Optimisation of the CLIC RTML

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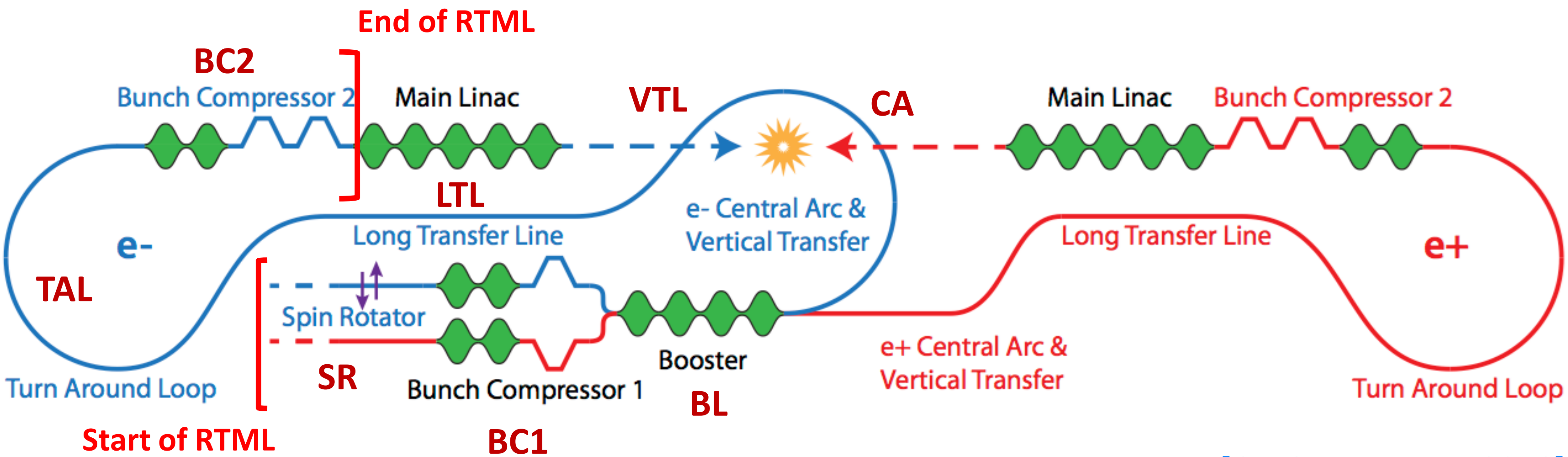
Outline

- Introduction
- Optimisation for baseline beam option, e-
- Optimisation for baseline beam option, e+
- Optimisation for other beam options
- Optimisation of BC2 RF structure
- Improved BBA procedure
- Conclusions and open questions

Introduction

RTML layout

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



[CLIC PIP report 2018]

RTML: Ring To Main Linac

❑ **RTML components:**

- **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**)
- **e^+:** BC1 → BL (shared with e^-) → CA → VTL → LTL → TAL → BC2

Motivation

- **Problems** in **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
  - Later, 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). However, the emittance budget was not achieved, and the structure also seems to be problematic (e.g. breakdown) as the aperture is still large
  - We also found that BC1 and BC2 might be not optimal. It's possible to further optimise the design with a reduced total voltage or cost
  - Besides, previous studies are not complete. Still a lot of things to be studied, such as bunch phase shift, LR wakefield, alternative options (such as new DR with reduced emittance, klystron based acceleration, etc.)

Motivation

❑ Aims of our study

- Optimise BC1 and BC2 for a minimum total voltage or cost
- Optimise the BC2 X-band structure for a minimum total number of klystrons or cost
- Keep the bunch well compressed at the end of RTML, with a full compression (upright phase space) and reasonable final bunch length and energy spread
- Reasonable emittance growth at the end of RTML (perfect machine without imperfections)
- Improve the Beam-Based Alignment (BBA) correction procedure, to achieve the emittance budget (90% corrections with static imperfections) at the end of RTML
- If possible, complete the study for:
  - e- and e+ beamlines
  - 380 GeV and 3 TeV (1.5 TeV) stages
  - Drive-beam based and klystron based acceleration modes
  - Old DR and new DR with reduced emittances
  - Study and eliminate the effect of the bunch phase shift (first-to-last) from the DR
  - Study the long-range wakefield effects

Simulation configuration

❑ Simulation tool: *Placet*

- Short-range wakefield, ISR and CSR effects are considered

❑ Previous configuration (similar with CDR) for 380 energy stage:

- **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, L=1.5 m, ϕ=90°, **To be optimised**
  - 1 chicane, θ = 4.54°, **To be optimised**
- **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**, L=0.23 m, ϕ=90°, **To be optimised**
  - 2 chicanes, θ_1 = 1.63°, θ_2 = 0.32°, **To be optimised**

Beam option

- 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 option

- Beam parameters used in our study:

	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 also be studied

RF structure parameters

- RF parameters (original design) used in our study:

	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 for baseline beam option

(380 GeV + DBA + old DR)

e-

Beam parameters

- **Beam parameters (380 GeV, DBA, old DR, e-)**

Parameter for RTML (e^-, 380 GeV)		Symbol	Unit	Value
Initial beam	Number of bunches per pulse	n_b		352
	Number of particles per bunch	n_p	10^9	5.2
	Bunch length	σ_z	um	1800
	Energy spread	σ_E	%	0.12
	Normalised horizontal emittance	$\varepsilon_{n,x}$	nm	700
	Normalised vertical emittance	$\varepsilon_{n,y}$	nm	5

Same with [CLIC PIP report 2018]

RF acc. structures

- **Bunch compressor 1 (BC1)**
  - **CLIC L-band**
  - 2 GHz, 1.5 m long, 2π/3 mode, phase = 90° (no acceleration)
  - Number of structures and gradient to be optimised
- **Booster linac (BL)**
  - **CLIC L-band**, same with BC1
  - 8*34 = 272 structures, G = 15.05 MV/m, on-crest, fixed
- **Bunch compressor 2 (BC2)**
  - **TD-31** X-band, **assumed to be the same with main linac (ML) at 380 GeV (DBA)**
  - 11.994 GHz, 275 mm long, 2π/3 mode, phase = 90° (no acceleration)
  - Number of structures and gradient to be optimised

Optimisation strategy

- Optimise BC1 and BC2 such that at the end of RTML
  - Full bunch compression
  - Bunch length ~ 70 μm
  - Small energy spread (< 1.7% - 2.0%)
  - Minimum emittance growth
    - $\Delta\varepsilon_x < 100$ nm, $\Delta\varepsilon_Y < 1$ nm
  - Minimum cost (total voltage)
- Free parameters used for optimisation
  - BC1 and BC2 total RF voltages: V_1, V_2
  - BC1 and BC2 chicane angles: θ_1, $\theta_{2,1}$, $\theta_{2,2}$
  - All matching sections are also reoptimised after BC1 and BC2 optimisation

Optimisation strategy

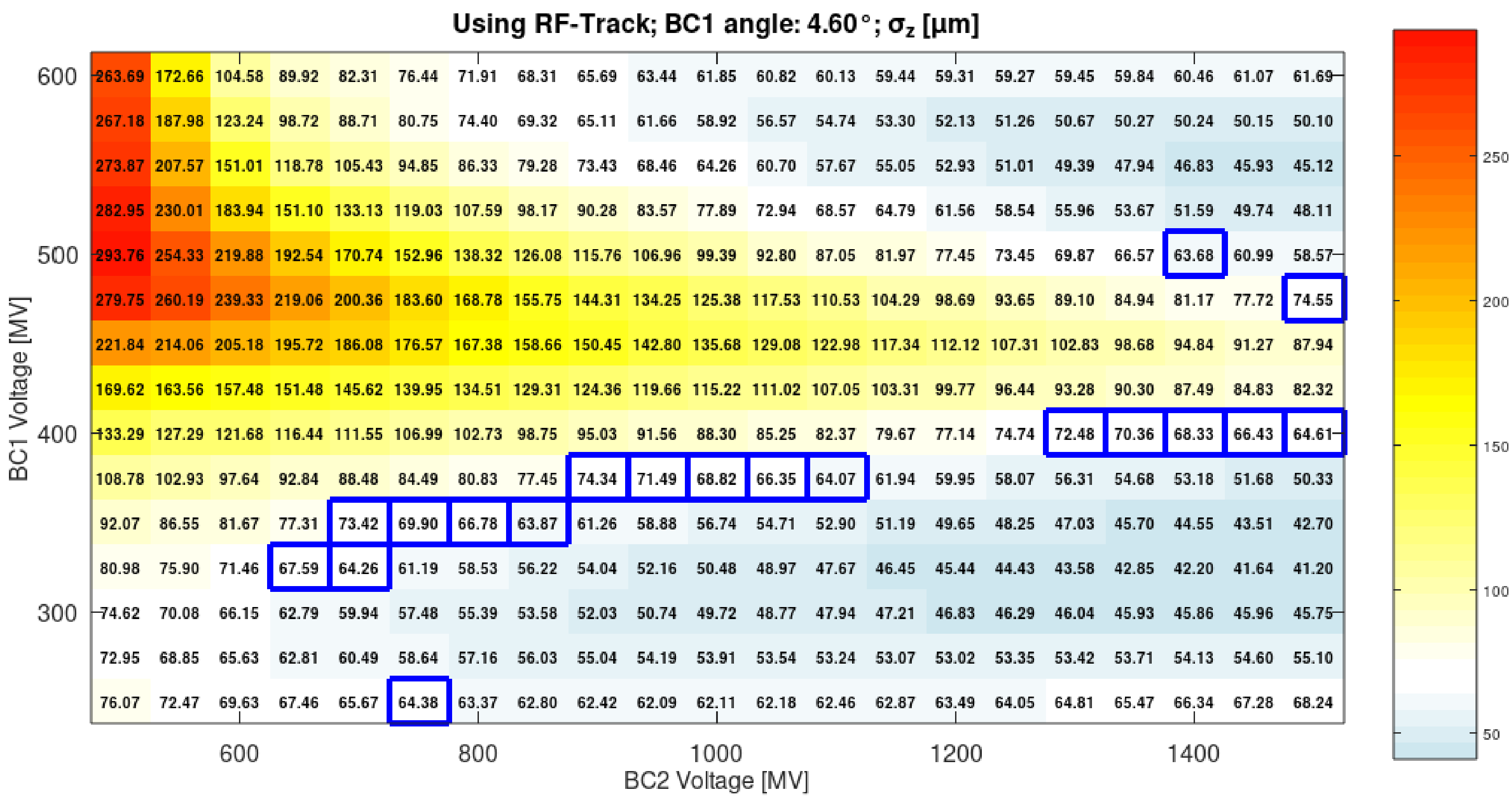
- Simulations:
  - **Fast simulation**: simulation using ***RF-Track*** for BC1 and BC2; analytic (longitudinal) simulation for all RF structures; no simulation for other sections. Side effects not considered
  - **Full simulation**: simulation using ***Placet*** for all sections. Side effects considered
- **3D scan** of BC1 angle and BC1 and BC2 voltages, with **fast simulation**
- Selection of parameters (**based on fast simulation** results) with **loose cut criteria**, for full simulation
  - $|\sigma_z - 70\ \mu m| < 7.0\ \mu m$; $\sigma_E < 2.0\%$
- Selection of parameters (**based on full simulation** results) with **tight cut criteria**, and choose the best one
  - $|\sigma_z - 70\ \mu m| < 0.5\text{-}2.0\ \mu m$; $\sigma_E < 1.7\text{-}1.9\%$; $\Delta\varepsilon_x < 60\text{-}90$ nm, $\Delta\varepsilon_Y < 0.6\text{-}0.9$ nm
- **Redesign BC1 and BC2** (choose the number of RF structures and gradients)
- Reoptimise all **matching sections** for minimum emittance growth

