Optimisation of the CLIC RTML

Y. Zhao, A. Latina, CERN

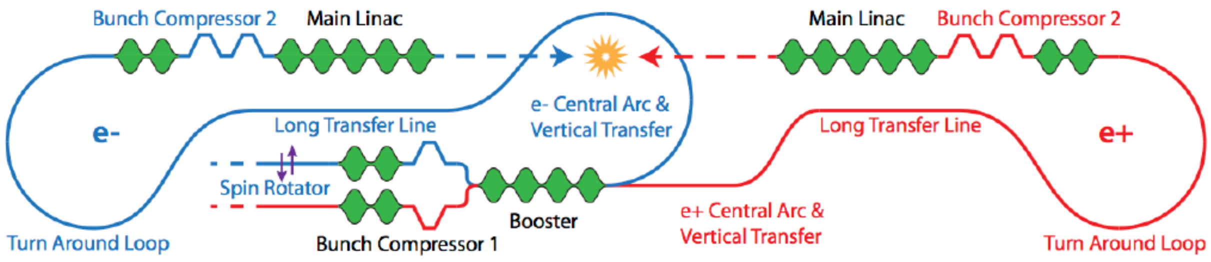
CLIC Mini Workshop @ CERN

11-13 December 2023

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)



Schematic layout of the CLIC RTML.

- Spin rotator (SR), used only for the e^- beam, aimed at a 90° 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 with the BC1 and is common to the e^- and e^+ beams. The beam will be accelerated from 2.86 GeV to 9 GeV in the BL.
- Central arc (CA) and vertical transfer line (VTL), that transport the beam to the underground main linac tunnel.
- Long transfer line (LTL), that transports the beam to the far end of the main linac.
- Turn around loop (TAL), that bends the beam by 180° and direct the beam towards the interaction point (IP).
- Bunch compressor 2 (BC2), composed of 12 GHz RF cavities working at zero acceleration mode and two chicanes.

Baseline definition

- **Baseline** 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

- **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		5.2×10^9
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		5.2×10^9
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 of the study

- In previous studies, there are some remaining problems that need to be solved:
  - In the CDR published 2012, RTML was well designed, but the imperfections were not considered. 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/λ = 0.218) would be problematic with break-down, huge power consumption and cost
  - In a later study (not finished and 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 emittance budgets were not achieved. Besides, the **aperture** (a_0 = 4.41 mm, a_0/λ = 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**
  - 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: V_1, V_2
  - Bending **angles** of BC1 and BC2 chicanes: θ_1, θ_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**: σ_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**
  - ✓ Final results will be shown after the gradient optimisation
  - ✓ **Total voltage is 47% lower than CDR**

Parameter	Symbol	Unit	BC1	BC2
Total RF voltage	V	MV	450	650
Bending angle	θ	$^\circ$	3.95	1.52

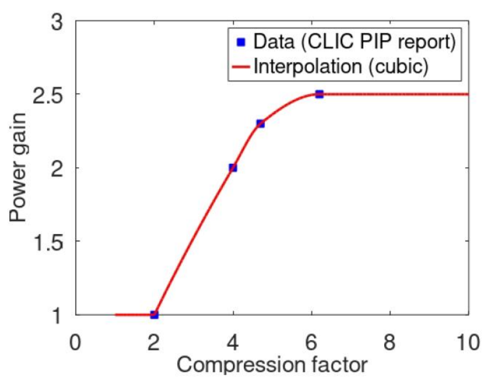
Optimisation of gradients

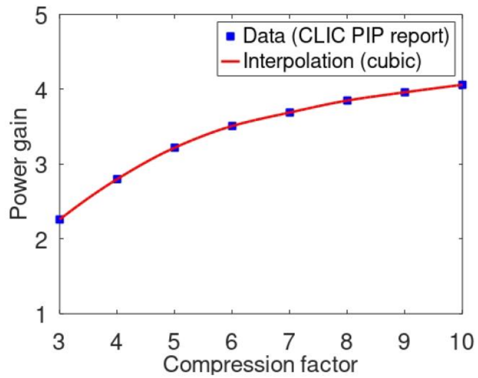
RF system assumptions in optimisation:

