Intensity-dependent effects in the Compact Linear Collider

P. Korysko
University of Oxford
CERN

Outline

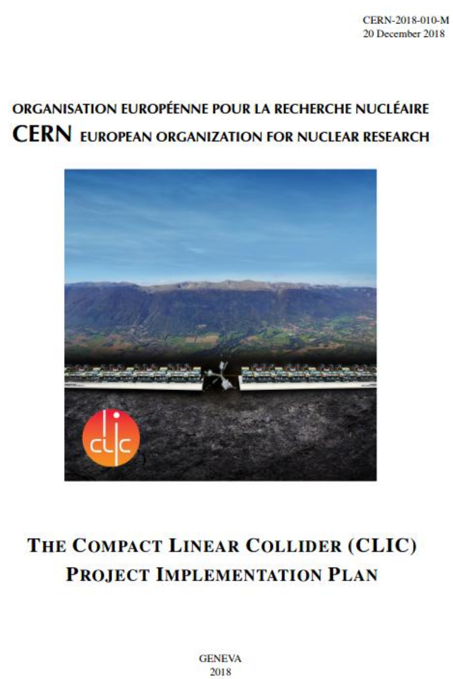
- The Compact Linear Collider, machine and parameters.
- Impact of short-range wakefields in the 380 GeV CLIC BDS.
  - Definition of short-range wakefields
  - Definition and impact of corrections (One-to-one, DFS, WFS)
  - Intensity-dependent effects on the beam size at the IP.
- Impact of long-range wakefields in the 380 GeV CLIC BDS.
  - Definition of long-range wakefields
  - Impact of different types of incoming errors on the luminosity.
- Conclusions

The Compact Linear Collider

Introduction
The Compact Linear Collider

The Compact Linear Collider is an electron/positron head-on collider at energies of up to 3 TeV. For an optimal exploitation of its physics potential, CLIC is intended to be built and operated in three stages, at collision energies of 380 GeV, 1.5 TeV and 3 TeV respectively, for a site length ranging from 11 to 50 km. The physics aims of CLIC include high-precision measurements of the Higgs boson's interactions with other particles and with itself.

The latest information and parameters can be found in the CLIC Project Implementation Plan [1] (2018).


CERN-2018-010-M
20 December 2018

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
PROJECT IMPLEMENTATION PLAN

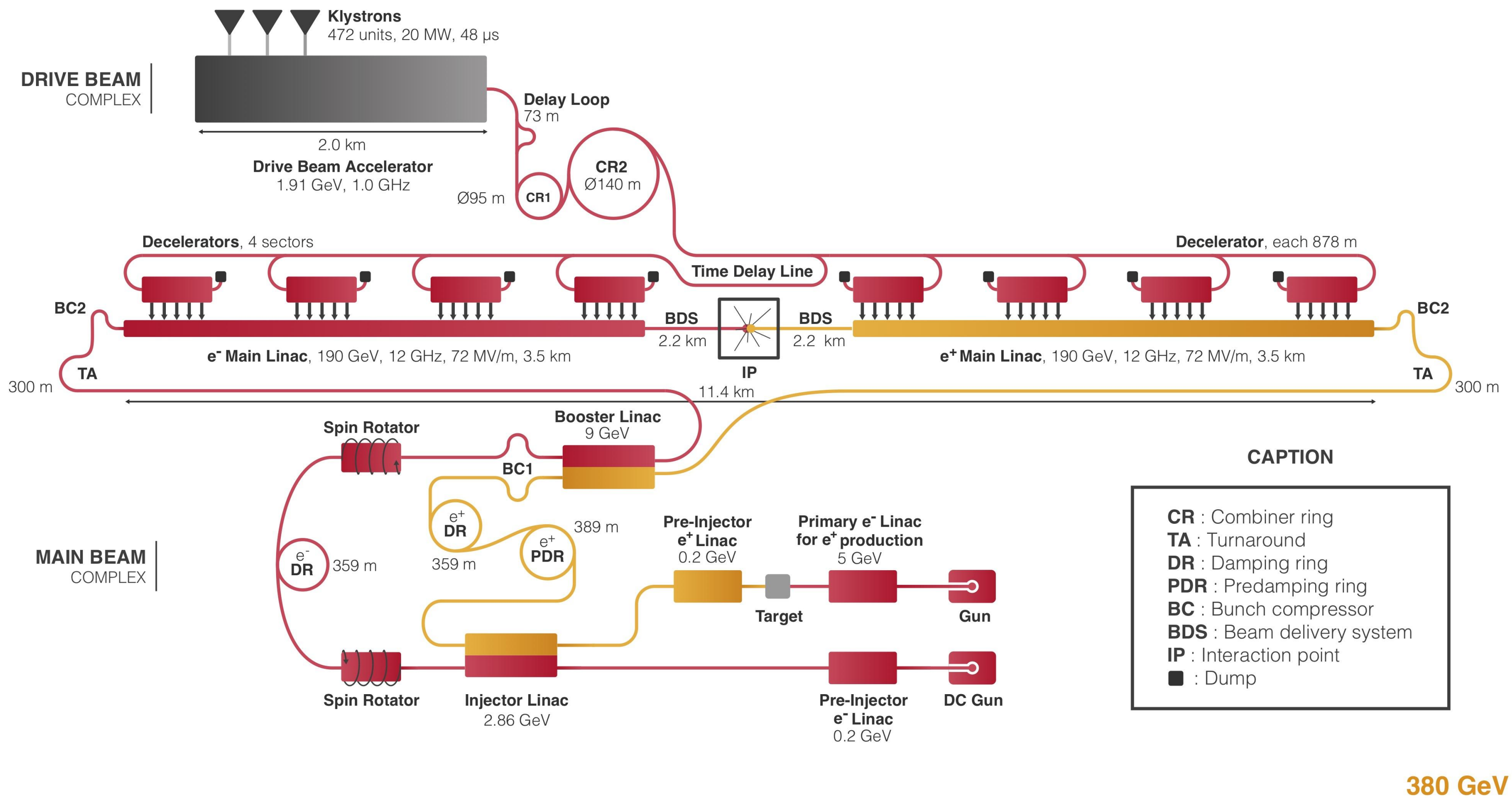
GENEVA
2018

Table: Key parameters of 380 GeV baseline collider.

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} cm^{-2}s^{-1}	1.5
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	10^{34} cm^{-2}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

Introduction
The Compact Linear Collider

CLIC would use a novel scheme, the two-beam-acceleration. The so-called **Drive Beam** would run parallel to the colliding Main Beam. The Drive Beam is decelerated in special devices called Power Extraction and Transfer Structures (PETS) that extract energy from the Drive Beam in the form of powerful Radio Frequency (RF) waves, which is then used to accelerate the Main Beam. Up to 90% of the energy of the Drive Beam is extracted and efficiently transfered to the Main Beam.



Introduction
The CLIC Beam Delivery System (BDS)

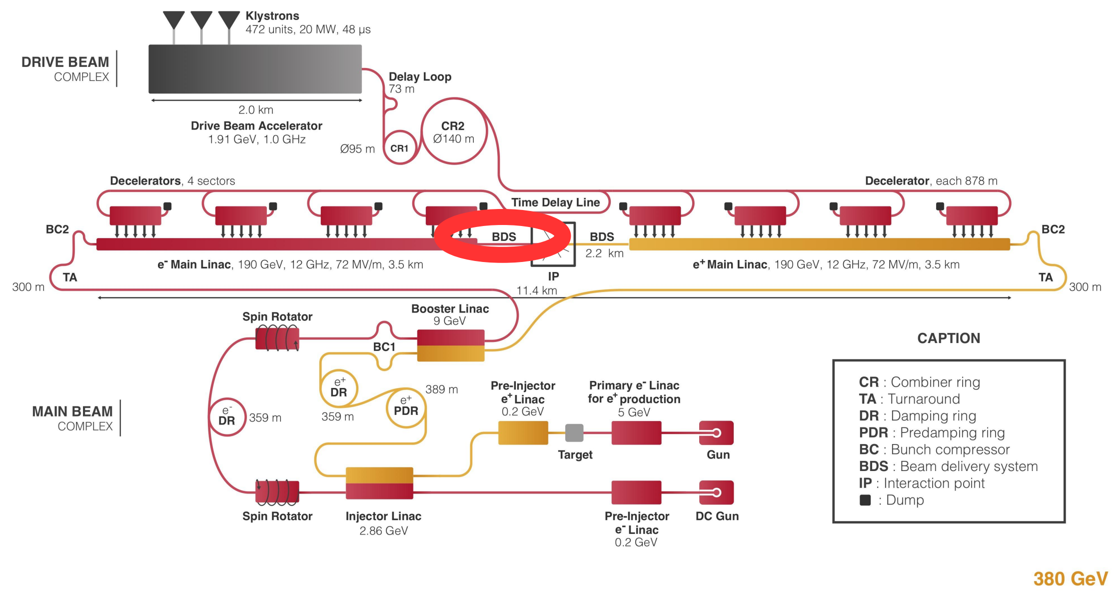


Table: CLIC 380 GeV beam parameters.

