Updates on yield optimisation for CLIC and FCC–ee positron sources

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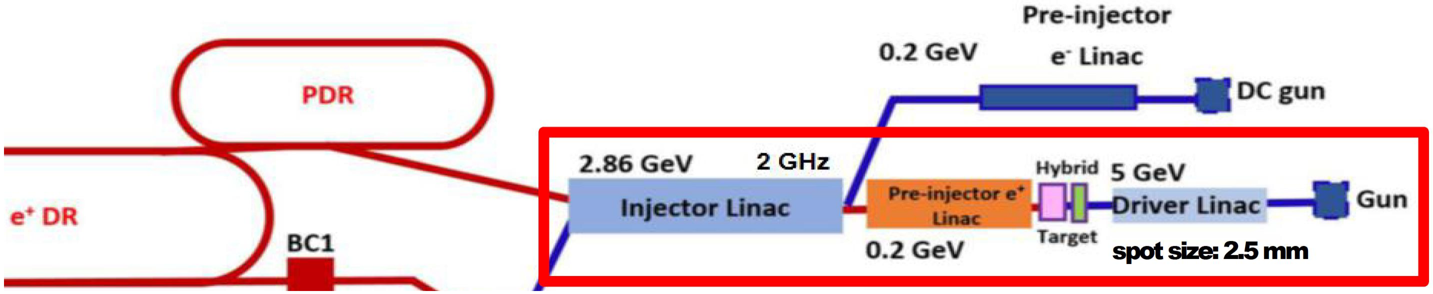
Outline

- Introduction
- Optimisation strategy
- Preliminary results
- Conclusions

Introduction

- CLIC positron source:
  - E-gun → Target → AMD → TW structures → Injector linac → (PDR)
    (e+ production)   (e+ capture & acceleration)

AMD: Adiabatic Matching Device



- FCC-ee positron source: (quite similar with CLIC)
  - E-gun → Target → AMD → TW structures → Injector linac → (DR)

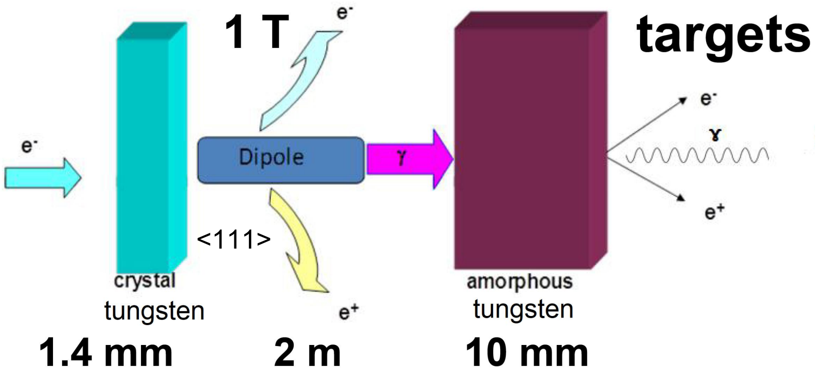
- Figures of merit
  - Accepted positron yield: Number of e+ (accepted by PDR/DR) produced per e-

$$\mathrm{yield}_{e+} = \frac{n_{e+}^{\mathrm{produced}}}{n_{e-}^{\mathrm{primary}}}$$

  - PEDD: Peak Energy Deposition Density (in target), < 35 J/g

Beam and target

- Electron beam hitting on target following gaussian distribution
  - Free parameters: energy, spot size (rms), emittance, etc.
- Two target schemes studied
- A hybrid target scheme:
  - Crystal W + Magnet + Amorphous W
- A conventional target scheme:
  - A single amorphous W
- Target free parameters:
  - Thicknesses
  - Distance

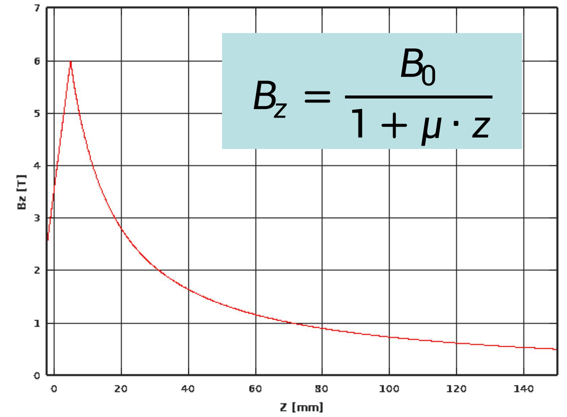


CLIC CDR target design

For CLIC, hybrid target not used, since it was found to be not necessary

Adiabatic Matching Device (AMD)

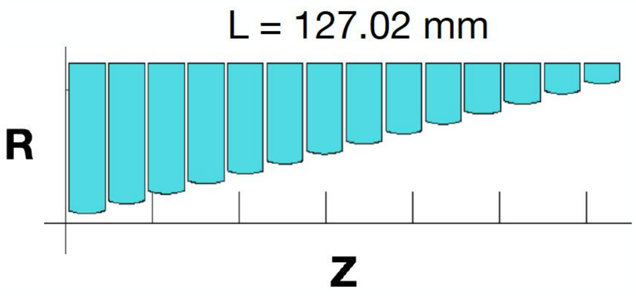
- Field map obtained in different ways:
- Analytic formula (used for CLIC) →
  - Linear fringe: Bz = K * (Z - 5 mm) + B0, K = 0.5 T/mm



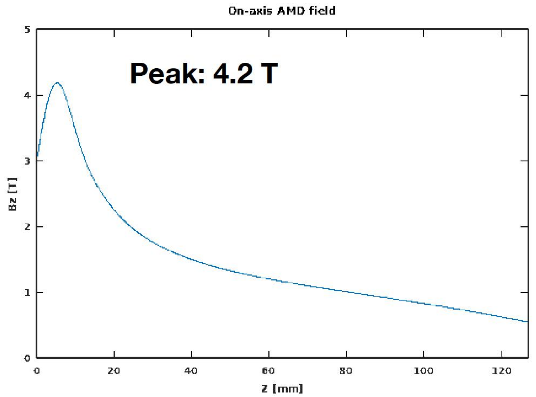
- Flux Concentrator (FC) simulations:
  - Modified SLAC-like FC (used for CLIC)
    - linear / non-linear shaped aperture
    - designed and simulated by Hugo Bajas (with Opera-2d)
  - FC + NC solenoid (used for FCC-ee)
    - designed and simulated by Pavel Martyshkin
- HTS solenoid simulation (used for FCC-ee)
  - A High-Temperature Superconductor (HTS)
  - easily to achieve strong magnetic field to capture positrons
  - designed and simulated by PSI magnet group

