Optimization of CLIC Positron Source

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Introduction

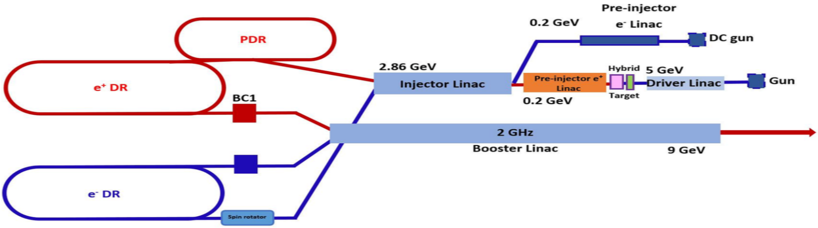

Figure: Schematic layout of the Main Beam injector complex

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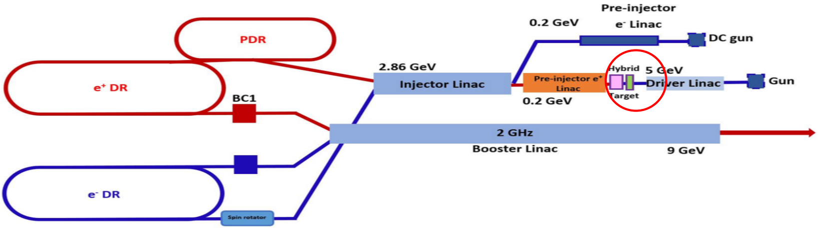

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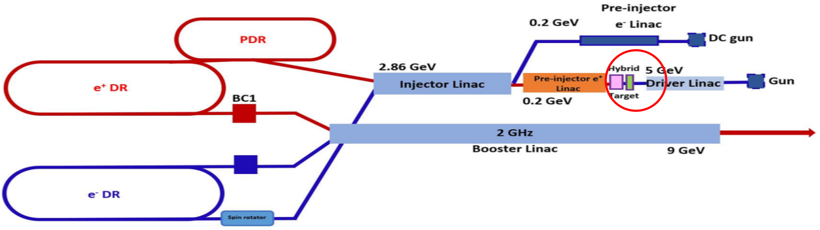

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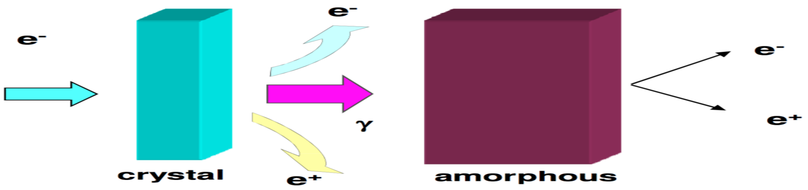


Figure: Positron source based on hybrid targets

Positron source overview - 3 TeV stage

In order to:

- Increase the positron yield
- Constrain the deposited energy in tungsten target

Three parameters are scanned[1]:

- Primary electron energy: 3, 4, 5 and 10 GeV
- Distance between crystal and amorphous target: 1.5, 2.0, 2.5 and 3 m
- Amorphous target thickness: 6, 8, 10 and 12 mm

Final parameters (CDR):

- Primary electron energy: 5 GeV
- Crystal thickness: 1.4 mm (determined by other project)
- Distance: 2 m
- Amorphous thickness: 10 mm

[1] From CLIC-note-808 by Olivier Dadoun.

Motivation

Main changes:

- The first stage of CLIC is set to be 380 GeV
  - More charges per bunch
  - More bunches per train
- The positron yield before the pre-damping ring has been improved from 0.39 to 0.97

So it is need to re-optimise the positron source in order to improve performance and save cost.

- Lower primary electron energy
- Fewer primary electron number

Fits to previous results

Table: Scanned results for 3, 4, 5 and 10 GeV primary electron

e(cm)	d(m)	Yield	P(kW)	Pedd (GeV/cm^3/e$^-$)	Pedd(J/g/train)
0.6	1.5	1.05	2.60	0.47	9.13
0.6	2.0	0.98	2.45	0.37	7.20
0.6	2.5	0.92	2.30	0.33	6.41
0.6	3.0	0.87	2.20	0.28	5.44
0.8	1.5	1.10	4.30	0.57	11.07
0.8	2.0	1.04	4.10	0.45	8.74
0.8	2.5	0.97	3.90	0.37	7.20
0.8	3.0	0.90	3.60	0.37	7.20
1.0	1.5	1.14	6.30	0.65	12.62
1.0	2.0	1.05	5.95	0.52	10.10
1.0	2.5	0.97	5.60	0.40	7.77
1.0	3.0	0.92	5.25	0.37	7.20
1.2	1.5	1.12	8.40	0.65	12.62
1.2	2.0	1.04	7.90	0.53	10.30
1.2	2.5	0.96	7.45	0.45	8.74
1.2	3.0	0.90	7.05	0.37	7.20