Scan range

- 3D scan range:
  - BC1 angle, θ_1 [°]: 3.5, 3.6, ..., 5.5
  - BC1 voltage, V_1 [MV]: 250, 275, ..., 600
  - BC2 voltage, V_2 [MV]: 500, 550, ..., 1500
- Other parameters:
  - Two BC2 chicanes assumed to have identical angle, $\theta_{2,1} = \theta_{2,2} = \theta_2$, which is always **optimised separately** for a full bunch compression, using **fast simulation**
  - Number of BC1, BC2 RF structures assumed for the **full simulation**: **N1 = 20, N2 = 80**

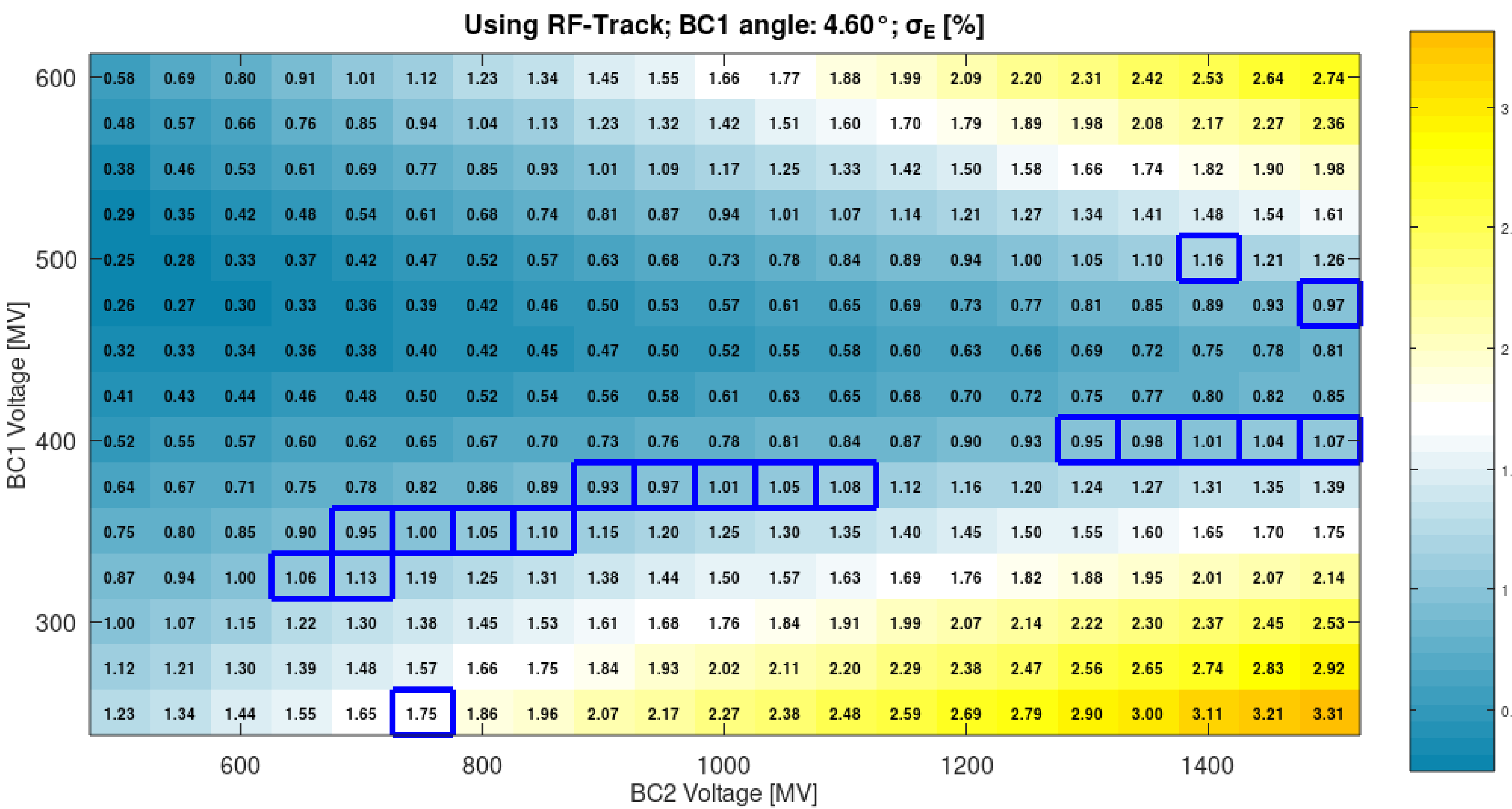
Example: $\theta_1 = 4.6°$

- Voltage scan with **fast simulation** for bunch length, $\boldsymbol{\sigma_z}$
  - Blue box marker represents loose cut criteria



Example: $\theta_1 = 4.6°$

- Voltage scan with **fast simulation** for energy spread, $\boldsymbol{\sigma_E}$
  - Blue box marker represents loose cut criteria



Optimisation results

- Selected parameters and results based on **full simulation**, with tight cut criteria
  - $|\sigma_z - 70\ \mu m| < 0.5\ \mu m$; $\sigma_E < 1.7\%$; $\Delta\varepsilon_x < 90$ nm, $\Delta\varepsilon_Y < 0.8$ nm

θ_1 [°]	V_1 [MV]	V_2 [MV]	V_1+V_2 [MV]	σ_z [μm]	σ_E [%]	ε_X [nm]	ε_Y [nm]
4.6	350	750	1100	69.8	1.0	787.6	5.63
4.0	450	650	1100	69.8	1.1	788.1	5.80
3.9	475	650	1125	70.2	1.1	783.8	5.81
3.8	500	650	1150	70.4	1.1	789.6	5.84
4.7	350	900	1250	69.7	1.0	783.8	5.64
4.1	450	800	1250	70.1	1.1	784.7	5.77
4.4	400	900	1300	70.2	1.0	778.5	5.68
3.7	550	800	1350	70.3	1.1	788.7	6.00
5.0	325	1100	1425	70.0	1.0	789.3	5.63
4.8	350	1100	1450	69.5	1.0	784.8	5.65
4.2	450	1050	1500	69.7	1.1	782.9	5.77
4.5	400	1150	1550	70.1	1.0	784.2	5.69
4.1	475	1100	1575	69.6	1.1	780.3	5.81
4.9	350	1300	1650	70.4	1.0	788.9	5.65

Seems to be the best result! (lowest voltage)

table sorted in order of increased V_1+V_2, ε_x and ε_Y

Optimisation results

- Redesign of BC1 and BC2
  - Other parameters are not changed (same with CDR design)
  - High gradient is assumed given that there is no acceleration

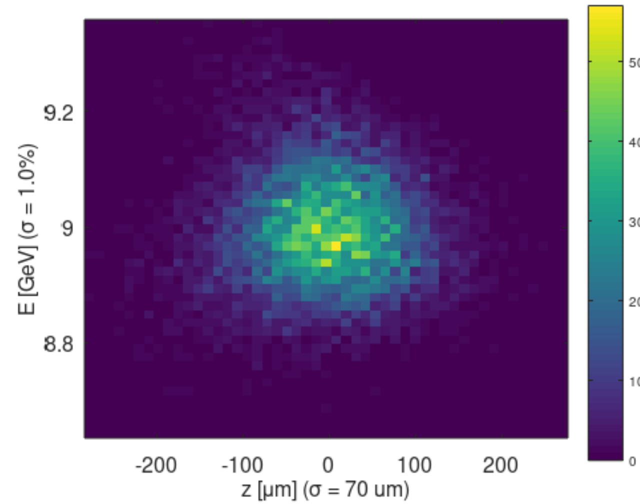
	Parameter	Value
BC1	Total RF voltage [MV]	350
	RF structure length [m]	1.5
	Number of RF structures	12
	RF gradient [MV/m]	19.444
	Chicane bending angle [°]	4.58
BC2	Total RF voltage [MV]	750
	RF structure length [m]	0.275
	Number of RF structures	32
	RF gradient [MV/m]	85.228
	Chicane 1 bending angle [°]	1.54
	Chicane 2 bending angle [°]	

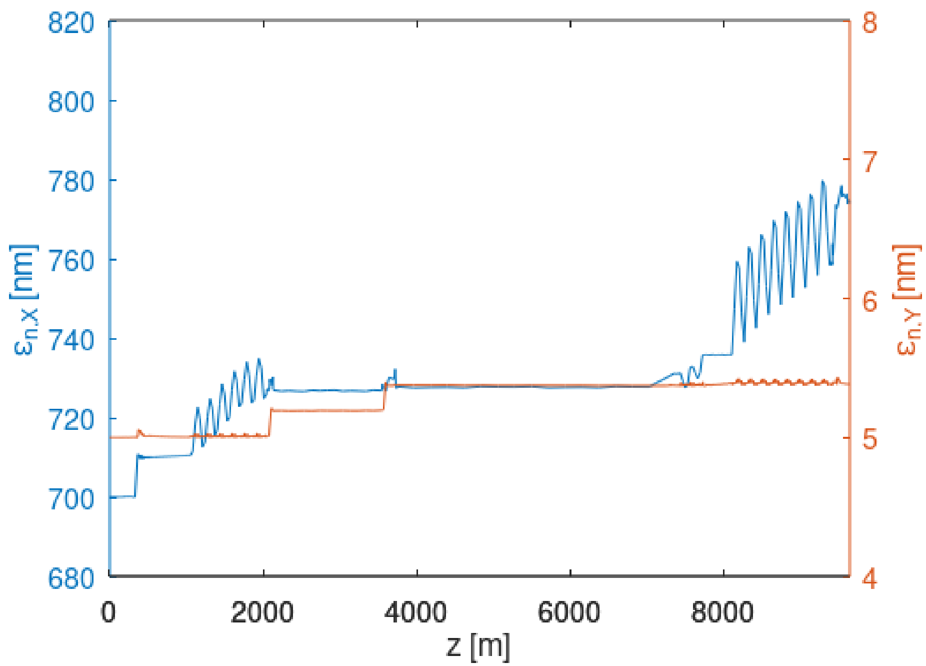
- Cost saving

Total RF voltage	Unit	Previous	Optimised	Cost saving
BC1 (L-band)	MV	400	350	13%
BC2 (X-band)	MV	1290	750	42%
BC1 + BC2	MV	1690	1100	35%

Optimisation results

- Final results after rematching
  - All matching sections for BC1 and BC2 are reoptimized
  - Perfect machine w/o imperfections



