Status of the tracking code PLACET2 and First Decelerator Lattice for CLIC 380 GeV

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Outline

1. Status of PLACET2
    - Introduction
    - Coherent Synchrotron Radiation
    - Power Extraction and Transfer Structures
    - Current Status
2. CLIC 380 GeV Decelerator Lattices
    - Introduction
    - Lattice Design
    - Results
    - Losses due to δ_0
    - Dependence on Emittance
    - Conclusions and Outlook

Status of PLACET2

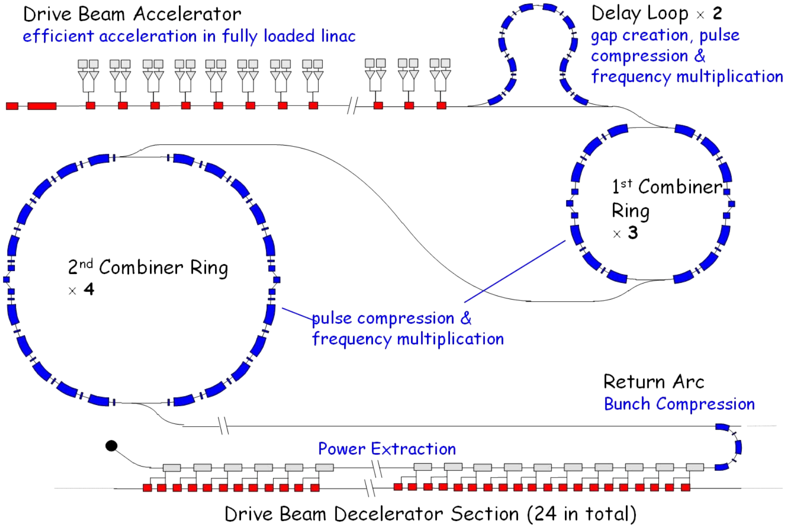
Introduction

PLACET2 tracking is:

- Multi-particle
- Multi-bunch
- Re-circulating
- Linear and Non-Linear
- Wakefields (short and long-range, transverse and longitudinal)
- Synchrotron Radiation (coherent and incoherent)

`gitlab.cern.ch/clic-software/placet/-/tree/PLACET2`

Re-Circulation Applications

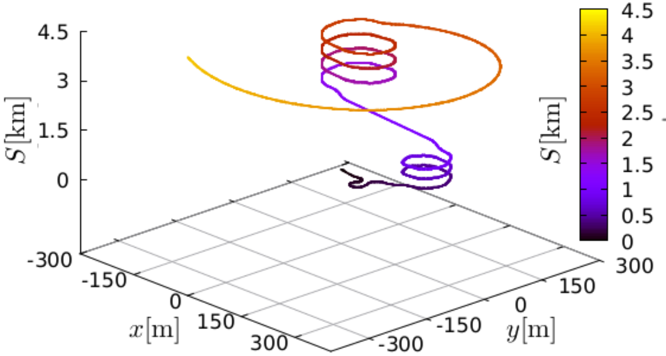


Energy Recovery Linacs (PERLE, LHeC, etc.)

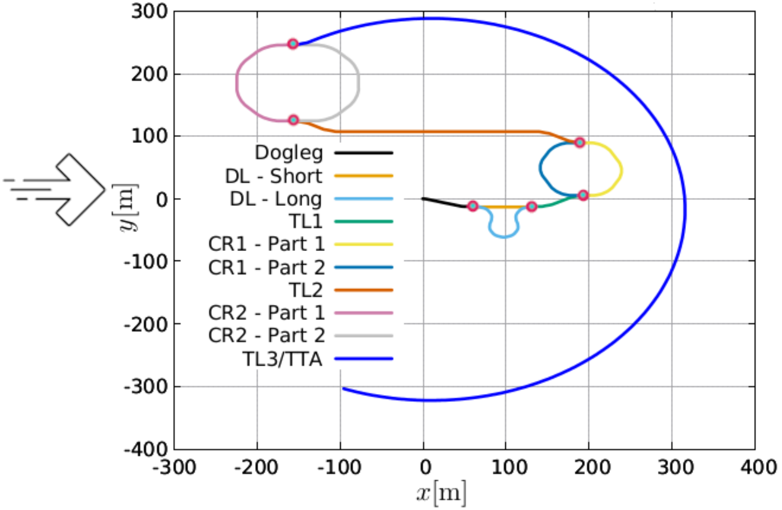
Muon Injection

Re-Circulation Applications

In CLIC's recombination complex 24 pulses are combinedby taking different pathways



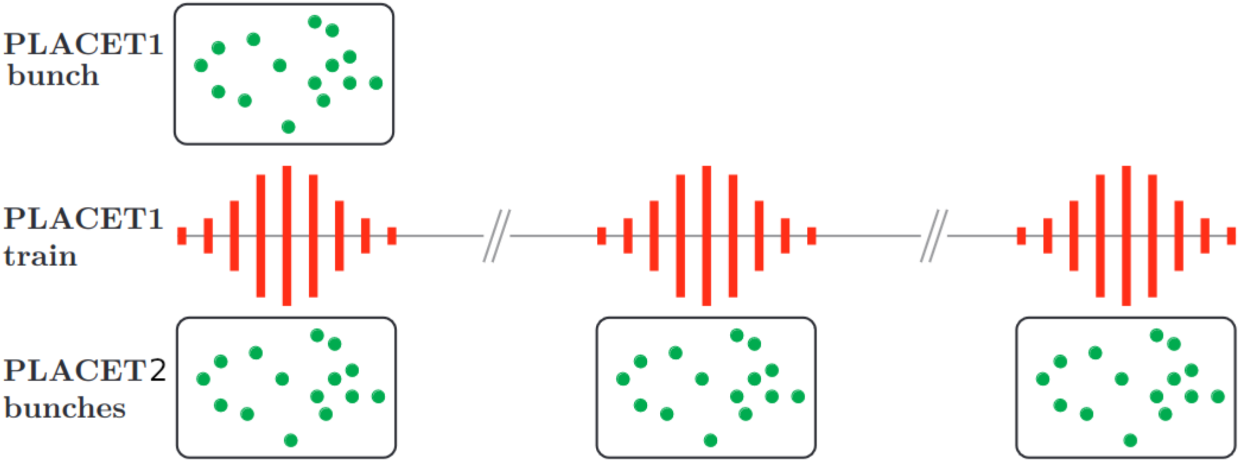
Traditional tracking codes would require simltaneous optimization of 24 lattices



PLACET 2 allows all bunches to be dispached correctly and full train optimization

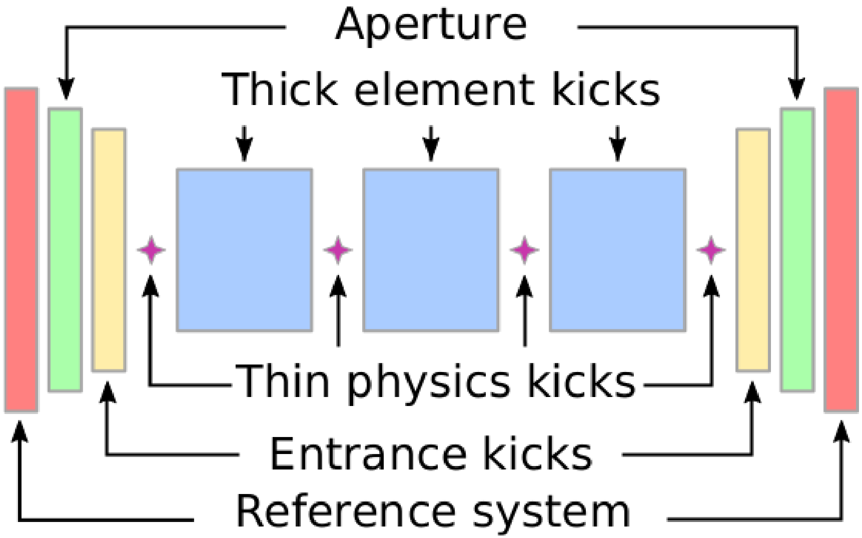
- Not tracking all bunch pathways simultaneously caused PLACET1 optimizations to not close dispersion for all bunches in the combiner rings
- Studies of other multi-bunch effects such as long-range wakefields in ERLs are also easily targeted by PLACET2