3 GeV

e(cm)	d(m)	Yield	P(kW)	Pedd (GeV/cm^3/e$^-$)	Pedd(J/g/train)
0.6	1.5	1.44	3.30	0.72	14.00
0.6	2.0	1.38	3.20	0.65	12.62
0.6	2.5	1.29	3.05	0.50	9.71
0.6	3.0	1.27	2.95	0.48	9.32
0.8	1.5	1.54	5.55	0.80	15.54
0.8	2.0	1.49	5.40	0.74	14.37
0.8	2.5	1.41	5.20	0.60	11.65
0.8	3.0	1.36	5.00	0.54	10.49
1.0	1.5	1.56	8.20	0.93	18.06
1.0	2.0	1.52	8.00	0.80	15.54
1.0	2.5	1.46	7.70	0.71	13.80
1.0	3.0	1.38	7.30	0.61	11.85
1.2	1.5	1.56	11.15	1.02	19.81
1.2	2.0	1.50	10.80	0.87	16.90
1.2	2.5	1.45	10.35	0.79	15.34
1.2	3.0	1.39	10.00	0.64	12.43

4 GeV

e(cm)	d(m)	Yield	P(kW)	Pedd (GeV/cm^3/e$^-$)	Pedd(J/g/train)
0.6	1.5	1.83	3.90	0.95	18.45
0.6	2.0	1.76	3.85	0.83	16.12
0.6	2.5	1.70	3.70	0.71	13.80
0.6	3.0	1.66	3.65	0.64	12.43
0.8	1.5	2.00	6.70	1.17	22.72
0.8	2.0	1.91	6.55	1.00	19.42
0.8	2.5	1.87	6.40	0.87	16.90
0.8	3.0	1.81	6.20	0.78	15.15
1.0	1.5	2.01	10.05	1.37	26.60
1.0	2.0	1.97	9.80	1.14	22.14
1.0	2.5	1.91	9.60	1.00	19.42
1.0	3.0	1.83	9.25	0.89	17.29
1.2	1.5	2.04	13.70	1.41	27.38
1.2	2.0	1.95	13.45	1.25	24.27
1.2	2.5	1.92	13.05	1.05	20.40
1.2	3.0	1.86	12.65	0.96	18.65

5 GeV

e(cm)	d(m)	Yield	P(kW)	Pedd (GeV/cm^3/e$^-$)	Pedd(J/g/train)
0.6	1.5	3.23	5.60	1.83	35.54
0.6	2.0	3.30	5.60	1.78	34.57
0.6	2.5	3.26	5.55	1.58	30.69
0.6	3.0	3.24	5.50	1.50	29.13
0.8	1.5	3.67	10.20	2.54	49.33
0.8	2.0	3.66	10.05	2.25	43.70
0.8	2.5	3.62	10.00	2.14	41.56
0.8	3.0	3.63	9.95	1.98	38.45
1.0	1.5	4.00	15.80	2.93	56.90
1.0	2.0	3.96	15.75	2.67	51.85
1.0	2.5	3.95	15.65	2.57	49.91
1.0	3.0	3.93	15.50	2.40	46.61
1.2	1.5	4.15	22.50	3.17	61.56
1.2	2.0	4.14	22.45	3.08	59.81
1.2	2.5	4.16	22.40	2.98	57.87
1.2	3.0	4.05	22.25	2.87	55.74

