CLIC Luminosity Studies

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for the CLIC Collaboration

Contents

- Motivations

- CLIC luminosity

- Z-pole operation

- Double the luminosity

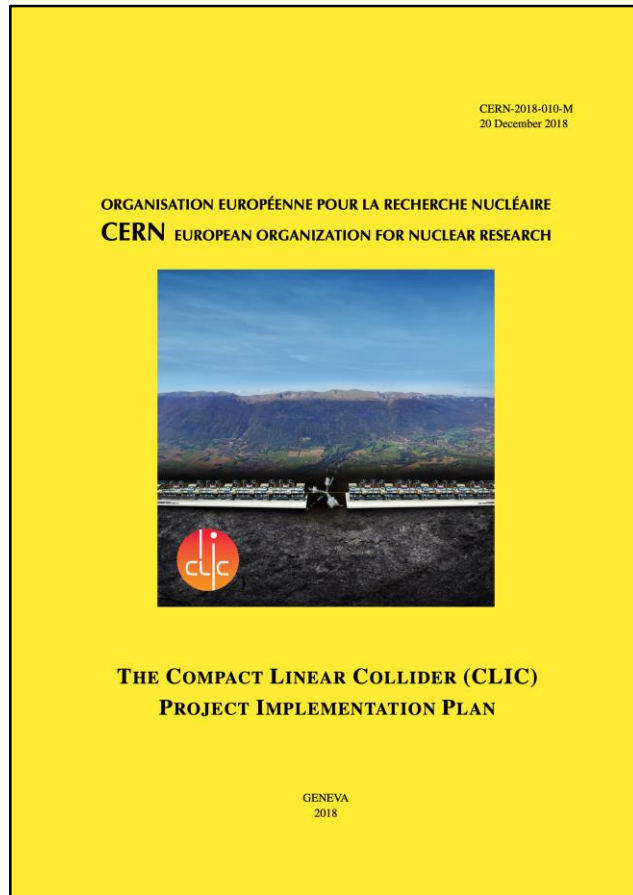- CLIC as a gamma-gamma collider

Enhance the CLIC performance?

In 2018 the CLIC study submitted a number of reports as input to the European Strategy for Particle Physics Update, among them a detailed description of the CLIC accelerator complex and its performance.

These reports, which include references to comprehensive background documents, are available at http://clic.cern/european-strategy

During the spring of 2019 three additional questions have come up concerning the performance of CLIC in various special operating conditions:
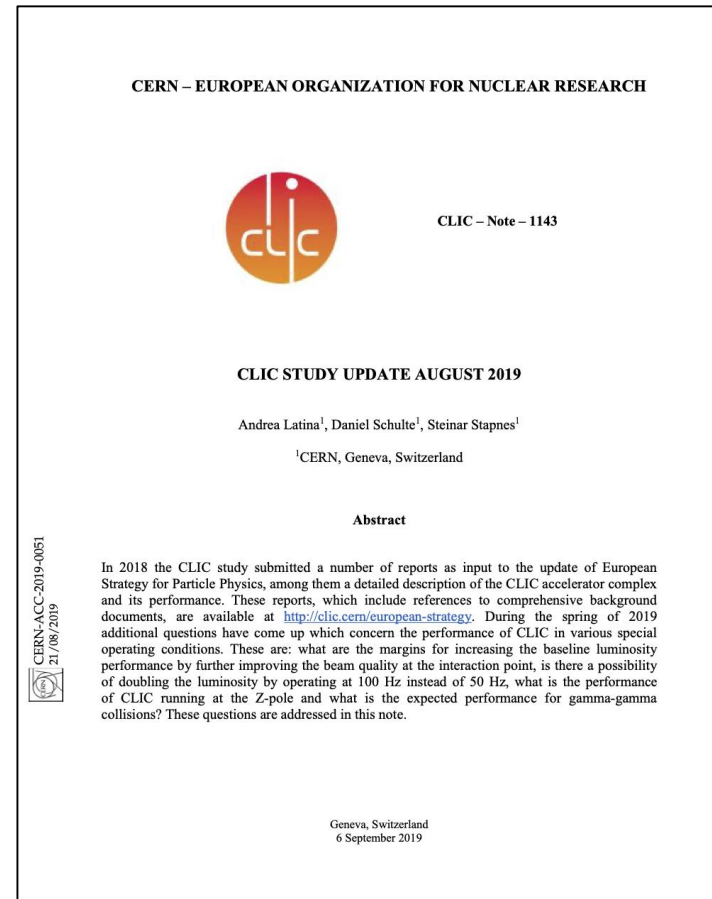
1) What are the margins for **increasing the baseline luminosity** performance by further improving the beam quality at the interaction point?

2) Is there a possibility of **doubling the luminosity** by operating at 100 Hz instead of 50 Hz?

