Optimisation of the CLIC positron source

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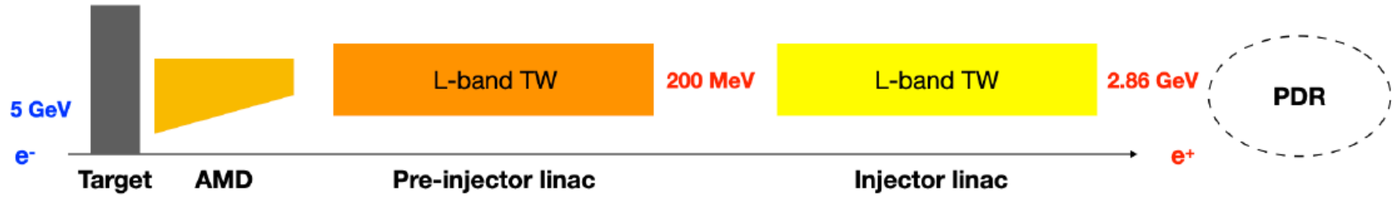
Outline

- Introduction
- New baseline
- Alternative options
- Conclusions

Introduction

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



- Requirements
  - Maximum positron yield accepted by PDR
  - Peak energy deposition density (PEDD) < 35 J/g

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

- "**Full**" Simulation
  - Target simulated with **Geant4** (with Gaussian beam profile)
  - **Realistic** magnetic field of the matching device (AMD) obtained from **Opera®**
  - **Analytic** field for NC **solenoids** @ 0.5 T. **Uniform** field assumed for the **chicane**
  - **3D field** for **L-band** from **CST**. Tracking simulated with **RF-Track**
- "**Fast**" simulation – for optimisations

PEDD < 30 J/g in fast simulation

  - Simulation up to pre-injector linac (~200 MeV) with **constant** field @ 0.5 T
  - Then use **analytic** formula (longitudinal tracking) up to PDR:

$$\Delta E = (2.86\,\mathrm{GeV} - E_{\mathrm{ref}}) \cdot \cos(2\pi f \cdot (t - t_{\mathrm{ref}}))$$

Beam parameters

- Primary e⁻ beam parameters
  - DBA: drive-beam based acceleration mode; KBA: klystron based acceleration mode
  - Spot size of 2.5 mm is from old baseline. We will reoptimise it

Electron beam parameter	Unit	380 GeV		1.5 & 3 TeV
Acceleration mode		DBA	KBA	DBA
Beam energy	GeV	5	5	5
Energy spread (σ_E/E)	%	0.1	0.1	0.1
Bunch length (σ_z)	mm	1	1	1
Spot size ($\sigma_{x,y}$)	mm	2.5	2.5	2.5
Emittance, $\epsilon^n_{x,y}$	mm·mrad	80	80	80
Number of bunches per train		**352**	**485**	**312**

✓ 1.5 TeV always has the same parameters and results as 3 TeV

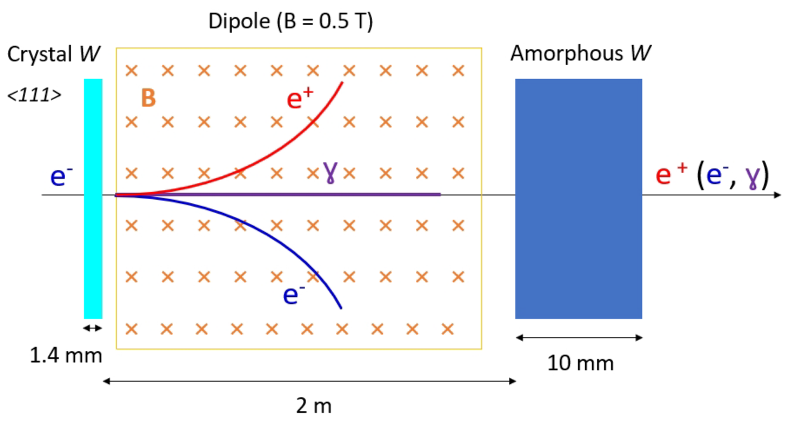
- Required e⁺ beam parameters at PDR entrance (accepted)
  - 20% safety margin is considered

Positron beam parameter	Unit	380 GeV		1.5 & 3 TeV
Acceleration mode		DBA	KBA	DBA
Beam energy	GeV	2.86	2.86	2.86
Number of bunches per train		**352**	**485**	**312**
Bunch population without safety margin	10^9	5.200	3.870	3.700
Bunch population with safety margin	10^9	6.240	4.644	4.440
Bunch charge without safety margin	nC	0.833	0.620	0.593
Bunch charge with safety margin	nC	**1.000**	**0.744**	**0.711**
PDR energy acceptance (±)	%	1.2	1.2	1.2
PDR time window (total length)	mm/c	20	20	20

