Simulation and optimisation of the Drive Beam Recombination Complex for CLIC

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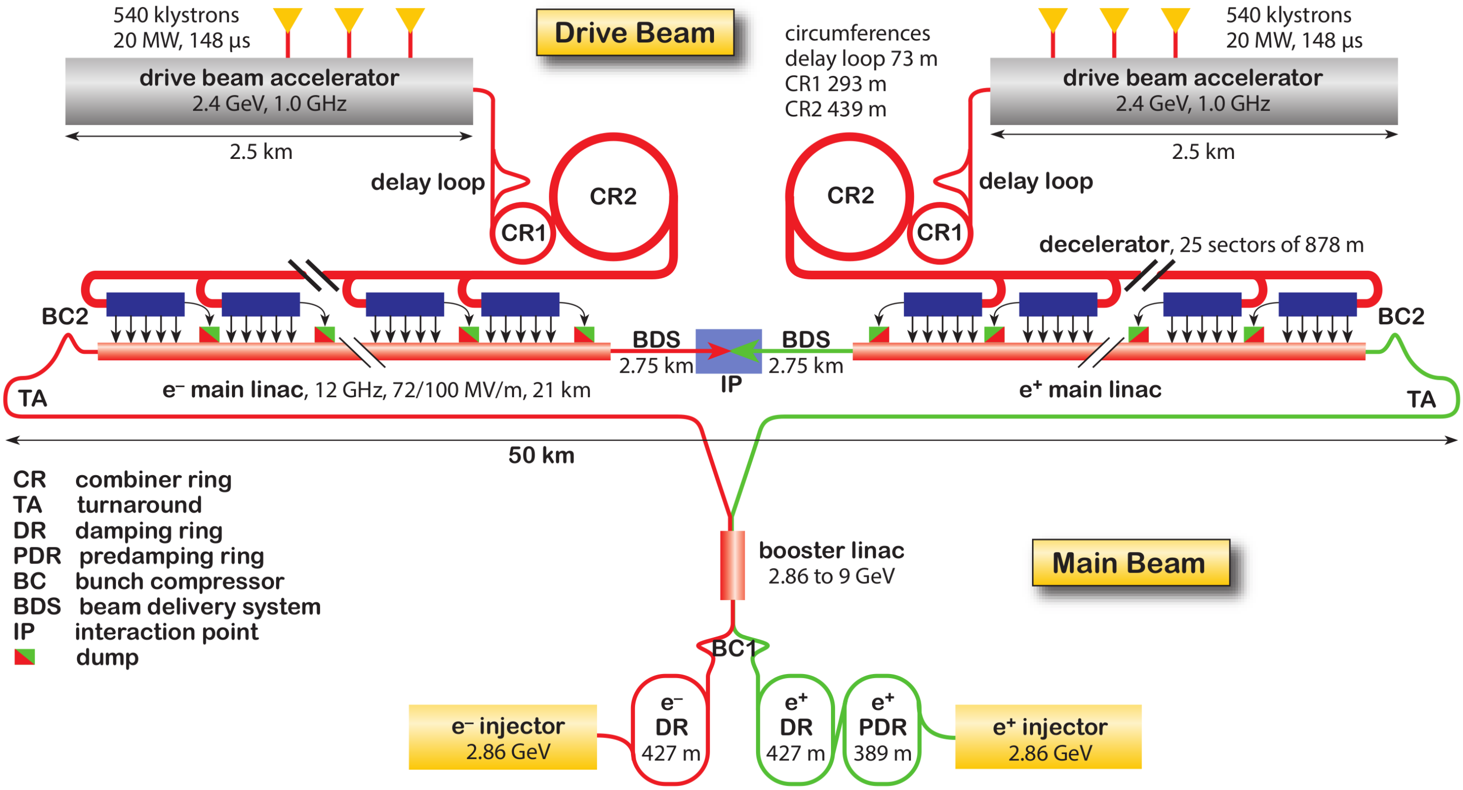
Outline

1. Introducing CLIC and the DBRC
2. Design challenges
3. Results
4. Optimisation techniques with particle losses
5. Conclusions and Outlook

Introducing CLIC and the DBRC

The Compact Linear Collider (CLIC)



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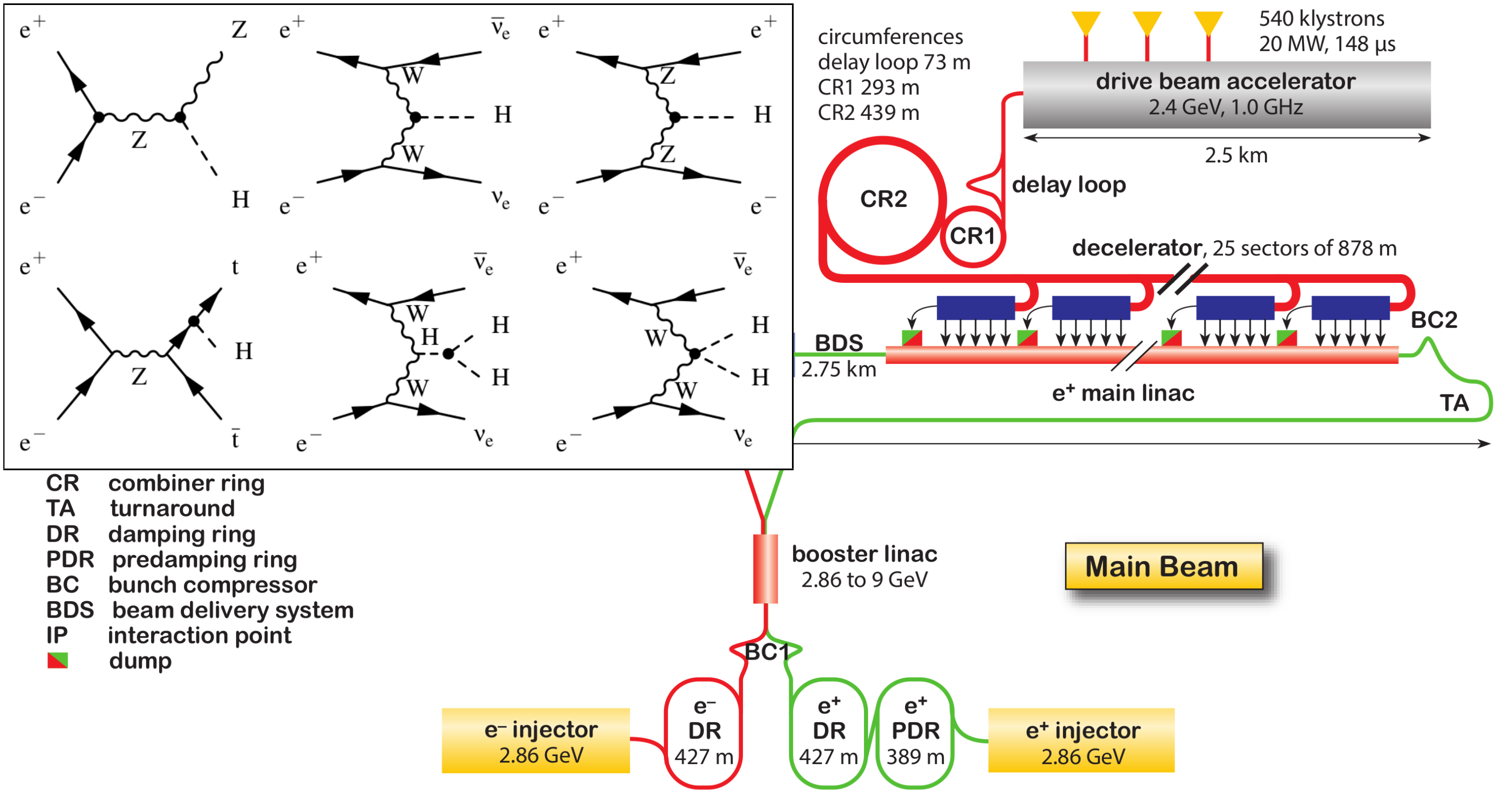

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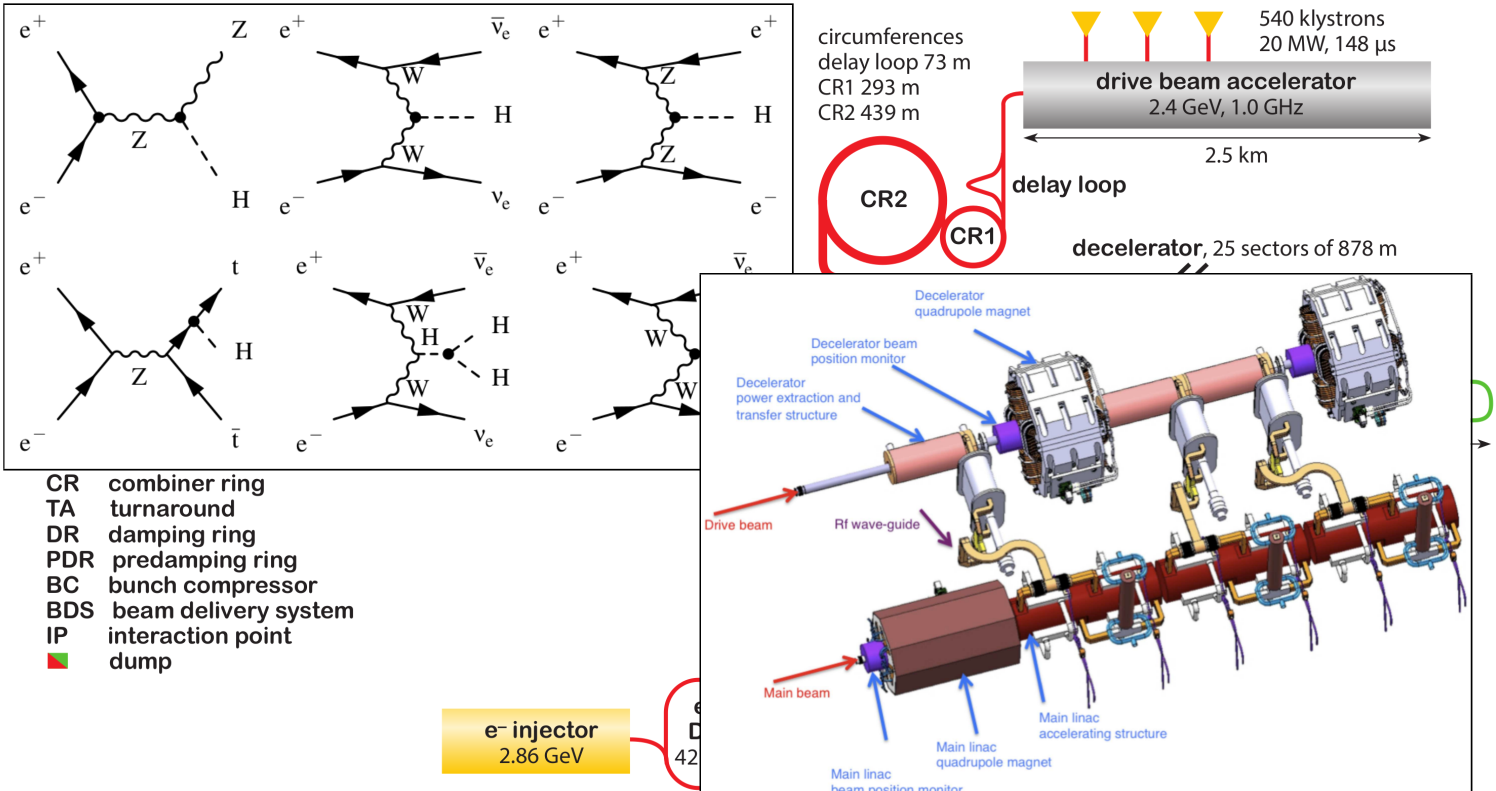

