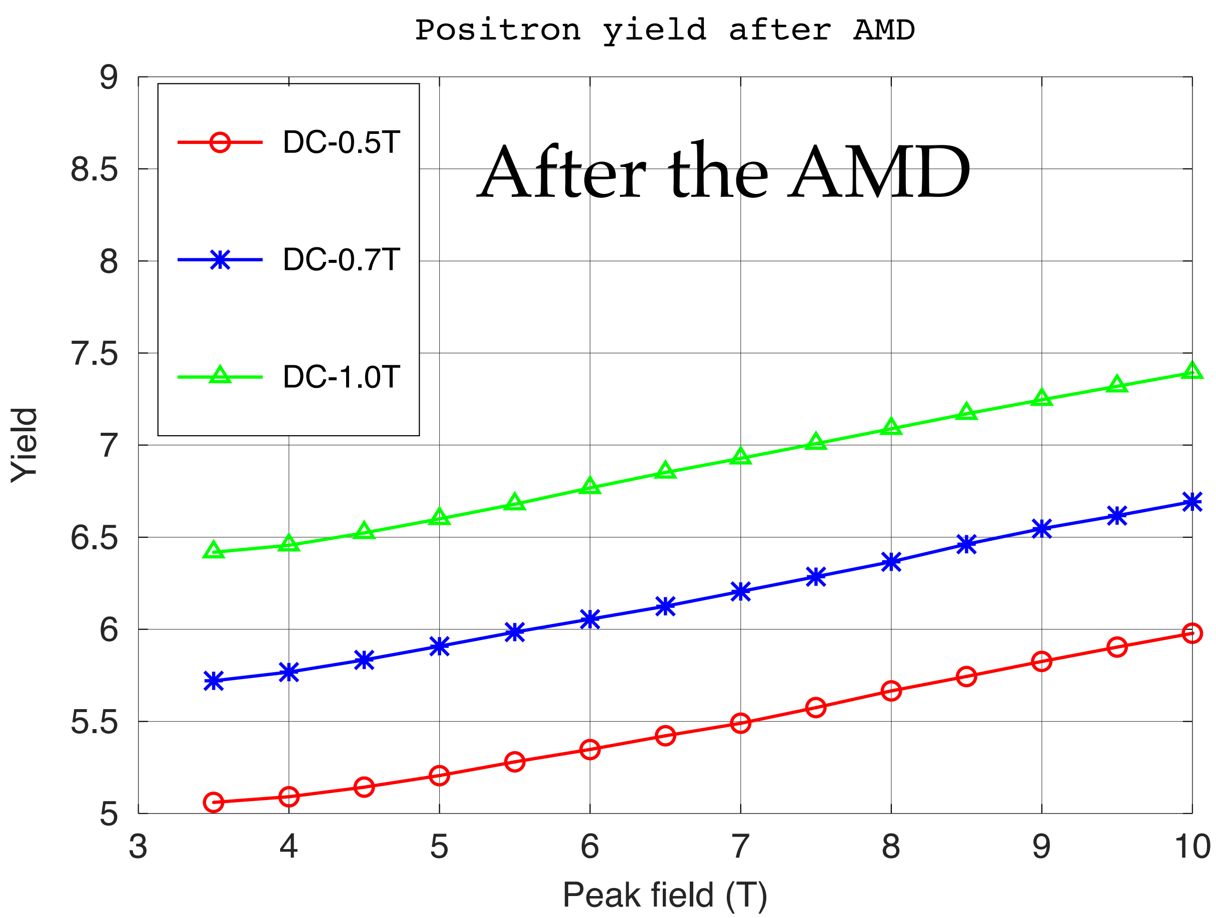
Choice of the FC peak and DC solenoid field