3) What is the performance of CLIC running at the **Z-pole** and what is the **expected performance for gamma-gamma collisions**?
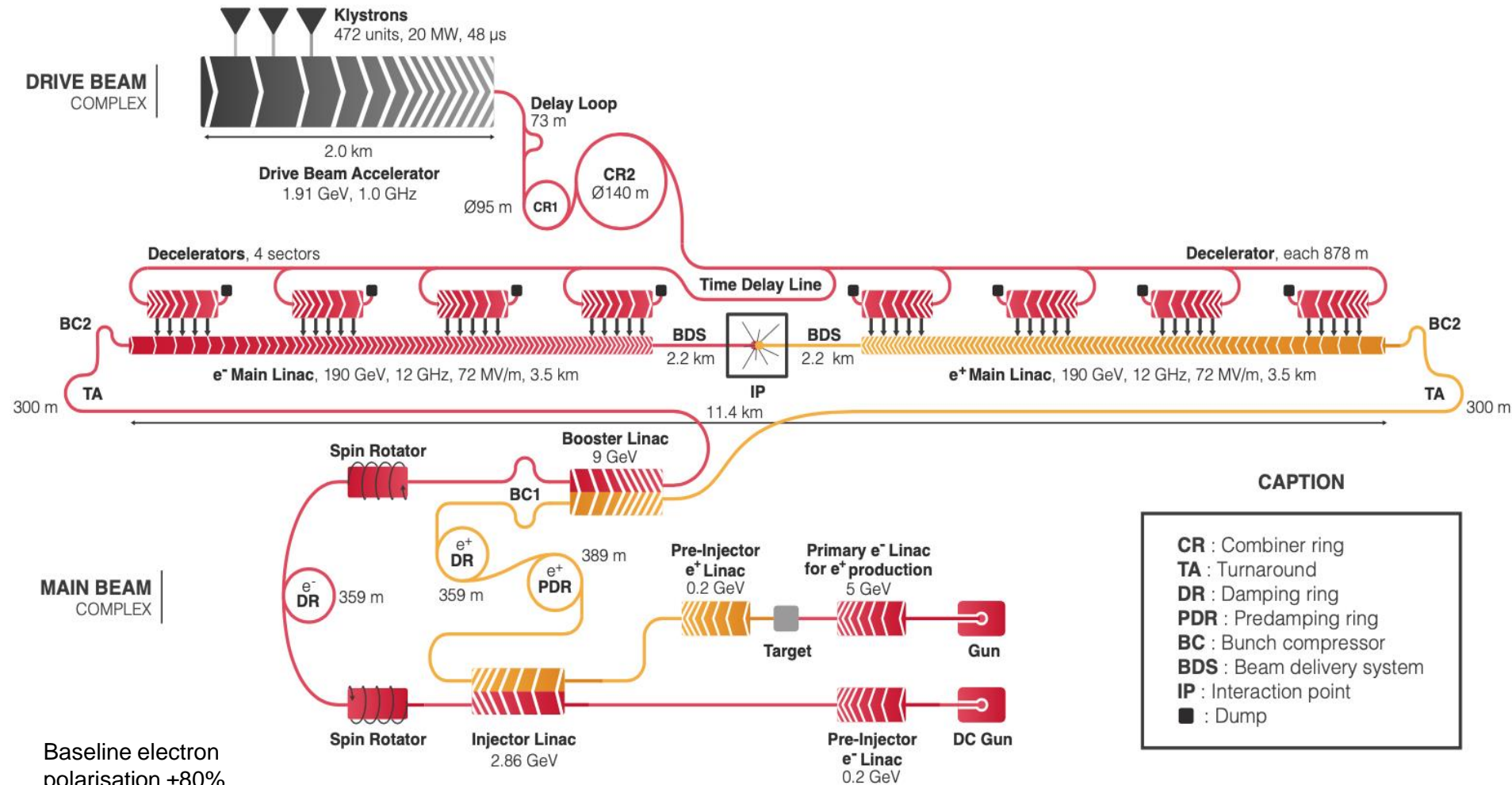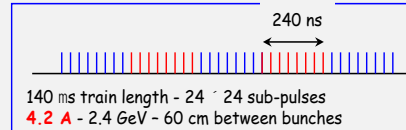
CLIC Project Implementation Plan

http://clic.cern/european-strategy
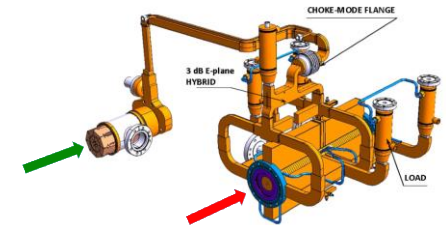
CLIC-Note-1143

http://cds.cern.ch/record/2687090

4

Layout of CLIC 380 GeV

Baseline electron polarisation ±80%

Layout of CLIC 380 GeV

Drive beam time structure - initial

240 ns

140 ms train length - 24 ´ 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

240 ns   5.8 ms

24 pulses – **101 A** – 2.5 cm between bunches

DRIVE BEAM COMPLEX

Klystrons
472 units, 20 MW, 48 μs

2.0 km

Drive Beam Accelerator
1.91 GeV, 1.0 GHz

Delay Loop
73 m

Ø95 m   CR1

CR2
Ø140 m

Decelerators, 4 sectors

Decelerator, each 878 m

Time Delay Line

BDS
2.2 km

BDS
2.2 km

BC2

BC2

e⁻ Main Linac, 190 GeV, 12 GHz, 72 MV/m, 3.5 km

e⁺ Main Linac, 190 GeV, 12 GHz, 72 MV/m, 3.5 km

TA
300 m

IP
11.4 km

TA
300 m

Spin Rotator

Booster Linac
9 GeV

BC1

MAIN BEAM COMPLEX

e⁻
DR   359 m

e⁺
DR

389 m

e⁺
PDR

359 m

Pre-Injector
e⁺ Linac
0.2 GeV

Primary e⁻ Linac
for e⁺ production
5 GeV

Target

Gun

Spin Rotator

Injector Linac
2.86 GeV

Pre-Injector
e⁻ Linac
0.2 GeV

DC Gun

CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Baseline electron
polarisation ±80%

Layout of CLIC 380 GeV

Drive beam time structure - initial

240 ns

140 ms train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

240 ns   5.8 ms

24 pulses – 101 A – 2.5 cm between bunches

Beam physics talks:

Positron source: **Yongke Zhao**, Thursday afternoon 1

ML: **Neven Blaskovic**, Thursday afternoon 2

BDS and ML: **Chetan Gohil**, 2x Thursday afternoon 2

BDS: **Jim Ogren**, Tuesday afternoon 1, Wednesday morning 1

BDS: **Dominik Arominski**, Tuesday afternoon 2

2x BDS: **Vera Cilento**, Thursday afternoon 2

Drive Beam Recombination Complex: **Raul Costa**, Thursday afternoon 2

DRIVE BEAM COMPLEX

Klystrons

BC2

TA   300 m

BC2

TA   300 m

MAIN BEAM COMPLEX

DR   359 m   359 m

Spin Rotator

Injector Linac
2.86 GeV

Target

Pre-Injector
e⁻ Linac
0.2 GeV

Gun

DC Gun

DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Baseline electron
polarisation ±80%