Parameter	Symbol	Value
Centre-of-mass energy	E_{CM}	380 GeV
Length of the BDS	L_{BDS}	1949 m
Number of bunches	n_b	352
Bunch population	N	5.2×10^9 e^-
RMS bunch length	σ_z	70 μm
Bunch separation	Δt_b	0.5 ns
IP RMS beam sizes	σ_x^*/σ_y^*	149/2.9 nm

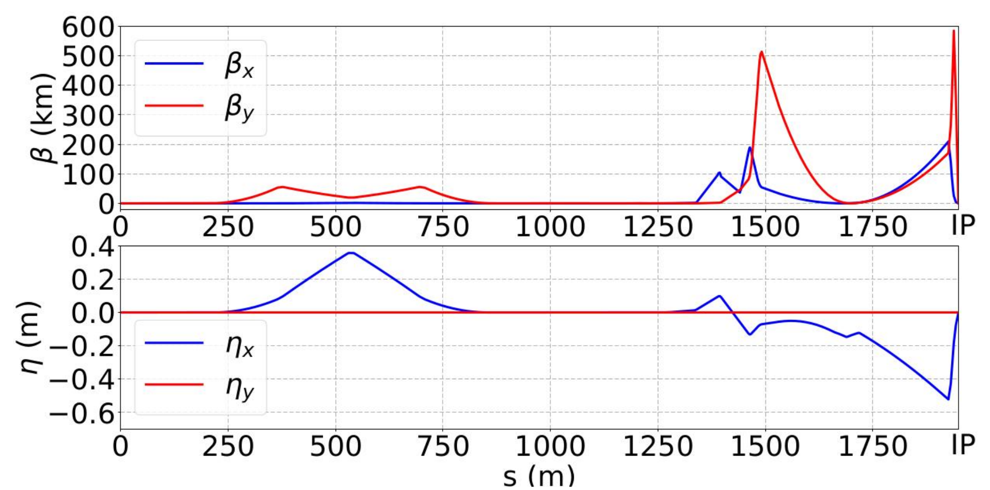
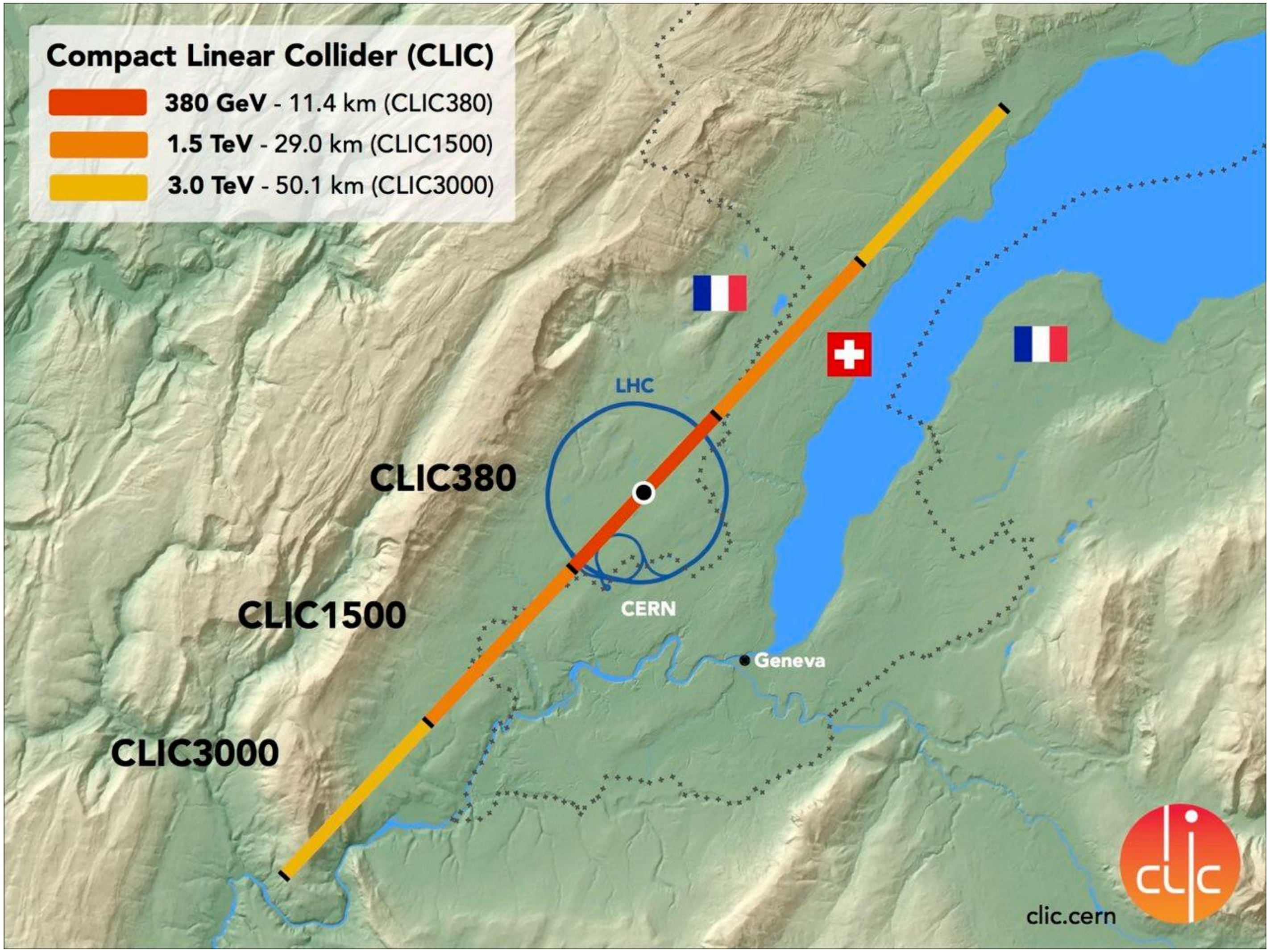


