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Simulation and optimisation of the CLIC and FCC-ee positron sources and the CompactLight beamline

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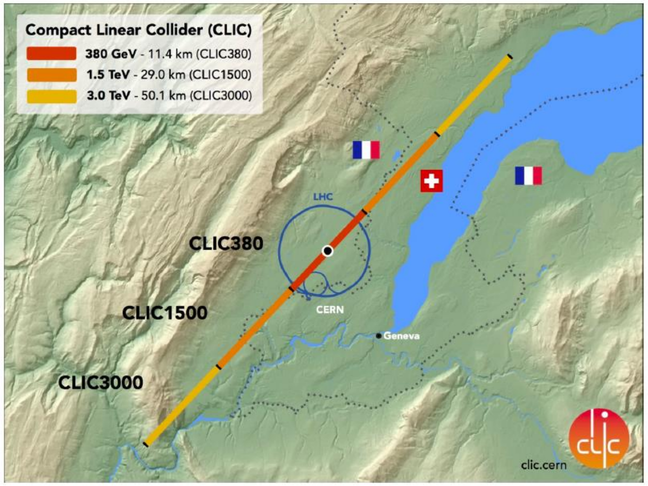
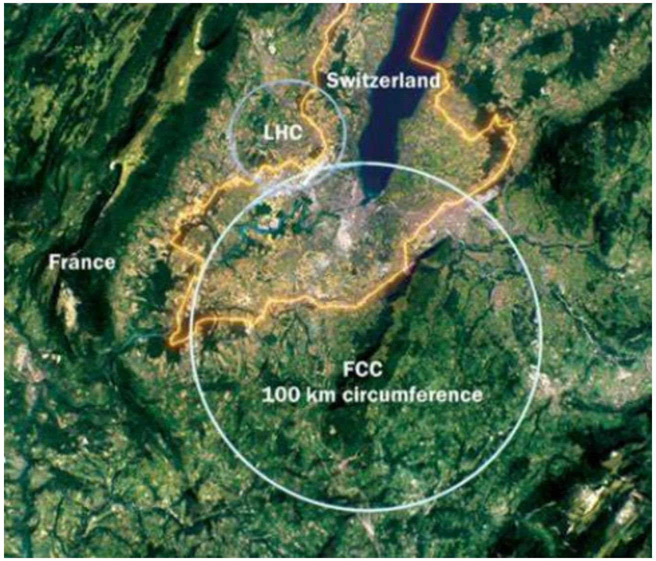
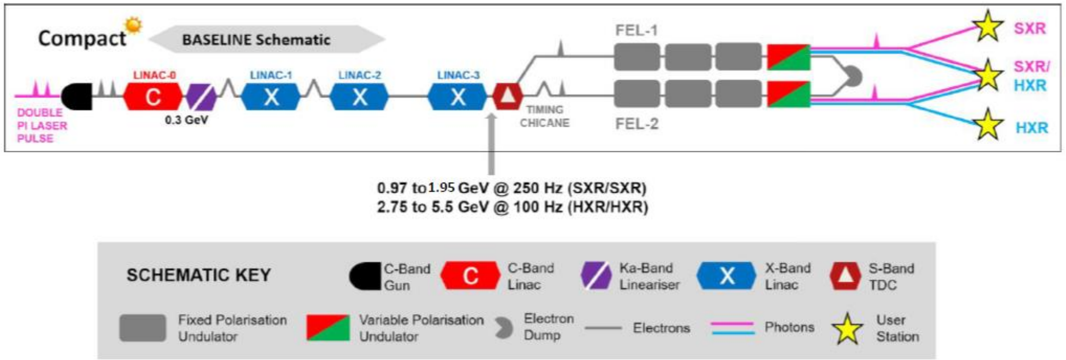
2023年6月10日

Outline

- **CLIC positron source**
- **FCC-ee positron source**
- **CompactLight optimization**
- **Conclusions**

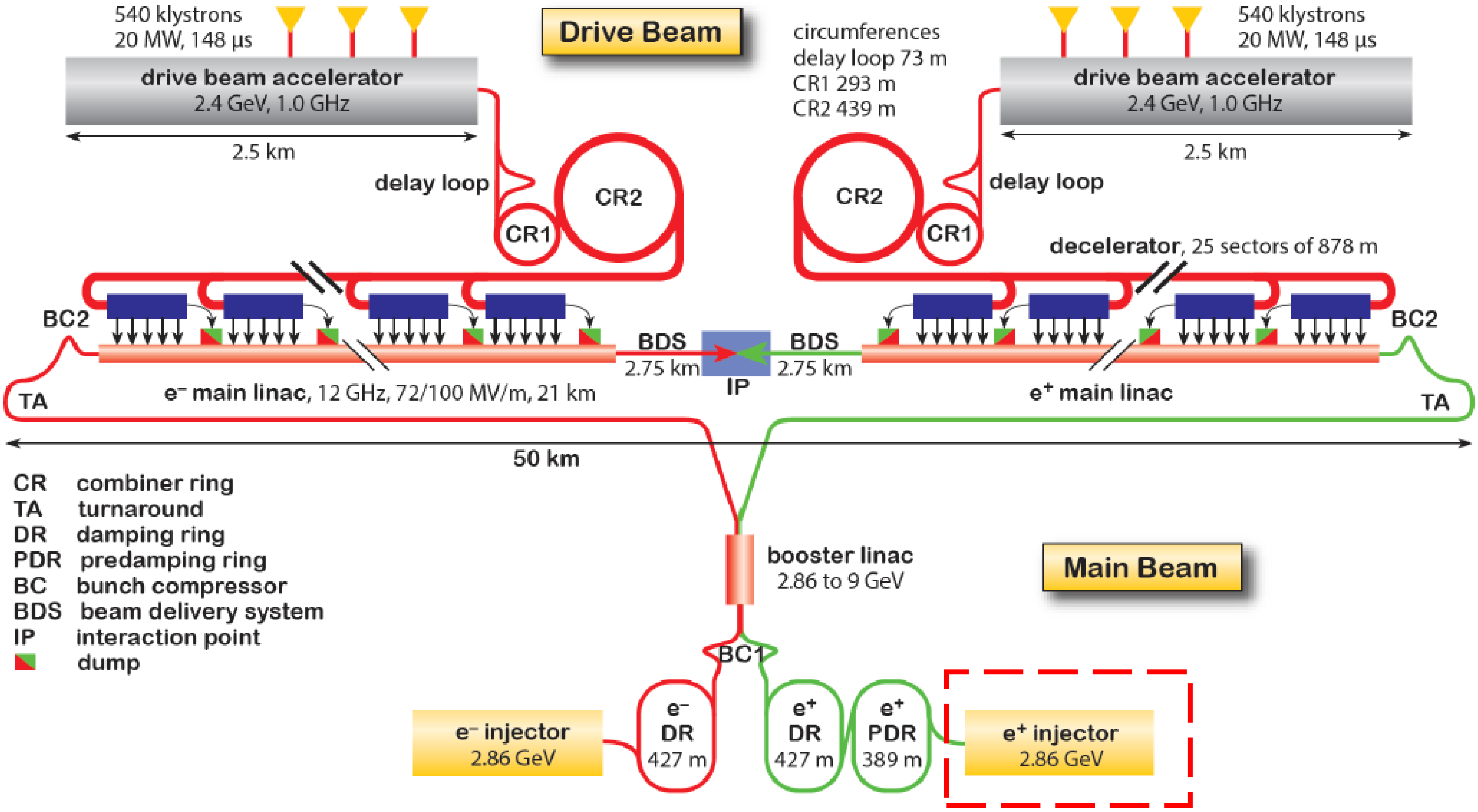






CLIC positron source

CLIC accelerator complex



Drive Beam

540 klystrons
20 MW, 148 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR1

CR2

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

540 klystrons
20 MW, 148 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR2

CR1

decelerator, 25 sectors of 878 m

BC2

BDS
2.75 km

IP

BDS
2.75 km

BC2

TA

e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km

e⁺ main linac

TA

50 km

booster linac
2.86 to 9 GeV

Main Beam

BC1

e⁻ injector
2.86 GeV

e⁻
DR
427 m

e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector
2.86 GeV

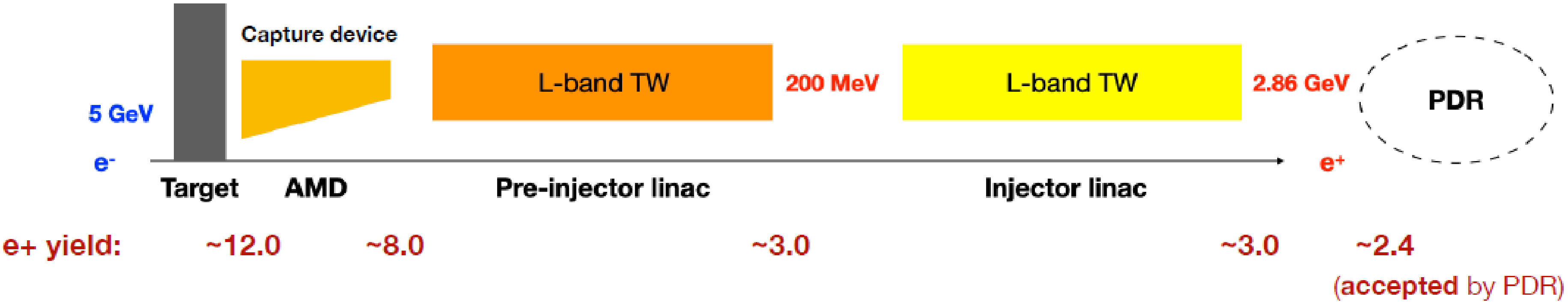
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Positron source

At 3 TeV stage

CLIC positron source

- Simulation of positron source: from **Target** to **Injector Linac**
  - Simulation tools: Geant4, Fot, RF-Track, Placet, Opera-2D/3D®



Positron yield: $\text{yield}_{e+} = \dfrac{n_{e+}^{\text{produced}}}{n_{e-}^{\text{primary}}}$

- A high positron yield (accepted by PDR) is very necessary:
  - Required by the high luminosity
  - Helps to reduce the drive beam power and cost
  - Can also reduce the energy deposition and avoid target damage

Target PEDD

- Peak Energy Deposition Density (PEDD) in W target required to be **< 35 J/g** (experience at SLAC)

