Optimisation of the CLIC positron source

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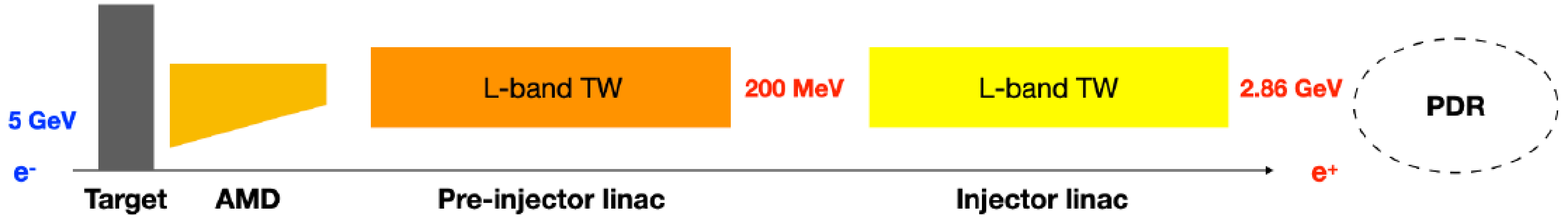
Outline

- Introduction
- Baseline option
- Alternative options
- Conclusions

Introduction

- Schematic layout (**baseline**) of the CLIC positron source



- Merit functions to optimize
  - Maximum accepted positron yield by PDR
  - Peak energy deposition density (PEDD) < 35 J/g

Accepted e^+ yield: $\eta = \frac{N_{e^+}^{\mathrm{PDR}}}{N_{e^-}^{\mathrm{Primary}}}$

- Simulation
  - Electron gun & drive beam linac are not simulated
  - Primary electron drive beam simulated with Gaussian sampling
  - Target simulated with Geant4
  - Matching device (AMD) magnetic field obtained from Opera®
  - Pre-injector linac (capture linac) simulated with RF-Track
  - Injector linac simulated with Placet

Beam parameters

- Primary e^- beam parameters

Drive-beam based mode assumed

  - Spot size is a free parameter

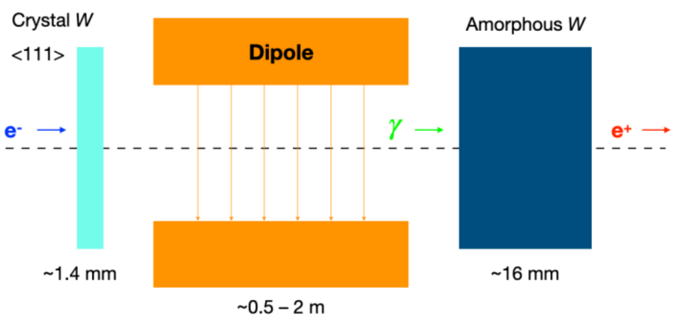
Electron beam parameter	Unit	380 GeV	3 TeV
Beam energy	GeV	5	
Number of bunches per train		352	312
Bunch length (RMS)	mm	1	
Energy spread (RMS)	%	0.1	
Emittance, $\epsilon^n_{x,y}$	mm·mrad	80	

- Required e^+ beam parameters at PDR entrance
  - 20% safety margin is included in the bunch charge

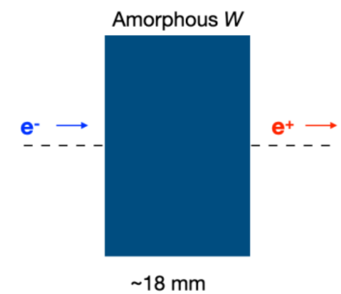
Positron beam parameter	Unit	380 GeV	3 TeV
Beam energy	GeV	2.86	
Number of bunches per train		352	312
Bunch population		6.24×10^9	4.44×10^9
Bunch charge	nC	1.00	0.71
PDR energy acceptance (±)	%	1.2	
PDR time window (total length)	mm/c	20	