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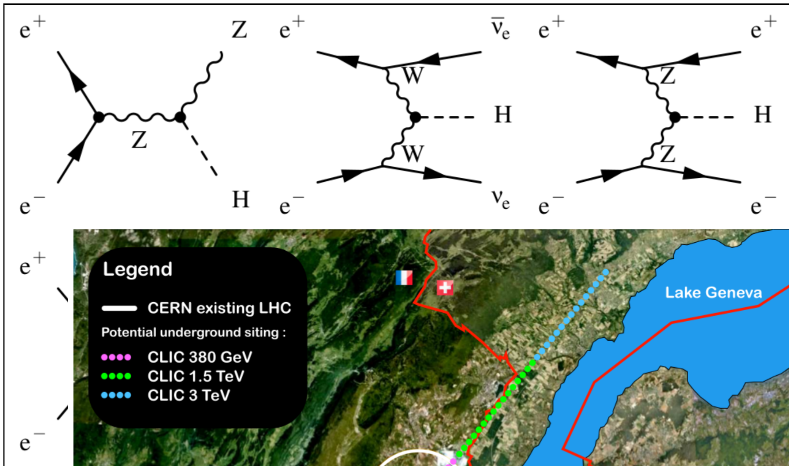
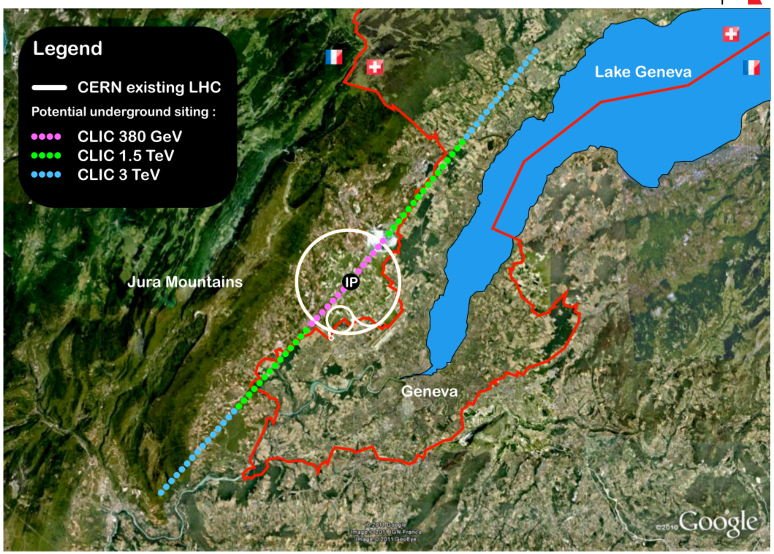
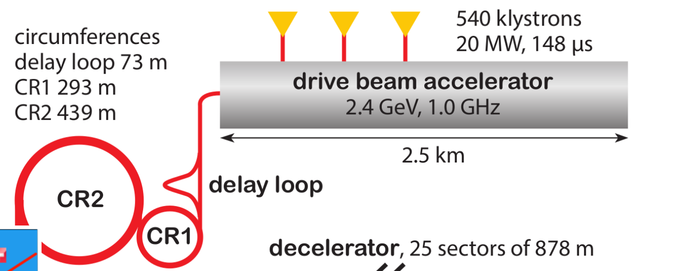
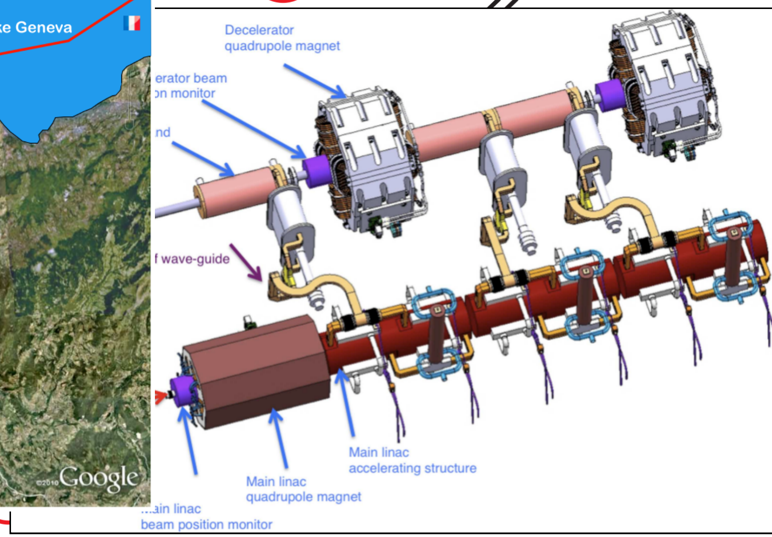








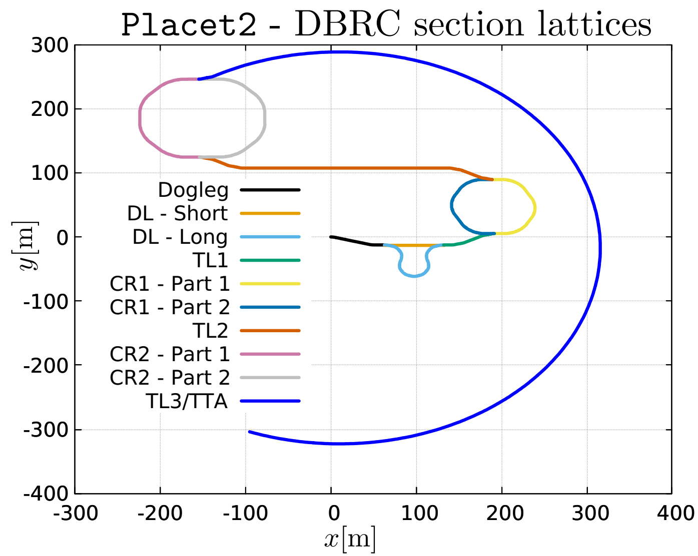
CLIC parameters

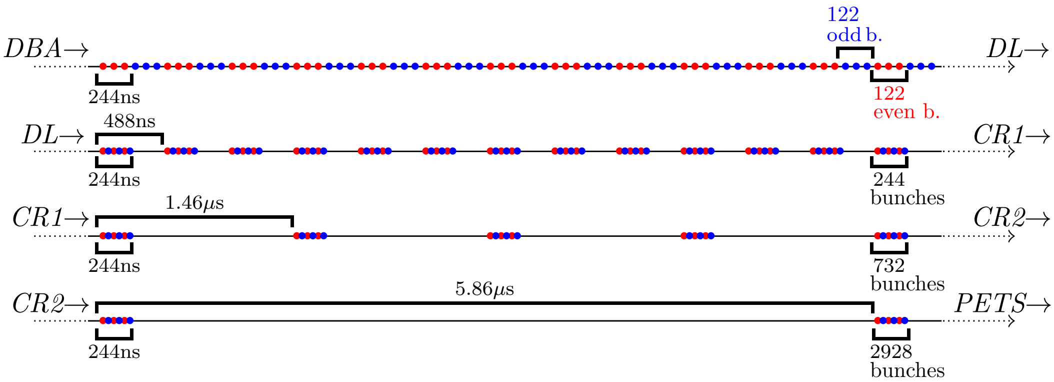
Parameter	**Symbol**	**Unit**	**Stage 1**	**Stage 2**	**Stage 3**
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	920/20	660/20	660/20
Normalised emittance (at IP)	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

The Drive Beam Recombination Complex

The DBRC is located between the drive beam linac and the deceleration sectors

It's role is to combine the drive beam by a factor 24× into high frequency pulses





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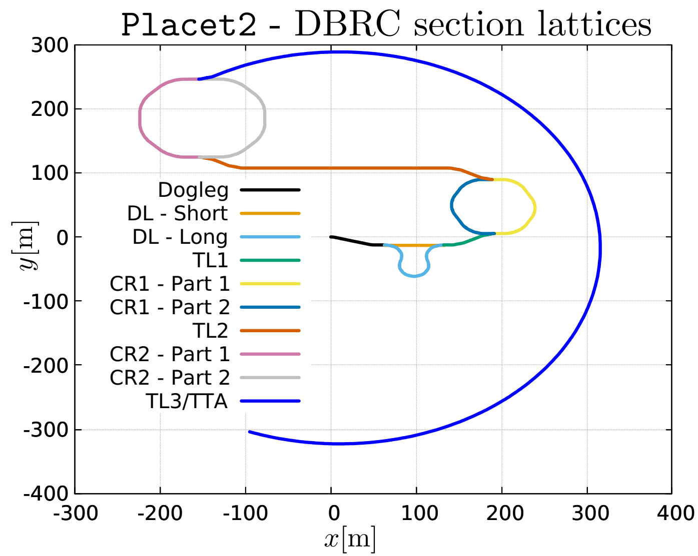


122 bunches 3/4.2 A*
0.49975 GHz 2ns ≡ 60cm
244 ns between bunches

2928 bunches 72/100 A*
11.994 GHz 83ps ≡ 2.5cm
244 ns between bunches

70760 bunches (≡ 142μs) train

5.9 μs

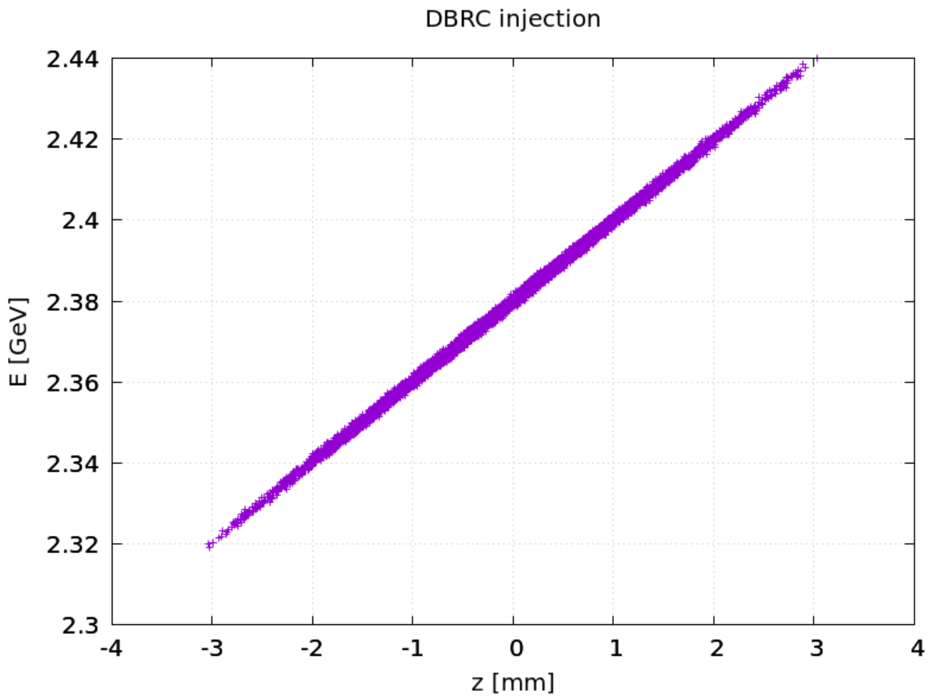
Beam parameters

Injection Parameters:

$$E = 1.9/2.38\,\text{GeV}^{*}$$
$$\delta = 0.85\,\%$$
$$\sigma_z = 1\,\text{mm}$$
$$\varepsilon_x = 50\,\mu\text{m}$$
$$\varepsilon_y = 50\,\mu\text{m}$$

Extraction Parameters:

$$\sigma_z = 1\,\text{mm}$$
$$\varepsilon_x < 150\,\mu\text{m}$$
$$\varepsilon_y < 150\,\mu\text{m}$$



