# Optimisation of the CLIC RTML

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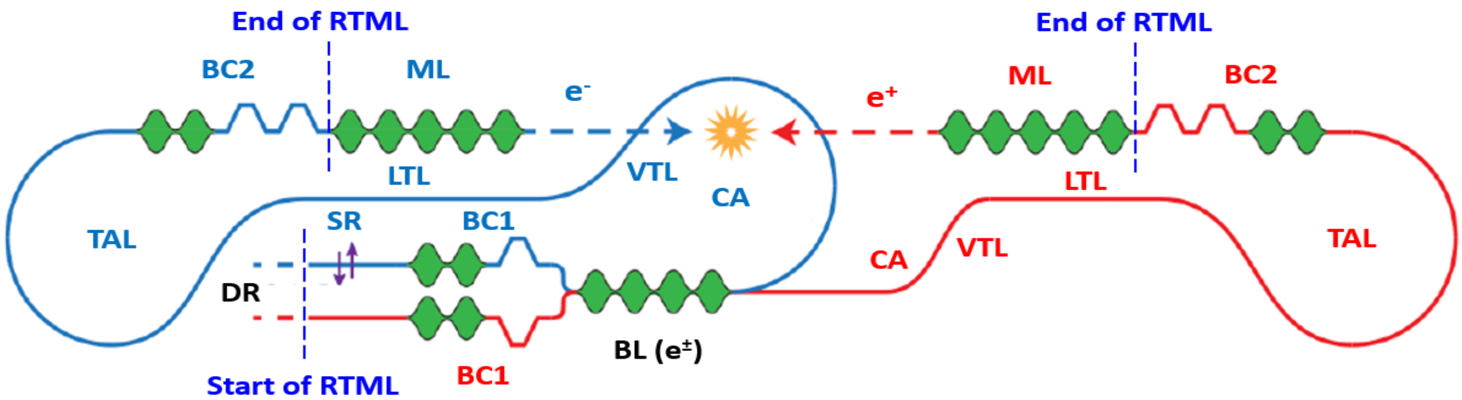
# Outline

- Introduction to CLIC RTML
- Optimisation of BC1 and BC2
- Static imperfections and BBA corrections
- Jitter amplifications
- Alternative booster linac
- Conclusions

# Ring To Main Linac (RTML)




- **Spin rotator (SR)**, used only for the $e^-$ beam, aimed at achieving any arbitrary spin rotation.
- **Bunch compressor 1 (BC1)**, composed of 2 GHz RF cavities working at zero acceleration mode and a chicane.
- **Booster linac (BL)**, composed of the same 2 GHz RF cavities as BC1, is common to the $e^-$ and $e^+$ beams and accelerates from 2.86 GeV to 9 GeV .
- **Central arc (CA)** and **vertical transfer line (VTL)** to transport the beam to the underground underground tunnel.
- **Long transfer line (LTL)** to transport the beam to the starting point of the two main linacs.
- **Turn around loop (TAL)** to bend the beam by 180° and direct it towards the interaction point (IP).
- **Bunch compressor 2 (BC2)**, composed of 12 GHz RF cavities working at zero acceleration mode and two chicanes.

# Beam parameters @ 380 GeV

- **Beam parameters assumed** at the **entrance of the RTML**

| Beam parameter | Unit | Value |
|---|---|---|
| Beam energy | GeV | 2.86 |
| Number of bunches per train | | 352 |
| Number of particles per bunch | | $5.2 \times 10^9$ |
| Bunch charge | nC | 0.83 |
| RMS bunch length | um | 1800 |
| RMS energy spread | % | 0.12 |
| Normalized emittance, $\epsilon_{n,x}$ | nm·rad | 700 |
| Normalized emittance, $\epsilon_{n,y}$ | nm·rad | 5 |

- **Beam parameters** by design (perfect machine) **required** at the **end of the RTML**

| Beam parameter | Unit | Value |
|---|---|---|
| Beam energy | GeV | 9 |
| Number of bunches per train | | 352 |
| Number of particles per bunch | | $5.2 \times 10^9$ |
| Bunch charge | nC | 0.83 |
| RMS bunch length | um | 70 |
| RMS energy spread | % | $< 1.7$ |
| Normalized emittance, $\epsilon_{n,x}$ | nm·rad | $< 800$ |
| Normalized emittance, $\epsilon_{n,y}$ | nm·rad | $< 6$ |

- Normalised **emittance budgets** at the **end of the RTML**, **required** for at least **90% machines** after BBA corrections

| Normalized emittance budgets | $\epsilon_{n,x}$ | $\epsilon_{n,y}$ |
|---|---|---|
| Without imperfections | $< 800$ | $< 6$ |
| With static imperfections | $< 820$ | $< 8$ |
| With dynamic imperfections | $< 850$ | $< 10$ |

# Motivation

- Some remaining problems in previous studies:
  - In the **CDR** published 2012, RTML was well designed, but the **imperfections were not studied**. Besides, a very **high gradient** (94 MV/m) was assumed for the BC2 X-band, which might be **not realistic and optimum**
  - In the CLIC **PIP report** published in 2018, the BC2 X-band iris aperture was simply increased by a factor of 1.5 to meet the emittance budgets with static imperfections. However, such a **large aperture** ($a_0$ = 5.44 mm, $a_0/\lambda$ = 0.218) would be problematic with **break-down, huge power consumption and cost**
  - In a later study (not finished and not published), a new long X-band structure similar with the **CompactLight X-band** was tried and tested. The power consumption and cost can be much smaller due to reduced aperture, but the **BBA didn't work**. Besides, the **aperture** ($a_0$ = 4.41 mm, $a_0/\lambda$ = 0.176) is **still a bit large** for CLIC
- Nevertheless, there is more we can do:
  - The total RF voltage and gradient of BC1 and BC2 was never optimised to reduce the **cost**
  - The **bunch phase shift** effect (raised in damping ring) was never considered and minimised
  - The **BBA corrections** might be also optimised to achieve more easily the emittance budgets