Target

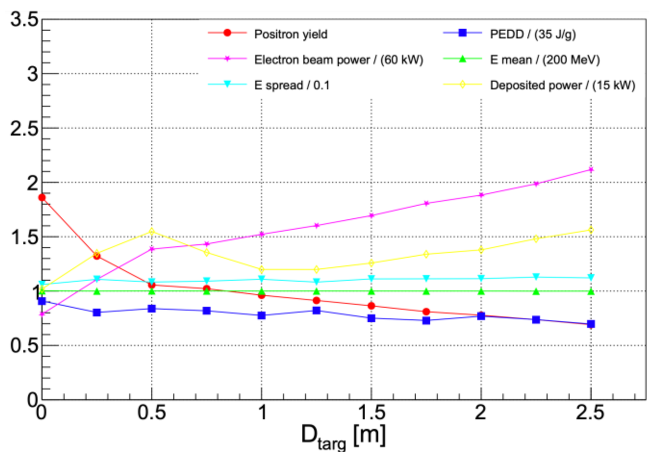
- Previously, in the old baseline of the CDR and the PIP report, a hybrid target was proposed to reduce the PEDD. However, we found that the yield is also reduced significantly. Therefore, in our new baseline, the conventional target is assumed



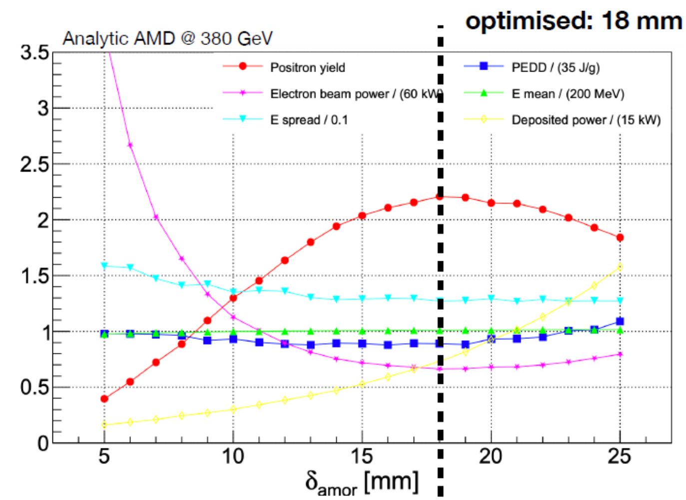
Hybrid target option (old baseline)



Conventional target option (**new baseline**)



Hybrid target distance scan (old plot)

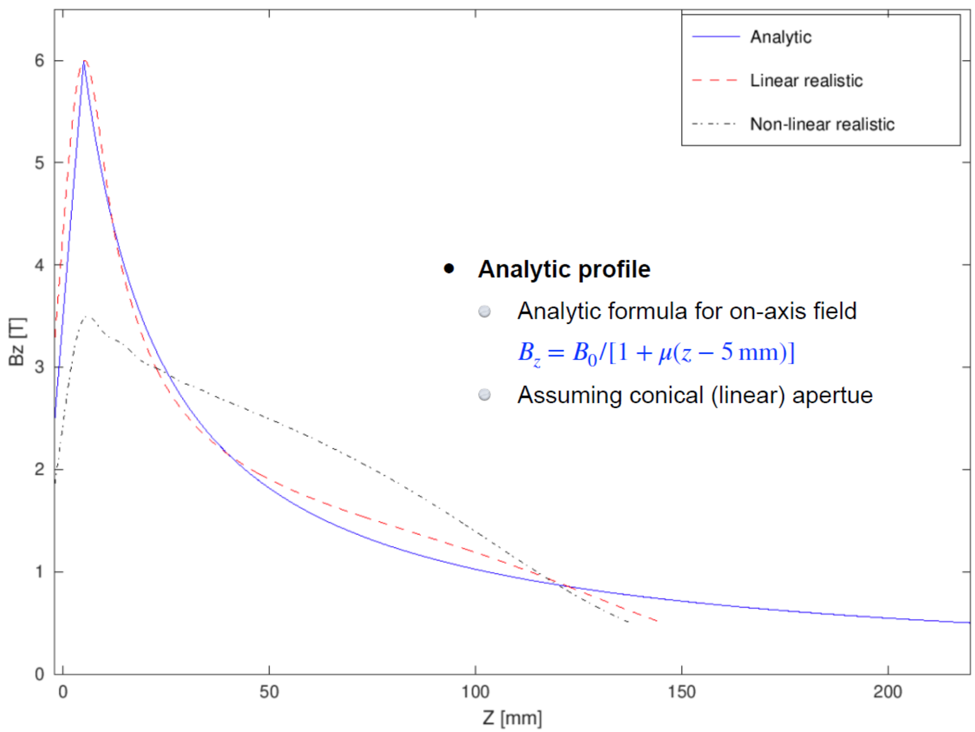


Conventional target thickness scan (old plot)