PEDD (normalised by yield):

$$\mathrm{PEDD} = \frac{\max(E_{\mathrm{dep}}^{W})}{V_{\mathrm{cell}} \cdot \rho_W \cdot n_{e^-}^{\mathrm{sim}}} \cdot \frac{n_b^{\mathrm{PDR}} \cdot n_{e^+}^{\mathrm{PDR}}}{\eta_{e^+}^{\mathrm{PDR}}}$$

$\max(E_{\mathrm{dep}}^{W})$ is the max deposited energy in a single mesh cell of the W target

$V_{\mathrm{cell}} = \Delta x \cdot \Delta y \cdot \Delta z = \underline{(0.5\,\mathrm{mm})}^3$ is the mesh cell volume

$\rho_W = 19.25\,\mathrm{g/cm^3}$ is density of the W target

$n_{e^-}^{\mathrm{sim}} = 10^4$ is the number of simulated e^-

$n_b^{\mathrm{PDR}} = 352\ (312)$ is the number of e^+ bunches per pulse required at the entrance of PDR

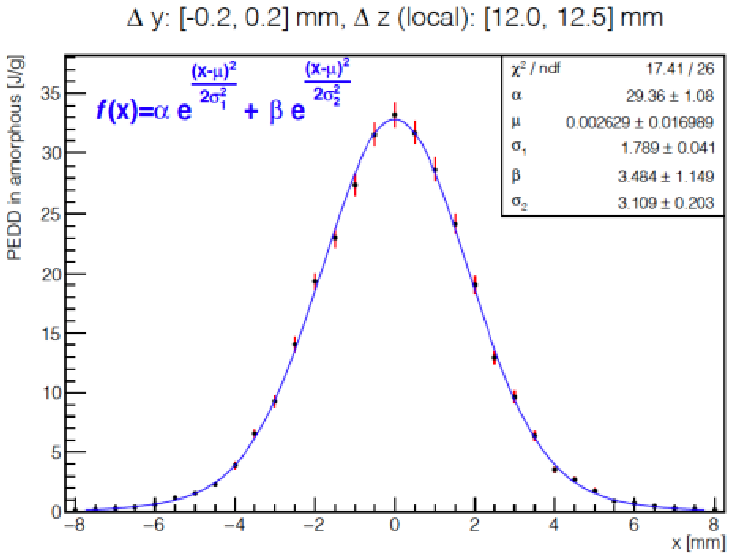
$n_{e^+}^{\mathrm{PDR}} = 6.24\ (4.44) \times 10^9$ is the number of e^+ per bunch required at the entrance of PDR

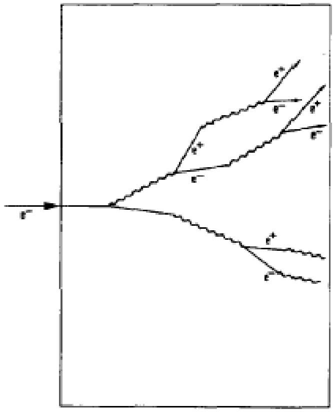
$\eta_{e^+}^{\mathrm{PDR}}$ is the yield of e⁺ accepted by the PDR

- A detailed study of mesh grid size also performed (in backup slides)

Numbers are for 380 GeV (1.5 TeV and 3 TeV) stages

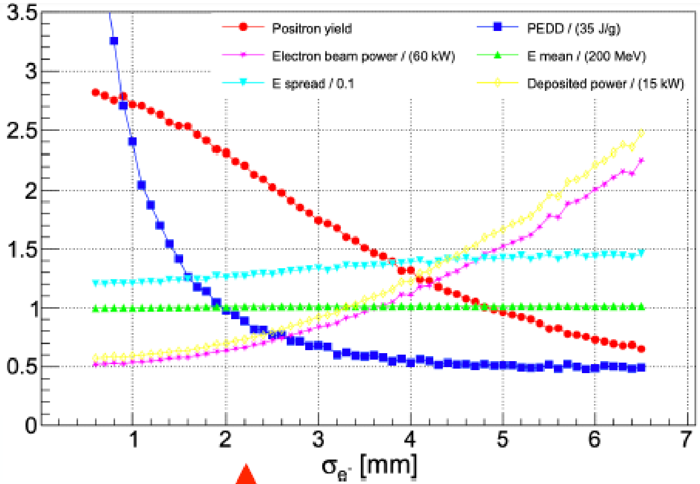
A 20% bunch charge safety margin already included





Optimisation procedure

- **Goals:**
  - **Higher e+ yield** (accepted by PDR)
  - **PEDD well below 35 J/g**
  - Lower deposited power, energy spread, …



Optimised: 2.2 mm

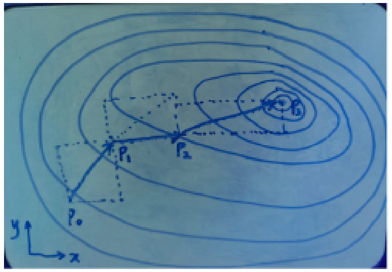
- **Procedure:** (based on iterative scans)

1. Define the default parameters to start with
2. Scan the parameters separately but simultaneously
   - Scan only one parameter at a time, with other parameters fixed to the default
   - Parameters can be scanned at the same time since the scans are independent
3. Choose new default parameters giving best results. And repeat the scan iteratively until all parameters are optimised and stable (plateaued in the scan)

- **Example:** (simplified optimisation of CLIC positron source)
  - **Evolution of optimised parameters**

Iteration	σ_{e^-}	δ_{amor}	B_0	L_{amd}	R_{amd}	ϕ_{dec}	ϕ_{acc}	E_{dec}	E_{acc}	η_{e^+}	PEDD
1	5.0	12	5.0	10	4	120	120	16	16	0.12	98.6
2	5.0	17	5.5	10	8	150	150	15	15	0.68	24.1
3	3.2	16	4.5	20	8	150	150	12	15	1.35	25.2
4	2.5	17	6.0	22	8	155	150	13	15	1.86	29.3
5	2.2	18	6.0	22	8	155	155	11	16	2.08	33.3
6	2.2	18	6.0	22	8	160	155	13	17	2.15	32.2

A simple illustration of the algorithm

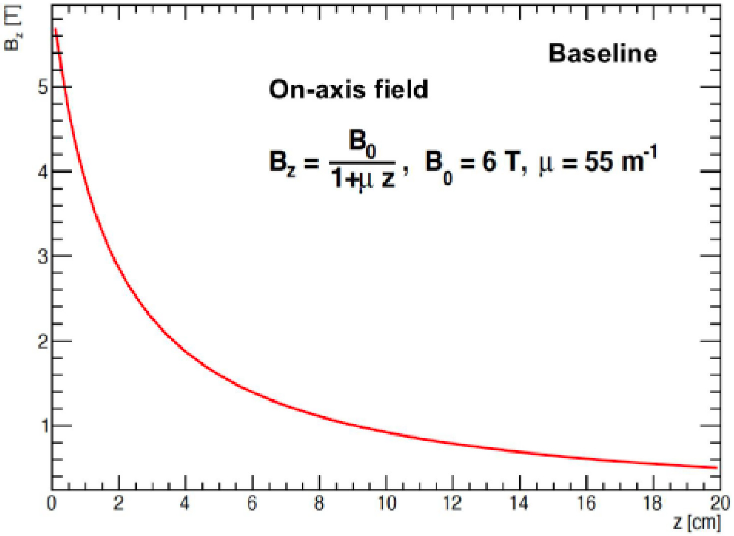


More in [CLIC-Note-1165]

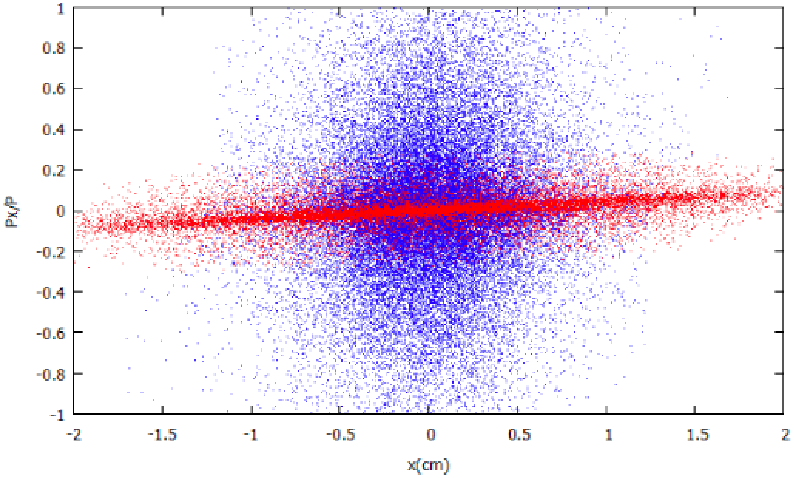
- Simpler, faster and more efficient
- Best optimisation achieved in 6 iterations
- ~25 times faster than old algorithm (Nelder-Mead method), benefiting from distributed / parallel computation

Capture device

- Adiabatic Matching Device (AMD) is used to capture e+, with an adiabatically tapered magnetic field
- Transverse divergence is reduced significantly after AMD, allowing a stable transport of the beam



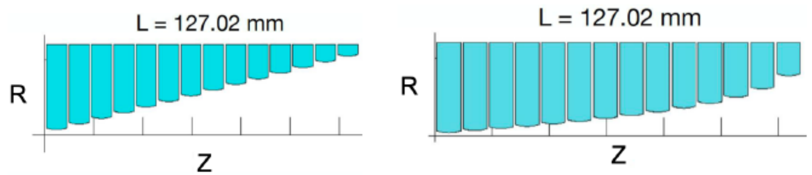
On-axis Bz (analytic adiabatic formula)



x’-x phase space before and after AMD
(divergence reduced significantly)