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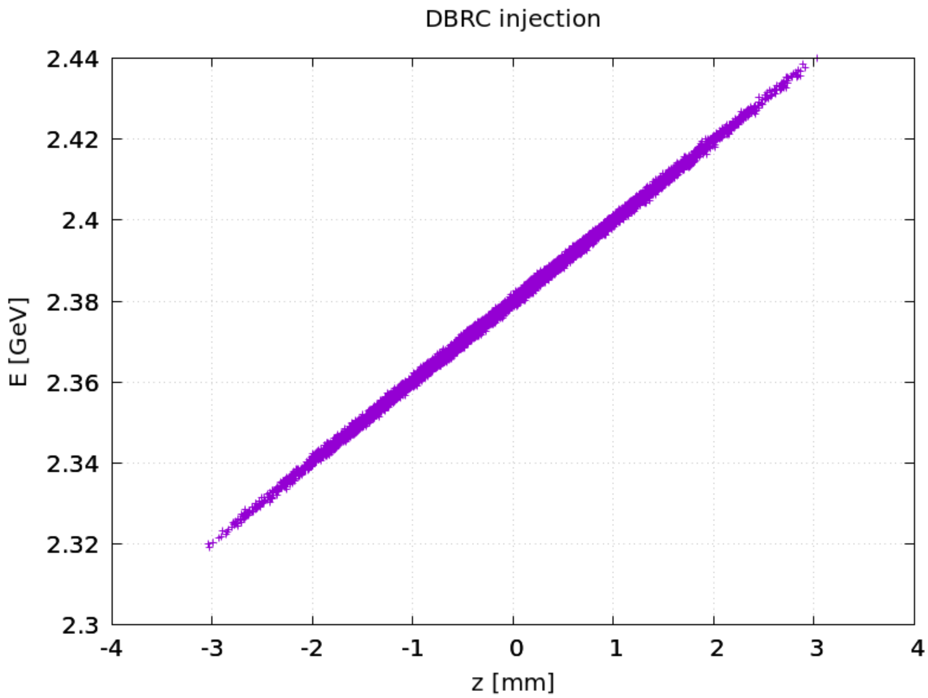
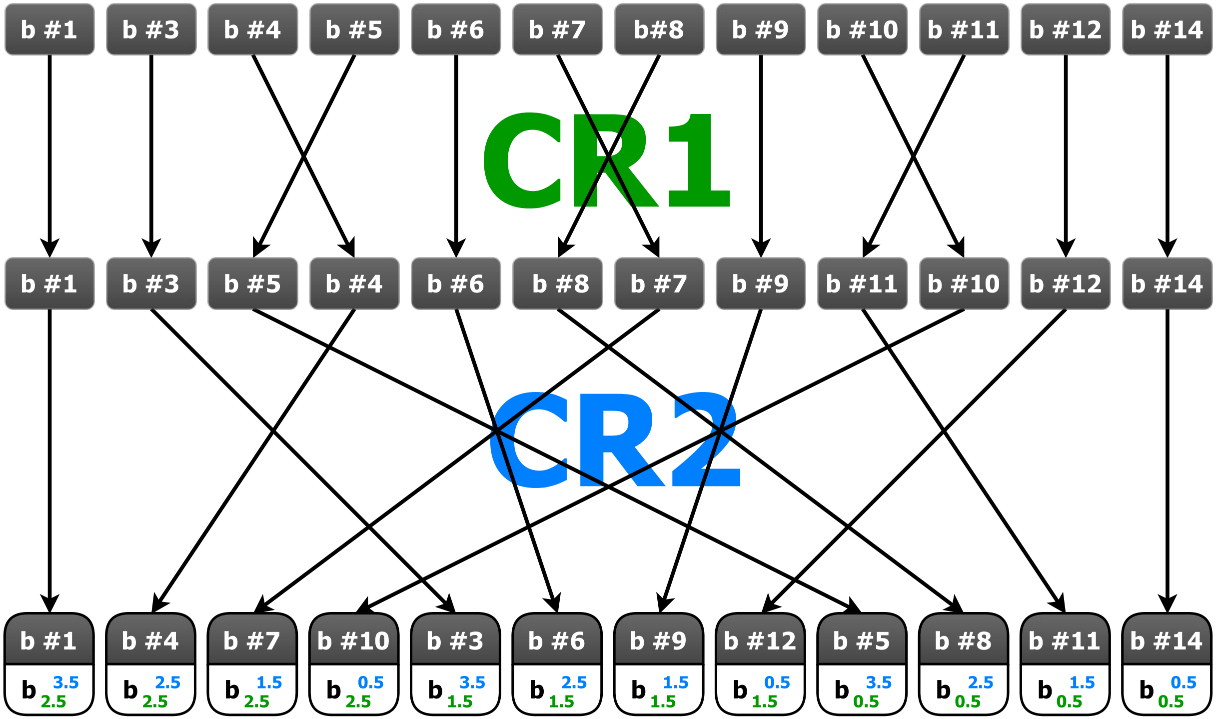


* The DB energy is 1.9 GeV for CLIC's 1st stage and 2.38 GeV for stages 2 and 3. Most optical properties of the lattice are similar.

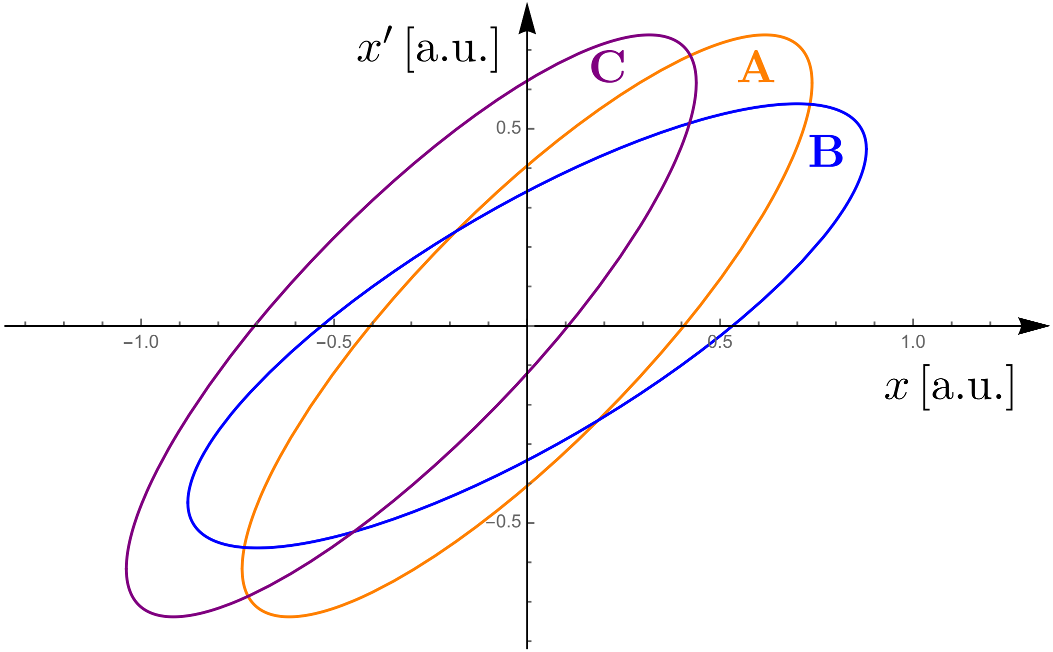
Notation

We are tracking 12 bunch "families" differentiated by the number of turns they take in CR1 and CR2: $\mathbf{b}_{\mathrm{CR1}}^{\mathrm{CR2}}$



Design challenges

Transverse pulse emittance



Targeting $\langle \varepsilon \rangle$ does not ensure twiss and centre-orbit match

We project all distributions on top of one-another and compute $\tilde{\varepsilon}$

$$\tilde{\varepsilon} \geq \langle \varepsilon \rangle$$

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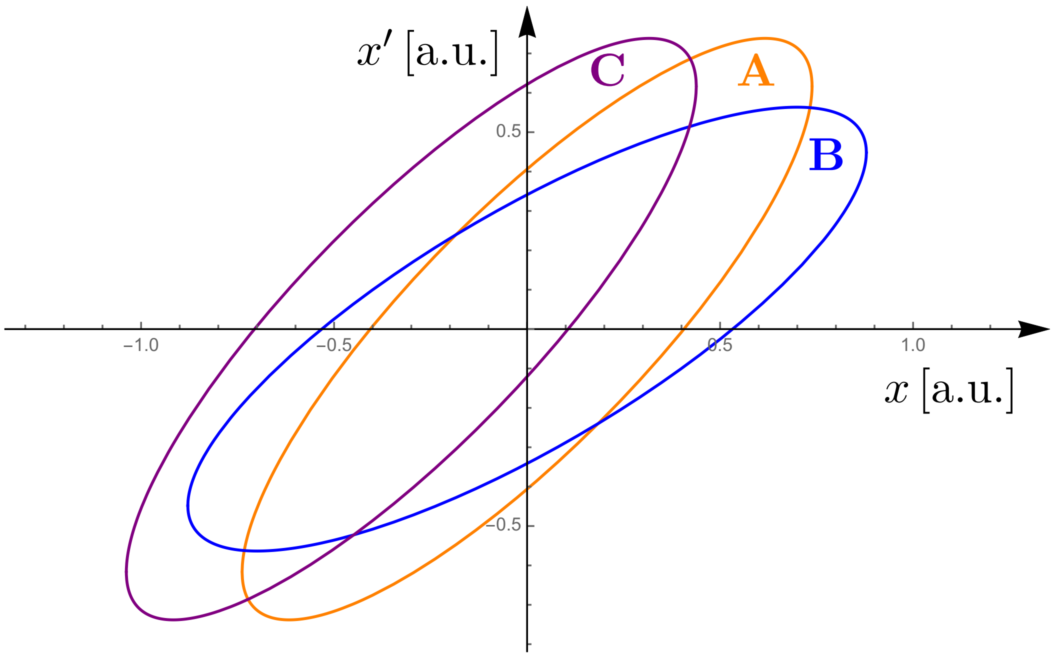

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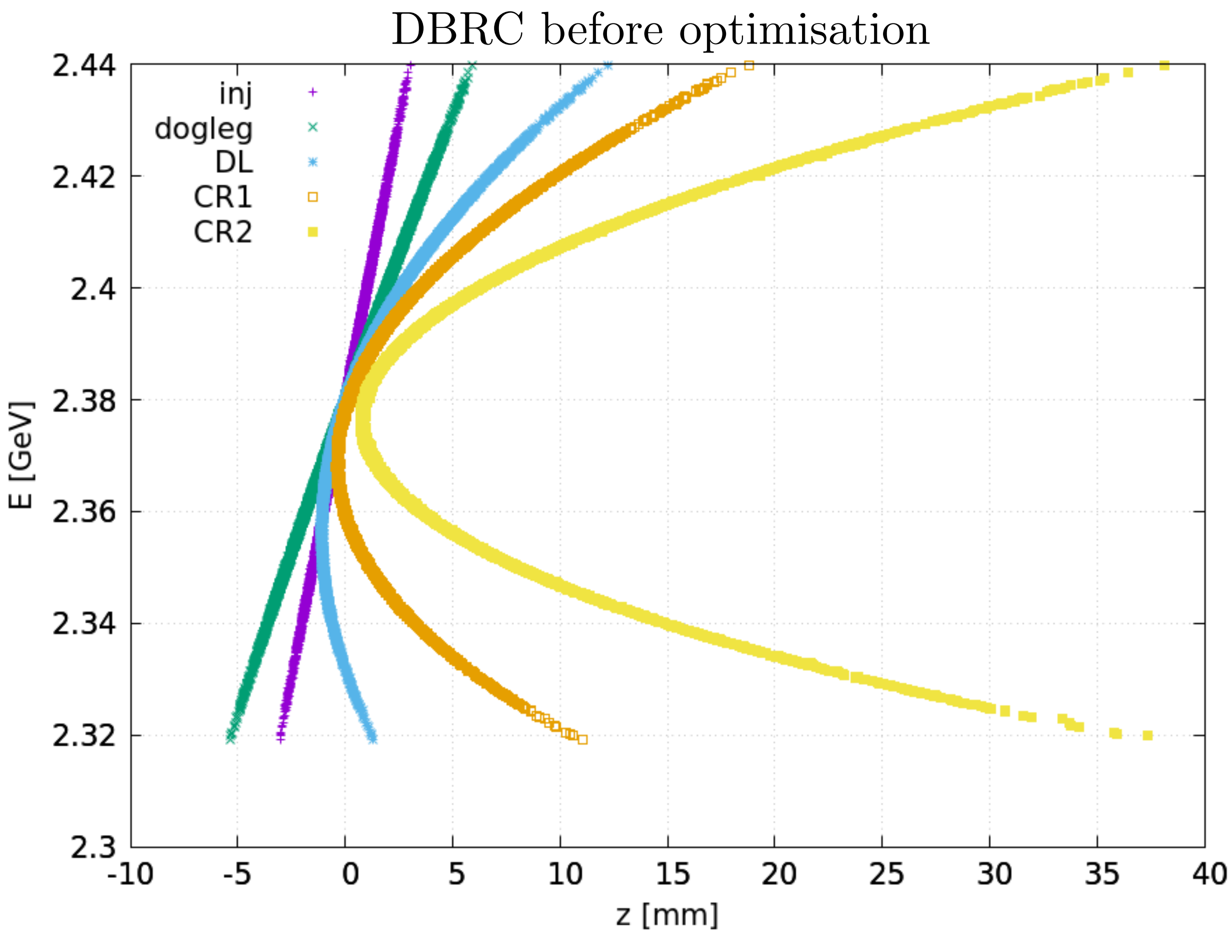
We project all distributions on top of one-another and compute $\tilde{\varepsilon}$

$$\tilde{\varepsilon} \geq \langle \varepsilon \rangle$$

Note: I'll talk more about emittance evaluation emittance later

Longitudinal profile



Source of the longitudinal issues

$$z\,(s) = z + R_{56}\delta + T_{566}\delta^2$$

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$$T_{566_{[n]}}\sim T_{566_{[n-1]}}+\left(R_{26_{[n-1]}}\right)^{2}T_{522_{[n]}}$$

