Start-to-end Beam-Based Alignment in the CLIC RTML

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Outline

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   - Ring To Main Linac
   - Static misalignment
   - Correction methods
2. Beam-based Alignment
   - Simulation conditions
   - Dispersion correction
   - Coupling correction
   - Multipoles
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Ring To Main Linac(RTML) [1]

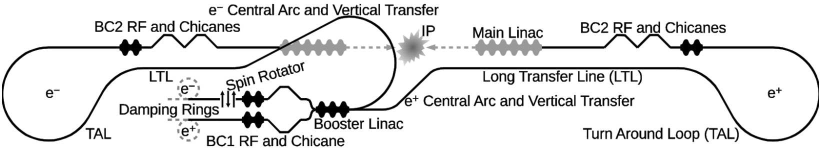


Figure: Sketch of RTML

- RTML connects the damping rings and the main linacs
- Match beam properties
- Two RTMLs with total length of approximately 27 km for each

Table: Beam properties at the start and end of the RTML for 3 TeV machine

Properties [units]		Value at the start	Value at the end
Particle energy [GeV]	E_0	2.86	9
r.m.s. bunch length [μm]	σ_s	1800	44
r.m.s energy spread [%]	σ_E	0.12	1.7
Normalized emittance [nm rad]	$\epsilon_{n,x}$	500	600
	$\epsilon_{n,y}$	5	10

We focus on the electron part.

Static Misalignment

The vertical emittance budget for static misalignment is $\epsilon_y < 8\ \mathrm{nm}\cdot\mathrm{rad}$

- 5 $\mathrm{nm}\cdot\mathrm{rad}$ - the initial emittance
- 1 $\mathrm{nm}\cdot\mathrm{rad}$ - lattice design emittance growth
- 2 $\mathrm{nm}\cdot\mathrm{rad}$ - static alignment emittance growth

The effect of magnets:

Table: The effect of mis-alignment on different magnets

	position offset	angle offset	roll
Dipole	ok	Dispersion	Dispersion
Quarupole	Dispersion	Dispersion	Coupling
Sextupole	Quadrupole, Coupling	Coupling	Couling ...

The effect of BPM:

- Position offset: wrong position measurement.
- Resolution: make corrections worse

Correction Methods - Dispersion

One to One (1:1)

- *BPM measurements:* $\boldsymbol{u}$. ($\boldsymbol{u}_0$*: results on perfect machine)*
- *Correctors strength:* θ.
- *Response Matrix:* $\boldsymbol{R}$
- $\theta = min\ \{\ ||\ \Delta\boldsymbol{u} - \boldsymbol{R}\theta||_2^2 + \beta_0^2\ ||\theta||_2^2\ \}$, *here* $\Delta\boldsymbol{u} = \boldsymbol{u} - \boldsymbol{u}_0$, β_0 *is a parameter.*

Dispersion Free Steering (DFS)—Correct the errors from BPM positions

- *Normal beam go through the Lattice, response matrix* R_1*, BPM readings:* $\boldsymbol{u}_1$ *- mis-aligned machine;* $\boldsymbol{u}_{d1}$ *- perfectly aligned machine*
- *Beams go through the scaled lattice, response matrix* R_2*, BPM readings:* $\boldsymbol{u}_2$ *mis-aligned machine;* $\boldsymbol{u}_{d2}$ *- perfectly aligned machine*
- *Dispersion matrix* $D = R_2 - R_1$*, Dispersion* $\eta = \boldsymbol{u}_2 - \boldsymbol{u}_1 - (\boldsymbol{u}_{d2} - \boldsymbol{u}_{d1})$
- $\theta = min\ \{\ ||\ \Delta\boldsymbol{u} - R_1\theta||_2^2 + \omega^2||\eta - D\theta||_2^2 + \beta_1^2\ ||\theta||_2^2\ \}$;

Correction Methods - Response Matrix

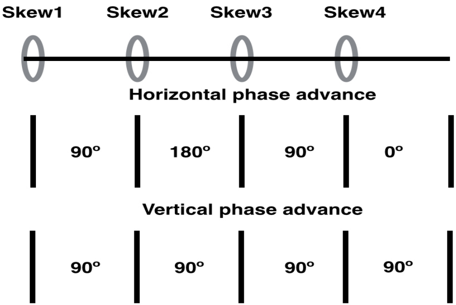
Matrix between the correctors strength and BPMs readings.