Beam Model



- PLACET1 uses 3 different bunch models:
  - a 4D single-bunch macro-particle ensemble
  - a 6D single-bunch macro-particle ensemble (for dispersion)
  - a sliced-beam model for accelerating structure and PETS (that can also be used to model a full train)
- PLACET3 can model each bunch individually as a 6D ensemble. It also allows for different-weighted particles (usefull for halo/tail studies)

Element Structure



Thick Kicks:

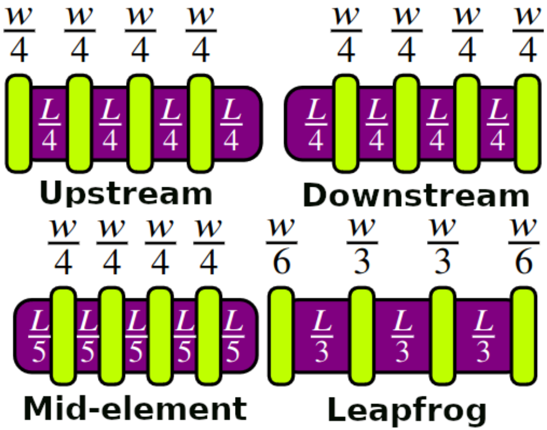
- Drifts
- Bends
- Quadrupoles
- Cavities
- etc

Thin Kicks:

- Correctors
- Multipoles
- Radiation
- Wakefields
- Readouts
- etc.

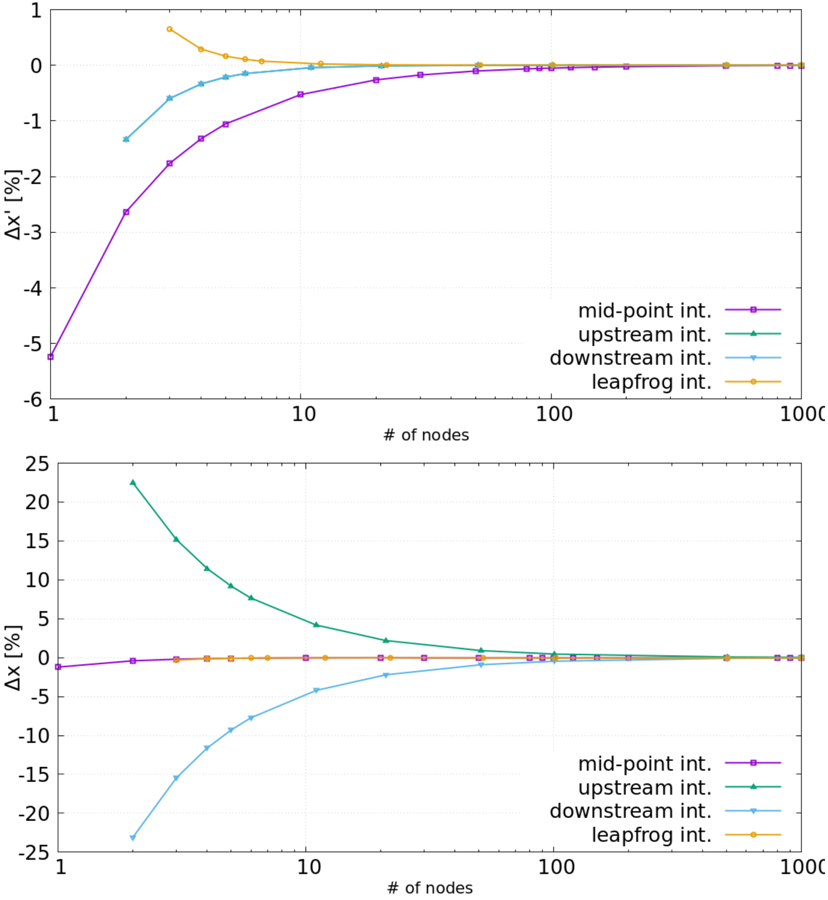
Element Slicing

Testing different slicing methods:

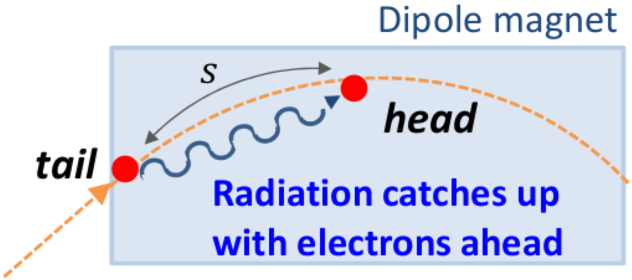


- Drift-Kick-Drift is simpler and allows for the 1-kick approximation (multipoles, correctors)
- Kick-Drift-Kick converges faster and some kicks require entrance/exit processing anyway (radiation, wakefields)

Short-Range Transverse Wakefield:



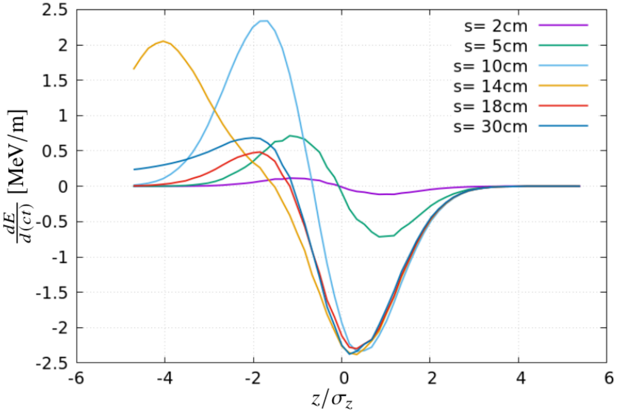
Coherent Synchrotron Radiation

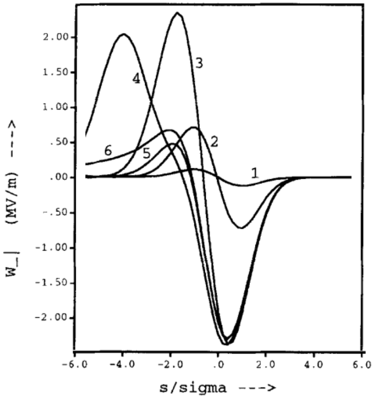


Radiation catches up with electrons ahead

S. Di Mitri - Lecture_We9

E. Saldin *et al*, ''On the coherent radiation of an electron bunch moving in an arc of a circle'', Proc. PAC97, 1997, Canada





