Optimisation of the CLIC positron source

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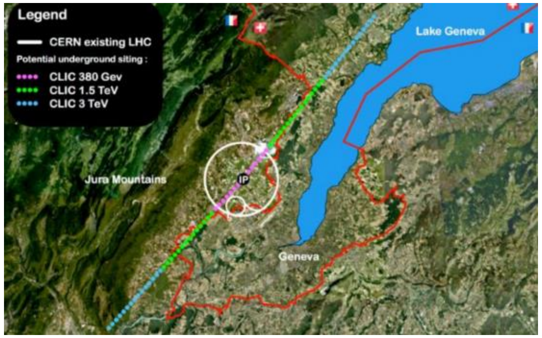
Outline

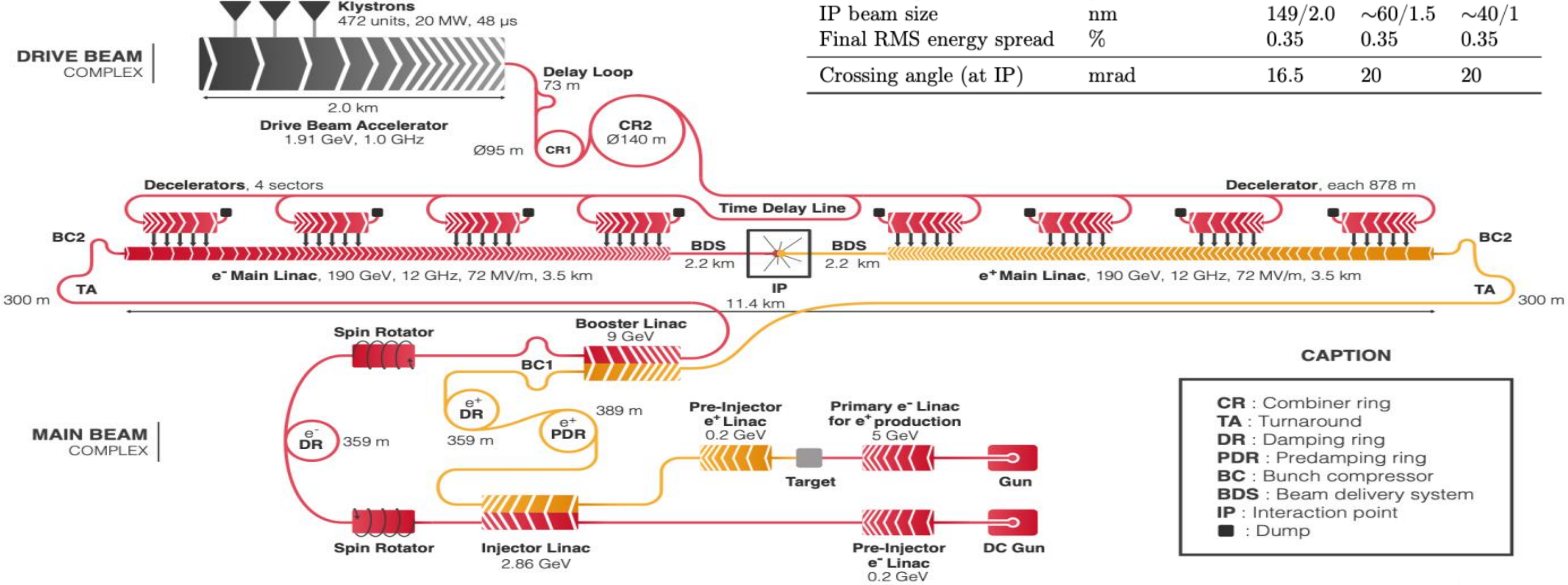
- Introduction
- Baseline option
- Alternative options
- Conclusions

Compact linear collider (CLIC)

- **Acceleration modes: drive beam-based (DBA), klystron-based (KBA)**
- **Stages: 380 GeV, 1.5 TeV, 3TeV**



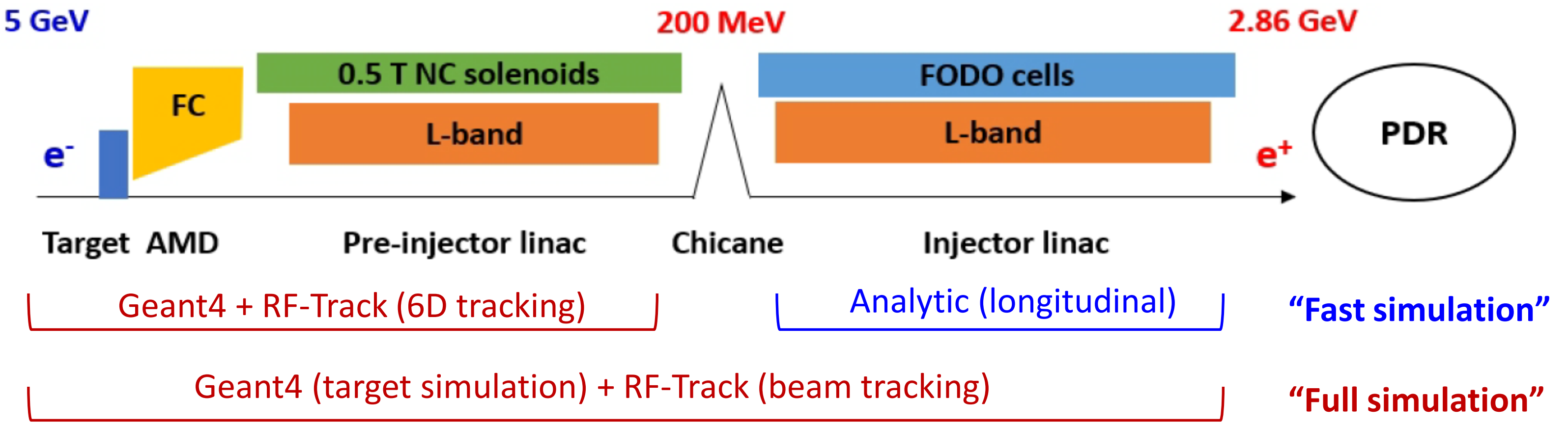
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20



Accelerator layout (DBA @ 380 GeV)

CLIC positron source

- **Latest baseline layout of CLIC positron source**



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

- **"Fast simulation"** – for optimisation
  - Simulation up to pre-injector linac (~200 MeV) with uniform solenoid field
  - Tracking (longitudinal) in injector linac with analytic formula
  - PEDD < 30 J/g