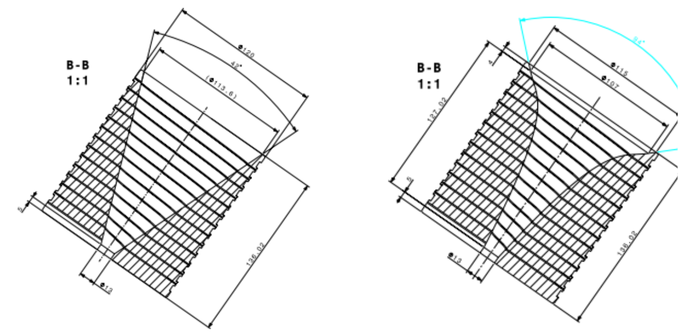
Adiabatic matching device (AMD)

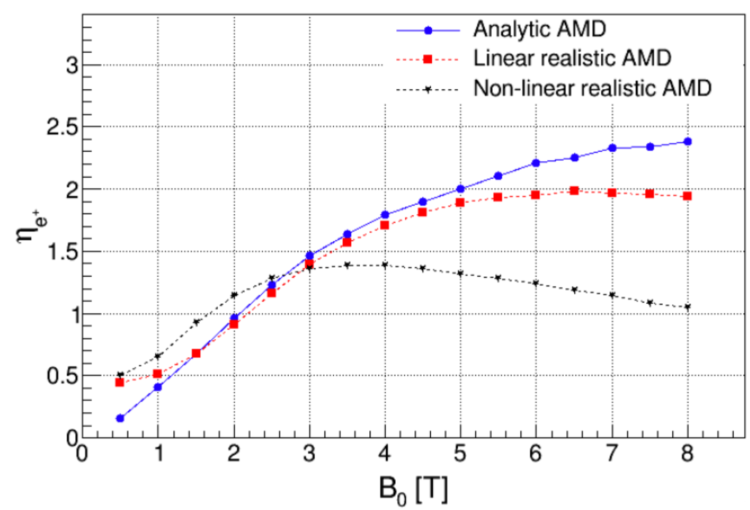
- Two main types of flux concentrator (FC) used as the AMD are studied
  - Linear aperture: higher peak field, much higher yield (**baseline**)
  - Non-linear aperture: lower power supply & voltage, lower yield
  - ✓ Manufacturing with EDM or 3D printing (to test at KEK)

Designed by H. Bajas



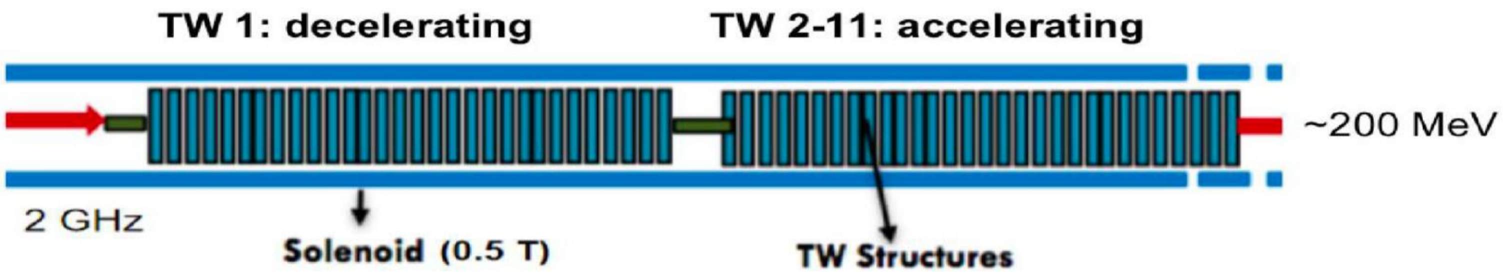
Field map (peak field scaled to optimised value)





Peak field optimization (max. allowed: 6 T)