M. Dohlus, T. Limberg / Nucl. Instr. and Meth. in Phys. Res. A 393 (1997) 494–499

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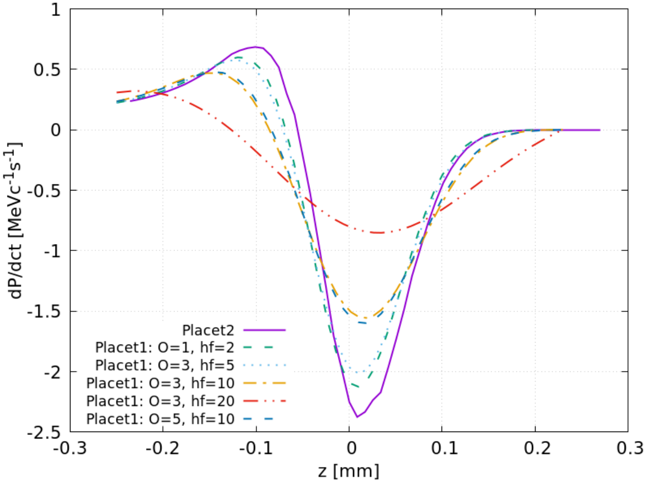
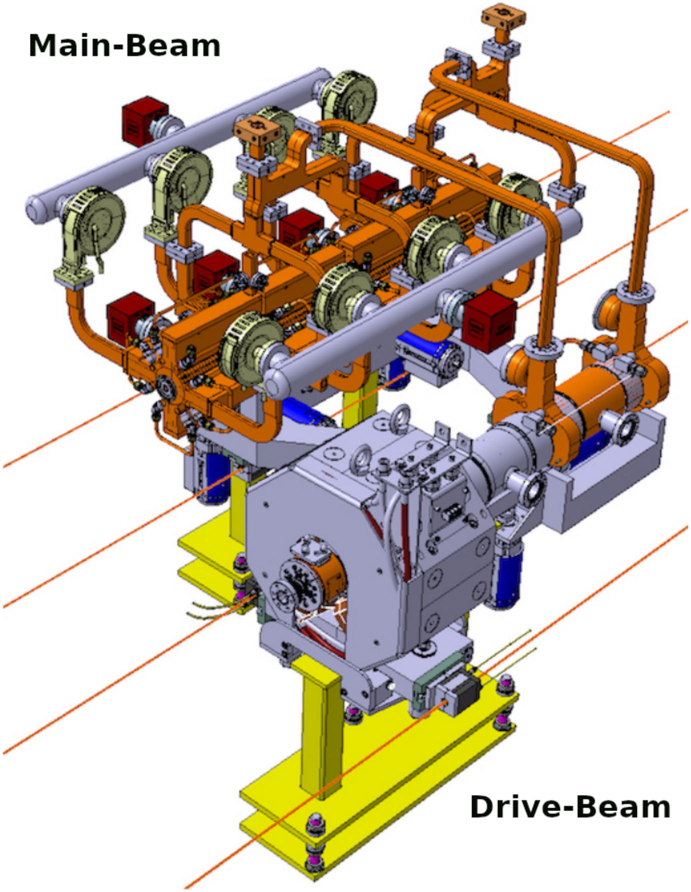


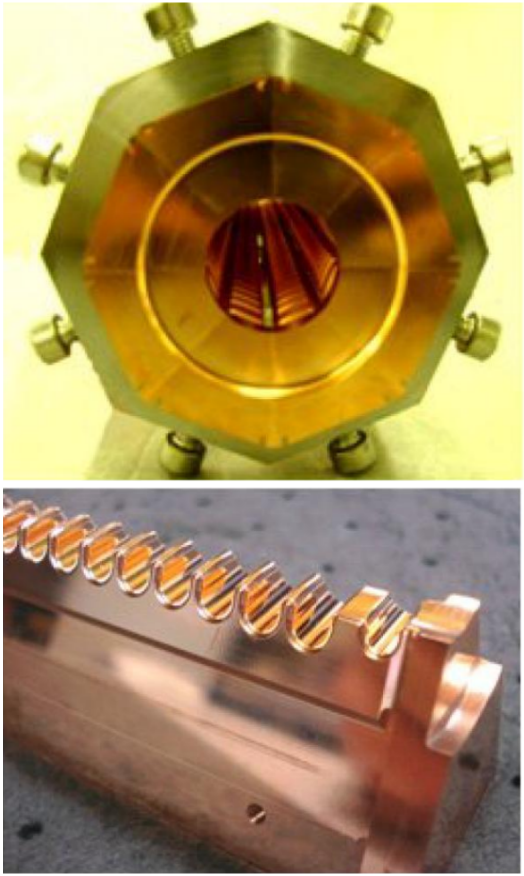
- PLACET1 gave the user ”too much freedom” in smoothing the charge distribution function
- The Saldin integral is not defined $z = z'$ so it was being truncated in the numerical integration

$$\frac{dE\left(z,\phi\right)}{d\left(ct\right)} = -\frac{2Nr_cmc^2}{3^{1/3}\rho^{2/3}}\left\{\frac{\lambda\left(z-z_{\mathrm{s}}\right)-\lambda\left(z-4z_{\mathrm{s}}\right)}{z_{\mathrm{s}}^{1/3}} + \int_{z-z_{\mathrm{s}}}^{z}\frac{\lambda'\left(z'\right)}{\left(z-z'\right)^{1/3}}dz'\right\}$$

$$I_{\mathrm{CSR}}\left(z,\phi\right) = \frac{3}{2}\left\{z_{\mathrm{s}}^{2/3}\lambda'\left(z-z_{\mathrm{s}}\right) + \int_{z-z_{\mathrm{s}}}^{z}\left(z-z_{\mathrm{s}}\right)^{2/3}\lambda''\left(z'\right)dz'\right\}$$

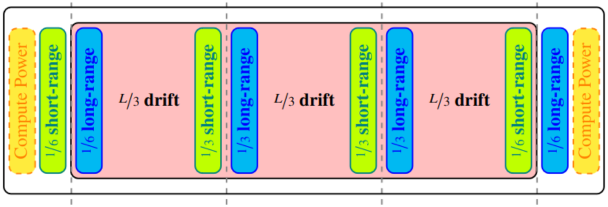
Power Extraction and Transfer Structures





Power Extraction and Transfer Structures

PETS extract power form the bunch through a longitudinal wakefield

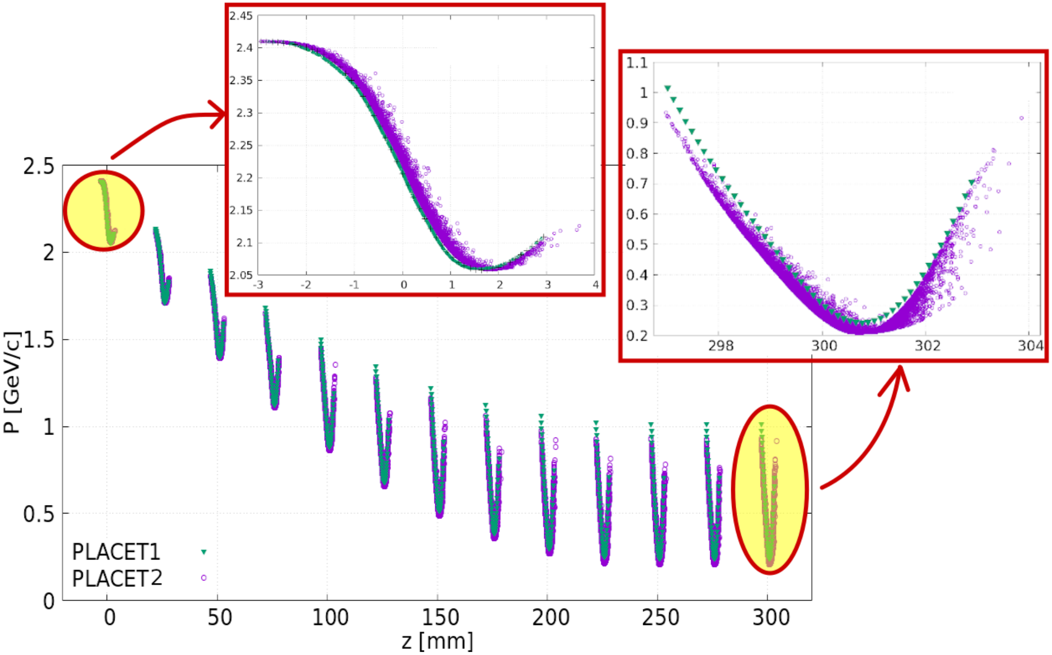


- At each node, a charge distribution is convoluted with the wakefunction, creating a discrete mesh
- Each macroparticle is interpolated with the mesh (giving us a continuous function)
- In between nodes, particles are allowed to slip longitudinally if they have high x' or y'

Entrance and Exit long-range kicks manage the trailing fields:

- Exit kick stores the wakefield and timing info
- Entrance kick checks timing of stored fields and deletes those no longer needed
- $t_{\text{wake}} = \frac{L_{\text{PETS}}}{c} \frac{1-\beta_g}{\beta_g}$
- The kick is only applied once the bunch enters the field
- Optionally, total beam energy is compared between entrance and exit to compute $P_{\text{Extracted}}$

PETS - Consequences of longitudinal slippage



Longitudinal slippage of high-amplitude particles causes am increase in σ_z and Δt (we'll come back to it)

Note: There has been a study of slippage for the 30 GHz CLIC but it was based on the full bunch being offset

D. Schulte, *Proc.* EPAC'02, Paris, France, 2002, MOPRI044

Current Status

- PLACET2 remains the only tool available for tracking re-circulating lattices
- CSR and the PETS were the 2 big remaining features of PLACET1 left to add
- A few features were added along the way (macro-particle weight, better dispersion-free twiss, etc.)