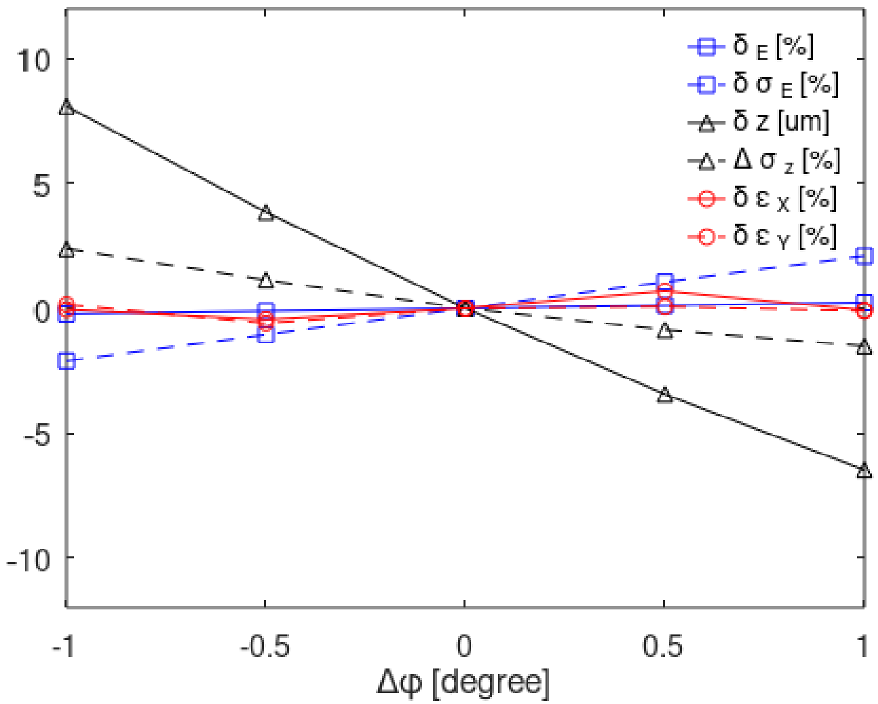


Results at end of RTML	Value
Bunch length [μm]	70.0
Energy spread [%]	1.0
Horizontal emittance [nm]	774.0
Vertical emittance [nm]	5.38

Perfect results!

Bunch phase shift from DR

- Propagation in RTML (from DR to ML)
  - -1° @ DR → 0.115° @ ML
  - +1° @ DR → -0.094° @ ML



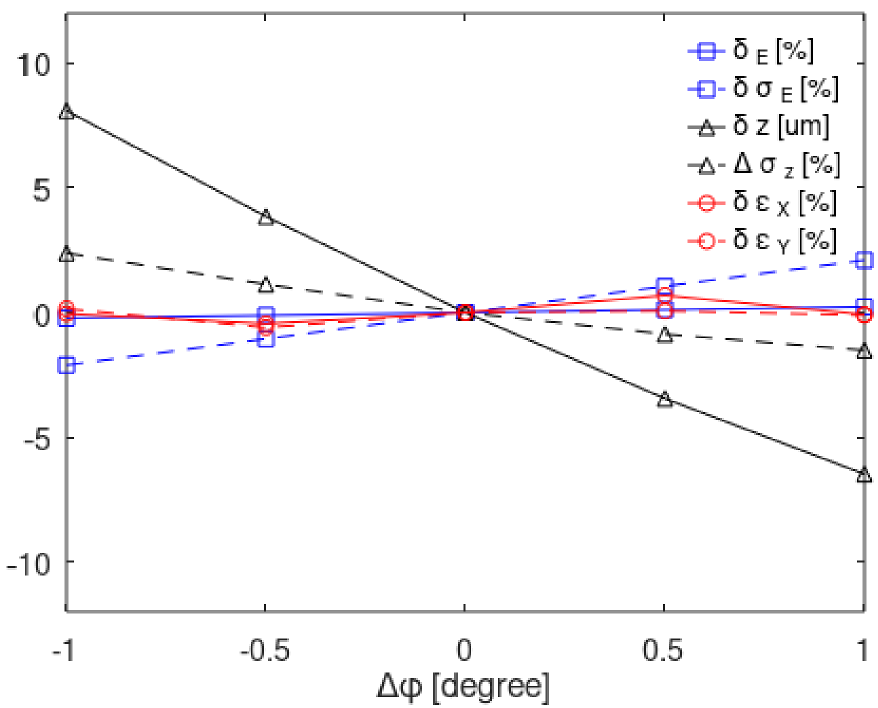
- The effect is acceptable, as the tolerance of the phase shift at the ML is 0.2°
- Besides, the effect can be reduced a half if looking at the middle bunch
- Nevertheless, we can still eliminate the effect by reducing the bending angle

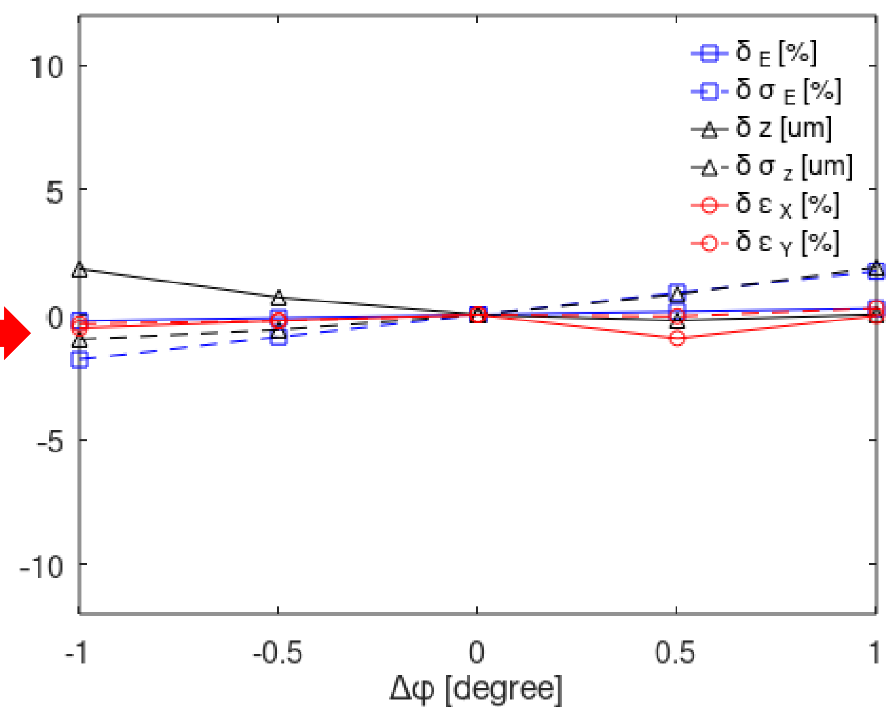
Bunch phase shift from DR

- Propagation in RTML (from DR to ML)

BC1 angle	**4.58°**
BC2 angle	**1.54°**
Final bunch length (1st bunch)	**70.0 um**
Final energy spread (1st bunch)	**1.00%**

BC1 angle	**4.50°**
BC2 angle	**1.51°**
Final bunch length (1st bunch)	**68.5 um**
Final energy spread (1st bunch)	**1.10%**





- The effect is much smaller though a better optimisation can be done

Optimisation for baseline beam option

(380 GeV + DBA + old DR)

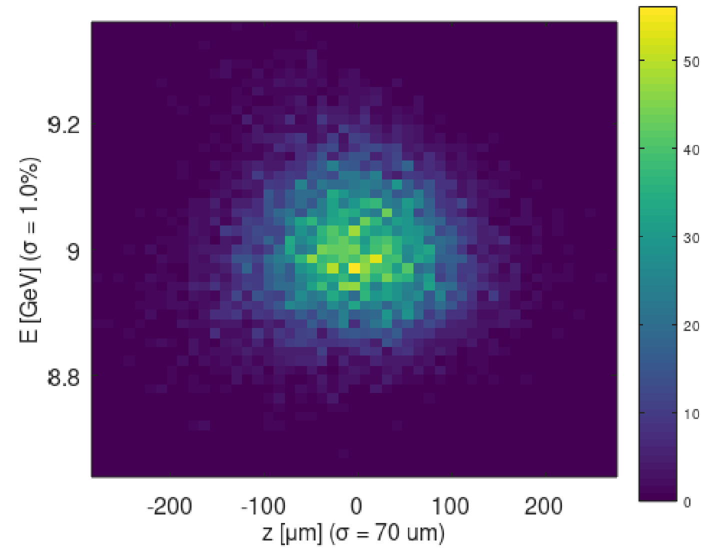
e+

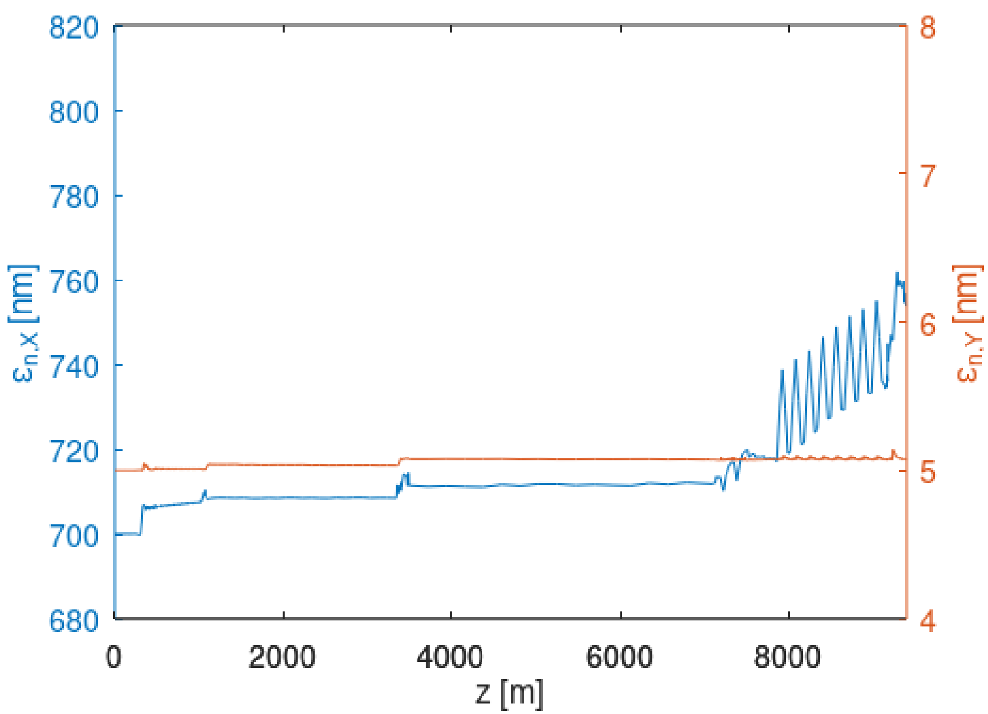
Configuration

- Beam parameters: same with e^-
- SR: not used (replaced with FODO lattice)
- BC1: same with e^-, but angle slightly tuned (4.59° instead of 4.58°)
- BL: same (shared) with e^-
- CA: much shorter than e^-, bent by 6° instead of 186°
- VTL: bent by ±2.6° instead of ±4°
- LTL: same with e^-
- TAL: same with e^-, but opposite bending angle
- BC2: same with e^-