10 GeV

Fits to previous results - yield v.s. energy

Thickness = 6 mm & Distance = 1.5 m

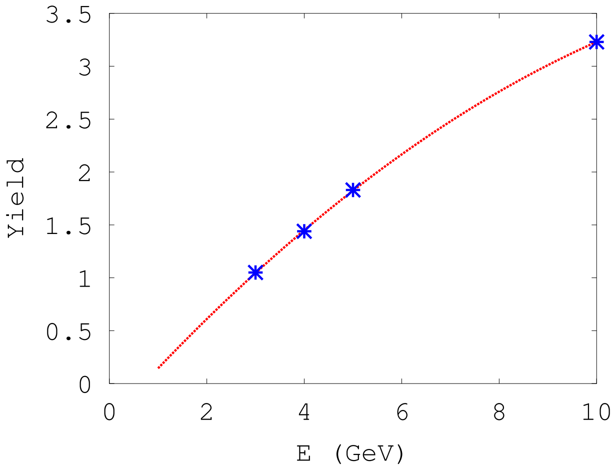
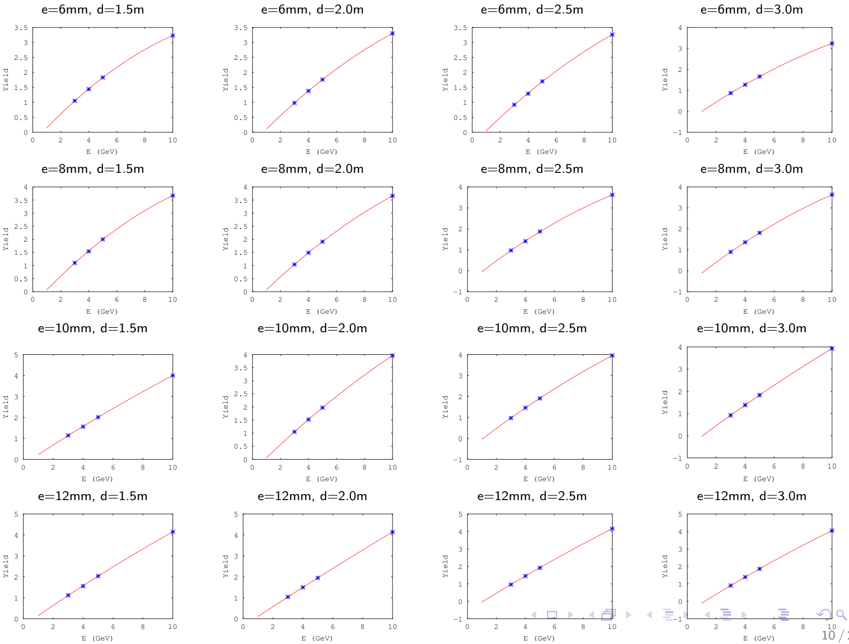


Figure: Fitted results of positron yield v.s. energy.

Fits to previous results - yield v.s. energy



Fit to previous results - continual

At each energy point, we find the maximal yield from the 16 fits.

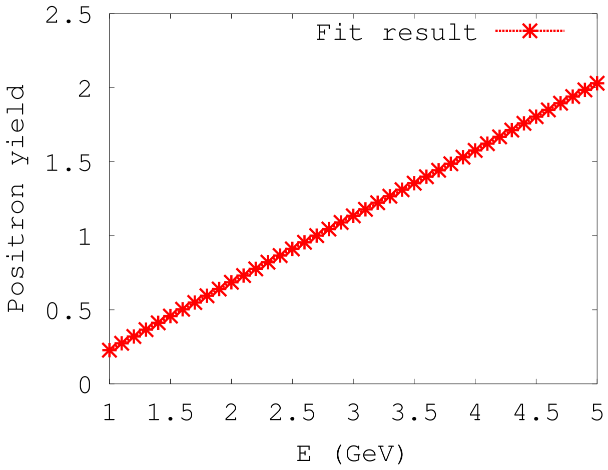


Figure: Positron yield for different energies

New positron options

We know:

- The transmission efficiency has been improved 2.5 times (0.39→0.97) by C. Bayar.
- The positron yield in CLIC CDR is 2.1** (after the AMD (20 cm))
  - The positron yield used for the fit is 1.97 after AMD (50 cm).
  - The positron yield is 2.8 for C. Bayar's improvement after AMD (20 cm).

Here we will use the positron yield 1.97 because all other data are from the CLIC-note-808.

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So the positron yield after the AMD can be reduced to:

- $1.97/2.5 \approx 0.8$ - if one set of target is used (The current keeps the same).
- $1.97/2.5/2 \approx 0.4$ - it two sets of targets are used (The current is doubled).

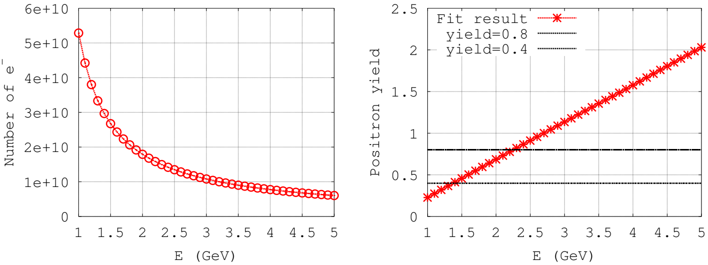

Figure: The number of electrons and the positron yield for different energies

New options for positron source

Table: Positron injector options for 380 GeV

	Option 1	Option 2	Option3	CDR
Beam energy (GeV)	2.3	1.4	5	5
Thick_2 (mm)	10	10	10	10
L (m)	1.5	1.5	2	2
Positron Yield	0.82	0.41	1.97	1.97
N_{e-} (10^9)	15.0	29.7	6.3	15.5
Bunch charge (nC)	2.4	4.75	1.0	2.38
Energy/bunch (J)	5.52	6.66	5.04	12.4
Average beam power (kW)	97	117	89	218