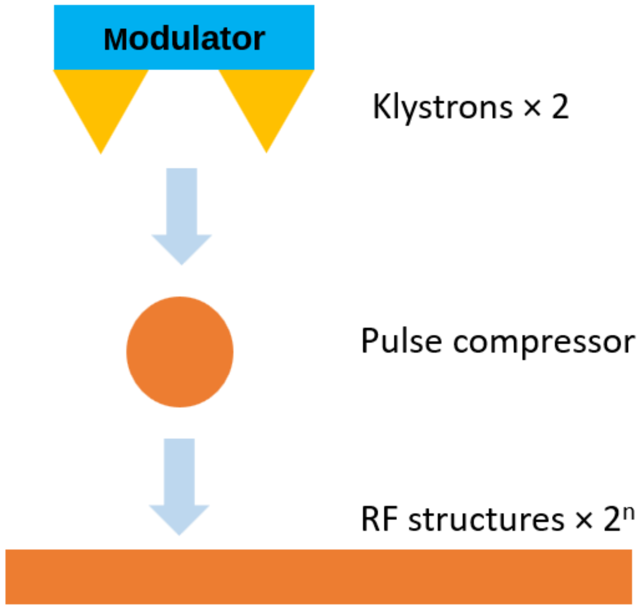
- Klystrons

Parameter	Unit	BC1	BC2
Output power	MW	50	51.4
Pulse length	μs	8	2

- Pulse compressors







Schematic layout of a RF unit

- Total RF transmission efficiency: 90%
- Cost estimation:
  - Klystron: 300 kCHF each
  - RF structure: 50 kCHF per meter
  - Other costs not considered

Optimisation of gradients

- *CLICopti* is used to estimate RF parameters (peak power, pulse length, breakdown, etc.)
  - Beam loading effects to be studied (though we think cost estimation is not affected at φ = 90˚)
- A scan of the number of RF units is performed to minimise the cost

Scan for BC1

N_{RF}	N_K	N_S	G [MV/m]	C [MCHF]
1	2	128	2.3	10.2
2	4	64	4.7	6.0
3	6	48	6.3	5.4
4	8	32	9.4	4.8
5	10	20	15.0	4.5
6	12	24	12.5	5.4

Scan for BC2

N_{RF}	N_K	N_S	G [MV/m]	C [MCHF]
1	2	128	18.5	2.36
2	4	64	36.9	2.08
3	6	48	49.2	2.46
4	8	32	73.9	2.84
5	10	40	59.1	3.55

N_{RF}: total number of RF units
N_K: total number of klystrons
N_S: total number of RF structures
G: RF gradient
C: total cost of klystrons and structures

- **Optimised parameters**
  - ✓ **Total cost in BC1 is same with CDR**
  - ✓ **Total cost in BC2 is 70% lower than CDR**

Parameter	Unit	BC1	BC2
Number of klystrons		10	4
Number of RF structures		20	64
RF gradient	MV/m	15	36.932