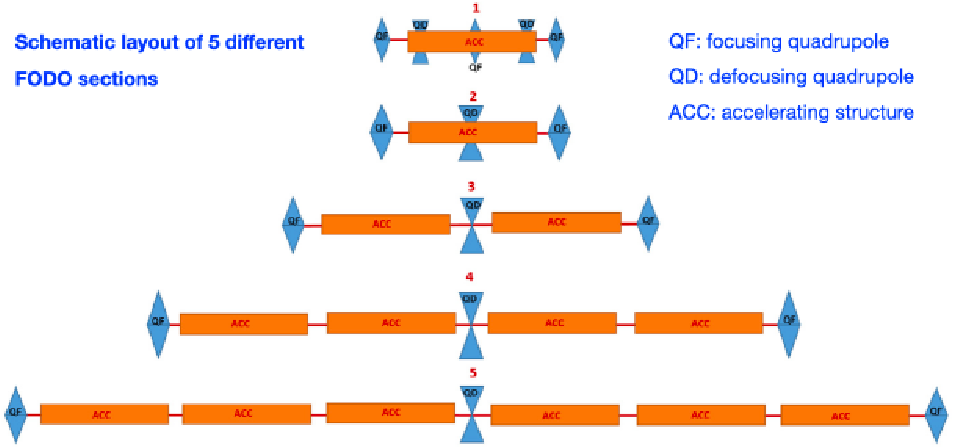
Pre-injector linac

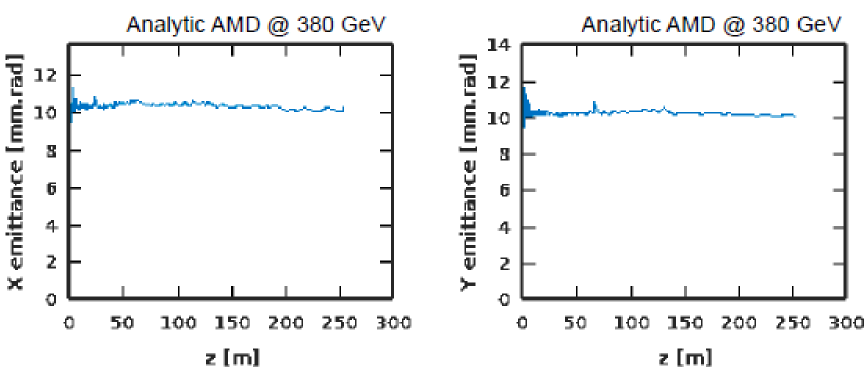


- CLIC L-band (similar with injector and booster linacs), 2 GHz travelling wave (TW) structures, $2\pi/3$
- 1.5 m long, 20 mm iris radius aperture, 200 mm distance
- Number of structures: 1 dec. + 10 acc. (phases optimised for max. PDR accepted yield)
- To simplify the study, RF gradients are fixed at 20 MV/m, acc. structures have the same phase
- NC solenoid (up to ~200 MeV): 0.5 T
- It is also found that (if technically allowed)
  - ✓ Yield can be increased with shorter distance (between dec. and acc. structures)
  - ✓ Yield can be increased with higher NC solenoid field

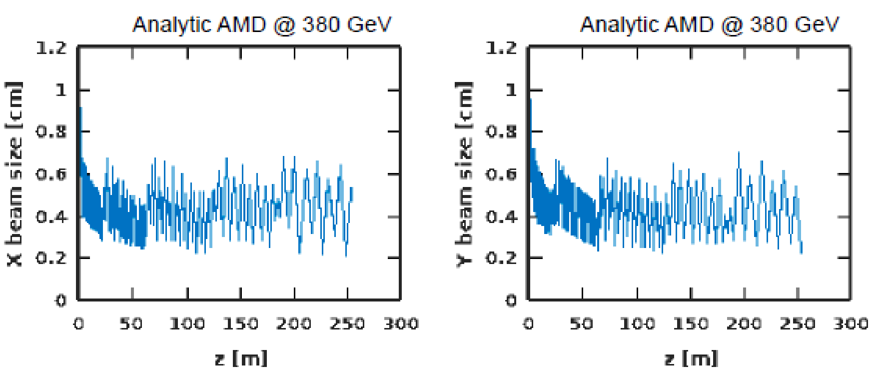
Injector linac

- **In optimisation** **analytic**
  - $\Delta E = (2.86\,\mathrm{GeV} - E_{\mathrm{ref}}) \cdot \cos[\omega \cdot (t - t_{\mathrm{ref}})]$
  - Reference particle with energy ~200 MeV
- **In final simulation**
  - based on previous design by C. Bayar
  - 5 different FODO sections
  - 143 quadupoles (16 for matching)
  - Good matching & no loss in yield





