Optimisation of the CLIC RTML

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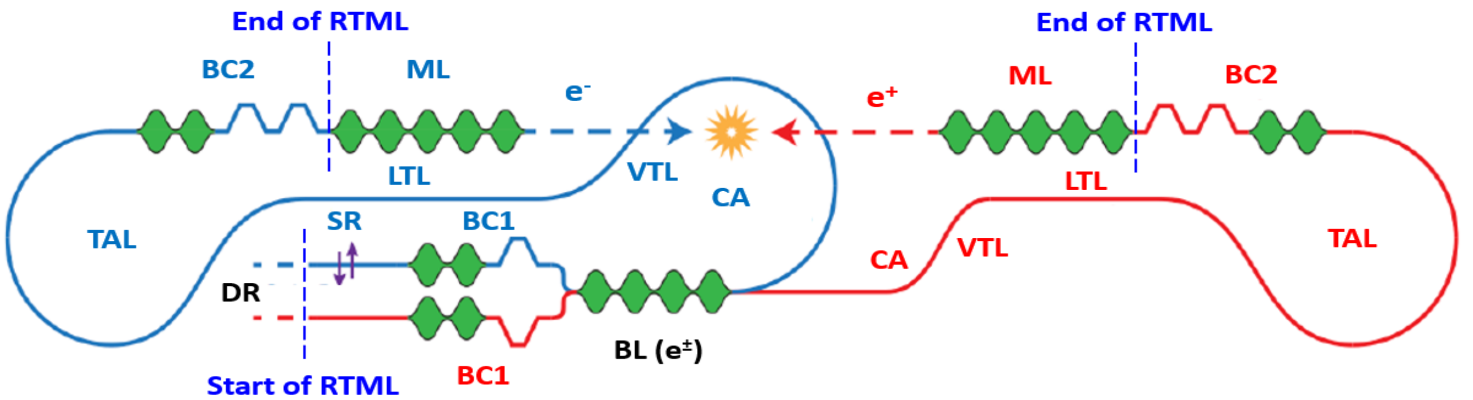
Outline

- 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		5.2×10^9
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

- 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/λ = 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/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 (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**: 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**
  - ✓ BC1 voltage is 12.5% higher than CDR
  - ✓ **BC2 voltage is 61.5% lower than CDR**
  - ✓ **Total BC1 & BC2 voltage is 47% lower**

Parameter	Symbol	Unit	BC1	BC2
Total RF voltage	V	MV	450	650
Bending angle	θ	°	3.95	1.55

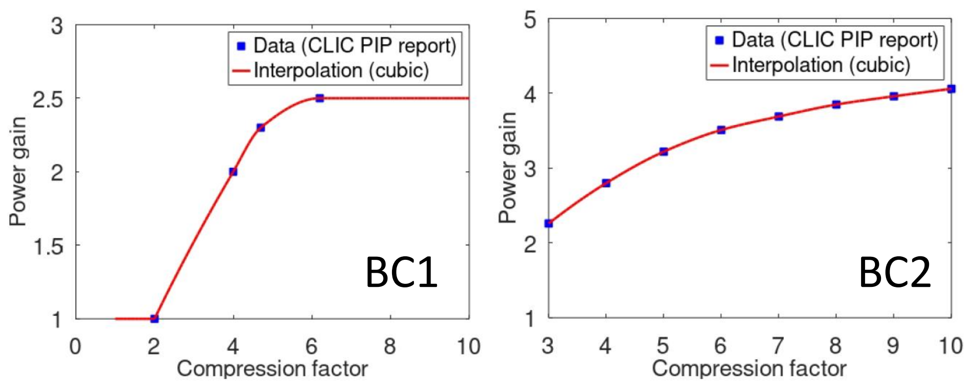
Optimisation of gradients

RF system assumptions in optimisation:

- Klystrons

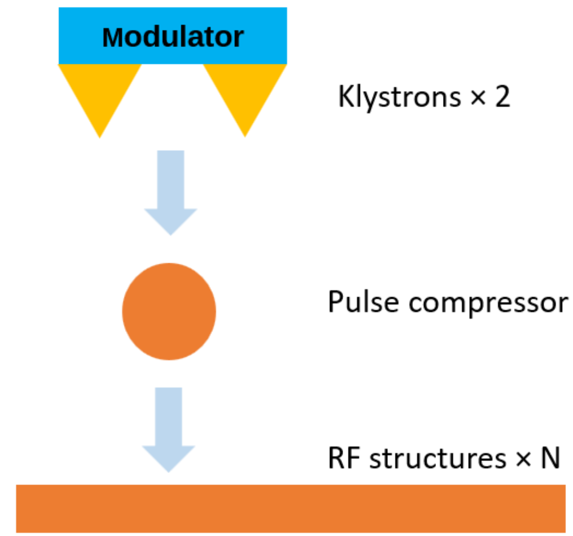
Parameter	Unit	L-band (BC1)	X-band (BC2)
Output power	MW	50	51.4
Pulse length	μs	8	2

- 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

- Cost assumptions in arbitrary unit (a.u.):
  - Klystron cost: 300 a.u. each
  - RF structure cost: 50 a.u. per meter

Optimisation of gradients

- *CLICopti* is used to estimate RF parameters (peak power, pulse length, breakdown, etc.)
    - Beam loading effect not considered for BC1, BC2 (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:

RF module options

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

Scan of BC2 structures (baseline option)

N_{RF}	N_K	N_S	G [MV/m]	C [a.u.]
4	8	32	74.916	2840
5	10	40	59.933	3550
6	12	48	49.944	4260
7	14	56	42.809	4970
8	16	64	37.458	5680

✓ **BC2 expected cost reduced by factors of 4.5 & 16.8 compared with CDR & PIP report!**

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

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	
BC1 RF cost	a.u.	4500 (3300)	4500	3600	
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
BC2 RF cost	a.u.	12900	47700	2840	2080
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	
BL RF cost	a.u.	62100		61200	

Final results after optimisation

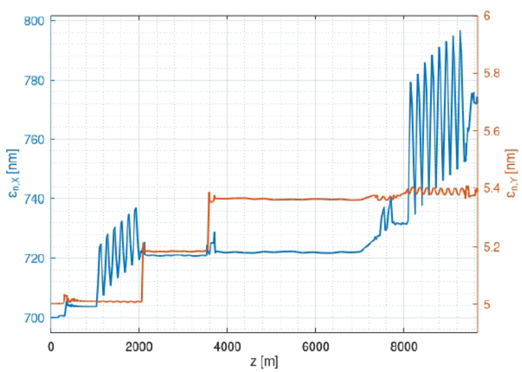
- Final results (e^- **beam**) at the end of the RTML (perfect machine):
  - CSR not simulated in CA & TAL by default (small impact but much longer time)
  - Optimised matching sections, **emittances growth reduced significantly** (**CDR, PIP $\varepsilon_{x,y}$: ~790 nm, ~5.8 nm**)

W/o CSR simulated in CA & TAL

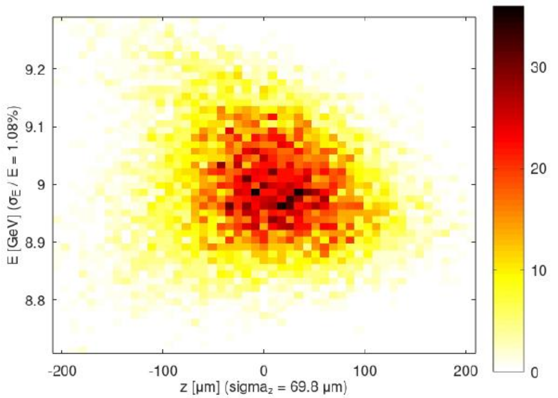
Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	69.8
Energy spread	σ_E/E	%	1.08
Horizontal normalised emittance	$\epsilon_{n,x}$	nm	772.2
Vertical normalised emittance	$\epsilon_{n,y}$	nm	5.39

W/ CSR simulated in all sections

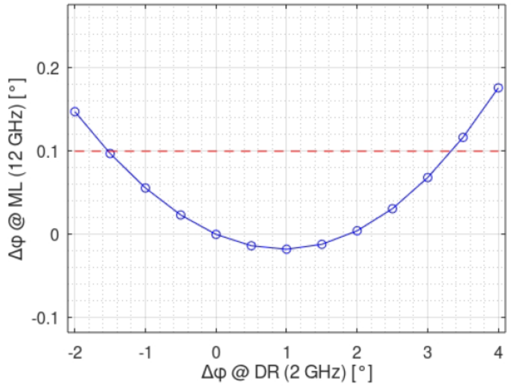
Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	70.4
Energy spread	σ_E/E	%	1.07
Horizontal normalised emittance	$\epsilon_{n,x}$	nm	773.8
Vertical normalised emittance	$\epsilon_{n,y}$	nm	5.40