Final results after optimisation

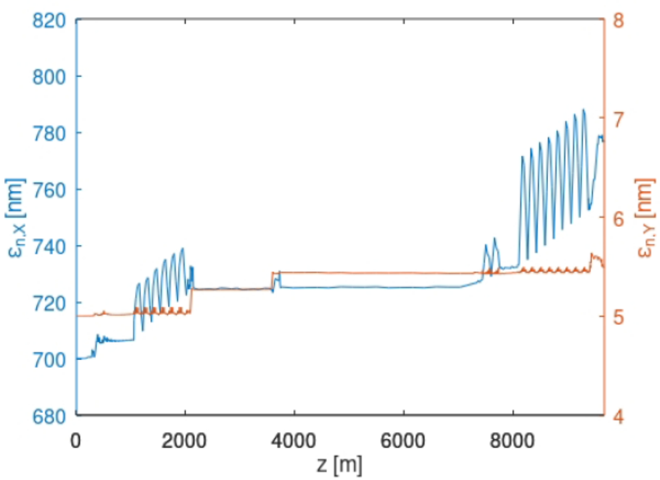
- Results at the end of the RTML:
  - Without imperfections (**perfect machine** by design)
  - BC1 and BC2 for e^+ are the same with e^-

e^- beam

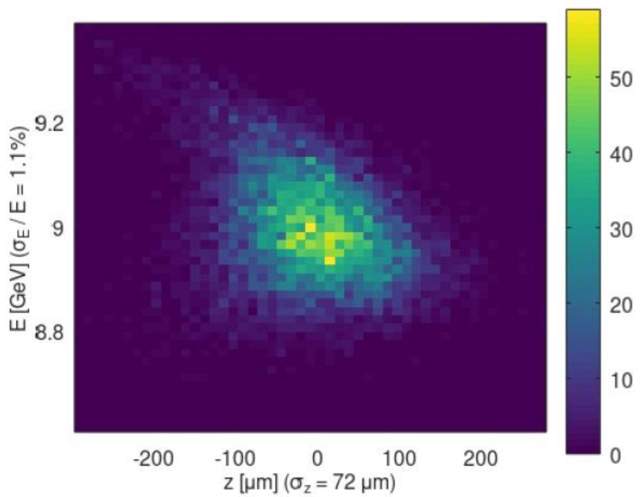
Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	71.9
Energy spread	σ_E/E	%	1.1
Horizontal normalized emittance	$\epsilon_{n,x}$	nm	776.5
Vertical normalized emittance	$\epsilon_{n,y}$	nm	5.5

e^+ beam

Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	71.0
Energy spread	σ_E/E	%	1.1
Horizontal normalized emittance	$\epsilon_{n,x}$	nm	763.0
Vertical normalized emittance	$\epsilon_{n,y}$	nm	5.1



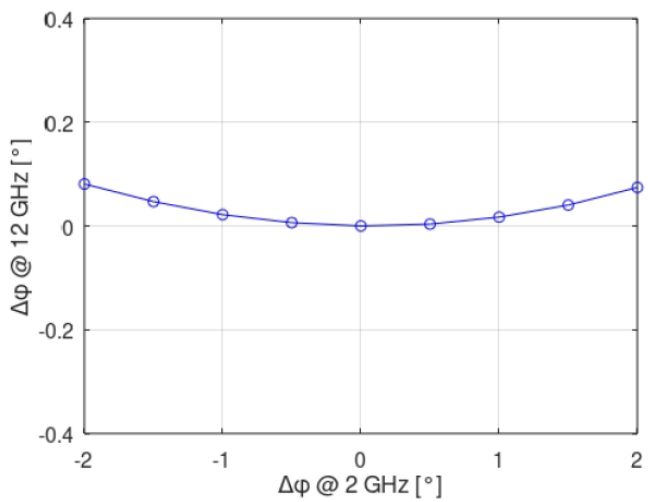
Emittance growth along RTML for the e^- beam