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

- **"Full Simulation"** – for final performance
  - Simulation up to injector linac (2.86 GeV), with analytic solenoid field and uniform chicane dipole field
  - PEDD < 35 J/g

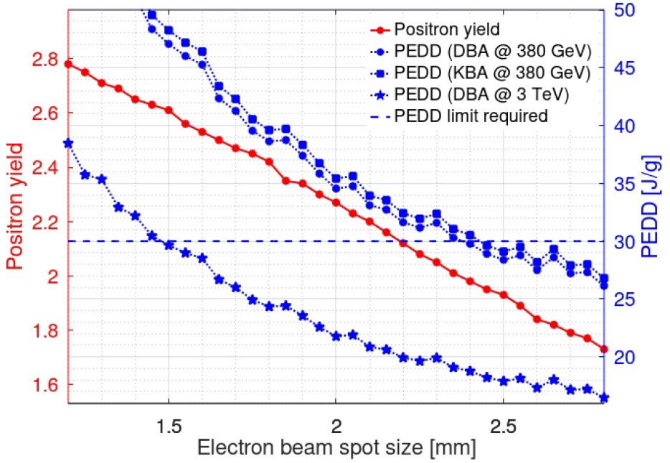
$$B_z = \frac{\mu_0 N I}{2}\left(\frac{l/2 - z}{l\sqrt{R^2 + (l/2 - z)^2}} + \frac{l/2 + z}{l\sqrt{R^2 + (l/2 + z)^2}}\right)$$

Beam parameters

- DBA: drive beam-based acceleration mode; KBA: klystron-based acceleration mode
- 1.5 TeV and 3 TeV stages share the same parameters and results

Beam parameter	Unit	380 GeV		1.5 & 3 TeV
Acceleration mode		DBA	KBA	DBA
Electron beam				
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	2.40	2.45	1.50
Normalized transverse emittance, $\epsilon^n_{x,y}$	mm·mrad	80	80	80
Number of bunches per train		352	485	312
Positron beam				
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 cut window (total length)	mm/c	20	20	20

- Beam size optimization:
  - **Old: 2.5 mm in all cases**

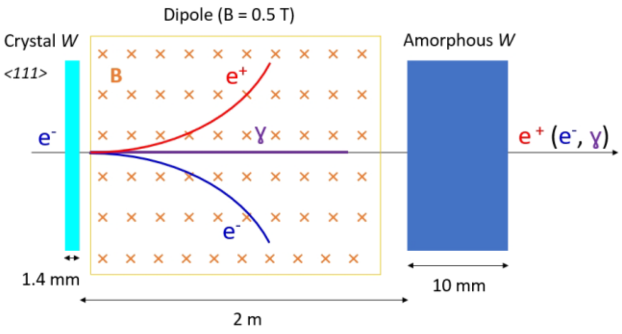


Scan of the electron beam spot size. PDR accepted positron yield and normalized PEDD are plotted at different energy stages for different acceleration modes

PDR acceptance cuts (longitudinal)

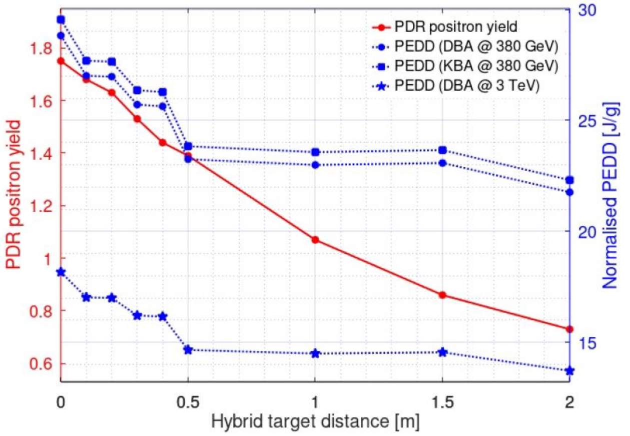
Target scheme

- **Old baseline**



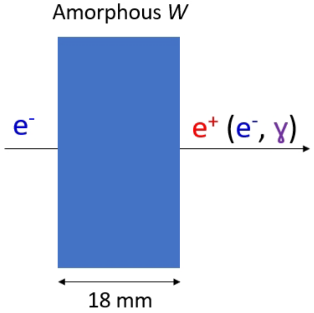
Hybrid target option (CDR version)

Reoptimised in an old report published in 2019



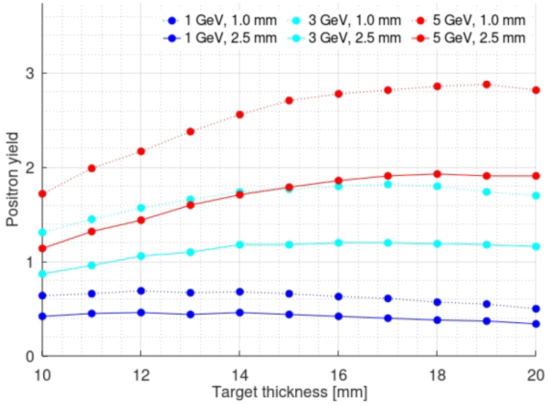
Hybrid target distance scan

- **New baseline**

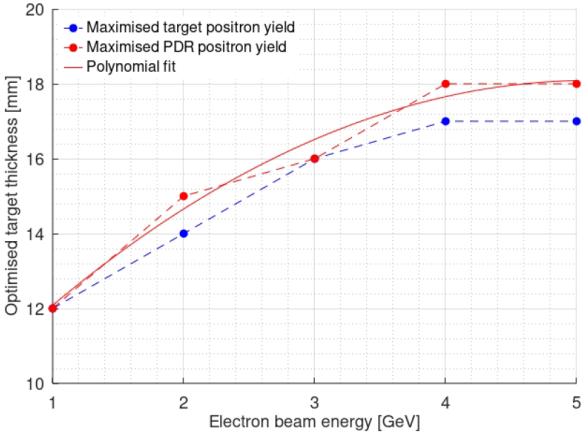


Single target option

Optimised thickness: 18 mm



Single target thickness scans

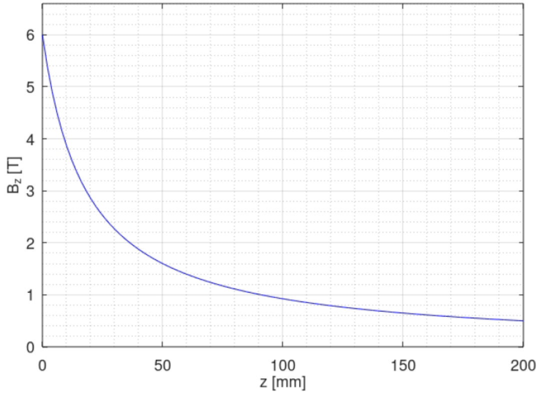


Optimised target thickness vs beam energy

✓ **Positron yield improved by a factor of 1.65**, **deposited power in target reduced by a factor of 2.1**, **compared with the old optimization report published in 2019**