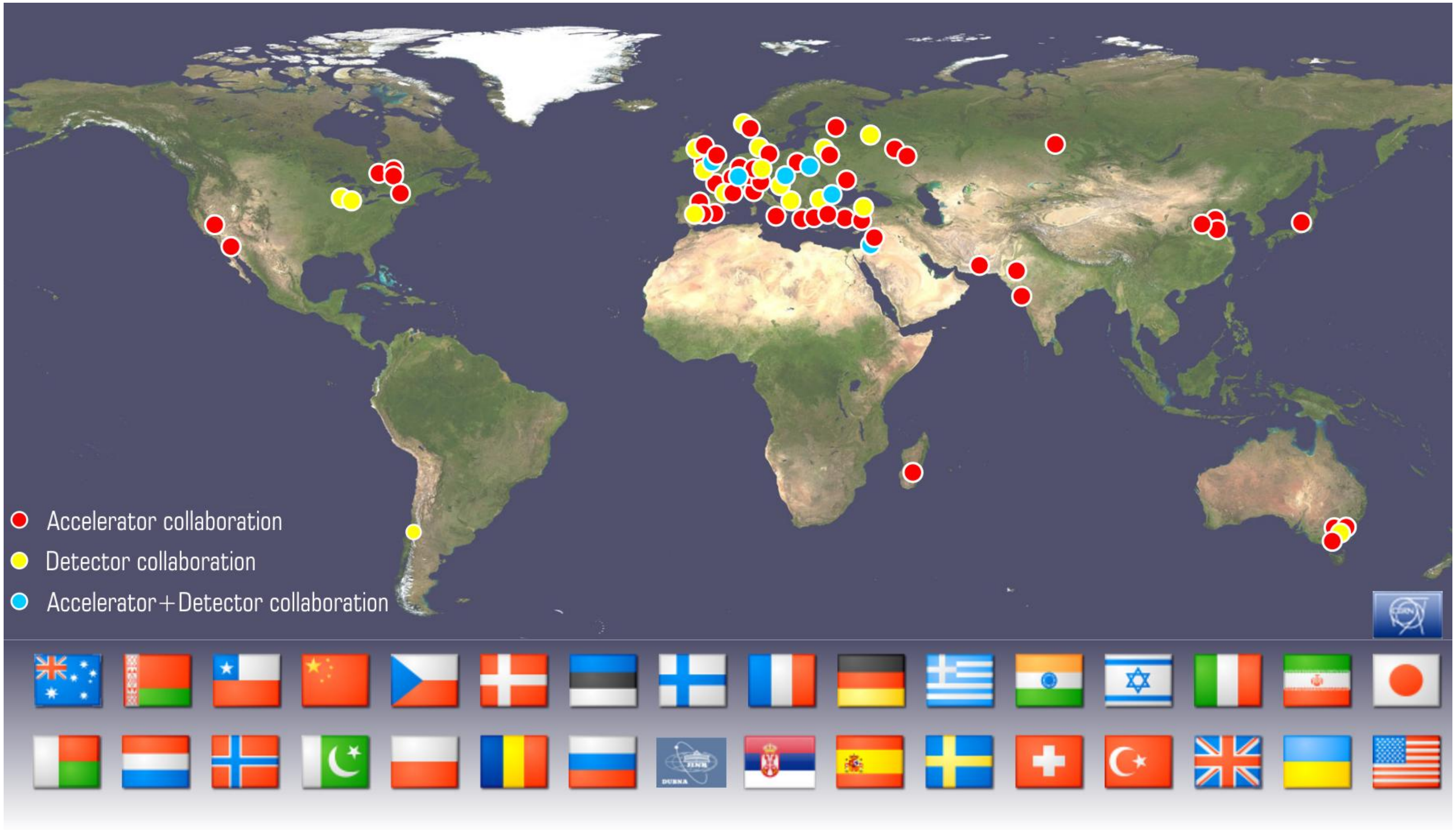
Figure: CLIC BDS 380 GeV Twiss parameters calculated with PLACET.

Introduction
The Compact Linear Collider



Introduction
The Compact Linear Collider

CLIC is a global collaboration of more than 70 institutes and laboratories from more than 30 countries around the world. The CLIC concept was initiated at CERN, however, the theory and the technology are being developed and tested at member institutes worldwide.



Impact of short-range wakefields in the 380 GeV CLIC BDS

Transverse and longitudinal wakefields

Transverse and longitudinal wakefields

The integrated fields seen by a test particle traveling on the same, or on a parallel path at a constant distance s behind a point charge Q are called the integrated longitudinal and transverse wakepotentials. They are defined as:

$$\tilde{W}_{\perp}(\Delta r, s) = \frac{1}{Q}\int_0^L \left[E_{\perp}(\Delta r, z, s) + c\hat{z} \times B(\Delta r, z, s)\right] dz$$

$$\tilde{W}_{\parallel}(s) = -\frac{1}{Q}\int_0^L \left[E_z(z, s)\right] dz$$

The transverse and longitudinal kicks felt by a particle, at position z along the bunch, due to all leading particles ($\forall z' : \ z' > z$):

$$\Delta r' = \frac{\Delta P_{\perp}}{P} = \frac{qQL}{Pc}\int_{-\infty}^{z} W_{\perp}(\Delta r(z'), z - z')\,\rho(z')\,dz'$$

$$\Delta P_{\parallel} = \frac{qQL}{c}\int_{-\infty}^{z} W_{\parallel}(z - z')\,\rho(z')\,dz'$$

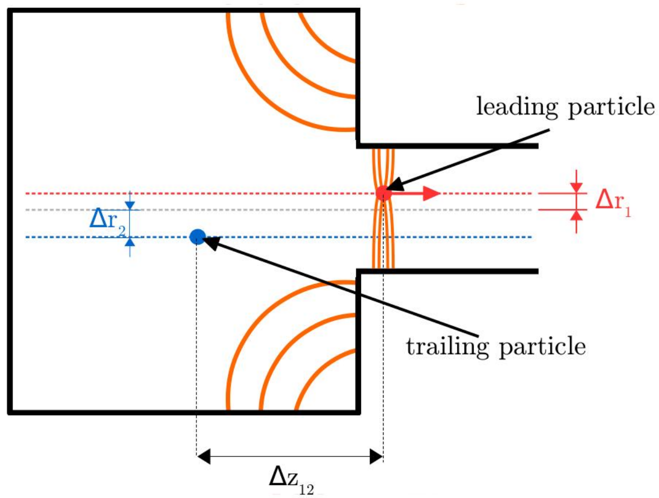


Figure: Scheme of the two-particle model.

with:

- $\rho(z')$ normalized line charge density of the bunch, such that $\int_{-\infty}^{\infty} \rho(z')\,dz' = 1$
- $\Delta r(z')$ transverse radial position of the leading particles as a function of their position z' along the bunch [mm]
- Q total charge of the bunch [C]
- q particle's charge [e]
- P particle's momentum [eV/c]
- $\Delta r'$ radial kick [rad]
- ΔP momentum loss [eV]

Impact of short-range wakefields in the 380 GeV CLIC BDS

CLIC orbit corrections

CLIC orbit corrections (1/3)
One-to-one correction

The One-to-one correction consists of minimizing the transverse position of the beam, with respect to the beam pipe centre measured at BPMs, using steering magnets [2].

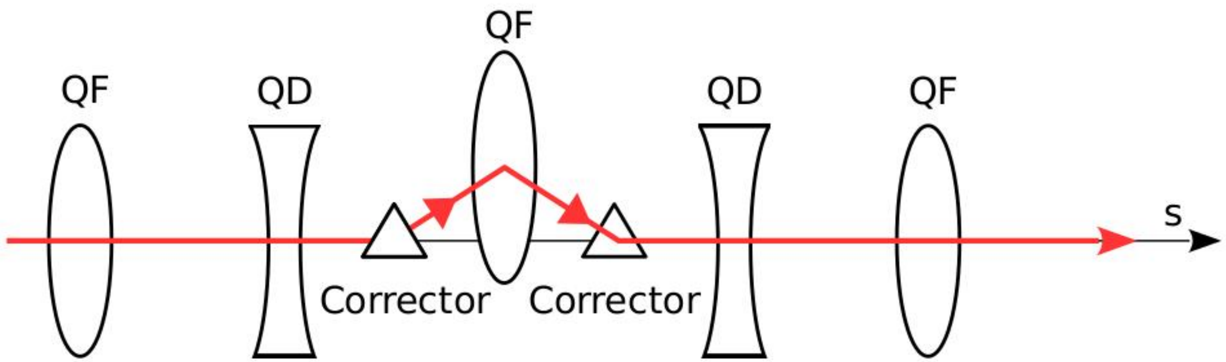


Figure : Schematic of the One-to-one correction. The beam orbit (in red) is deflected by correctors (triangles) in order to pass through the center of the BPM, which is inside a quadrupole in this case.

CLIC orbit correction (2/3)
Dispersion Free Steering (DFS) correction

In the simulations, two beams are tracked with two different energies, E_1 and E_2. Steering magnets are then used to correct the orbit and reduce the orbit difference between the two beams $\Delta_{y,E}$ [3].