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Table: Positron injector options for 3 TeV

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Thick_2 (mm)	10	10	10	10
L (m)	1.5	1.5	2	2
Positron Yield	0.82	0.41	1.97	1.97
N_{e-} (10^9)	10.6	21.1	4.4	11
Bunch charge (nC)	1.7	3.4	0.7	1.8
Energy/bunch (J)	3.91	4.73	3.52	8.8
Average beam power (kW)	61	74	55	137

Scan of RF cavity parameters

In order to design the RF cavities for the primary electron linac, several parameters about the cavities are scanned with the library "Optimiser" (implemented with the formula from PRST-AB 14, 2011 & SLAC report 577).

- Frequency f is fix to 2 GHz.
- $\epsilon_x = \epsilon_y = 10\ \mu rad$
- $\delta_E = 0.6\%$ & $\sigma_z = 300\ \mu m$
- a_1, a_2 (a/λ): iris apertures at the two ends, in 0.10 .. 0.20, λ is the wave length.
- d_1, d_2 ($d/\frac{\lambda}{3}$): iris thickness at the two ends, in 0.11 .. 0.40
- n_{cell}: 10 .. 50
- Gradient: 10 ... 30 MV/m

Selection criterion:

- Integral for transverse stability $A \times W_\perp \int \frac{\beta}{E} \mathrm{d}s < 0.4$ (Taken form the booster linac study), we assume a constant $\beta = 16$ m.
- Filling time < 600 ns - the pulse length is 244 ns.
- The mantissa of the number of RF units > 0.9 to avoid inefficiency.
- MaxAllowableBeamTime $>$ train length

Example: seveal plots of Option 1 for 380 GeV stage

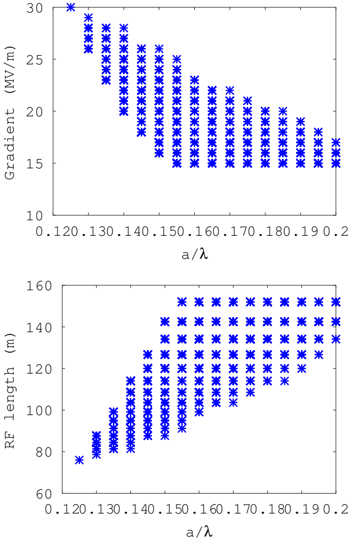

Figure: Gradient, beam stability, RF length and power loaded v.s. a/λ

RF pulse compressor - SLED

CLIC assume klystron like:

- frequency: 2 GHz
- repetition: 50 Hz
- pulse length: 8 μs
- power: 50 MW

RF pulse compressor - SLED

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- pulse length: 8 μs
- power: 50 MW

But the bunch length is few hundred nano seconds. We need the pluse compressor in order to compress the klystron pulse.

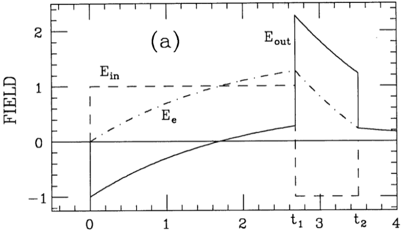

Figure: Output voltage for SLED

Formula about SLED

SLED:

$Gain = V_{max}^2$

$V_{max} = \frac{\alpha}{gC} \mathrm{e}^{-T_f/T_c} (2 - \mathrm{e}^{-t_1/T_c}) \left[1 - (1-g)^C\right] - \alpha + 1$

$\alpha = 2\beta/(1+\beta)$, β is coupler factor for the SLED.

$Q_L = Q_0/(1+\beta)$, Q_0 is quality factor of SLED storage cavity.

$C = 1 - \frac{L}{g v_{g0} T_c} = 1 + \frac{T_f}{T_c \ln(1-g)}$

$T_c = 2Q_L/\omega$, ω is the angular frequency.

$T_f = t_2 - t_1 = t_{f\_acc} + t_{beam}$, t_{f_acc} is the filling time of RF cavity.

$t_1 = t_{kly} - T_f$, t_{kly} is the pluse length of the klystron.