Normalised emittances (RMS) vs Z position



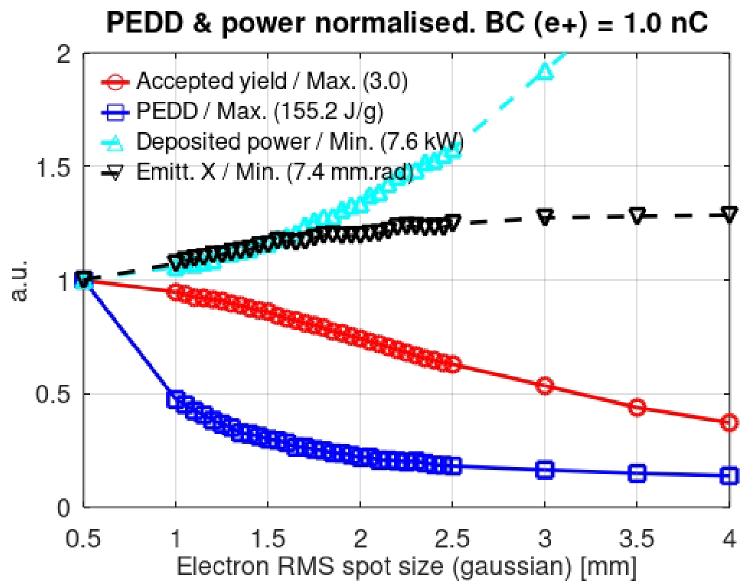
Beam sizes (RMS) vs Z position

✓ **The analytic formula is used, as it was found to have consistent final results with Placet simulation**

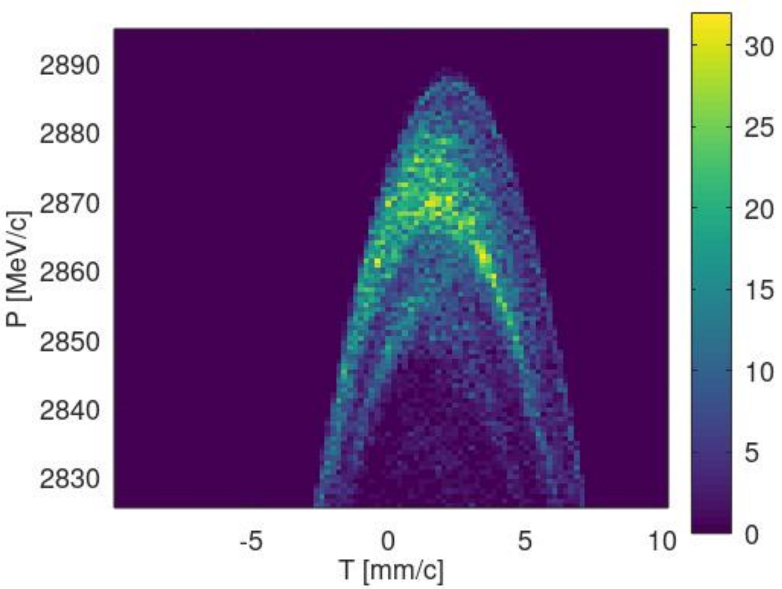
Baseline final results

- Optimisation results

Positron beam parameter	Unit	380 GeV	3 TeV
Optimised electron beam spot size, $\sigma_{x,y}$	mm	2.10	1.40
Electron bunch charge required	nC	0.47	0.28
Electron beam power required	kW	39.3	20.3
Positron bunch charge required at PDR entrance	nC	1.00	0.71
Positron yield accepted by PDR		2.12	2.58
Normalised total deposited power in target	kW	10.6	5.5
Normalised PEDD in target	J/g	32.0	31.6



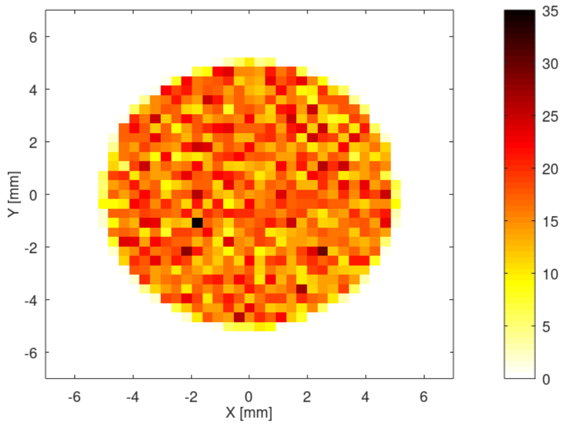
Primary e^- beam **spot size** scan (380 GeV)