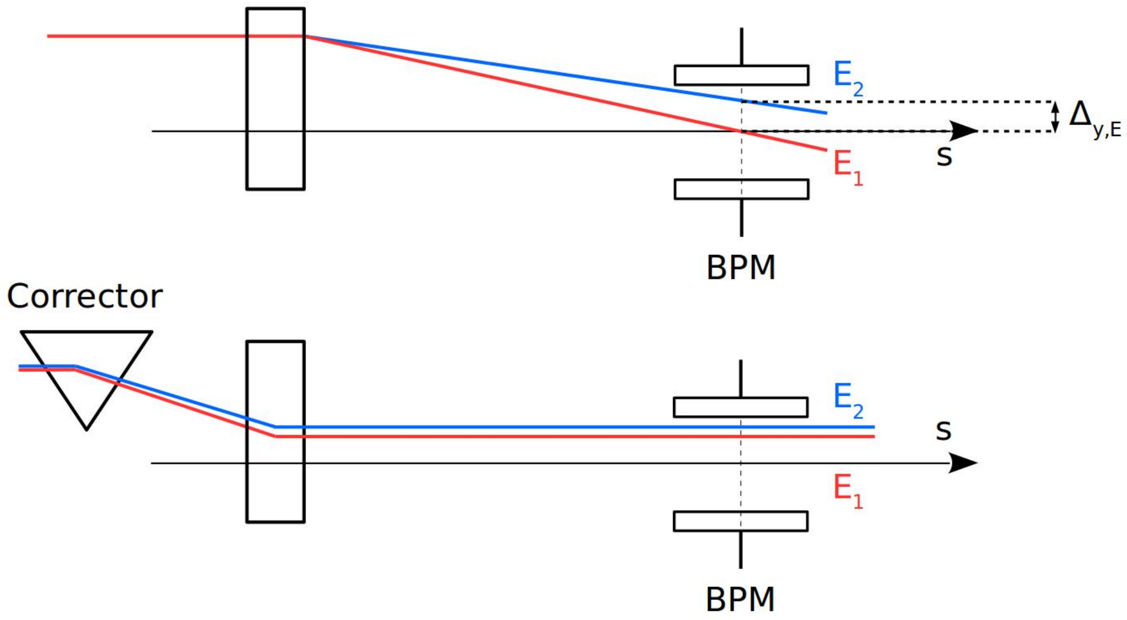


Figure: Schematic of the Dispersion Free Steering correction.

CLIC orbit correction (3/3)
Wakefield Free Steering (WFS) correction

The Wakefield Free Steering is an algorithm which corrects the difference on the orbit introduced by wakefields. In the simulations, two beams are tracked with two different charges Q_1 and Q_2. Steering magnets are then used to correct the orbit and reduce the orbit difference between the two beams $\Delta_{y,Q}$ [4].

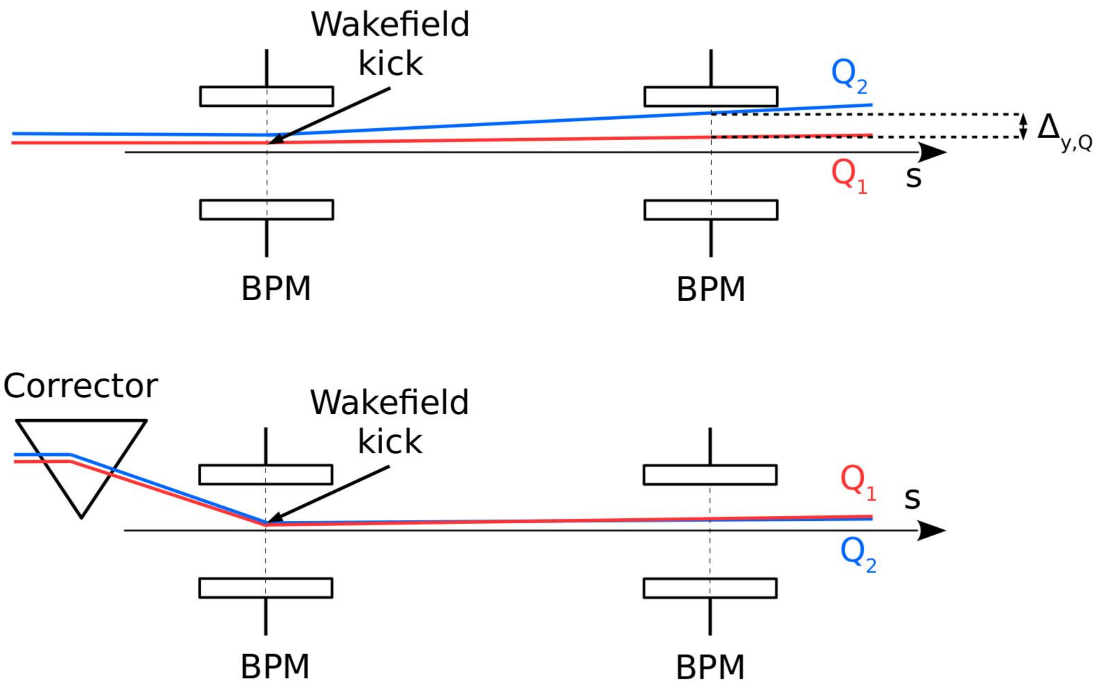


Figure: Schematic of the Wakefields Free Steering corrections.

Sextupole knobs

- First order knobs correction by changing the position of final focus sextupoles.
- Second order knobs correction by changing the strength of the final focus sextupoles.

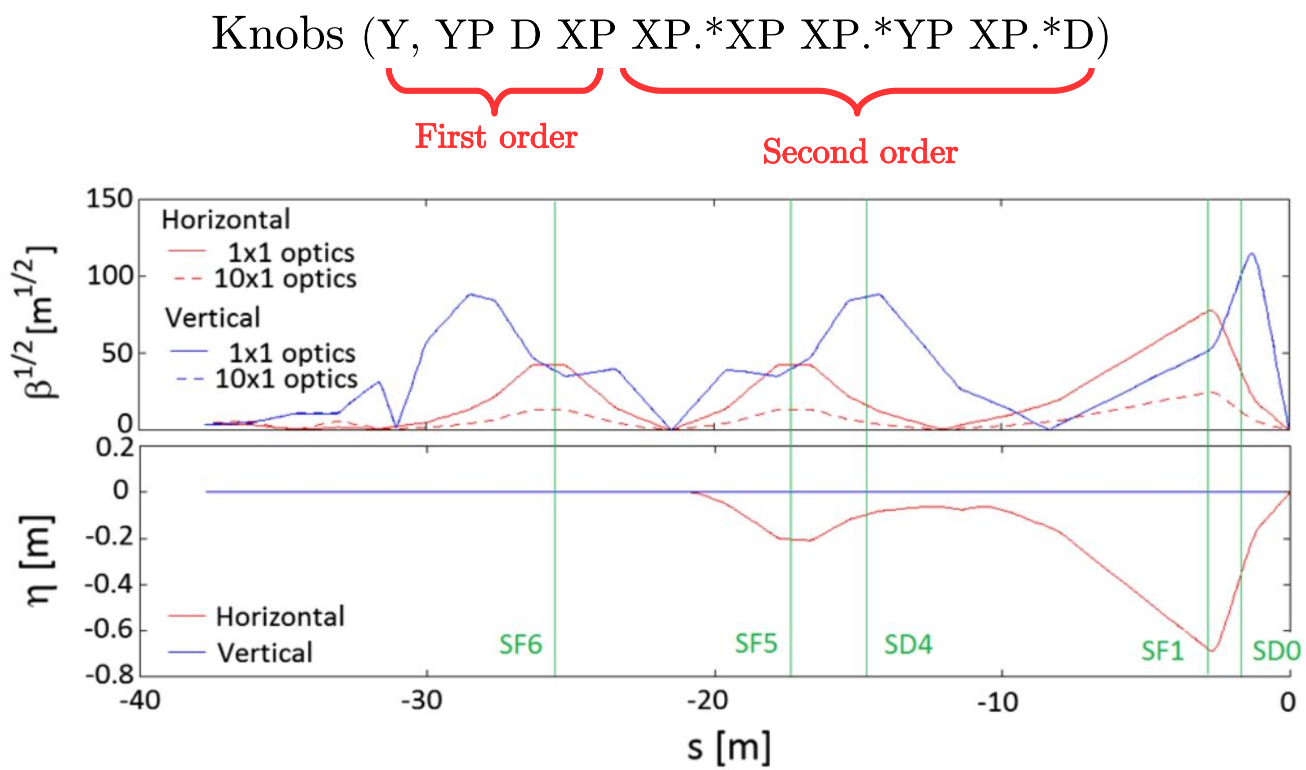


Figure: Positions of the sextupole knobs in the Accelerator Test Facility 2 (ATF2) [5].