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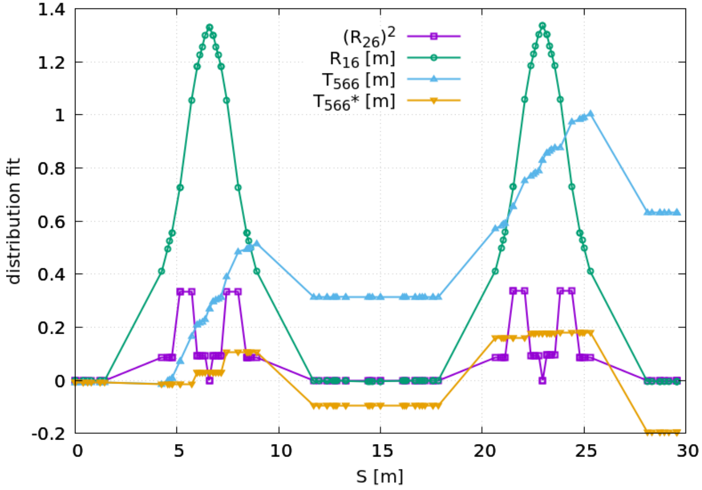
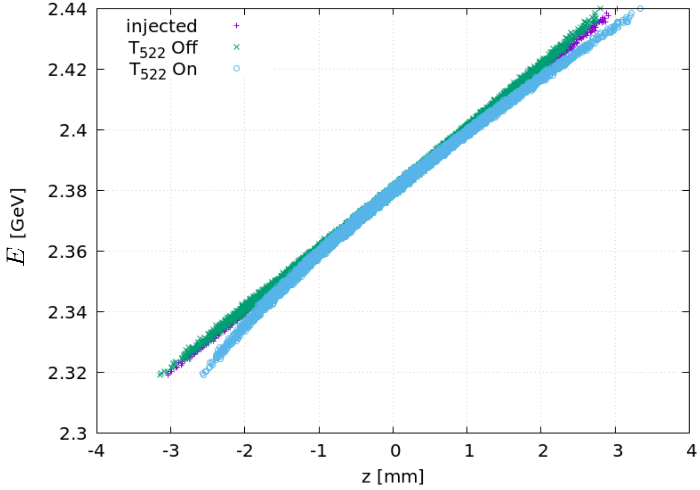
$$T_{566_{[n]}} \sim T_{566_{[n-1]}} + \left(R_{26_{[n-1]}}\right)^2 T_{522_{[n]}}$$

$$T_{522_{[\mathrm{Drift}]}} = \frac{L}{2}$$

T_{566} tracking - single arc (CR2)

`Placet2` can now track individual tensor elements

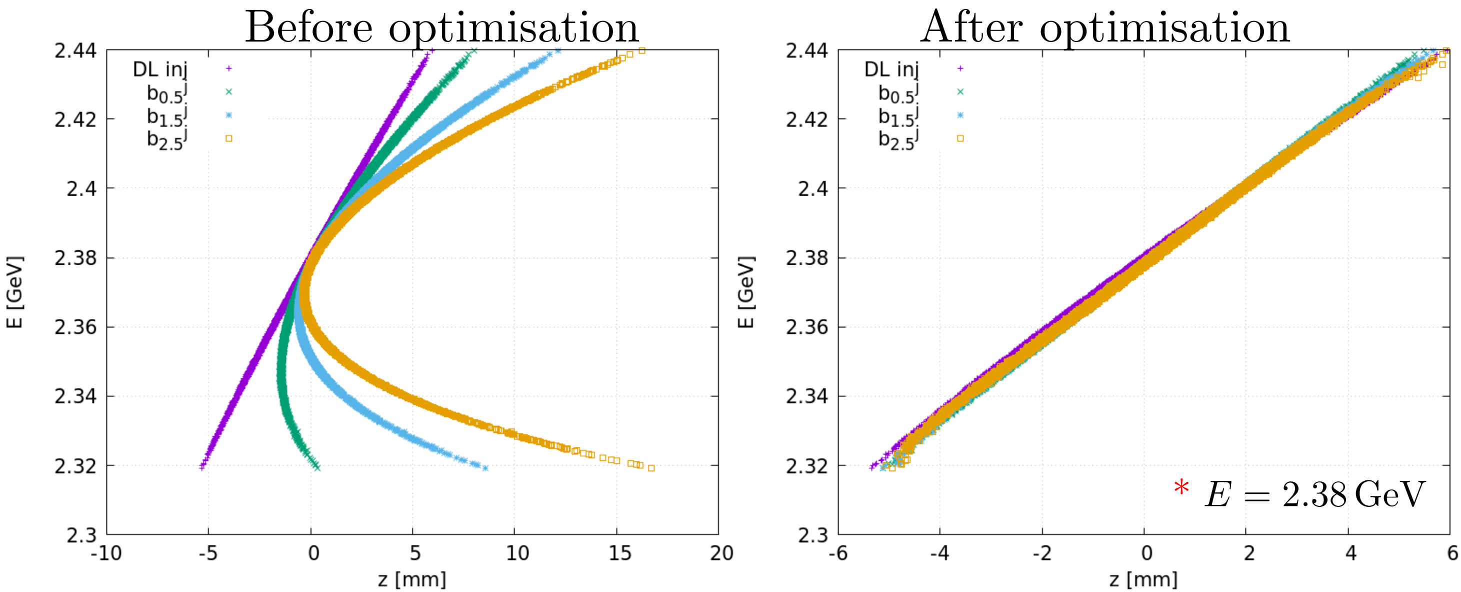




* If $T_{522} = T_{544} = 0$

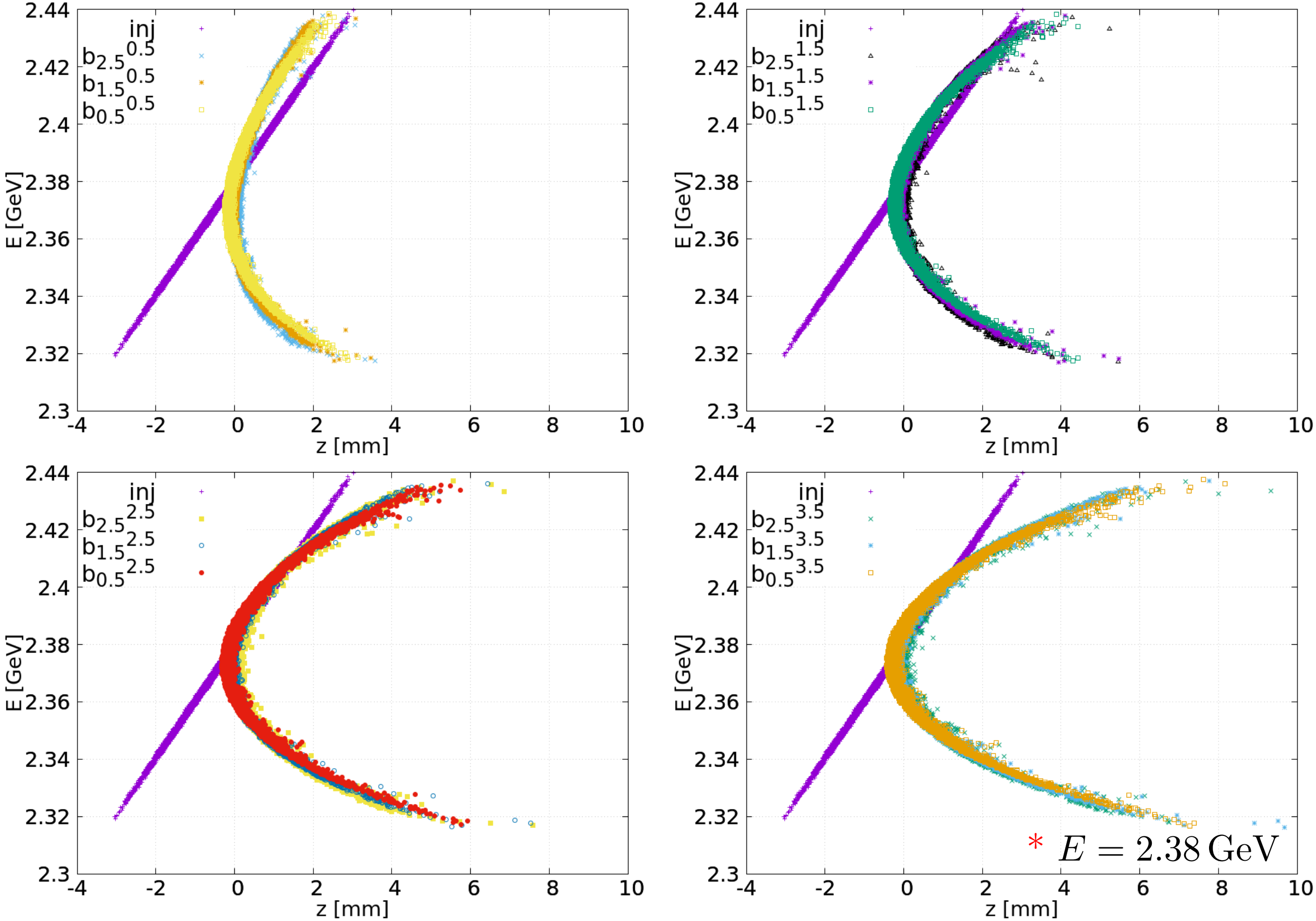
Results

Combiner Ring 1 optimisation

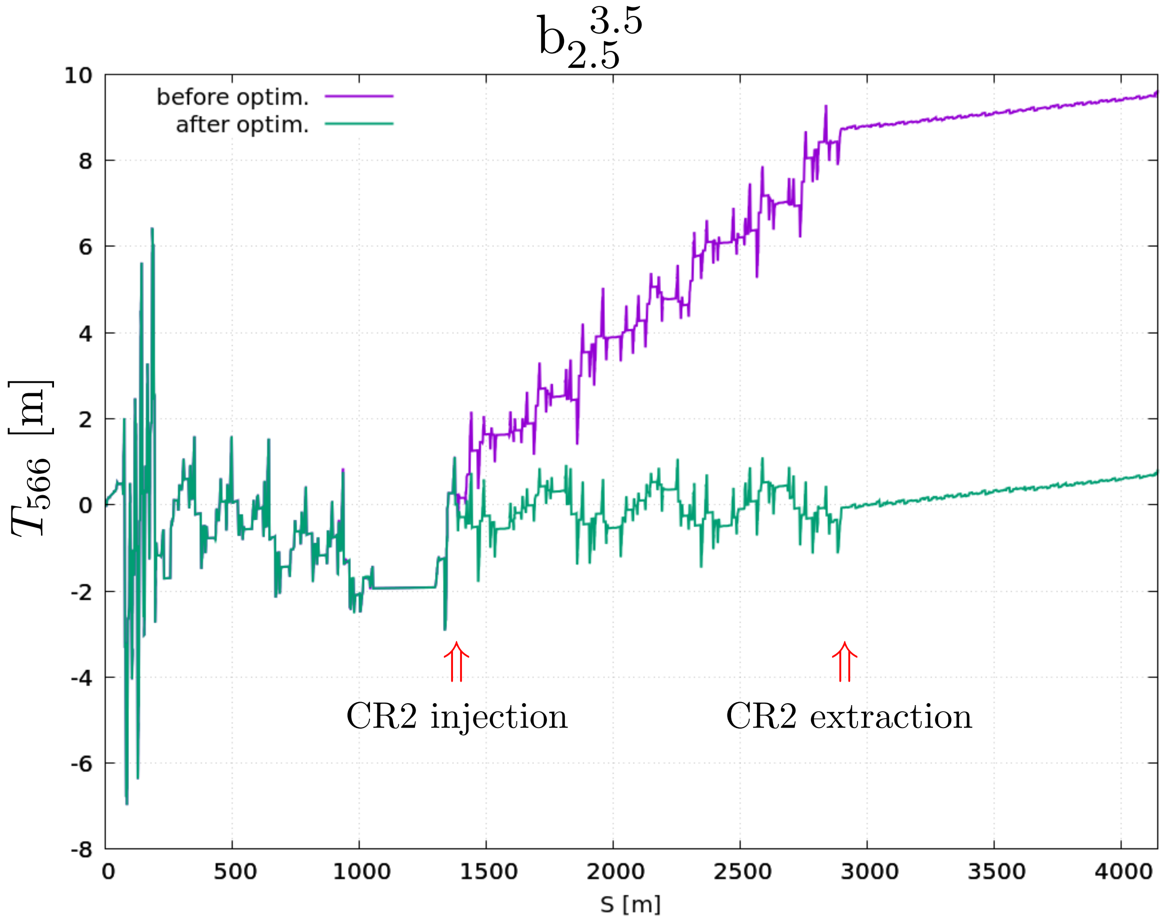


Emittance [μm]	$b_{0.5}^{j}$	$b_{1.5}^{j}$	$b_{2.5}^{j}$	$\langle \varepsilon_i \rangle$	$\tilde{\varepsilon}_i$
Horizontal	79	72	90	80	88
Vertical	56	56	64	59	59