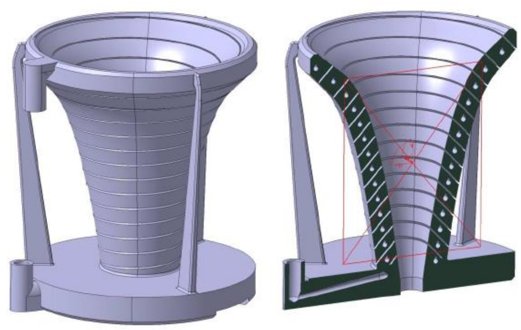
Capture device

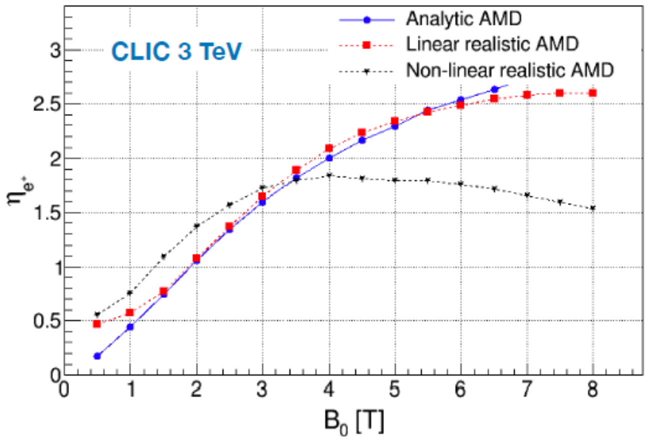
- Flux concentrator (FC) used as AMD
  - Traditional, mature technology
  - Limited peak field (B0 < 6 T)
  - Limited aperture (tapered, small entrance)
  - Max e+ yield ~ 2.5 (up to now)

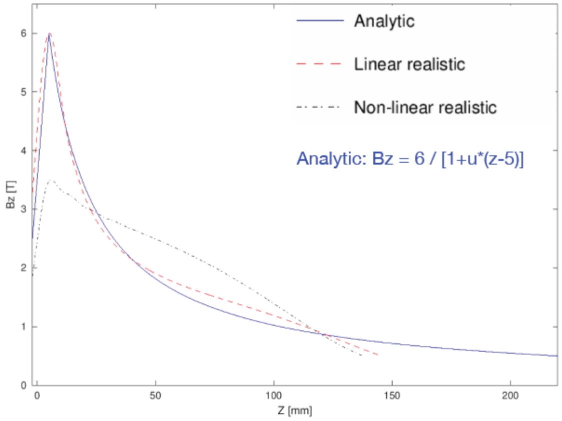


CLIC FC with linear or non-linear shaped apertures

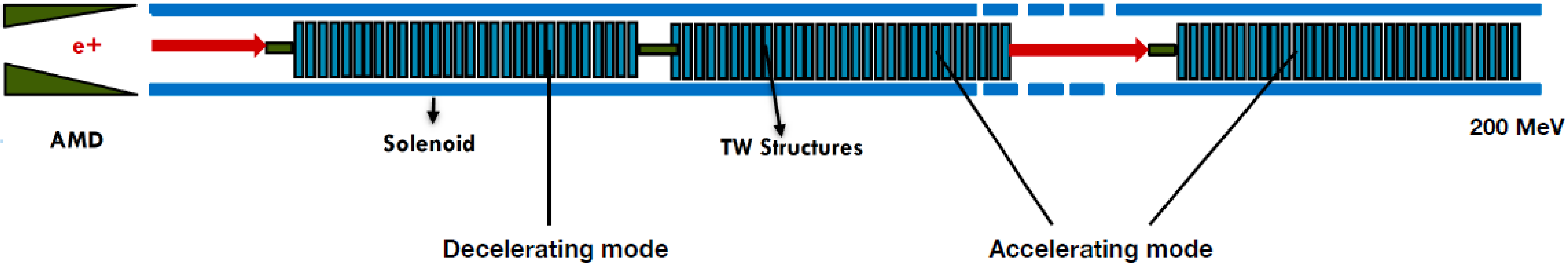
Parameters	Linear (baseline)	Non-linear (alternative)
Entrance (R)	6.5 mm	6.5 mm
Current frequency	25 kHz	25 kHz
Peak current	20 kA	18 kA
Peak Bz	6.0 T	3.5 T
e+ yield	2.41	1.71
PEDD	32.8 J/g	32.4 J/g
Total voltage	10.3 kV	4.4 kV
Force on 1st turn	10 kN	2.6 kN



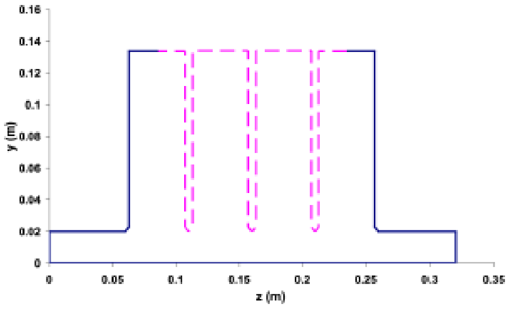




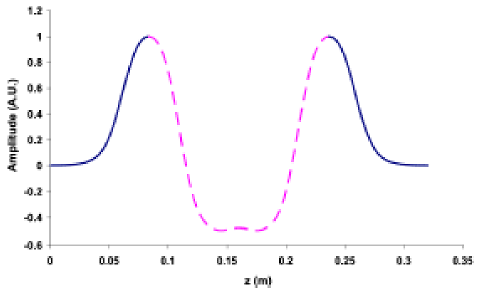
Pre-injector linac (capture linac)



- **L-band** travelling wave (**TW**) RF, 2π/3 mode, **2 GHz**
- NC solenoid: **0.5 T**
- Structure length 1.5 m (**30 cells**)
- Distance (gap) 20 cm
- Aperture radius **20 mm**
- Number of structures: **11**
    - **1 for deceleration**
    - **10 for acceleration**
- Gradient **~ 20 MV/m**
- Phases and gradients **optimised** such that yield is maximum and beam energy at the exit is as close to 200 MeV as possible



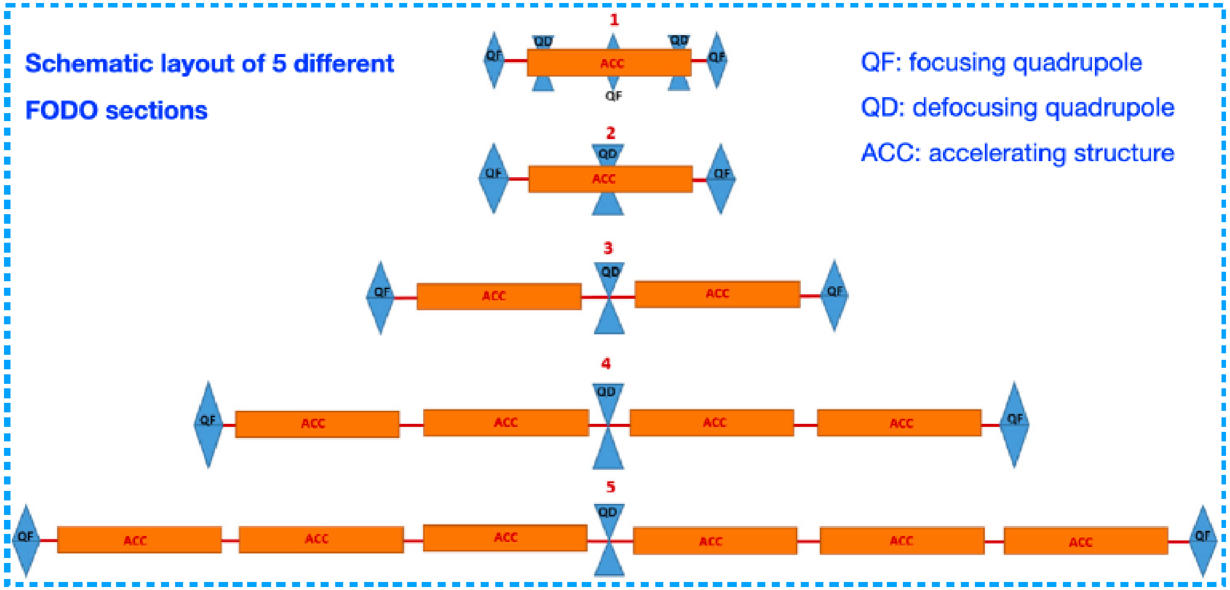
Pillbox cavity geometry (4 cells)



On-axis Ez (4 cells)

Injector linac (positron linac)

- Composed of 5 FODO sections
- Each section has 3-4 matching quadrupoles

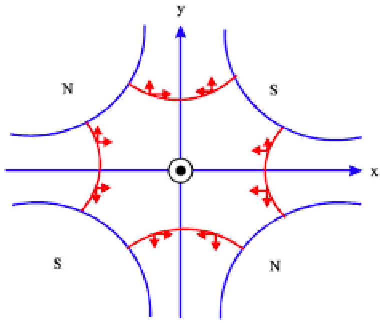


Schematic layout of 5 different FODO sections

QF: focusing quadrupole

QD: defocusing quadrupole

ACC: accelerating structure



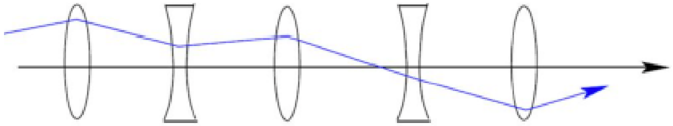
Forces in Quadrupole

$$\begin{aligned} B_x &= G\,y \\ B_y &= G\,x \end{aligned} \quad \Rightarrow \quad \begin{aligned} F_x &= -qv_z B_y = -qv_z G\,x \\ F_y &= qv_z B_x = qv_z G\,y \end{aligned}$$

G is the gradient of the quadrupole magnet:

$$G = \frac{2\mu_0 n I}{r^2_{\text{aperture}}} \left[\frac{T}{m}\right] = \frac{B_{\text{poles}}}{r_{\text{aperture}}} \left[\frac{T}{m}\right]$$

Section	Quadrupoles	Cavities
1	4+33	8
2	3+37	18
3	3+29	36
4	3+15	28
5	3+13	36
Total	143	126