Adiabatic matching device (AMD)

- **Old baseline**
  - AMD **never designed**
  - Large **uniform aperture** (40 mm) assumed
  - Using **analytic field** (adiabatic formula)



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

B_0 = 6 T, μ = 55 m^{-1}

On-axis Bz (analytic)

- **New baseline**
  - Flux concentrator (FC) designed (*H. Bajas et al.*) with Opera®
  - Pulsed half-sine current (peak 20 kA) @ 25 kHz
  - Realistic field and tapered aperture
  - Manufacturing (*S. Doebert et al.*) with EDM or 3D printing in progress. To be tested at the KEK test bench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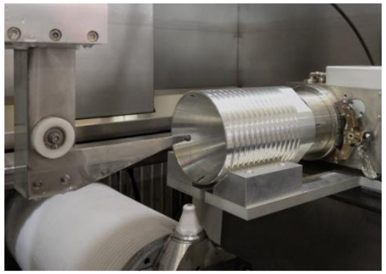
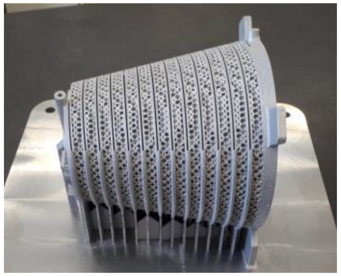
Flux Concentrator Optimization for Future Positron Sources

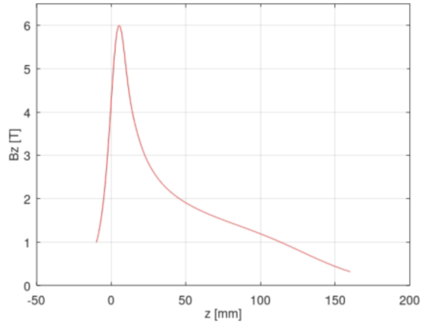
H. Bajas, S. Doebert, A. Latina, and Y. Zhao



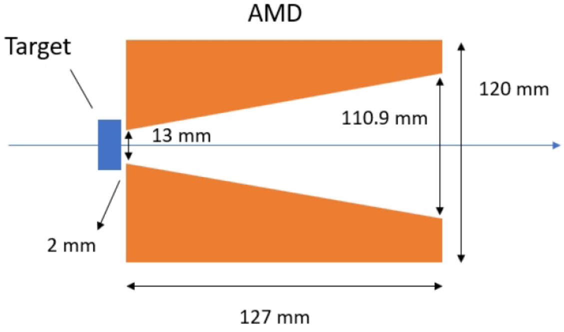
EDM



3D printing



On-axis Bz (Opera® simulation)

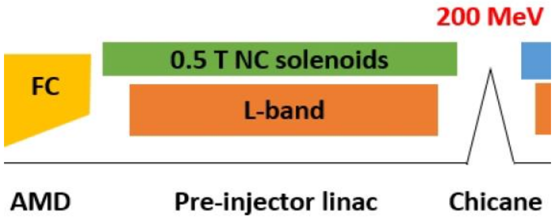


Schematic layout

Pre-injector linac

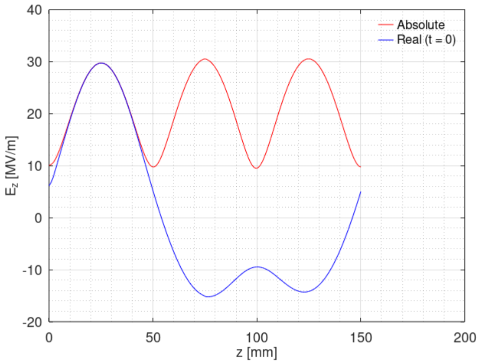
- Pre-injector linac (also called capture linac in FCC-ee) up to ~200 MeV
- Linac design is same as the old studies (old report published in 2019)
- The “CLIC L-band” structure is assumed
  - also used in the injector linac, booster linac and bunch compresspor 1
- Constant aperture (20 mm radius) is assumed, though designed aperture is tapered
  - a new design of 3 m long structure similar to FCC-ee with constant aperture is in progress
- Distance between structures: 20 cm
- Number of structures: 11
  - 1 at decelerating phase + 10 at accelerating phase (only two phases used)
- Average RF gradient: fixed at 20 MV/m (for simplification)
- Surrounded with NC solenoids (up to ~200 MeV): 0.5 T
  - **Old**: **uniform solenoid Bz**: Bz = 0.5 T
  - **New**: **analytic solenoid Bz with optimized solenoid layout**

$$B_z = \frac{\mu_0 N I}{2}\left(\frac{l/2 - z}{l\sqrt{R^2 + (l/2 - z)^2}} + \frac{l/2 + z}{l\sqrt{R^2 + (l/2 + z)^2}}\right)$$



Structure parameters

Parameter	Unit	Value
Structure name		CLIC L-band
RF frequency	GHz	1.999
Structure length	m	1.5
Number of cells		30
Phase advance per cell	°	120
Working RF phase	°	90
First iris radius	mm	20
Last iris radius	mm	14
First iris thickness	mm	8
Last iris thickness	mm	8

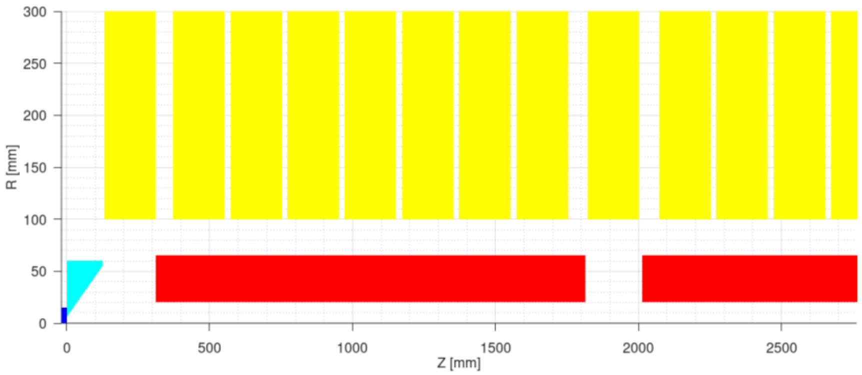


On-axis Ez (3 cells)