# RF structures

- RF structure parameters
  - The *CLIC* ***L-band*** (1.5 m long) is assumed in **BC1**, which is the **same with booster linac (BL)**
  - The *CLIC* ***TD-31 X-band*** (275 mm long) is assumed in **BC2**, just to be the same with the **main linac** (380 GeV, drive-beam based)

✓ Original designs are used, without any change in the iris and structure length

| Parameter | Unit | BC1 | BC2 |
|---|---|---|---|
| Structure name | | CLIC L-band | CLIC TD-31 X-band |
| RF frequency | GHz | 1.999 | 11.994 |
| Structure length | m | 1.5 | 0.275 |
| Number of cells | | 30 | 33 |
| Phase advance per cell | ° | 120 | 120 |
| Working RF phase | ° | 90 | 90 |
| First iris radius | mm | 20 | 4.062 |
| Last iris radius | mm | 14 | 2.6 |
| First iris thickness | mm | 8 | 2.525 |
| Last iris thickness | mm | 8 | 1.433 |

# Optimisation of voltages and angles

- Simulation tools
  - ***Placet***: for *full simulation* and start-to-end optimisation. Side effects (wakefield, CSR, ISR) considered
  - ***RF-Track***: for *fast simulation* and bunch longitudinal optimisation. Only BC1 and BC2 chicanes are simulated. Side effects not considered
- **Free parameters** to optimise
  - Total RF **voltages** of BC1 and BC2: $\mathbf{V_1, V_2}$
  - Bending **angles** of BC1 and BC2 chicanes: $\boldsymbol{\theta_1, \theta_2}$
  - ✓ The two chicanes of BC2 are assumed to be identical, to simplify the optimisation and minimise emittance growth due to ISR effect
- **Goals** to be achieved:
  - Final **bunch length**: $\sigma_z$ ~ 70 um
  - Final **energy spread**: $\sigma_E/E < 1.7\%$
  - **Emittances** (by design): $\varepsilon_{n,x} < 800$ nm, $\varepsilon_{n,y} < 6$ nm
  - Minimum bunch **phase shift effect** after RTML
  - Minimum **emittance growth** along RTML
  - Minimum **total RF voltage** in BC1 and BC2

- **Optimised parameters**
  - ✓ BC1 voltage is ~10% higher than CDR
  - ✓ **BC2 voltage is ~60% lower than CDR**

| Parameter | Symbol | Unit | BC1 | BC2 |
|---|---|---|---|---|
| Total RF voltage | $V$ | MV | 450 | 650 |
| Bending angle | $\theta$ | $^\circ$ | 3.95 | 1.55 |

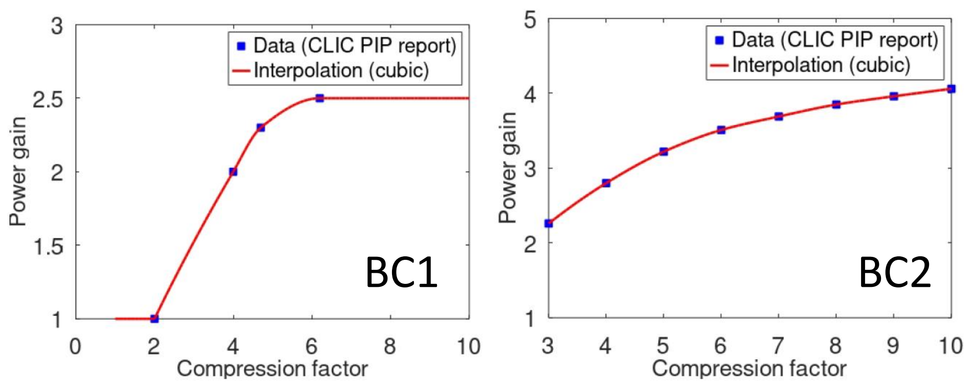
# Optimisation of gradients

**RF system** assumptions in optimisation:

- Klystrons

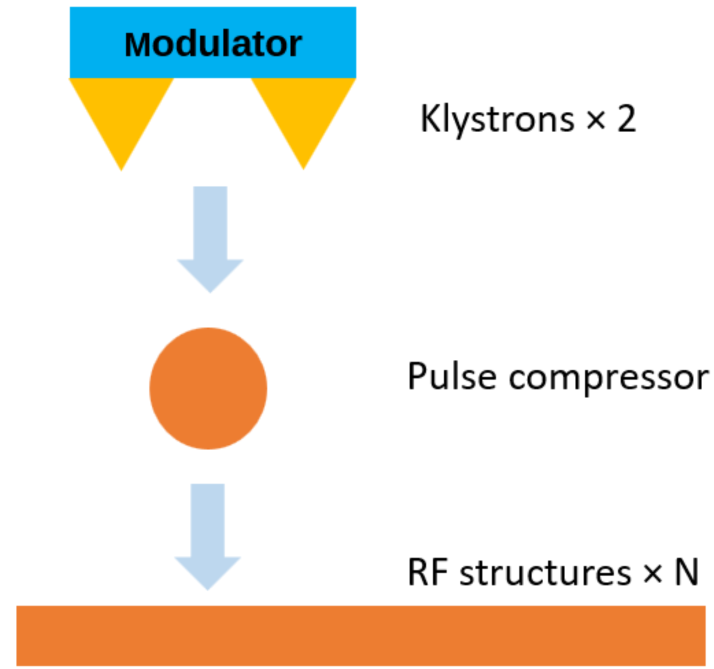
| Parameter | Unit | L-band (BC1) | X-band (BC2) |
|---|---|---|---|
| Output power | MW | 50 | 51.4 |
| Pulse length | $\mu$s | 8 | 2 |

- Pulse compressors




- Total RF transmission efficiency considered: 90%
- Layout:

| RF structures per Module (N) | BC1 (L-band) | BC2 (X-band) |
|---|---|---|
| **Baseline** option | **4** | **8** |
| **Alternative** option | **$2^n$** | **$2^n$** |