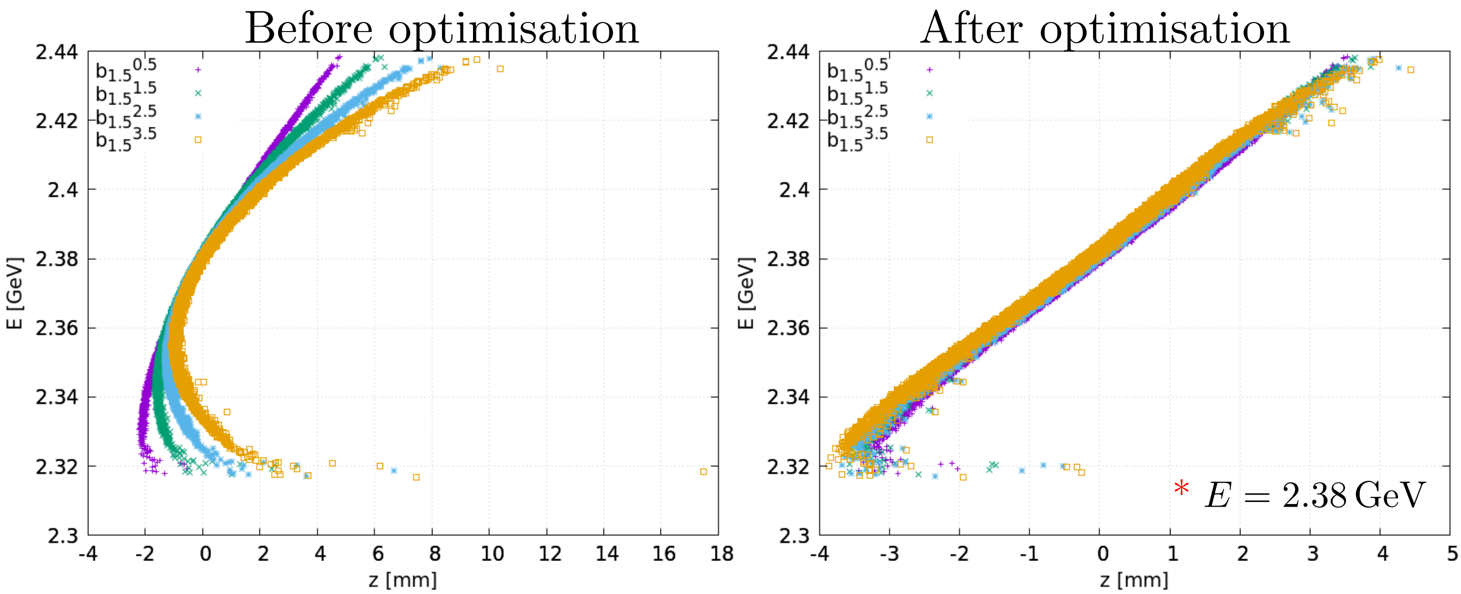
Longitudinal profile before CR2 optimisation



80 μm results - T_{566} correction

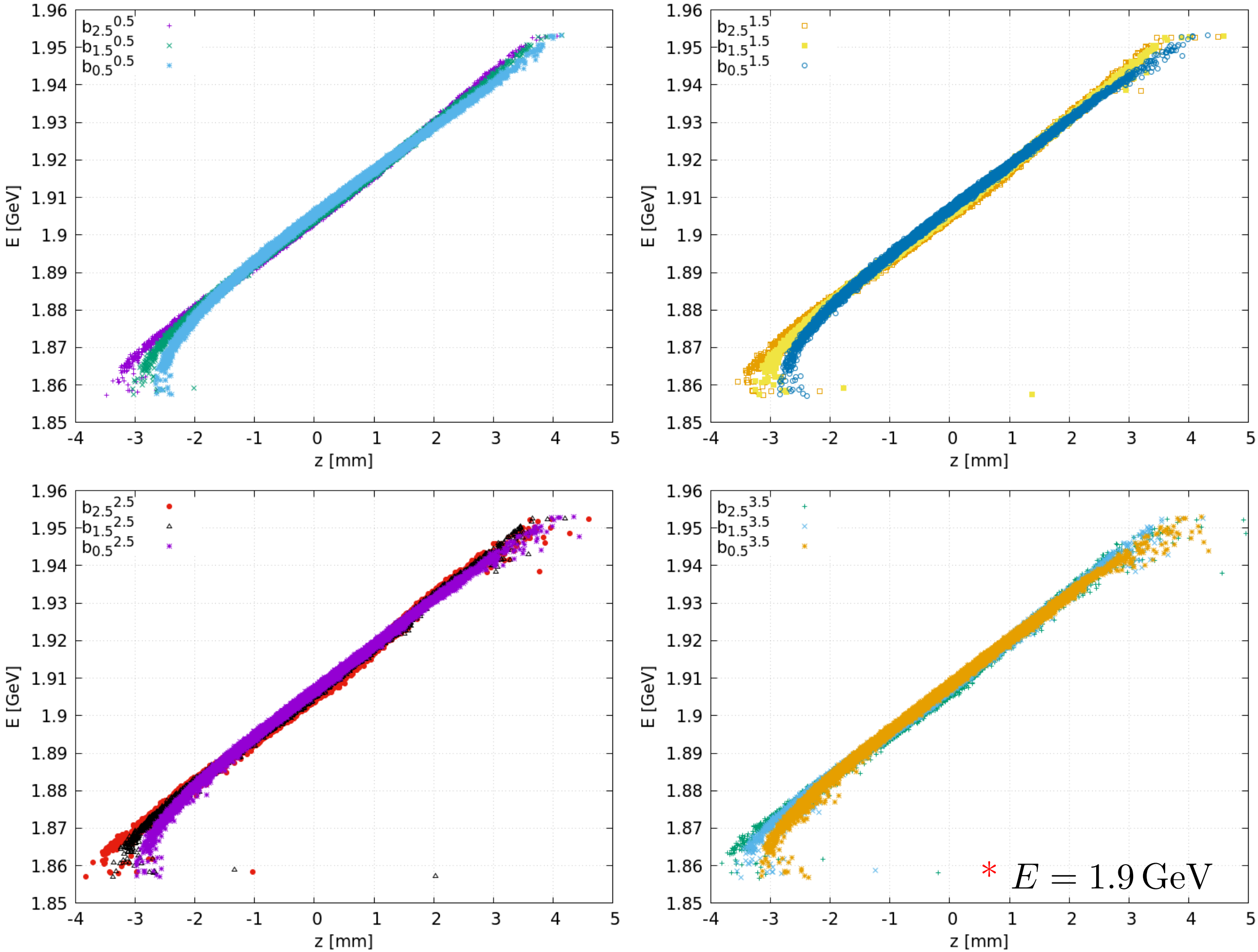


Combiner Ring 2 optimisation



Emittance [μm]	$\mathrm{b}_{1.5}^{0.5}$	$\mathrm{b}_{1.5}^{1.5}$	$\mathrm{b}_{1.5}^{2.5}$	$\mathrm{b}_{1.5}^{3.5}$	$\langle\varepsilon_i\rangle$	$\tilde{\varepsilon}_i$	$\tilde{\varepsilon}_i\left(\mathrm{b}_i{}^j\right)$
Horizontal	75	77	89	96	84	87	120
Vertical	65	70	70	76	70	70	71

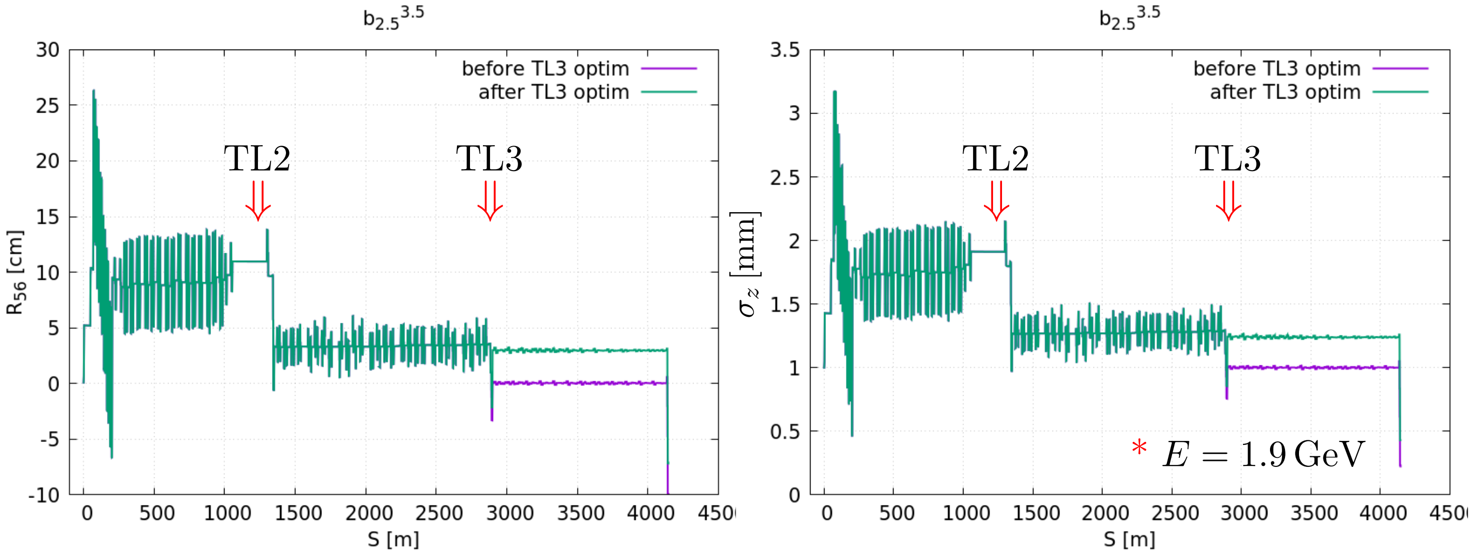
Longitudinal profile after CR2 optimisation



Extraction results (after TTA)

Bunch	S_{total} [m]	ε_x [μm]	ε_y [μm]	T_{566} [m]	σ_z [mm]
${b_{2.5}}^{3.5}$	4145	207	161	0.23	0.43
${b_{2.5}}^{2.5}$	3706	169	137	0.21	0.42
${b_{2.5}}^{1.5}$	3267	166	154	0.21	0.42
${b_{2.5}}^{0.5}$	2828	116	98	0.22	0.41
${b_{1.5}}^{3.5}$	3853	106	142	0.35	0.42
${b_{1.5}}^{2.5}$	3414	84	107	0.36	0.42
${b_{1.5}}^{1.5}$	2975	87	98	0.38	0.42
${b_{1.5}}^{0.5}$	2536	80	85	0.39	0.42
${b_{0.5}}^{3.5}$	3560	107	146	0.54	0.43
${b_{0.5}}^{2.5}$	3121	96	113	0.54	0.43
${b_{0.5}}^{1.5}$	2682	89	101	0.57	0.43
${b_{0.5}}^{0.5}$	2243	108	91	0.59	0.43
${b_i}^j$	–	117	112	–	–

