Optimisation of the BC2 RF structures for the CLIC RTML

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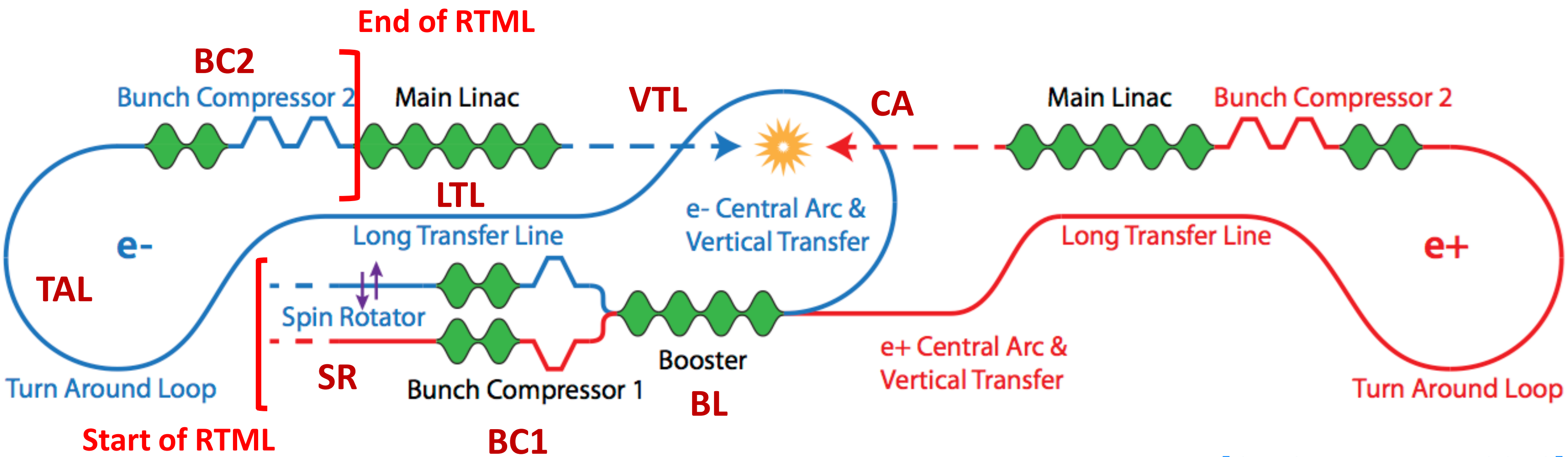
Outline

- Introduction to CLIC RTML
- Optimisation of BC2 RF structure
- Imperfections and BBA corrections
- Conclusions

Introduction to CLIC RTML

Layout of CLIC RTML

- **Schematic layout of RTML** (downstream of the DR)



[CLIC PIP report 2018]

RTML: Ring To Main Linac

- **RTML components (study focused on e$^-$):**
  - Spin Rotator (**SR**) → Bunch Compressor 1 (**BC1**) → Booster Linac (**BL**) → Central Arc (**CA**) → Vertical Transfer Line (**VTL**) → Long Transfer Line (**LTL**) → Turn Around Loop (**TAL**) → Bunch Compressor 2 (**BC2**)

Beam parameters

❑ Beam parameters for RTML

- Study **focused on CLIC baseline** collider design (**drive-beam based** acceleration)
- **To be updated to the latest parameters (lower emittances)**

Beam parameter	Symbol	Unit	RTML entrance		RTML exit	
Collision energy	E_cm		380 GeV	3 TeV	380 GeV	3 TeV
Beam energy	E	GeV	2.86	2.86	9	9
Bunch charge	q	nC	0.832	0.592	0.832	0.592
No. of particles per bunch	N_p	10^9	5.2	3.7	5.2	3.7
No. of bunches per pulse	N_b		352	312	352	312
Bunch length (rms)	σ_z	μm	1800	1800	~70	~42
Energy spread (rms)	σ_E	%	~0.12	~0.12	< 1.7	< 1.7
Normalised emittances	ε_n_x	nm	700	700	< 800	< 800
(w/o imperfections)	ε_n_y	nm	5	5	< 6	< 6

[CLIC PIP report 2018]

- ○ 1.5 TeV energy stage has the same parameters with 3 TeV

Simulation configuration

- **Study focused on 380 GeV energy stage**
- **Simulation tool: Placet**
  - Short-range wakefield, ISR and CSR effects are considered
- **Same configuration with previous studies** (except for BC2 RF structures)
  - **Spin Rotator (SR):** 90° spin rotation
    - Arc bend: 13.9°; Max. solenoid field: 6 T
  - **BC1:** 1.8 mm—235 μm bunch length compression
    - RF: **2 GHz**, 2π/3, 12 cavities (L=1.5 m, a=17 mm, d=42 mm), G≈22.11 MV/m, ϕ=90°
    - Energy chirp: $\mu_{BC1} \sim -5.9\ m^{-1}$
    - 1 chicane, θ = 4.54°
  - **Booster Linac (BL):** 2.86 GeV—9 GeV acceleration
    - RF: 224 cavities (same with BC1), G≈18.27 MV/m, ϕ=0
  - **CA, VTL and LTL:** transfer of beam
  - **BC2:** 235 μm—70 μm bunch length compression
    - RF: **12 GHz**, ϕ=90°; **RF structure parameters to be optimised**
    - Energy chirp: $\mu_{BC2} \sim -49.5$ m-1
    - 2 chicanes, $\theta_1 = 1.63°$, $\theta_2 = 0.32°$