Hugo's AMD designs

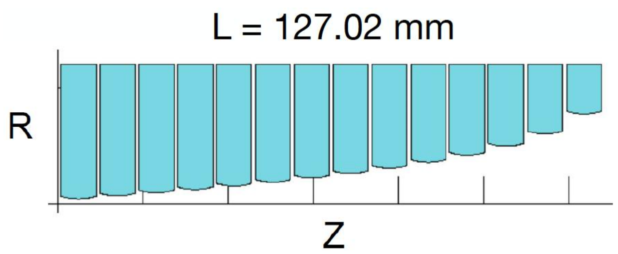
- **FC with linear aperture** **Peak (B0) is floated (scaled from below fields) in optimisation**
  - has the advantage of larger positron yield, but also requires larger power supply and forces which might cause damage



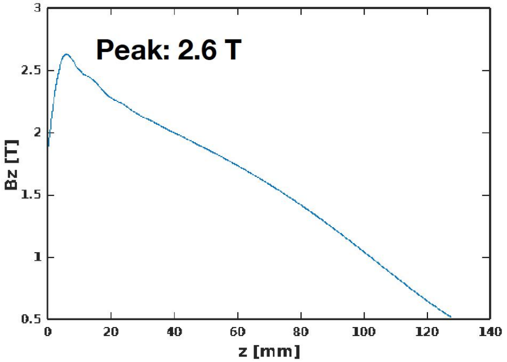
Voltage & Force	
U total	7.18 kV
U internal max	79.6 V
Fz turn 1	-2.39 kN
Fr turn 1	4.30 kN
F turn1	4.92 kN



- **FC with non-linear aperture**
  - has the advantage of reduced power supply, voltages and forces, but also has reduced positron yield
  - might give a PEDD beyond the 35 J/g limit (but PEDD can be reduced with larger spot size, which also affects the yield)



Voltage & Force	
U total	3.28 kV
U internal max	33.4 V
Fz turn 1	-0.13 kN
Fr turn 1	1.49 kN
F turn1	1.49 kN



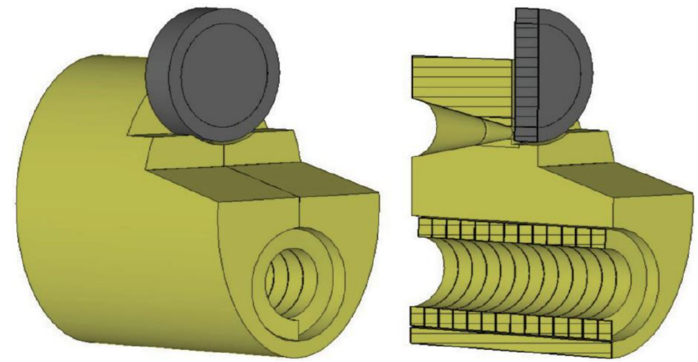
Pavel's AMD designs

FC with smaller aperture

- has the advantage of higher field peak
  - FC peak field: 7 T
  - DC solenoid field: 0.5 T (constant)
  - 3D field map used

Front gap	Length	End gap	Ri1	Ri2
3 mm	74 mm	36 mm	4 mm	22 mm

Aperture is linear

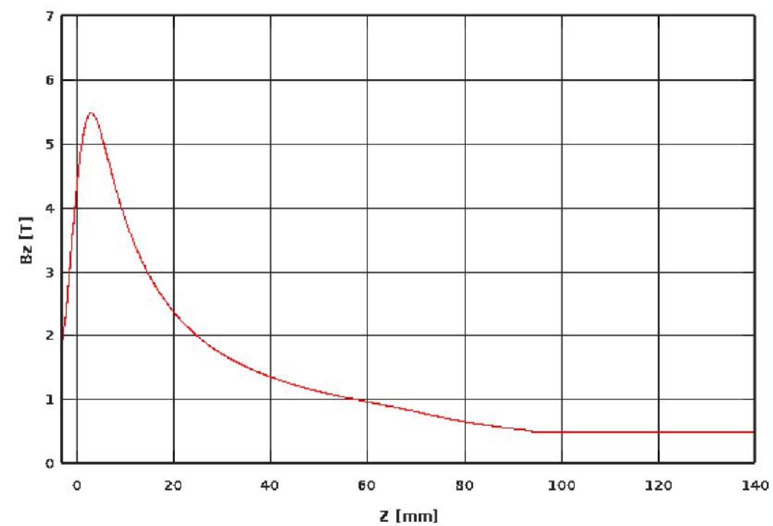


FC with larger aperture

- has the advantage of larger aperture
  - FC peak field: 5 T
  - DC solenoid field: 0.5 T (constant)
  - 3D field map used

Front gap	Length	End gap	Ri1	Ri2
3 mm	100 mm	40 mm	8 mm	31.5 mm

On-axis Bz field (larger aperture)



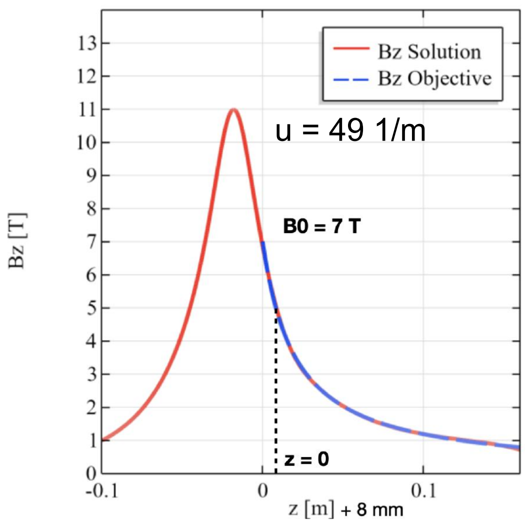
- Consistent performance observed (<**10%**) compared with Hugo's FC design at similar peak field

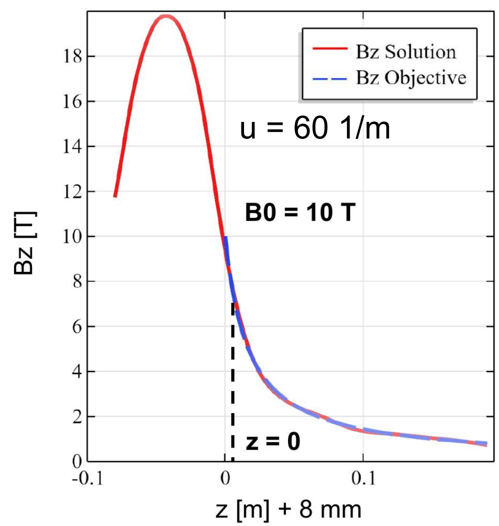
PSI HTS solenoid as AMD

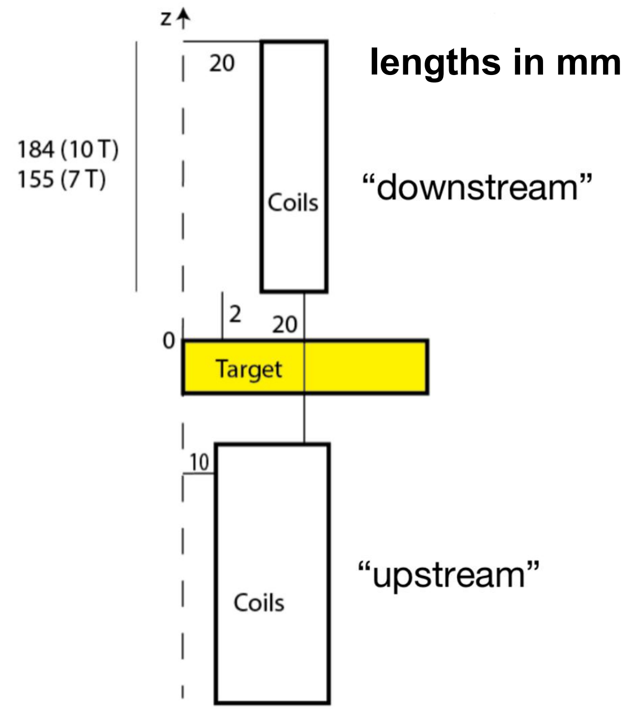
- Agrees well with analytic formula

$$\mathbf{B_z} = \frac{\mathbf{B_0}}{\mathbf{1} + \mu \cdot (\mathbf{z} + \mathbf{8}\ \mathrm{mm})}$$