R_{56} in the transfer lines



The decrease in bunch length originates in non-zero R_{56}
(unwanted side-effect of previous optimisation scans)

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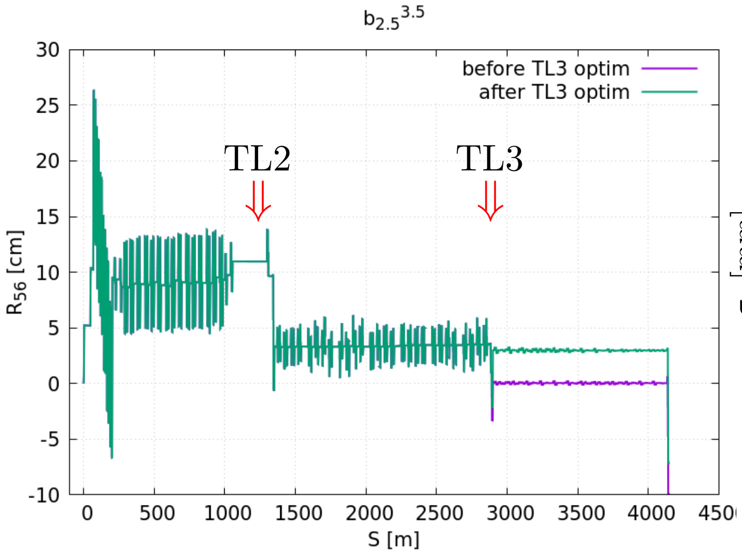

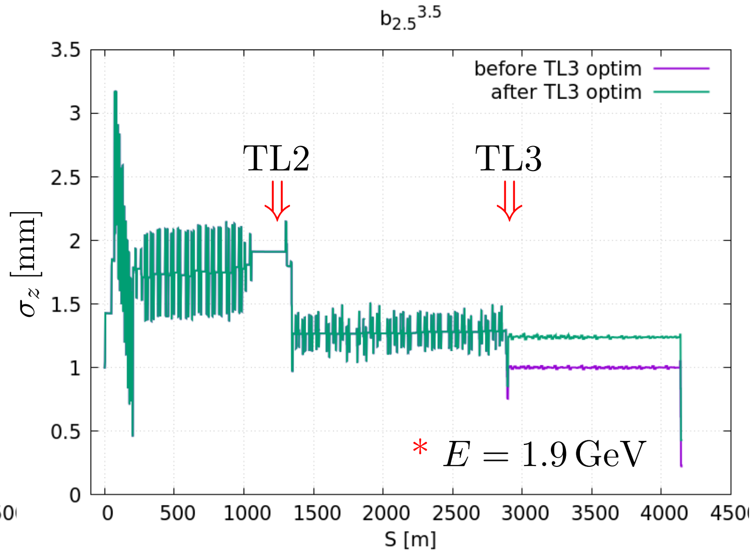

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TL3 has already been optimised to have $R_{56} \sim 0$

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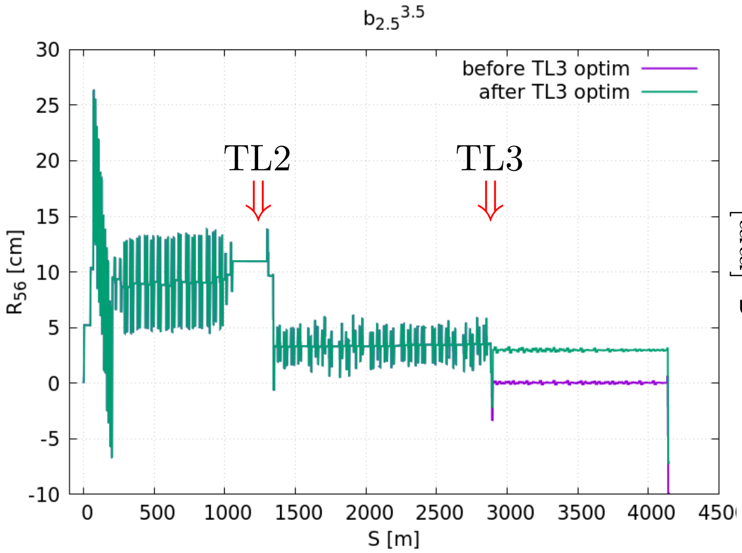

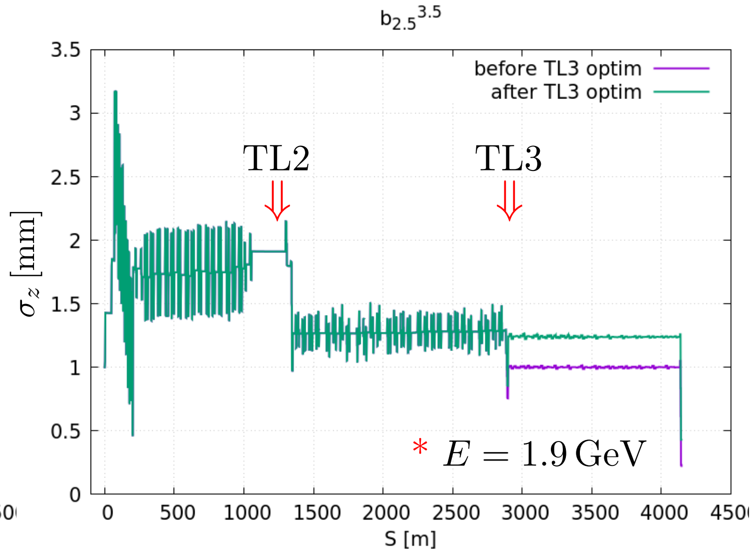

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TL2 is next...

Optimisation techniques with particle losses

General technique

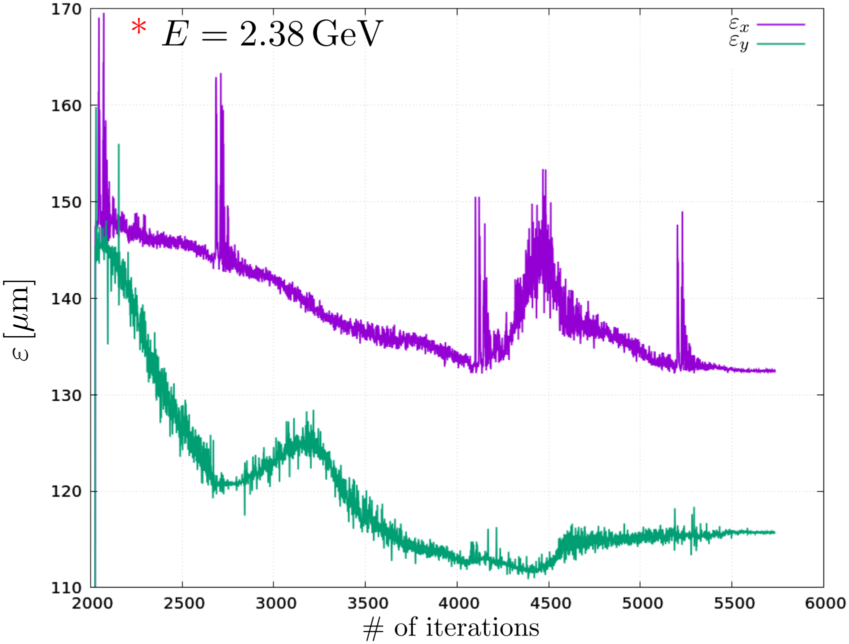
Optimisation is performed by changing optical strengths of some elements

`Placet2`'s API to `Octave` to access Nelder-Mead's downhill simplex algorithm

We Define element families (7-40) and minimize $w_1\varepsilon_x + w_2\varepsilon_y + w_3 T_{566}{}^*$

Takes a lot of computing time and fine tuning

Ex: partial CR2 optimisation



* In reality minimizing the error of a linear fit is more efficient

Emittance evaluation from a particle distribution

In multiple particle tracking we evaluate emittance as

$$\varepsilon_q = \sqrt{\det\left(\begin{bmatrix} \operatorname{cov}(q,q) & \operatorname{cov}(q,q') \\ \operatorname{cov}(q',q) & \operatorname{cov}(q',q') \end{bmatrix}\right)}$$

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However, **if particle losses are possible during optimisation**, increasing particle loss will decrease the ε_q evaluation

The optimisation scan will therefore "attempt" to lose more particles!

Emittance evaluation from a particle distribution

When 1st attempting to address this, we added a term to the merit function such that

$$w_1\varepsilon_x + w_2\varepsilon_y + w_3T_{566} + W_4N_{\text{Losses}}\ ; \quad W_4 \gg w_i$$

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We have therefore decided to remove the N_{Losses} term and revise the way the merit function evaluates ε_q.

Instead of using the full distribution, we compute ε_q using a fixed number of macro particles (99% of the original distribution)