Optimisation results

- Final results after rematching
  - Some matching sections are reoptimized
  - Perfect machine w/o imperfections



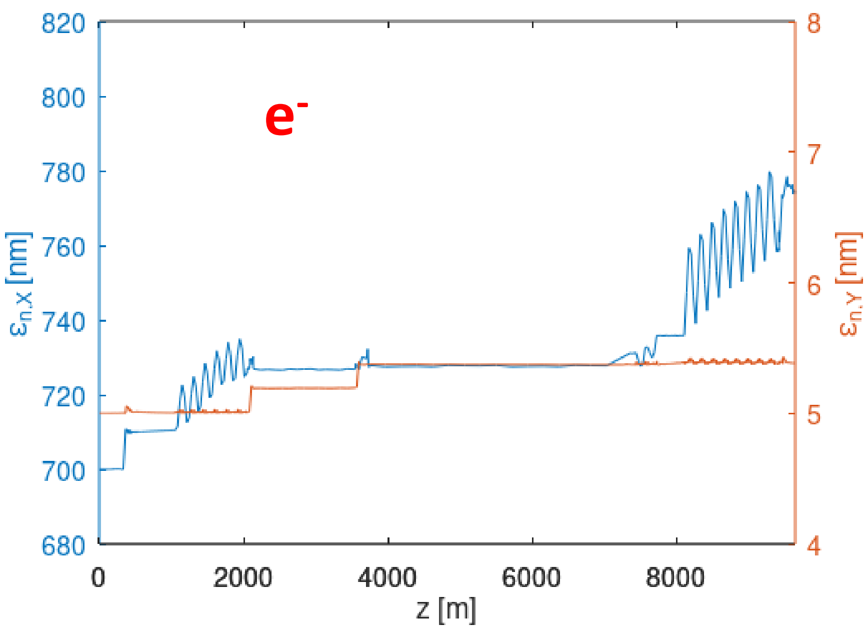


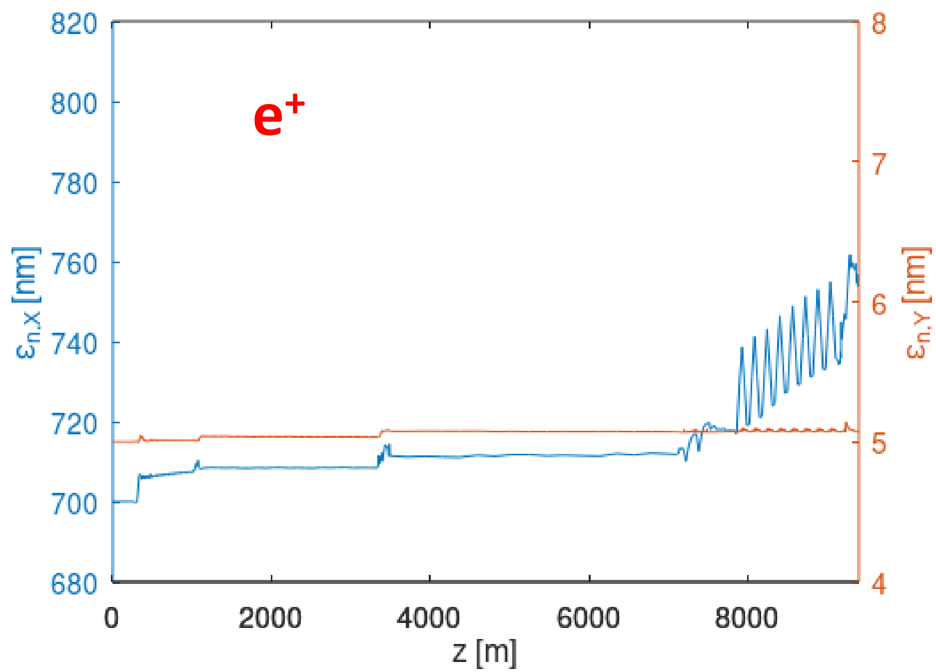
Results at end of RTML	Value
Bunch length [μm]	69.9
Energy spread [%]	1.0
Horizontal emittance [nm]	754.0
Vertical emittance [nm]	5.07

Perfect results!

Optimisation results

- Comparison with e⁻





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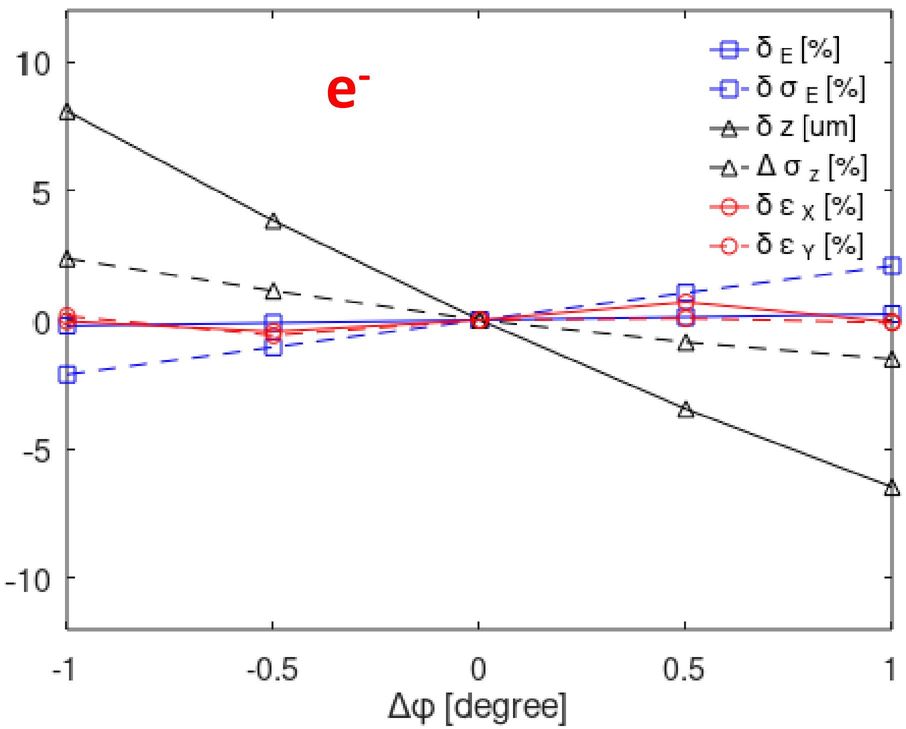
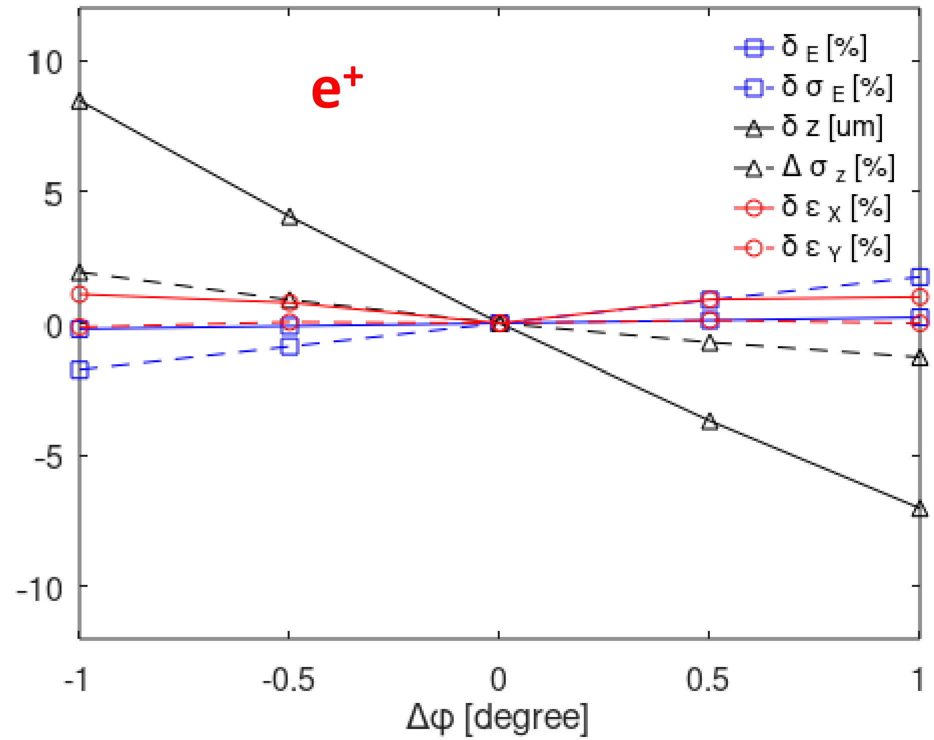
Vertical emittance [nm]	5.38

Results at end of RTML	Value
Bunch length [µm]	69.9
Energy spread [%]	1.0
Horizontal emittance [nm]	754.0
Vertical emittance [nm]	5.07