- This matrix is got from BPMs readings when giving correctors a kick.
- For beams with different energy, response matrices are different.

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ \vdots \\ u_m \end{pmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1n} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2n} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{m1} & R_{m2} & R_{m3} & \cdots & R_{mn} \end{bmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \vdots \\ \theta_n \end{pmatrix}$$

Correction Methods - Coupling

In principle at least four skew quadrupoles are needed to perform a coupling correction.



- Local correction - The four coupled beam items $< xy >$, $< x'y >$, $< xy' >$ and $< x'y' >$ are minimized locally
- Global correction - Minimize the final emittance

General simulation conditions

- Each quadrupole is followed by a dipole corrector
- The magnets and BPMs are randomly mis-aligned with σ_{pos}
- 100 machines with different random seeds are simulated.
- 10,000 particles in one bunch
- ISR and wake field are included.

BBA on the RTML

Only quadrupoles and BPMs are mis-aligned.

- SR $\rightarrow$ TAL, $\sigma_{\text{pos}} = 30\ \mu\text{m}$, $\sigma_{\text{res}} = 1\ \mu\text{m}$
- BC2, $\sigma_{\text{pos}} = 10\ \mu\text{m}$, $\sigma_{\text{res}} = 0.1\ \mu\text{m}$ (the RF cavity is 12 GHz X-band structures like in the ML with larger apertures)

One to one and DFS corrections are applied.

Parameters Optimisation

Three parameters

- *OTO* - $\theta = min\ \{ \|\ \Delta \mathbf{u} - \mathbf{R}\theta\|_2^2 + \beta_0^2\ \|\theta\|_2^2\ \}$
- *DFS* - $\theta = min\ \{ \|\ \Delta \mathbf{u} - R_1\theta\|_2^2 + \omega^2 \|\eta - D\theta\|_2^2 + \beta_1^2\ \|\theta\|_2^2\ \}$

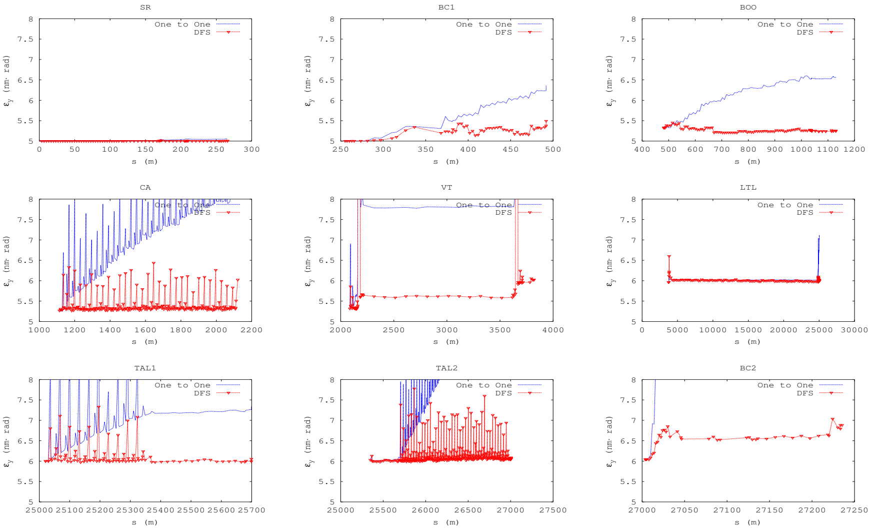
β_0 and β_1

- *SR $\rightarrow$ TAL, we set $\beta_0 = 5$ and $\beta_1 = 3$*
- *BC2, scan the region $[1:7] \times [1:7]$ and get $\beta_0 = 1$ and $\beta_1 = 1$*