$$\mu_{\mathrm{BC}} = \frac{1}{E}\frac{dE}{ds}$$

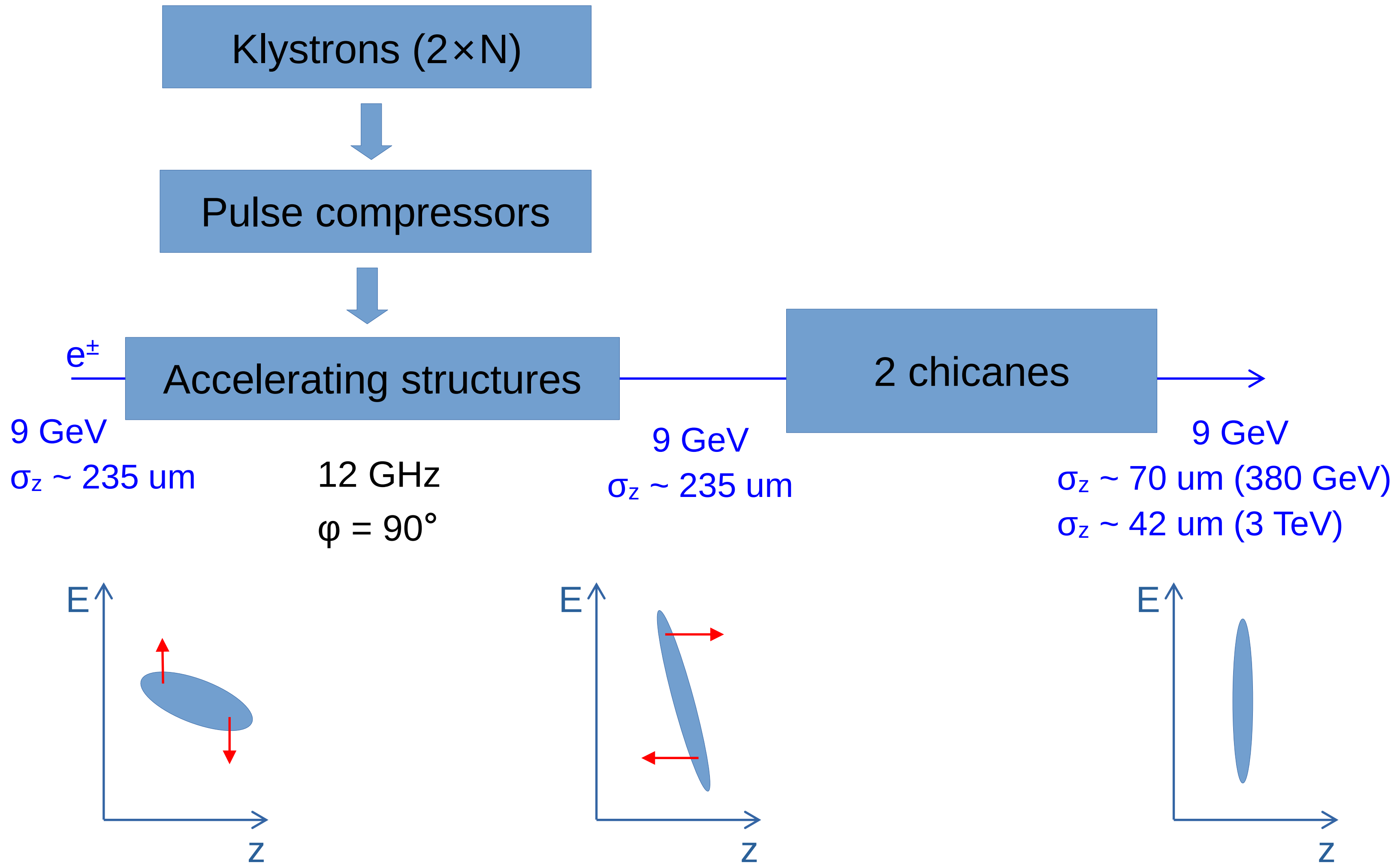
Optimisation of BC2 RF structure

Motivation

- **Problems** in all **previous** CLIC RTML studies:
  - To achieve emittance budget (90% corrections) with static imperfections, a very large iris aperture radius (a_0 = 5.44 mm, a_0/λ = 0.218) of the BC2 RF X-band structure (230 mm long) was assumed, which has very large power consumption and cost. Besides, the structure is problematic (e.g. breakdown) due to the very large aperture
  - To reduce the power consumption and cost, a new X-band structure (modified from mm 925 long CompactLight X-band) was assumed, with a smaller iris aperture radius (a_0 = 4.41 mm, a_0/λ = 0.176). Besides, the emittance budget was not achieved, and the structure also seems to be problematic (e.g. breakdown) as the aperture is still large
- **Aims of our study**
  - Optimise the structure for a minimum total cost
  - Keep the bunch well compressed at the end of BC2
  - Achieve emittance budget at the end of RTML, with the optimised structure and improved Beam-Based Alignment (BBA) correction procedure