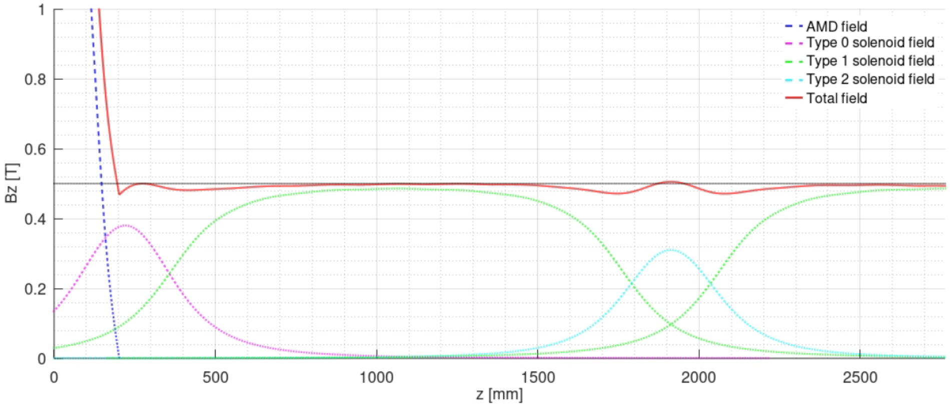
Pre-injector linac

- Layout of solenoids along pre-injector linac
  - ○ Each structure (1.5 m) surrounded by 7 (18 cm long) solenoids (similar to FCC-ee but more compact)
    - ✓ FCC-ee has 9 (20 cm long) solenoids surrounding each structure (3 m)
  - ○ Three types of solenoids with same designs but different peak fields (turns and currents) are assumed
    - ○ Type 0: matching solenoid between AMD and RF structure
    - ○ Type 1: regular solenoids surrounding RF structure
    - ○ Type 2: matching solenoid between RF structures

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



Schematic layout of solenoids

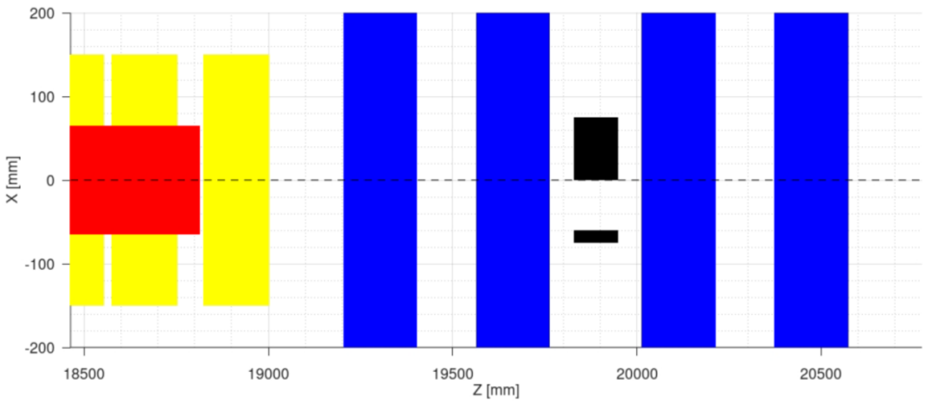


On-axis Bz of different components

✓ From FCC-ee study, we learned that the final performances are consistent between using 1D and 3D fields (even between uniform and simulated fields). So, the analytic solenoid field should be reliable enough to be used for the moment

Collimation

- A chicane (composed of four dipoles with identical designs) and a collimator in the middle are used to reduce electrons and photons. Similar to SuperKEKB and FCC-ee designs
- Uniform By field is assumed in the dipoles in the tracking
  - ✓ From FCC-ee study, we learned that final performances are consistent between using uniform and 3D simulated fields



Schematic layout of chicane and collimator

Chicane parameters

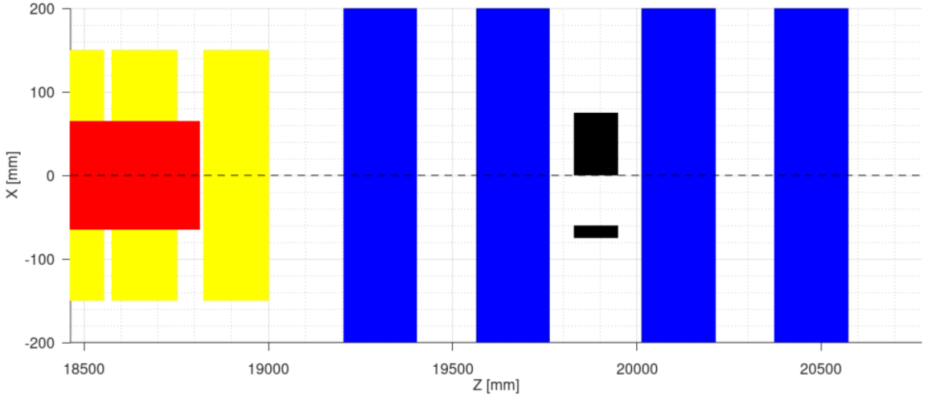
Parameter	Symbol	Unit	Value
Dipole length	l	mm	200
Reference energy	e_0	MeV	200
Bending angle	θ	°	4.8, -4.8, -4.8, 4.8
Beam pipe aperture inside dipoles (total width)	D_x, D_y	mm	120, 50
Beam pipe aperture for collimator (total width)	D_x, D_y	mm	180, 60
Distance between chicane and other sections	d_0,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