Impact of short-range wakefields in the 380 GeV CLIC BDS

Simulation conditions

Simulation conditions (1/2)

Simulated errors:

- Static errors:

  - Misalignement of quadrupoles, sextupoles, BPMs of 50 um RMS.

  - Strength error of quadrupoles, sextupoles of 0.1% RMS.

  - Roll error for quadrupoles and sextupoles of 200 urad RMS.

Corrections applied:

- One-to-one
- DFS
- WFS
- Knobs (Y, YP D XP XP.*XP XP.*YP XP.*D)

First order: Y, YP D XP

Second order: XP.*XP XP.*YP XP.*D

Simulation procedure:

- 100 machines with the previously cited static imperfections.
- Apply the cited corrections and the knobs on the distribution at the IP.
- Measure the vertical beam size at the IP.

Tracking code used: PLACET

Simulation conditions (2/2)

Wakefield sources: X-band cavity BPMs (C-BPMs), wakepotentials calcultated with GdfidL.

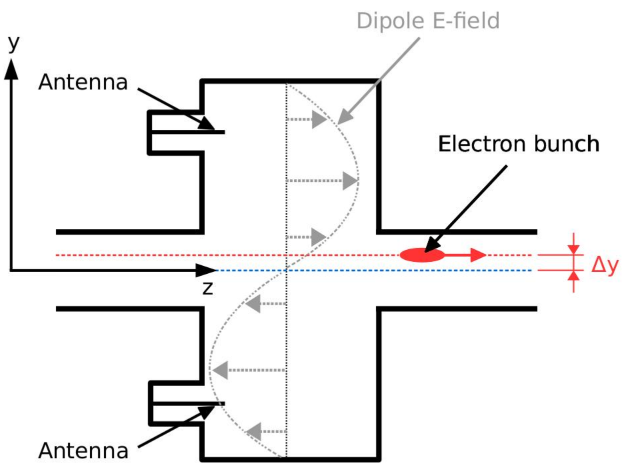


Figure: Schematic of a C-BPM.

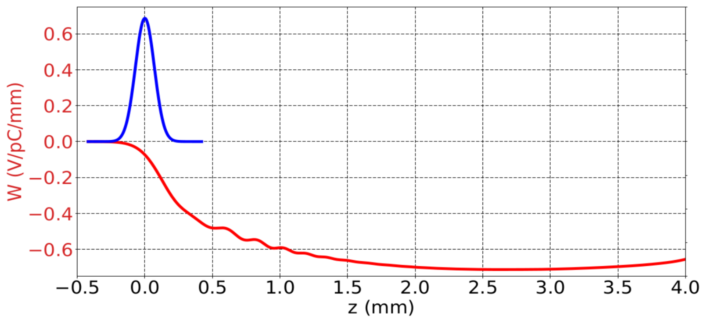


Figure : Transverse wakepotential in V/pC/mm of the CLIC C-BPM, calculated with GdfidL for a vertical offset of 1 mm, Gaussian bunch length of 70 µm and 1 pC charge (in red). For reference, the distribution of the electrons in one bunch is shown (in blue).

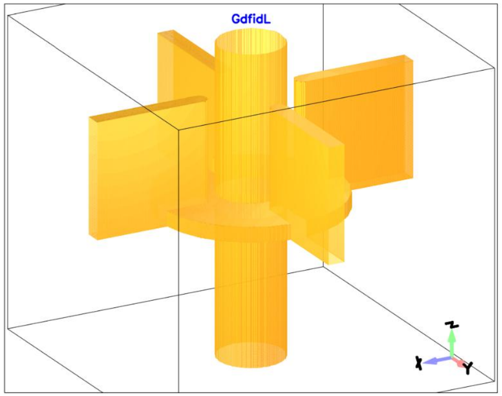


Figure: Geometry of the CLIC C-BPM, generated with GdfidL.

Table: Positions of CLIC 380 GeV BDS C-BPMs.

#	s (m)	#	s (m)	#	s (m)	#	s (m)	#	s (m)
1	0.0	28	158.9	55	868.4	82	971.4	109	1131.2
2	5.5	29	159.4	56	868.9	83	979.8	110	1131.7
3	11.0	30	178.1	57	869.5	84	980.3	111	1140.1
4	16.5	31	178.6	58	870.0	85	998.4	112	1147.0
5	17.0	32	197.2	59	870.6	86	998.9	113	1159.5
6	26.4	33	202.0	60	871.1	87	999.8	114	1172.0
7	36.3	34	205.0	61	871.8	88	1000.3	115	1184.3
8	36.8	35	211.0	62	872.3	89	1018.4	116	1193.0
9	40.3	36	212.3	63	884.4	90	1018.9	117	1205.9
10	40.8	37	363.5	64	884.9	91	1027.3	118	1218.8
11	44.4	38	364.8	65	885.5	92	1027.8	119	1231.2
12	44.9	39	376.0	66	886.0	93	1036.2	120	1246.8
13	48.5	40	377.3	67	886.9	94	1036.7	121	1279.9
14	49.0	41	528.5	68	887.4	95	1054.8	122	1333.9
15	52.5	42	529.8	69	905.5	96	1055.3	123	1337.1
16	53.0	43	541.0	70	906.0	97	1056.2	124	1391.0
17	62.4	44	542.3	71	914.4	98	1056.7	125	1394.2
18	62.9	45	693.5	72	914.9	99	1074.8	126	1460.6
19	72.3	46	694.8	73	923.3	100	1075.3	127	1463.8
20	72.8	47	706.0	74	923.8	101	1083.7	128	1483.6
21	82.2	48	707.3	75	941.9	102	1084.2	129	1488.6
22	101.3	49	858.5	76	942.4	103	1092.6	130	1658.2
23	101.8	50	859.8	77	943.4	104	1093.1	131	1687.4
24	120.5	51	866.1	78	943.9	105	1111.2	132	1716.7
25	121.0	52	866.6	79	961.9	106	1111.7	133	1925.7
26	139.7	53	867.3	80	962.4	107	1112.6	134	1938.4
27	140.2	54	867.8	81	970.9	108	1113.1		

The short-range wakefield sources taken into account are the 134 CLIC C-BPMs.

Impact of short-range wakefields in the 380 GeV CLIC BDS

Impact of corrections and of short-range wakefields

Impact of corrections in the CLIC 380 GeV BDS

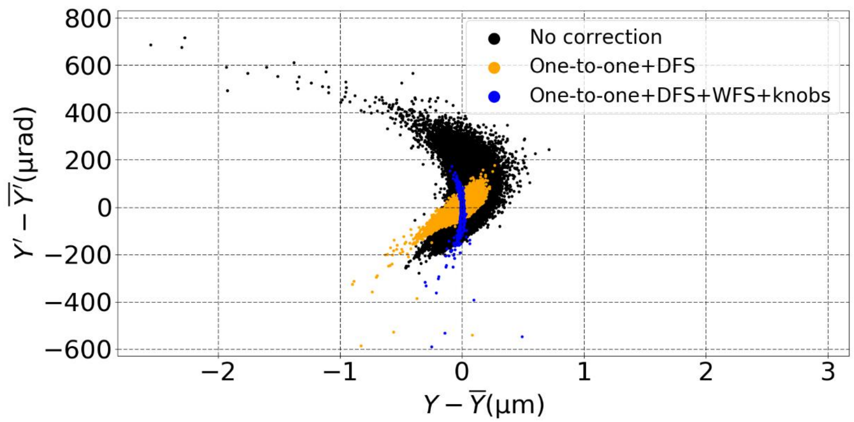


Figure : Centered vertical phase space at the 380 GeV CLIC BDS IP, $Y' - \overline{Y'}$ vs. $Y - \overline{Y}$, for 3 cases: no correction, One-to-one steering, DFS, WFS and One-to-one steering, DFS, WFS and knobs, calculated with PLACET with wakefields.