FODO lattice

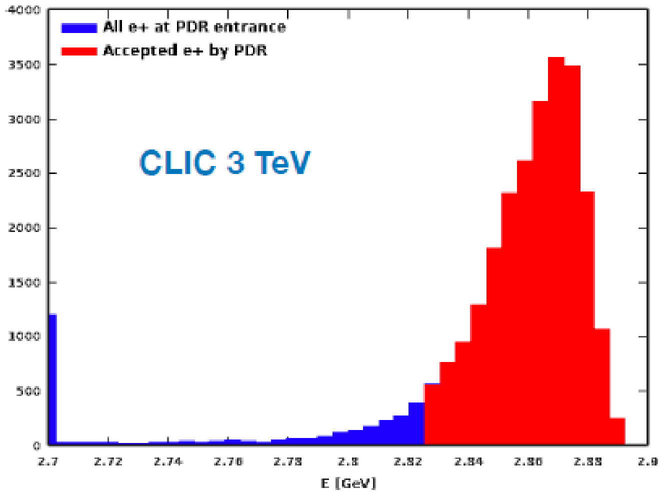
focusing strength of a quadruple: $k\ [m^{-2}] = \frac{0.2998 \cdot G}{P\ [\text{GeV/c}]}$

focal length of a quadrupole: $f = \frac{1}{k \cdot L_Q}$

Positrons at Pre-damping ring (PDR) entrance

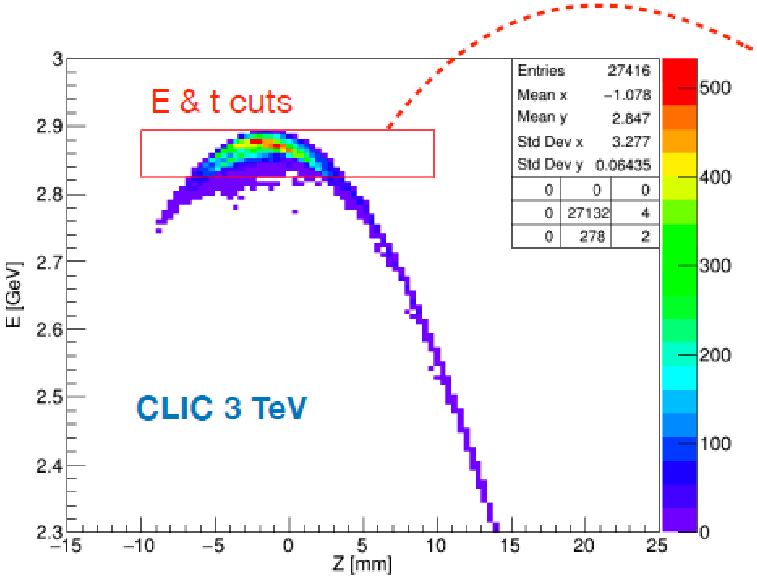
- **e⁺ parameters at the entrance of PDR**

Parameter	380 GeV	1.5 TeV & 3 TeV
Energy acceptance (±)	1.2%	1.2%
Time window (total)	20 mm/c	20 mm/c
Bunch charge	5.2 x 10^9	3.7 x 10^9
Bunch charge safety margin	20%	20%

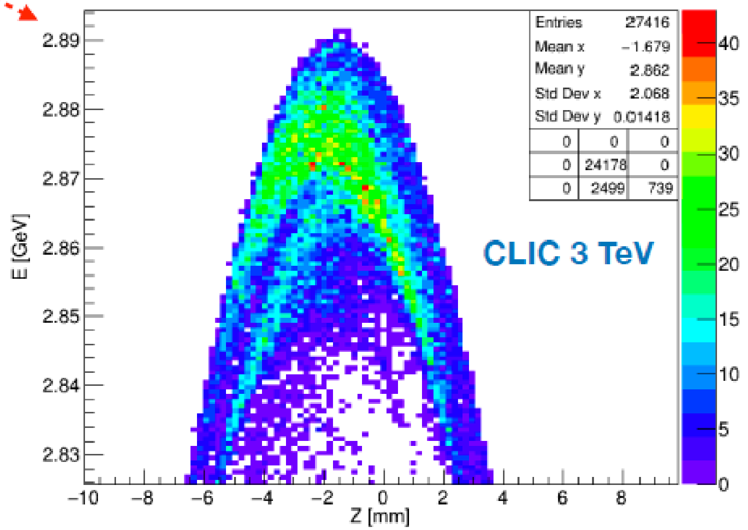


Energy cut (2.86 GeV ± 34.3 MeV)

- **Longitudinal phase space at the entrance of PDR**



All e+ at PDR entrance



Accepted e+ by PDR

FCC-ee positron source

FCC-ee positron source

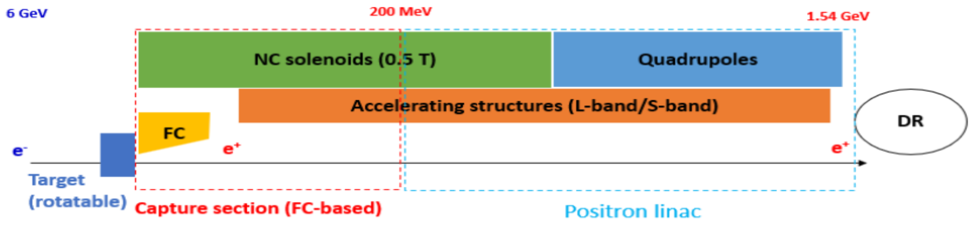
- FCC-ee positron source is similar with CLIC, except for beam parameters, linac type, DR requirements, etc.

Primary e$^-$ parameters	Values	Units
Beam energy	**6**	GeV
Spot size (rms)	**0.5**	mm
Bunch length (rms)	1	mm
Energy spread (rms)	0.1	%
Normalised trans. emittance (rms)	15	mm·mrad
No. of bunches per train	2	
Repetition rate	200	Hz

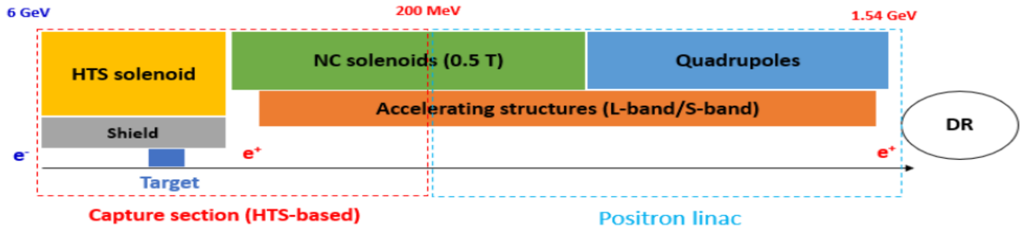
e+ parameters at DR entrance	Values
Repetition rate	**200 Hz**
No. of bunches (per train)	**2**
Bunch charge (w/ 100% safety margin)	**8 nC**
Energy window (@ 1.54 GeV)	**±3.8%**
Time window (to be discussed)	**16.7 mm/c (40° @ 2 GHz)**
No transverse cuts (to be discussed)	

➢ To be matched to DR acceptance (in progress)

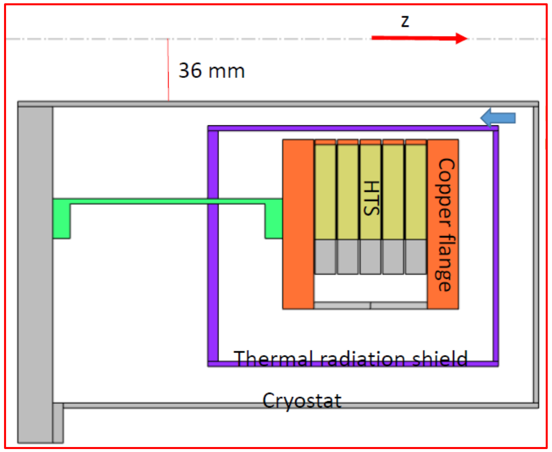
- **FC-based layout (baseline)**



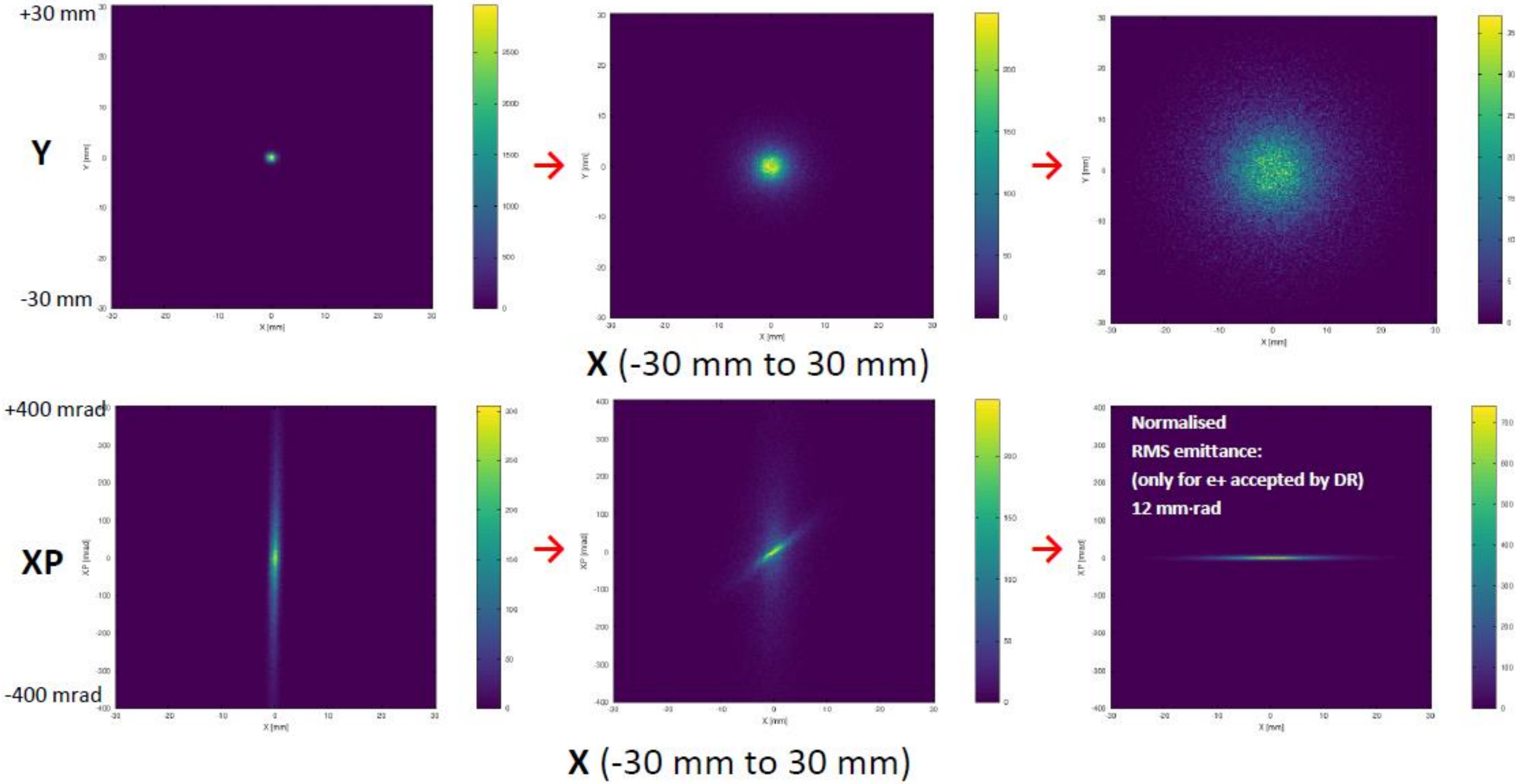
- **HTS-based layout, *V0* (alternative)** – ***study focused on this scenario***