Bunch phase shift from DR

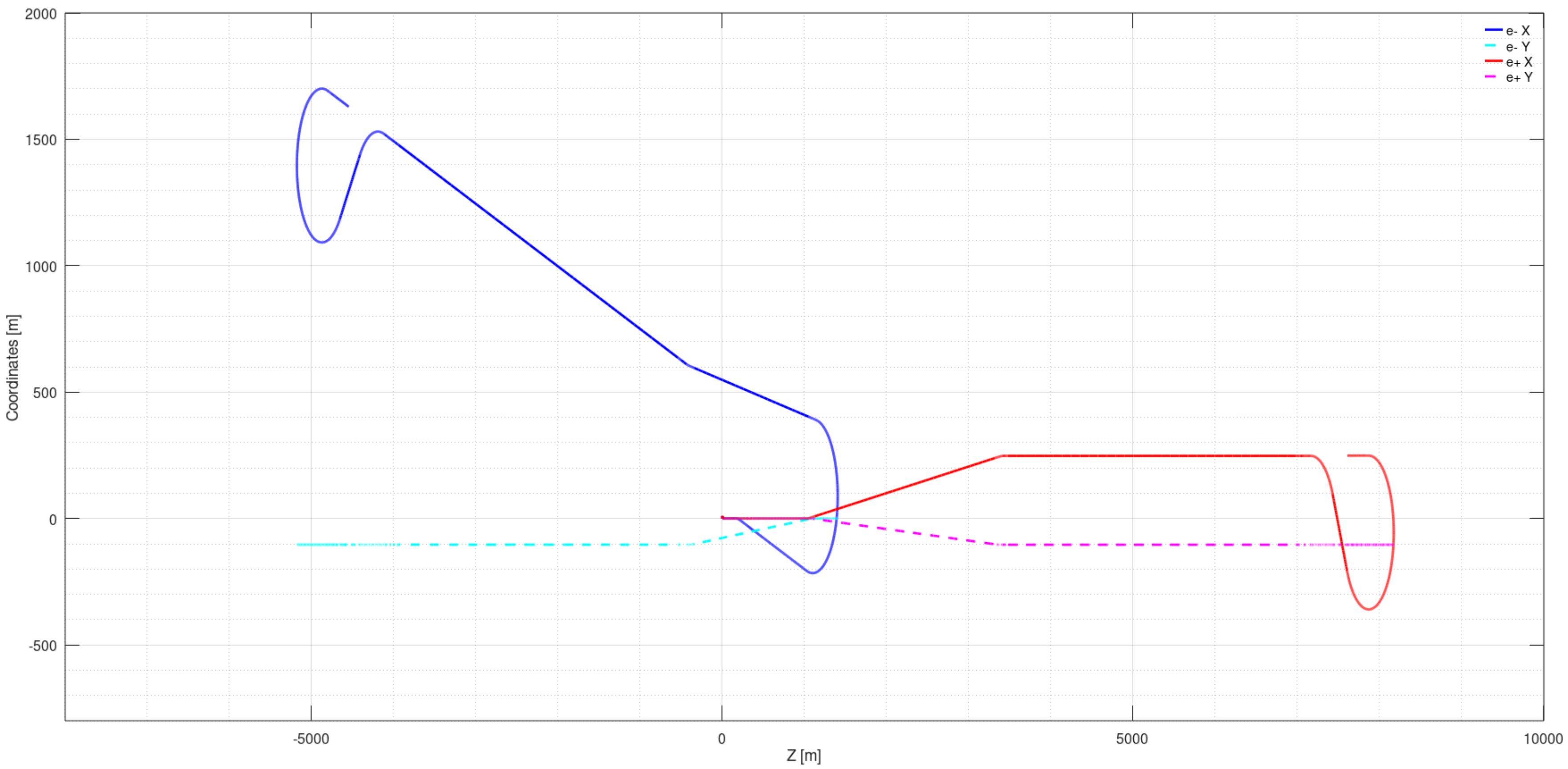
- Propagation in RTML (from DR to ML)
  - **consistent with e-**
  - **Phase shift elimination with reduced angle not yet implemented**





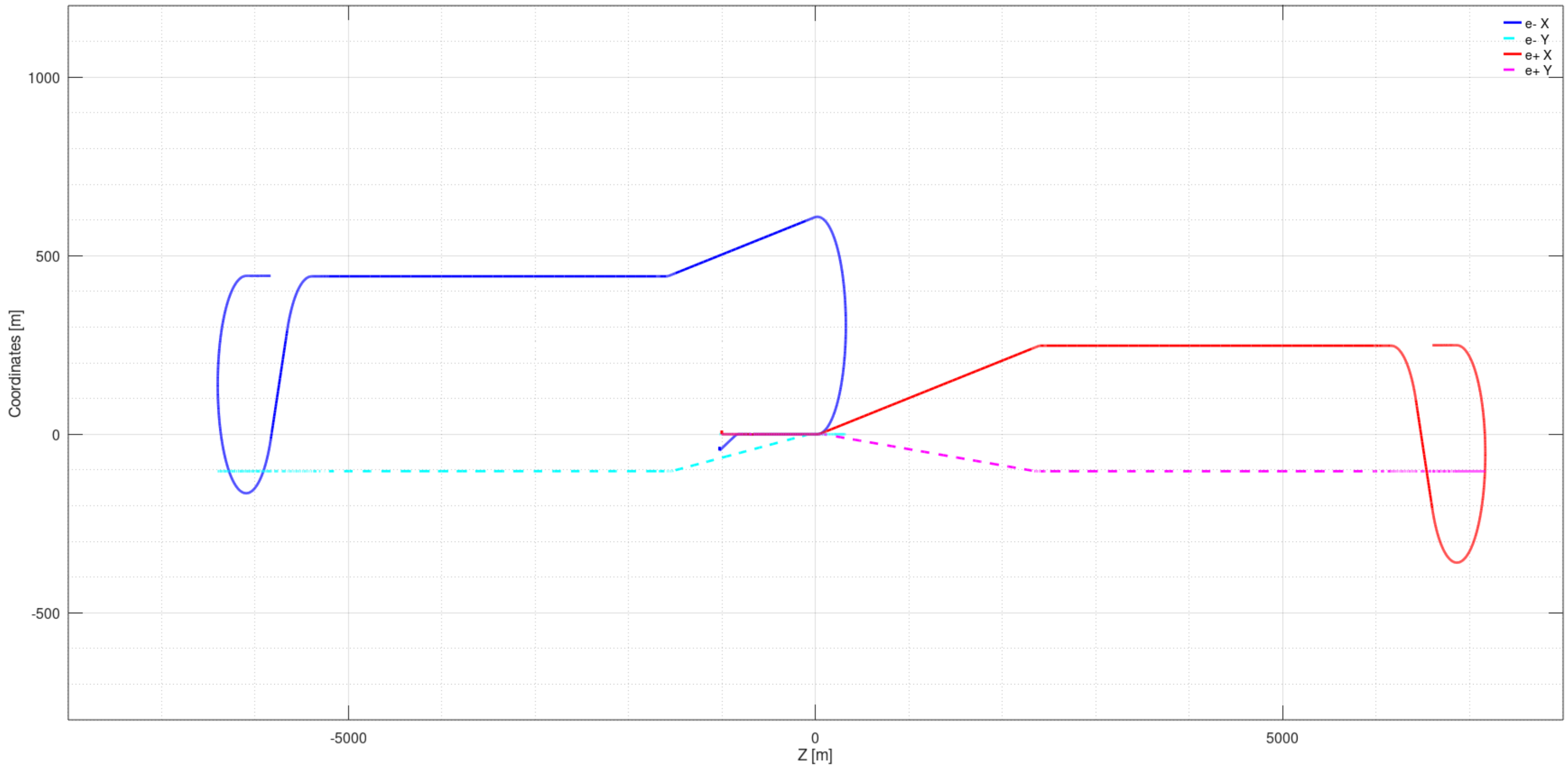
Footprint matching

- Drawing of raw footprint from *Placet*



Footprint

- e- beamline aligned (rotated by 13.9°) to share the same booster linac with e+
- Exit of booster linac is set as (0, 0) point



- Mismatching between e- and e+ horizontally and longitudinally
- Increasing e+ CA bending angle might help?
- Maybe not a big problem? Leave it for the moment?

Optimisation for other beam options

	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			
	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	
BC1	RF structure type			CLIC L-band											
	RF total voltage	V_1	MV	350				350				350			
	RF structure length	L_1	m	1.5											
	Number of RF structures	N_1		12				12				12			
	RF average gradient	G_1	MV/m	19.444				19.444				19.444			
	Chicane angle	θ_1	°	4.58	4.60			4.59	4.60			4.40	4.41		
Booster linac	RF structure length	L_{bo}	m	1.5											
	Number of RF structures	N_{bo}		272											
BC2	RF structure type			TD-31				CLIC-K				CLIC-G*			
	RF total voltage	V_2	MV	750				750				1200			
	RF structure length	L_2	m	0.275				0.23				0.23			
	Number of RF structures	N_2		32				40				64			
	RF average gradient	G_2	MV/m	85.228				81.522				81.522			
	Chicane 1 angle	$\theta_{2,1}$	°	1.54				1.53				1.30			
	Chicane 2 angle	$\theta_{2,2}$	°	1.54				1.53				1.30			
Final results (Nominal)	Bunch length	σ_z	um	70.0	69.9			70.1	70.0			44.2	44.0		
	Energy spread	σ_E	%	1.0	1.0	In progress		1.0	1.0	In progress		1.8	1.8	In progress	
	Normalised horizontal emittance	$\varepsilon_{n,x}$	nm	774.0	754.0			569.0	561.4			560.5	543.9		
	Normalised vertical emittance	$\varepsilon_{n,y}$	nm	5.38	5.07			5.46	5.06			5.49	5.12		

Optimisation of BC2 RF structure

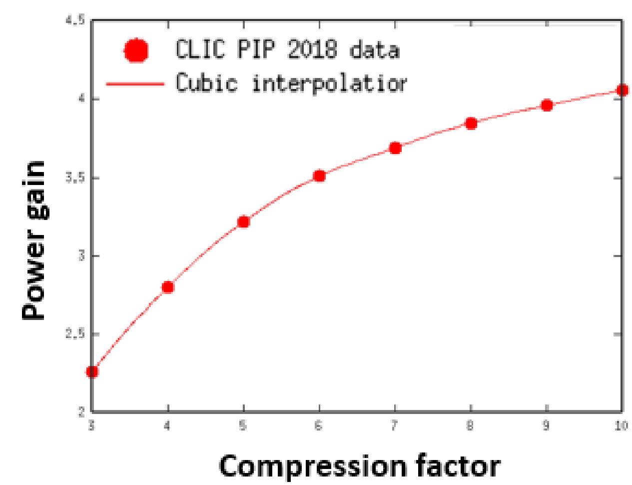
(very preliminary!)

Optimisation based on TD31 structure

- Original parameters (designed for ML, DBA @ 380 GeV)

				TD-31	CLIC-K	CLIC-G*
	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
BC2	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

- X-band RF system assumed in optimisation
  - Klystron output: 51.4 MW (70% efficiency), 2 μs,
  - Pulse compressor: power gain from interpolation →
  - RF transmission efficiency: 90%
  - Number of klystrons per modulator: 2
  - Number of RF structures per modulator: no limitation



[CLIC PIP report 2018]