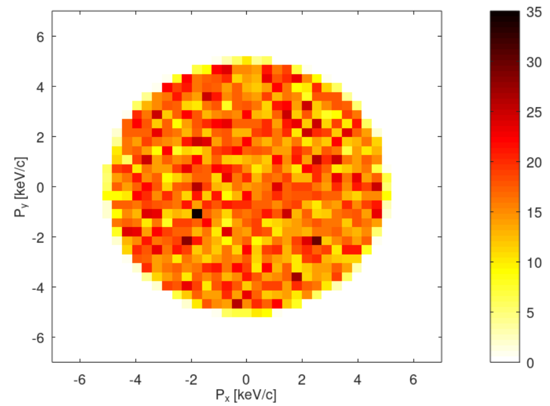
Longitudinal e^+ phase space (PDR accepted)

Alternative option 1: uniform beam

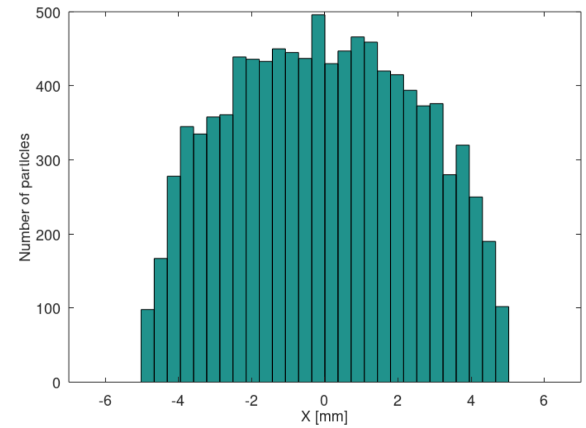
- Primary e⁻ beam with uniform transverse distribution



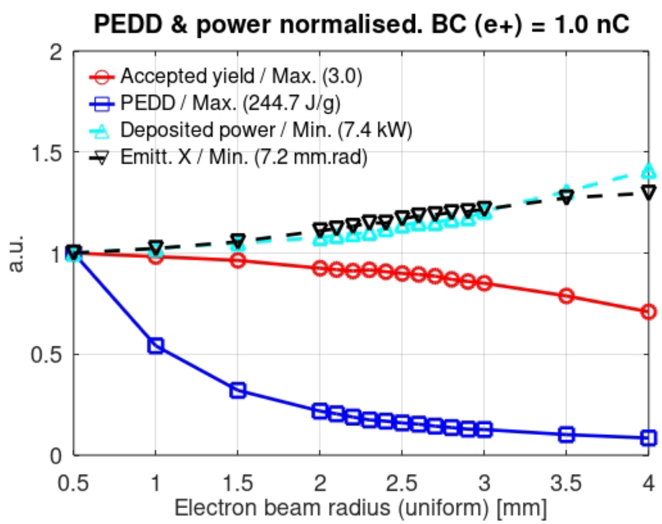
Transverse position



Transverse momentum



Horizontal position



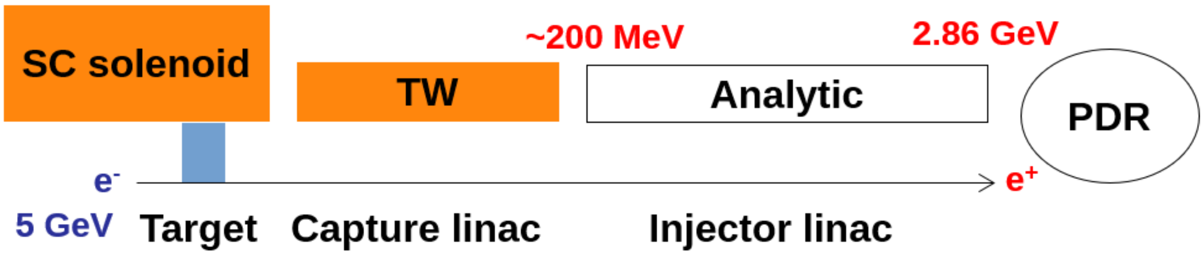
Beam radius scan

- Optimisation results

Positron beam parameter	Unit	380 GeV	3 TeV
Optimised electron beam radius, $R_{x,y}$	mm	2.90	2.10
Electron bunch charge required	nC	0.39	0.26
Electron beam power required	kW	32.5	19.0
Positron bunch charge required at PDR entrance	nC	1.00	0.71
Positron yield accepted by PDR		2.57	2.74
Normalised total deposited power in target	kW	8.7	5.1
Normalised PEDD in target	J/g	31.5	31.5

Alternative option 2: SC AMD

- Schematic layout with a SC solenoid as AMD (idea from FCC-ee study)