$Q_{0\_acc} = 1.58 \times 10^4$, the quality factor of RF accelerating cavity.

$\tau_0 = \frac{t_{f\_acc}\omega}{2Q_{0\_acc}}$

$g = 1 - \mathrm{e}^{-2\tau_0}$, related with the group velocity.

Input:

t_{f_acc} & $t_{kly} = 8\ \mu s$

Parameters:

$\beta = 8$ & $Q_0 \in [1 \times 10^5, 3 \times 10^5]$

RF pulse compressor - SLED

We can get the power gain factor for different output pulse length.

Table: Power gain for 380 GeV Stage

t_{pulse} (ns)	226	276	326	376	426	476	526	576	626	676
Q_0 (10^4)	12.3	13.0	13.6	14.2	14.8	15.8	16.3	16.8	17.3	
gain	6.50	6.31	6.12	5.95	5.78	5.62	5.47	5.32	5.18	5.04

Table: Power gain for 3 TeV Stage

t_{pulse} (ns)	206	256	306	356	406	456	506	556	606	656
Q_0 (10^4)	12.1	12.8	13.4	14.0	14.6	15.1	15.6	16.1	16.6	17.1
gain	6.58	6.38	6.19	6.01	5.84	5.68	5.52	5.37	5.23	5.09

Cost estimation

$$Cost = A \times N_{RF} + B \times Length$$

If we take:

- A: Cost per klystron - 300k CHF
- B: Cost per length - 50k CHF

We can estimate the cost the electron linac and find the best parameter set.

Considering the voltage in SLED decrease rapidly (SLED II can avoid this), we give a scale factor 0.9 to the power gain.

380 GeV stage

Table: Positron injector options

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Energy/bunch (J)	5.52	6.66	5.04	12.4
Average beam power (kW)	97	117	89	218
Gradient (MV/m)	16	12	24	21
N_{cell}	40	35	30	25
t_{fill} (ns)	298	140	535	258
P_{load} (MW)	184	234	112	186
P_{total} (MW)	13134	15397	19063	35387
N_{RF}	52	56	70	140
Efficiency (%)	34.2	53.3	19.1	33.6
Cost (M a.u.)	22.7	22.5	31.4	53.8

3 TeV Stage

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Gradient (MV/m)	20	14	24	20
N_{cell}	35	40	30	35
t_{fill} (ns)	411	217	558	400
P_{load} (MW)	154	217	89	163
P_{total} (MW)	10032	10685	12353	23218
N_{RF}	42	40	56	97
Efficiency (%)	24.7	39.2	14.6	24.8
Cost (M a.u.)	18.3	16.9	27.1	41.5

Scale power gain

If we set scale factor = 0.4, it mean the power gain is about 2.

Table: Positron injector options for 380 GeV

	Option 1	Option 2	Option3	CDR
Beam energy (GeV)	2.3	1.4	5	5
Cost (M a.u.)	42.2	42.9	55.6	105.4

Table: Positron injector options for 3 TeV

	Option 1	Option 2	Option3	CDR
Beam energy (GeV)	2.3	1.4	5	5
Cost (M a.u.)	33.1	32.0	46.3	78.1

The acceptance of the AMD and pre-injector

The above study has not considered the divergence of the generated positrons.

And we can guess that the lower electron energy will increase the positron divergence.

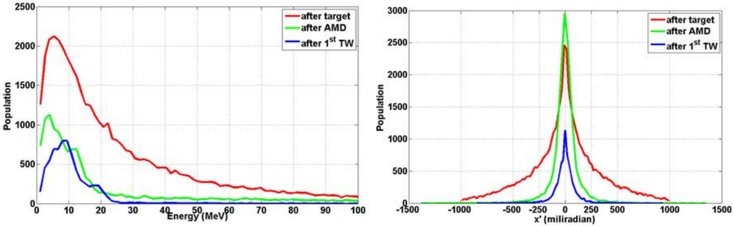

Figure: Acceptance about the positron capture[1]

Only $x' \in [-250, 250]$ mrad can be accepted.

$E \in [0, 30]$ MeV ?

The fit can not provide these information. We need the GEANT4 to get these.

[1]Figures are from C. Bayar.

Conclusion & Next step

Conclusion

- The positron yield - energy relation is fitted using the results in CLIC-note-808
- Three options are proposed for the positron injector.
- RF cavities are scanned for each option.
- The pulse compressors are also optimised for 380 GeV and 3 TeV stage.
- The cost for three options are evaluated.

Next step:

- Use GEANT4 to simulate the positron injector
- Do further optimization.

Thank you