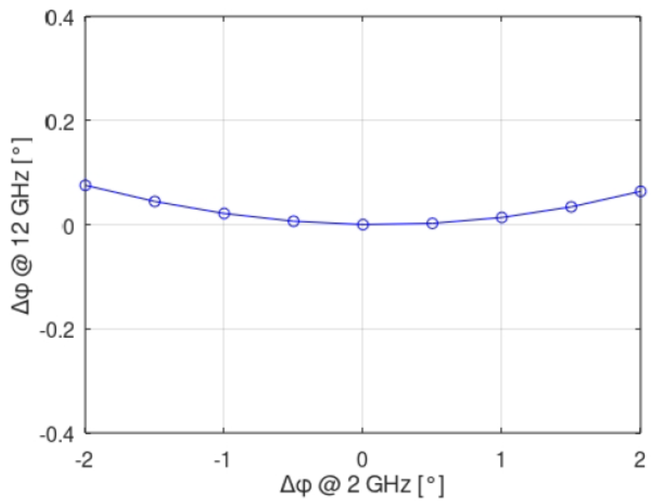
Longitudinal phase space at the end of the RTML for the e^- beam

Final results after optimisation

- The **bunch phase shift effect** (between the first and the last bunches in the train) from the **damping ring** (2 GHz) is also considered in the BC1 and BC2 optimisation. **Very good performance** is achieved at the entrance of the **main linac** (12 GHz):
  - Maximum acceptance for the damping ring
  - Minimum effect at the main linac
  - ✓ For example: the tolerance is ±0.1° at the entrance of the main linac, corresponding to about ±2.2° acceptance at the end of the damping ring (doing a fit in the plot below), which is much higher (safer) than the expected ±1°



e⁻ beam



e⁺ beam

Static imperfections and BBA corrections

- **Static imperfections** considered in the RTML

Imperfection	Unit	CA & TAL	Other sections
RMS positron error	μm	30	100
RMS tilt error	μrad	30	100
RMS roll error	μrad	30	100
Quadrupole strength		10^{-4}	10^{-3}
Other magnet strength		10^{-3}	
BPM resolution	μm	1	
Magnetic-center shift w/ strength		0.35 μm / 5%	

- **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 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

New: test beam energy difference of 2% (megnetic strength scaling everywhere)

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

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

ε^i: initial emittance at the entrance of the RTML

ε^m: measured emittance (1% RMS uncertainty assumed)