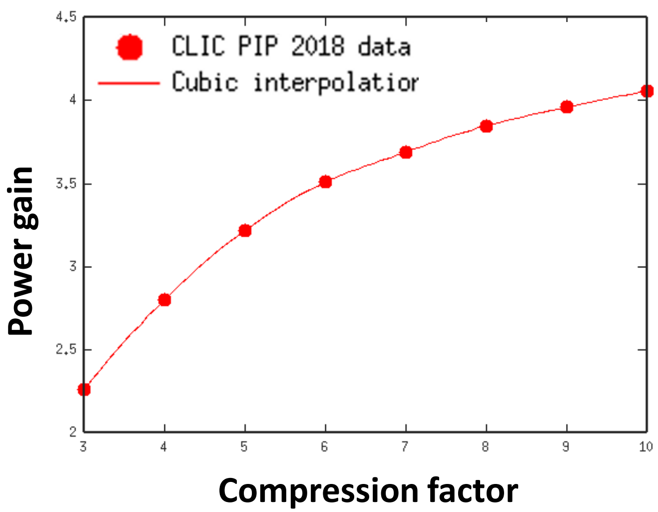
BC2 layout

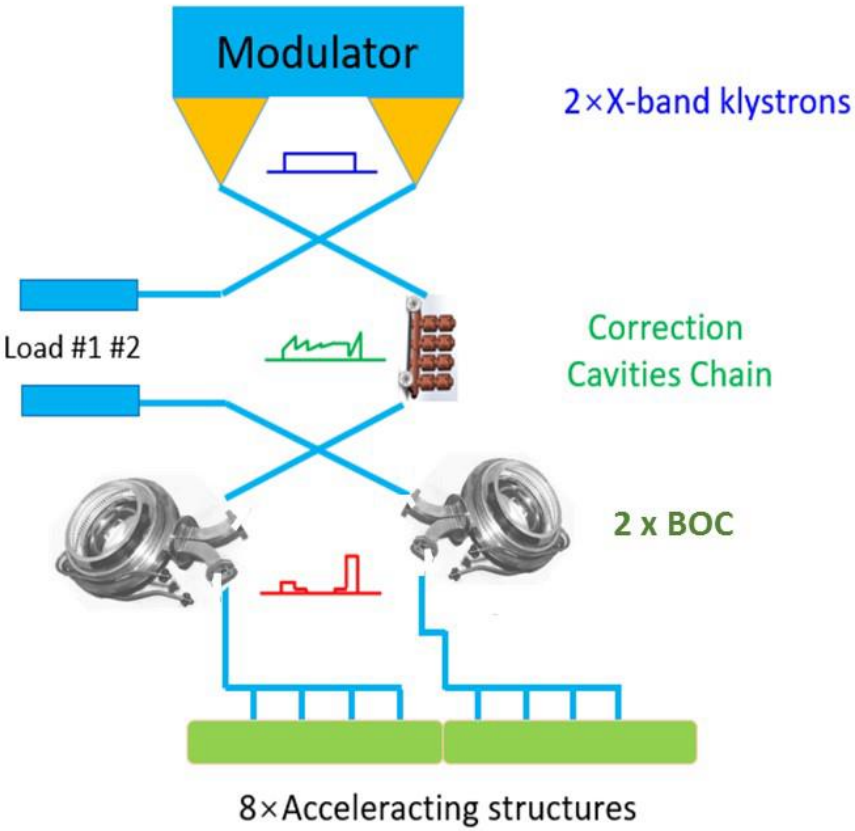
- **BC2 RF system and chicanes:**



BC2 RF system

- Based on CLIC PIP report 2018, the followings are assumed:
  - **Klystron**:
    - Peak power: 51.4 MW
    - Efficiency: 70%
    - Pulse length: 2 μs
    - Work in pairs
  - **Pulse compressor**:





RF transmission efficiency: 90%

[CLIC PIP report 2018]

Structure optimisation starting point

- **Optimisation based on an existing design *"CLIC-K"* [1], designed for the alternative CLIC Main Linac design (klystron-based acceleration)**

Parameters	CLIC-G	CLIC-K	
Frequency	11.994 GHz	11.994 GHz	
Accelerating gradient	100 MV/m	~~75 MV/m~~	→ **to be optimised**
Active length	0.23 m	0.23 m	
RF phase advance per cell	120 °	120 °	
Number of cells	28	28	
Average iris radius / RF wavelength	0.11	~~0.1175~~	
First iris radius / RF wavelength	0.126	~~0.145~~	→ **to be optimised**
Last iris radius / RF wavelength	0.094	~~0.09~~	
First iris thickness / cell length	0.2	0.25	
Last iris thickness / cell length	0.12	0.134	
Bunch spacing	0.15 m	0.15 m	
Number of particles per bunch	3.72×10^9	~~3.87×10^9~~	→ **5.2×10^9**
Number of bunches per train	312	~~485~~	→ **352**

[1] J. Liu and A. Grudiev, "RF design of accelerating structure for the main linac of the klystron-based first stage of CLIC at 380 GeV", CLIC-Note-1082, 2018

Structure optimisation procedure

❑ 1D scan is performed to optimise the RF structure parameters:

- Average iris radius / wavelength: a_0/λ; Iris radius difference / wavelength: $\Delta a/\lambda$
- Average iris thickness / cell length: d_0/l; Iris thickness difference / cell length: $\Delta d/l$

❑ To simplify the optimisation, the followings are assumed:

- ✓ During scan of a parameter, the other parameters are fixed to the initial design values
- ✓ For a **RF unit**, **number of klystrons** is always **2**, and **number of structures** is always **8**
- ✓ For given gradient, the *CLICopti* [1] tool is used to estimate the RF performance. For example:

Parameter		Symbol	Unit	Value	
CLICopti estimation	Average gradient (loaded)	G	MV/m	**75**	**69.5**
	Peak input power required (beam loaded)	P_0	MW	48.7	43.5
	RF-to-beam efficiency	η	%	39.8	41.3
	Pulse length	τ_{RF}	ns	264.6	264.6
Calculation	Pulse Compressor power gain (from interpolation)	g_{PC}		3.78	3.78
	Number of structures per 2 klystrons	N_{as}		**7 (7.18)**	**8 (8.04)**

Gradient too large — Gradient is OK

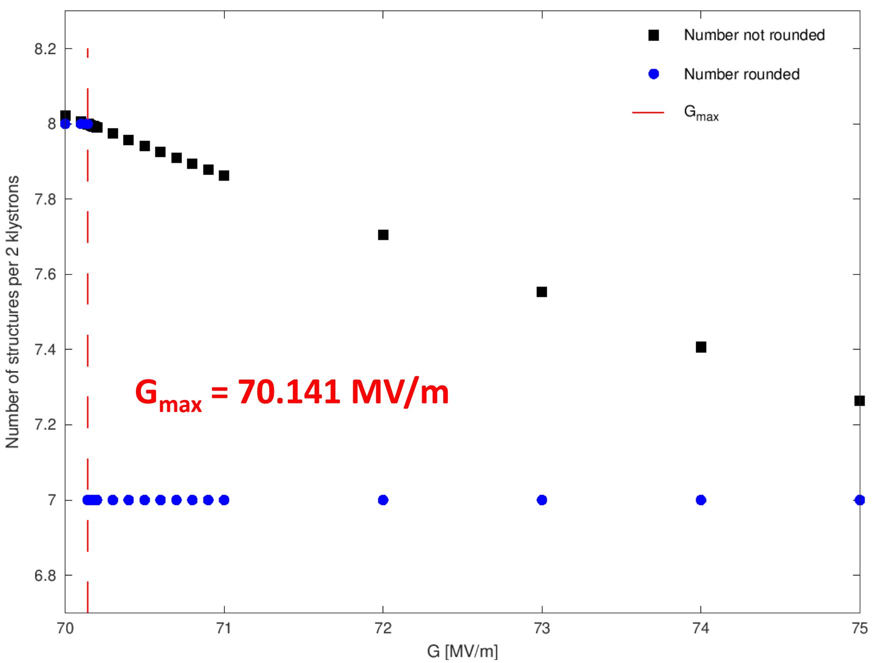
[1] K. Sjobak and A. Grudiev, “The CLICopti RF structure parameter estimator”, CLIC-Note-1031, 2014