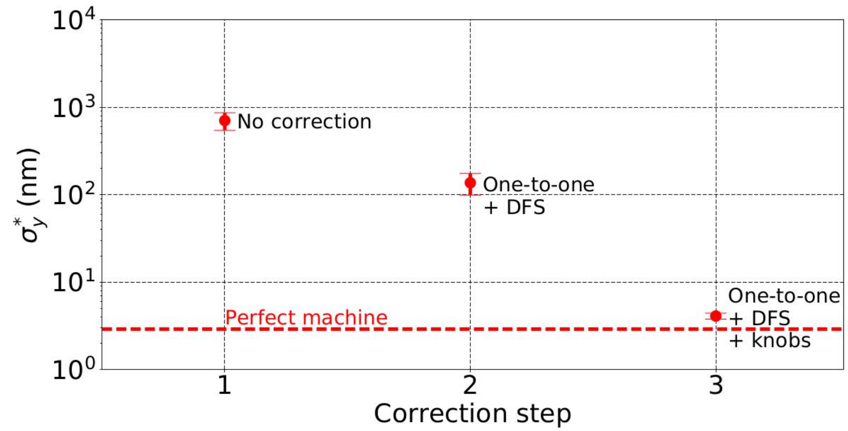


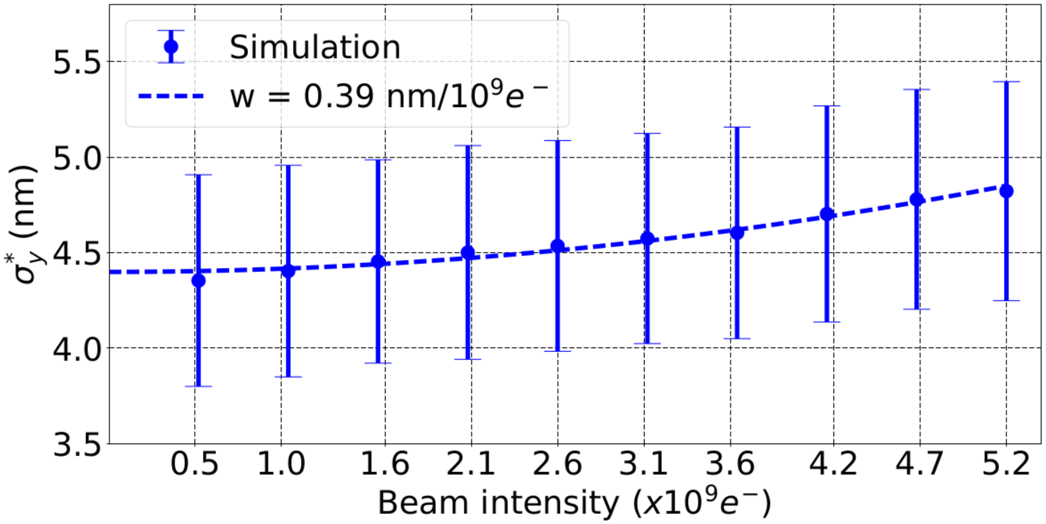
Figure : Average vertical beam size at the 380 GeV CLIC IP (σ_y^*) vs. correction step: One-to-one, DFS, WFS corrections and IP tuning knobs. The red dashed line show the vertical beam size at the IP for a perfect machine, 2.9 nm, calculated with PLACET with wakefields.

Table : Impact of the corrections on the CLIC 380 GeV vertical beam size at the IP (σ_y^*) for 100 machines with wakefields and with a beam intensity of 5.2×10^9 e^-, calculated with PLACET with wakefields.

Correction	$\overline{\sigma_y^*}$
No correction	706 ± 160 nm
One-to-one + DFS	137 ± 38,0 nm
One-to-one + DFS + knobs	4.82 ± 0.570 nm

Orbit corrections and knobs reduce the beam size by a factor 147.

Impact of short-range wakefields in the CLIC 380 GeV BDS



$$w[nm/10^9 e] = \frac{\left(\sqrt{\sigma_{y,q}^2 - \sigma_{y,0}^2}\right)}{q}$$

Figure : Vertical IP beam size σ_y^* vs. beam intensity in the 380 GeV BDS, calculated with PLACET with wakefields.

Table : Intensity-dependent effects due to wakefields on the vertical IP beam size (σ_y^*) in the 380 GeV BDS, calculated with PLACET with wakefields.

Beam intensity	$\overline{\sigma_y^*}$ **(nm)**	w (nm/10^9 e^-)
5.2×10^8 e^-	4.35 ± 0.55	0.39
5.2×10^9 e^-	4.82 ± 0.57	

Short-range wakefields have a slight effect in the 380 GeV BDS.

Impact of long-range wakefields in the 380 GeV CLIC BDS

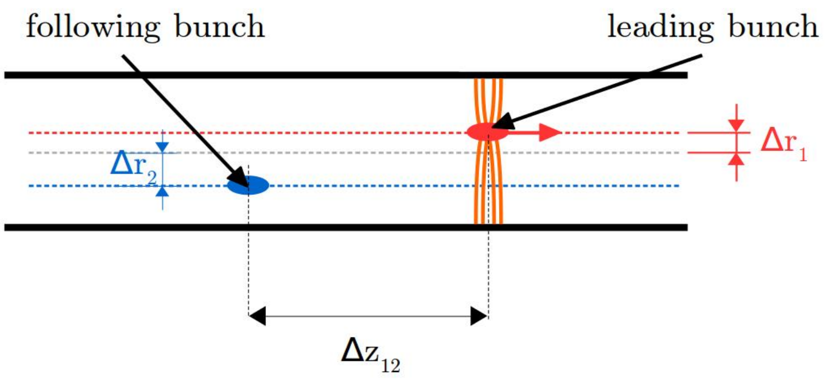
Long-range wakefields

Long-range wakefields in the CLIC BDS
Resistive walls wakefield

- Electrons going through the pipe interacts with the surrounding structure and generates a wake field.
- This wake field produces a transverse kick for the following bunches.
- The following model is used for the transverse wake function [6]:

$$W(z)=\frac{c}{\pi b^3}\sqrt{\left(\frac{Z_0}{\sigma_r \pi z}\right)}L$$

With b the radius of the beam pipe, Z_0 the impedance of the vacuum, σ_r the conductivity of the pipe and L the length of the beam line element.



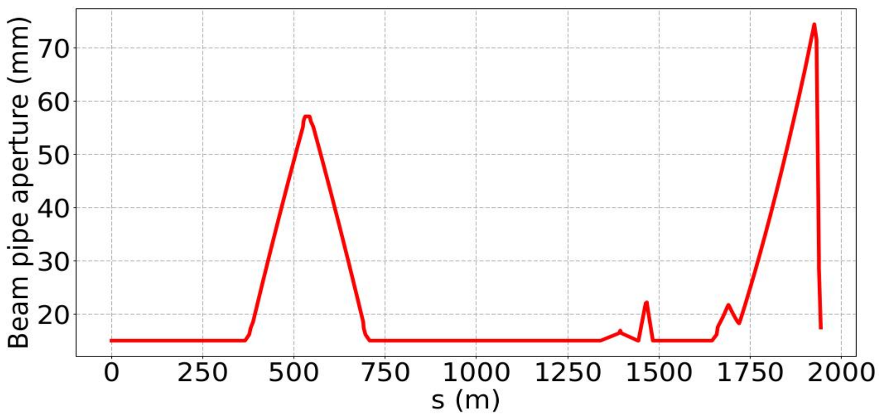


Figure: The CLIC BDS beam aperture profile.

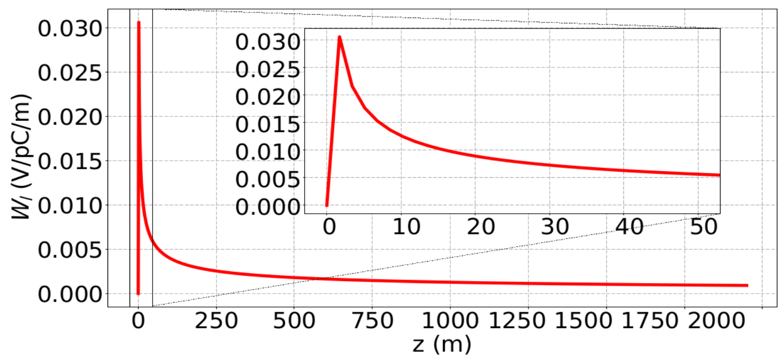


Figure : The CLIC resistive walls wakepotential for a copper beam pipe with a constant radius of 15 mm for the length of the CLIC BDS (~1949 m). The zoom shows the wakepotential for the length of a train (~ 52.8 m).