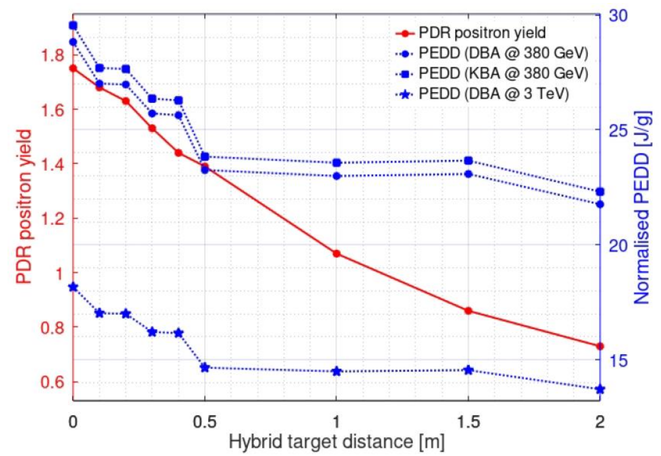
PDR acceptance cuts

Target

- **Old baseline**

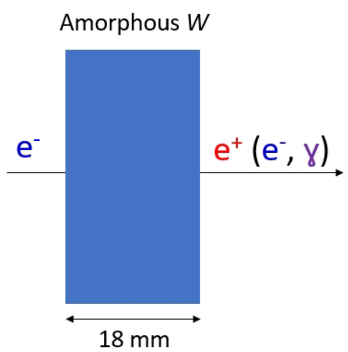


Hybrid target option

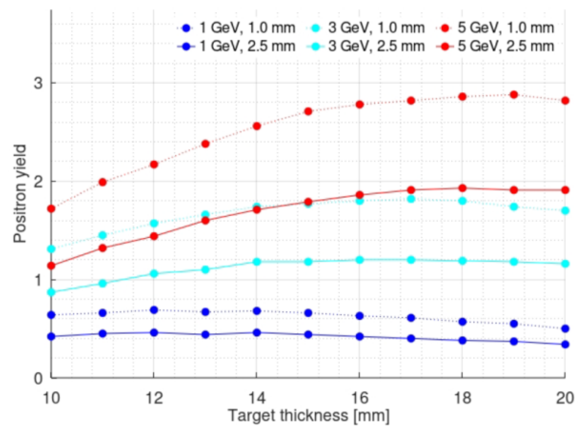


Hybrid target distance scan

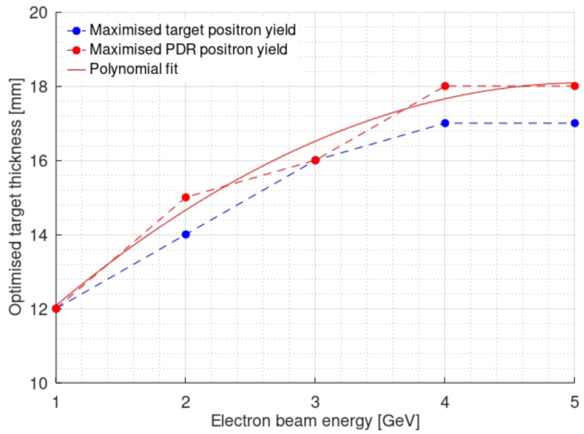
- **New baseline**



Single target option



Single target thickness scans



Optimised target thickness vs beam energy

Target

- DBA @ 380 GeV

Parameter	Unit	Old baseline	New baseline
Electron beam energy	GeV	5	5
Electron beam spot size	mm	2.50	2.40
Electron bunch charge needed	nC	1.37	0.51
Normalised electron beam power	kW	120.5	44.4
Target profile		Hybrid	Single
Target thickness	mm	1.4, 10	18
Distance of hybrid target	m	2	-
Normalised PEDD in amorphous target	J/g	21.8	29.8
Normalised deposited power in amorphous target	kW	12.3	12.0
PDR positron yield	e^+/e^-	**0.73**	**1.98**

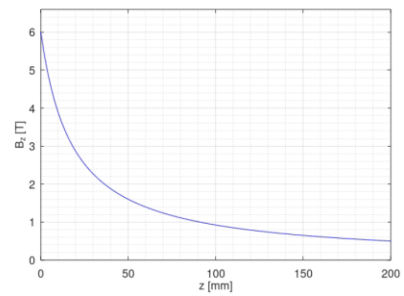
- DBA @ 3 TeV

Parameter	Unit	Old baseline	New baseline
Electron beam energy	GeV	5	5
Electron beam spot size	mm	2.5	1.50
Electron bunch charge needed	nC	0.97	0.27
Normalised electron beam power	kW	76.0	21.2
Target profile		Hybrid	Single
Target thickness	mm	1.4, 10	18
Distance of hybrid target	m	2	-
Normalised PEDD in amorphous target	J/g	13.7	29.6
Normalised deposited power in amorphous target	kW	7.7	5.7
PDR positron yield	e^+/e^-	**0.73**	**2.61**