(z = 0 is target exit, where e+ capture started)





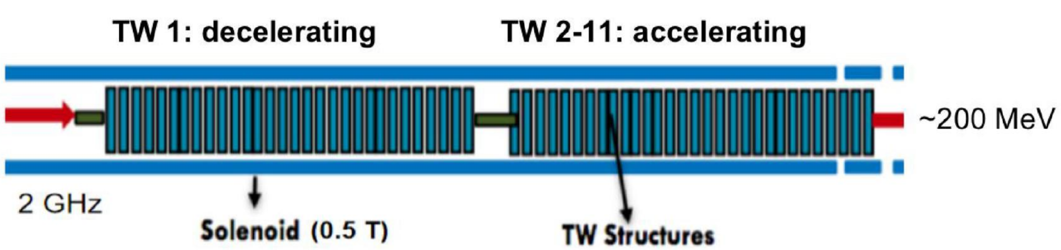


2D field map used

- Fringe field (z < 0) neglected in optimisation, since final results affected not much (~3%)
- Analytic formula (the one above) used in optimisation, with B0 being floated
- u and length are estimated (from existed designs with B0 = 7 T and 10 T) and fixed for different B0

Travelling wave (TW) structures

- L-band used as pre-injector linac in optimisation (as the yield of S-band found to be smaller)
- L-band configuration
  - Working mode: 2π/3, frequency: 2 GHz, NC solenoid: 0.5 T*
  - Number of structures: 1 dec. + 10 acc.
  - Structure length: 1.5 m, distance: 0.2 m*, aperture: R = 20 mm
  - Phases and gradients optimised separately, such that yield is maximum, with the energy at the exit as close to 200 MeV as possible



* If technically allowed, a higher field was found to achieve larger yield (e.g. improved ~25% with 0.8 T)

* If technically allowed, the first distance can be reduced to achieve larger yield

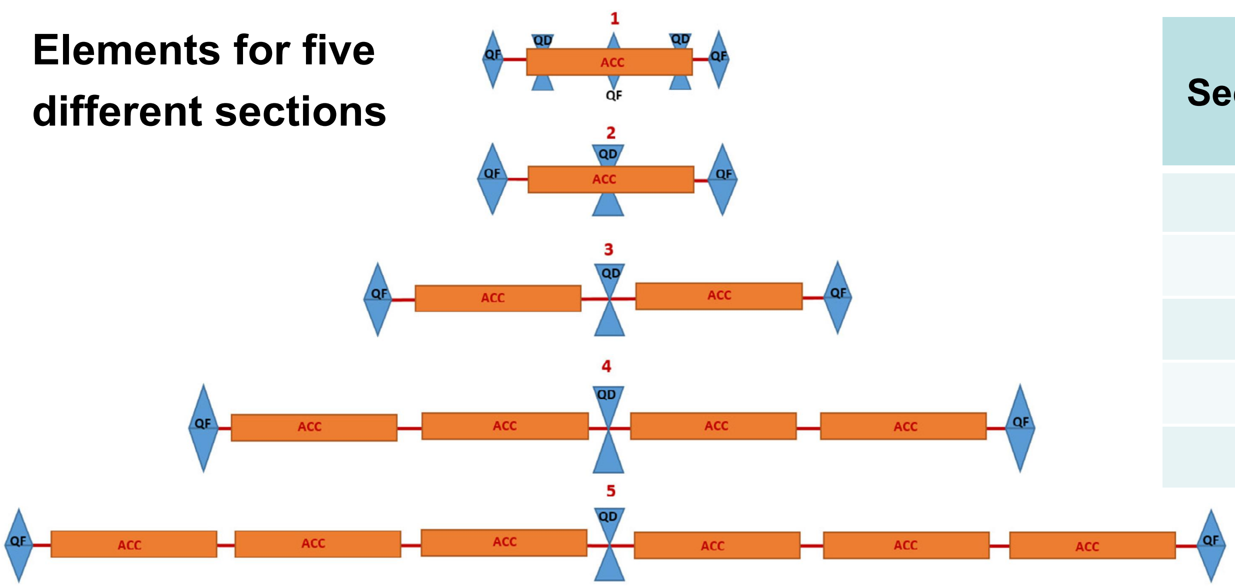
Injector linac

- Injector linac is supposed to accelerate positrons to 2.86 GeV (CLIC) or 1.54 GeV (FCC-ee)
- In optimisation, analytic formula used (for CLIC and FCC-ee)

$$E = E_0 + \Delta E \cdot \cos(2\pi\omega \cdot \Delta t),\ \Delta E = 2.86\, GeV - 200\, MeV,\ \Delta t = t - t_{ref}$$

- For CLIC, injector linac is also simulated using the existed design from Cafer Bayar

Elements for five different sections



Section	Number of matching quadrupoles	Number of elements
1	4	8
2	3	18
3	3	14
4	3	7
5	3	6

Optimisation strategy

- For the free parameters, it is not realistic to scan in the full space
  - Simulation time and storage space not allowed

- Procedure of optimisation algorithm

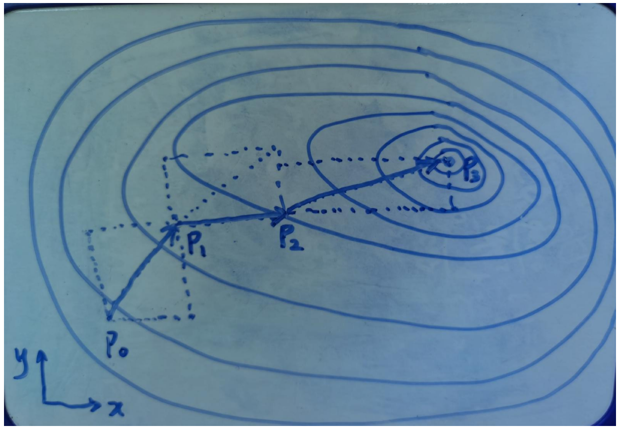
① **Default** parameters are necessary, to start with

② Then **scan** only **one parameter at a time**, with the other parameters **fixed to the default**

③ Change the default and do scan **iteratively**, until all parameters are optimised

- Discriminant variables as figure of merit
  - ✓ Accepted positron yield
  - ✓ PEDD
  - ✓ Primary beam power (used for different primary energies, proportional to cost)
  - ✓ Deposited power in target, etc.