The long-range wakefield sources taken into account are the resistive walls.

Impact of long-range wakefields in the 380 GeV CLIC BDS

Simulation conditions and intensity-dependent effects

Simulation conditions and intensity-dependent effects

Simulation conditions:

- A train of 352 bunches is injected at the entrance of the BDS.
- Each bunch is made of one macro-particle.
- Incoming position and angle offset of the train to study the impact of long-range wakefields. Amplitude of the incoming offsets: 0.01, 0.05, 0.1σ_y or $\sigma_{y'}$ with σ_y and $\sigma_{y'}$ the beam size and the beam divergence at the entrance of the BDS.

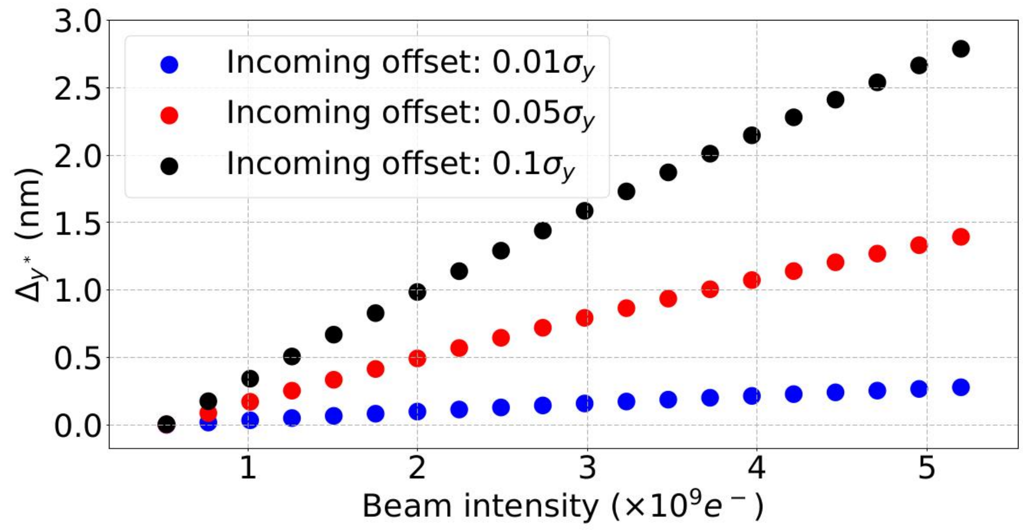


Figure : Vertical orbit deflection at the IP between the first and last bunch of a train Δy^* vs. beam intensity for three incoming constant position offsets of the train of bunches in the 380 GeV CLIC BDS: $0.01\sigma_y$, $0.05\sigma_y$ and $0.1\sigma_y$, calculated with PLACET with resistive walls.

$\sigma_y = 0.66\,\mu m$

$\sigma_{y'} = 0.14\,\mu rad$

Impact of long-range wakefields in the CLIC 380 GeV BDS for a constant offset

- Study of the impact of long-range wakefields for a train injected in the BDS with a constant vertical position and an angle offset of $0.01\sigma_y$ and $0.01\sigma_{y'}$ respectively on the vertical orbit deflection at the IP normalized by the IP beam size, Δ_y/σ_y^* (left).
- Same study was done for both vertical and horizontal incoming offsets (right).

$\sigma_{y'}=0.14\,\mu rad$ $\quad\sigma_y=0.66\,\mu m$ $\quad\sigma_y^*=2.9\,nm$

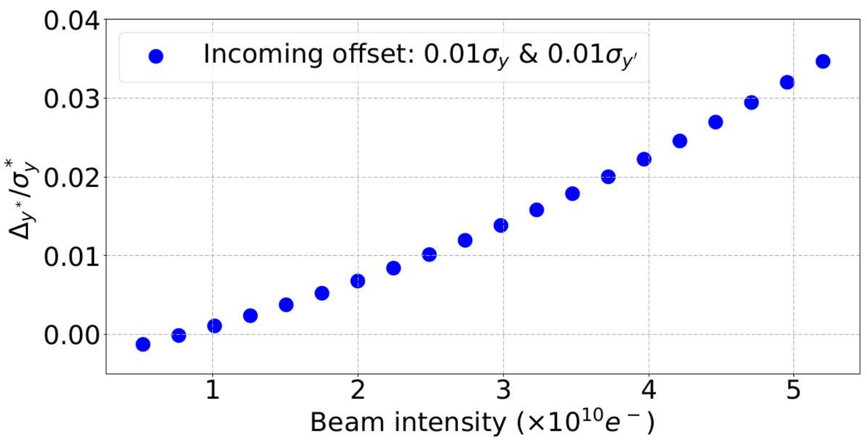


Figure : Vertical orbit deflection at the IP between the first and last bunch of a train normalised by the IP vertical beam size ($\Delta y^*/\sigma_y^*$) vs. beam intensity for a train with incoming constant horizontal position and angle offsets of respectively $0.01\sigma_x$ and $0.01\sigma_{x'}$ and vertical incoming position and angle offsets of respectively $0.01\sigma_y$ and $0.01\sigma_{y'}$ in the 380 GeV GeV BDS, calculated with PLACET with resistive walls.

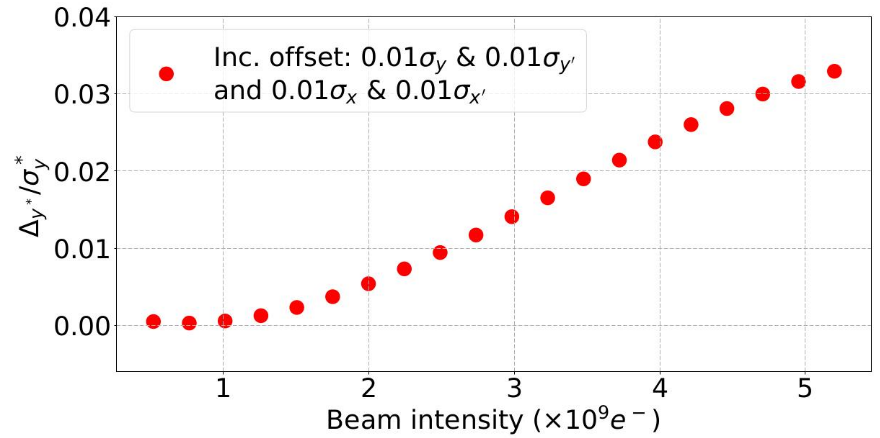


Figure : Vertical orbit deflection at the IP between the first and last bunch of a train normalised by the IP vertical beam size ($\Delta y^*/\sigma_y^*$) vs. beam intensity for a train with incoming constant horizontal position and angle offsets of respectively $0.01\sigma_x$ and $0.01\sigma_{x'}$ and vertical incoming position and angle offsets of respectively $0.01\sigma_y$ and $0.01\sigma_{y'}$ in the 380 GeV CLIC BDS, calculated with PLACET with resistive walls.

Impact of long-range wakefields in the CLIC 380 GeV BDS for a random offset

- Study of the impact of long-range wakefields for a train injected in the BDS with a random horizontal and vertical position and an angle offsets.
- The distribution of random incoming position and angle offset is a normal distribution with a zero mean and variance of 2.6x10^{-4}, leading to a +/− 5% incoming vertical and horizontal angle and position offsets.