Adiabatic matching device (AMD)

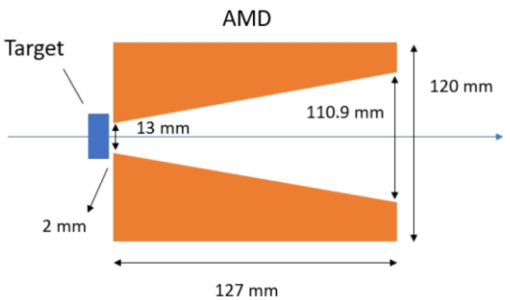
- **Old baseline**
  - Constant large aperture (40 mm)
  - Analytic field from the adiabatic formula

$$B_z = \frac{B_0}{1 + \mu \cdot z}$$

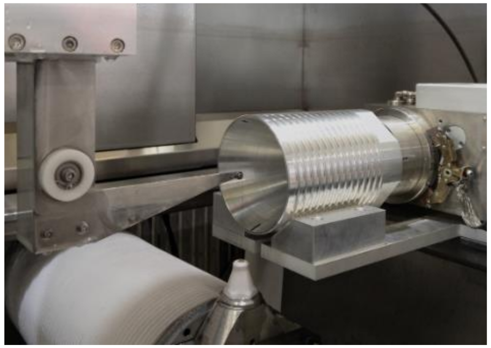


On-axis Bz field

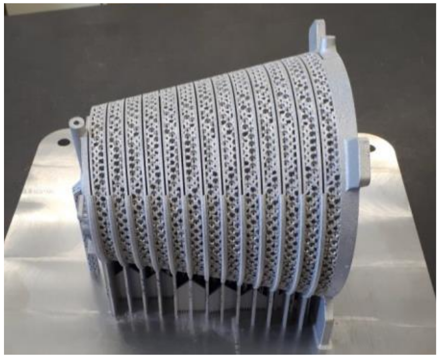
- **New baseline**
  - FC designed (*H. Bajas et al.*) with Opera®
  - Realistic field and tapered aperture
  - Manufacturing (*S. Doebert et al.*) with EDM or 3D printing in progress