Collimation

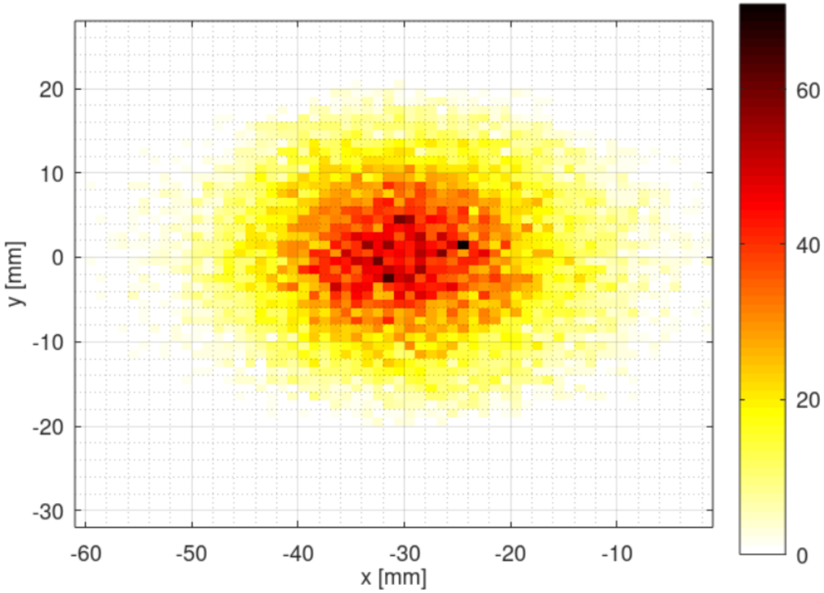
- Collimator

Collimator parameters

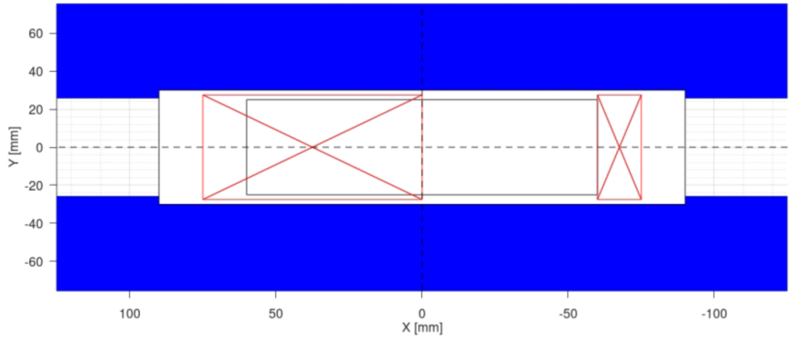
Parameter	Symbol	Unit	Value
Collimator length	l	mm	120
Offset of the aperture	x_0	mm	-30
Aperture (total width)	D_x, D_y	mm	60, 60



Schematic layout of chicane and collimator (Z-X plane)



Beam positions at the entrance of collimator

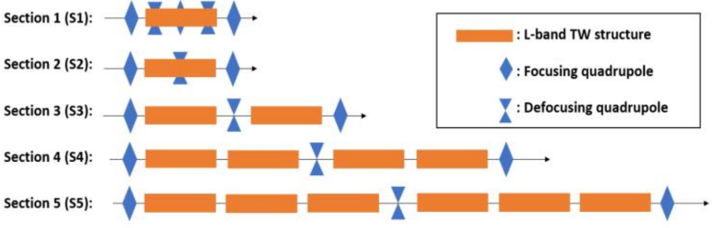


Schematic layout of chicane and collimator (X-Y plane)

Injector linac

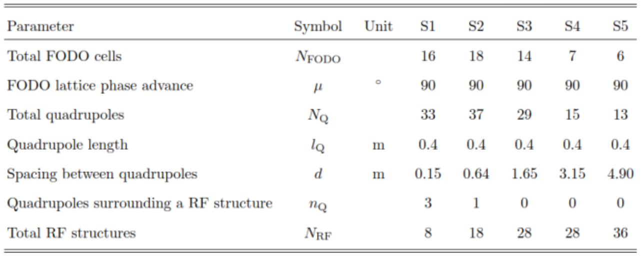
- Injector linac accelerates both e^- and e^+ from 200 MeV to 2.86 GeV
- Same RF structure (“CLIC L-band”) as in pre-injector linac. Using existing design

Designed by C. BAYAR *et al.*

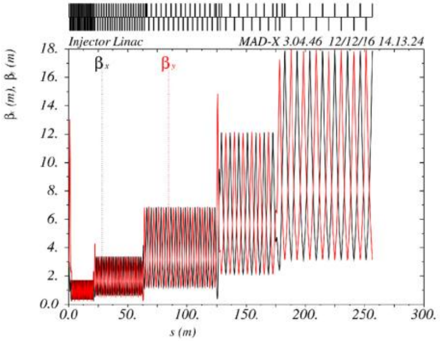


Schematic layout

Lattice parameters

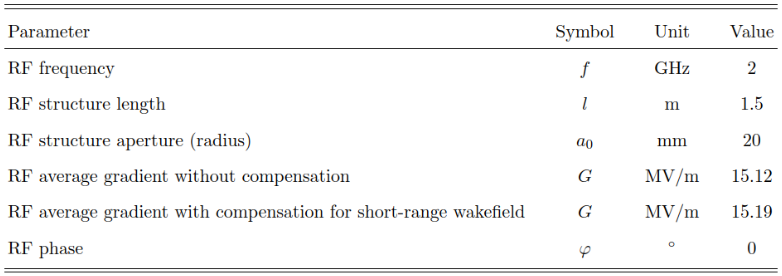


Parameter	Symbol	Unit	S1	S2	S3	S4	S5
Total FODO cells	N_{FODO}		16	18	14	7	6
FODO lattice phase advance	μ	°	90	90	90	90	90
Total quadrupoles	N_Q		33	37	29	15	13
Quadrupole length	l_Q	m	0.4	0.4	0.4	0.4	0.4
Spacing between quadrupoles	d	m	0.15	0.64	1.65	3.15	4.90
Quadrupoles surrounding a RF structure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