Optimisation based on TD31 structure

- Optimisation strategy

  - **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: $\Delta d/l$

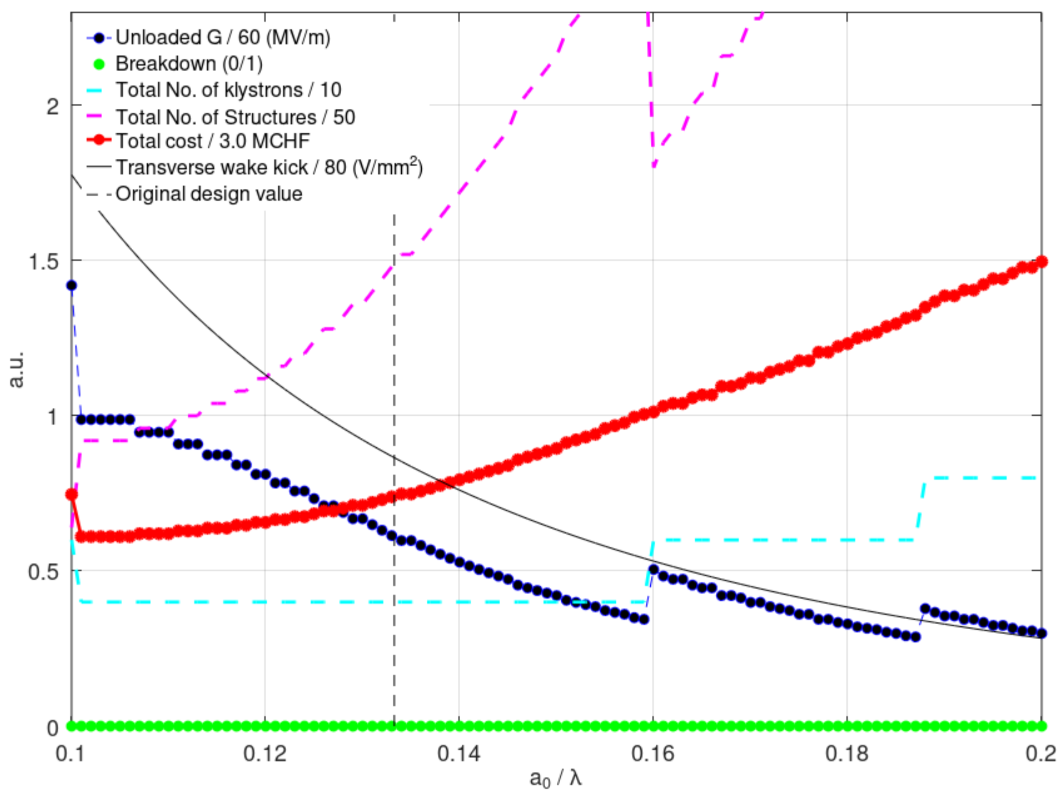
  - **To simplify the optimisation, the followings are assumed:**
    - ✓ During scan of a parameter, the other parameters are fixed to the original design values
    - ✓ The *CLICopti* tool is used to estimate the RF performance, such as break-down, peak power
    - ✓ Beam loading not considered as the structure works at 90° phase
    - ✓ Gradient is optimised such that there is no break-down and the total cost is minimum
    - ✓ Cost for klystron: 300 kCHF per klystron
    - ✓ Cost for RF structure: 50 kCHF per meter of structure

Optimisation based on TD31 structure

- Gradient is optimised for each scan value, as follows:
  - Scan total number of structures in range: N = [2, 4, 6, ..., 160] (to simplify the FODO lattice design)
  - For each N, calculate the gradient G = V / N / L, where V = 750 MV, L = 275 mm
  - Estimate the peak power and break-down status
  - Estimate the number of klystrons needed
  - Estimate the minimum total cost (of klystrons and structures)
- Then use the optimised gradient to estimate other figures of merit

Optimisation based on TD31 structure

- Optimisation results (first iteration): scan of a_0 / λ

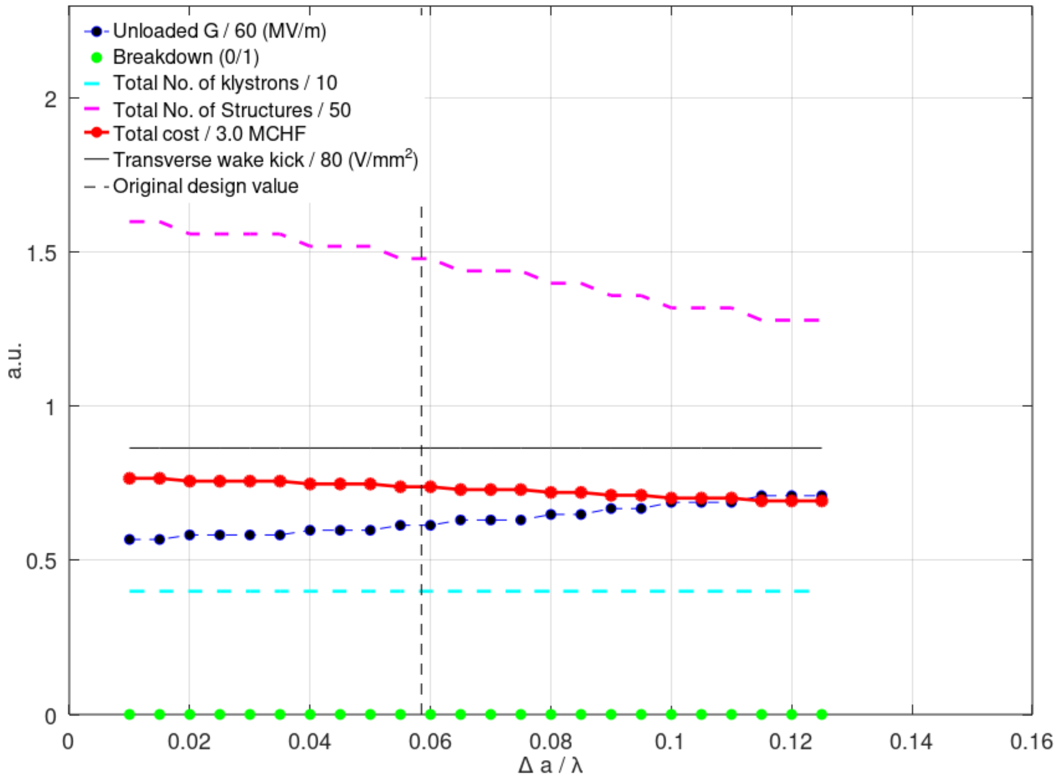


Parameter	Original (baseline)	Original (opt.)	Min. cost
a_0 / λ	0.1333	0.1333	0.106
G (MV/m)	85.228	36.855	59.289
No. of klystrons	10	4	4
No. of structures	32	74	46
Total cost (MCHF)	3.44	2.22	1.83
Trans. kick (V/mm²)	69.2	69.2	123.3

(saving 35%) (saving 47%)

Optimisation based on TD31 structure

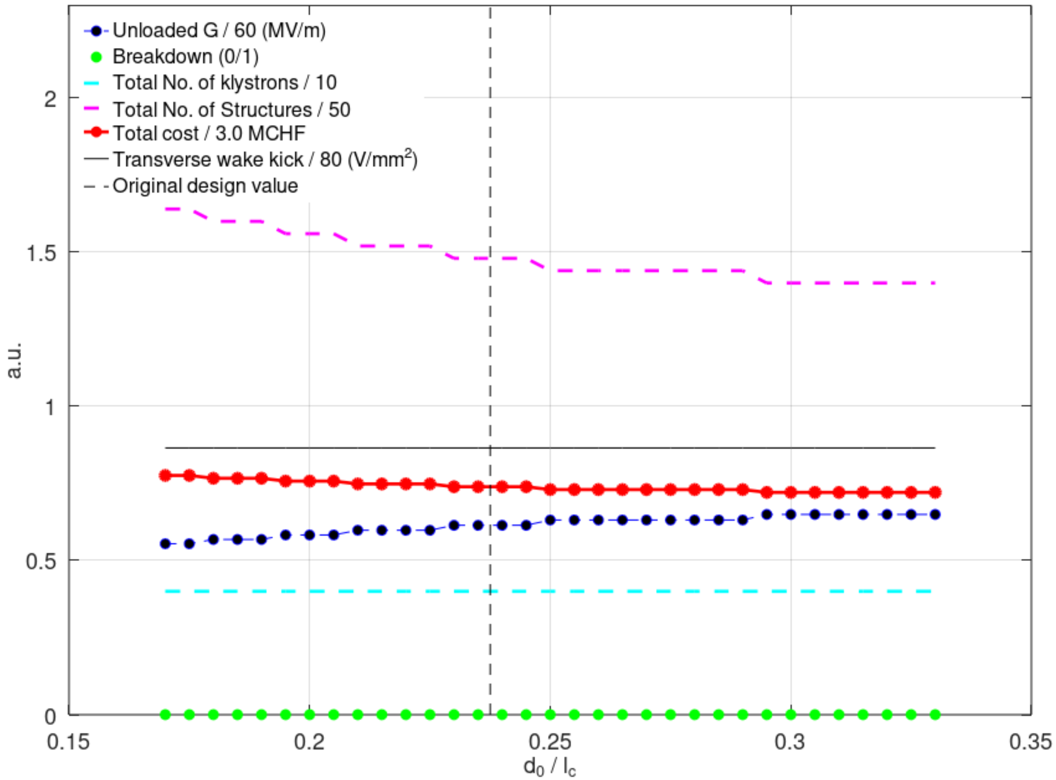
- Optimisation results (first iteration): scan of Δa / λ



Parameter	Original (baseline)	Original (opt.)	Min. cost
Δa / λ	0.0585	0.0585	0.115
G (MV/m)	85.228	36.855	42.614
No. of klystrons	10	4	4
No. of structures	32	74	64
Total cost (MCHF)	3.44	2.22	2.08
Trans. kick (V/mm^2)	69.2	69.2	69.2
		(saving 35%)	(saving 40%)

Optimisation based on TD31 structure

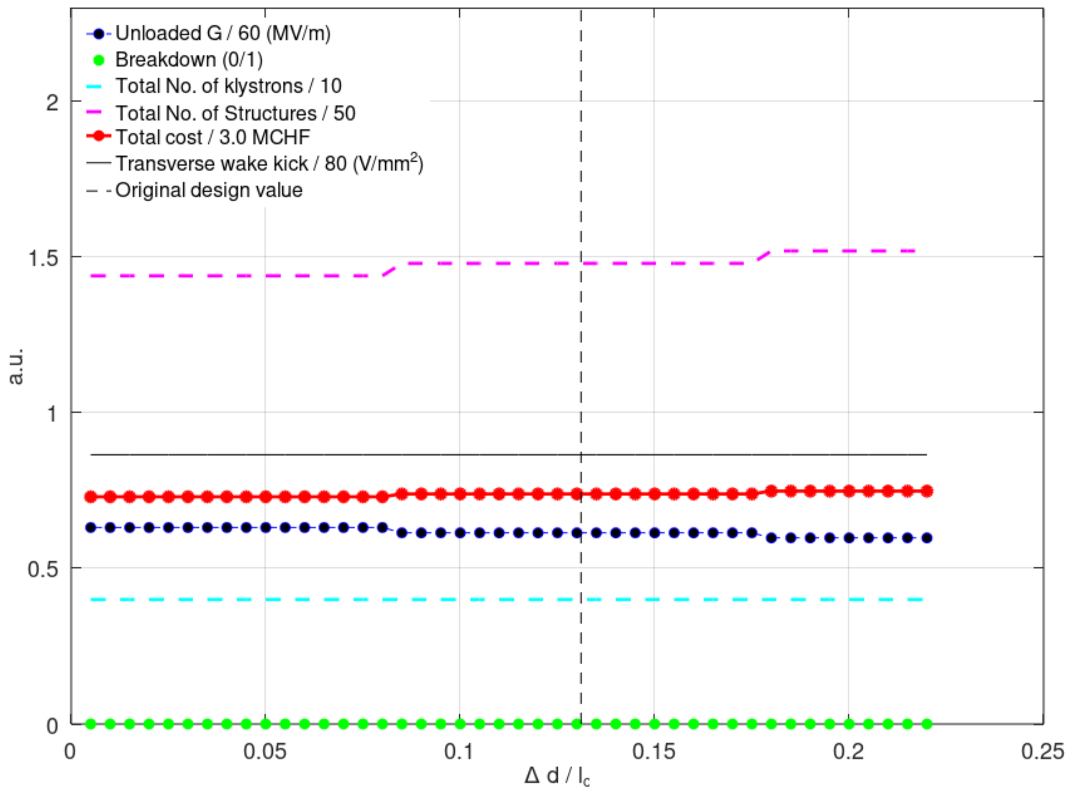
- Optimisation results (first iteration): scan of d_0 / l