CLIC 380 GeV main parameters

Parameter	Symbol	Unit	
Centre-of-mass energy	$\sqrt{s}$	GeV	380
Repetition frequency	f_{rep}	Hz	50
Number of bunches per train	n_b		352
Bunch separation	Δt	ns	0.5
Pulse length	τ_{RF}	ns	244
Accelerating gradient	G	MV/m	72
Total luminosity	$\mathcal{L}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.9
Main tunnel length		km	11.4
Number of particles per bunch	N	10^9	5.2
Bunch length	σ_z	μm	70
IP beam size	σ_x/σ_y	nm	149/2.9
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20

Beam parameters in the main linac

Particles per bunch	5.2×10^9	Bunches per pulse	352
Bunch spacing	$15\,\mathrm{cm}$	Bunch length	$70\,\mu\mathrm{m}$
Initial R.M.S. energy spread	$\leq 2\%$	Final R.M.S. energy spread	0.35%
Initial horizontal emittance	$\leq 850\,\mathrm{nm}$	Final horizontal emittance	$\leq 900\,\mathrm{nm}$
Initial vertical emittance	$\leq 10\,\mathrm{nm}$	Final vertical emittance	$\leq 20\,\mathrm{nm}$

CLIC luminosity optimization

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} f_r n_b. \implies \mathcal{L} \propto H_D \frac{N}{\sigma_x} \frac{1}{\sqrt{\beta_y \epsilon_y}} N n_b f_r.$$

- $H_D \approx 1$, luminosity enhancement factor, includes the geometry of the collision and beam-beam effects

- N/σ_x is proportional to the number of beamstrahlung photons, and is fixed by the experimental requirements

- N, bunch charge is limited by emittance growth due to wakefields in the main linac

- n_b, the number of bunches is limited by the long-range wakefield suppression, and by the RF pulse length

- f_r = 50 Hz, rep. rate is limited by power consumption

- β_y at the IP has an optimum and depends on the beam-beam effects

The only free parameter for optimization is the normalized vertical emittance at the IP, ε_y

CLIC baseline luminosity

Vertical emittance estimations and budgets:

at DR extraction:	5 nm	
at RTML exit:	< 10 nm	
at ML exit:	< 20 nm	
at IP:	< 30 nm	>90% probability required

These numbers account for the effects of static and dynamic imperfections *(the main sources of imperfections are <u>misalignments</u> and <u>ground motion</u>)*

The **baseline luminosity** has been computed with 30 nm vertical emittance @ IP:

$$L = 1.5 \times 10^{34} \ cm^{-2}s^{-1}$$

($L_{1\%} = 0.9 \times 10^{34} \ cm^{-2}s^{-1}$, within 1% of the peak energy)

CLIC low emittance preservation

RTML emittance budgets:

at DR extraction: 5 nm

at RTML exit: < 10 nm

Table 2.5: Static imperfections considered.

Imperfection	RTML w/o CA and TAL	CA and TAL
R.M.S. position error	100 μm	30 μm
R.M.S. tilt error	100 μrad	30 μrad
R.M.S. roll error	100 μrad	30 μrad
$\Delta B/B$ quadrupoles	10^{-3}	10^{-4}
$\Delta B/B$ other magnets	10^{-3}	
Magnetic-center shift w/strength	0.35 μm / 5%	
BPM resolution	1 μm	
Sextupole movers step size	-	1 μm
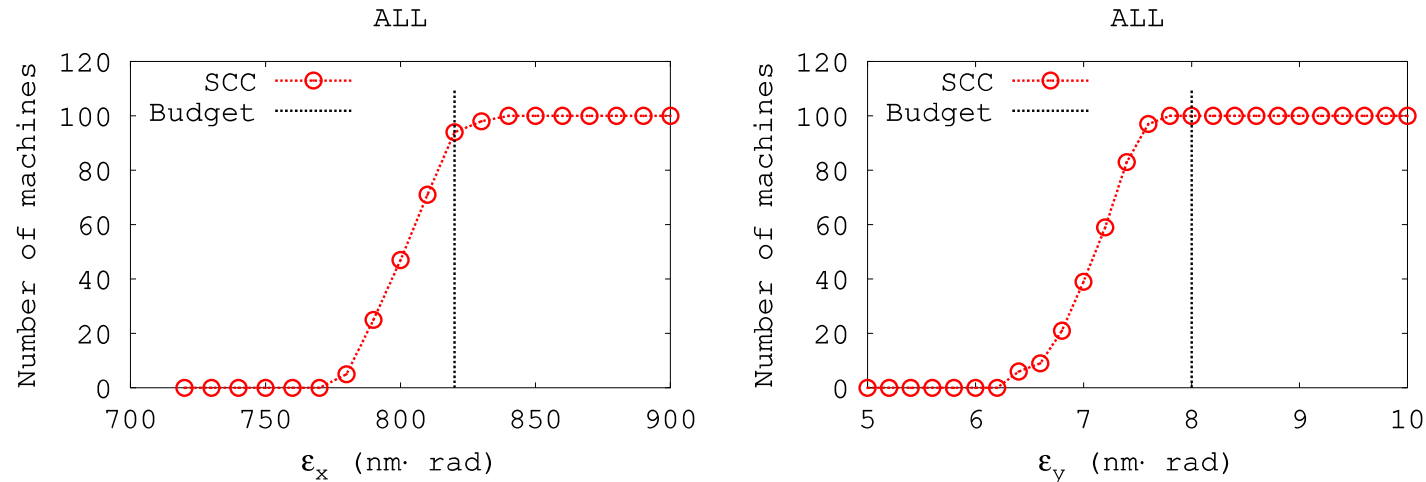
Figure 2.4: Emittance at the end of the electron RTML after beam-based alignment and tuning. In the horizontal plane just 6 out of 100 machines exceed the budget; in the vertical plane all machines are below the budget. The acronym SCC means Sextupole Coupling Correction, i.e. the final step of the tuning procedure.