Structure optimisation procedure

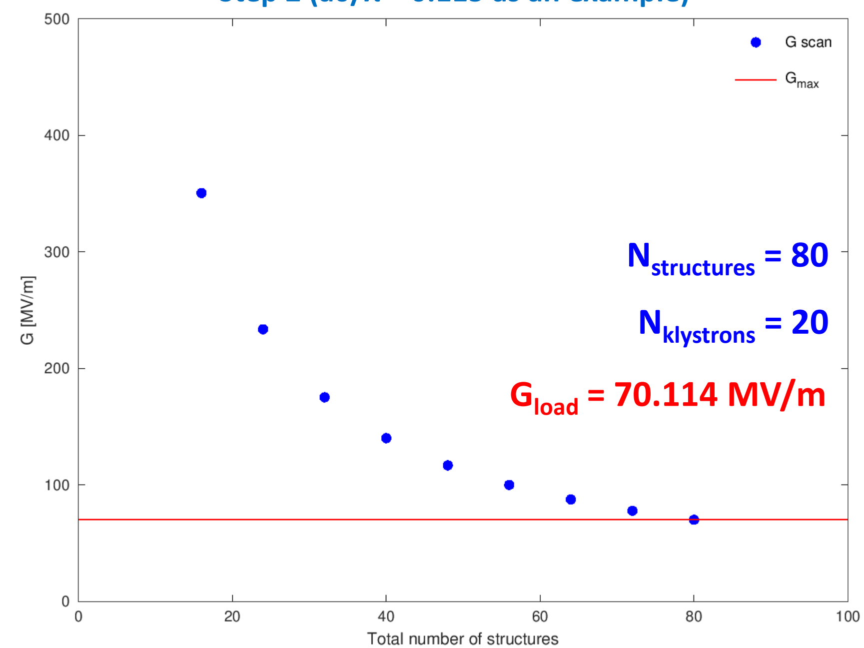
- **For given RF structure parameters, the loaded gradient (average) is estimated by:**

1. Scan the **loaded gradient** (in reduced steps), to find the maximum limit on the gradient (G_{max})
2. Scan the **total number of structures** (in step of 8), to find the final loaded gradient (G_{load}), given fixed total voltage 1290.1 MV of BC2 RF structures as used in previous studies

Step 1 (a0/λ = 0.115 as an example)

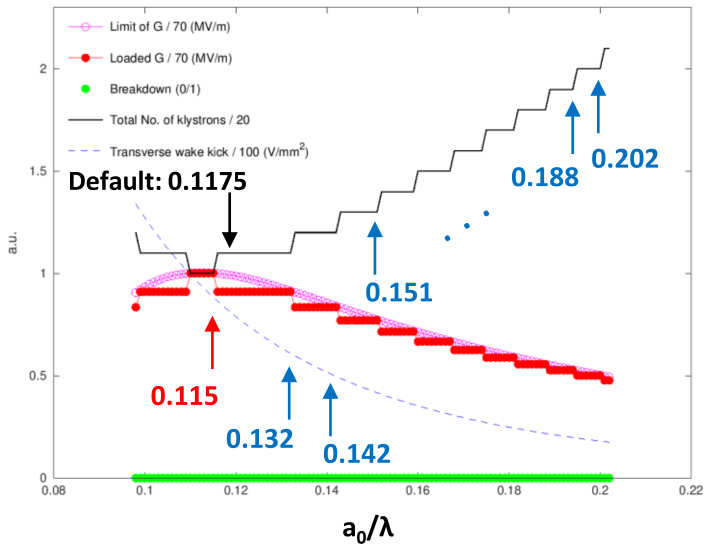


Step 2 (a0/λ = 0.115 as an example)



Structure optimisation results

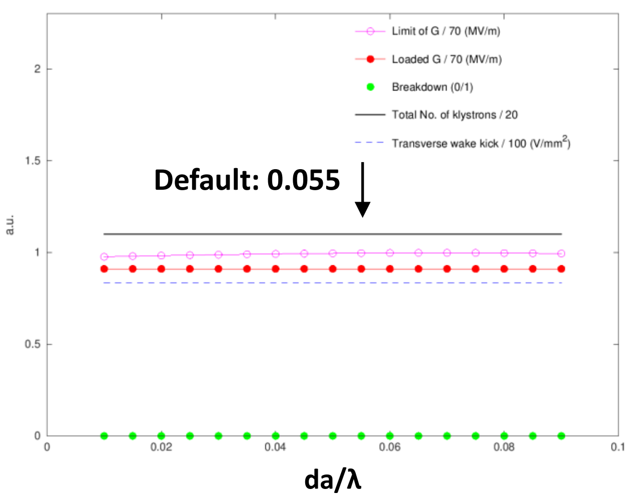
❑ Scan results:

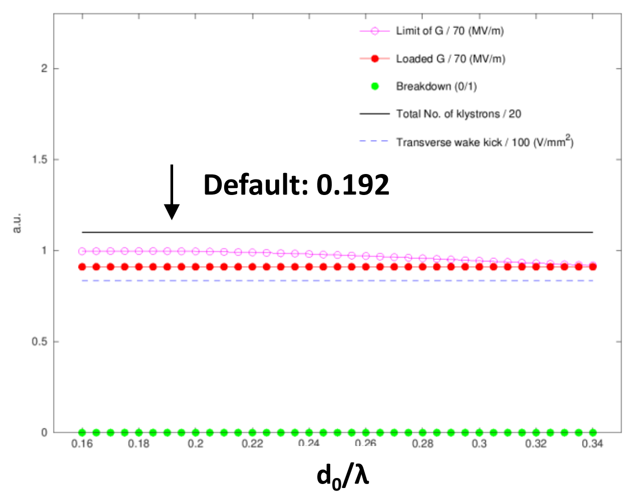


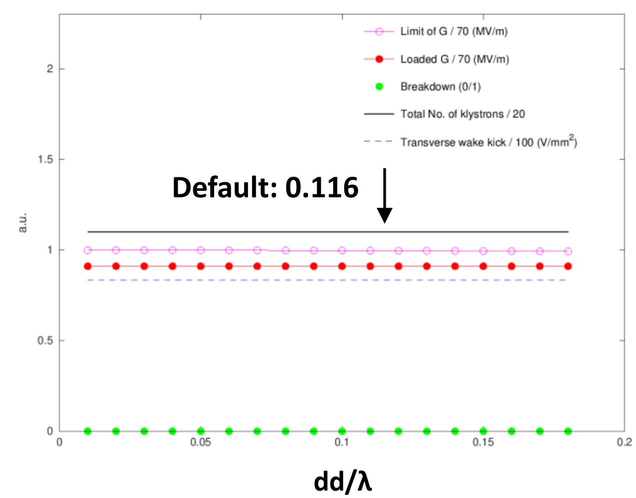
❑ Results affected only by a_0/λ:

- ○ Cost increased with aperture, but wakefield reduced
- ○ Optimal (min. cost) value: $a_0/\lambda = 0.115$
- ○ Alternative values (in case needed to reduce transverse wakefield in BBA test):
  - ▪ a_0/λ = 0.132, 0.142, 0.151, ..., 0.188, 0.202

➢ **Default values kept for other parameters**



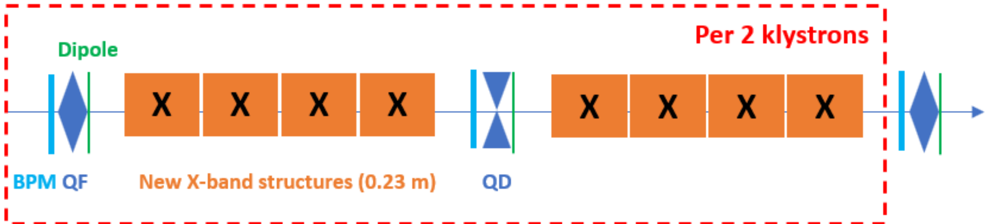




New BC2 RF lattice

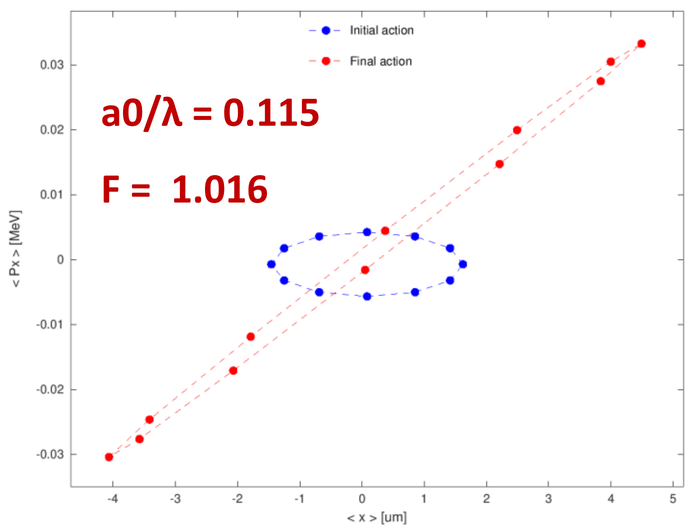
❑ Lattice for new BC2 RF structures:

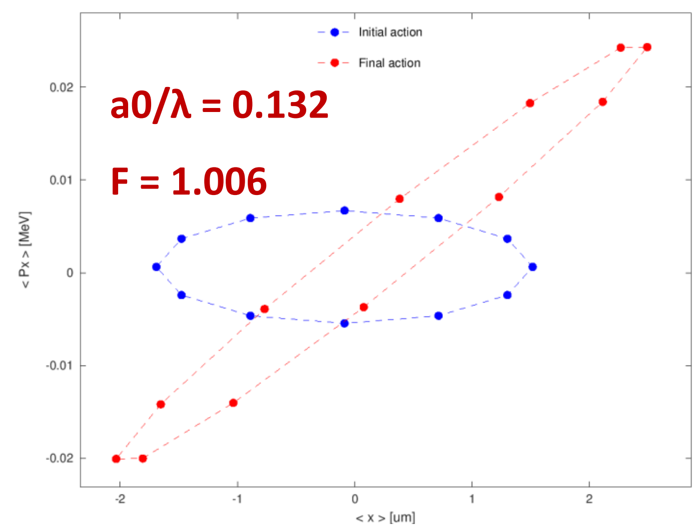
- Rematching is also performed before and after the BC2 RF section



a_0/λ	0.115	0.132	0.142	0.151	···
$N_{structures}$	80	88	96	104	···
$N_{klystrons}$	20	22	24	26	···
G (MV/m)	70.114	63.740	58.428	53.934	···

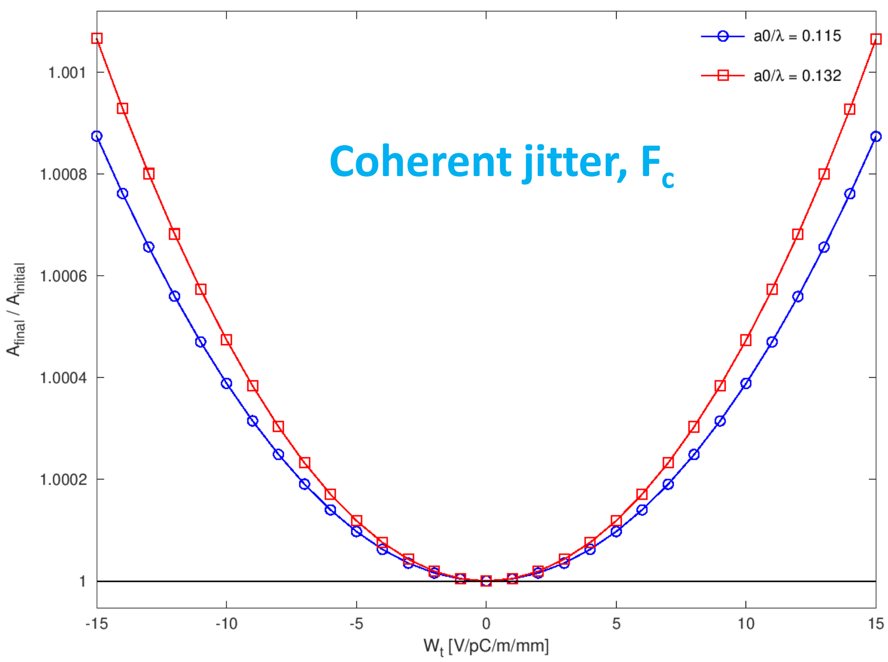
❑ Amplification factor (F = final action / initial action) of BC2 RF structures for short-range wakefield (simulated with RF-Track):