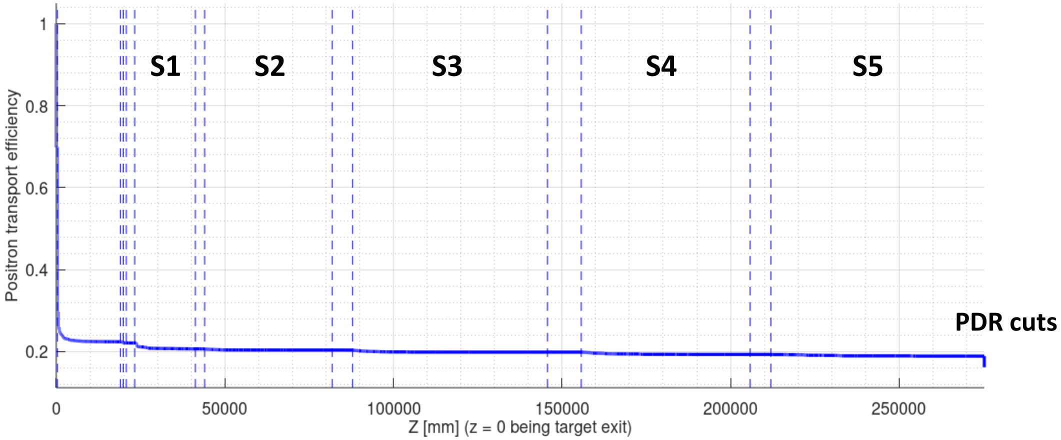


Beta functions

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

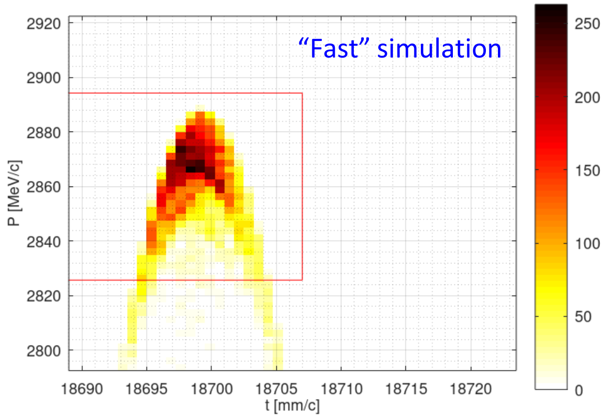


Transport efficiency of positrons from target

Final performance

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

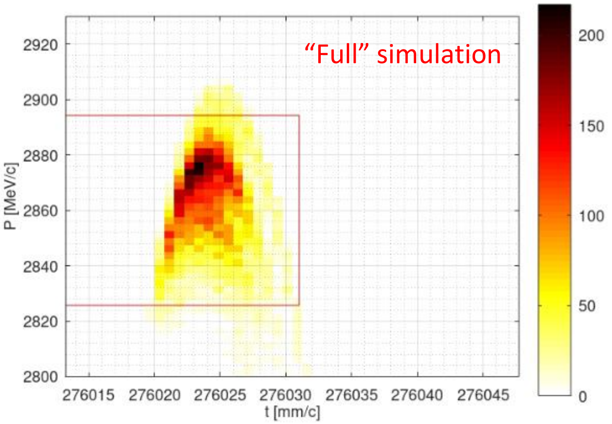
Parameter	Unit	380 GeV		1.5 & 3 TeV
Acceleration mode		DBA	KBA	DBA
Optimised electron beam spot size	mm	2.40	2.45	1.50
Positron yield accepted by PDR		**1.98**	**1.95**	**2.61**
Electron bunch charge required	nC	0.51	0.38	0.27
Electron beam power required	kW	44.4	46.3	21.2
Normalised PEDD in target	J/g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



Longitudinal phase space @ 2.86 GeV

- “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



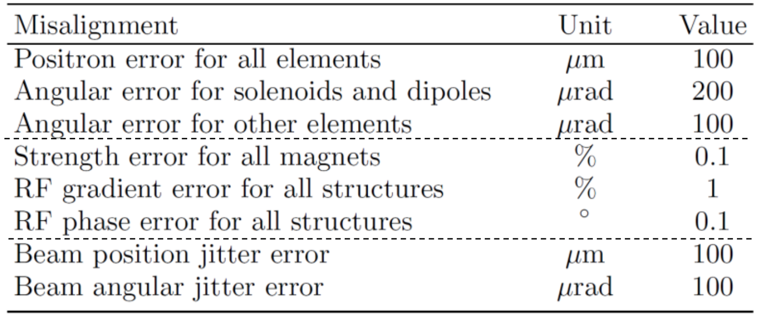
Longitudinal phase space @ 2.86 GeV

✓ **Final positron yield: ~1.8 (380 GeV) – 2.4 (3 TeV)**

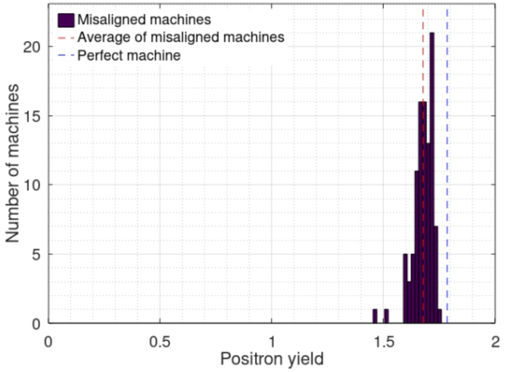
Misalignments

- 100 randomly misaligned machines simulated

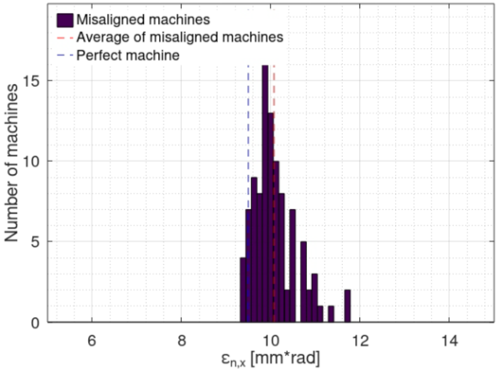
Misalignments & beam jitters (RMS)



Misalignment	Unit	Value
Positron error for all elements	μm	100
Angular error for solenoids and dipoles	μrad	200
Angular error for other elements	μrad	100
Strength error for all magnets	%	0.1
RF gradient error for all structures	%	1
RF phase error for all structures	°	0.1
Beam position jitter error	μm	100
Beam angular jitter error	μrad	100



Positron yield of all machines

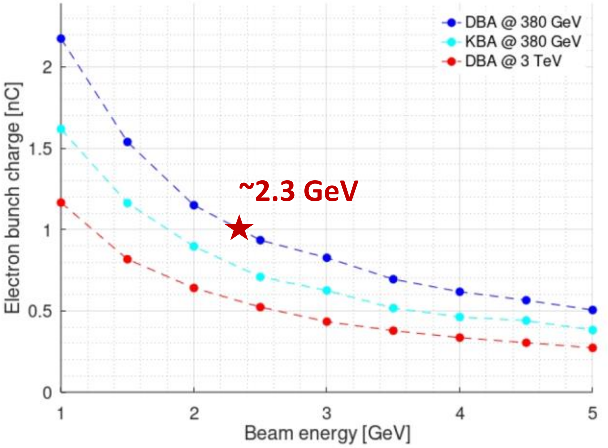


Normalized emittance of all machines

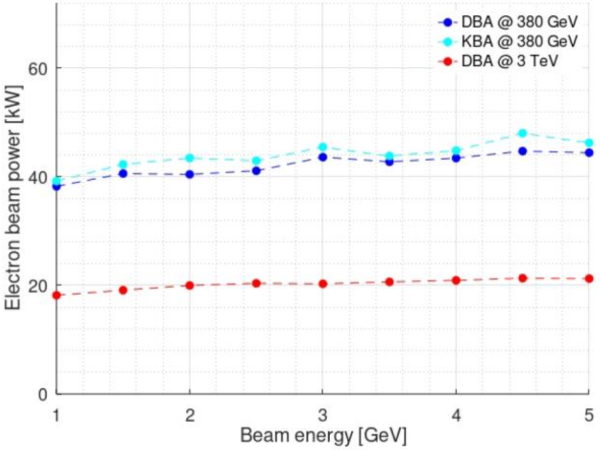
- ✓ **Average positron yield reduced by 6%. Emittance also increased by 6%. Results are acceptable**
- ✓ **Beam-based alignment corrections are not very necessary**