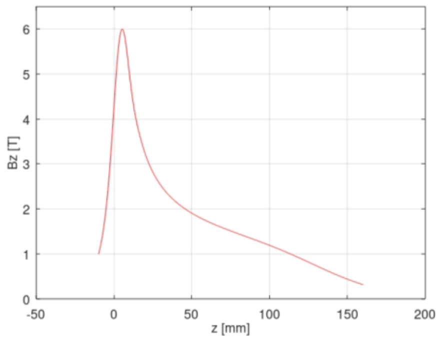
Schematic layout



EDM



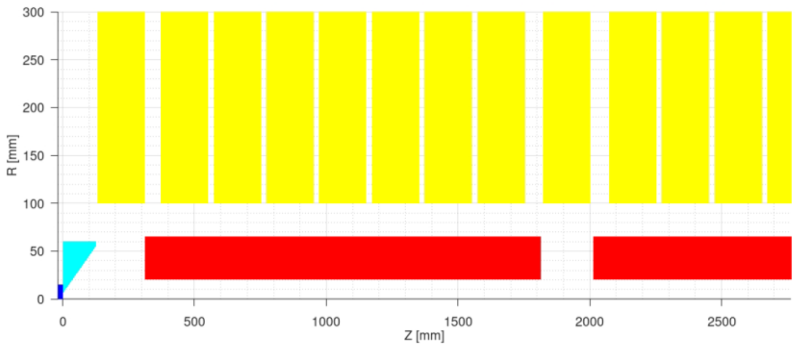
3D printing

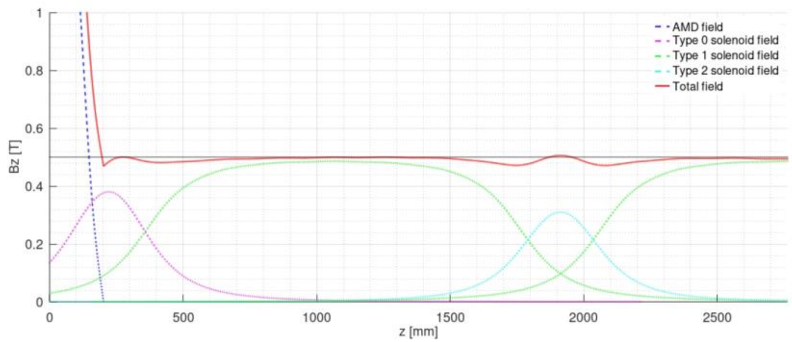


On-axis Bz field

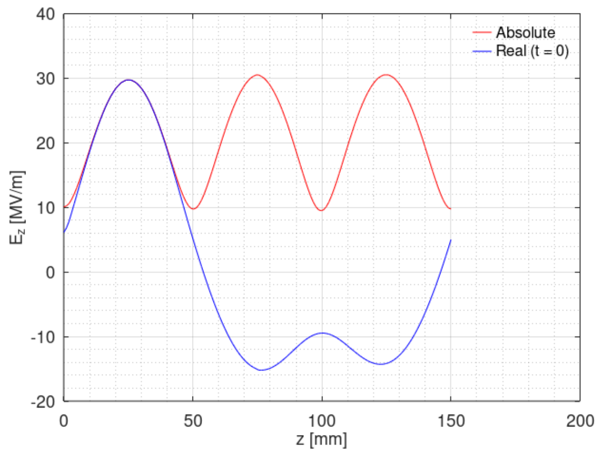
Pre-injector linac

- CLIC L-band (similar with injector and booster linacs), 2 GHz travelling wave (TW) structures, 2π/3
- 1.5 m long, 20 mm constant iris radius aperture assumed, 200 mm distance
- Number of structures: 1 at dec. phase + 10 at acc. phase (two phases used and optimised for max. PDR accepted positron yield)
- To simplify the study, RF gradients are fixed at 20 MV/m
- Surrounded with NC solenoids (up to ~200 MeV): ~0.5 T





Schematic layout and on-axis Bz field (partial)



On-axis Ez field (3 cells)

NC solenoid types

Parameter	Symbol	Unit	Type 0	Type 1	Type 2
Average radius	R	mm	200	200	200
Length	l	mm	180	180	180
Peak field	B_0	T	0.38	0.23	0.31

Chicane

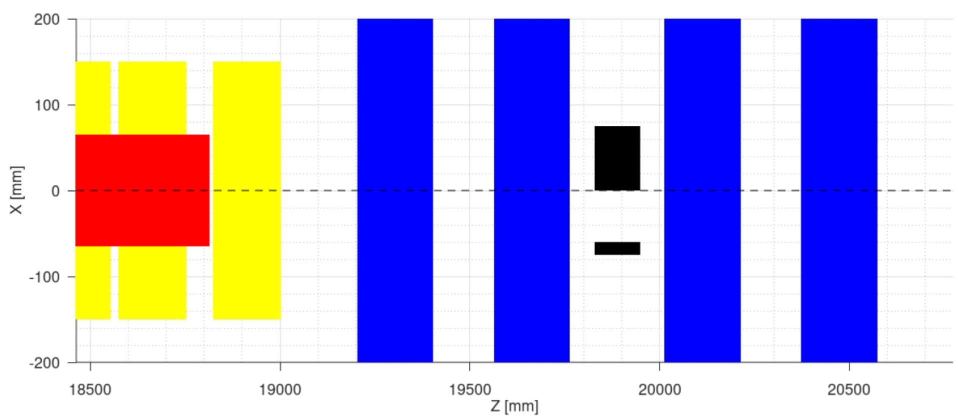
- Chicane (and collimator) parameters

Chicane

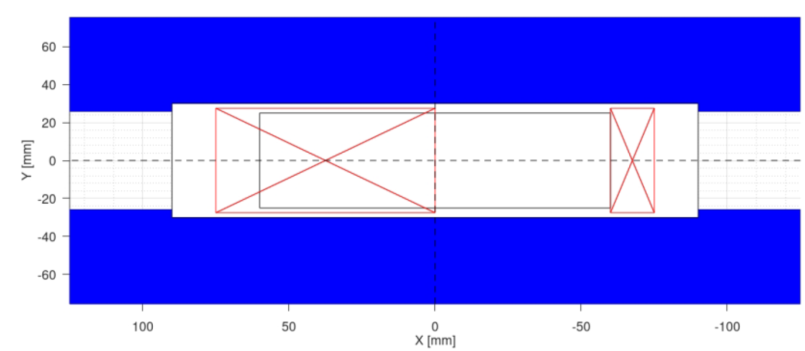
Parameter	Symbol	Unit	Value
Dipole length	l	mm	200
Reference energy	e_0	MeV	200
Bending angle	θ	°	4.8, -4.8, -4.8, 4.8
Beam pipe aperture inside dipoles (total width)	D_x, D_y	mm	120, 50
Beam pipe aperture for collimator (total width)	D_x, D_y	mm	180, 60
Distance between chicane and other sections	d_0, d_4	mm	200, 200
Distance between dipoles	d_1, d_2, d_3	mm	160, 250, 160

Collimator

Parameter	Symbol	Unit	Value
Collimator length	l	mm	120
Offset of the aperture	x_0	mm	-30
Aperture (total width)	D_x, D_y	mm	60, 60



Schematic layout in X-Z plane



Schematic layout in X-Y plane

Injector linac

- Accelerate both e^- and e^+ from 200 MeV to **2.86 GeV**.
- Same L-band RF structure as in pre-injector linac