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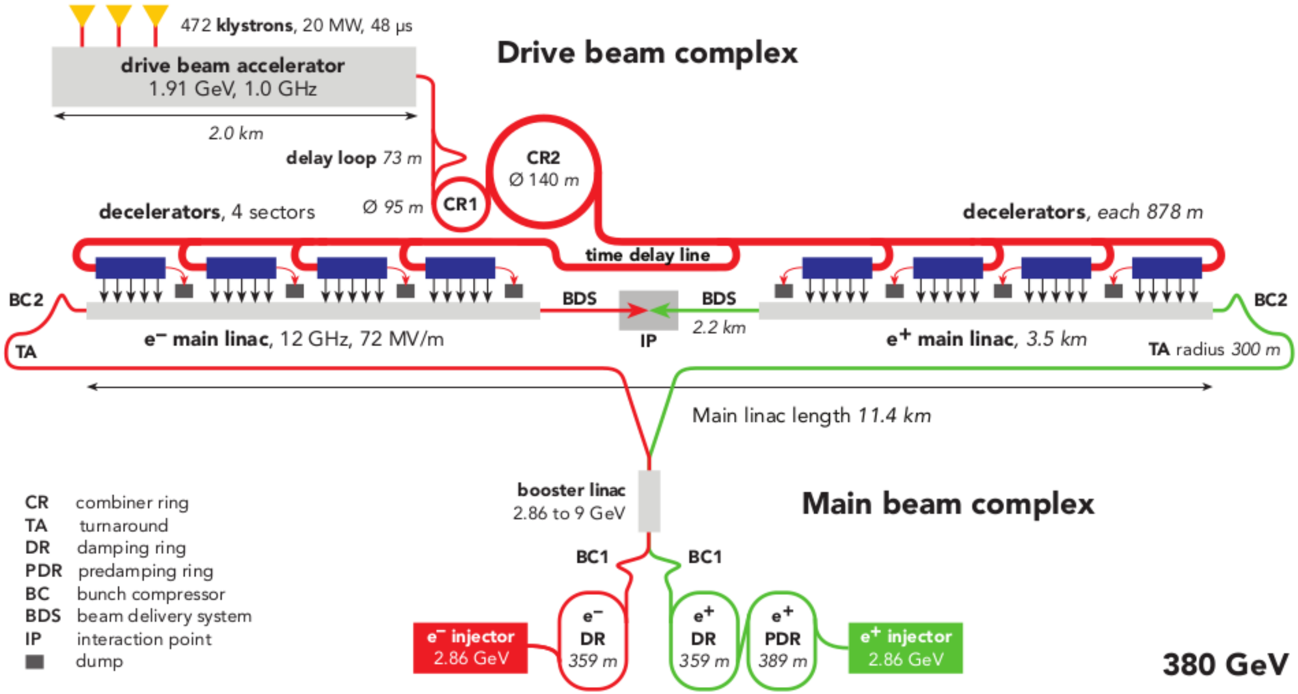
We're now ready for PLACET3!

- Multiple species
- Non-relativistic particles
- Muon decay
- Space-charge
- etc.

We'll hear from Paula soon!

CLIC 380 GeV Decelerator Lattices

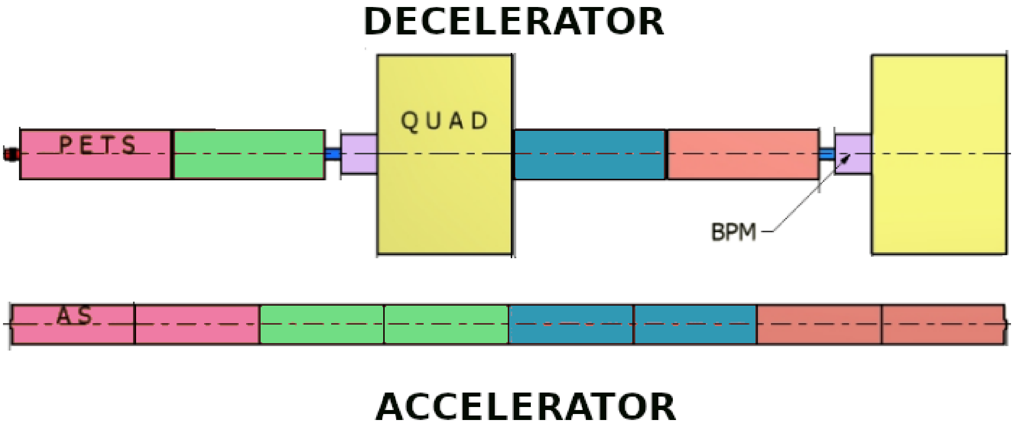
Introduction



Previous Studies

- D. Schulte, "Stability of the Drive Beam in the Decelerator of CLIC", *Proc. EPAC'02*, Paris, France, 2002, MOPRI044, pp. 497-499.
- E. Adli and D. Schulte, "Beam-Based Alignment for the CLIC Decelerator", *Proc. EPAC'08*, Genoa, Italy, 2008, MOPP001, pp. 547-549.
- D. Schulte and R. Tomás, "Dynamic Effects in the New CLIC Main Linac", *Proc. PAC'09*, Vancouver, Canada, 2009, TH6PFP046, pp. 3811-3813.
- D. Schulte, G. Sterbini and E. Adli, "A Comparative Study for the CLIC Drive Beam Decelerator Optics", *Proc. IPAC'12*, New Orleans, USA, 2012,TUPPR035, pp. 1897-1899.
- G. Sterbini and D. Schulte, "Beam-based Alignment of CLIC Drive Beam Decelerator using Girders Movers", *Proc. IPAC'11*, San Sebastian, Spain, 2011, TUPC019, pp. 1036-1038.
- etc.