Schematic layout of a RF unit

**New results w.r.t CLIC week (12/2023) in the following slides ...**

# Optimisation of gradients

- *CLICopti* is used to estimate RF parameters (peak power, pulse length, breakdown, etc.)
  - Beam loading effects to be studied for BC1, BC2 (though we think cost estimation is not affected at φ = 90˚)
- Booster linac (BL) is also reoptimized (similar with BC1)
- Energy and energy chirp losses are also compensated:

| RF voltage | Unit | BC1 | BC2 | Booster linac |
|---|---|---|---|---|
| Before compensation | MV | 450 | 650 | 6140 |
| After compensation | MV | 450.5 | 659.3 | 6156.3 |

- A scan of the number of RF units is performed to minimise the cost. As a result:

| Parameter | Unit | Old | | New | |
|---|---|---|---|---|---|
| | | **CDR** | **PIP** | **Baseline** | **Alternative** |
| BC1 RF total voltage | MV | 399 | 477 | 450.5 | |
| BC1 structure length | m | 1.5 | | 1.5 | |
| BC1 RF gradient | MV/m | 13.3 | 15.9 | 18.770 | |
| BC1 RF peak power | MW | 23.8 | 34.0 | 47.3 | |
| BC1 RF-to-beam efficiency | % | 24.8 | 22.9 | 20.8 | |
| BC1 number of klystrons | | 10 (6) | 10 | 8 | |
| BC1 number of RF structures | | 20 | | 16 | |
| BC2 RF total voltage | MV | 1686.4 | 1763.0 | 659.3 | |
| BC2 structure length | m | 0.23 | | 0.275 | 0.275 |
| BC2 structure aperture | mm | **3.63** | **5.44** | **3.33** | |
| BC2 RF gradient | MV/m | **94** | **98.27** | **74.916** | **37.458** |
| BC2 RF peak power | MW | **88.4** | **355.6** | **39.3** | **9.8** |
| BC2 RF-to-beam efficiency | % | 24.5 | 7.5 | 45.1 | 56.5 |
| **BC2 number of klystrons** | | **40** | **156** | **8** | **4** |
| **BC2 number of RF structures** | | **78** | | **32** | **64** |
| BL total voltage | MV | 6168.6 | | 6156.3 | |
| BL structure length | m | 1.5 | | 1.5 | |
| BL RF gradient | MV/m | 14.9 | | 15.089 | |
| BL RF peak power | MW | 54.1 | | 55.1 | |
| BL RF-to-beam efficiency | % | 20.0 | | 19.9 | |
| BL number of klystrons | | 138 | | 136 | |
| BL number of RF structures | | 276 | | 272 | |

| **RF structures per Module (N)** | **BC1 (L-band)** | **BC2 (X-band)** |
|---|---|---|
| **Baseline option** | **4** | **8** |
| **Alternative option** | **$2^n$** | **$2^n$** |

**Updates w.r.t CLIC week (12/2023):**

- **New baseline of RF (more conservative)**

✓ **BC2 expected cost reduced significantly compared with CDR / PIP report!**

- **Baseline RF system option will be studied in the following slides ...**

# Final results after optimisation

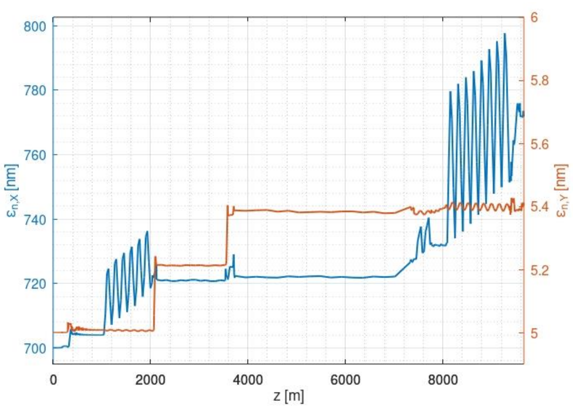
- Final results ($e^-$ beam) at the end of the RTML (perfect machine):
  - CSR not simulated in CA & TAL by default (small impact but much longer time)
  - Optimised matching sections, **emittances growth reduced significantly** (**CDR, PIP $\varepsilon_{x,y}$: ~790 nm, ~5.8 nm**)

**W/o CSR simulated in CA & TAL**

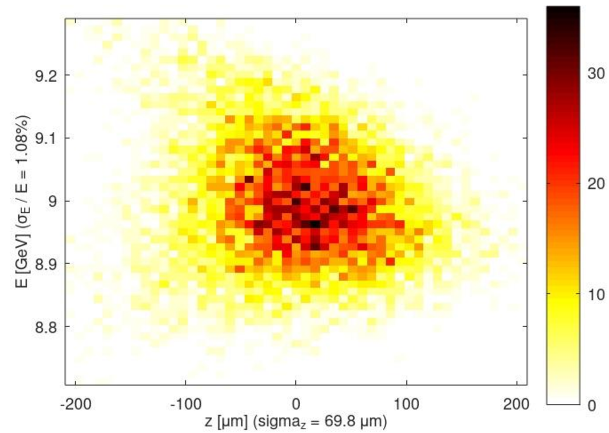
| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Bunch length | $\sigma_z$ | $\mu m$ | 69.8 |
| Energy spread | $\sigma_E/E$ | % | 1.1 |
| Horizontal normalized emittance | $\epsilon_{n,x}$ | nm | 771.5 |
| Vertical normalized emittance | $\epsilon_{n,y}$ | nm | 5.40 |

**W/ CSR simulated in all sections**

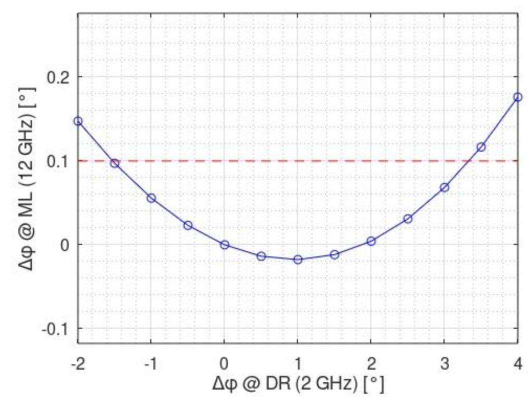
| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Bunch length | $\sigma_z$ | $\mu m$ | 70.4 |
| Energy spread | $\sigma_E/E$ | % | 1.1 |
| Horizontal normalized emittance | $\epsilon_{n,x}$ | nm | 775.2 |
| Vertical normalized emittance | $\epsilon_{n,y}$ | nm | 5.43 |