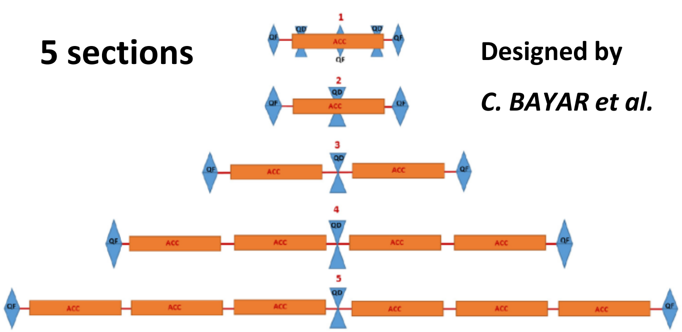
Lattice parameters

Parameter	Symbol	Unit	S1	S2	S3	S4	S5
Total FODO cells	N_{FODO}		16	18	14	7	6
FODO lattice phase advance	μ	°	90	90	90	90	90
Total quadrupoles	N_{Q}		33	37	29	15	13
Quadrupole length	l_{Q}	m	0.4	0.4	0.4	0.4	0.4
Spacing between quadrupoles	d	m	0.15	0.64	1.65	3.15	4.90
Quadrupoles surrounding a RF structure	n_{Q}		3	1	0	0	0
Total RF structures	N_{RF}		8	18	28	28	36

RF parameters (common for all sections)

Parameter	Symbol	Unit	Value
RF frequency	f	GHz	2
RF structure length	l	m	1.5
RF structure aperture (radius)	a_0	mm	20
RF average gradient without compensation	G	MV/m	15.12
RF average gradient with compensation for short-range wakefield	G	MV/m	15.19
RF phase	φ	°	0

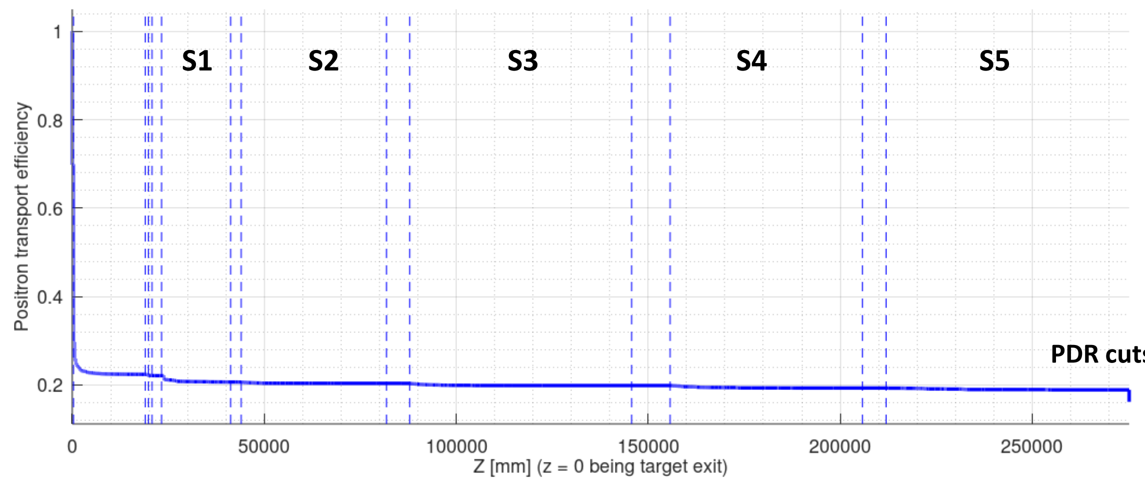
5 sections



Designed by

C. BAYAR et al.

Schematic layout



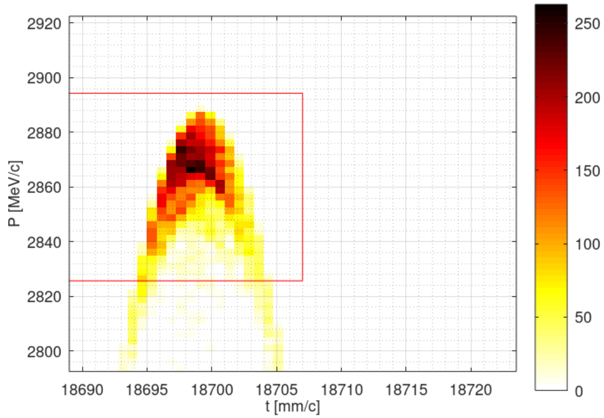
Transport efficiency

Preliminary. Matching optimisation in progress.