ω

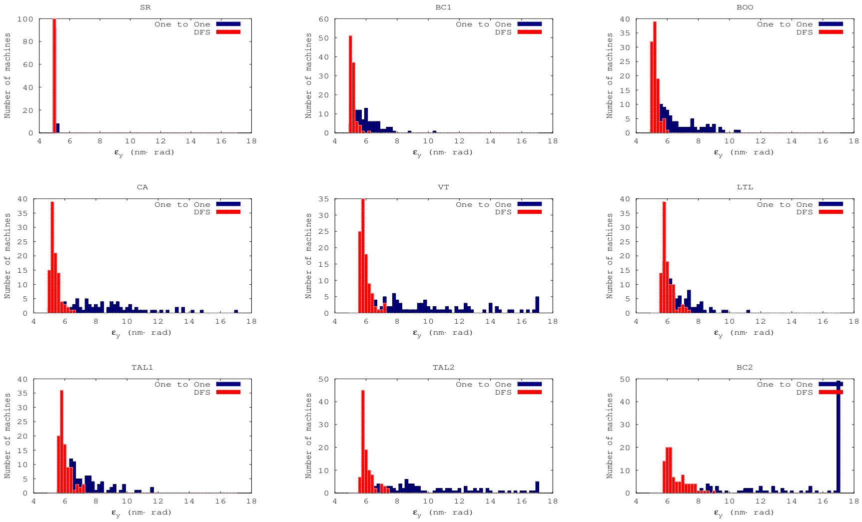
- *SR $\rightarrow$ TAL, we set $\omega = 30$*
- *BC2, final emittance is not sensitive to ω in the region [10:100]. We set $\omega = 30$ too.*

Dispersion result - Vertical emittance



The emittance growth is almost from BC1, VT and BC2.

Dispersion result



93% of the machines stay in the budget ($< 8\ \mathrm{nm\cdot rad}$).

More magnets misalignment

This is very good. So we can add more elements errors!

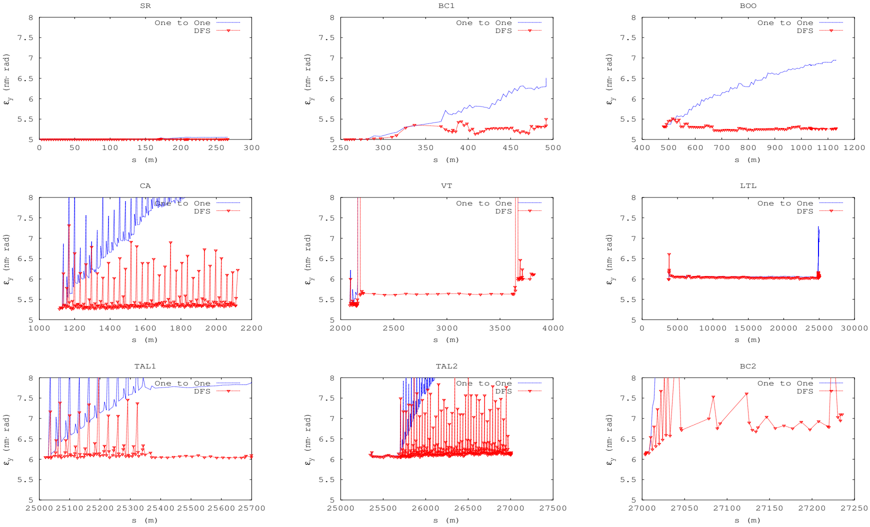
- Angle offset errors are added.
- Roll errors are added
- Dipole magnets are also mis-aligned

The angle errors are 30 μrad SR $\rightarrow$ TAL, 10 μrad for BC2.

The coupling will appear!

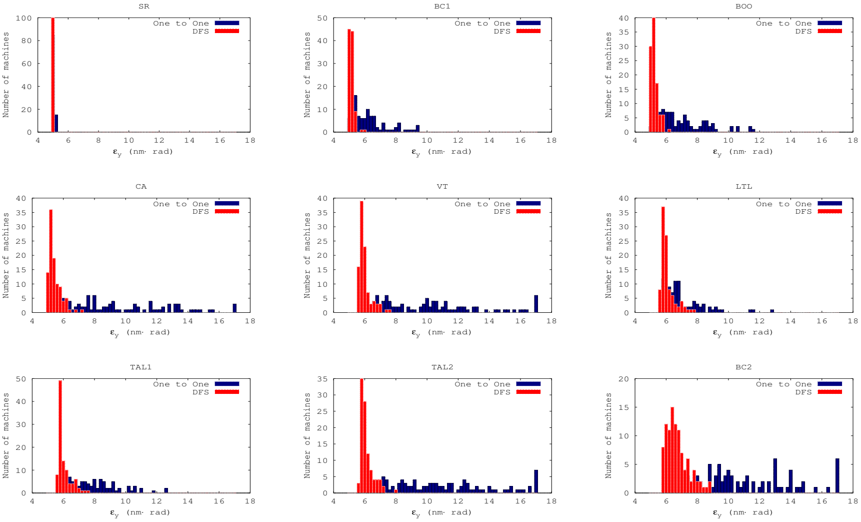
We apply the BBA first.