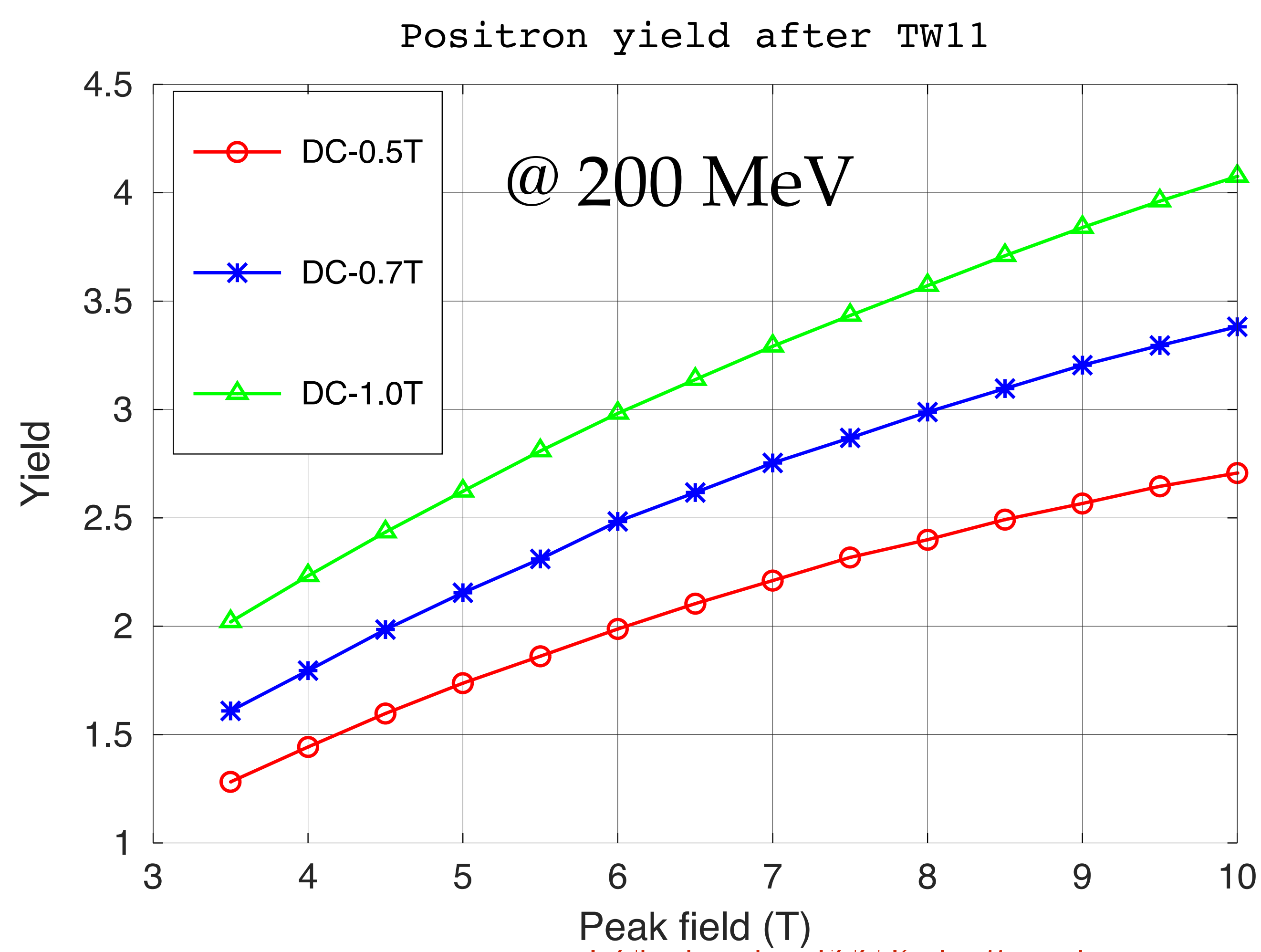
Preliminary

- **<u>Total positron yield</u>** as a function of the FC peak magnetic field for different values of the DC solenoid field.
- The simulations are done for the hybrid scheme with the ideal AMD filed profile starting from the target.