Baseline final results

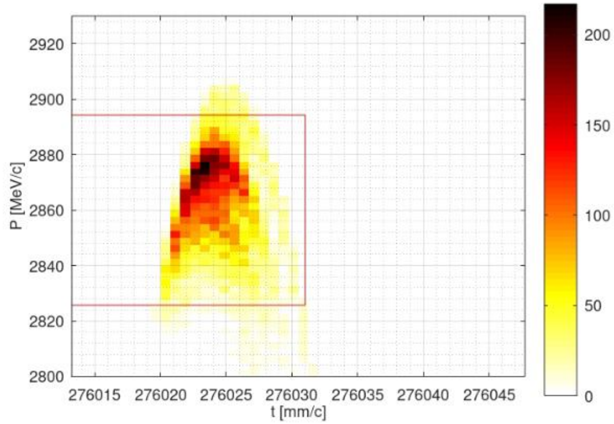
- “Fast” simulation results
  - Less realistic, but **much faster** (especially for optimisations)

Parameter	Unit	380 GeV		1.5 & 3 TeV
Acceleration mode		DBA	KBA	DBA
Optimised electron beam spot size	mm	2.40	2.45	1.50
Positron yield accepted by PDR		**1.98**	**1.95**	**2.61**
Electron bunch charge required	nC	0.51	0.38	0.27
Electron beam power required	kW	44.4	46.3	21.2
Normalised PEDD in target	J/g	29.8	29.6	29.6
Normalised total deposited power in target	kW	12.0	12.4	5.7



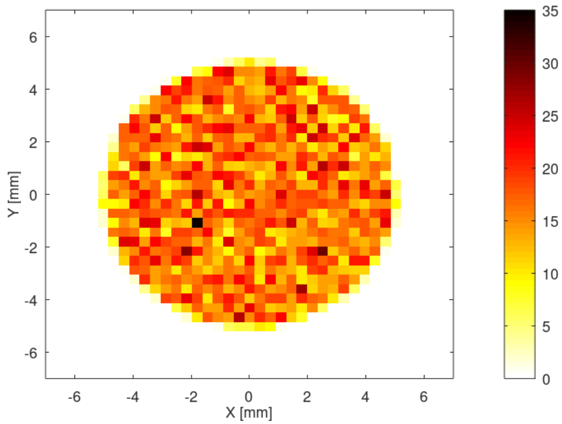
- “Full” simulation results
  - ~12% loss of yield compared with “fast” simulation, but **more realistic**

Parameter	Unit	380 GeV		1.5 & 3 TeV
Acceleration mode		DBA	KBA	DBA
Optimised electron beam spot size	mm	2.40	2.45	1.50
Positron yield accepted by PDR		**1.78**	**1.74**	**2.36**
Electron bunch charge required	nC	0.56	0.43	0.30
Electron bunch charge assumed for collective effects	nC	0.8	0.6	0.4
Electron beam power required	kW	49.4	51.8	23.5
Normalised PEDD in target	J/g	33.1	33.2	32.8
Normalised total deposited power in target	kW	13.3	13.9	6.3

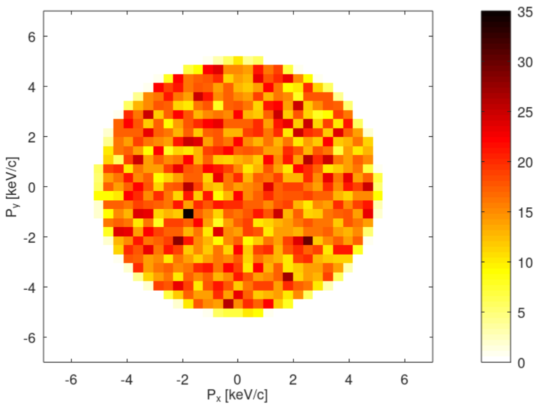


Alternative options: uniform beam

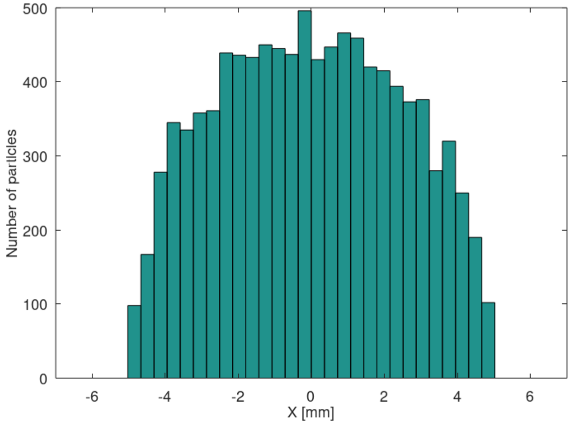
- Primary e⁻ beam with uniform profile (transverse distribution)