HTS solenoid (PSI design)



Transverse phase spaces

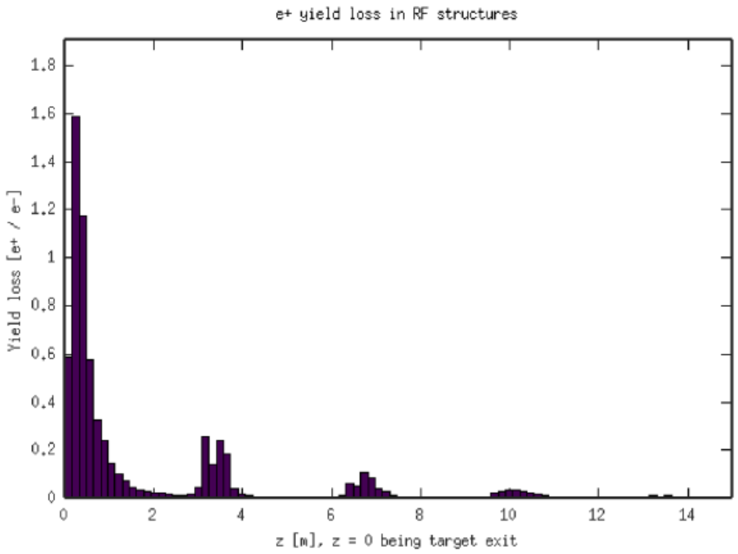


Normalised
RMS emittance:
(only for e+ accepted by DR)
12 mm-rad

Target exit → **HTS solenoid cryostat exit** → **Capture linac exit**

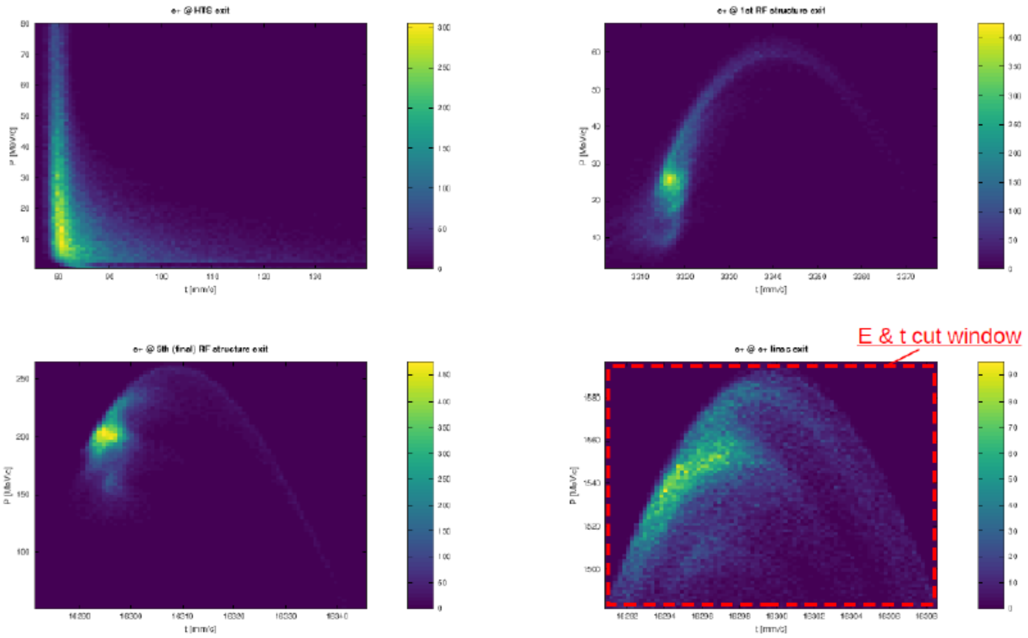
Longitudinal phase spaces

Yield loss in RF structures (up to 200 MeV)



The RF phases of the 5 capture linac structures are all optimised for the maximum e+ yield

Longitudinal phase spaces at the exits of the HTS solenoid, 1st RF structure, 5th RF structure (200 MeV) and e+ linac (analytic)

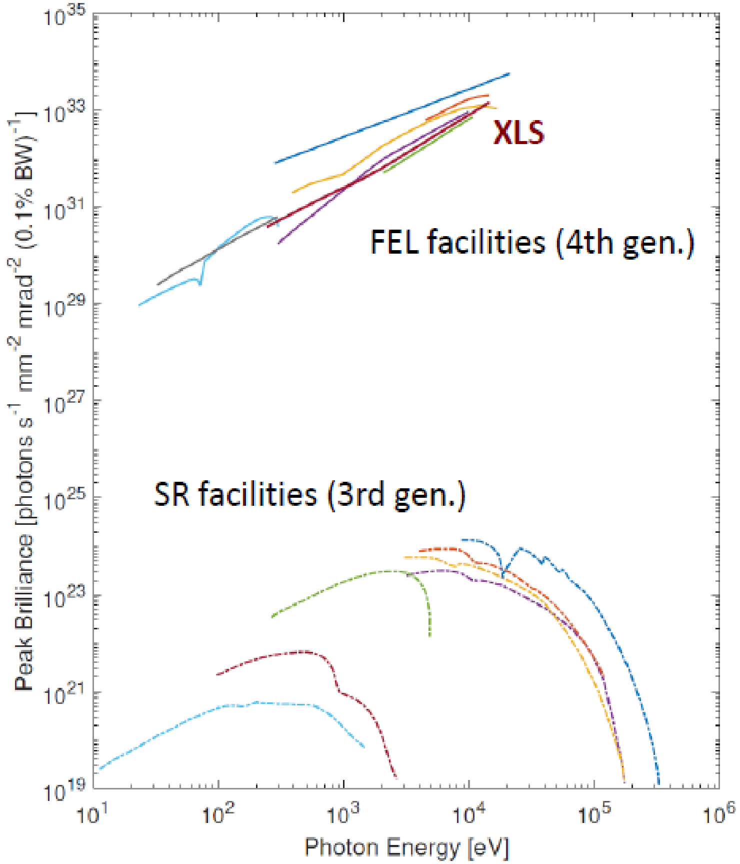


E & t cut window

CompactLight optimisation

CompactLight project

- Target performance compared to other light sources

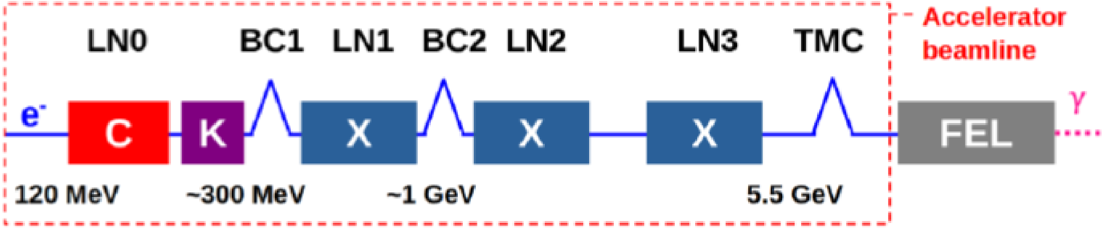


- Some **advantages** of XLS:
  - Lower construction and operation **cost**
  - Reduced **power consumption**
  - Much smaller **footprint**

Main parameters of the CompactLight FEL

Parameter	**Unit**	**Soft-x-ray FEL**	**Hard-x-ray FEL**
Photon energy	keV	0.25 – 2.0	2.0 – 16.0
Wavelength	nm	5.0 – 0.6	0.6 – 0.08
Repetition rate	Hz	1000	100
Pulse duration	fs	0.1 – 50	1 – 50
Polarization		Variable, selectable	Variable, selectable
Two-pulse delay	fs	±100	±100
Two-colour separation	%	20	10
Synchronization	fs	<10	<10

Accelerator beamline



Bunch charge: 75 pC

- **LN0**: Linac-0 (C-band)
- LN0 followed by a **K-band lineariser**
- **BC1-BC2**: Bunch compressors
- **LN1-LN3**: Linac-1 to Linac-3 (X-band)
- **TMC**: Timing chicane
- FEL: FEL undulator

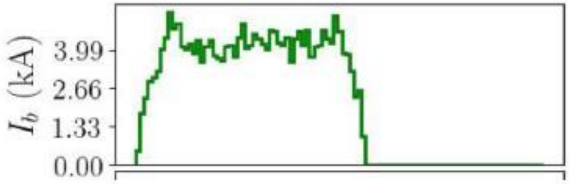
Input e⁻ parameters (120MeV)

Parameter	Unit	Value
E	MeV	123.8
σ_E/E	%	0.07
σ_z	um	315.1
σ_x	um	59.9
σ_y	um	35.4
$\varepsilon_{n,x}$	mm·mrad	0.14
$\varepsilon_{n,y}$	mm·mrad	0.14

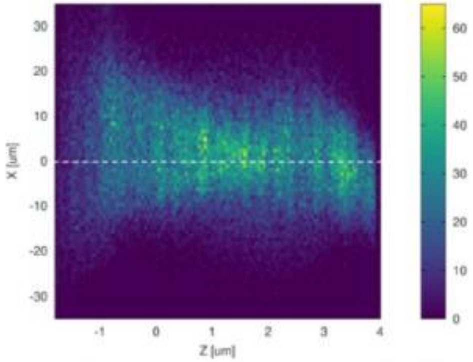
RF parameters	*f* (Hz)	*L* (m)	*G* (MV/m)	*φ* (°)
LN0 (C-band)	6	1.90	15	26
K-band	36	0.31	24.5	192
LN1 (X-band)	12	0.92	65	35
LN2 (X-band)	12	0.92	65	10
LN3 (X-band)	12	0.92	65	10

FEL requirements

- FEL requirements on electrons (5.5 GeV) performance (numbers just for reference):
    - Beam energy: 5.5 GeV. Energy spread: 0.01%
    - Flat-top current profile. Peak current: 5 kA
    - Bunch-length: 5 um (full-width)
    - Bunch charge: 75 pC
    - Normalised emitt. $\varepsilon_{x,y}$: 0.2 um
    - Small transv. beam centroid offsets (including x, y, x', y')
    - Small jitter sensitivities
    - Etc.