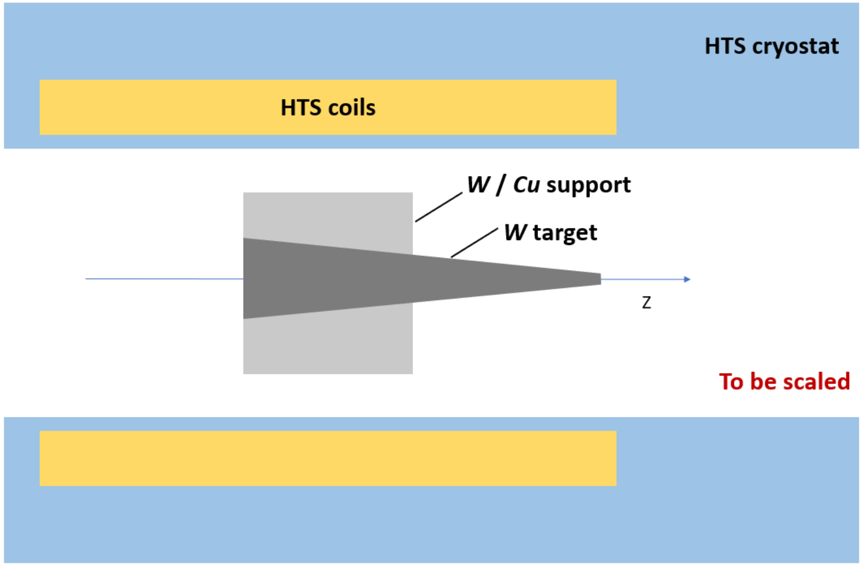


- Optimisation results of using the FCC-ee HTS AMD for CLIC
  - Reoptimisation of the HTS field (analytic) shows very little improvement

Positron beam parameter	Unit	380 GeV	3 TeV
Optimised electron beam spot size	mm	1.85	1.20
Optimised target exit face position	mm	75	62
Electron bunch charge required	nC	0.38	0.22
Electron beam power required	kW	32.1	16.2
Positron bunch charge required at PDR entrance	nC	1.00	0.71
Positron yield accepted by PDR		2.60	3.22
Normalised total deposited power in target	kW	8.6	4.4
Normalised PEDD in target	J/g	32.5	31.2

Alternative option 3: tapered target + SC AMD

- Tapered target (idea from FCC-ee study)
  - Target to be put inside a SC AMD
  - FCC-ee HTS AMD field is used



- Optimisation results

Parameter	Unit	380 GeV	3 TeV
Tungsten or copper support length	mm	15	
Optimised target length	mm	27.6	26.1
Optimised target radius at the entrance	mm	5.4	3.5
Optimised target radius at the exit	mm	0.55	0.33
Optimised electron beam spot size	mm	1.80	0.95
Optimised target exit face position	mm	84	63
Electron bunch charge required	nC	0.32	0.15
Electron beam power required	kW	30.1	12.5
Positron bunch charge required at PDR entrance	nC	1.00	0.71
Positron yield accepted by PDR		3.12	4.84
Normalised total deposited power in target	kW	6.6	2.6
Normalised PEDD in target	J/g	31.7	32.3

Alternative option 4: Uniform beam + tapered target + SC AMD

- Optimisation results (uniform beam + tapered target + FCC-ee HTS AMD)

Parameter	Unit	380 GeV	3 TeV
Tungsten or copper support length	mm	15	
Optimised target length	mm	30.5	30.2
Optimised target radius at the entrance	mm	4.5	3.1
Optimised target radius at the exit	mm	0.54	0.32
Optimised electron beam radius	mm	2.30	1.40
Optimised target exit face position	mm	94.3	64
Electron bunch charge required	nC	0.24	0.12
Electron beam power required	kW	22.7	10.7
Positron bunch charge required at PDR entrance	nC	1.00	0.71
Positron yield accepted by PDR		4.20	5.72
Normalised total deposited power in target	kW	6.6	2.9
Normalised PEDD in target	J/g	32.4	32.9

Alternative option 5: lower beam energy

- Lower e⁻ drive beam energy requires shorter drive beam linac, but larger bunch charge
- Optimisation results

380 GeV

Parameter	Unit	Values	
Electron beam energy	GeV	1	3
Optimised electron beam spot size, $\sigma_{x,y}$	mm	2.30	2.15
Optimised target thickness	mm	13	16
Electron bunch charge required	nC	2.17	0.78
Electron beam power required	kW	35.3	38.1
Positron bunch charge required at PDR entrance	nC	1.00	1.00
Positron yield accepted by PDR		0.46	1.29
Normalised total deposited power in target	kW	9.5	9.7
Normalised PEDD in target	J/g	32.3	32.4