$$B(z) = \frac{B_0}{1 + \mu z}$$





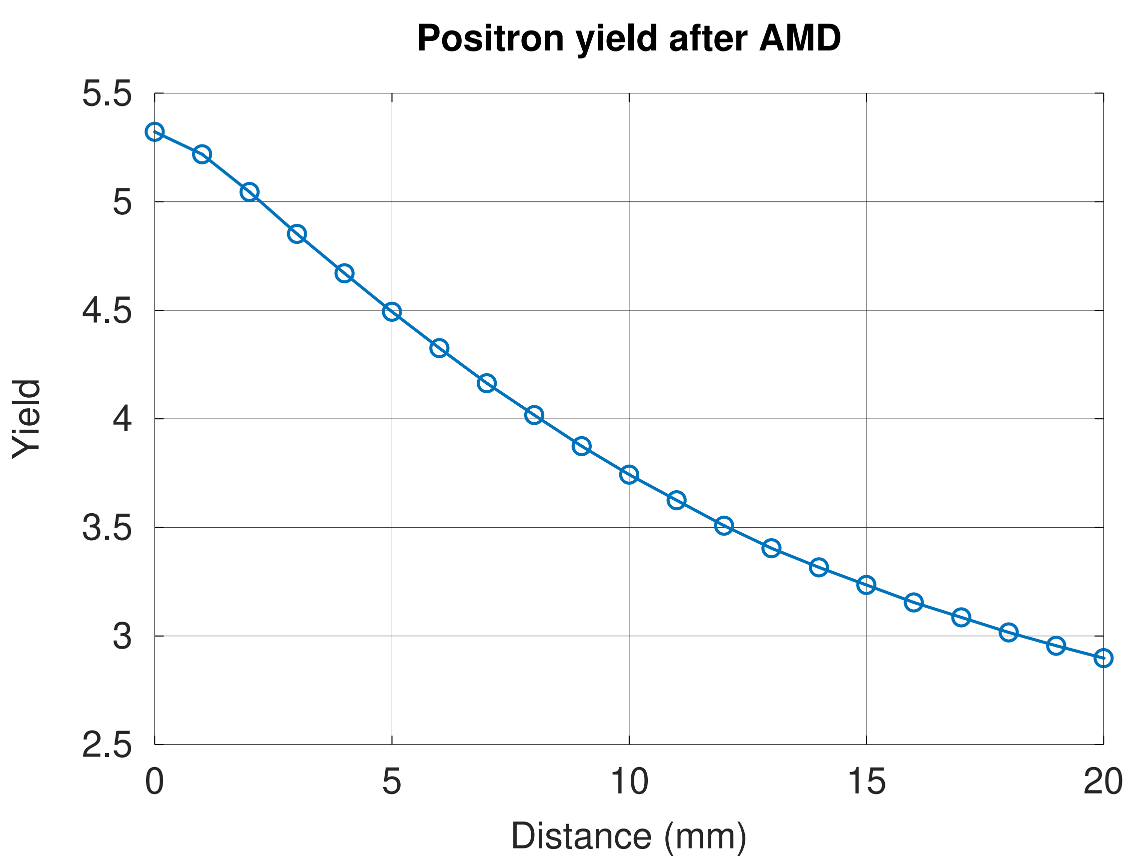


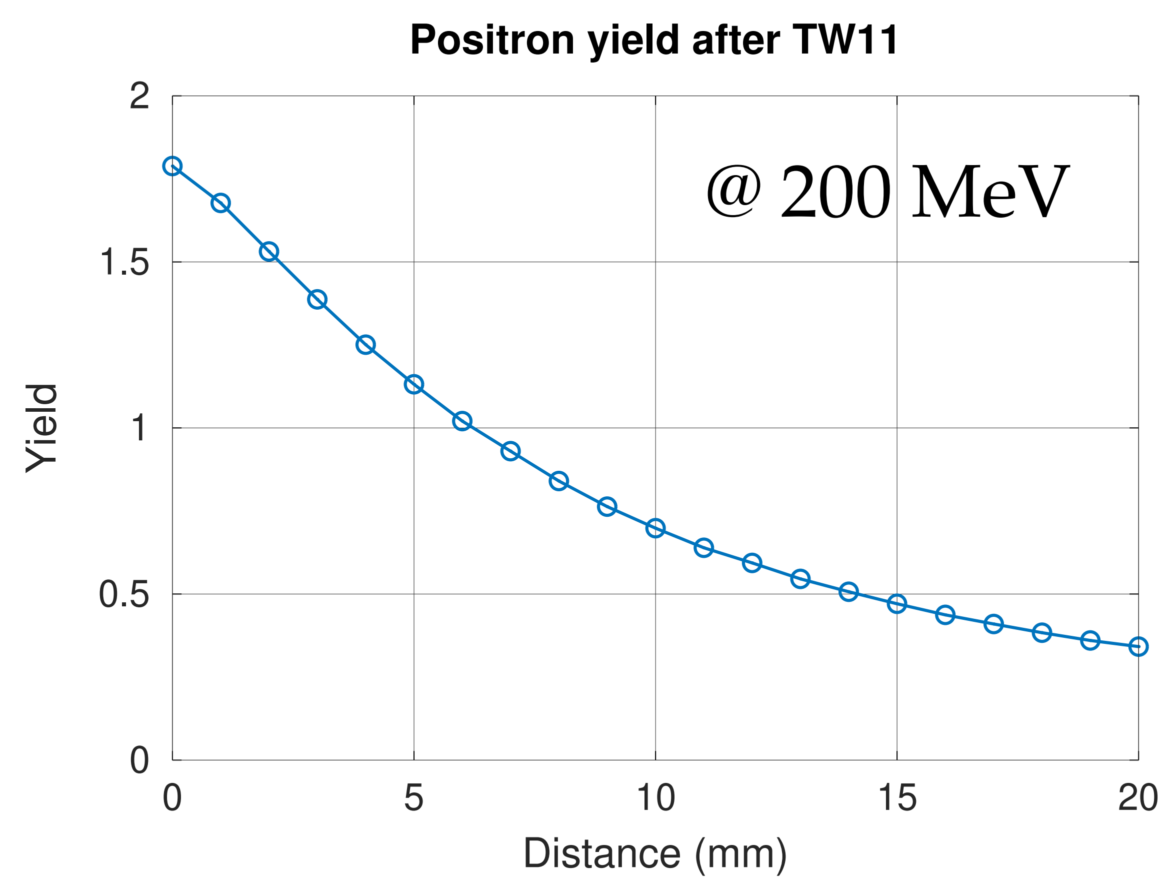
AMD peak filed location

Preliminary

- **Total positron yield** as a function of the offset between the target and the AMD peak magnetic field.
- The simulations are done for the hybrid scheme with the ideal AMD filed profile (B_{max} = 5 T, B_{DC} = 0.5 T, μ = 100 m^{-1}).

Distance (mm)	Yield@AMD	Yield@TW1	Yield@TW11
0	5.3221	1.9766	1.7888
1	5.2186	1.8682	1.6774
2	5.0449	1.7133	1.5313
3	4.8521	1.5673	1.3872
4	4.6702	1.4173	1.2507
5	4.4931	1.2915	1.1315
6	4.3255	1.1750	1.0209
7	4.1642	1.0697	0.9303
8	4.0176	0.9749	0.8402
9	3.8745	0.8925	0.7633
10	3.7432	0.8172	0.6983





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.**

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	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)	+/- 8 %
Energy of the DR	1.15 GeV	500 MeV	NO/1.1 GeV	1.54 GeV

*FCC-ee under study

Summary

- FCC-ee can employ the conventional/hybrid positron source. *No showstopper identified* => studies ongoing.
- Current studies: both schemes can provide *the comparable positron 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).
- 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 => *investigation of the bypass line for e+ generation/capture*.

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	36	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18