**Emittance growth along RTML**




**Longitudinal phase space at the end**




**Bunch phase shift effect**

- **Bunch phase shift effect** from the DR (2 GHz) to the ML (12 GHz) minimised:
  - Assuming ±0.1° tolerance at ML, corresponding **acceptance for DR improved significantly**: **[-1.5°, +3.3°]**, much better than the required ±1.0°

# Static imperfections and BBA corrections

- **Imperfections** considered (**same with previous** studies)
  - Numbers in PIP report (Table 2.5) might be too conservative (or maybe typos, as the numbers cannot be found in any previous studies). But more conservative errors can still be studied

| Imperfection | Unit | CA & TAL | Other sections |
|---|---|---|---|
| Magnet and BPM positron error | $\mu$m | 30 | |
| Magnet and BPM tilt error | $\mu$rad | 100 | |
| Magnet and BPM roll error | $\mu$rad | 100 | |
| Quadrupole strength error | % | 0.01 | 0.1 |
| Other magnet strength error | % | 0.1 | |
| BPM resolution | $\mu$m | 1 | |
| Magnetic-center shift w/ strength | | 0.35 $\mu$m / 5% | |
| Emittance measurement uncertainty | % | 1 | |

**Updates w.r.t CLIC week (12/2023):**
- **BPM errors considered (mistake fixed)**
- **Erros now same with previous studies**

- **Beam based alignment (BBA)** correction **methods**
  - **One-to-one (OTO) correction**: orbit correction

$$\begin{pmatrix} \mathbf{b} \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} & \mathbf{R} \\ \beta_0 & \mathbf{I} \end{pmatrix} \cdot \theta$$

b: BPM readings  R: orbit response matrix  θ: dipole kicker corrections

  - **Dispersion-free steering (DFS) correction**: orbit & dispersion correction

$$\begin{pmatrix} & \mathbf{b} \\ \omega_d & (\eta - \eta_0) \\ & \mathbf{0} \end{pmatrix} = \begin{pmatrix} & \mathbf{R} \\ \omega_d & \mathbf{D} \\ \beta_1 & \mathbf{I} \end{pmatrix} \cdot \theta$$

η: dispersion  D: dispersion response matrix
Test beam: energy difference of 5% by megnetic strength scaling in all sections

  - **Sextupole-based emittance tuning (SBET) correction**: emittance optimisation by moving sextupoles

Merit function: $$M = \sqrt{\left(\frac{\epsilon_x^m - \epsilon_x^i}{\epsilon_x^s - \epsilon_x^i}\right)^2 + \left(\frac{\epsilon_y^m - \epsilon_y^i}{\epsilon_y^s - \epsilon_y^i}\right)^2}$$

$\varepsilon^i$: initial emittance at the entrance of the RTML
$\varepsilon^m$: measured emittance (1% RMS uncertainty assumed)
$\varepsilon^s$: emittance budget for static imperfections

# Static imperfections and BBA corrections

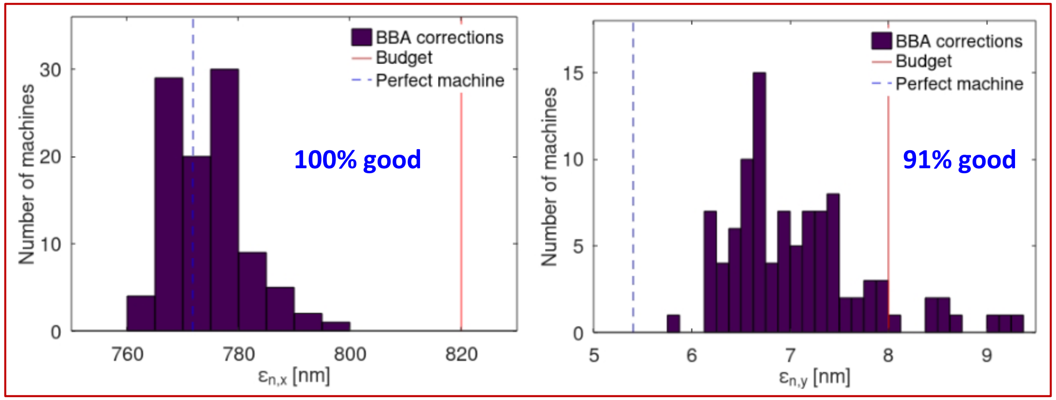
- BBA correction **procedure**
  1. ST—LTL: OTO + DFS
  2. CA—LTL: SBET
  3. TAL1: OTO + DFS + SBET
  4. TAL2: OTO + DFS + SBET
  5. BC2: OTO + DFS + SBET

✓ Small overlap between sections
✓ Section split into bins with 20% overlap
✓ In each bin, correction in a few iterations
✓ DFS followed OTO after all bins in a section
✓ Always the first 8 sextupoles used in SBET
✓ TAL too long, split into 2 sections

- BBA parameters
  - To be optimized for each section

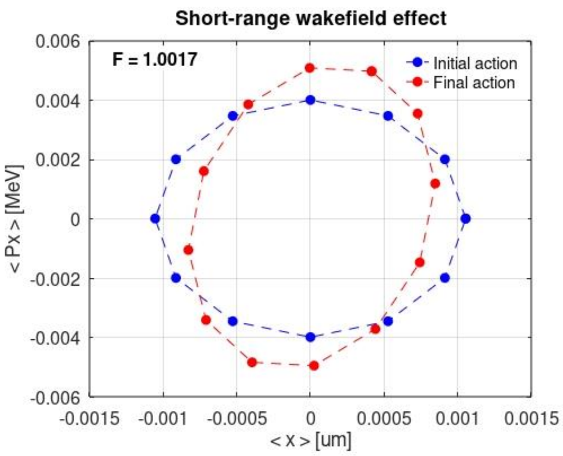
| Parameter | Value |
|---|---|
| $\beta_0$ (OTO) | 2 |
| $\beta_1$ (DFS) | 2 |
| $\omega_d$ (DFS) | 30 |
| Number of quadrupoles per bin | 100 |
| Bin overlap | 20% |
| Number of iterations (OTO) | 2 |
| Number of iterations (DFS) | 2 |