3 TeV

Parameter	Unit	Values	
Electron beam energy	GeV	1	3
Optimised electron beam spot size, $\sigma_{x,y}$	mm	1.45	1.35
Optimised target thickness	mm	13	16
Electron bunch charge required	nC	1.20	0.43
Electron beam power required	kW	17.2	19.3
Positron bunch charge required at PDR entrance	nC	0.71	0.71
Positron yield accepted by PDR		0.59	1.64
Normalised total deposited power in target	kW	4.6	4.9
Normalised PEDD in target	J/g	31.8	32.6

Comparison of results

- Comparison of all options
  - **UB**: using **uniform** e- drive beam, otherwise same with baseline
  - **HTS**: using FCC-ee **HTS AMD**, otherwise same with baseline
  - **TT**: using **tapered target** + HTS AMD, otherwise same with baseline
  - **UB-TT**: using **uniform** beam + **tapered** target + HTS AMD, otherwise same with baseline
  - **LE**: using **lower** e- drive beam **energy**, otherwise same with baseline

380 GeV

Parameter	Unit	Baseline	UB	HTS	TT	UB-TT	LE
Electron beam energy	GeV	5	5	5	5	5	3
Electron beam spot size or radius	mm	2.10	2.90	1.85	1.80	2.30	2.15
Electron bunch charge required	nC	0.47	0.39	0.38	0.32	0.24	0.78
Electron beam power required	kW	39.3	32.5	32.1	30.1	22.7	38.1
Normalised PEDD in target	J/g	32.0	31.5	32.5	31.7	32.4	32.4
Positron bunch charge required at PDR entrance	nC	1.00	1.00	1.00	1.00	1.00	1.00
Positron yield accepted by PDR	e^+/e^-	2.12	2.57	2.60	3.12	4.20	1.29

3 TeV

Parameter	Unit	Baseline	UB	HTS	TT	UB-TT	LE
Electron beam energy	GeV	5	5	5	5	5	1
Electron beam spot size or radius	mm	1.40	2.10	1.20	0.95	1.40	1.45
Electron bunch charge required	nC	0.28	0.26	0.22	0.15	0.12	1.20
Electron beam power required	kW	20.3	19.0	16.2	12.5	10.7	17.2
Normalised PEDD in target	J/g	31.6	31.5	31.2	32.3	32.9	31.8
Positron bunch charge required at PDR entrance	nC	0.71	0.71	0.71	0.71	0.71	0.71
Positron yield accepted by PDR	e^+/e^-	2.58	2.74	3.22	4.84	5.72	0.59

Conclusions

- Though yields were likely over-estimated previously, a comparison is made
  - AMD aperture seems not simulated in previous studies (not tapered): ~25% yield loss
  - PDR energy acceptance seems too large in previous studies (1.2% rms): ~15% yield loss
  - Compared with the old **CDR baseline** published in 2012 (η = 0.4 @ 3 TeV), the **new baseline** yield (2.1 @ 380 GeV, 2.6 @ 3 TeV) is increased by factors of **6.5**
  - Compared with the old **PIP baseline** published in 2018 (η = 1.0 @ 3 TeV), the **new baseline** yield is increased by a factor of **2.6**
  - Compared with a **report by Y. Han** published in 2019 (1.3 @ 380 GeV, 1.9 @ 3 TeV), the yields are increased by **63%** and **33%**
- **Alternative options** (though a bit challenging), **compared with the new baseline**, at 380 GeV (3 TeV), can further improve the yield:
  - Yield is increased by 21% (6%) if using uniform e- drive beam
  - Yield is increased by 23% (25%) if using FCC-ee HTS AMD
  - Yield is increased by 47% (88%) if using tapered target + HTS AMD
  - Yield is increased by 98% (122%) if using uniform beam + tapered target + HTS AMD
  - 0.8 (1.2) nC e- bunch is required if energy reduced to 3 (1) GeV
- Next steps
  - Try to design a lattice for the uniform drive beam (quite challenging)

Acknowledgement

- **Thanks very much for your attention!**
- We thank H. Bajas for his efforts in designing the flux concentrator for the baseline CLIC AMD when he worked at CERN.
- We also thank J. Kosse, B. Auchmann, M. Duda, et al. from PSI for providing the HTS solenoid field map designed for the FCC-ee AMD.

Backup