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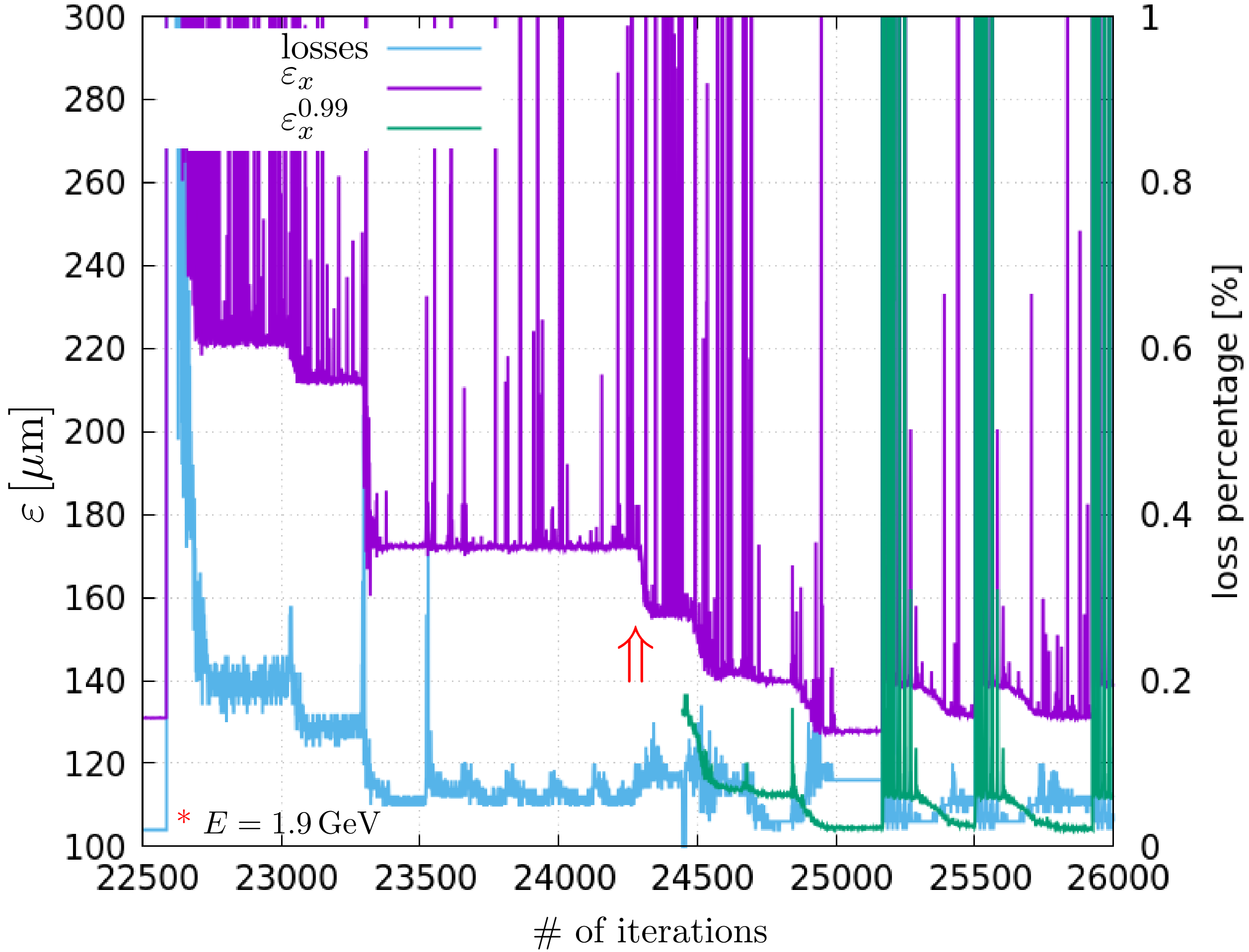
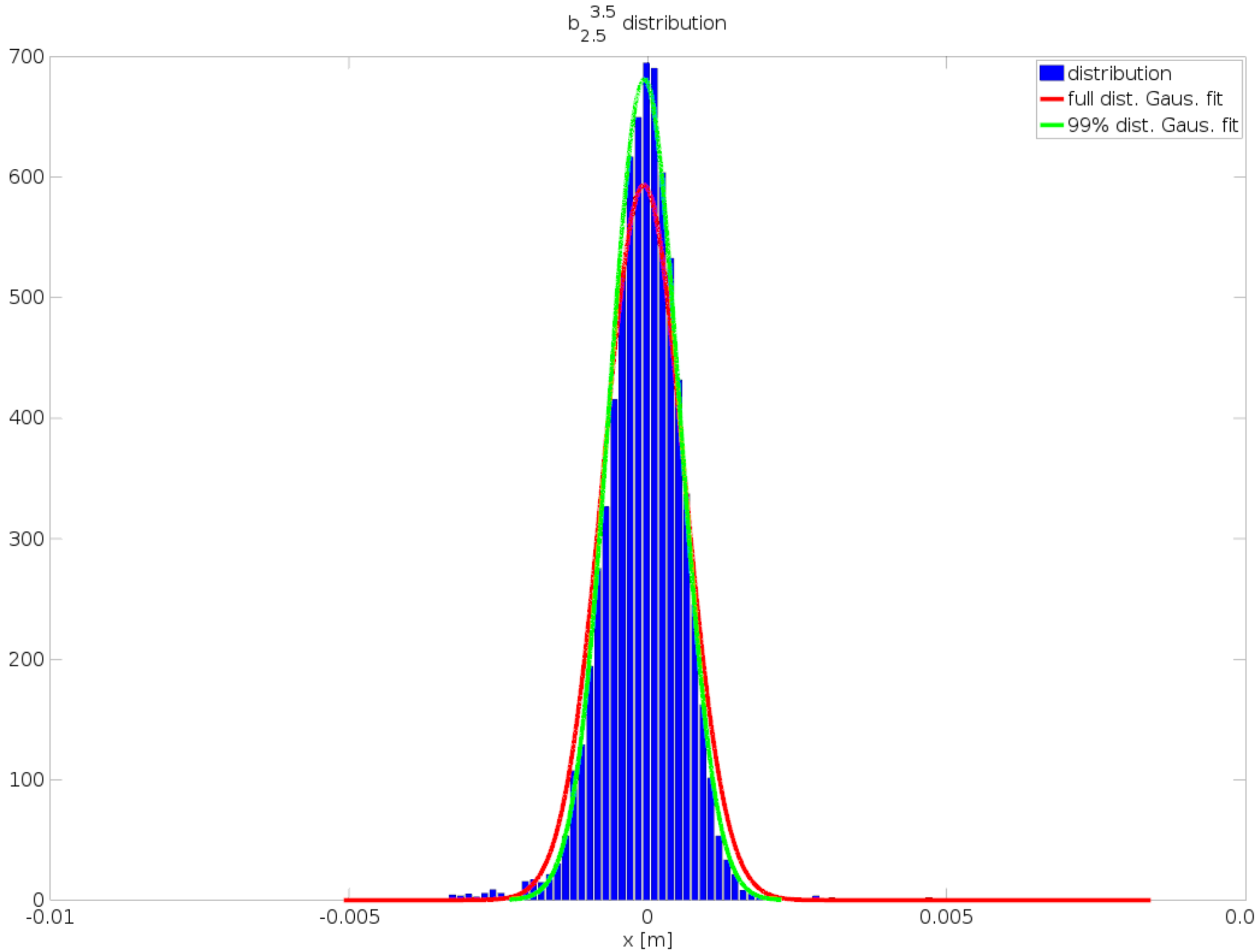
This also provides a better fit to the particle distribution (since the bunch is not actually Gaussian at extraction)

Emittance evaluation from a particle distribution



Gaussian fit comparison



Conclusions and Outlook

Conclusions

- `Placet2` has been updated to track individual tensor elements
- The main DBRC design challenges were identified and addressed
- With an injected beam of 50 μm, the latest lattice has minimal T_{566} ($< 60\,$cm) while meting the emittance budget ($\varepsilon_x = 117\,\mu$m ; $\varepsilon_y = 112\,\mu$m)
- The transfer lines present some unwanted R_{56} ($\sim$ -7 cm)
- Particle loss and long non-Gaussian tails are detrimental to the performance of our optimisation scans
- When losses are possible, estimating ε using 99% of the particle distribution improves the performance of optimisation scans
- It also provides a better fit for distributions with long tails

Outlook

- DBRC
  - Remove R_{56} from TL2 (or update the final chicane)
  - Implement the delay loop's short path
  - Try to optimise for $\delta = 1\%$
  - Implement misalignments and beam-based alignment techniques

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  - Implement CSR (and update ISR)
  - Implement decelerators
  - Improve parallelization, LXplus support, etc...

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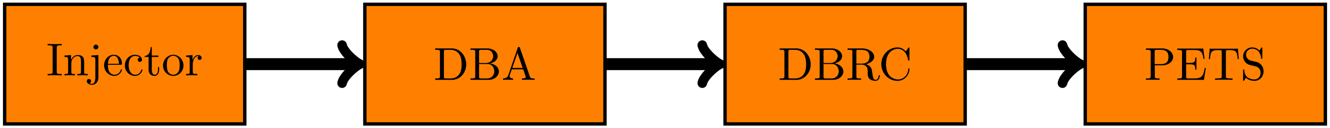
- Full drive beam integration



The end

Thank you

Extra slides

Full drive beam integration (status)

Output:

$\varepsilon_x \leq 35\,\mu\text{m}$

$\varepsilon_y \leq 35\,\mu\text{m}$

$E = 50\,\text{MeV}$

$\delta = 0.95\%$

Full drive beam integration (status)

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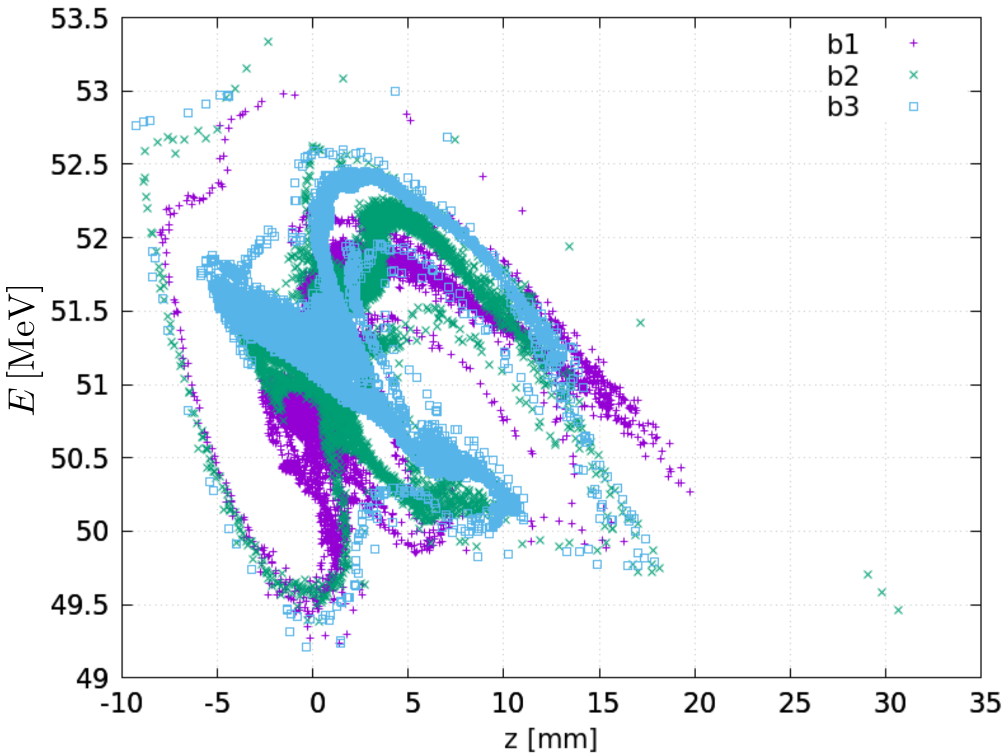
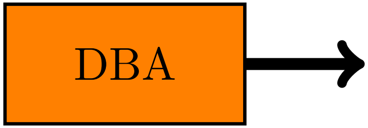


* Thanks to Steffen Doebert and Shahin Hajari for the distributions

Full drive beam integration (status)



Input:

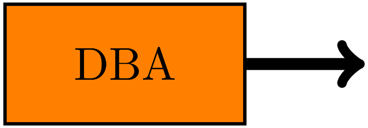
$\varepsilon_q = 30\,\mu\text{m}$

$E = 50\,\text{MeV}$

$\delta = 1\%$

Gaussian

Full drive beam integration (status)



Input:

$\varepsilon_q = 30\,\mu\text{m}$

$E = 50\,\text{MeV}$

$\delta = 1\%$

Gaussian

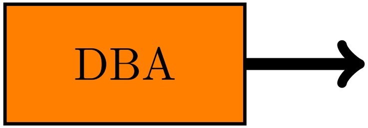
Output:

$\varepsilon_q = 31\,\mu\text{m}$

$E = 1.9\,\text{GeV}$

$\delta = 0.84\%$

Full drive beam integration (status)



Input:

$\varepsilon_q = 30\,\mu\text{m}$

$E = 50\,\text{MeV}$

$\delta = 1\%$

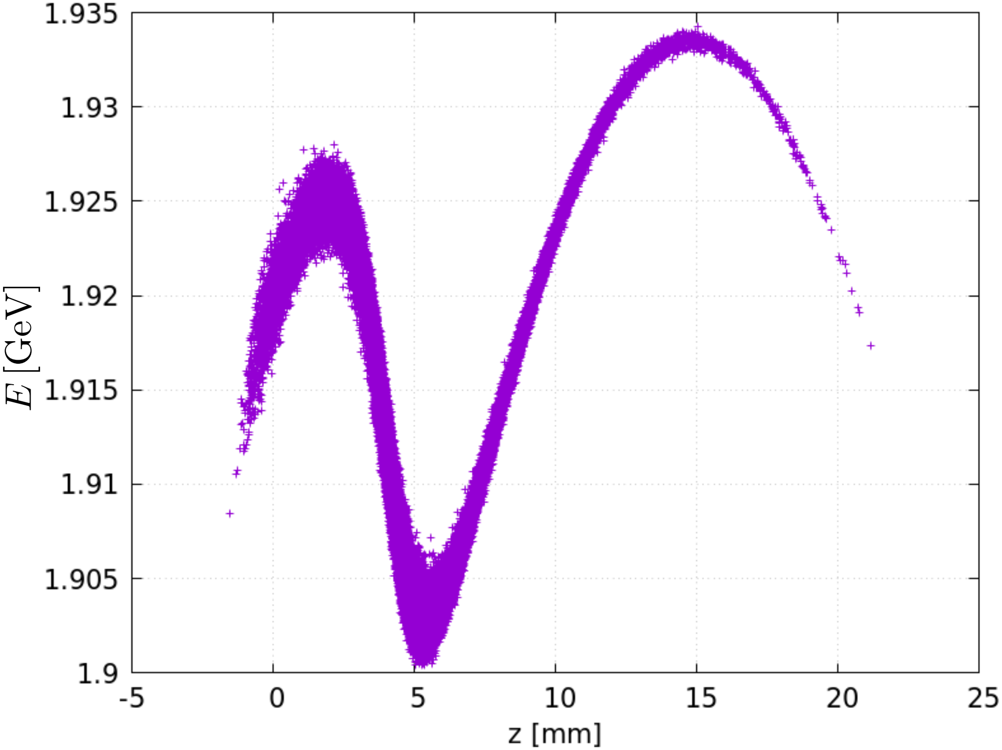
Gaussian

Output:

$\varepsilon_q = 31\,\mu\text{m}$

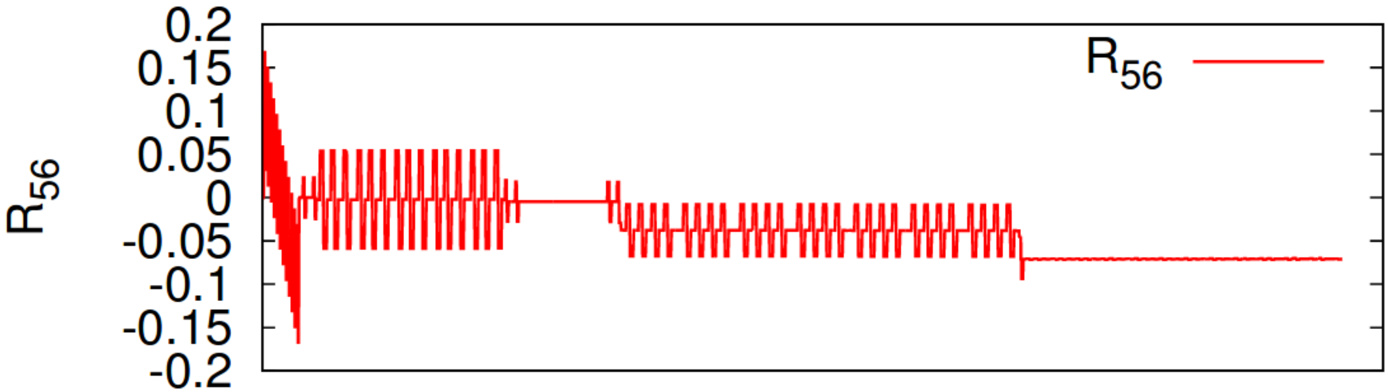
$E = 1.9\,\text{GeV}$

$\delta = 0.84\%$



* Thanks to Avni Aksoy and Andrea Latina for the distribution

R_{56} before optimisation

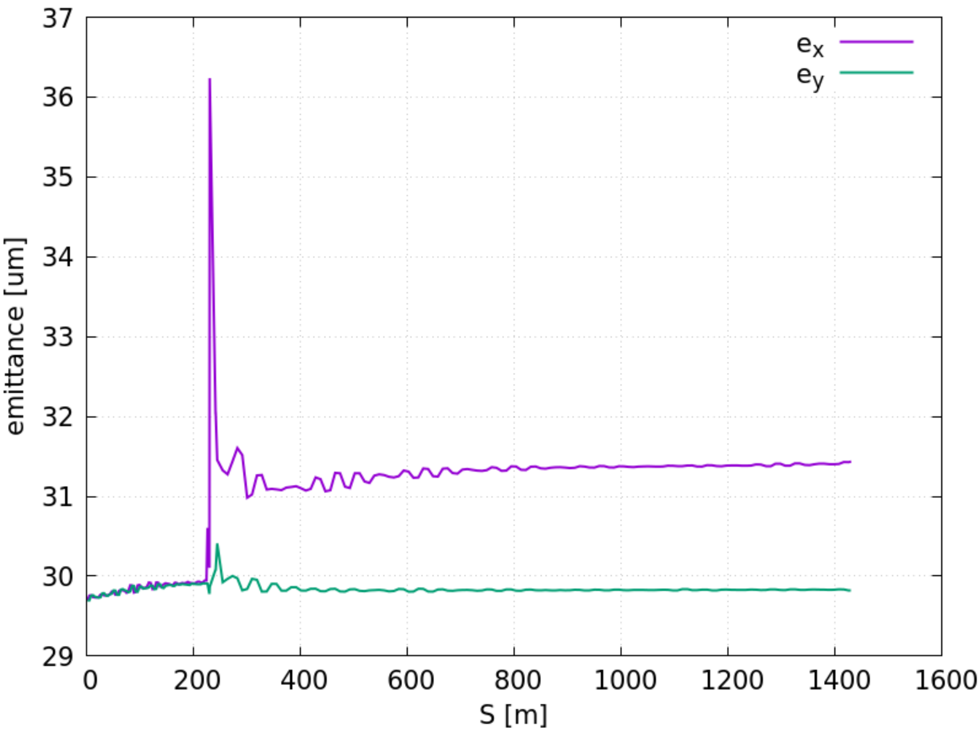


* From Eduardo Marin's CLIC Workshop 2016

DBA simulation parameters

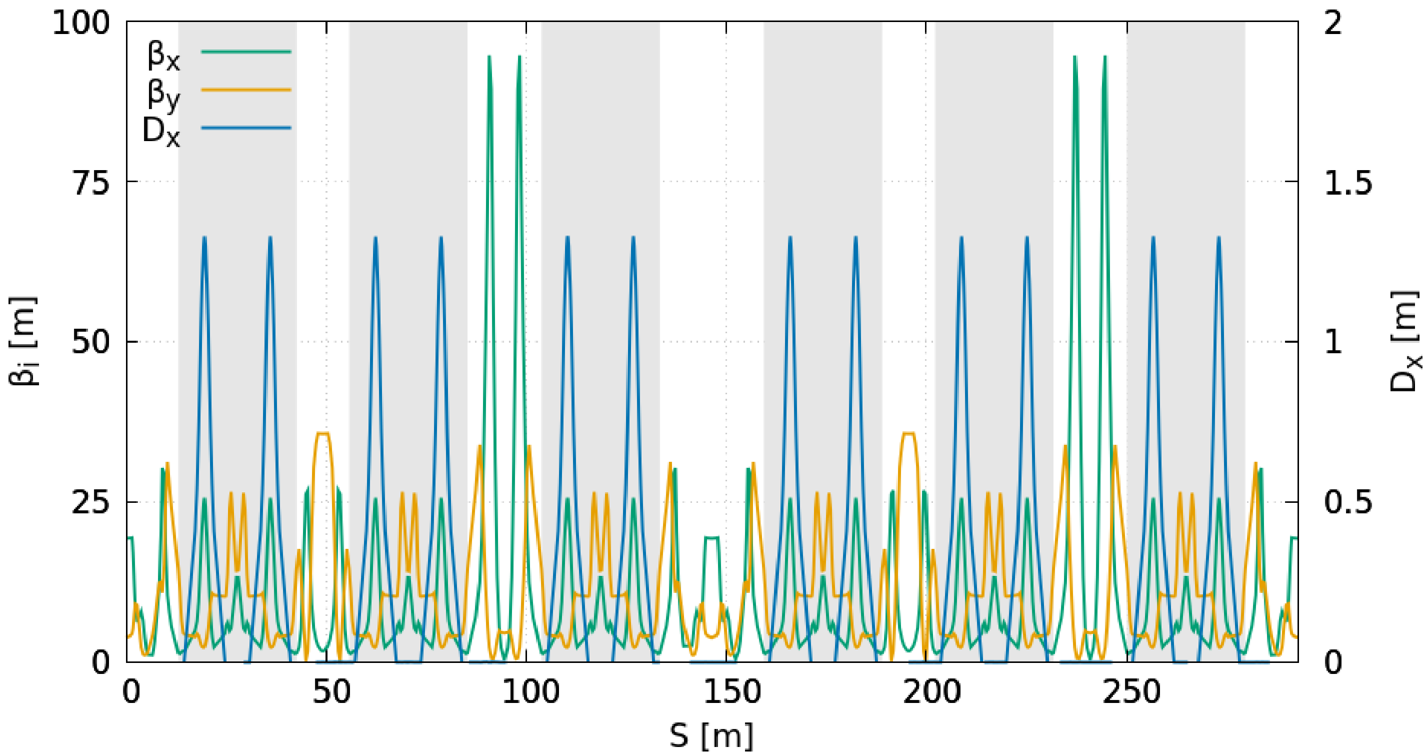
DBA simulation parameters:	
Initial energy (MeV)	50
Final energy (GeV)	1.9
Initial Energy Spread (%)	1.0
Bunch Charge (nC)	8.4
Initial emittance (μm)	30
BPM resolution (μm)	10
Misalignment errors - Quad. and Acc. (μm rms)	200
Pitch errors - Acc. (μrad rms)	200

DBA simulations (WFS)

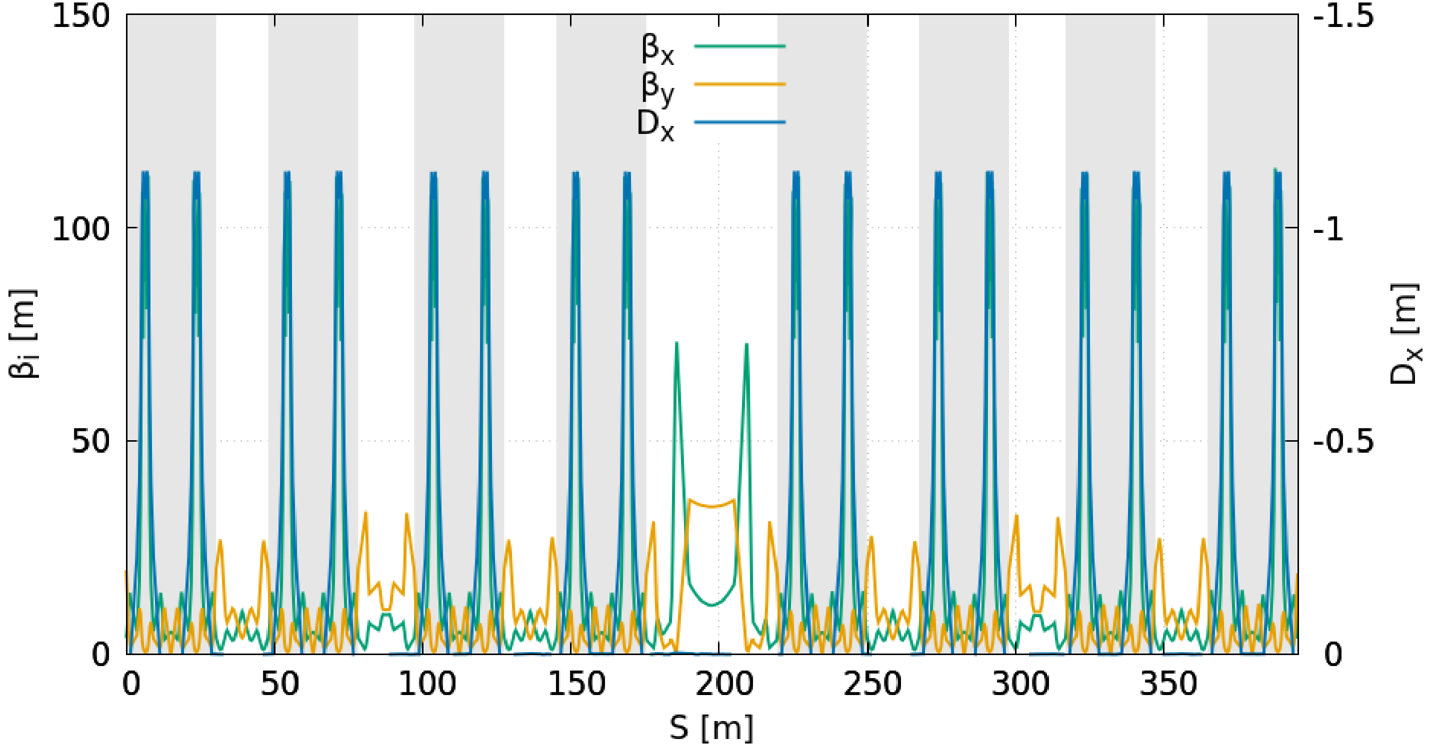


- Average final emittance: $\varepsilon_x = 31\ \mu\text{m}$, $\varepsilon_y = 30\ \mu\text{m}$
- Final energy spread of $0.836\% \pm 0.004\%$

CR1 Lattice



CR2 Lattice



β_x
β_y
D_x
150
100
50
0
-1.5
-1
-0.5
0
β_i [m]
D_x [m]
0
50
100
150
200
250
300
350
S [m]