- Results (100 random misaligned machines)
  - 91% good machines (required: 90%)
  - To be optimised, though satisfied
  * To understand why X emittance is much better than Y

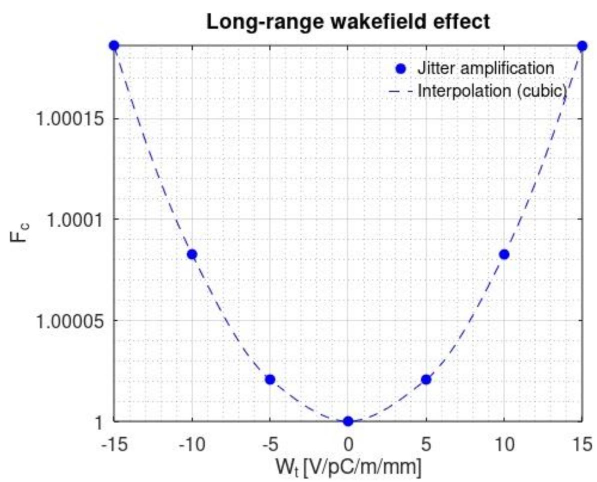


# Jitter amplifications

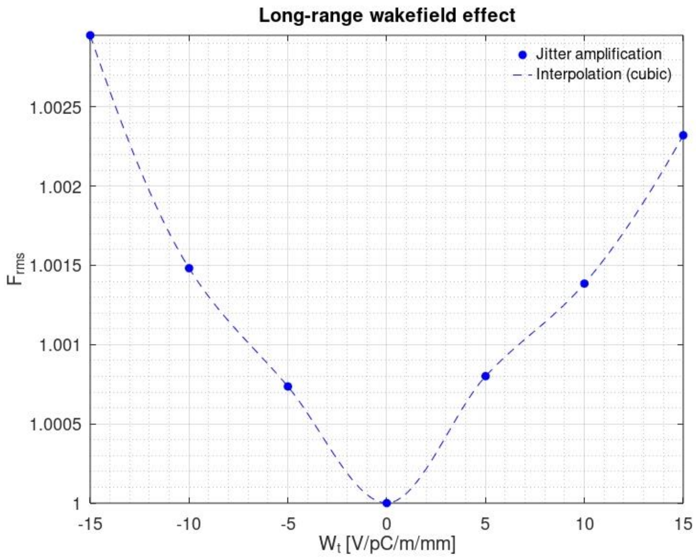
- Short-range wakefield




- Long-range wakefield (coherent)




- Long-range wakefield (incoherent)
  - 1000 random trains simulated
  - 352 bunches per train
  - Kick on next bunch simulated
  - Worst bunch considered



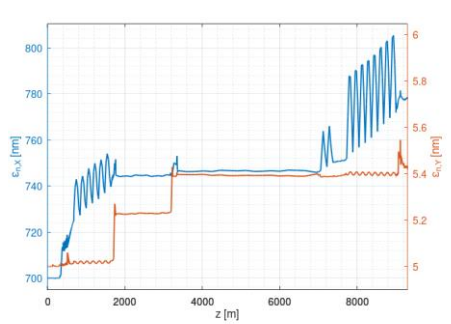

✓ Effects are very small!

# Alternative booster linac: X-band

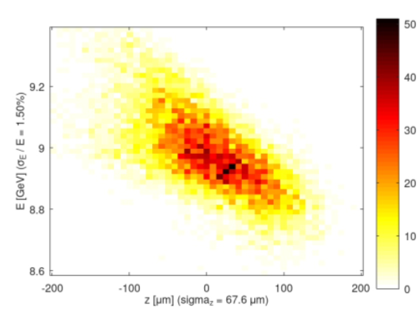
- Optimised configuration

| Parameter | Unit | Baseline BL | Alternative BL |
|---|---|---|---|
| BC1 voltage | MV | 450.5 | 489.5 |
| BC1 RF gradient | MV/m | 18.770 | 20.394 |
| BC1 RF peak power required | MW | 47.3 | 55.9 |
| BC1 RF-to-beam efficiency | % | 20.8 | 19.8 |
| BC1 number of klystrons | | 8 | 8 |
| BC1 number of RF structures | | 16 | 16 |
| BC1 output bunch length | $\mu$m | **407** | **201** |
| BC2 voltage | MV | 659.3 | 2442.1 |
| BC2 RF gradient | MV/m | 74.916 | 79.289 |
| BC2 RF peak power required | MW | 39.3 | 44.0 |
| BC2 RF-to-beam efficiency | % | 45.1 | 43.5 |
| BC2 number of klystrons | | **8** | **28** |
| BC2 number of RF structures | | **32** | **112** |
| BL voltage | MV | 6156.3 | 6190.3 |
| BL structure length | m | **1.5** | **0.275** |
| BL RF gradient | MV/m | **15.089** | **58.144** |
| BL RF peak power required | MW | 55.1 | 43.1 |
| BL RF-to-beam efficiency | % | **19.9** | **43.7** |
| BL number of klystrons | | **136** | **96** |
| BL number of RF structures | | **272** | **384** |
| BL total length | m | **530.4** | **153.6** |

**Emittance growth along RTML**




**Longitudinal phase space at the end**




- Results (quite good)

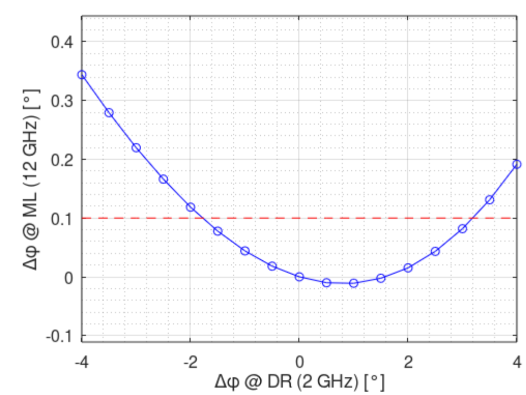
**W/o CSR simulated in CA & TAL**

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Bunch length | $\sigma_z$ | $\mu$m | 67.7 |
| Energy spread | $\sigma_E/E$ | % | 1.5 |
| Horizontal normalized emittance | $\epsilon_{n,x}$ | nm | 777.8 |
| Vertical normalized emittance | $\epsilon_{n,y}$ | nm | 5.42 |