Emittance growth along RTML



Longitudinal phase space at the end



Bunch phase shift effect

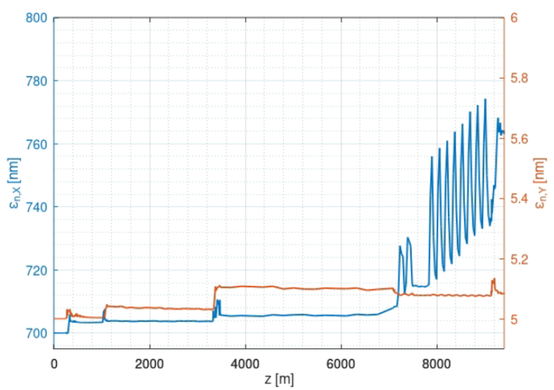
- **Bunch phase shift effect** from the DR (2 GHz) to the ML (12 GHz) minimised:
  - Assuming ±0.1° tolerance at main linac (ML), the corresponding **acceptance for DR improved significantly**: **[-1.53°, +3.34°]**, much better than the required ±1°

Final results after optimisation

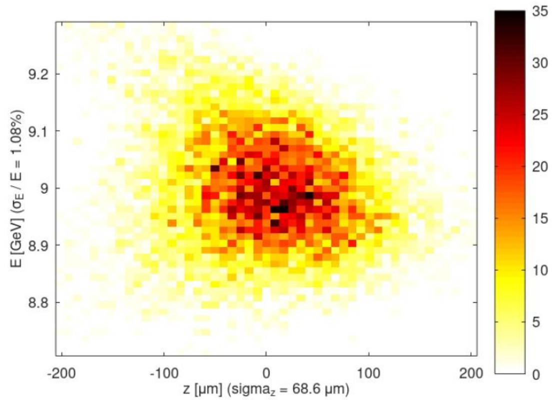
- Final results (**e^+ beam**) at the end of the RTML (perfect machine):

W/ CSR simulated in all sections

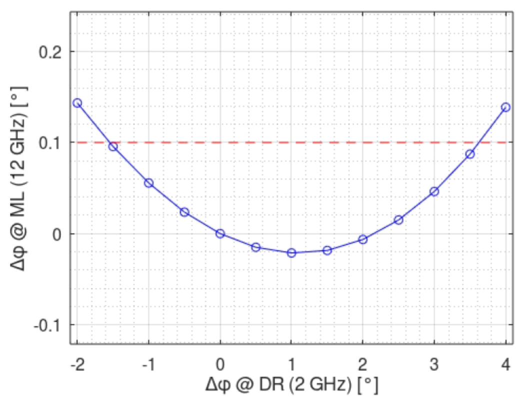
Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	68.6
Energy spread	σ_E/E	%	1.08
Horizontal normalised emittance	$\epsilon_{n,x}$	nm	763.1
Vertical normalised emittance	$\epsilon_{n,y}$	nm	5.08



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 main linac (ML), the corresponding **acceptance for DR improved significantly**: **[-1.55°, +3.63°]**, much better than the required ±1°

Static imperfections and BBA corrections

- Study performed for **e^- beam** (for e^+ beam it would be easier)
- **Imperfections** considered (**same with previous** studies)

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

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

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. ST—LTL: OTO + DFS
  2. CA—LTL: SBET
  3. TAL—BC2: OTO + DFS
  4. TAL—BC2: SBET

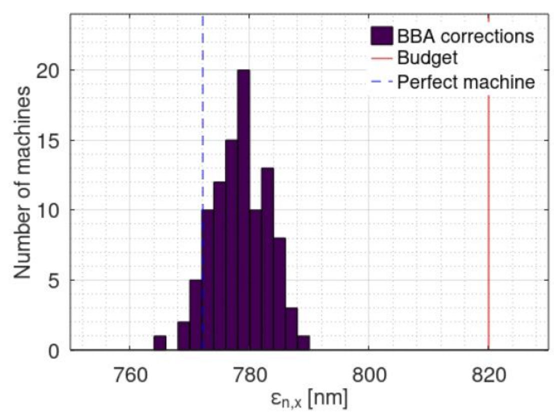
✓ Small overlap between sections
✓ Section split into bins with 20% overlap
✓ In each bin, correction in a few iterations
✓ DFS followed OTO after all bins in a section
✓ Always the first 5 sextupoles used in SBET
✓ TAL too long, split into 2 sections