BBA result



The final emittance become a little worse and has some fluctuation.

BBA result



92% of the machines stay in the budget ($< 8\ \mathrm{nm} \cdot \mathrm{rad}$).

Coupling correction

Then we do the coupling correction.

- Local correction - The four coupled beam items $< xy >$, $< x'y >$, $< xy' >$ and $< x'y' >$ are minimized locally
- Global correction - Minimize the final emittance

Two skew sections are added:

- Before the Central Arc
- Before the BC2

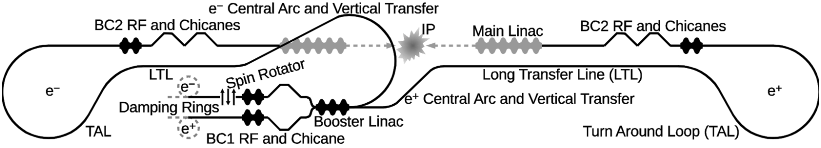
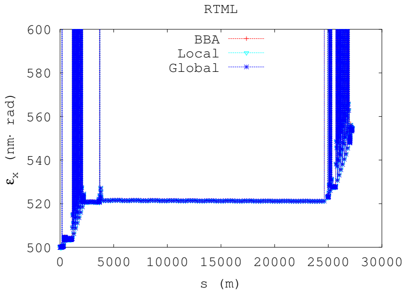
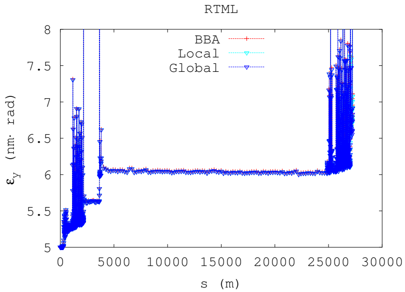


Figure: Sketch of RTML

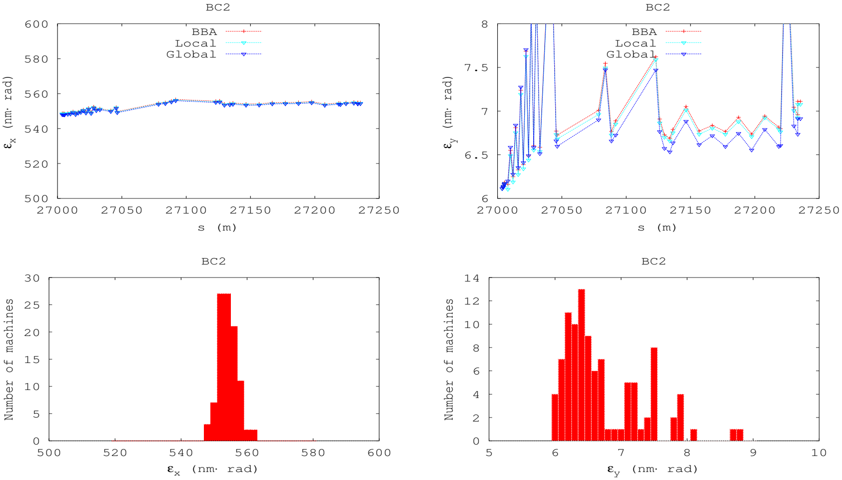
Coupling correction-BC2

Compare to the perfect RTML lattice, the vertical emittance does not grow much before BC2. *So the coupling correction effect is small before BC2.*