The CLIC Module



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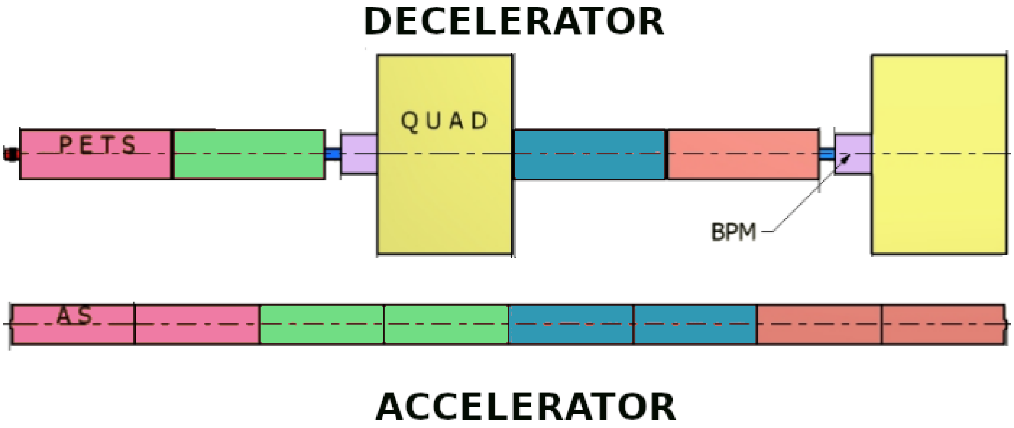
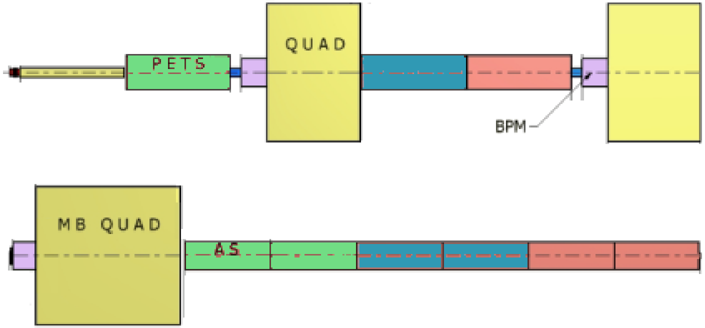
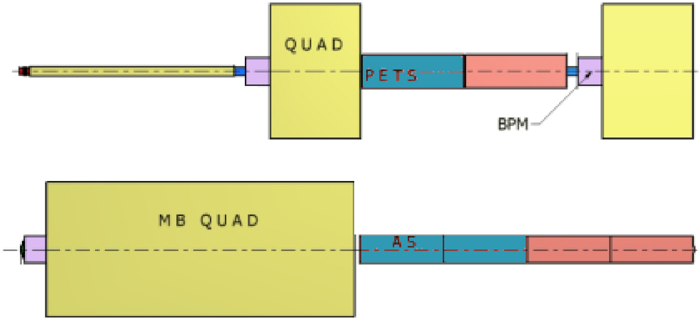


Type 1 Module



Type 2 Module

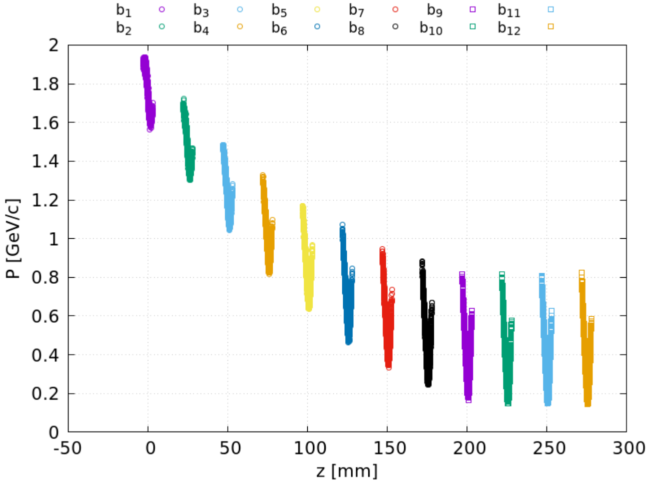


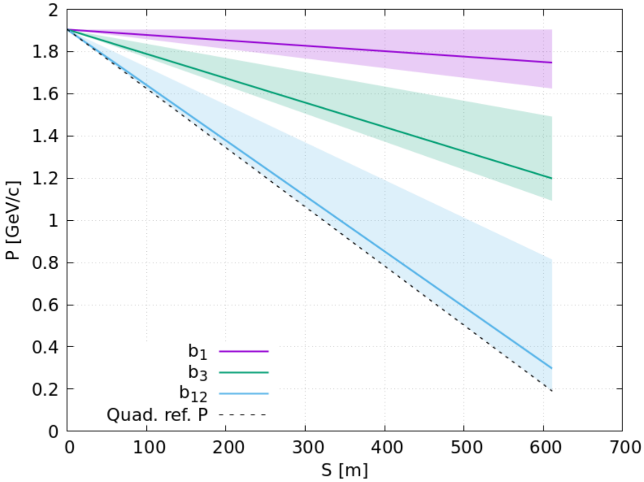
380 GeV Decelerator Lattice

On the decelerator side we have a simple FODO with:

- Round 1.91 GeV beam (previous: 2.4 GeV)
- $L_{\mathrm{cell}} = 2.343\,\mathrm{m}$ (previous: 2.01 m)
- $\beta_{\mathrm{max}} = 4\,\mathrm{m}$
- 2 to 4 PETS per FODO cell
- $L_{\mathrm{PETS}} = 206\,\mathrm{mm}$ (previous: 213 mm)
- Reference energy according E_{min} (next slide)
- Empty PETS slots as required by the Main-Beam (in a bit)

FODO reference energy

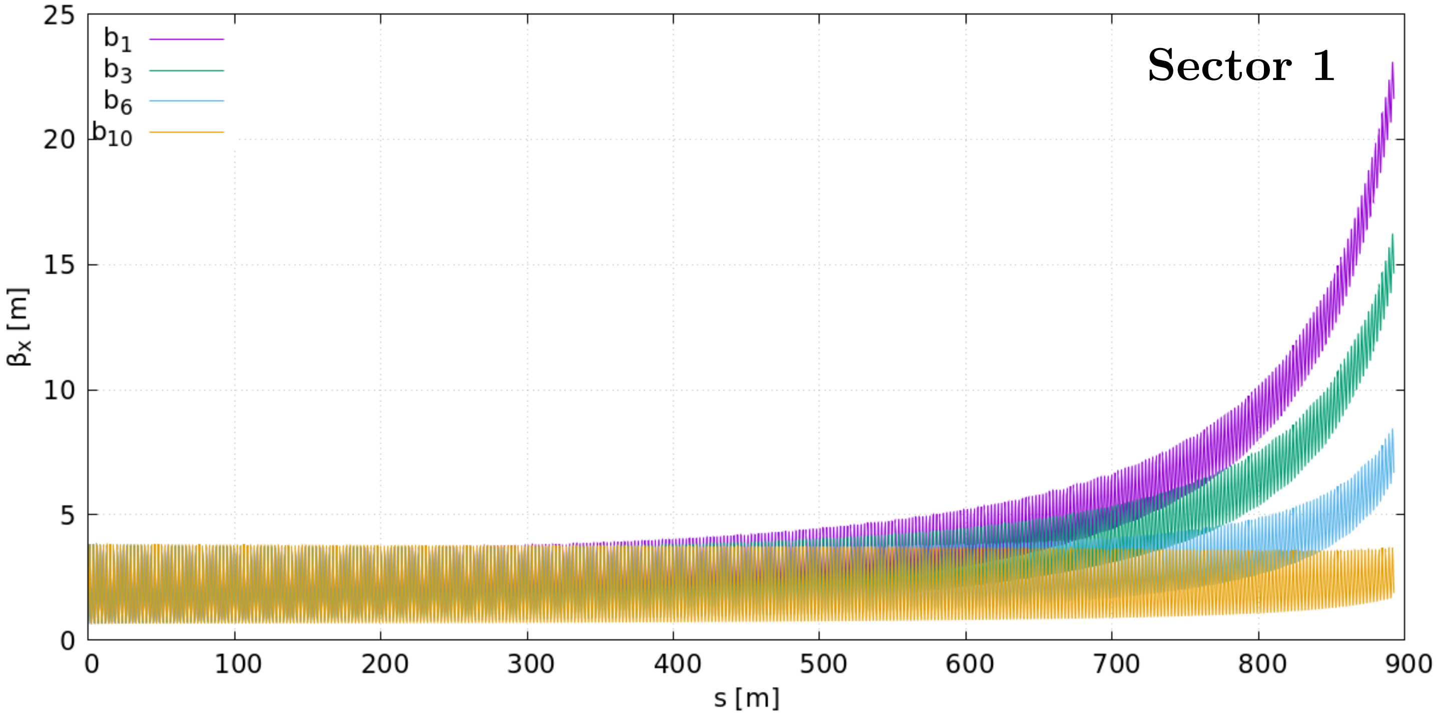




The reference energy is computed for the lowest energy particle of pulse steady-state, which is located roughly $1\sigma_z$ behind the bunch's center of mass