**W/ CSR simulated in all sections**

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Bunch length | $\sigma_z$ | $\mu$m | 71.3 |
| Energy spread | $\sigma_E/E$ | % | 1.5 |
| Horizontal normalized emittance | $\epsilon_{n,x}$ | nm | 779.2 |
| Vertical normalized emittance | $\epsilon_{n,y}$ | nm | 5.45 |

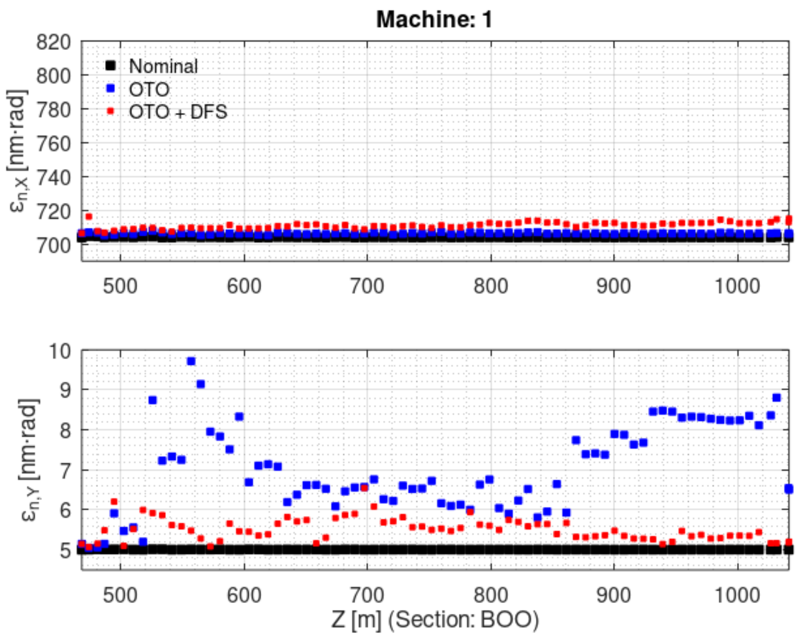
**Bunch phase shift effect**



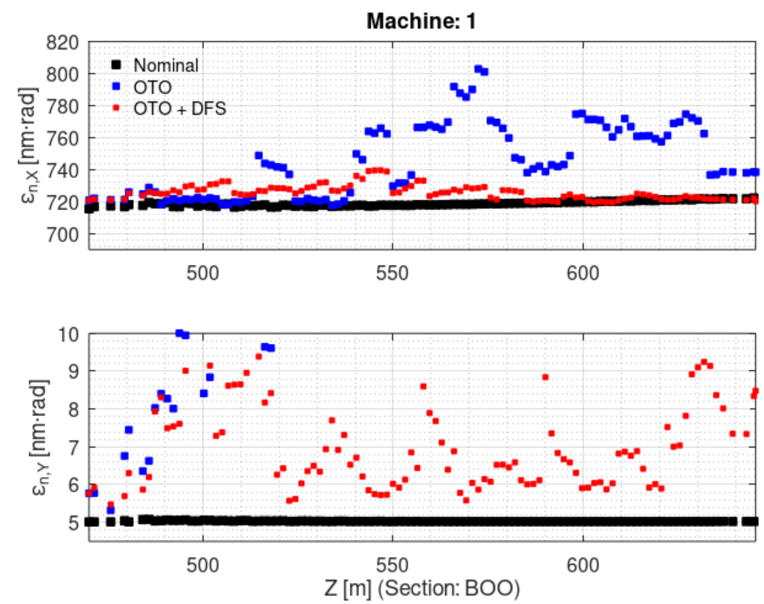

**Large acceptance for DR: [-1.8°, +3.5°]**

# Alternative booster linac: X-band

- **BBA** study is still **in progress**, which seems **quite difficult** compared with the baseline option (L-band BL)
- Possible **solutions** that would help: reduce a bit the **imperfections**, better **matching** sections, optimise **BBA** parameters and methods, reduce **FODO** length, reduce **bunch length** (complicated w/ significant non-linear effects), use **C-band**, etc.




Baseline (L-band BL)




Alternative (X-band BL)

# Conclusions

- CLIC **RTML** studied and optimised, for **$e^-$** ( **$e^+$** study will follow, which is similar and easier), at **380 GeV** stage, for the **drive-beam based** option.
- Some **remaining tough problems** in the RTML are finally **solved**, by reoptimising the bunch compressors, matching sections and the BBA methods
  - **BC2** RF structure **same with ML** now, with **aperture and expected costs reduced significantly**
  - **Bunch phase shift** effect at ML also minimised with **large acceptance for the DR**
  - Conservative **static imperfections** considered and studied**. Emittance budget** achieved with **91%** good machines **after BBA** corrections
  - **Jitter amplification** due to wakefield also studied and found to be **negligible**
- **Baseline** design of RTML (L-band BL) is almost (to be improved a bit) **finished**. Results are already satisfied and **ready for documentation**
- **Alternative option of BL** using **X-band** (same with ML) instead of L-band is designed, with BC1 & BC2 also redesigned shows good nominal results (perfect machine). **BBA** study seems difficult but **still in progress**
- **Next steps**
  - **BBA** results for **L-band** BL **can be improved.** For **X-band** BL is **in progress** (try also **C-band** if BBA doesn't work)
  - Try **larger (more conservative) errors** (e.g. 30 µm → **100 µm** position error in some sections, such as **LTL**)
  - **Beam loading** study (to cooperate with *J. Olivares, P. Wang, A. Grudiev* from CERN)
  - Alternative options that can be done and discussed:
    - 380 GeV → 3 TeV, Drive-beam based → Klystron based, Old DR → New DR (low emittance), etc.