Example of the algorithm



More in [CLIC-Note-1165]

Beam parameters

- Beam parameters used in simulation
  - Parameters in red color are free parameters and already optimised

Beam parameters		CLIC (all stages)		FCC-ee	Unit
		380 GeV	1.5 (3) TeV		
Primary e–	Energy	5		6	GeV
	Spot size (rms)	Floated (depending on AMD used)			mm
	Bunch length (rms)	1		1	mm
	Emittance	80		–	mm·mrad
	Energy spread (rms)	0.1		0.1	%
	Divergence (rms)	–		0.01	mrad
	Nb of bunches / pulse	352	312	25	
	Repetition rate	50		100	Hz
e+ accepted by PDR (DR)	Bunch charge	5.2E+09	3.7E+09	2.1E+10	e+
	Safety margin	20		100	%
	Energy acceptance (±)	1.20		3.80	%
	Time window (total)	19.8		9.33	mm
	Energy required	2.86		1.54	GeV

Optimised parameters (CLIC)

Free parameters optimised for different AMD options

Analytic AMD

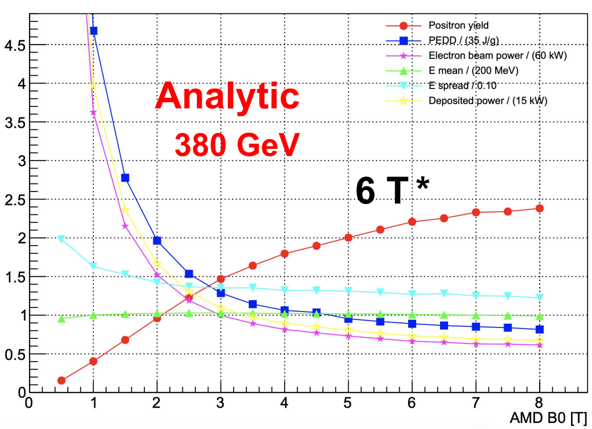
Parameter	380 GeV	3 TeV
Electron energy	5 GeV	
Spot size	2.2 mm	1.5 mm
Emittance	80 mm.mrad	
Amor. thickness	18 mm	
Target-AMD gap	2 mm	
AMD peak Bz	6 T	
AMD length	22 cm	
AMD entr. radius	8 mm	
AMD-TW gap	50 mm	
TW dec. gradient	13 MV/m	
TW acc. gradient	17 MV/m	

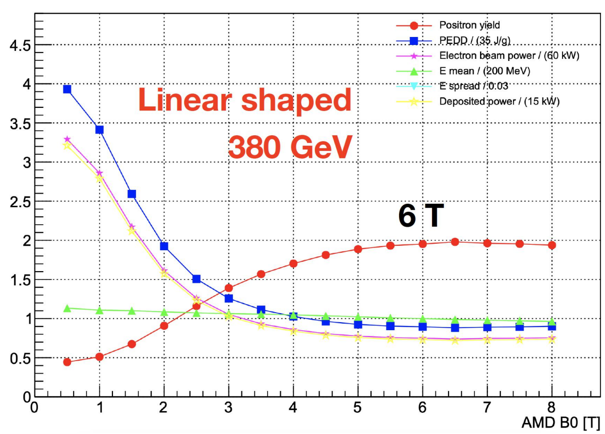
Simulated AMD with linear / non-linear apertures

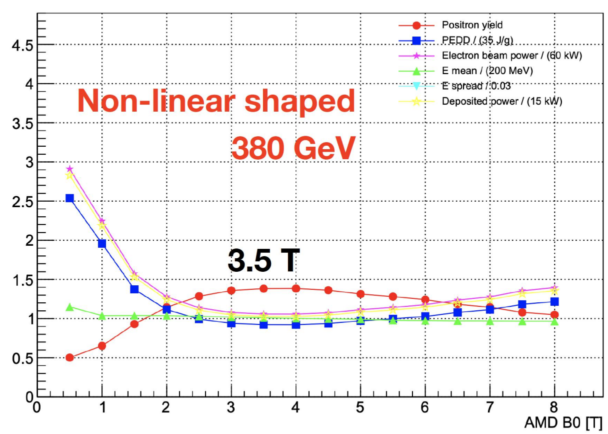
Parameter	380 GeV	3 TeV
Electron energy	5 GeV	
Spot size	2.3 mm	1.5 mm
Emittance	80 mm.mrad	
Amor. thickness	18 mm	
Target-AMD gap	2 mm	
AMD peak Bz	6 T	
AMD-TW gap	50 mm	
TW dec. gradient	20 MV/m	
TW acc. gradient	19 MV/m	

Parameter	380 GeV	3 TeV
Electron energy	5 GeV	
Spot size	2.8 mm	1.8 mm
Emittance	80 mm.mrad	
Amor. thickness	17 mm	
Target-AMD gap	2 mm	
AMD peak Bz	3.5 T	4 T
AMD-TW gap	50 mm	
TW dec. gradient	20 MV/m	
TW acc. gradient	20 MV/m	

Final optimisation scan of AMD peak field (380 GeV)







* 6 T is the maximum allowed (technical limitations) in our study, though yield can benefit from higher field

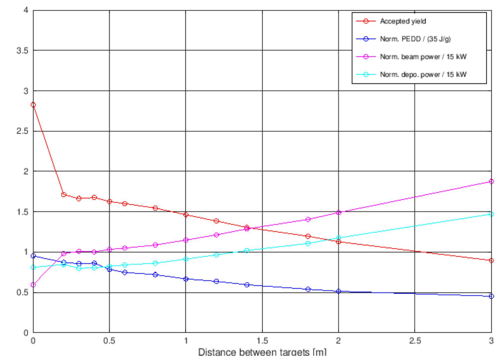
Optimised parameters (FCC–ee)

Free parameters optimised for different cases

- **Hybrid target scheme (with FC as AMD)**

Parameters	FC as AMD		Unit
	Ri = 4	Ri = 8	mm
Primary energy	6		GeV
Spot size	1.5	1.3	mm
Crystal thickness	1.8		mm
Distance	0		m
Amorphous thickness	4.5		X_0