Parameter	Original (baseline)	Original (opt.)	Min. cost
d_0 / l	0.2375	0.2375	0.2950
G (MV/m)	85.228	36.855	38.961
No. of klystrons	10	4	4
No. of structures	32	74	70
Total cost (MCHF)	3.44	2.22	2.16
Trans. kick (V/mm²)	69.2	69.2	69.2
		(saving 35%)	(saving 37%)

Optimisation based on TD31 structure

- Optimisation results (first iteration): scan of Δd / l

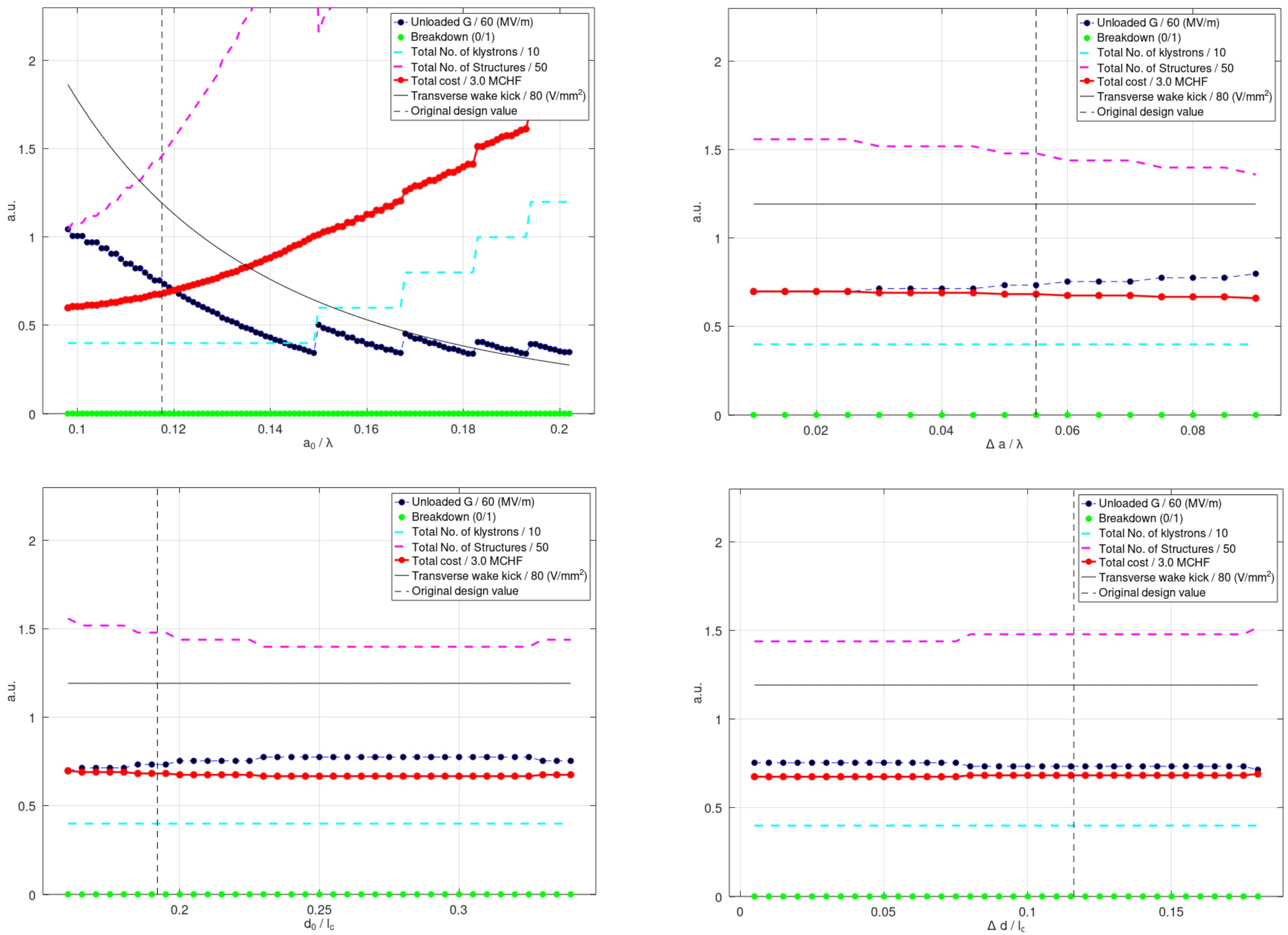


Parameter	Original (baseline)	Original (opt.)	Min. cost
Δd / l	0.1311	0.1311	0.080
G (MV/m)	85.228	36.855	37.879
No. of klystrons	10	4	4
No. of structures	32	74	72
Total cost (MCHF)	3.44	2.22	2.19
Trans. kick (V/mm²)	69.2	69.2	69.2

(saving 35%) (saving 36%)

Optimisation based on CLIC-K structure

- Test scan of CLIC-K used for BC2 (DBA @ 380 GeV)



Improved BBA procedure

(old results as presented at LCWS’23)

Imperfections

❑ Normalised emittance budgets for RTML

➢ **Study focused on static imperfections**

	Initial	Final emittance$^{(\star)}$		
		by Design	with Static Imperfections	with Dynamic Imperfections
ϵ_x [nm]	700	< 800	< 820	< 850
ϵ_y [nm]	5	< 6	< 8	< 10

$^{(\star)}$ 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

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

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

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

BBA procedure

□ 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

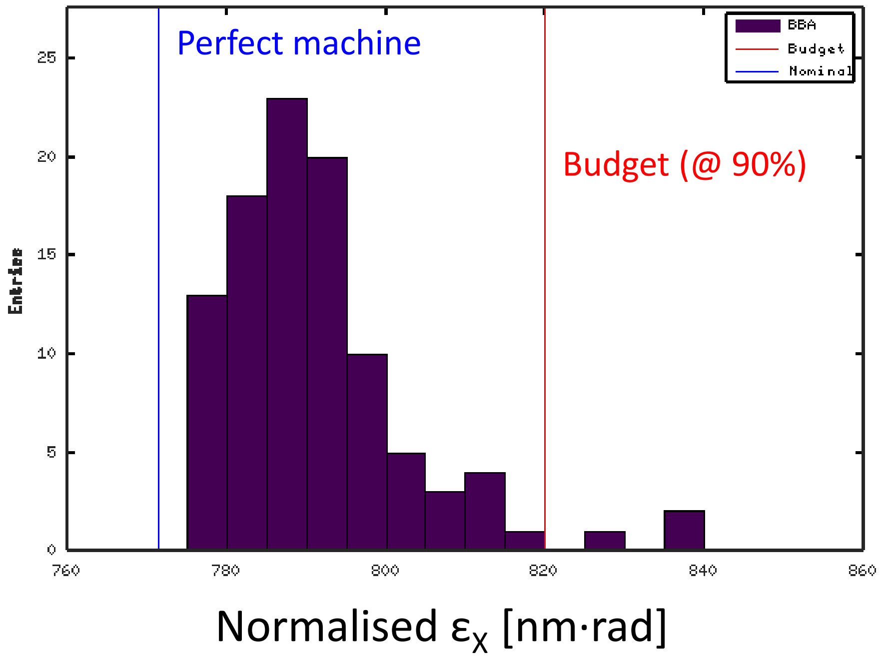
4) ST: TAL—BC2

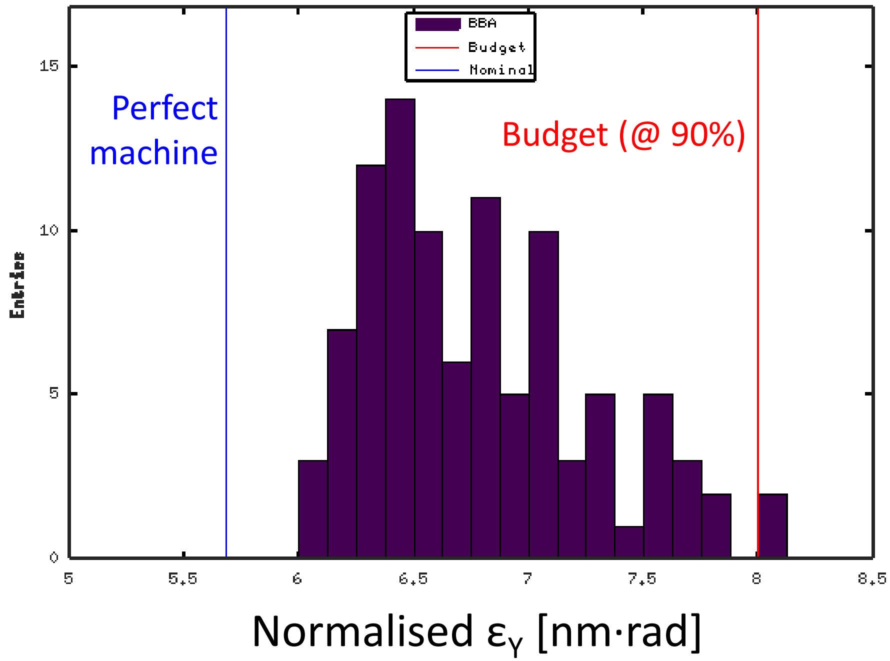
- The **first 5 sextupoles** of TAL tuned for minimum merit

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

BBA results (DBA @ 380 GeV, old DR, e-)

- **BBA correction results for 100 random machines w/ imperfections:**
  - **BC2 RF: CLIC-K structure (structure optimised: $a_0/\lambda = 0.115$)**
  - **BC2 toltal voltage is still 1209 MV instead of 750 MV (BC1, BC2 not optimised)**





- **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**

Good results!

BBA works well.

Conclusions

- BC1 and BC2 reoptimised for the CLIC RTML, and very good results obtained at the end of RTML. As a baseline, the same X-band structure (original design) is assumed with the main linac. Expected total cost reduction is ~35% for BC1 and BC2, compared with CDR and previous designs
- Effect of bunch phase shift from DR is studied and well eliminated
- Studies of the e^+ and other options are also presented. Consistent bunch phase shift between e- and e+ but there is a mismatching in the footprint
- Alternative X-band structures are also studied by optimising the baseline structure. Very preliminary results (optimisation based on TD31) show a further cost reduction of 35% (original design with very low gradient) - 50% (reduced aperture) in BC2, but the BBA needs to be checked
- An improved BBA procedure is developed and works well (but not yet tested for the new optimisations)

Open questions

- **Still a lot to be done.** The study is far more complicated than expected with so many options and tasks. Not possible to do all **optimisations, BBA tests and other studies** for all options. How to simplify the study?
    - DR options: old DR, new DR with reduced emittances
    - Energy options: 380 GeV, 3 TeV
    - Beam option: e-, e+
    - Acceleration mode options: DBA, KBA
    - RF structure options: BC1 & BL: CLIC L-band; BC2: TD-31, CLIC-K, CLIC-G*
- Is it necessary to optimise the X-band structure?
    - The same structure with main linac is preferred (as the design is already qualified and BC2 is negligible compared to main linac which has 20,592-143,232 structures)?
    - Or a lower cost of BC2 (e.g. 2.2 MCHF→1.8 MCHF, reduced by 18%) is preferred?