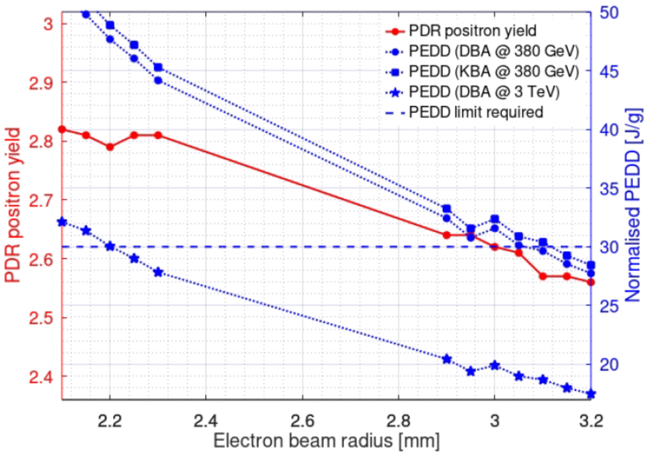
Transverse positions



Transverse momentums



Horizontal position



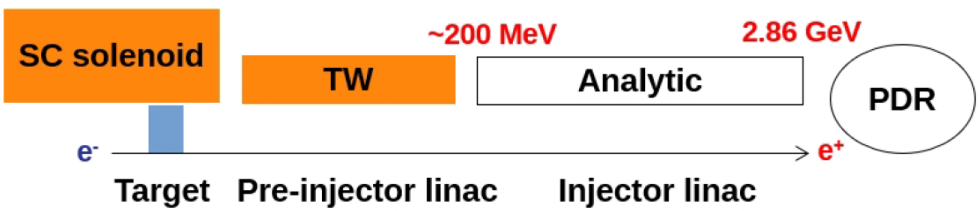
Beam radius scan

- Optimisation results (e.g. DBA @ 380 GeV)

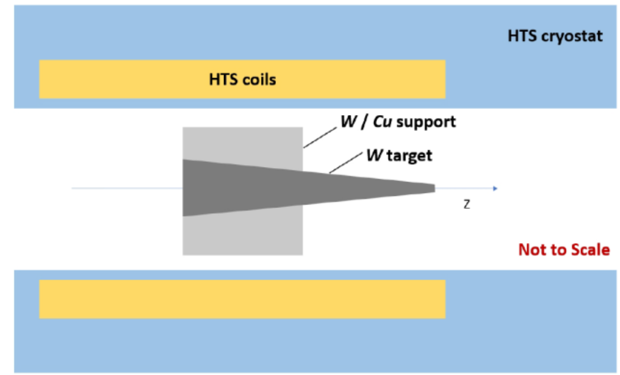
Parameter	Unit	Gaussian	Uniform
Optimised electron beam size, $\sigma_{x,y}$ or $R_{x,y}$	mm	2.40	3.10
PDR positron yield		1.98	2.57
Electron bunch charge required	nC	0.51	0.39
Electron beam power required	kW	44.4	34.2
Normalised PEDD in target	J/g	29.8	29.6
Normalised total deposited power in target	kW	12.0	9.4

Alternative options: SC AMD

- Using a SC solenoid as AMD (HTS solenoid field from PSI for FCC-ee study)
- Target can then be tapered to increase yield (originally conceived by *Nicolas Vallis* from PSI for FCC-ee study)

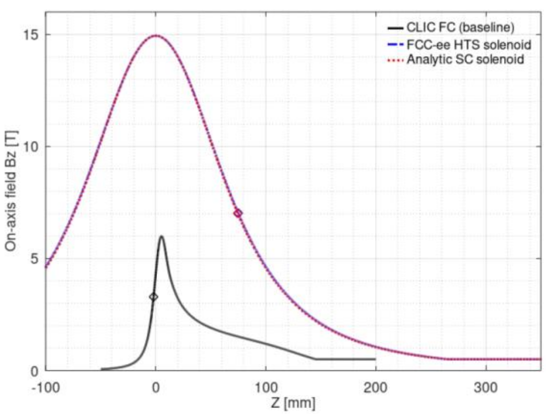


Schematic layout based on a SC AMD



Schematic layout for tapered target

- Optimisation results
  - The FCC-ee HTS field is found to be already optimal even also for CLIC positron source



On-axis Bz field comparison

Results for DBA @ 380 GeV & 3 TeV

Parameter	Unit	FC	HTS	HTS-TT	HTS-TT-UB
Optimised electron beam size (σ_x or R_x)	mm	2.40	2.10	1.70	2.25
Positron yield accepted by PDR		1.98	2.49	3.37	4.42
Electron bunch charge required	nC	0.51	0.40	0.30	0.23
Electron beam power required	kW	44.4	35.3	26.1	19.9
Normalised PEDD in target	J/g	29.8	29.2	29.9	29.8
Normalised total deposited power in target	kW	12.0	9.5	6.0	5.9

Parameter	Unit	FC	HTS	HTS-TT	HTS-TT-UB
Optimised electron beam size (σ_x or R_x)	mm	1.50	1.30	0.90	1.35
Positron yield accepted by PDR		2.61	3.21	5.20	6.00
Electron bunch charge required	nC	0.27	0.22	0.14	0.12
Electron beam power required	kW	21.2	17.3	10.7	9.2
Normalised PEDD in target	J/g	29.6	29.8	30.0	29.9
Normalised total deposited power in target	kW	5.7	4.6	2.3	2.5