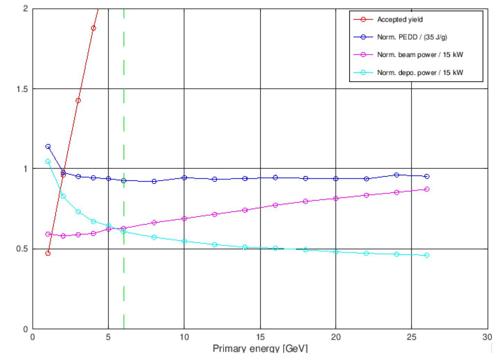
distance scan →



- **Conventional target scheme (with FC as AMD)**

Parameters	FC as AMD		Unit
	Ri = 4	Ri = 8	mm
Primary energy	6 (4)		GeV
Spot size	1.5	1.3	mm
Amorphous thickness	5.0		X_0

energy scan →

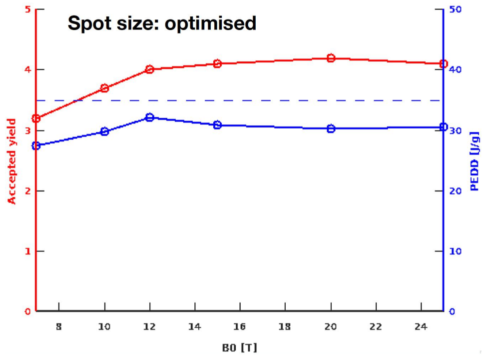


- **Conventional target scheme (with HTS as AMD)**

Parameters	HTS as AMD	Unit
Primary energy	6 (4)	GeV
Spot size	1.0	mm
Amorphous thickness	5.0	X_0
B0 (z = 0)	15 (12)	T
Bz @ Target exit (z = 8 mm)	6.6 (5.7)	T

$$B_z = \frac{B_0}{1 + \mu \cdot (z + 8\ \mathrm{mm})}$$

B0 scan →



Preliminary results

Results for CLIC and FCC-ee

- Injector linac simulated (with PLACET) for CLIC
- Powers and PEDD always normalised to required e+ bunch charge by accepted yield

Different AMD options		Accepted yield	e^- beam power [kW]	PEDD [J/g]
CLIC @ 380GeV	**Analytic AMD**	2.15	40.8	32.2
	Linear FC	**1.91**	**45.9**	33.0
	Non–linear FC	1.31	67.2	33.5
CLIC @ 1.5 (3) TeV	**Analytic AMD**	2.50	22.2	31.7
	Linear FC	**2.42**	**22.9**	32.7
	Non–linear FC	1.76	31.4	32.5
FCC–ee @ Hybrid target	**Small aperture FC**	2.29	44.1	32.3
	Large aperture FC	**2.83**	35.7	33.3
FCC–ee @ Conventional target	**Small aperture FC**	2.19	45.9	32.3
	Large aperture FC	**2.67 (1.88)**	**37.7 (35.8*)**	32.4 (33.1)
	HTS as AMD	**4.10 (2.88)**	**24.6 (23.3*)**	30.9 (30.6)

* For FCC-ee, primary energy fixed at 6 GeV (baseline). But 4 GeV is found to reduce beam power by 5%

Preliminary results

Positron production and capture efficiencies

CLIC, 380 GeV Linear FC as AMD	Target	AMD	TW structures	PDR accepted
e+ Yield	11.6	7.67	2.45	1.91
Efficiency		66%	32%	78%

Spot size: 2.3 mm
R_AMD: 6.5-55 mm

CLIC, 3 TeV Linear FC as AMD	Target	AMD	TW structures	PDR accepted
e+ Yield	11.5	8.15	3.00	2.42
Efficiency		71%	37%	81%

Spot size: 1.5 mm
R_AMD: 6.5-43 mm

FCC-ee Large aperture FC	Target	AMD	TW structures	DR accepted
e+ Yield	13.7	10.3	3.54	2.67
Efficiency		76%	34%	75%

Spot size: 1.3 mm
R_AMD: 8-32 mm

FCC-ee HTS as AMD	Target	AMD	TW structures	DR accepted
e+ Yield	13.6	9.09	5.29	4.10
Efficiency		67%	58%	78%

Spot size: 1.0 mm
R_AMD: 20 mm

- Positron capture efficiency mainly affected by **spot size** and **AMD aperture**

Conclusions

- CLIC and FCC-ee positron sources optimised for different AMD options
- Preliminary simulation and optimised results presented
- CLIC:
  - FC with linear aperture achieves a maximised yield of 2.42 e+/e-. A factor of 2.4 (6.0) of Project Implementation Plan (CDR) baseline results
  - A non-linear FC has reduced yield (~30%) but benefits from lower voltage and forces
- FCC-ee:
  - Hybrid target achieves maximised yield only when distance between crystal and amorphous is 0. Yield (optimised) for hybrid target is ~6% higher than conventional target. More (radiation, thermal load, etc.) to be considered in the optimisation
  - For conventional target, the primary e- beam power can be ~5% lower if energy reduced from 6 GeV to 4 GeV, but 6 GeV is anyway necessary for the current injector layout
  - FC with a larger aperture behaves better than a small aperture, with higher yield (> 20%), with a yield of 2.67 e+/e-. A factor of 2.6 of the baseline result
  - Compared to FC, an optimised HTS solenoid can improve the yield by ~50%, with a yield of 4.10 e+/e-, and Bz at target exit being ~6 T

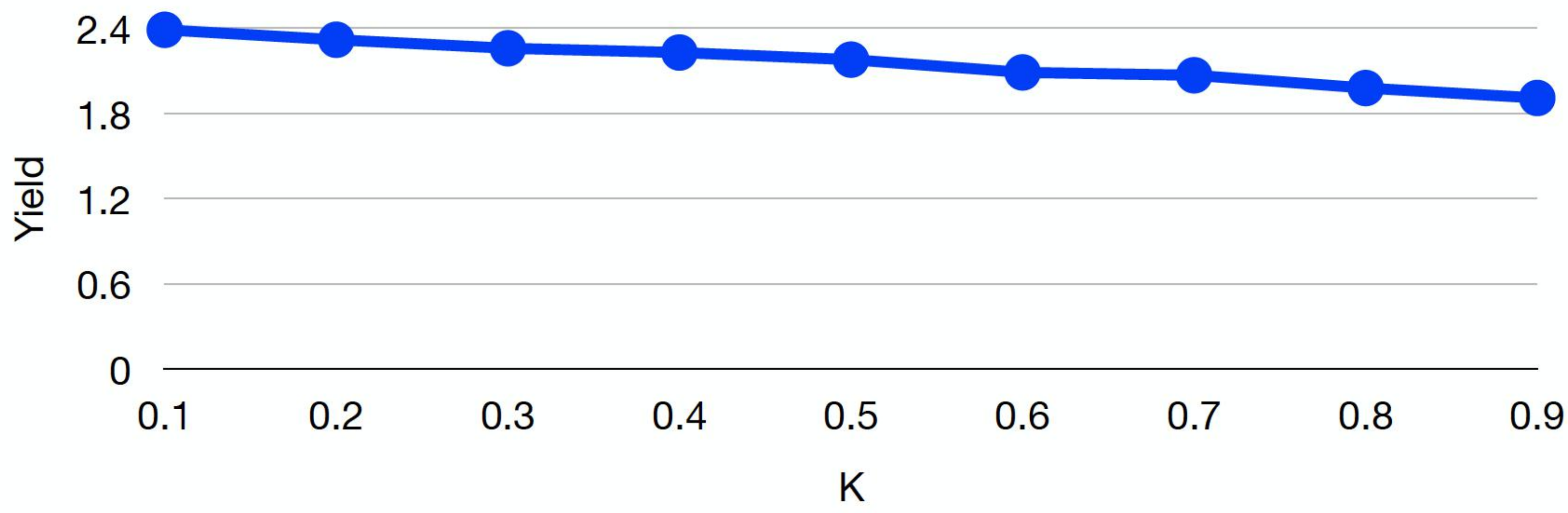
BACKUP

Analytic AMD

- K factor effects on the results (380 GeV):