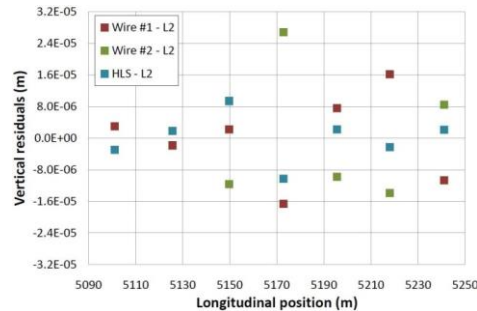# CLIC low emittance preservation

Main linac

Quadrupoles stabilized to O(1nm) @ 1Hz

Straight references

1) Pre-align BPMs+quads accuracy O(10μm) over about 200 m
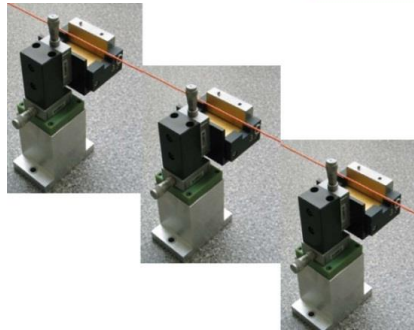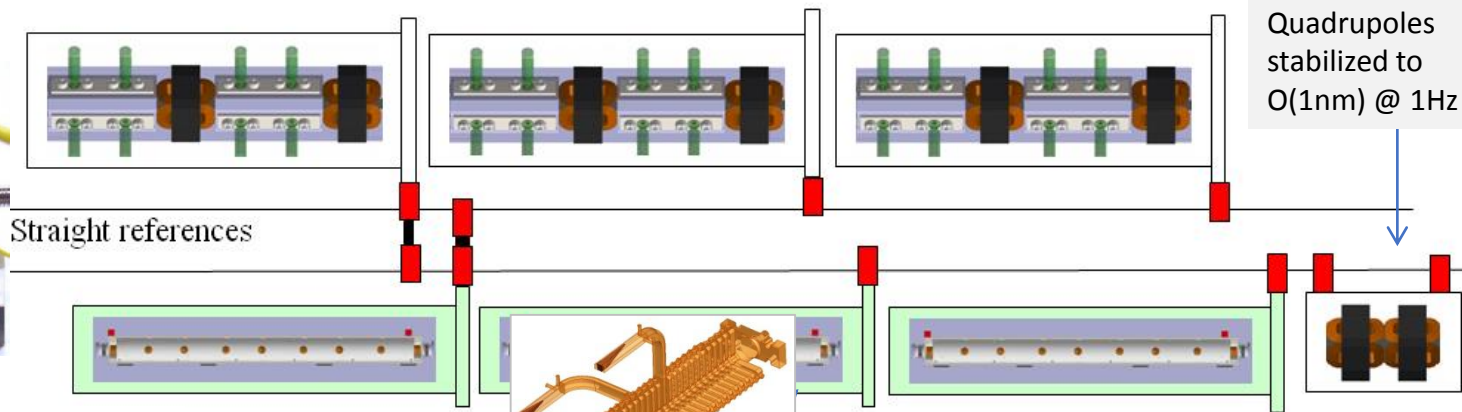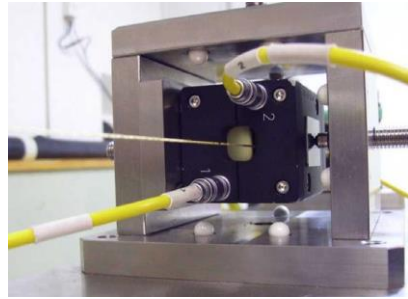
3) Use wake-field monitors accuracy O(3.5μm)

2) Beam-based alignment

Test of prototype shows vertical RMS error of 11 μm

Wire #1 - L2
Wire #2 - L2
HLS - L2

Vertical residuals (m)

Longitudinal position (m)

CLIC low emittance preservation

Main Linac

Table 2.8: Key alignment specifications for the ML components and the resulting emittance growth. The values after simple steering (1-2-1), Dispersion Free Steering (DFS) and realignment of the accelerating structures using the wakefield monitors (RF) are shown.

Imperfection	With respect to	Value	$\Delta\epsilon_y$ [nm] 1-2-1	DFS	RF
Girder end point	Wire reference	12 μm	12.91	12.81	0.07
Girder end point	Articulation point	5 μm	1.31	1.30	0.02
Quadrupole roll	Longitudinal axis	100 μrad	0.05	0.05	0.05
BPM offset	Wire reference	14 μm	188.99	7.12	0.06
Cavity offset	Girder axis	14 μm	5.39	5.35	0.03
Cavity tilt	Girder axis	141 μrad	0.12	0.40	0.27
BPM resolution		0.1 μm	0.01	0.76	0.03
Wake monitor	Structure centre	3.5 μm	0.01	0.01	0.35
All			204.53	25.88	0.83

1) State-of-the-art pre-alignment: PACMAN Project
2) Beam-based alignment techniques
- 1-2-1: orbit steering
- Dispersion-Free Correction
- RF structure alignment for wakefield compensation
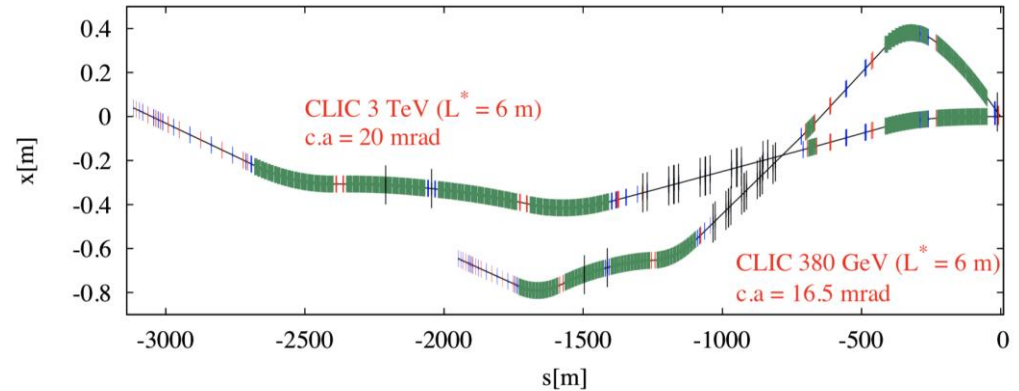
Average of 100 simulated realistic scenarios