Acknowledgement

- **Thanks very much for your attention and comments!**

- Many thanks to

  - Y. Han, C. Gohil, X. Liu et al. for their contributions in previous studies and simulation code development

  - H. Bartosik, A. Grudiev, Y. Papaphilippou, D. Schulte, P. Wang, etc. for helpful discussions

  - ...

BACKUP

Footprint

- CDR 2012

The distance between the first bunches of the two trains is 1100 ns, which allows to independently perform beam loading compensation for each train. This corresponds to a path length difference to the beginning of the linacs of 330 m.

The optimum solution for RF operation and train timing would be to power the booster linac with two separate RF pulses for electrons and positrons. This would require the two trains to be separated by 3.6 μs. It would increase the RF efficiency, simplify the beam loading compensation [75] and improve the train combination. The only drawback is that the path length difference would increase to 1200 m, a value that cannot easily be incorporated into the current civil engineering layout.

3.3.3.4 Central arc and transfer to tunnel

The central arcs transport the beams from the booster linac both horizontally and down 100 m vertically to the main linac tunnels. The beam lines also compensate for the timing offset between electrons andpositrons.

The electrons are bent by 180° in the central arc to send them towards the end of their linac. The arc has an average radius of 305 m. The lattice is copied from the lattice of the turn-around loops (see below). It is achromatic, almost isochronous, and optimized for acceptable emittance growth due to incoherent synchrotron radiation (ISR). A dog-leg follows this arc to correct the horizontal offset. The vertical transfer to the tunnel takes place in the straight section of the dog-leg. Two vertical arcs are connected by a simple periodic lattice. To limit the slope of the beamline, the straight section is about 1400 m long. Horizontal and vertical bends are separated to simplify the lattices and to avoid coupling of the planes. The total length of electron arc and transfer is 2400 m.

The positron beam is already pointed in the right direction, so the central arc is just a dog-leg with the vertical transfer to the tunnel embedded as for the electrons. To correct the bunch train timing, the path length for the positrons needs to be shorter compared to the electron path length. The current baseline in the civil engineering layout has a difference of 221.8 m. The total length of positron dog-leg and transfer is 2180 m which does not influence the beam dynamics. The lattices of the arcs are similar to those for electrons.

- PIP 2018

Line (LTL) and the Turn-Around Loop (TAL). The positron RTML is composed of the same subsystems as the electron line, with the exception of the SR which is absent. A sketch of the whole RTML lines is visible in Fig. 2.3. The RF system of the booster linac, which accelerates both electrons and positron trains, determines the position and the length of the two arms of the RTML. An optimisation of the booster RF system aimed at minimising cost while maximising efficiency, lead to having the two electron / positron pulses separated by ≈ 3.4 μs. This imposes a path-length difference from the booster to the IP of about 1020 m.

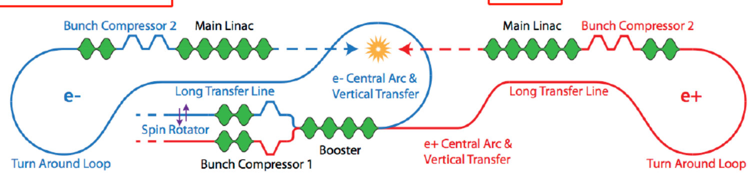


Figure 2.3: Sketch RTML section, all subsystems are visible (dimensions not-to-scale).

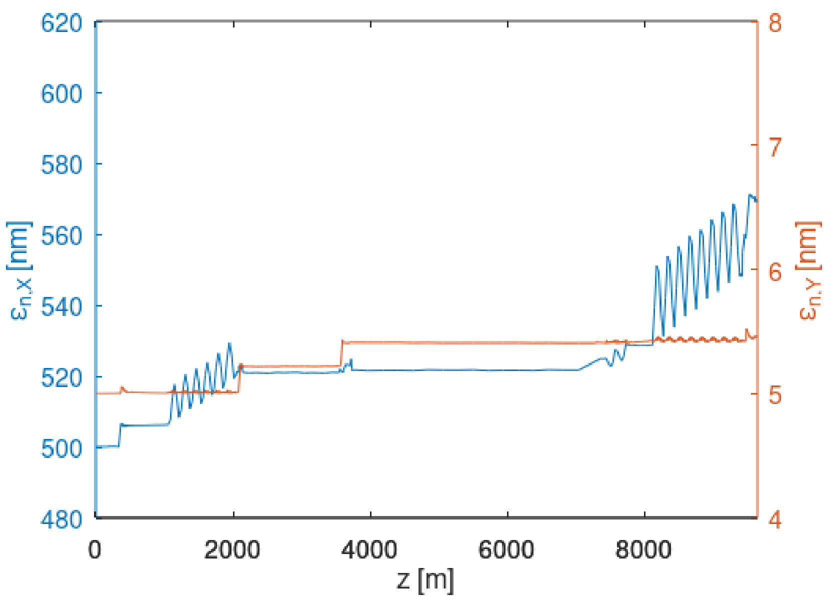
Seems that e+ CA & VT lattice needs to be corrected

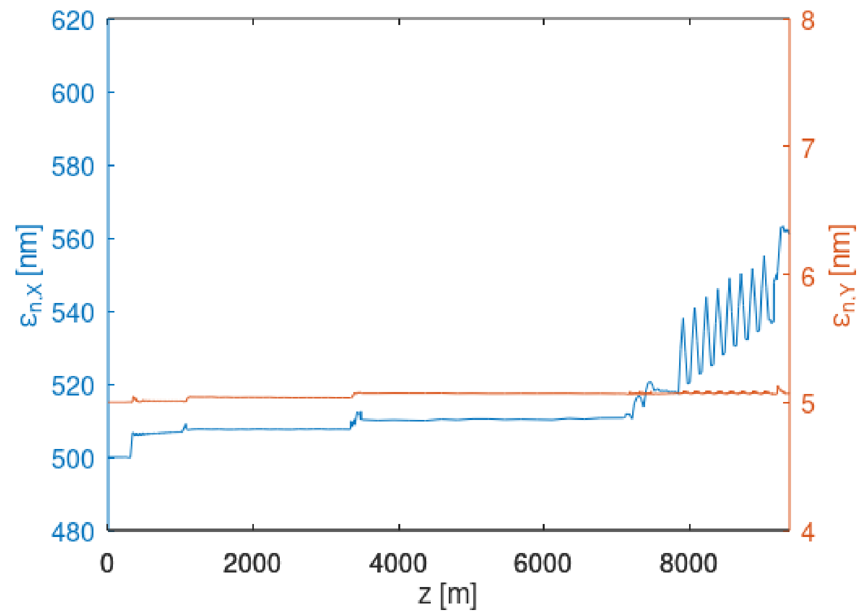
In current lattice of CA and VT:

- e- dog-leg bending: 6 degree
- e+ dog-leg bending: 6 degree (should be larger or longer?)
- Path length difference: 223.5 m

380 GeV, KBA, Old DR, e-

- Results for e- (left) and e+ (right)



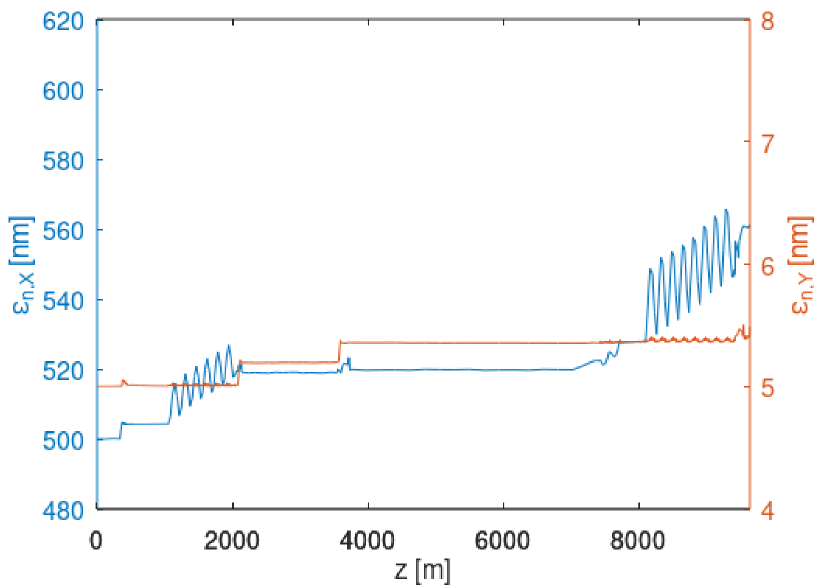


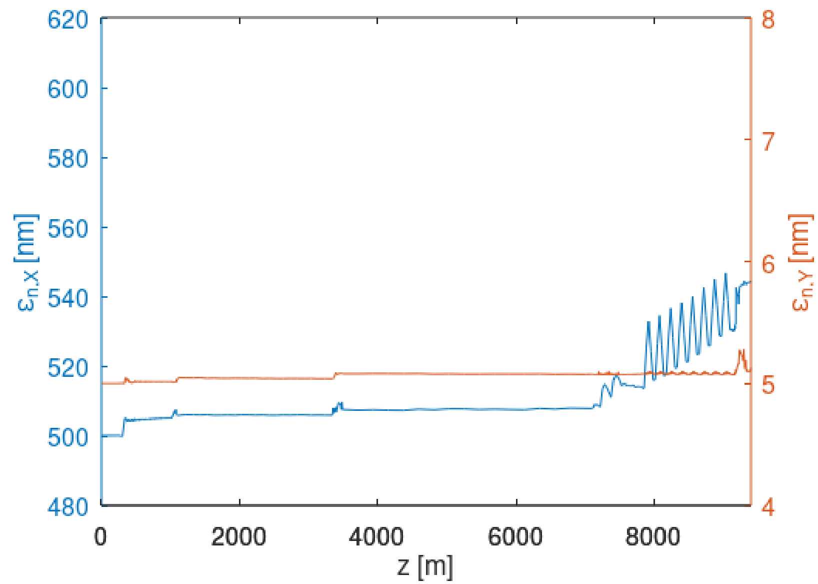
Results at end of RTML	Value
Bunch length [μm]	70.1
Energy spread [%]	1.0
Horizontal emittance [nm]	569.0
Vertical emittance [nm]	5.46

Results at end of RTML	Value
Bunch length [μm]	70.0
Energy spread [%]	1
Horizontal emittance [nm]	561.4
Vertical emittance [nm]	5.06

3 TeV, DBA, Old DR

- Results for e- (left) and e+ (right)





Results at end of RTML	Value
Bunch length [µm]	44.2
Energy spread [%]	1.8
Horizontal emittance [nm]	560.5
Vertical emittance [nm]	5.49

Results at end of RTML	Value
Bunch length [µm]	44.0
Energy spread [%]	1.8
Horizontal emittance [nm]	543.9
Vertical emittance [nm]	5.12