Bz = K * (Z - 5 mm) + B0,   K = 0.5 T/mm, B0 = 6 T

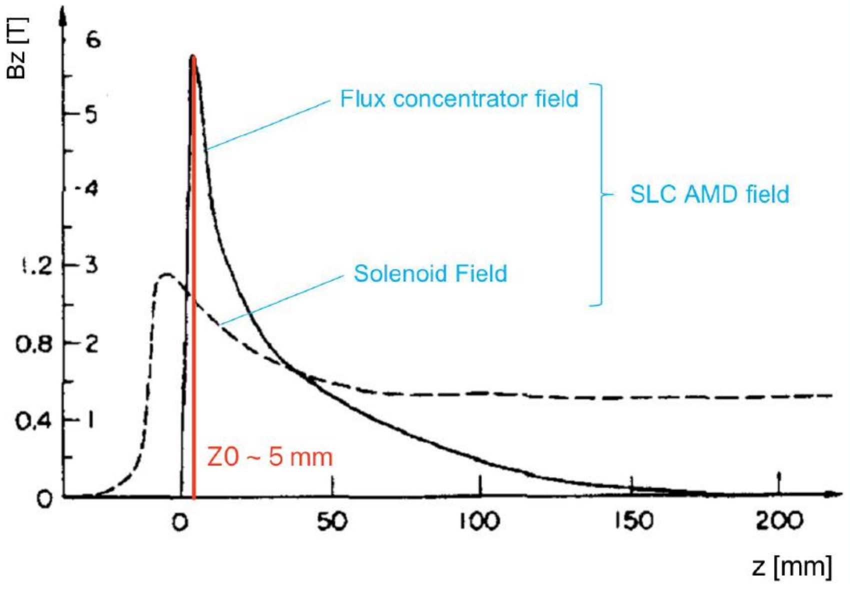
K	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
Yield	2.39	2.32	2.26	2.23	**2.18**	2.09	2.07	1.98	1.91
Diff.	10%	6%	4%	2%	-	4%	5%	9%	12%

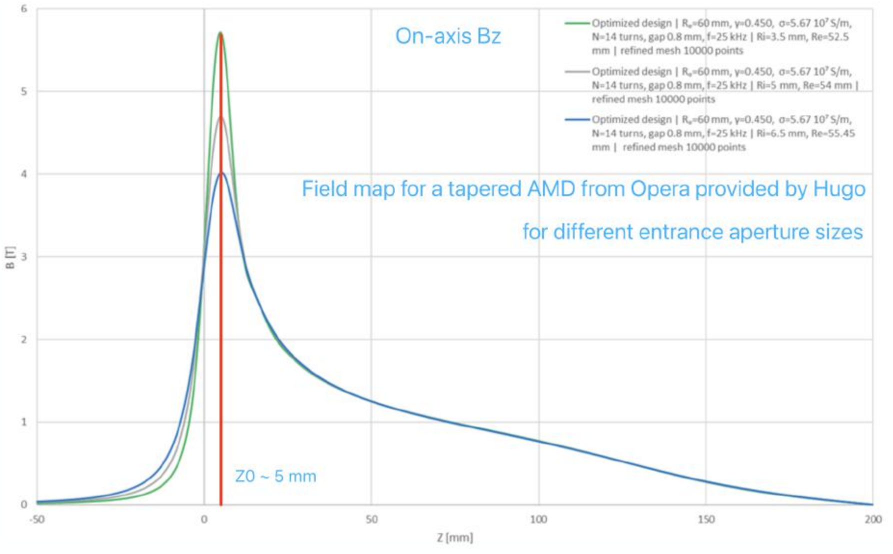


- Change of K in a reasonable range does not affect the results much. Expected difference in reality < 5%

Analytic AMD

- Field peak chosen at Z0 = 5 mm based on the following facts:
  - SLAC SLC AMD filed peak was around z = 5mm
  - Opera AMD field peak from Hugo found to be always around z = 5 mm, **independent** of number of turns, turn gap, current, frequency, inner aperture size and shape





Hugo's AMD designs

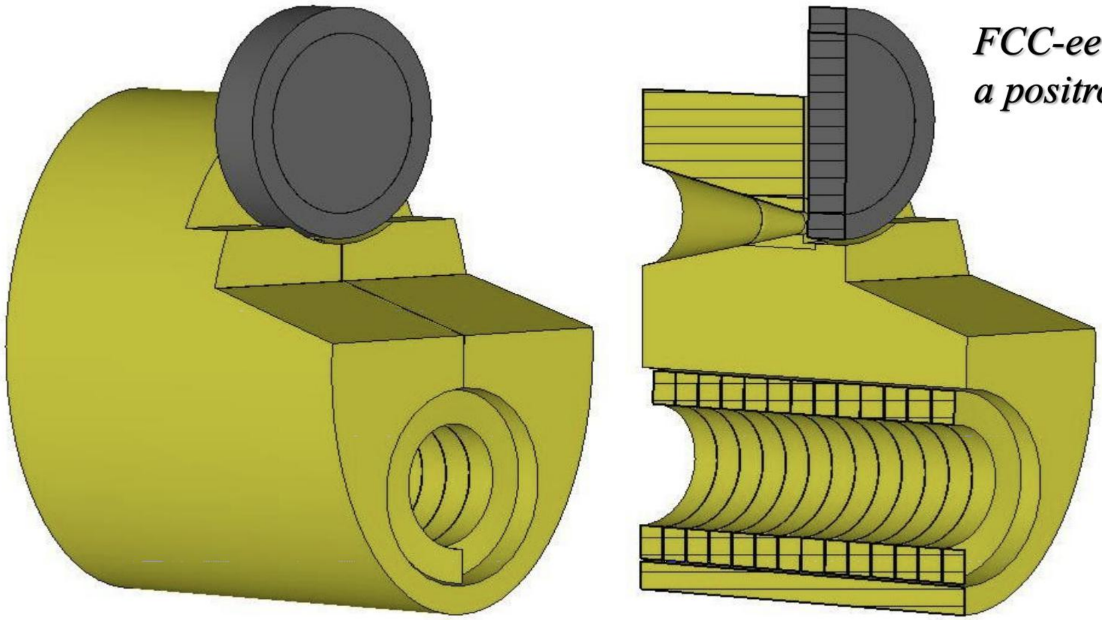
- FC with linear aperture

$R_{entrance}$ [mm]	R_{exit} [mm]	R_{outer} [mm]	D_{coil} [mm]	Gap [mm]	I_{peak} [kA]	f [kHz]
6.50	55.45	60	8.33	0.8	13.8	25