Alternative options: lower energy electrons

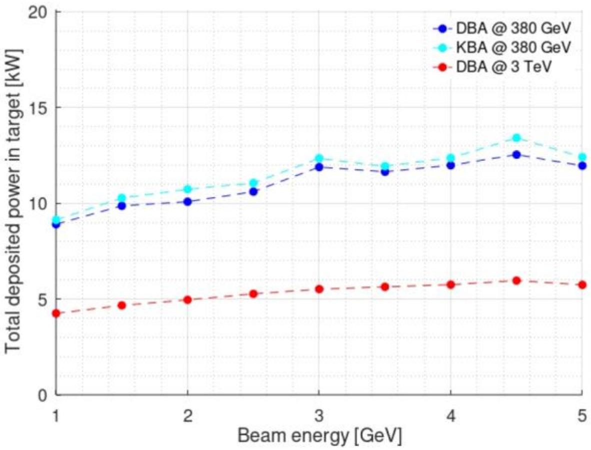
- Lower energy electron beam leads to shorter electron linac and smaller cost
- Target thickness and beam spot size are reoptimized for different energies:
- Scan of e$^-$ beam energy



Required electron bunch charge vs energy



Normliased beam power vs energy

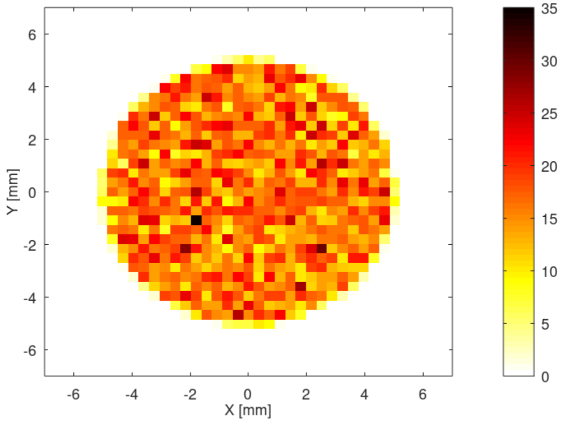


Normliased deposited power in target vs energy

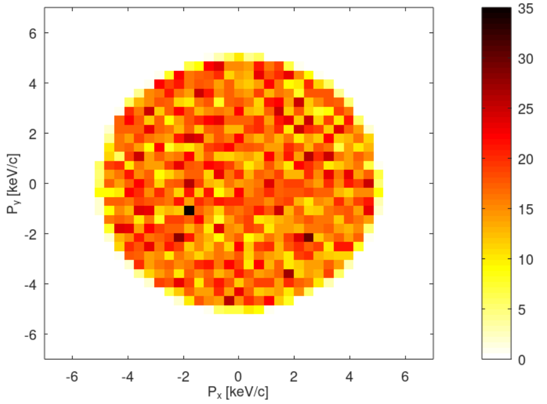
- ✓ 2.3 GeV might be a good alternative with 1 nC electron bunch charge required
- ✓ Energy (also linac length) is reduced by 50% compared with 5 GeV baseline
- ✓ More studies and design of the electron beam linac are in progress

Alternative options: uniform beam

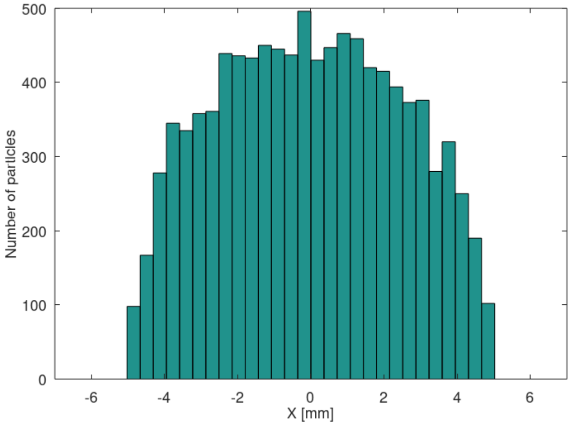
- Primary e^- beam with uniform profile (transverse distribution)



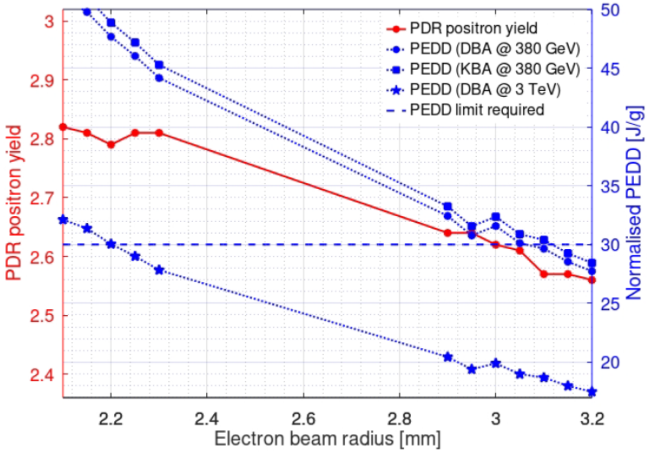
Transverse positions



Transverse momentums



Horizontal position



Beam radius scan

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

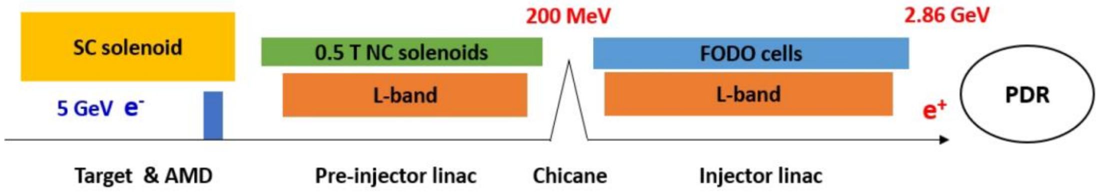
Parameter	Unit	Gaussian	Uniform
Optimised electron beam size, $\sigma_{x,y}$ or $R_{x,y}$	mm	2.40	3.10
PDR positron yield		1.98	2.57
Electron bunch charge required	nC	0.51	0.39
Electron beam power required	kW	44.4	34.2
Normalised PEDD in target	J/g	29.8	29.6
Normalised total deposited power in target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