- BBA parameters
  - simplified: same in all sections

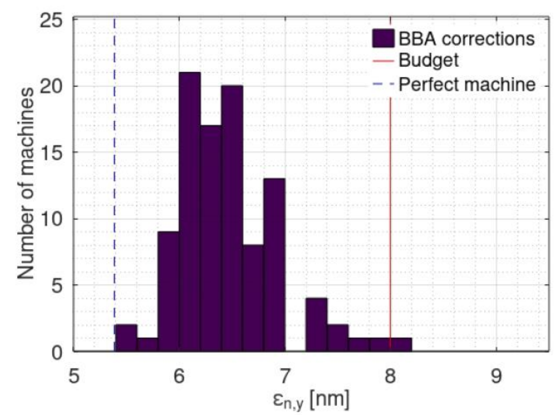
Parameter	Value
β_0 (OTO)	1
β_1 (DFS)	1
ω_d (DFS)	30
Number of quadrupoles per bin	40
Bin overlap	50%
Number of iterations (OTO)	3
Number of iterations (DFS)	3

- Results (100 random misaligned machines)
  - 99% good machines (required: ≥ 90%)

100% good in X

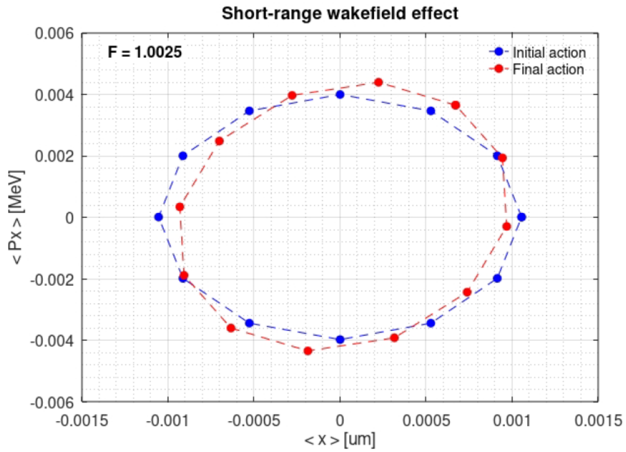


99% good in Y

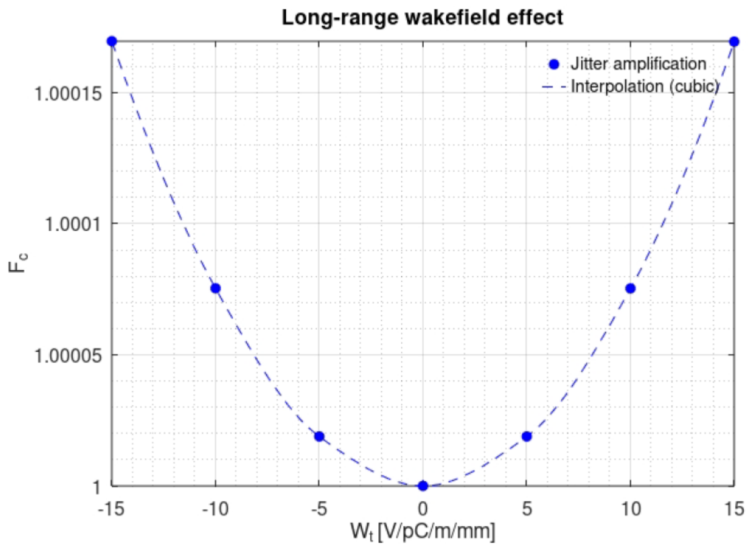


Jitter amplifications

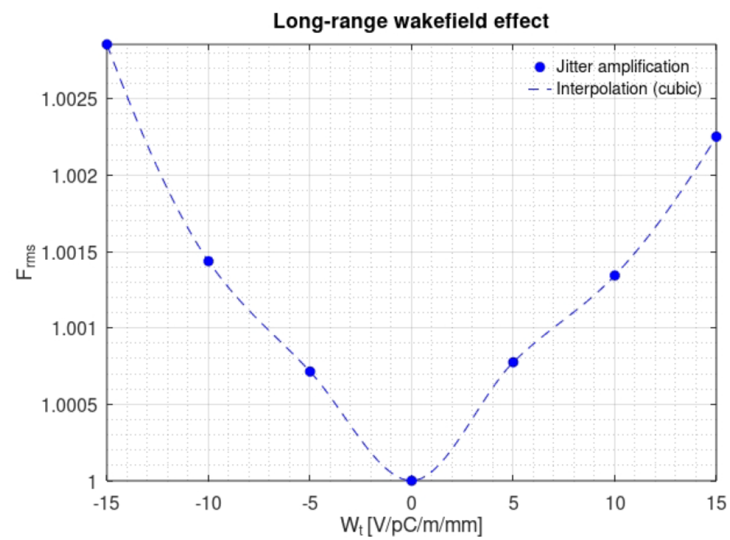
- Short-range wakefield



- Long-range wakefield (coherent)



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



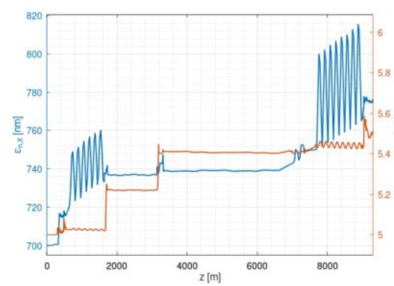
✓ Effects are all very small!

Alternatives for booster linac

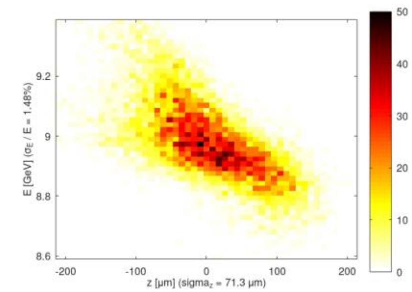
- X-band structure
  - Assuming the same structure (a_0 = 3.33 mm) with BC2 and main linac (ML)
  - Redesigned with an **input bunch length** of **~200 µm** (a good compromise to avoid non-linear effects in BC1 and booster linac)
  - **Satisfied nominal results** (perfect machine)
  - But BBA is not working well in the booster linac

Nominal results at RTML end

Parameter	Symbol	Unit	Value
Bunch length	σ_z	μm	71.3
Energy spread	σ_E/E	%	1.5
Horizontal normalised emittance	$\epsilon_{n,x}$	nm	774.7
Vertical normalised emittance	$\epsilon_{n,y}$	nm	5.51

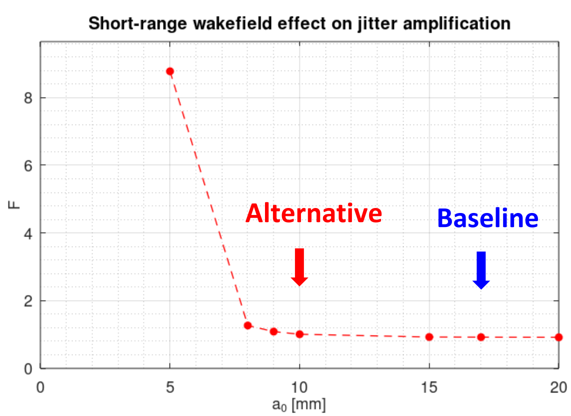


Nominal emittance growth along RTML



Nominal longitudinal phase space at RTML end

- Smaller aperture L-band structure
  - Seems that the aperture can be reduced to a_0 = **10 mm**



Study in progress

Conclusions

- CLIC **RTML** studied and **optimised**, 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 main linac** 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 **99%** good machines **after BBA** corrections
  - **Jitter amplification** due to wakefield also studied and found to be **negligible**
- **Baseline** design is **finished**. Results are quite **satisfied** and **ready for documentation** (e.g. Readiness Report)
- **Alternative options of booster linac** investigated. Using **X-band** seems **difficult** (good nominal results, but BBA not working). **Smaller aperture L-band seems possible**. Study **in progress**
- **Next steps**
  - Look at **larger errors** (more conservative), e.g. 30 μm → 100 μm position error in some sections, such as in LTL
  - **Beam loading** effect and compensation (to cooperate with *J. Olivares, P. Wang, A. Grudiev* from CERN)
  - Look at **other beam options**:
    - Klystron based option, 3 TeV energy stage, Lower emittance DR, etc.

Acknowledgements

Thanks very much for your attention!

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

Backup

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: 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