- FC with non-linear aperture

$R_{entrance}$ [mm]	R_{exit} [mm]	R_{outer} [mm]	D_{coil} [mm]	Gap [mm]	I_{peak} [kA]	f [kHz]
6.52	43.22	60	8.33	0.8	13.8	25

Pavel's AMD dsigns



FCC-ee FC Computer model with a positron production target

- Elliptical cylinder 120x180 mm
- Total length is140 mm
- Conical part length is 70 mm
- Min cone diameter is 8 mm
- Max cone diameter is 44 mm
- Cone angle is ≈29 degrees
- Cylindrical hole diameter is 70 mm
- Coil has 13 turns

- Current profile is a half of sine with a pulse length of 25 µs
- Peak current is ~ 20 kA (peak field is 7 Tesla)
- Gap between coil turns is 0.4 mm
- Gap between coil and FC body is 1 mm
- Turns size is 9.6x14 mm

- Target (W74Re26) diameter is 90 mm, thickness is 15.8 mm
- Gap between target and FC front face is 2mm

Preliminary results (CLIC)

Optimised results

- Injector linac: analytic (Placet simulation can give the same yields as the analytic does)
- Results (normalised to required e+ bunch charge)

Results	**Analytic AMD**		**Opera AMD linear shaped**		**Opera AMD non-linear shaped**	
	380 GeV	**3 TeV**	**380 GeV**	**3 TeV**	**380 GeV**	**3 TeV**
Accepted **yield**	2.15	2.50	1.91	2.42	1.31	1.76
PEDD [J/g]	32.2	31.7	33.0	32.7	33.5	32.5
Beam **power** [kW]	40.8	22.2	45.9	22.9	67.2	31.4
Deposited power [kW]	11.2	6.1	12.6	6.3	16.3	7.7
E_mean @ TW exit [MeV]	202	201	199	199	202	198
E_spread @ TW exit	13%	13%	21%	21%	23%	23%
Accepted E_mean [GeV]	2.860	2.860	2.860	2.860	2.860	2.860

Preliminary results (FCC–ee)

Optimised results

Hybrid target scheme

- For AMD with a small aperture

Results with optimised parameters	Values	Unit
Accepted yield	2.29	e+/e-
Normalised PEDD	32.3	J/g
Normalised beam power	44.1	kW
Normalised deposited power	15.0	kW

- For AMD with a large aperture

Results with optimised parameters	Values	Unit
Accepted yield	**2.83**	e+/e-
Normalised PEDD	**33.3**	J/g
Normalised beam power	35.7	kW
Normalised deposited power	12.2	kW

Conventional target scheme

- For AMD with a small aperture

Results with optimised parameters	Values	Unit
Accepted yield	2.19	e+/e-
Normalised PEDD	32.3	J/g
Normalised beam power	45.9	kW
Normalised deposited power	11.1	kW

- For AMD with a large aperture

Results with optimised parameters	Values	Unit
Accepted yield	**2.67**	e+/e-
Normalised PEDD	**32.4**	J/g
Normalised beam power	37.7	kW
Normalised deposited power	9.12	kW

HTS solenoid as AMD

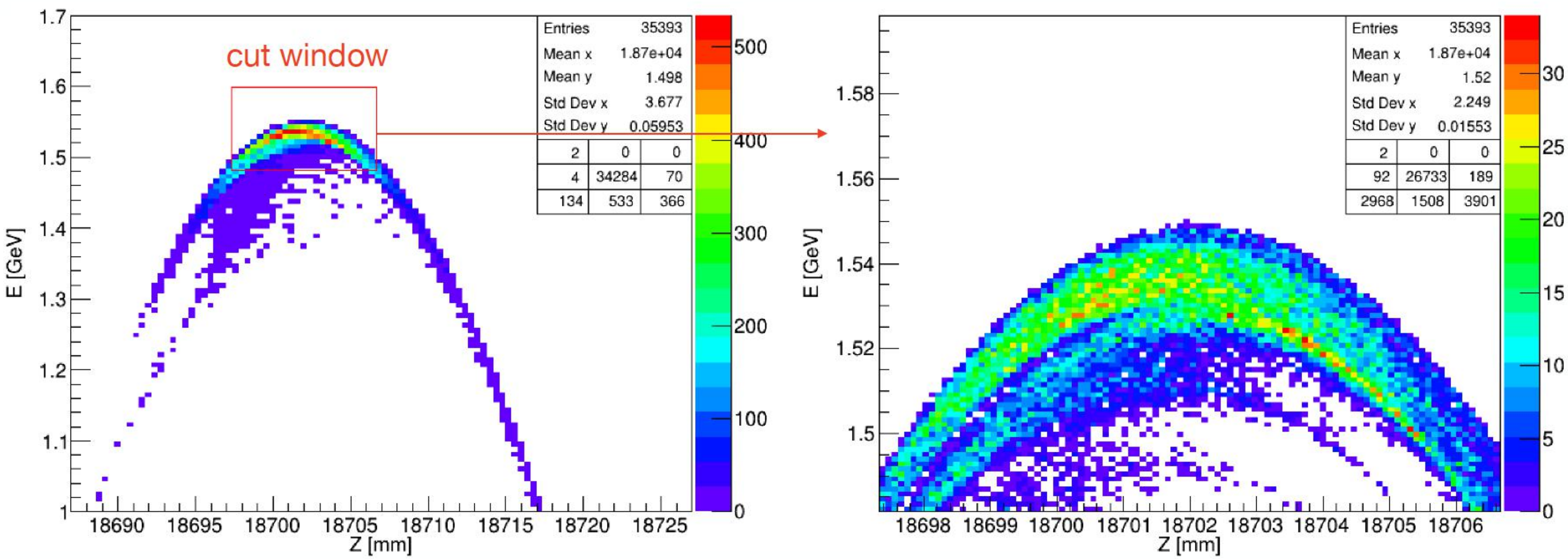
e- energy	Accepted yield	Beam power [kW]	PEDD [J/g]	Deposited power [kW]
4 GeV	2.88	23.3	30.6	6.56
6 GeV	4.10	24.6	30.9	5.98

Preliminary results (FCC–ee)