Note: the emittance growth budget in the ML is set 10 nm
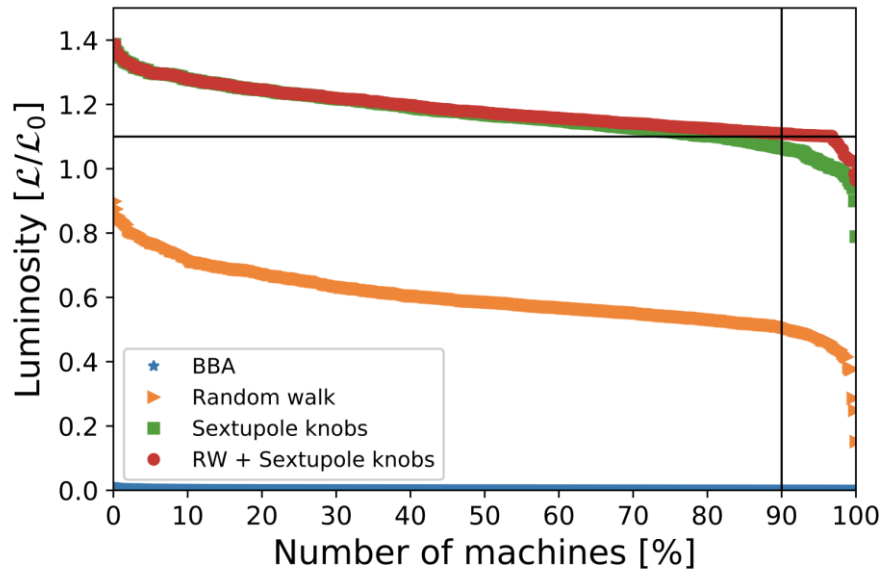
CLIC low emittance preservation

CLIC BDS

Beam-based alignment
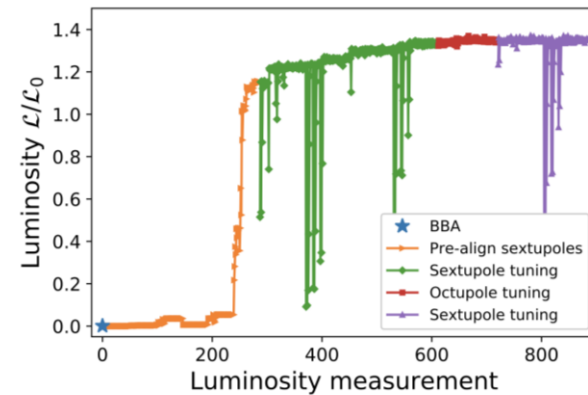
Sextupoles knobs

CLIC BDS tuning

Final results: 484 machines successfully tuned

484/500 = **96.8% success rate**

See J. Ogren's presentation this afternoon

CLIC luminosity figures

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These numbers account for the effects of static and dynamic imperfections *(the main sources of imperfections are <u>misalignments</u> and <u>ground motion</u>)*

The **baseline luminosity** has been computed with 30 nm vertical emittance @ IP:

$$L = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

($L_{1\%} = 0.9 \times 10^{34}$ cm^{-2}s^{-1}, within 1% of the peak energy)

But this is a conservative estimate:

- Without imperfections, in a machine where emittance growth does not occur:

$$L = 4.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

- Realistic integrated start-to-end simulations of static imperfections and mitigation techniques reach:

$$L = 3.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

One can therefore expect that the actual luminosity will exceed the baseline by a substantial amount.

Doubling the CLIC luminosity

- Increase the rep rate from 50 to 100 Hz

  Relatively little increase in the power consumption

  - a large fraction of the power is used by systems where consumption is independent of the repetition rate

  - the power required by the RF systems increases by about a factor two, the total power consumption only increases +50 MW, from 170 to 220 MW, i.e. less than 30% increase

  - There is a modest associated cost increase that must to be evaluated in detail, but is expected to be at the ∼ 5% level

Doubling the CLIC luminosity

- Minor modifications required:

  - Larger stray fields at 100 Hz, as measured at CLEAR – appropriate shielding of the beam pipe would reduce to acceptable levels [See C. Gohil's presentation on Thursday afternoon]

  - The charging supplies of the modulators in the drive beam complex, would need to have double the charging capacity. This is technologically straightforward and is only a question of cost.

  - Klystrons do not need to be modified since the peak power requirement is unchanged and the increased average power going from 50 to 100 Hz is less than the average power increase for the higher energy stages which require longer pulses

  - The damping time for a beam train is 20 ms, but for 100 Hz operation, two trains are cooled at the same time, extracting and replacing one of them every 10 ms. This requires doubling the RF-to-beam power but has the beneficial effect that the transient beam loading is reduced since a larger fraction of the circumference is filled with beam.

  - In the main linac, the increased repetition rate doubles the heat deposited in the structures so the capacity of the cooling of the structures and the ventilation system will need to be improved.