[Fig. from the CDR]



Optimisation strategy

- Simulation tools: Octave, RF-Track, Placet (6D tracking, side effects included), Genesis
- Optimisation algorithm: "*Nelder-Mead simplex method*" (*fminsearch* in Octave)
- Merit function ("objective function"), ***F***, composed of different "separate" merit functions, f_i, defined based on different requirements:

$$F = \sqrt{\sum_{i=1}^{n} \frac{f_i^2}{n}}$$

(to be minimised)

- Energy requirement:

$$f_1 = \begin{Bmatrix} 30 \cdot |\Delta E| \text{ (if } \Delta E \leqslant 0) \\ 20 \cdot |\Delta E| \text{ (if } \Delta E > 0) \end{Bmatrix} / \text{GeV}, \quad \Delta E = \langle E \rangle - 5.5 \text{ GeV}$$

- Peak current requirement:

$$f_2 = \begin{Bmatrix} 4 \cdot |\Delta I_{\text{peak}}| \text{ (if } \Delta I_{\text{peak}} \leqslant 0.5 \text{ kA)} \\ 6 \cdot |\Delta I_{\text{peak}}| \text{ (if } \Delta I_{\text{peak}} > 0.5 \text{ kA)} \end{Bmatrix} / \text{kA}, \quad \Delta I_{\text{peak}} = I_{\text{peak}} - 5 \text{ kA}$$

- Flat-top requirement:

$$f_3 = 12 \cdot \sigma_I^{\text{sliced}} / \langle I^{\text{sliced}} \rangle$$

I^{sliced} is sliced beam current at full bunch length.

- Energy spread requirement:

$$f_4 = \max(0,\ 1.2 \times 10^4 \cdot \Delta \frac{\sigma_E}{E}), \quad \Delta \frac{\sigma_E}{E} = \frac{\sigma_E}{E} - 0.01\%$$

- Emittance requirement:

$$f_5 = \max(0,\ 25 \cdot \Delta \epsilon_{x,y} / (\text{mm} \cdot \text{mrad})), \quad \Delta \epsilon_{x,y} = \epsilon_{x,y} - 0.15 \text{ mm} \cdot \text{mrad}$$

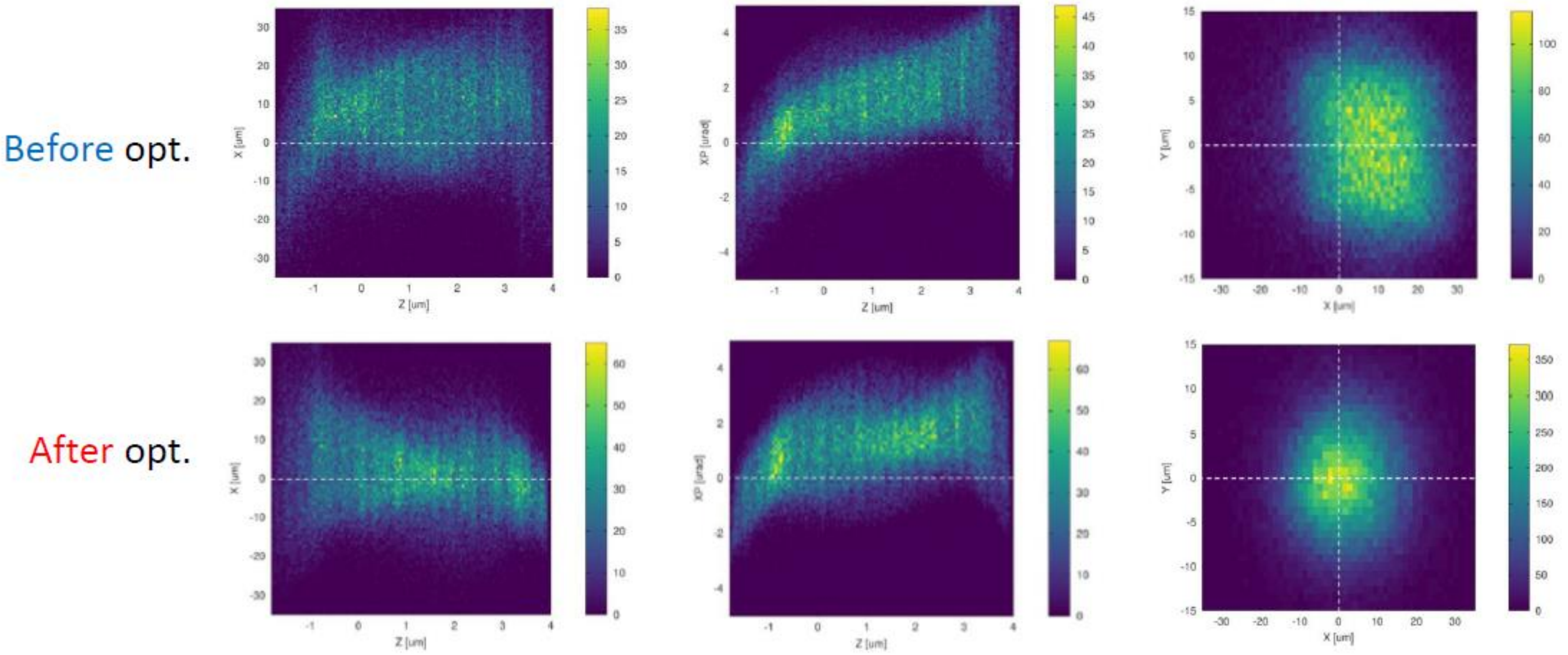
- Transverse offset requirement:

$$f_6 = 0.4 \cdot \langle |\delta_{x,y}^{\text{sliced}}| \rangle / \mu\text{m} \text{ or } 0.4 \cdot \langle |\delta_{x',y'}^{\text{sliced}}| \rangle / \mu\text{rad}$$

$\delta_{x,y,x',y'}^{\text{sliced}}$ is sliced beam centroid offset

Optimisation results (beam)

- As a result of the optimisation
  - The longitudinal performance is not changed much
  - The **transverse performance is improved significantly**
- Transverse beam centroid offsets:

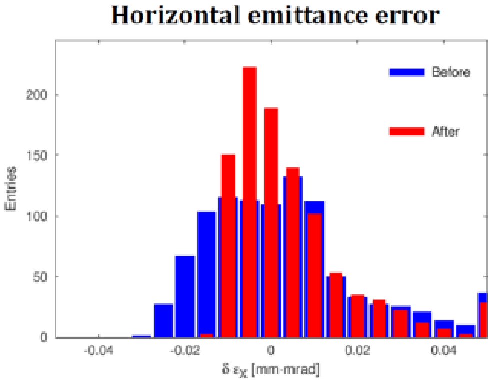


Optimisation results (beam)

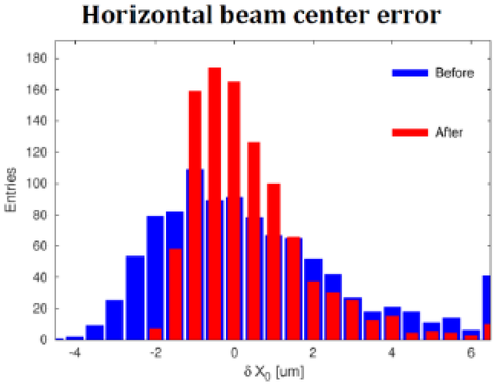
- Emittance growth (projected emittance)

Emittance growth	**Before optimisation**	**After optimisation**
Horizontal (X)	**43%**	**14%**
Vertical (Y)	**7%**	**0**