ε^s: emittance budget for static imperfections

Static imperfections and BBA corrections

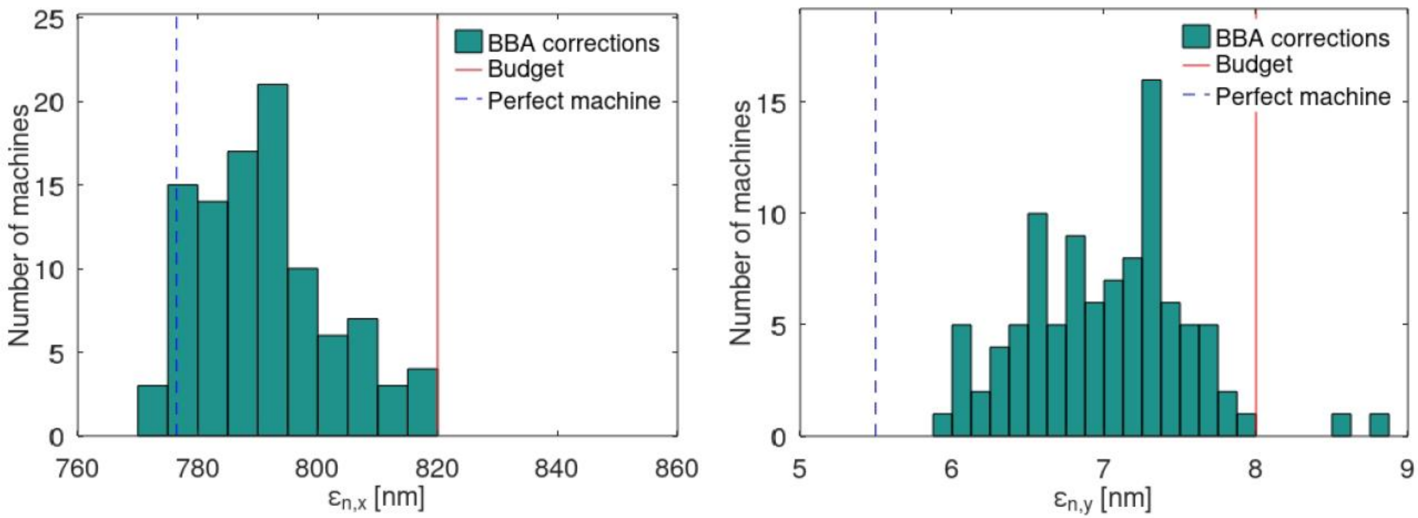
- BBA correction **procedure**

1. OTO + DFS: SR—BC1—BL—CA—VTL—LTL
   - A small overlap between the neighboring sections
   - Each section is split into several bins with the same number of quadrupoles per bin. A 20% overlap between neighboring bins
   - In each bin, correction is performed for a few iterations
   - **New:** In the LTL section, if OTO only correction gives better performance (measured emittances) than OTO + DFS, the DFS correction is then not applied
2. SBET: CA—VTL—LTL
   - The first 5 sextupoles of the CA section are used
3. OTO + DFS: TAL—BC2
   - The TAL section is split into 2 subsections, TAL1 and TAL2, but with the same BBA parameters
   - Similar corrections with step 1
4. SBET: TAL—BC2
   - The first 5 sextupoles of the TAL section are used

✓ The BBA parameters (β_0, β_1, ω_d, N_{bins}, $N_{iterations}$, etc.) are also reoptimised

Static imperfections and BBA corrections

- Results after BBA corrections
  - Study performed only for the **e⁻** beam (since the e⁺ beam is expected to have better performance)
  - 100 randomly misaligned machines (with only static imperfections) simulated