# Acknowledgements

**Thanks very much for your attention!**

We thank C. Gohil, Y. Han and X. Liu for their contributions to previous development of the simulation framework.

We also thank J. Olivares, P. Wang, A. Grudiev, D. Schulte, Y. Papaphilippou and H. Bartosik for the helpful discussions.

# Backup

# Baseline definition

- **<u>Baseline</u>** configuration (baseline is studied and presented, unless otherwise specified):
  - Energy stage of collison: **380 GeV**
  - Main linac mode: **drive-beam based** acceleration
  - Old damping ring design assumed
  - Booster linac: L-band structure
- **Alternative** configurations that can be studied (beam parameters, requirements, RF structures and emittance budgets are all different from baseline)
  - Energy stages: 1.5 TeV & **3 TeV** energy stages (to be studied)
  - Main linac mode: **klystron based** acceleration (to be studied)
  - A **new damping ring design** proposed in 2019, which has much lower horizontal emittances, but higher energy spread, tighter emittance budgets, more difficult RTML design and larger beam-beam effects in BDS, etc. (to be discussed and studied)
  - Booster linac: X-band (being studied)

# Beam parameters: alternatives

- Collection of previous beam parameters (so many versions):

| | RTML parameters | Input $e^-$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 380 GeV (or 500 GeV) | | | | 3 TeV | | | |
| | | $\sigma_z$ [um] | $\sigma_E$ [%] | $\varepsilon_X$ [nm] | $\varepsilon_Y$ [nm] | $\sigma_z$ [um] | $\sigma_E$ [%] | $\varepsilon_X$ [nm] | $\varepsilon_Y$ [nm] |
| | **F. Stulle, LINAC paper (2010)** | | | | | 1600 | 0.13 | 500 | 5 |
| | **CLIC CDR (2012) Sec 3.2, 1 GHz DR** | 1800 | 0.1 | 456000 | 4.8 | 1800 | 0.12 | 500 | 5 |
| | **CLIC CDR (2012) Sec 3.2, 2 GHz DR** | 1600 | 0.1 | 472000 | 4.8 | 1800 | 0.12 | 500 | 5 |
| | **CLIC CDR (2012) Sec 3.3** | 1800 | 0.12 | 1800 | 5 | 1800 | 0.12 | 500 | 5 |
| | **CLIC update report (2016)** | | | | | | | | |
| | **Y. Han, IPAC papers (2015,2016,2017)** | | | 700 | 5 | | | 500 | 5 |
| | **Y. Han, JINST paper (2017)** | | | | | 1800 | | 500 | 5 |
| | **CLIC PIP report (2018) Sec 2.3, 2 GHz DR, for $N_b = 4.1\times10^9$** | | | | | | | 535.9 | 6.5 |
| **Drive-beam based** | **CLIC PIP report (2018) Sec 2.4** | 1800 | | 700 | 5 | | | | |
| | **CLIC PIP report (2018) Sec 8.7, 2 GHz DR, Uniform DR w/ IBS, for $N_b = 5.7\times10^9$** | 1500 | 0.11 | 478.9 | 5 | | | | |
| | **CLIC PIP report (2018) Sec 8.7, 2 GHz DR, Traperzium DR w/ IBS, for $N_b = 5.7\times10^9$** | 1300 | 0.13 | 535.9 | 6.5 | | | | |
| | **D. Schulte Academic Training slides (2018)** | 1600 | | 700 | 5 | | | | |
| | **S. Papadopoulou, PRAB paper (2019), Uniform original DR w/ IBS, for $N_b = 4.1\times10^9$** | | | | | 1500 | 0.11 | 478.9 | 5 |
| | **S. Papadopoulou, PRAB paper (2019), Uniform alternative DR w/ IBS, for $N_b = 4.1\times10^9$** | | | | | 1600 | 0.15 | 648.7 | 4.5 |
| (new DR design) | **S. Papadopoulou, PRAB paper (2019), Traperzium DR w/ IBS, for $N_b = 4.1\times10^9$** | | | | | 1600 | 0.15 | 434.7 | 4.2 |
| | **S. Papadopoulou, PRAB paper (2019), Traperzium DR w/ IBS, for $N_b = 5.7\times10^9$** | 1600 | 0.15 | 472.0 | 4.6 | | | | |
| | **C. Gohil, PhD Thesis (2020)** | 1800 | 0.11 | 700 | 5 | | | | |
| **Klystron based** | **CLIC PIP report (2018)** | | | | | | | | |
| | **O. Brunner, CLIC-Note-1174 (2022)** | | | < 500 | < 5 | | | | |

# Beam parameters: alternatives

- Beam parameters to be used:

| | Parameter (optimised) | Symbol | Unit | 380 GeV | | | | 3 TeV | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | DBA | | KBA | | DBA | |
| | | | | Old DR | New DR | Old DR | New DR | Old DR | New DR |
| | | | | e- / e+ | e- / e+ | e- / e+ | e- / e+ | e- / e+ | e- / e+ |
| Initial beam at entrance of RTML | Number of bunches per pulse | $n_b$ | | 352 | | 485 | | 312 | |
| | Number of particles per bunch | $n_p$ | $10^9$ | 5.2 | | 3.87 | | 3.7 | |
| | Bunch charge | $C_b$ | nC | 0.83 | | 0.62 | | 0.59 | |
| | Bunch length | $\sigma_z$ | um | **1800** | 1600 | 1800 | 1600 | 1800 | 1600 |
| | Energy spread | $\sigma_E$ | % | **0.12** | 0.15 | 0.12 | 0.15 | 0.12 | 0.15 |
| | Normalised horizontal emittance | $\varepsilon_{n,x}$ | nm | **700** | 472 | 500 | 434.7 | 500 | 434.7 |
| | Normalised vertical emittance | $\varepsilon_{n,y}$ | nm | **5** | 4.6 | 5 | 4.2 | 5 | 4.2 |
| Requirement at exit of RTML (nominal, perfect machine) | Bunch length | $\sigma_z$ | um | **70** | 70 | 70 | 70 | 44 | 44 |
| | Energy spread (maximum) | $\sigma_E$ | % | **1.7** | 1.7 | 1.7 | 1.7 | 2.0 | 2.0 |
| | Normalised horizontal emittance | $\varepsilon_{n,x}$ | nm | **800** | | | | | |
| | Normalised vertical emittance | $\varepsilon_{n,y}$ | nm | **6** | | | | | |
| Emittance budget at exit of RTML (w/ static imperfections) | Normalised horizontal emittance | $\varepsilon_{n,x}$ | nm | **820** | | | | | |
| | Normalised vertical emittance | $\varepsilon_{n,y}$ | nm | **8** | | | | | |
| Emittance budget at exit of RTML (w/ static & dynamic imperfections) | Normalised horizontal emittance | $\varepsilon_{n,x}$ | nm | **850** | | 600? | | 600? | |
| | Normalised vertical emittance | $\varepsilon_{n,y}$ | nm | **10** | | 10 | | 10 | |