Operation at Z-pole

A) Extract beam when it reaches 45GeV in linac
- Requires some modification in main linac, long transfer line
- Could be done as a stage during the construction
- Allows to use $N=N_0$

B) Accelerate beam at lower gradient in the main linac to reach 45GeV at the end
- Little hardware modification required
- Reduced charge $N=x_1 N_0$

C) Accelerate beam at full gradient in first part of linac then drift through the rest of it
- Little hardware modification required
- Could even consider to accelerate above final energy and then decelerate
- Reduced charge $N=x_2 N_0$

D) Accelerate beam at lower gradient but modify the lattice design
- Allows to make beam more stable $N=x_3 N_0$
- Important modification of main linac required
- Has impact on nominal design

Expected behaviour: $1 \geq x_3 \geq x_2 \geq x_1 \approx 0.25$

See:
D. Schulte, "CLIC Operation At Z Pole", CLIC Workshop 2017, https://indico.cern.ch/event/577810

Operation at Z-pole

- Can the final doublet be used at 45 Gev with no important modifications?
  - A factor 4-5 is possible depending on the technology
  - ⇒ Z0 has to be explicitly foreseen the design
  - ⇒ Can likely not go further down without intervention
  - ⇒ Cannot easily run at Z0 for higher energy stages
  - ⇒ Maybe can replace doublet (or part of it) for dedicated Z0 run
  - ⇒ Need to check tolerances (field quality)
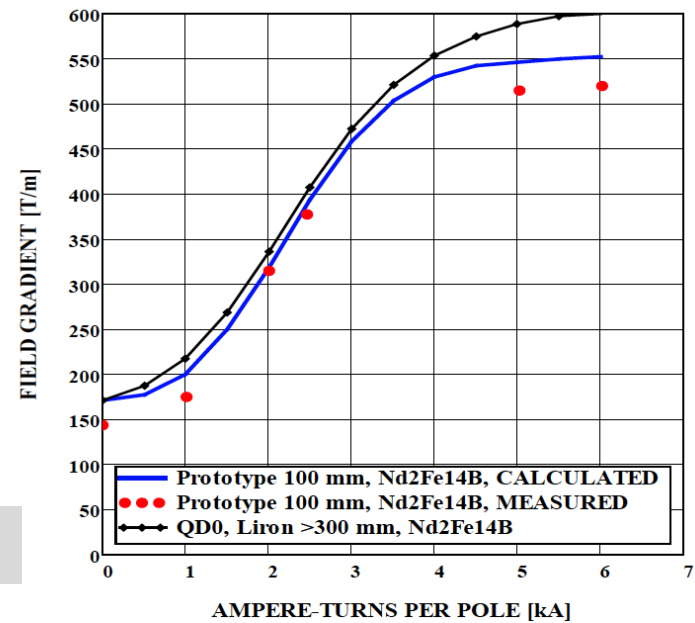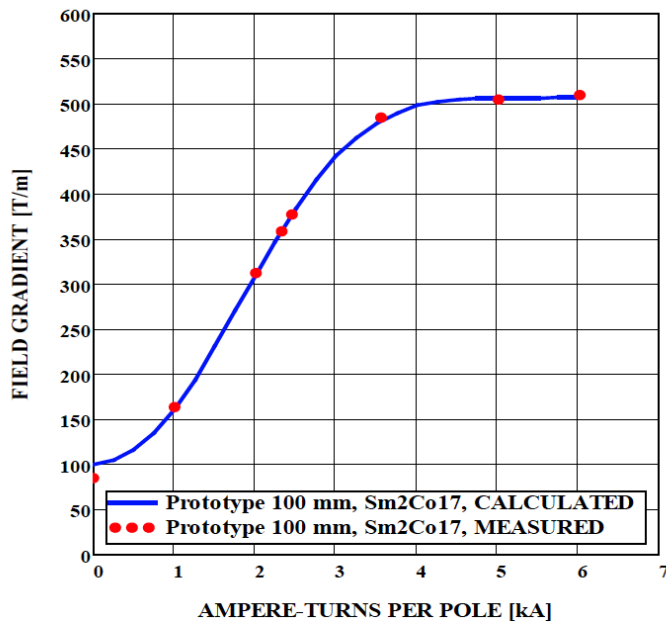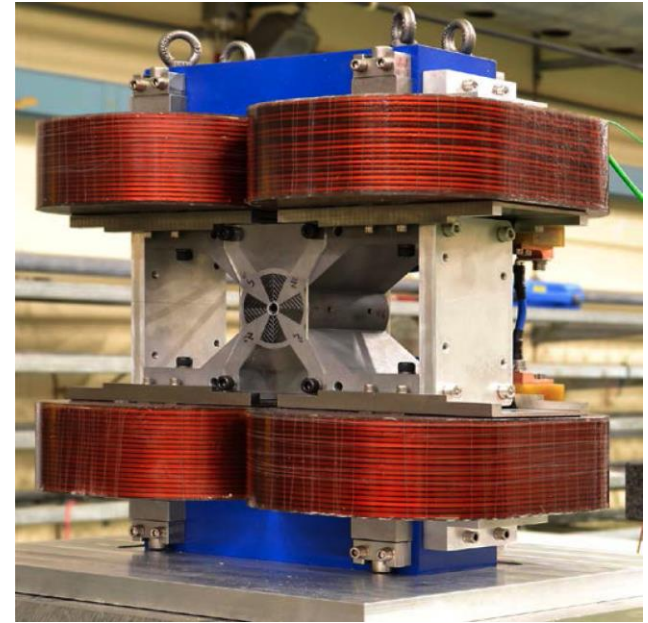
M. Modena

Operation at Z-pole

- Need to operate CLIC at an energy E = 91.2 GeV.

- The main linac gradient is reduced by about a factor four

- The bunch charge is reduced by a similar amount but the normalised emittances and bunch length remain the same

- The beam size at the interaction point will increase with the square root of 1/E in the transverse planes,

- Operating the fully installed 380 GeV CLIC accelerator complex but at the Z-pole results in a luminosity of about

$$\mathbf{L = 2.3 \times 10^{32} \ cm^{-2}s^{-1}}$$

For more details on measurements of the electroweak couplings of the Z boson at CLIC, including dedicated running at the Z-pole check:

See:
Blaising, Jean-Jacques and Roloff, Philipp Gerhard, Electroweak couplings of the Z boson at CLIC, Aug. 2019, CLICdp-Note-2019-004, http://cds.cern.ch/record/2687329

Operation at Z-pole

Tentative Luminosities [D. Schulte, 2017]

Charge ratio	L	$L_{0.99}$	Pot. Scenarios
0.25	$1.9 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $1.7 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$1.9 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $1.7 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	B
0.5	$8.4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $7.6 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$8.2 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $7.5 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	C?, D?
1.0	$3.8 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $3.5 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$3.5 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ $3.2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	A