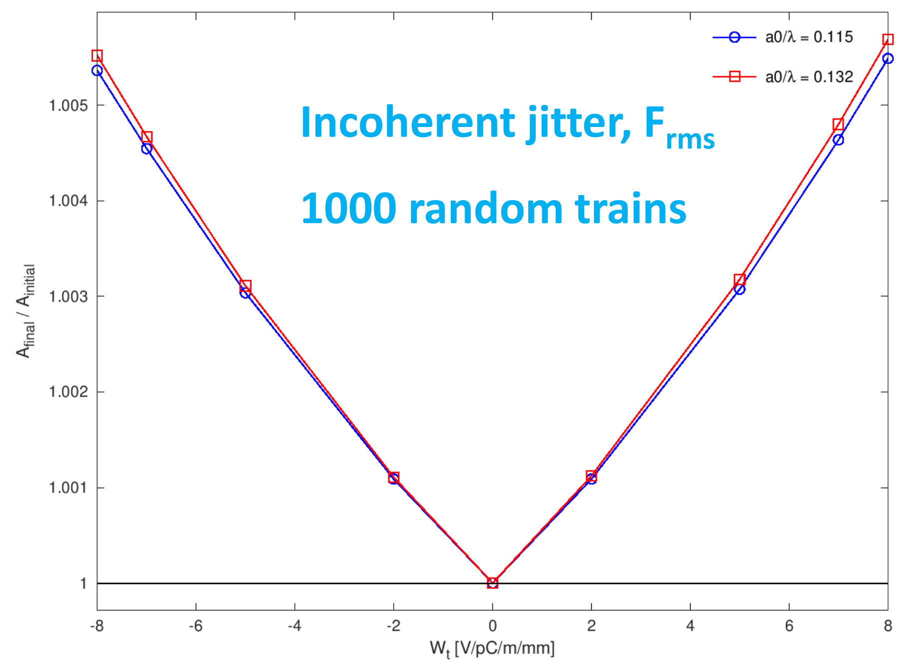




Long-range wakefield

- **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):**
  - Looking at the worst bunch

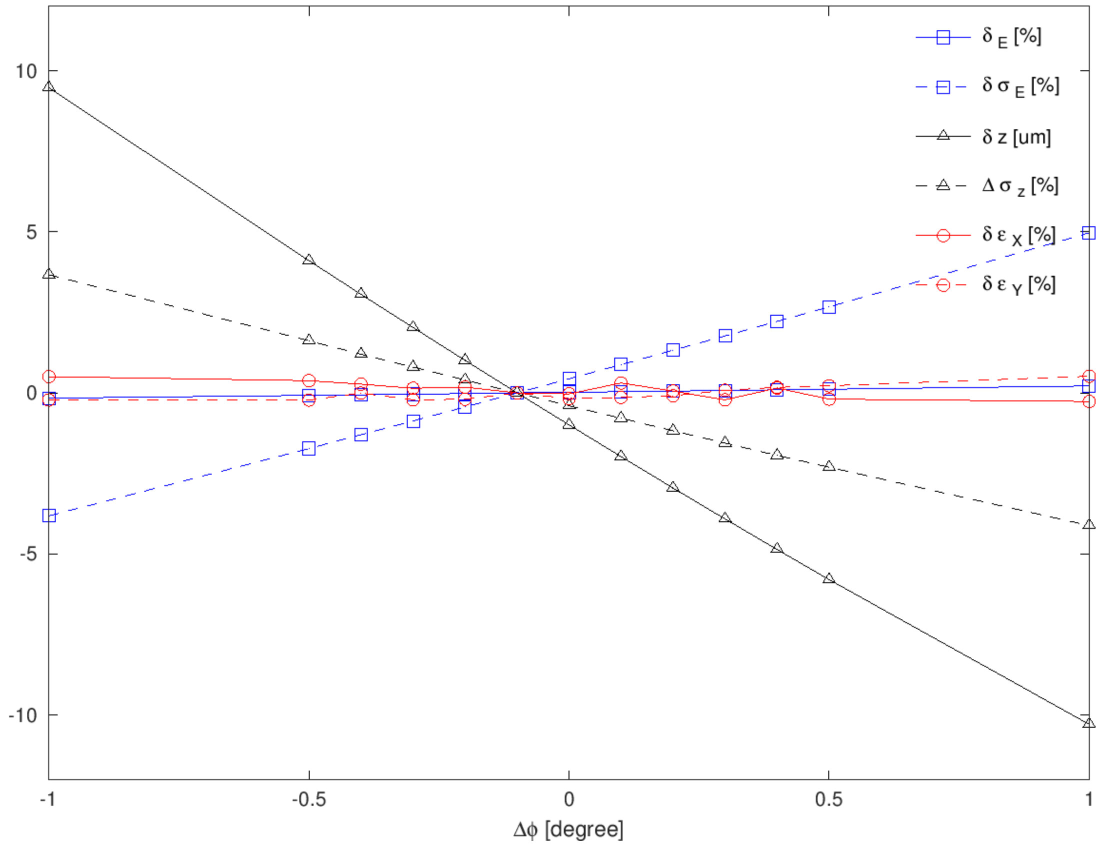




The effects are very small!

Bunch phase shift

- A **bunch phase shift** of **1°** (of the last bunch) is assumed for the beam **from the DR**
- **The impact (on the last bunch) at the end of RTML is shown below:**



Bunch phase shift at the Main Linac:

0.144° (10 um @ 12 GHz),

which is acceptable (< 0.2°)

Imperfections and BBA corrections

Imperfections

- **Normalised emittance budgets for RTML**
  - **Study focused on static imperfections**

	Initial	Final emittance(⋆) by Design	with Static Imperfections	with Dynamic Imperfections
ϵ_x [nm]	700	< 800	< 820	< 850
ϵ_y [nm]	5	< 6	< 8	< 10

(⋆) 90^{th} percentile.

[CLIC PIP report 2018]

- **Static imperfections considered in our study**

Imperfection	RTML w/o CA and TAL	CA and TAL
R.M.S. position error	100 μm	30 μm
R.M.S. tilt error	100 μrad	30 μrad
R.M.S. roll error	100 μrad	30 μrad
$\Delta B/B$ quadrupoles	10^{-3}	10^{-4}
$\Delta B/B$ other magnets	10^{-3}	
Magnetic-center shift w/strength	0.35 μm / 5%	
BPM resolution	1 μm	
Sextupole movers step size	-	1 μm

[CLIC PIP report 2018]

BBA correction methods

One-To-One (OTO) correction

- Orbit correction (correctors $\boldsymbol{\theta}$: dipole strengths)
- **b**: nominal BPM readings
- **R**: linear orbit response matrix