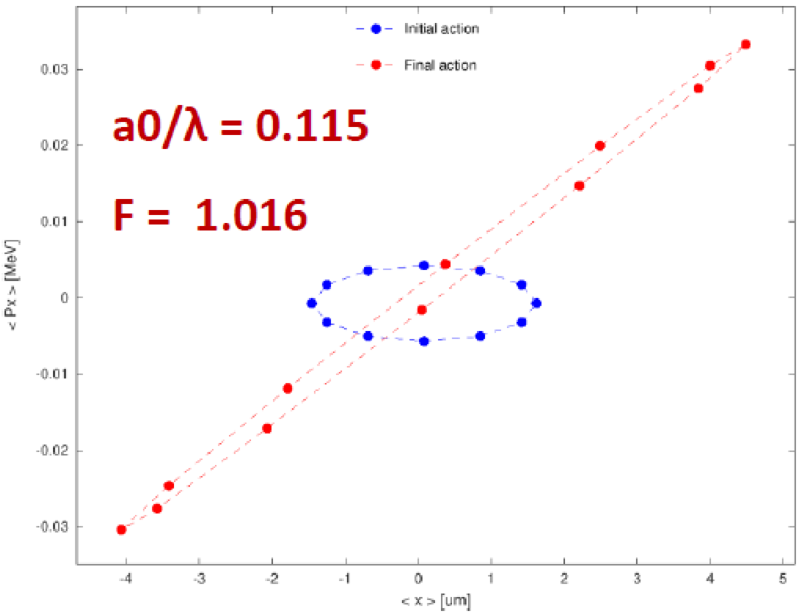


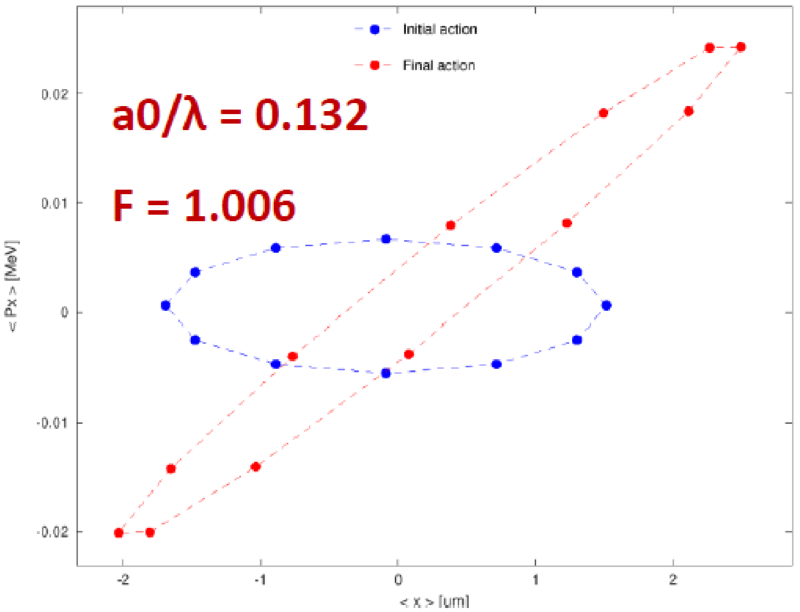
Horizontal: 100% good machines   Vertical: 97% good machines

✓ **Good results**: **97%** machines after corrections are below the emittance budgets, which meets very well the **90%** requirement

Jitter amplifications

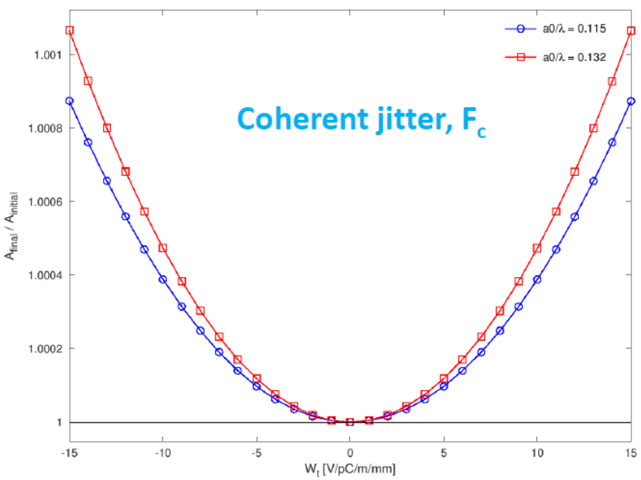
- Short-range wakefield
  - Amplification factor (F = final action / initial action) of BC2 RF structures for short range wakefield (simulated with RF Track)
  - The jitter effect is **expected to be small**, though the **plots are from old studies** (old lattice before optimisation & CLIC-K structure)