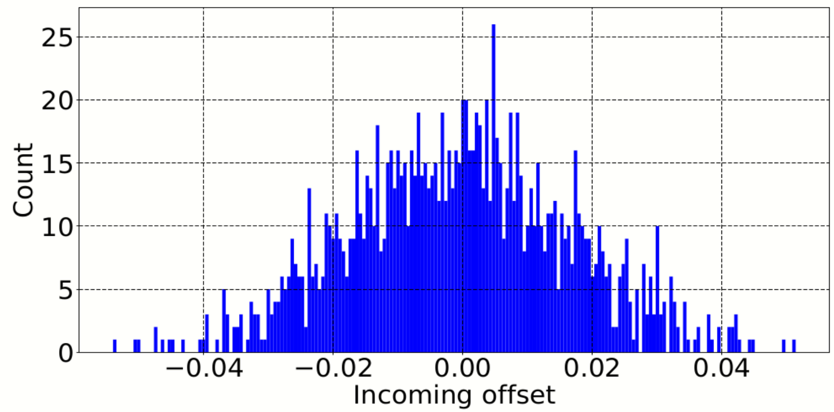
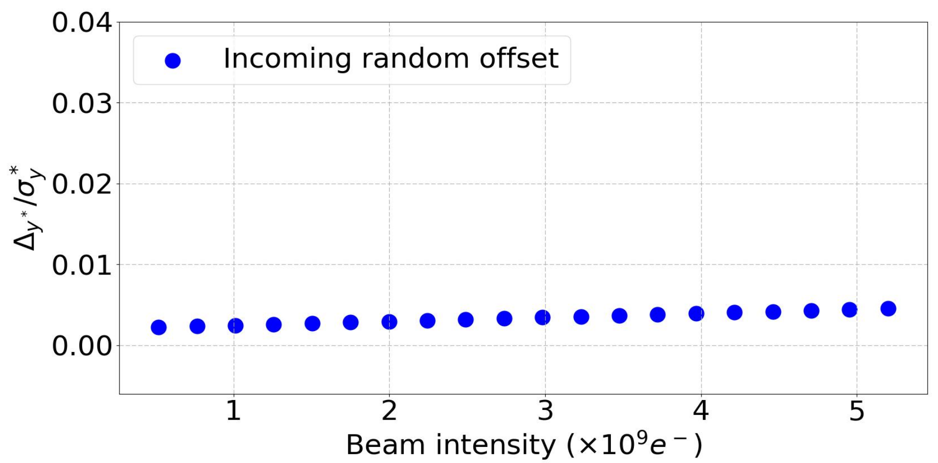


Figure : Distribution of incoming position and angle offsets from -0.05$\sigma_{x,y}$ to 0.05$\sigma_{x,y}$.



Random incoming offsets lead to a negligible effect of long-range wakefields

Impact of long-range wakefields in the CLIC 380 GeV BDS Luminosity

- Study of the impact of luminosity degradation due to the vertical orbit deflection at the IP with Guinea-Pig, a code simulating the impact of beam-beam effects on luminosity and background [7].

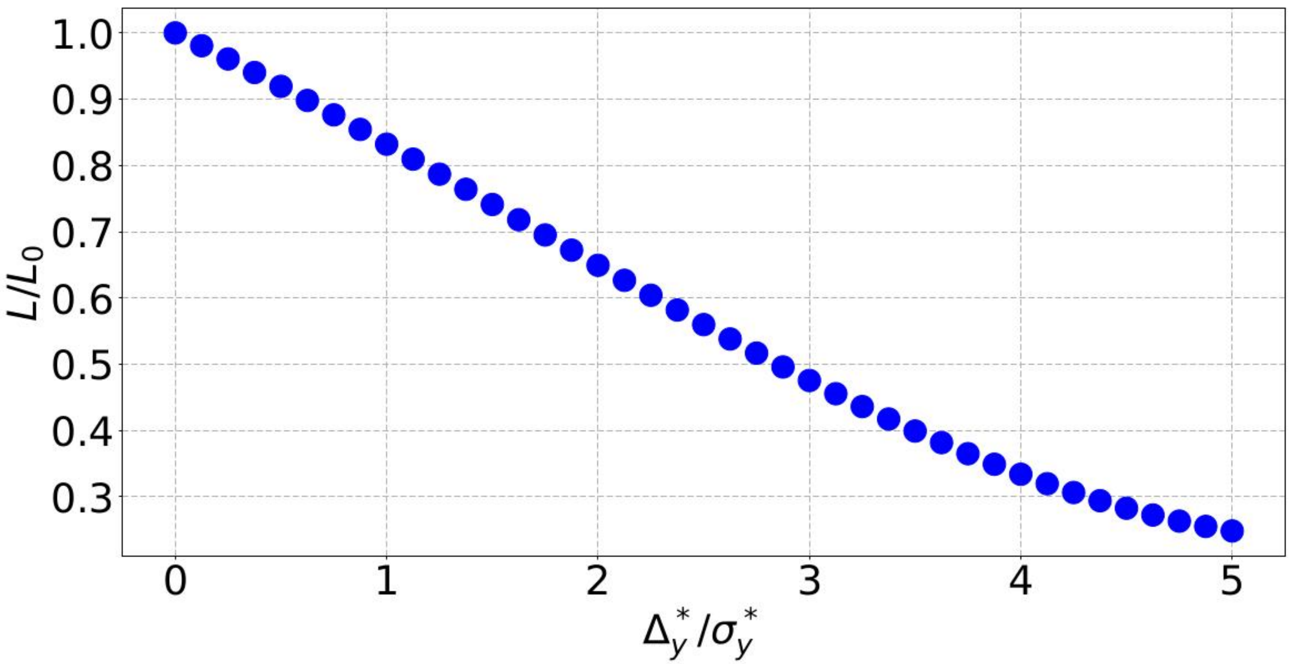


Figure : CLIC 380 GeV BDS luminosity degradation vs. relative vertical offset of the colliding beams.

$$L = f_{coll}\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*}F$$

Impact of long-range wakefields in the CLIC 380 GeV BDS Summary

Table : Impact of different incoming vertical position and angle offsets on the relative vertical offset Δ_y^* at the IP and the luminosity for low and high beam intensities in the CLIC 380 GeV BDS.

Case	Δ_y^* [nm]	Δ_y^*/σ_y^*	$\mathbf{L/L_0}$
Inc. position offset 0.1σ_y			
$0.52 \times 10^9\ e^-$	0.006	0.002	~ 1.0
$5.2 \times 10^9\ e^-$	2.79	0.96	0.84
Inc. angle offset 0.1$\sigma_{y'}$			
$0.52 \times 10^9\ e^-$	0.002	0.001	~ 1.0
$5.2 \times 10^9\ e^-$	1.71	0.59	0.91
Inc. offsets 0.01σ_y & 0.01$\sigma_{y'}$			
$0.52 \times 10^9\ e^-$	0.003	0.001	~ 1.0
$5.2 \times 10^9\ e^-$	0.087	0.03	~ 1.0
Inc. offsets 0.01σ_y & 0.01$\sigma_{y'}$ and 0.01σ_x & 0.01$\sigma_{x'}$			
$0.52 \times 10^9\ e^-$	0.003	0.001	~ 1.0
$5.2 \times 10^9\ e^-$	0.087	0.03	~ 1.0
Inc. random offsets around zero			
$0.52 \times 10^9\ e^-$	0.006	0.002	~ 1.0
$5.2 \times 10^9\ e^-$	0.015	0.005	~ 1.0

Long-range wakefields have a significant impact in the CLIC 380 GeV BDS. An intra-train feedback system would be necessary in order to achieve the luminosity goals.

Acknowledgements

Special thanks to:

- Philip Burrows from the University of Oxford.
- Andrea Latina and Daniel Schulte from CERN.
- Angeles Faus-Golfe from IJCLab.

Conclusion and outlook

- The intensity-dependent effects due to short-range wakefields are negligible in the CLIC 380 GeV BDS. The intensity-dependent parameter w is around 0.39 nm/10^9 e^-, representing an increase on the vertical beam size at the IP of 0.47 nm between 0.52×10^9 e^- and 5.2×10^9 e^-.

- The intensity-dependent effects due to long-range wakefields have a significant impact on the luminosity for an initial position offset is of $0.1\sigma_y$, leading to a luminosity loss of 16%. An initial angle offset of $0.1\sigma_{y'}$ leads to a luminosity loss of 9%. For smaller incoming angle and position offset amplitudes, the effect on the luminosity is negligible.

- An intra-train feedback system would be necessary in order to correct those effects and to achieve the required luminosity goals. Such a system has been studied to correct the vertical jitters generated by ground motion [8].

- A prototype feedback system was tested in ATF2 and gave promising results [9]. The next step will be to implement this feedback and study its impact on the luminosity losses due to intensity-dependent effects.

Thank you