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

Dispersion-Free Steering (DFS) correction

- Orbit and dispersion correction (same correctors with OTO)
- $\boldsymbol{\eta}$, $\boldsymbol{\eta}_0$: measured and target dispersion
- **D**: dispersion response matrix
- ω_d: weighting factor
- β_0, β_1: regularization parameters

$$\begin{pmatrix} & \mathbf{b} \\ \omega_d & (\boldsymbol{\eta} - \boldsymbol{\eta}_0) \\ & \mathbf{0} \end{pmatrix} = \begin{pmatrix} & \mathbf{R} \\ \omega_d & \mathbf{D} \\ \beta_1 & \mathbf{I} \end{pmatrix} \cdot \boldsymbol{\theta}$$

$$\omega_d^2 = \frac{\sigma^2_{\text{bpm offset}} + \sigma^2_{\text{bpm precision}}}{2\sigma^2_{\text{bpm precision}}}$$

Test beam (2% energy difference) obtained by scaling strengths of all RTML magnets

Sextupole Tuning (ST) correction

- Emittance optimisation
- Correctors: sextupole positions
- Simplex search (Octave: fminsearch) method

1% RMS uncertainty always applied to the emittance

Procedure of BBA corrections

☐ Improved procedure of corrections:

1) OTO + DFS: SR—BC1—BL—CA—VTL—LTL

- DFS is not applied if the merit of "OTO + DFS" is worse than "OTO only" correction

2) ST: CA—VTL—LTL

- The **first 5 sextupoles** of CA are tuned for minimum merit

3) OTO + DFS: TAL—BC2

- $\beta_0 = \beta_1 = 0$ for BC2 (0.5 for other sections)
- DFS is not applied if the merit of "OTO + DFS" is worse than "OTO only" correction

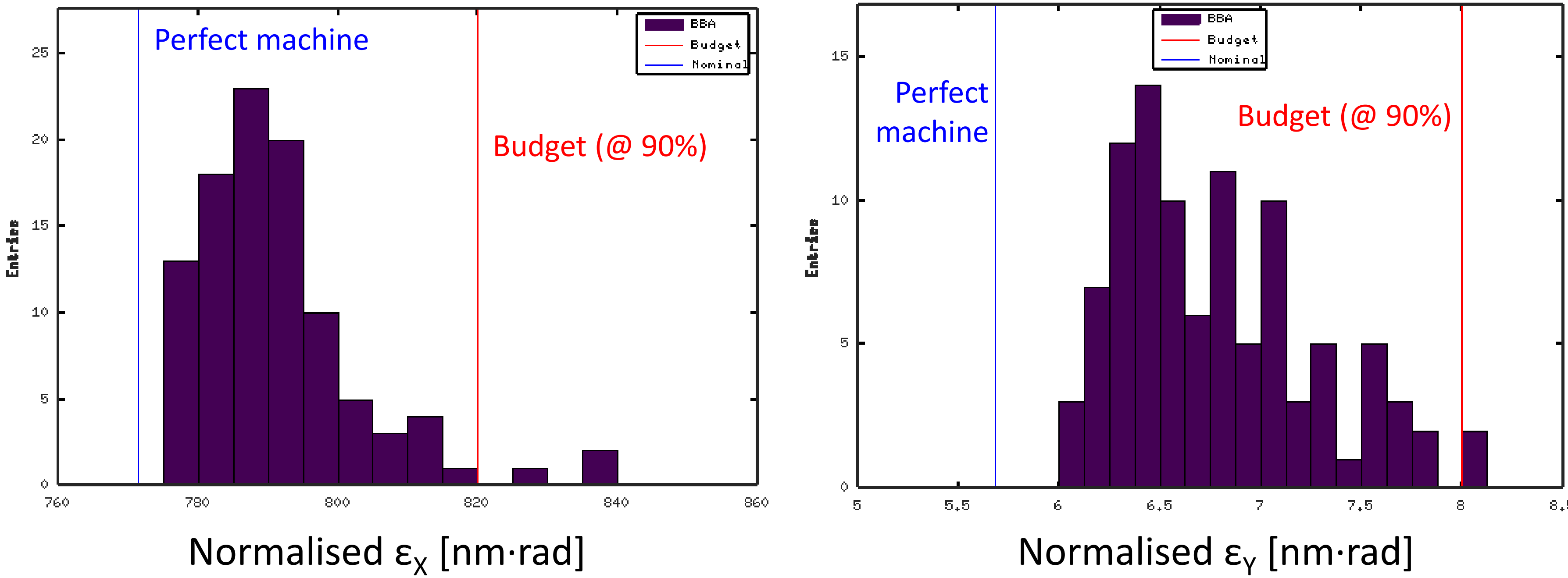
4) ST: TAL—BC2

- The **first 5 sextupoles** of TAL tuned for minimum merit

$$\text{Merit} = \sqrt{\left(\frac{\varepsilon_x/nm - 700}{820 - 700}\right)^2 + \left(\frac{\varepsilon_y/nm - 5}{8 - 5}\right)^2}$$

Preliminary BBA correction results

- **BBA correction results for 100 random machines w/ imperfections:**
  - **a_0/λ = 0.115 (a_0 = 2.875 mm), with minimum cost**



- **Total cost: 6.92 MCHF (assuming 50 kCHF/m per structure, 300 kCHF per klystron)**
- **Number of good machines (below both X and Y budget emittances): 94%**
- **The results can still be improved by tuning further the bad machines:**

☺ **Perfect results!**

Machine number	11	27	30	56	87	92
Normalised ε_X [nm·rad]	825.5	836.0	796.2	796.7	790.4	839.8
Normalised ε_Y [nm·rad]	6.64	7.23	8.06	9.10	8.04	7.00

Conclusions & next steps

- **RF structures reoptimised** (**study focused on e^- at 380 GeV**) for the **CLIC RTML BC2** (**focused on drive-beam based acceleration**), based on an existing X-band design, "CLIC-K", designed for the CLIC klystron-based main linac. **Bunch length compression is kept the same** with before
- **Total cost** of klystrons (N = 20) and structures (N = 80) **minimised** (estimation: **6.92 MCHF**), with optimised aperture **$a_0/\lambda = 0.115$** (**$a_0 = 2.875$ mm**), and loaded gradient 70.114 MV/m
- Effects of **long-range wakefield** and **bunch phase shift** also studied, and found to be **acceptable**
- Beam-based alignment (**BBA**) correction procedure is also **simplified and improved**. **Emittance budget** (**90%** good machines required) at the end of RTML (**focused on static imperfections**) is successfully achieved with **94% (or higher) good machines**
- With much smaller aperture and lower cost, much better structure performance and stability, and better BBA corrections, **all problems in previous studies are perfectly solved now!**
- Next steps:
  - Study other options: e^+ and 3 TeV stage, etc.