- The **baseline option** is: 380 GeV + drive-beam based acceleration (DBA) + old DR, as it was used in most previous RTML and ML studies, and has the lowest energy spread (which makes the optimisation much easier with much lower voltage or cost), and the emittance budget is clear and much easier to achieve, and beam-beam effect in BDS is smaller and was well studied, etc. But the other options will probably also be studied

# Optimisation of gradients

- Scan of the number of RF units is performed to minimise the cost

Table 9: Scan of number of modulators for BC1 RF system for the baseline option. Symbol conventions: $N_{RF}$: total number of modulators, $N_K$: total number of klystrons, $N_S$: total number of structures, $G$: average loaded gradient, $C$: total cost.

| $N_{RF}$ | $N_K$ | $N_S$ | $G$ [MV/m] | $C$ [MCHF] |
|---|---|---|---|---|
| 4 | 8 | 16 | 18.770 | 3.60 |
| 5 | 10 | 20 | 15.016 | 4.50 |
| 6 | 12 | 24 | 12.513 | 5.40 |
| 7 | 14 | 28 | 10.725 | 6.30 |
| 8 | 16 | 32 | 9.385 | 7.20 |

Table 10: Scan of number of modulators for BC2 RF system for the baseline option. Symbol conventions: $N_{RF}$: total number of modulators, $N_K$: total number of klystrons, $N_S$: total number of structures, $G$: average loaded gradient, $C$: total cost.

| $N_{RF}$ | $N_K$ | $N_S$ | $G$ [MV/m] | $C$ [MCHF] |
|---|---|---|---|---|
| 4 | 8 | 32 | 74.916 | 2.84 |
| 5 | 10 | 40 | 59.933 | 3.55 |
| 6 | 12 | 48 | 49.944 | 4.26 |
| 7 | 14 | 56 | 42.809 | 4.97 |
| 8 | 16 | 64 | 37.458 | 5.68 |

Table 11: Scan of number of modulators for booster linac RF system for the baseline option. Symbol conventions: $N_{RF}$: total number of modulators, $N_K$: total number of klystrons, $N_S$: total number of structures, $G$: average loaded gradient, $C$: total cost.

| $N_{RF}$ | $N_K$ | $N_S$ | $G$ [MV/m] | $C$ [MCHF] |
|---|---|---|---|---|
| 68 | 136 | 272 | 15.089 | 61.20 |
| 69 | 138 | 276 | 14.870 | 62.10 |
| 70 | 140 | 280 | 14.658 | 63.00 |
| 71 | 142 | 284 | 14.452 | 63.90 |
| 72 | 144 | 288 | 14.251 | 64.80 |

Table 12: Scan of number of modulators for BC1 RF system for the alternative option. Symbol conventions: $N_{RF}$: total number of modulators, $N_K$: total number of klystrons, $N_S$: total number of structures, $G$: average loaded gradient, $C$: total cost.

| $N_{RF}$ | $N_K$ | $N_S$ | $G$ [MV/m] | $C$ [MCHF] |
|---|---|---|---|---|
| 1 | 2 | 64 | 4.692 | 5.40 |
| 2 | 4 | 32 | 9.385 | 3.60 |
| 3 | 6 | 24 | 12.513 | 3.60 |
| 4 | 8 | 16 | 18.770 | 3.60 |
| 5 | 10 | 20 | 15.016 | 4.50 |
| 6 | 12 | 12 | 25.026 | 4.50 |
| 7 | 14 | 14 | 21.451 | 5.25 |
| 8 | 16 | 8 | 37.539 | 5.40 |

Table 13: Scan of number of modulators for BC2 RF system for the alternative option. Symbol conventions: $N_{RF}$: total number of modulators, $N_K$: total number of klystrons, $N_S$: total number of structures, $G$: average loaded gradient, $C$: total cost.

| $N_{RF}$ | $N_K$ | $N_S$ | $G$ [MV/m] | $C$ [MCHF] |
|---|---|---|---|---|
| 1 | 2 | 128 | 18.729 | 2.36 |
| 2 | 4 | 64 | 37.458 | 2.08 |
| 3 | 6 | 48 | 49.944 | 2.46 |
| 4 | 8 | 32 | 74.916 | 2.84 |
| 5 | 10 | 40 | 59.933 | 3.55 |
| 6 | 12 | 48 | 49.944 | 4.26 |
| 7 | 14 | 28 | 85.618 | 4.58 |
| 8 | 16 | 32 | 74.916 | 5.24 |

Table 14: Scan of number of modulators for booster linac RF system for the alternative option. Symbol conventions: $N_{RF}$: total number of modulators, $N_K$: total number of klystrons, $N_S$: total number of structures, $G$: average loaded gradient, $C$: total cost.

| $N_{RF}$ | $N_K$ | $N_S$ | $G$ [MV/m] | $C$ [MCHF] |
|---|---|---|---|---|
| 67 | 134 | 536 | 7.657 | 80.40 |
| 68 | 136 | 272 | 15.089 | 61.20 |
| 69 | 138 | 276 | 14.870 | 62.10 |
| 70 | 140 | 280 | 14.658 | 63.00 |
| 71 | 142 | 284 | 14.452 | 63.90 |
| 72 | 144 | 288 | 14.251 | 64.80 |
| 73 | 146 | 292 | 14.056 | 65.70 |