- Jitter sensitivity
  - 1000 random jittered machines


Horizontal emittance error

Before opt.:	**σ = 22.5 µm·mrad**
After opt.:	**σ = 16.8 µm·mrad**


Horizontal beam center error

Before opt.:	**σ = 2.74 µm**
After opt.:	**σ = 1.56 µm**

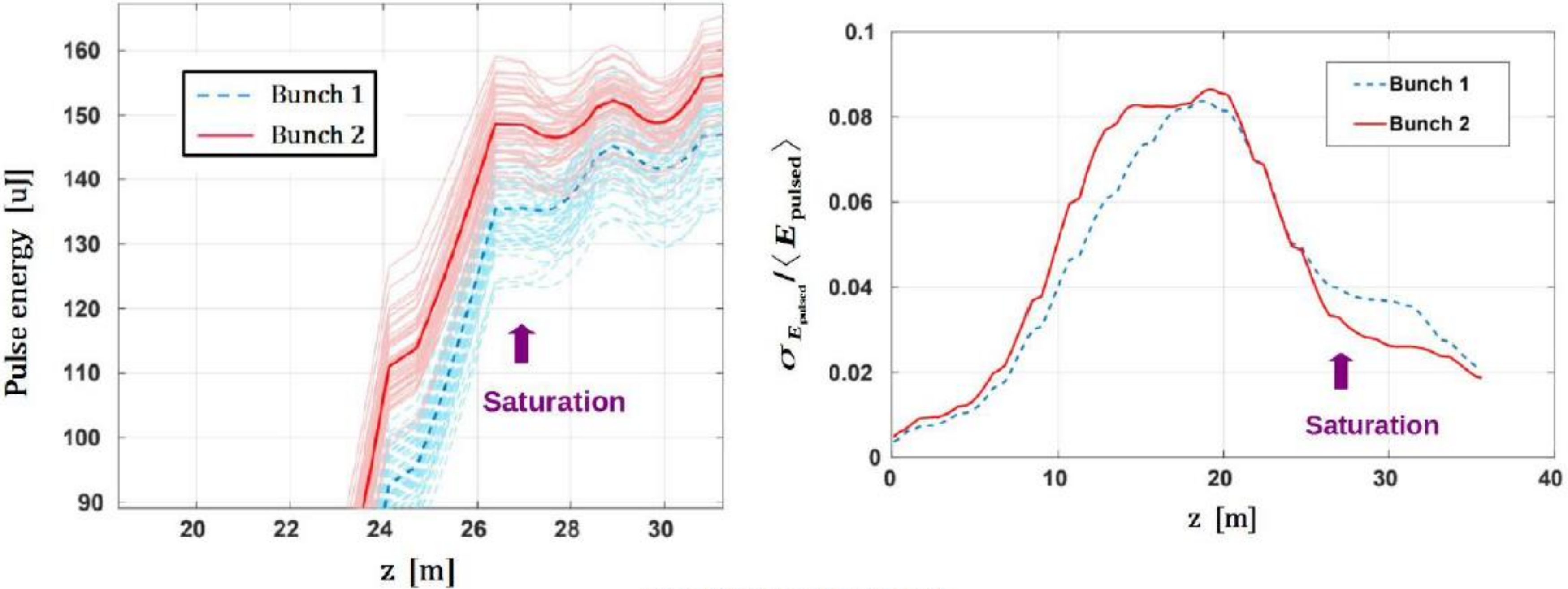
- Jitter sources considered:
  - Bunch charge variation: σ = 2%
  - Injector laser timing error: σ = 25 fs
  - RF gradient error (C-band, X-band): σ = 0.04%
  - RF phase offset (C-band, X-band): σ = 0.05°

Optimisation results (photons)

- FEL pulsed energy and stability
  - 50 independent shot noise realisations
  - Pulse energy at saturation increased by 10%
  - Stability of FEL output improved. Fluctuation reduced by 20%

☐ Bunch 1: Before opt.

☐ Bunch 2: After opt.



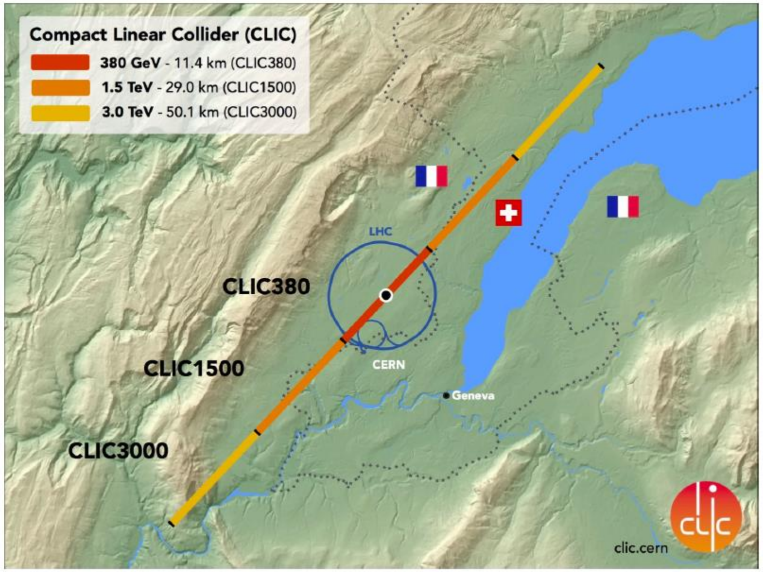
[Figs. from the FEL experts]

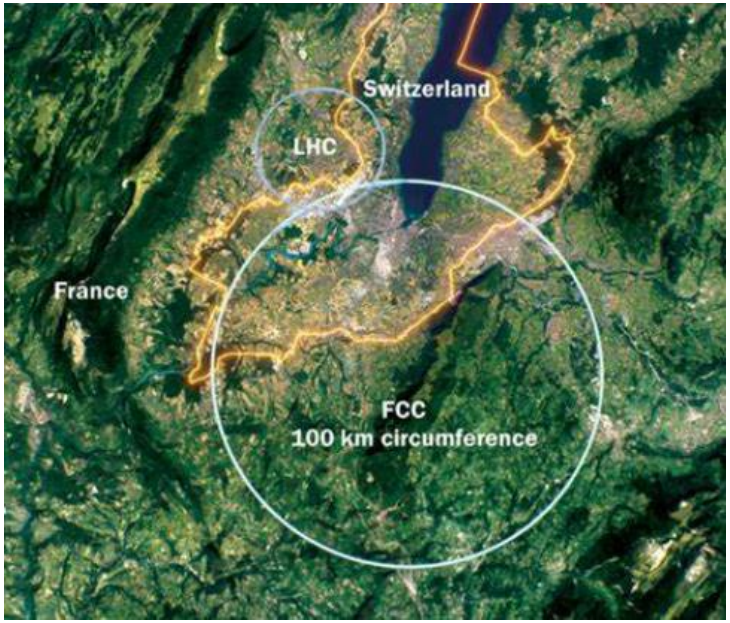
Conclusions

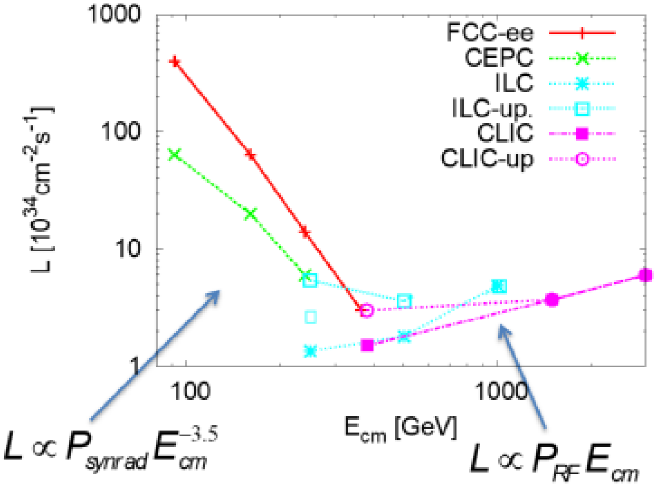
- Brief introduction of the CLIC and FCC-ee positron sources, and the simulation and optimisation
    - ➢ New simple optimisation procedure developed, which is much easier and faster
- Brief introduction of the CompactLight (light source) project, and the optimisation of the accelerator beamline
    - ➢ New simple optimisation strategy developed, with significant improvements in electron beam quality and FEL efficiency and stability