Note: The right-hand plot was made for a ”compact” lattice (no empty PETS slots), each sector will scale slightly differently

Twiss Functions



We are matched for the steady-state so the initial 9 bunches slowly missmatch

How to Place PETS/Empty Slots

"**The total number of PETS per decelerator is 1,273.**" - PIP

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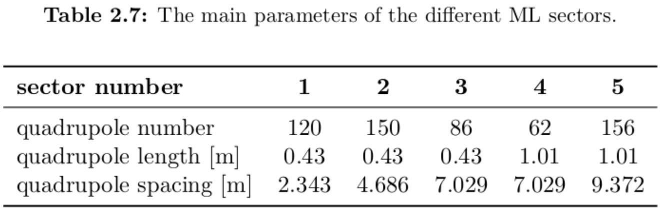

Table 2.7: The main parameters of the different ML sectors.

sector number	**1**	**2**	**3**	**4**	**5**
quadrupole number	120	150	86	62	156
quadrupole length [m]	0.43	0.43	0.43	1.01	1.01
quadrupole spacing [m]	2.343	4.686	7.029	7.029	9.372

- From quadrupole spacing, we can imply 10,320 structures per linac, and therefore 1,290 PETS per decelerator
- This is also what we find in `https://gitlab.cern.ch/clic-simulations/clic-380-gev/-/tree/master/ML_DriveBeam`

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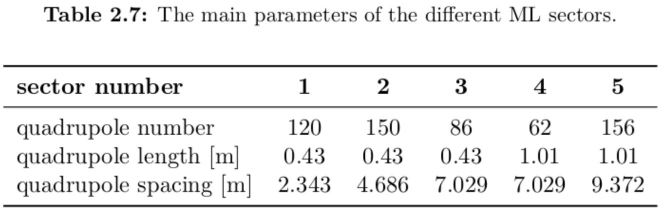

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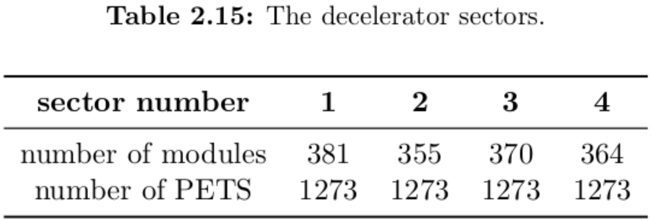

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sector number	**1**	**2**	**3**	**4**
number of modules	381	355	370	364
number of PETS	1273	1273	1273	1273

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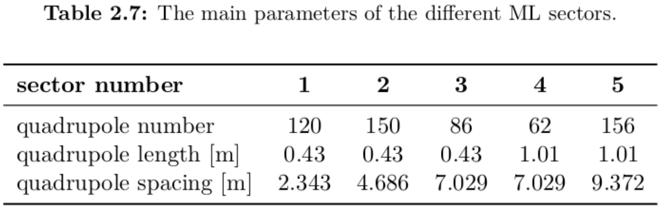

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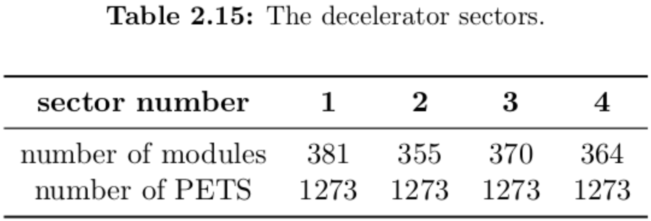

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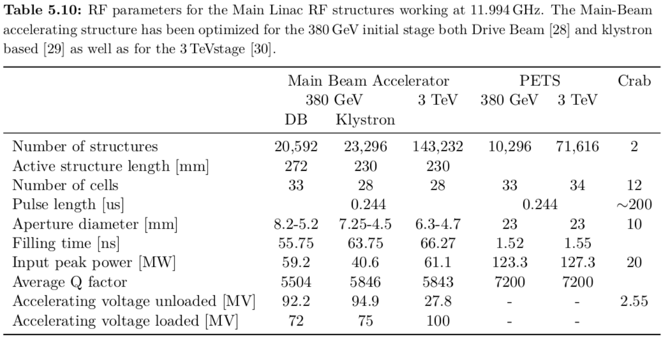

Table 5.10: RF parameters for the Main Linac RF structures working at 11.994 GHz. The Main-Beam accelerating structure has been optimized for the 380 GeV initial stage both Drive Beam [28] and klystron based [29] as well as for the 3 TeVstage [30].

	Main Beam Accelerator			PETS		Crab
	380 GeV		3 TeV	380 GeV	3 TeV	
	DB	Klystron				
Number of structures	20,592	23,296	143,232	10,296	71,616	2
Active structure length [mm]	272	230	230			
Number of cells	33	28	28	33	34	12
Pulse length [us]	0.244			0.244		~200
Aperture diameter [mm]	8.2-5.2	7.25-4.5	6.3-4.7	23	23	10
Filling time [ns]	55.75	63.75	66.27	1.52	1.55	
Input peak power [MW]	59.2	40.6	61.1	123.3	127.3	20
Average Q factor	5504	5846	5843	7200	7200	
Accelerating voltage unloaded [MV]	92.2	94.9	27.8	-	-	2.55
Accelerating voltage loaded [MV]	72	75	100	-	-	

10,296/8=1,287

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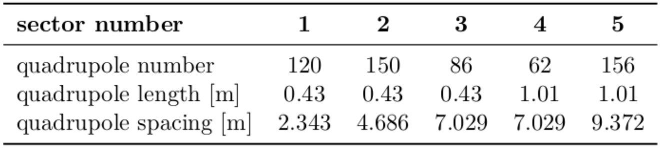

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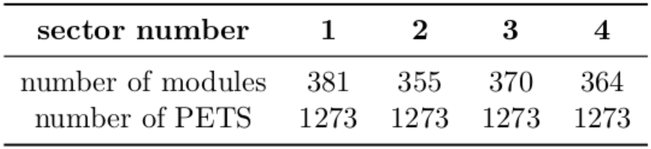

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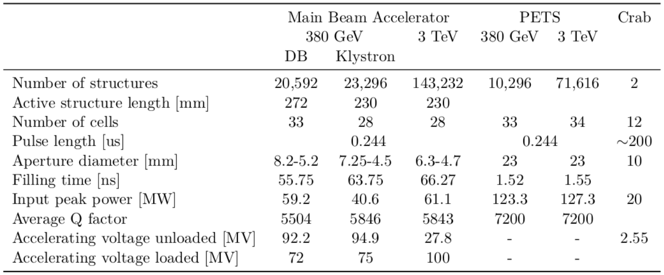

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10,296/8=1,287

- **The gitlab repository has a gradient of 69 MV/m and table 5.10 does not give us ratios so we opted by the 1,273 option**

Decelerator Lattice Design

Each module {...} has 2 quadrupoles and 4 PETS slots which can be filled (**P**) or empty (**E**).