Acknowledgement

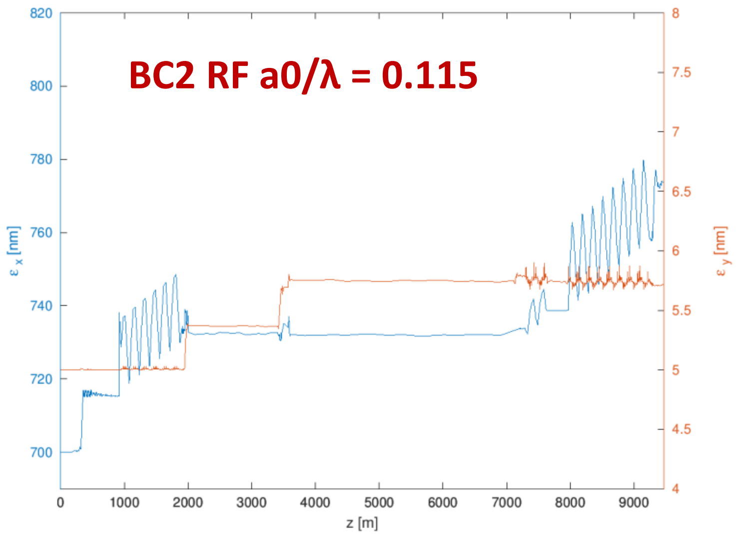
- **Our work is based on many previous studies. Many thanks specially to:**

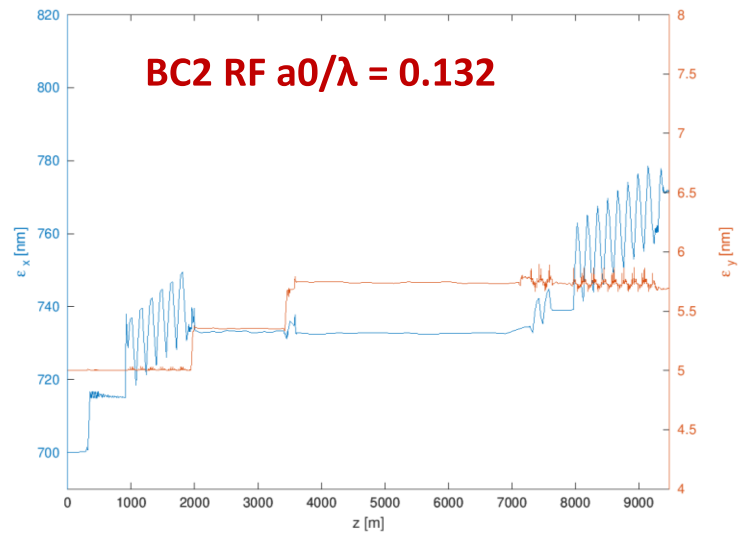
- **Y. Han, C. Gohil, X. Liu et al. for their contributions in previous studies and simulation code development**
- K. Sjobak, A. Grudiev and J. Ogren for their contributions to the CLICopti tool development
- J. Liu and A. Grudiev for their contributions to the design of the CLIC klystron-based (CLIC-K) X-band
- ...

Backup

RTML emittance growth

❑ **Emittance growth along the whole RTML (w/o imperfections):**





BC2 RF structure parameters

Parameter		Symbol	Unit	Value (RF performance estimated with CLICopti)		
				Y. Han & C. Gohil (2017-19)	X. Liu (2019-20)	Y. Zhao (2022-23)
Beam	Collision energy	E_cm	GeV	380	380	380
	Number of bunches	N_b		352	352	352
	Number of particles per bunch	N_p	10^9	5.2	5.2	5.2
	Beam current	I_b	A	~1.67	~1.67	~1.67
	Train length	τ_b	ns	176	176	176
Structure	RF frequency	f_RF	GHz	12	11.994	11.994
	Active length (incl. couplers)	L_as	mm	230	924.8	230
	Number of cells (incl. couplers)	N_c		22	108	28
	Wavelength	λ	mm	~25	~25	~25
	Average iris radius / λ	a0_n = a0/λ		~0.218	~0.176	0.115
	Average iris radius	a0	mm	~5.44	~4.41	2.875
	Iris radius difference / λ	da_n = da/λ		~0.095	~0.095	0.055
	Cell length	l	mm	~10.41	~8.33	~8.33
	Average iris thickness / cell length	d0_n = d0/l		~0.821	~0.424	0.192
	Average iris thickness	d0	mm	~8.54	~3.53	~1.60
	Iris thickness difference / cell length	dd_n = dd/l		~0.020	~0.025	0.116
	RF phase advance per cell	Δϕ	degree	150	120	120
	Average gradient (loaded)	G	MV/m	70.115	63.41	70.114
	Peak input power required (beam loaded)	P_0	MW	unknown	184.5	43.3
	RF-to-beam efficiency	η	%	unknown	30.6	40.6
	Pulse length (t_r + t_f + t_b)	τ_RF	ns	unknown	296.8	272.8
	Max. allowed beam time (for given BDR)	τ_b_max	ns	unknown	0	292.5
	Breakdown (for given BDR = 10^{-6} breakdowns/pulse/meter)			unknown	Yes	No
	Average transverse SR wakefield kick	wk_t	V/mm^2	13.84	26.53	88.44
RF system	Klystron output pulse length (assumed)	τ_K	μs	2	2	2
	Klystron output power (assumed)	P_K	MW	51.4	51.4	51.4
	RF transmission efficiency (assumed)	η_RF	%	90	90	90
	PC compression factor	k_PC		unknown	6.74	7.33
	PC power gain (from interpolation)	g_PC		unknown	3.65	3.75
	Number of structures per 1 klystron	N_as_1K		unknown	0 (0.91)	4 (4.00)
	Number of structures per 2 klystrons	N_as_2K		unknown	1 (1.83)	8 (8.00)
	Number of structures per 4 klystrons	N_as_4K		unknown	3 (3.66)	16 (16.01)
	Number of structures per 8 klystrons	N_as_8K		unknown	7 (7.32)	32 (32.02)
Cost	Total number of structures	N_as		80	22	80
	Total number of klystrons	N_K		unknown	25	20
	Cost for structure		kCHF/m	50	50	50
	Cost per klystron		kCHF	300	300	300
	Total cost estimate		MCHF	unknown	8.52	6.92
BBA test	Within RTML emittance budget		%	94	83	94