Coupling correction - BC2



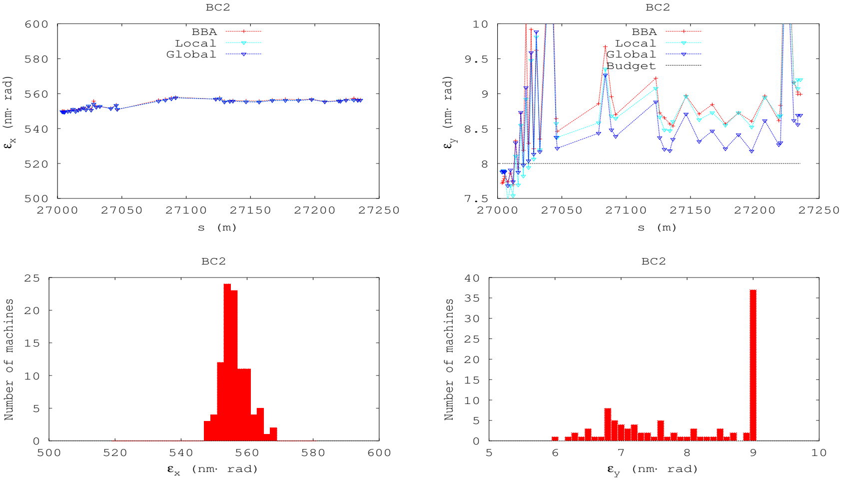
- Great vertical emittance improvement for global coupling correction.
- The vertical emittance growth is almost from the RF parts.

The final vertical emittance will stay in the budget in the condition:

- Dipoles, Quadrupols and BPMs are mis-aligned
- SR $\rightarrow$ TAL, $\sigma_{\mathrm{pos}} = 30\ \mu\mathrm{m}$, $\sigma_{\mathrm{res}} = 1\ \mu\mathrm{m}$ and $\sigma_{\mathrm{roll}} = 30\ \mu\mathrm{rad}$
- BC2, $\sigma_{\mathrm{pos}} = 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{res}} = 0.1\ \mu\mathrm{m}$ and $\sigma_{\mathrm{roll}} = 10\ \mu\mathrm{rad}$

Then we try to mis-aligned Multipoles. The results become worse.

Multipole errors



- Horizontal emittance is OK.
- 48% of the machines stay in the budget.

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3. Conclusion & Plan

Conclusion & Plan

- We successfully applied the BBA on the whole CLIC RTML.
- We still can not correct errors from multipoles.

Table: The effect of mis-alignment on different magnets

	position offset	angle offset	roll
Dipole	OK	OK	OK
Quarupole	OK	OK	OK
Sextupole	Quadrupole, Coupling	Coupling	Couling ...

Plan:

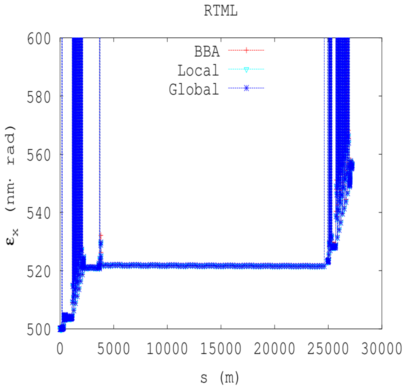
- Correct larger element errors, i.e., $\sigma = 50$ or $100\ \mu\mathrm{m}$
- Study how to correct the multipole errors
- Study BC1 and BC2 more carefully, which contribute most of the vertical emittance growth

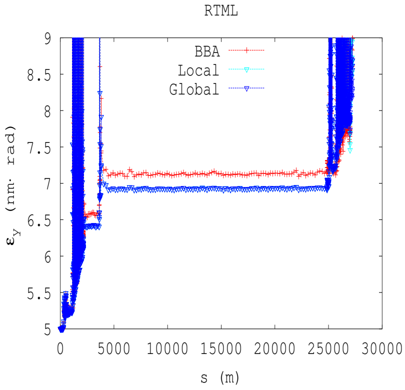
Thank you!

- CLIC CDR-Volume1, page 138
- CLIC CDR-Volume1, page 141
- Thibaut Lienart, CLIC Note 943, page 33.

Backup

Multipole


RTML
BBA
Local
Global
600
580
560
540
520
500
0
5000
10000
15000
20000
25000
30000
εx (nm· rad)
s (m)


RTML
BBA
Local
Global
9
8.5
8
7.5
7
6.5
6
5.5
5
0
5000
10000
15000
20000
25000
30000
εy (nm· rad)
s (m)