To match the Main-Linac we have to construct 5 super-cells with different fill factors:

- $S_1 \rightarrow \{\text{EPPP}\} \rightarrow 75\%$
- $S_2 \rightarrow \{\text{EPPP}\}\{\text{PPPP}\} \rightarrow 88\%$
- $S_3 \rightarrow \{\text{EPPP}\}\{\text{PPPP}\}\{\text{PPPP}\} \rightarrow 92\%$
- $S_4 \rightarrow \{\text{EEPP}\}\{\text{PPPP}\}\{\text{PPPP}\} \rightarrow 83\%$
- $S_5 \rightarrow \{\text{EEPP}\}\{\text{PPPP}\}\{\text{PPPP}\}\{\text{PPPP}\} \rightarrow 88\%$

Decelerator Lattice Design

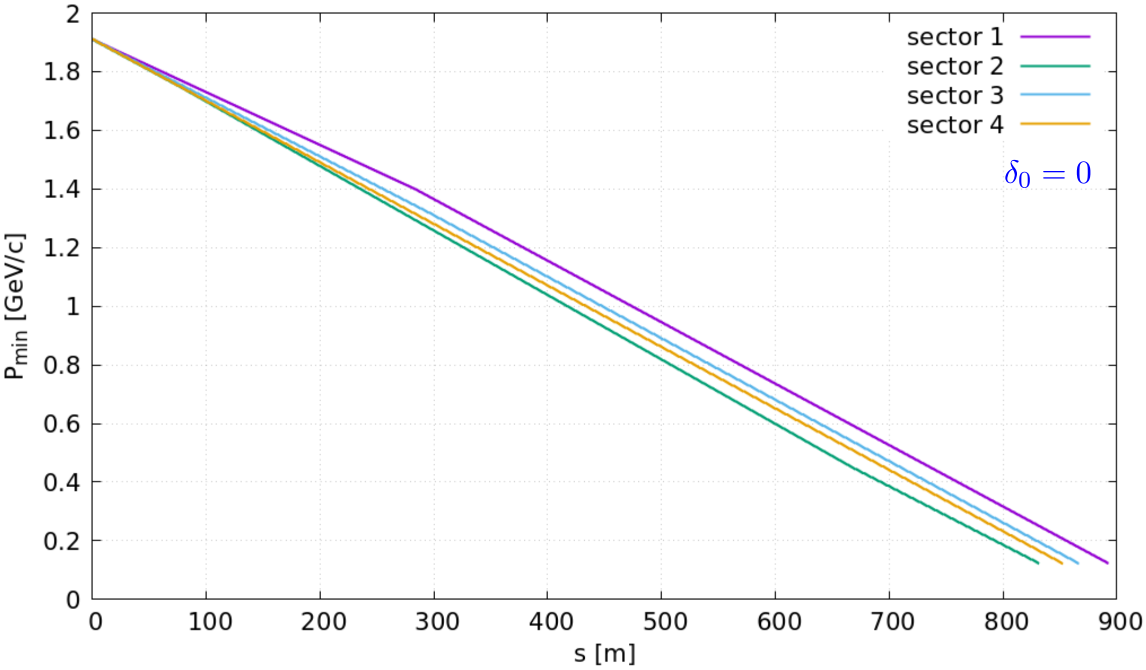
Matching the number of PETS and modules to Table 2.15:

- Decelerator 1 (381 Modules, 1273 PETS, 893 m)
  - $121 \times S_1$
  - $130 \times S_2$
- Decelerator 2 (355 Modules, 1273 PETS, 832 m)
  - $17 \times S_2$
  - $84 \times S_3$
  - $23 \times S_4$
- Decelerator 3 (370 Modules, 1273 PETS, 867 m)
  - $42 \times S_4$
  - $61 \times S_5$ *
- Decelerator 4 (364 Modules, 1273 PETS, 853 m)
  - $91 \times S_5$ *

* The last slot of the decelerator is empty

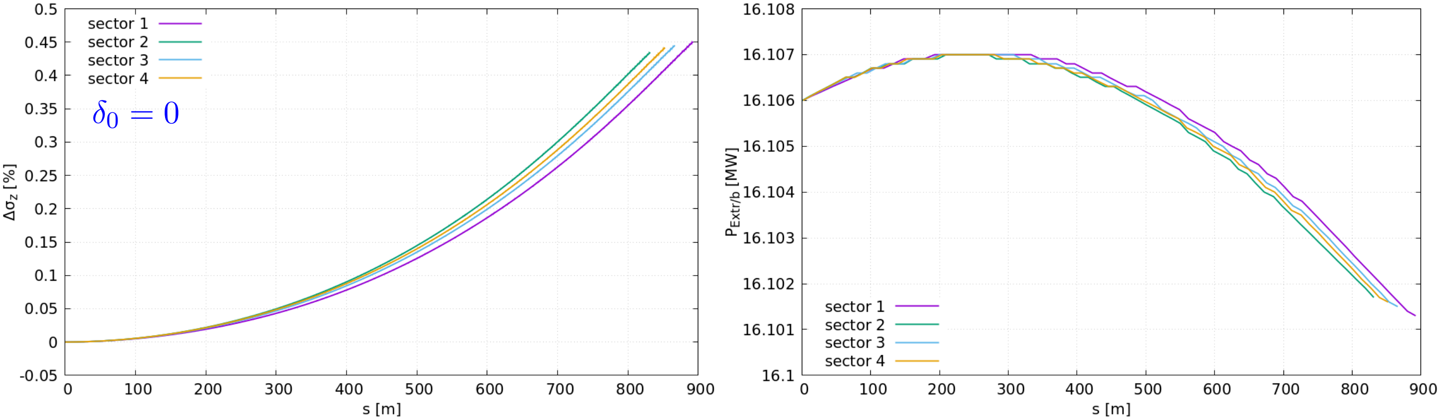
`gitlab.cern.ch/clic-simulations/clic-380-gev/-/tree/master/DB_Decelerators`

Results - Energy Loss



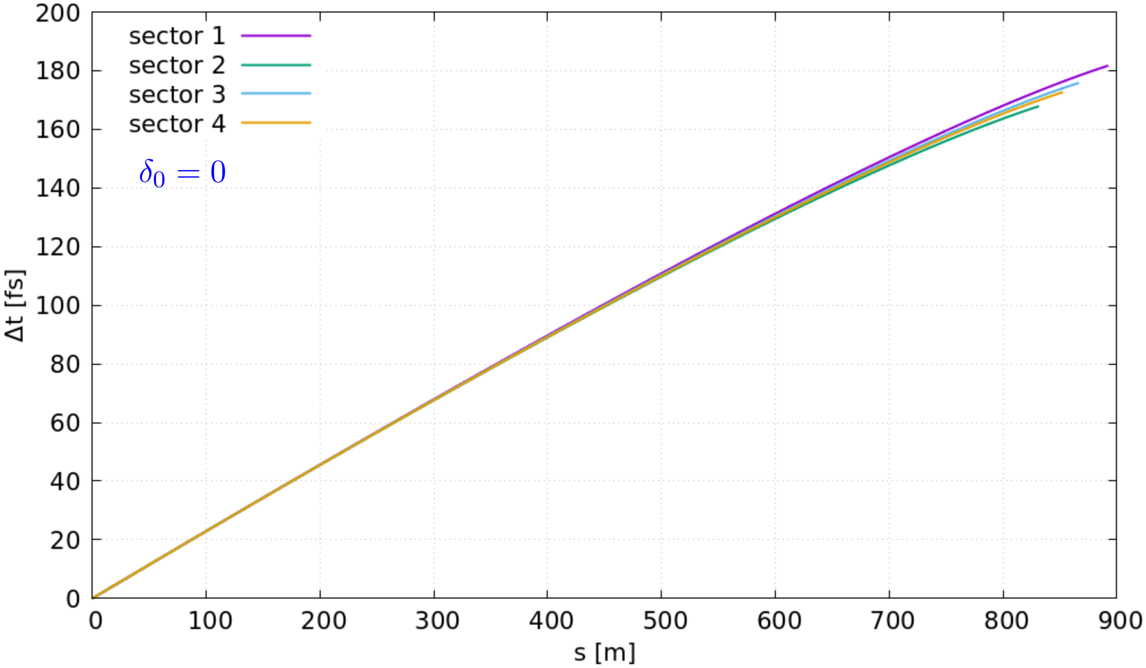
As expected, all four lattices extract the same amount of energy

Results - Bunch Length and Extracted Power



- σ_z increases $\sim 0.45\%$ so one would expected a mild decrease in extracted power
- Instead we first observe a smallincrease in $P_{\text{Extracted}}$, and a later decrease
- This can be explained by a mild change of shape of the distribution
- All four sectors are within the tolerance

Results - Longitudinal Slippage



- Slippage of the centroid poses a bigger threat since we expect a an RF timing error 47 fs to be significative
- However, this is a static* effect, so the RF system should be tunable to counteract it

Losses due to δ_0

- Seeing that the final energy spread is 50%, one could expect $\delta_0 = 0.85\%$ at injection would have no impact on beam dynamics but...