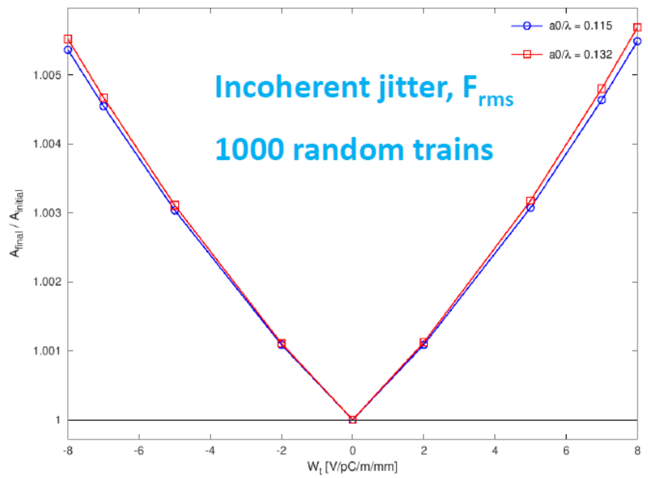




Jitter amplifications

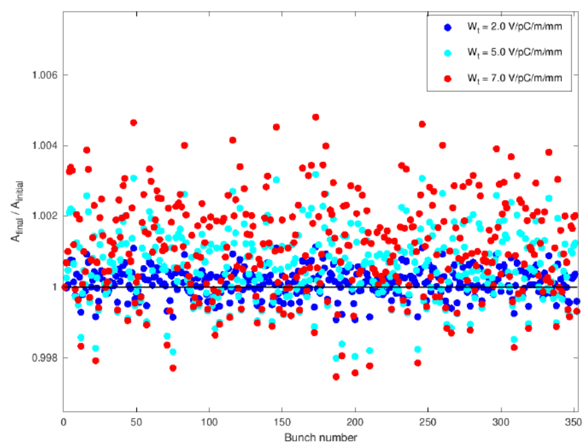
- Long-range wakefield
  - Amplification factor of BC2 RF structures for long range wakefield (simulated with RF Track), as a function of the transverse kick (on the next bunch). Always looking at the worst bunch
  - The effect is **expected to be small**, though the **plots are from old studies** (old lattice before optimisation & CLIC-K structure)





Incoherent jitter

a0_n = 0.132



Alternative booster linac with X-band

- **Motivation:** the baseline **booster linac** will use 272 CLIC L-band (L = 1.5 m, G ≈ 15 MV/m) structures. If X-band structures (the TD-31, same with BC2 and main linac) can be used, the linac will be shorter and more power efficient
- Possible **solutions**:
  - X-band linac + Ka-band lineariser
    - Emittance growth seems very large and BBA corrections might be very difficult
    - BC1 and BC2 also need reoptimisation which might be bit complicated (especially regarding the bunch length, the cost, the bunch phase shift effect, etc.)
  - Extra bunch length compression (BC) + X-band linac + energy compressor (EC)
    - Phase tuning or sextupoles will be needed to compensate non-linear phase slip effect
    - Emittance growth due to ISR & CSR effects might be quite large
- Too early to draw any conclusions. **Studies are still on-going**

Conclusions

- The CLIC RTML is studied and optimised, for both **e$^-$** and **e$^+$** beams, 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 and the BBA corrections (original RF structure design is kept)
- The **cost** in BC2 is also **minimised** and is reduced by 70% compared with the design in CDR and PIP report
- The **bunch phase shift** effect from the damping ring to the main linac is also **minimised** and **very good performance** is achieved
- Static imperfections are studied. **Emittance budgets well achieved** after the new BBA corrections with 97% good machines
- Next steps
  - Alternative X-band booster linac option (in progress)
  - Beam loading study (to cooperate with J. Olivares, P. Wang, A. Grudiev from CERN)
  - Jitter studies (plots to be updated)
  - Alternative studies that can be done:
    - 380 GeV → 3 TeV
    - Drive-beam based → Klystron based
    - Old damping ring → New damping ring

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

Beam parameters: alternatives

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

	RTML parameters	Input e^-							
		380 GeV (or 500 GeV)				3 TeV			
		σ_z [um]	σ_E [%]	ε_X [nm]	ε_Y [nm]	σ_z [um]	σ_E [%]	ε_X [nm]	ε_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	σ_z	um	**1800**		1600		1800		1600		1800		1600	
	Energy spread	σ_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	σ_z	um	**70**		70		70		70		44		44	
	Energy spread (maximum)	σ_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

RF parameters: alternatives

- RF parameters (original design) 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	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			
BC1	RF structure type			**CLIC L-band**											
	RF structure length	L	m	1.5											
	RF frequency	f	GHz	11.994											
	Phase advance per cell		°	120											
	Number of cells			30											
	Iris radius, a1		mm	20											
	Iris radius, a2		mm	14											
	Iris thickness, d1		mm	8											
	Iris thickness, d2		mm	8											
Booster linac	RF structure type			same with BC1											
	Number of RF structures	N		272											
	RF average gradient	G	MV/m	15.049											
BC2	RF structure type			**TD-31**				**CLIC-K**				**CLIC-G***			
	RF structure length	L	m	0.275				0.23				0.23			
	RF frequency	f	GHz	11.994											
	Phase advance per cell		°	120				120				120			
	Number of cells			33				28				28			
	Iris radius, a1		mm	4.062				3.6242				3.15			
	Iris radius, a2		mm	2.600				2.2496				2.35			
	Iris thickness, d1		mm	2.525				2.0829				1.67			
	Iris thickness, d2		mm	1.433				1.1164				1.00			