✓ **Significant improvement in yield (30%)**

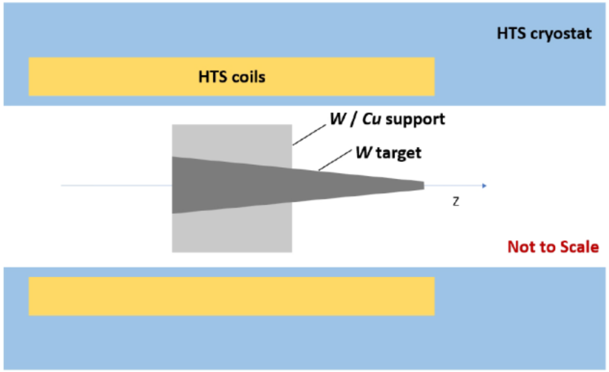
✓ **Uniform beam production is very challenging (to be designed)**

Alternative options: SC AMD

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

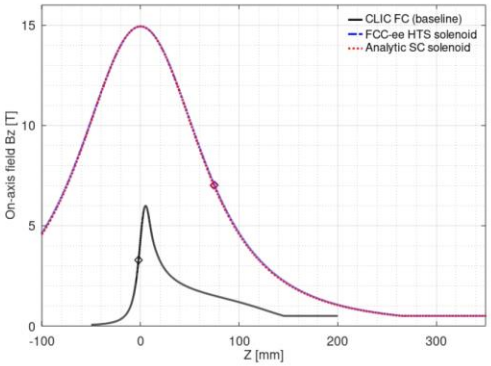


Schematic layout based on a SC AMD



Schematic layout for tapered target

- Optimization results of using analytic SC solenoid field
  - The optimized field is the same as the FCC-ee HTS solenoid field (designed by PSI)



On-axis Bz field comparison

Results (DBA @ 380 GeV)

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

- ○ **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**

✓ **Significant improvement in yield (25%) using SC AMD, though much lower than FCC-ee (~50%)**

✓ **Also significant improvements in other challenging options**

Conclusions

- **Baseline** configurations **updated** for the **CLIC positron source**, for both drive-beam based and klystron based modes, at both 380 GeV and 3 (1.5) TeV stages
- **Start-to-end optimisations** with **higher positron yield than any previous studies**
- **Much more realistic simulations than any previous studies**, with a **PDR accepted positron yield** of **~1.8** @ 380 GeV (**~2.4** @ 3 TeV)
- **Alternative options** investigated that can **improve the yield significantly**, such as using lower energy electron beam, uniform electron beam, SC solenoid based AMD, tapered target, etc, though some options seem **quite challenging**
- Next steps
  - Start-to-end design of electron linac (< 5 GeV) for positrons, injector linac (2.86 GeV) and booster linac (9 GeV) with new L-band structures (in collaboration with A. Kurtulus, A. Grudiev)

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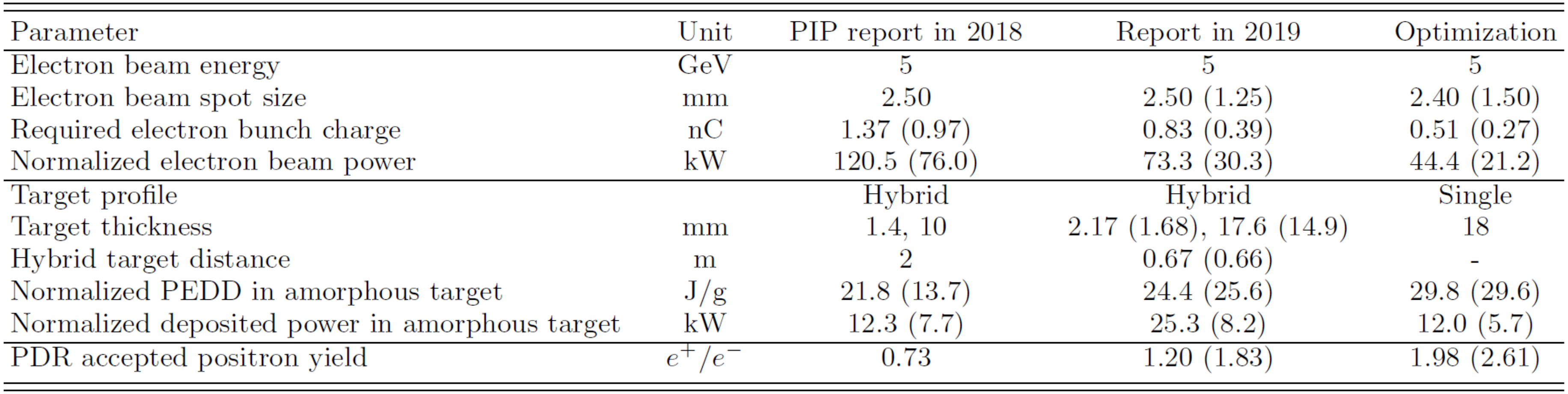
- We also thank N. Vallis from PSI for discussions about the tapered target option.

Backup

Target scheme



Parameter	Unit	PIP report in 2018	Report in 2019	Optimization
Electron beam energy	GeV	5	5	5
Electron beam spot size	mm	2.50	2.50 (1.25)	2.40 (1.50)
Required electron bunch charge	nC	1.37 (0.97)	0.83 (0.39)	0.51 (0.27)
Normalized electron beam power	kW	120.5 (76.0)	73.3 (30.3)	44.4 (21.2)
Target profile		Hybrid	Hybrid	Single
Target thickness	mm	1.4, 10	2.17 (1.68), 17.6 (14.9)	18
Hybrid target distance	m	2	0.67 (0.66)	-
Normalized PEDD in amorphous target	J/g	21.8 (13.7)	24.4 (25.6)	29.8 (29.6)
Normalized deposited power in amorphous target	kW	12.3 (7.7)	25.3 (8.2)	12.0 (5.7)
PDR accepted positron yield	e^+/e^-	0.73	1.20 (1.83)	1.98 (2.61)

Comparison of the old and optimized target configurations and “fast simulation” results at the 380 GeV energy stage (or 1.5 and 3TeV energy stages) for the DBA acceleration mode.