Tentative guesses for what scenarios may allow to do
- Several issues to be looked at
- E.g. ignoring the issue of the uncorrelated beam energy spread
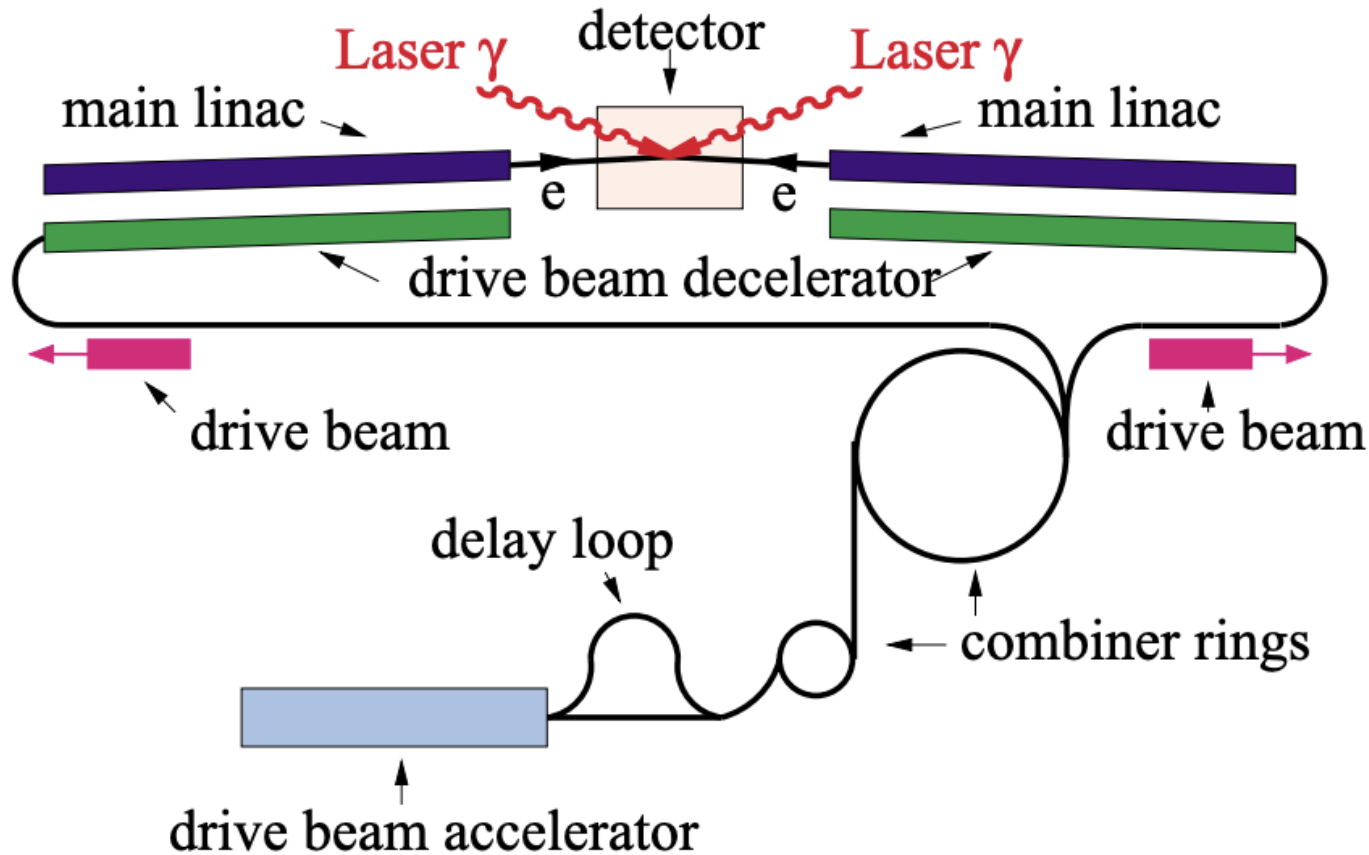- Will have to update the estimates

Large range of luminosities
- strong dependence on the charge (slightly more than quadratic due to H_D)

Luminosity spectrum is always quite good
- in worst case 90% of luminosity above 99% of cms energy

CLIC as a γ-γ collider

Two advantages of γ-γ collider:
- Larger cross sections
- Polarized collisions (80% polarization of the electron beams)

CLIC as a γ-γ collider

- Three parameters to optimize:
  - Recoil parameter: x=4.82 tuned to maximise energy extraction and avoid destructive $\gamma\gamma_L$ collisions

$$x \approx \frac{4E_0\omega_0}{m^2c^4}; \qquad \hbar\omega_{\max} = \frac{x}{x+1}E_0$$