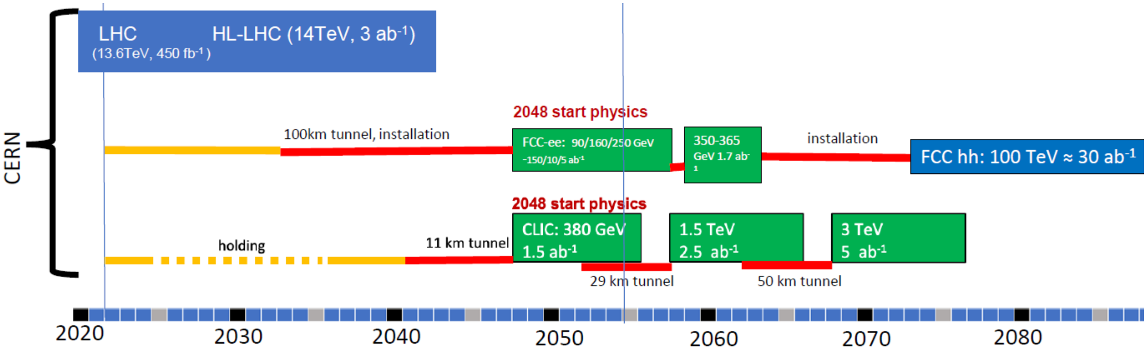
BACKUP

CLIC and FCC-ee experiments



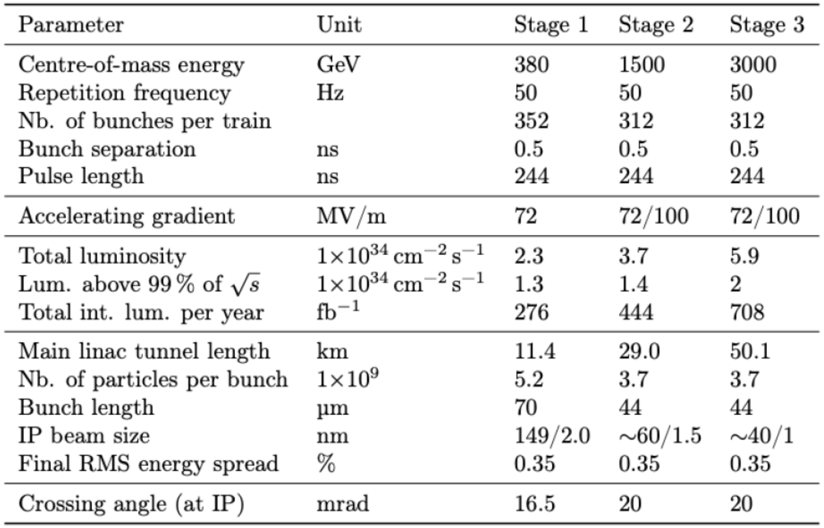






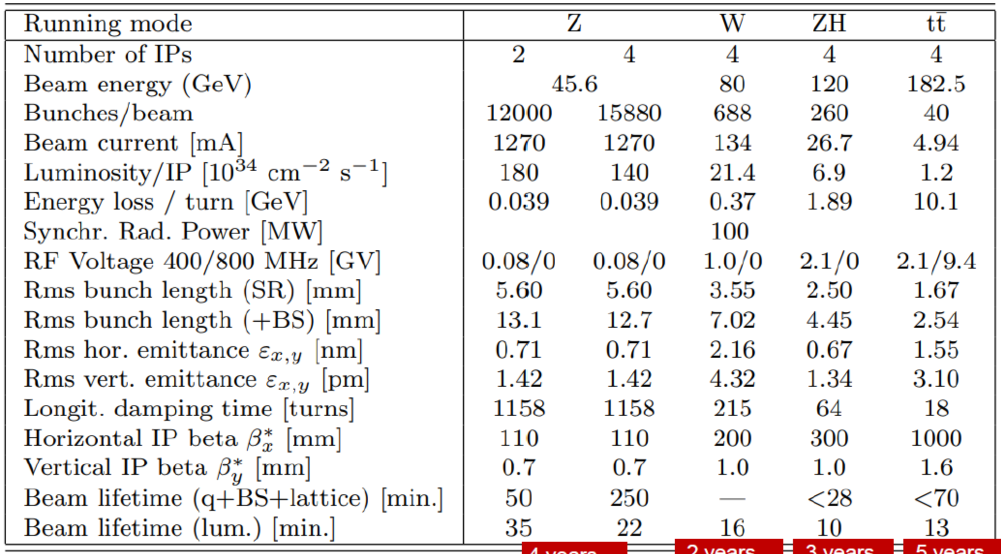
CLIC and FCC-ee parameters

- Beam parameters



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

CLIC parameters



Running mode	Z		W	ZH	$t\bar{t}$
Number of IPs	2	4	4	4	4
Beam energy (GeV)	45.6		80	120	182.5
Bunches/beam	12000	15880	688	260	40
Beam current [mA]	1270	1270	134	26.7	4.94
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	180	140	21.4	6.9	1.2
Energy loss / turn [GeV]	0.039	0.039	0.37	1.89	10.1
Synchr. Rad. Power [MW]	100				
RF Voltage 400/800 MHz [GV]	0.08/0	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	5.60	3.55	2.50	1.67
Rms bunch length (+BS) [mm]	13.1	12.7	7.02	4.45	2.54
Rms hor. emittance $\varepsilon_{x,y}$ [nm]	0.71	0.71	2.16	0.67	1.55
Rms vert. emittance $\varepsilon_{x,y}$ [pm]	1.42	1.42	4.32	1.34	3.10
Longit. damping time [turns]	1158	1158	215	64	18
Horizontal IP beta β_x^* [mm]	110	110	200	300	1000
Vertical IP beta β_y^* [mm]	0.7	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	250	—	<28	<70
Beam lifetime (lum.) [min.]	35	22	16	10	13

4 years
5×10^{12} Z

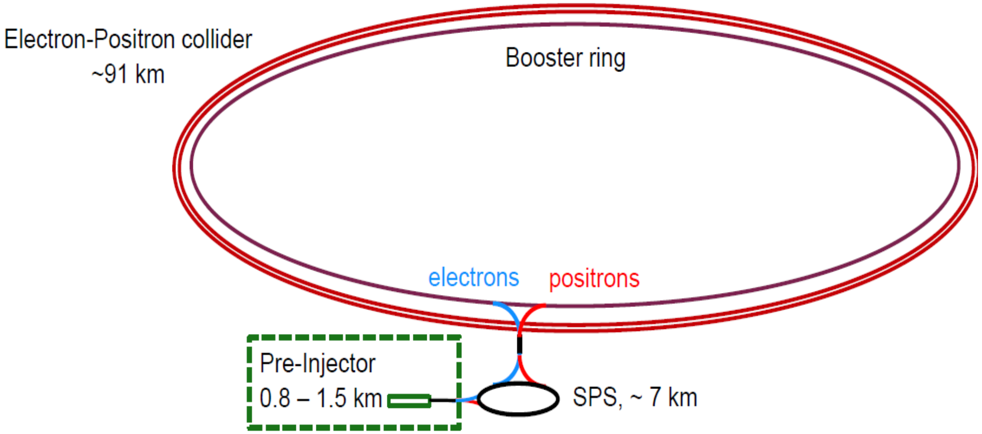
2 years
$> 10^{8}$ WW

3 years
2×10^{6} H

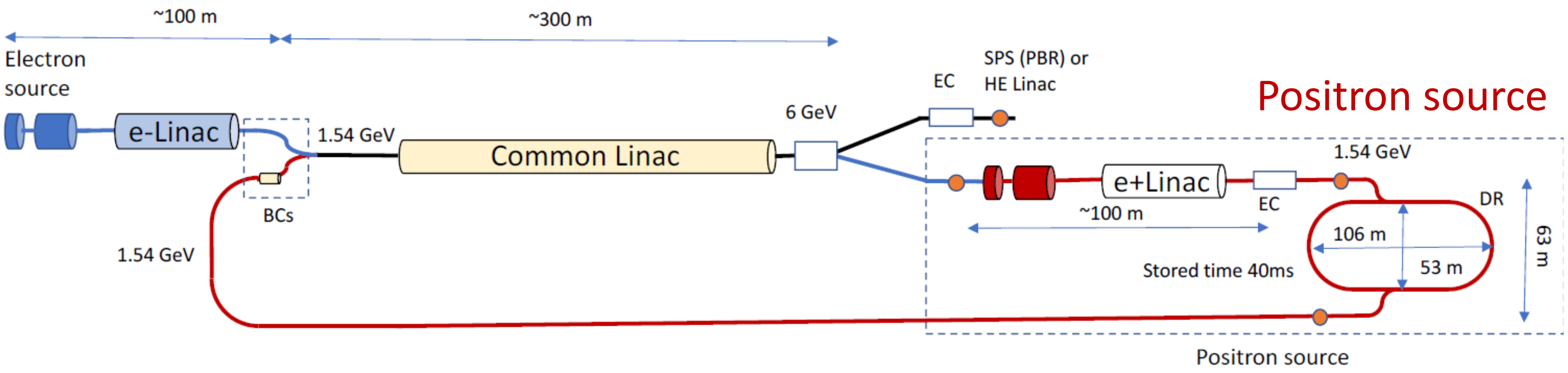
5 years
2×10^{6} tt pairs

FCC-ee parameters

FCC-ee Pre-injector complex

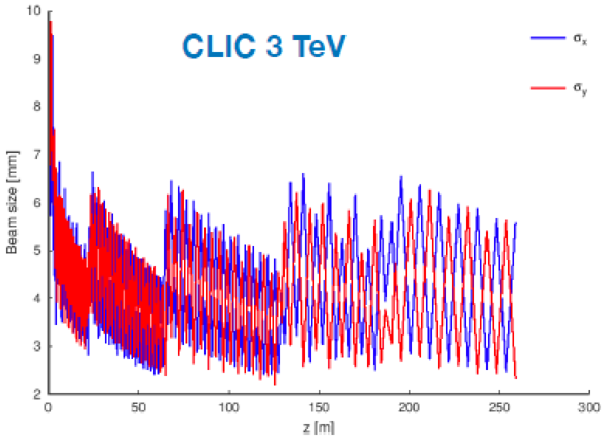


	CDR0	HE Linac	Unit
Ring for injection	SPS/PBR	BR	
Injection energy	6	20	GeV
Bunch charge (max)	4 (5)		nC
Repetition rate	200		Hz
Number of bunches	2		
Bunch spacing	25		ns
Normalized emittance (x, y) (rms)	10, 10		mm.mrad
Energy spread (rms)	<0.1		%
Bunch length (rms)	~1		mm
ΔQ/Q	<3		%
Energy spread (rms)	<0.1		%
Bunches/beam	~10000		

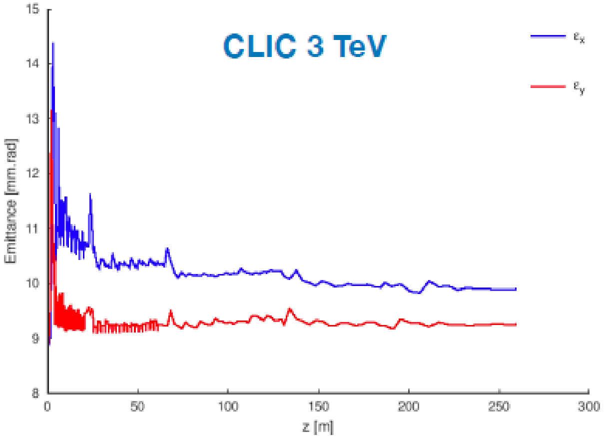


Injector linac (positron linac)

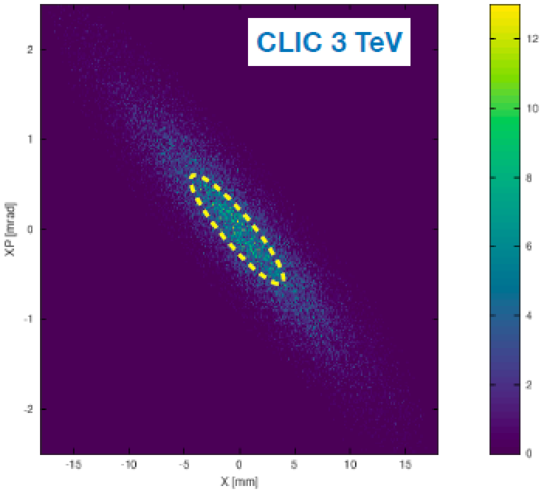
- Beam size evolution

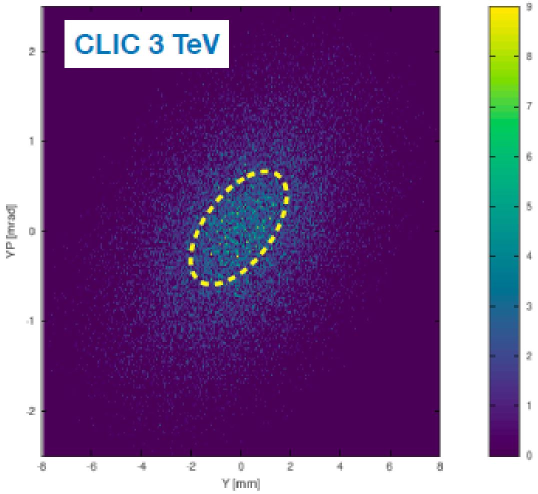


- Beam emittance evolution



- Final beam emittance (rms, normalised)





$$x' = p_x/p_z ; \quad y' = p_y/p_z$$

$$\epsilon_{\text{geometric}} = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}^2} = \frac{\text{Area}}{\pi}$$

$$\epsilon_{\text{normalised}} = \beta_{\text{rel}} \cdot \gamma_{\text{rel}} \cdot \epsilon_{\text{geometric}}$$

$$\beta_{\text{rel}} = \frac{v}{c} = \frac{Pc}{E} ; \quad \gamma_{\text{rel}} = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{m_0 c^2}$$

X emittance:
9.91 mm.rad

Y emittance:
9.27 mm.rad