- **FC: FC based AMD. New baseline**
- **HTS: FCC-ee HTS based AMD**
- **HTS-TT: HTS + Tapered target**
- **HTS-TT-UB: HTS + Tapered target + Uniform beam**

Alternative options: lower energy electrons

- Lower energy electron beam leads to shorter electron linac and smaller cost
- Target thickness and beam spot size are reoptimised for different energies:

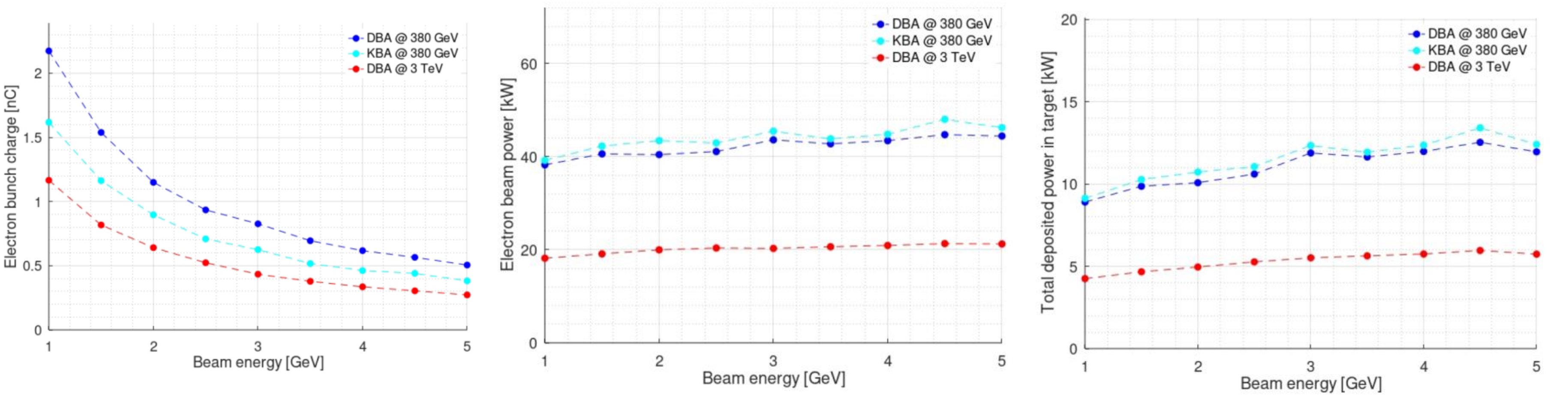
Optimised target thickness

Electron beam energy [GeV]	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Optimised target thickness [mm]	12.0	13.5	14.5	15.5	16.5	17.0	17.5	18.0	18.0

Optimised e$^-$ beam spot size

Electron beam energy [GeV]	1	1.5	2	2.5	3	3.5	4	4.5	5
Optimised spot size (DBA @ 380 GeV) [mm]	2.50	2.50	2.40	2.40	2.50	2.45	2.40	2.45	2.40
Optimised spot size (KBA @ 380 GeV) [mm]	2.50	2.55	2.50	2.45	2.55	2.45	2.45	2.60	2.45
Optimised spot size (DBA @ 1.5 & 3 TeV) [mm]	1.60	1.55	1.55	1.55	1.55	1.50	1.50	1.50	1.50

- Scan of e$^-$ beam energy (2.3 GeV might be a good alternative with 1 nC bunch charge required)



Bunch charge vs energy **Normliased beam power vs energy** **Normliased deposited power in target vs energy**

Conclusions

- **New baseline** configurations for the **CLIC positron source**, for both drive-beam based and klystron based modes, at both 380 GeV and 3 (1.5) TeV stages
- Hybrid target (old baseline) replaced by **single target option**, with **yield improved by a factor of ~2.7** @ 380 GeV (**~3.6** @ 3 TeV), with **reoptimised spot size**
- **Start-to-end optimisations** with **higher positron yield than any previous studies** (though our simulatin is more conservative and realistic)
- **Much more realistic simulations than any previous studies**, up to the end of injector linac, with a preliminary **PDR accepted positron yield** of **~1.8** @ 380 GeV (**~2.4** @ 3 TeV)
- **Alternative options** also investigated that can **improve the yield significantly**, such as using uniform electron beam, FCC-ee HTS solenoid based AMD, tapered target, etc. But some options **might be challenging**
- Alternative **lower electron energy option** also investigated. Might be a good alternative to reduce the energy 5 GeV to **2.3 GeV**. More studies are in progress

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 FCC-ee.
- We also thank *N. Vallis* from PSI for discussions about the tapered target option.

Backup