$$E_{\gamma,\max} = 0.83\, E_0$$

  - k_L=1, density of the laser pulse [Larger values lead to more luminosity in the peak, but increase even more the luminosity at lower energies do to the electron performing more than one Compton scattering]
  - ρ = 1, distance d between the beam laser and the photon photon collision point normalised to the beam size and energy, d=1.1 mm
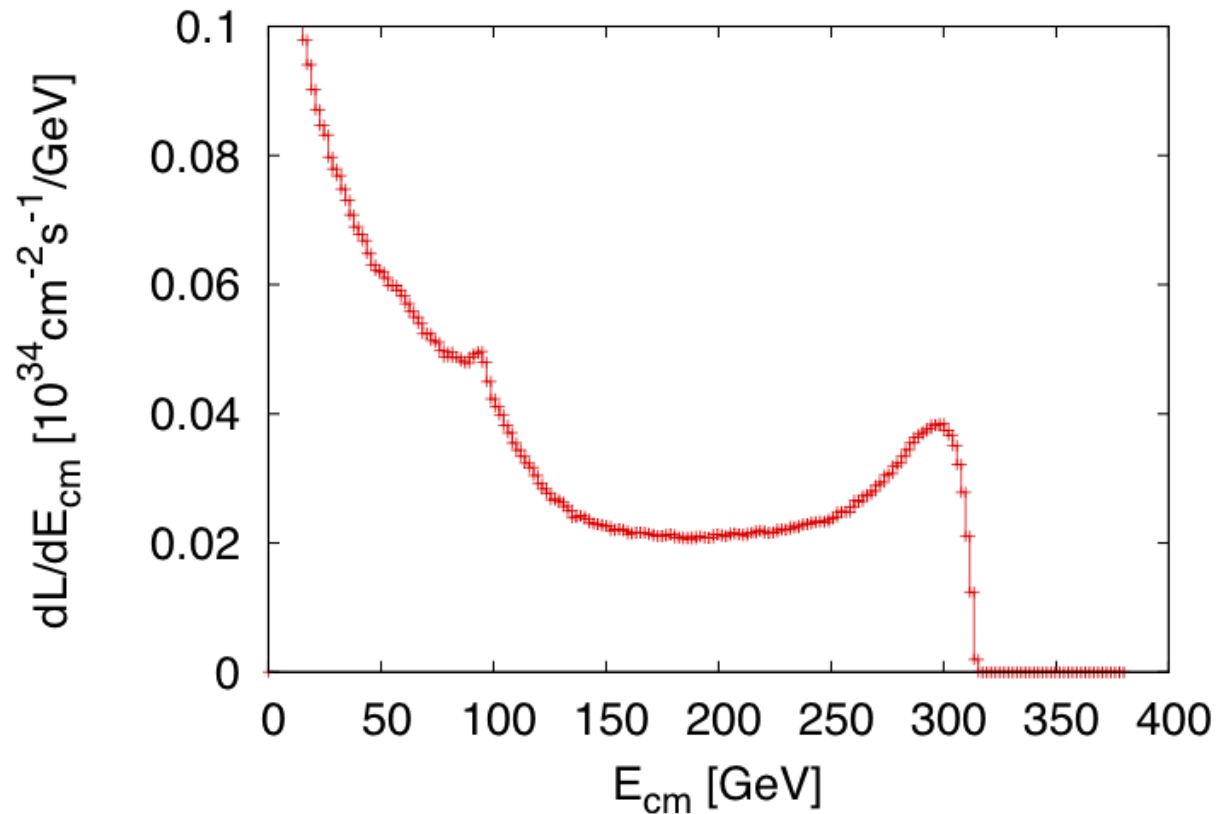
$$\rho = \frac{d}{\gamma\sigma_y^\star}$$

References:

- M. Velasco, "Physics at Photon Colliders", Miniworkshop on Future γ-γ colliders, Beijing, China, April 23-26, 2017

- V. Telnov, "γγ colliders at ILC/CLIC", Photon beam workshop, Padova, November 27-28, 2017

CLIC as a γ-γ collider
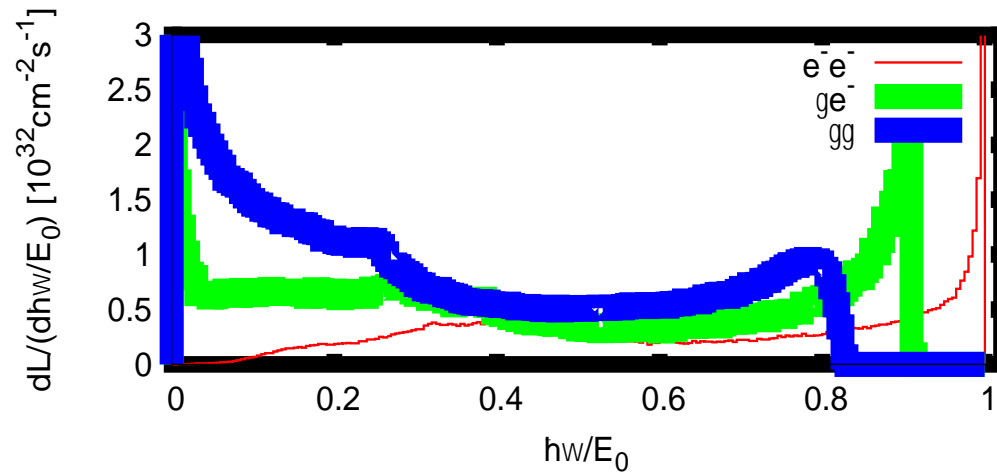
Luminosity spectra for CLIC 380 GeV

Using a laser pulse thickness of $K_L = 1$ and a distance of laser beam and photon-photon collision point of $\rho = 1$ one finds a luminosity of about **L = 1.3 × 10³³ cm⁻²s⁻¹** above a centre-of-mass energy of 228 GeV.

CLIC as a γ-γ collider

Luminosity spectra for CLIC 380 GeV

Parameter	Unit	$e^- e^-$	$e^- \gamma$	$\gamma \gamma$
Total Lumi. (L)	$[10^{33} cm^{-2} s^{-1}]$	0.7	1.1	1.73
Peak Lumi. (L_{peak})	$[10^{33} cm^{-2} s^{-1}]$	0.3	-	0.9

Luminosity from e-e- collisions is lower than e+e- collisions, due to defocusing repulsive beam-beam forces.

Reference:

E. Marin, "Gamma-gamma considerations for CLIC", Photon beam workshop, Padova, November 27-28, 2017

Summary

In studies performed after the submission of European Strategy Update documents as well as subsequent meetings and discussions, the CLIC study has found

- CLIC baseline luminosity is **L=1.5 x 10^{34} cm^{-2}s^{-1}**. Realistic simulations of static imperfections. show **L=3 x 10^{34} cm^{-2}s^{-1}**. Doubling the rep rate offers the possibility of further increasing luminosity performance at 380 GeV **by factor two to three** without major additional costs or additional power consumption.

- Running high luminosity at the **Z-pole is possible** with a staged installation or as a dedicated operating period with L=2.3 x 10^{32} cm^{-2}s^{-1}.

- Furthermore, **gamma-gamma collisions at up to ~315 GeV are possible** with luminosity spectra interesting for physics

- The luminosities discussed above can be delivered to one detector as in the baseline CLIC scenario, or shared on two detectors using either **push-pull** or **by constructing a second BDS** and interaction point. The latter would add substantially to the costs (~ 15%) of the accelerator.