Optimised results

Conventional target scheme

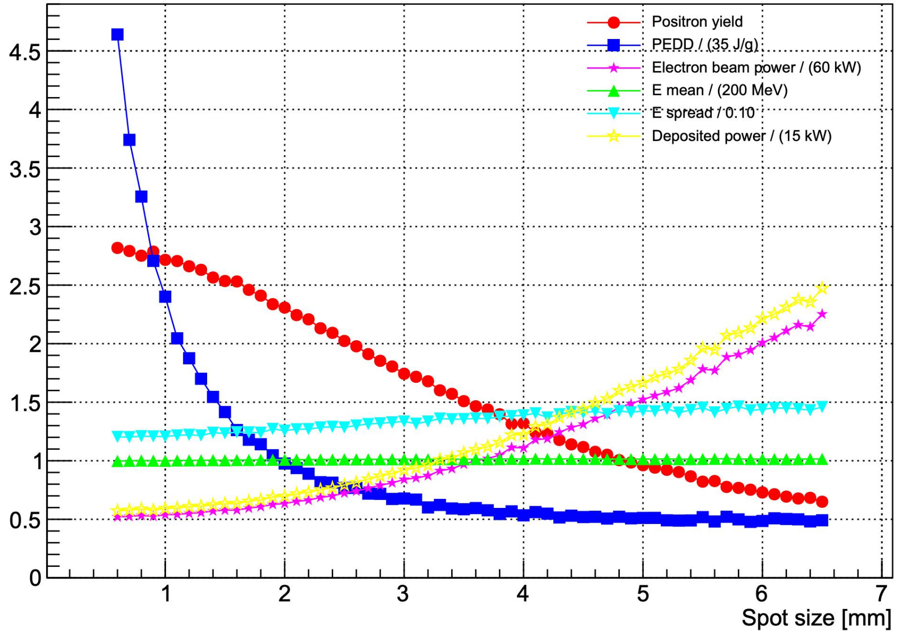
- For AMD with a large aperture
- At injector linac (analytic) exit, as well as acceptance window

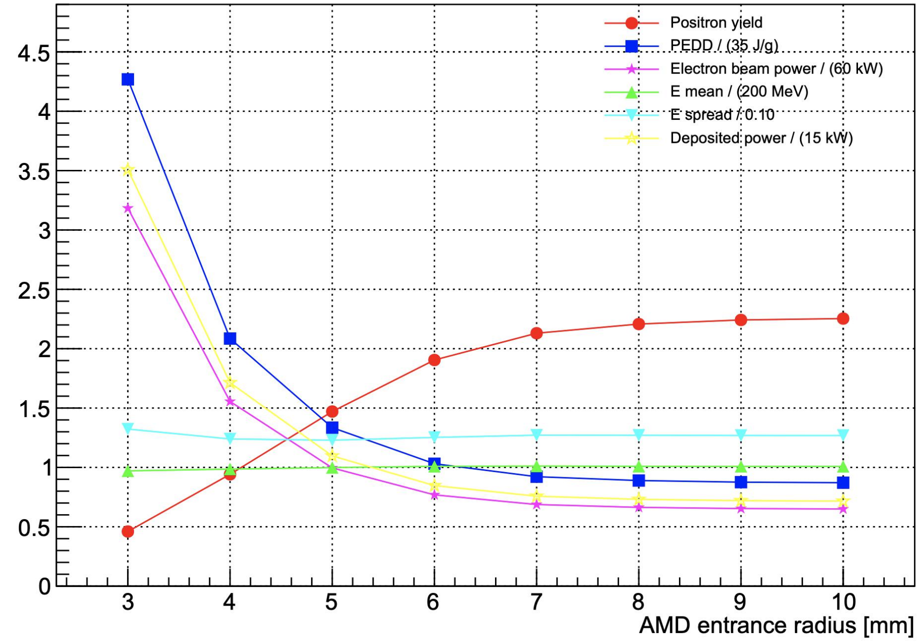


spot size: 1.3 mm

Optimisation scan plots (CLIC, 380 GeV)

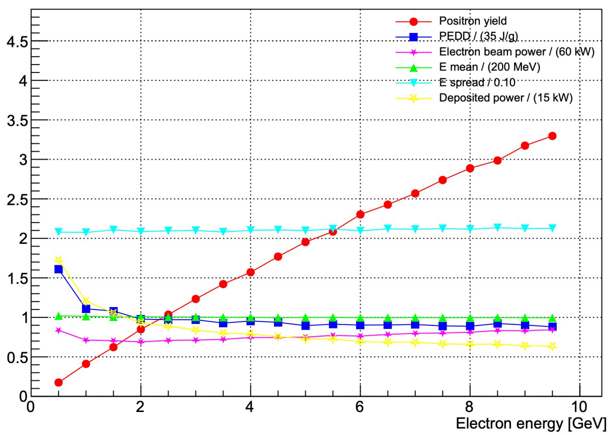
- Analytic AMD
- Scan of spot size, AMD aperture

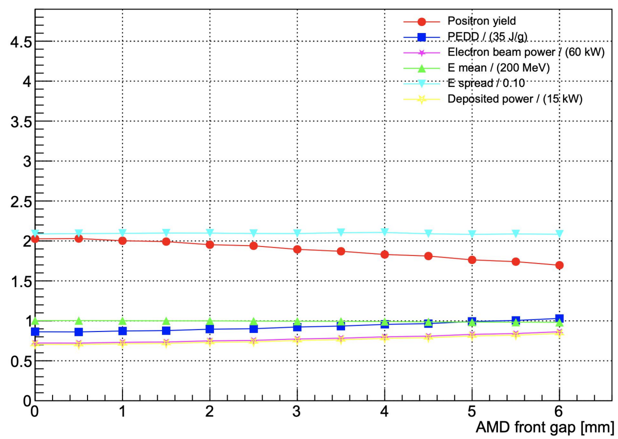


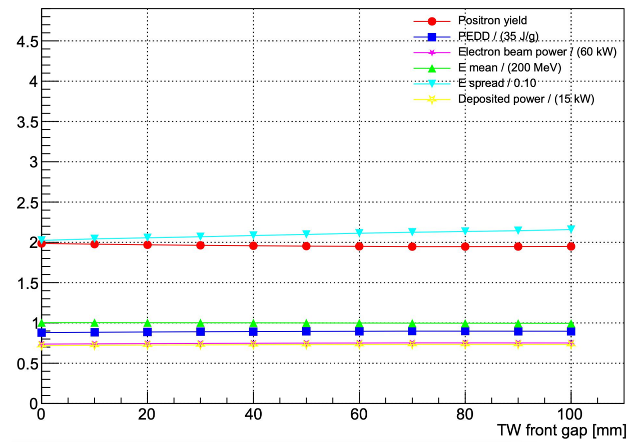


Optimisation scan plots (CLIC, 380 GeV)

- FC with linear aperture
- Scan of primary e$^-$ energy, distance between target and AMD, distance between AMD and TW







Comparison with old results (CLIC)

- Comparison with previous results
  - Stage: 1.5 (3) TeV   Primary e^- energy: 5 GeV
  - Previous results recalculated by removing 25% yield over-estimation due to old AMD aperture simulation
  - PEDD in old results re-normalised to updated bunch charge

Results	Spot size	Distance betw. targets	Final eff. e^+ yield	PEDD [J/g]	
CDR (2012)	2.5 mm	2 m	0.31	38.8	
Implementary plan report (2018)	2.5 mm	2 m	0.78	15.6	
Yanliang HAN (2019)	1.25 mm	0.65 m	1.55	29.0	
		0	2.78	35.0	(my test)
Yongke (2020)	1.7 mm	0	2.22	31.2	
Yongke (2021)	1.5 mm	–	2.50	31.7	

- The yield improved significantly in my results mainly due to the constraint on the distance between hybrid targets is removed (as confirmed by the test)

BACKUP