- **The baseline BC2 RF structure is assumed to be the same with the main linac**

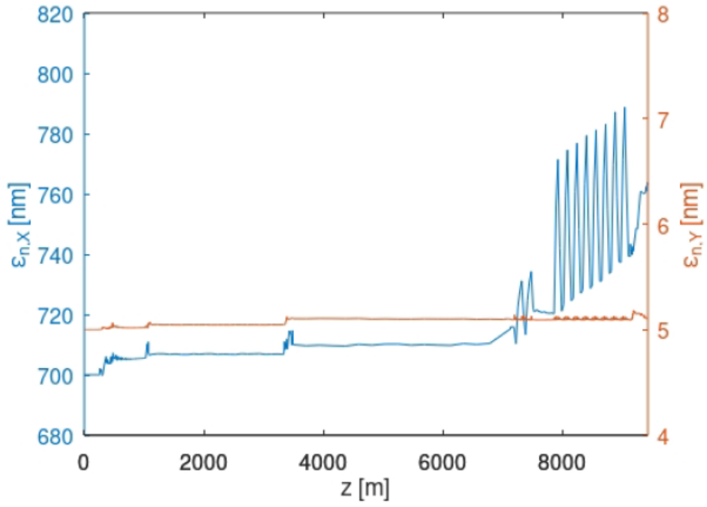
Optimisation of gradients

- Comparison of RF configurations and expected costs for BC1 and BC2 with previous studies

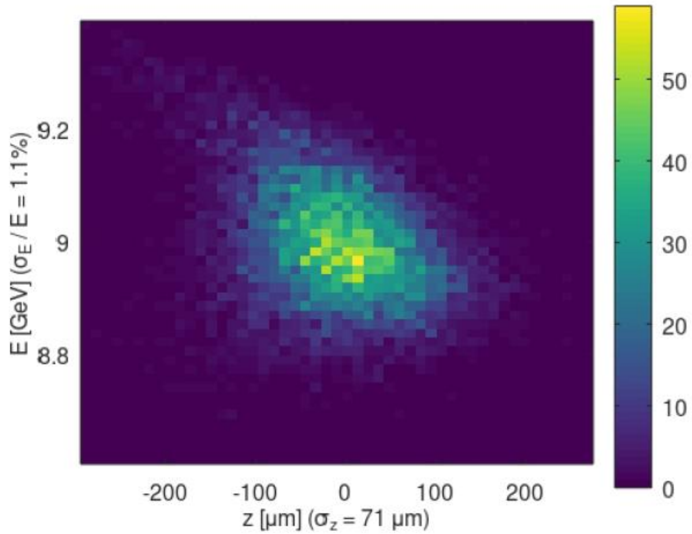
Parameter	Unit	CDR	Optimized
BC1 number of klystrons		10	10
BC1 number of RF structures		20	20
BC1 structure length	m	1.5	1.5
BC1 RF gradient	MV/m	13.3	15
BC1 RF cost	MCHF	4.5	4.5
BC2 number of klystrons		20	4
BC2 number of RF structures		78	64
BC2 structure length	m	0.230	0.275
BC2 RF gradient	MV/m	94	36.932
BC2 RF cost	MCHF	6.90	2.08

Final results after optimisation

- Results at the end of the RTML:
  - Without imperfections (**perfect machine** by design)
  - BC1 and BC2 for e^+ is very similar with e^-



Emittance growth along RTML for the **e^+** beam



Longitudinal phase space at the end of the RTML for the **e^+** beam