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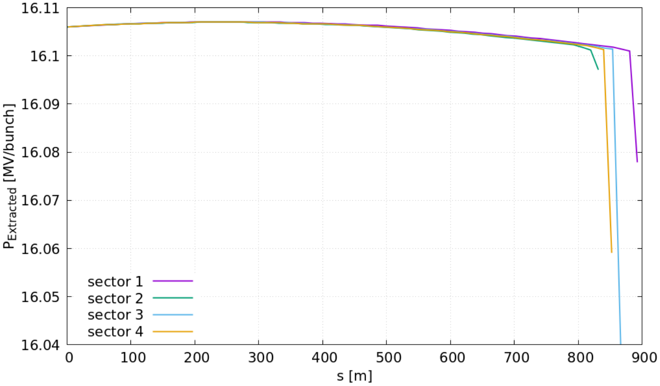

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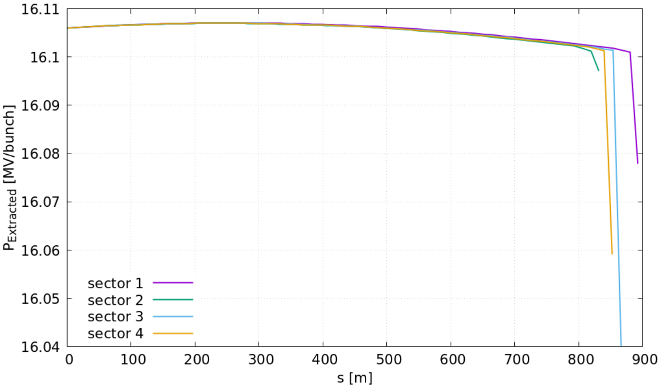

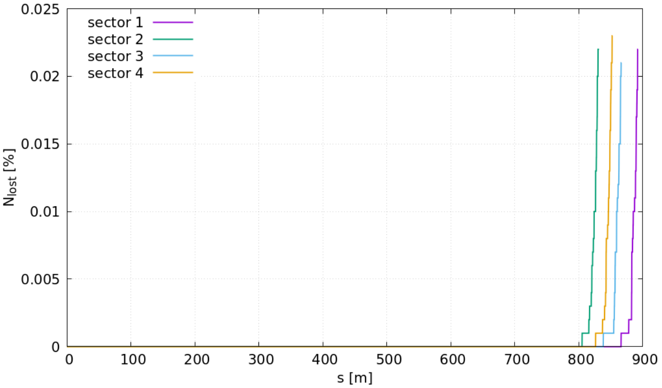

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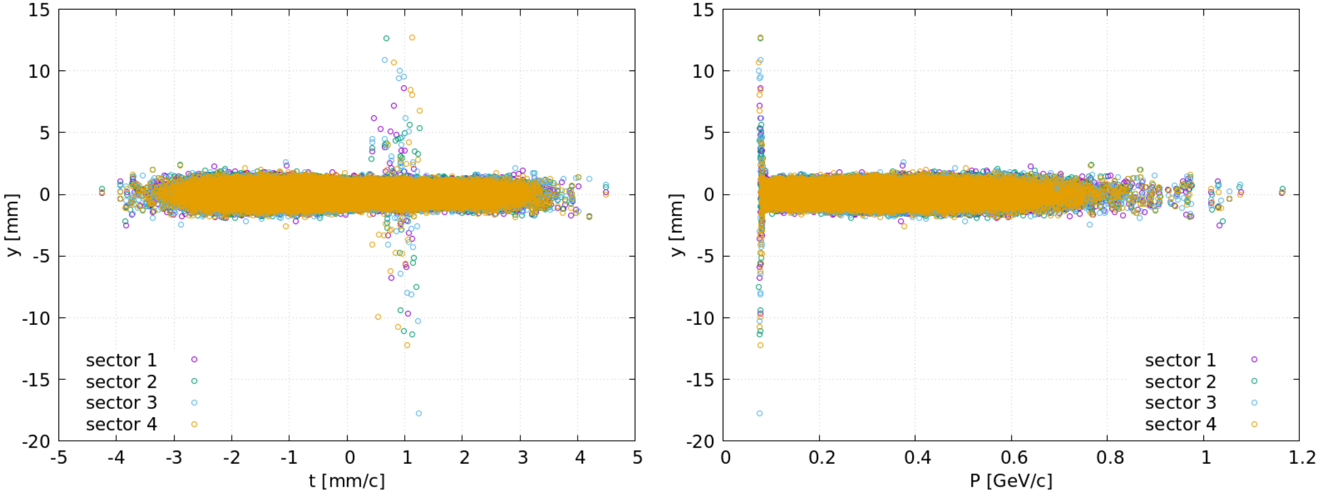
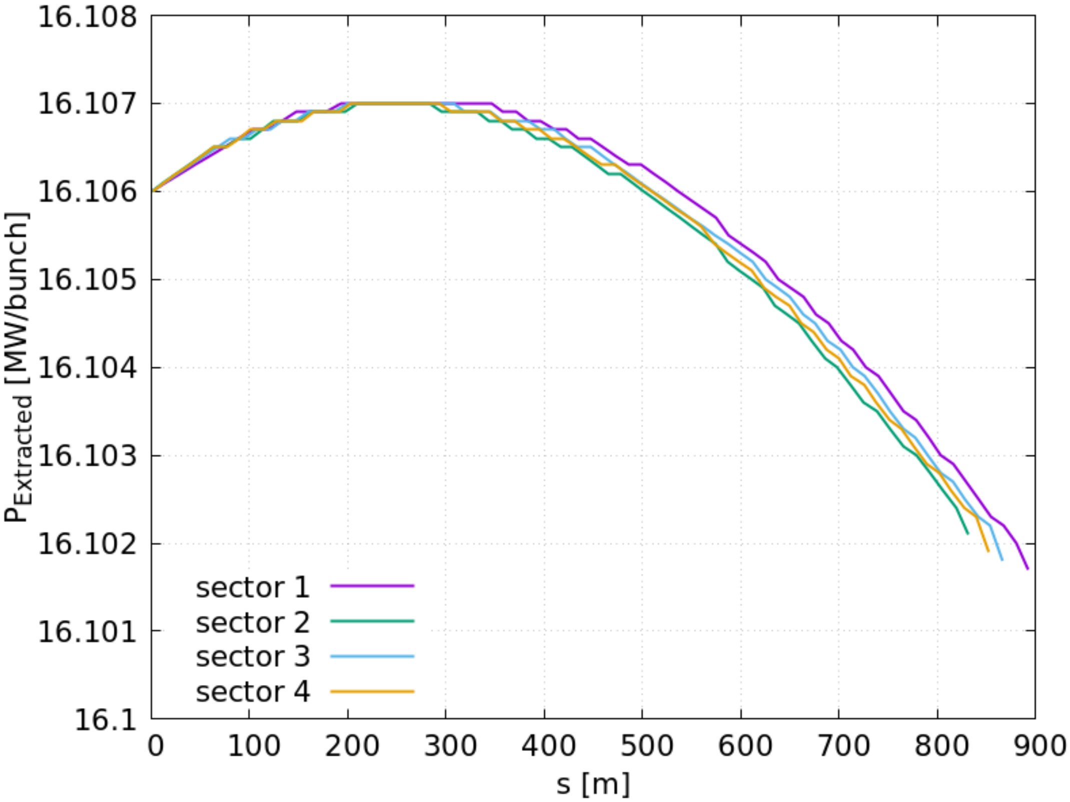


- Particles are lost at the field maximum
- With $\delta_0 = 0.85\%$, some particles are bellow the reference energy
- A small percentage of particles at the lower end of the distribution is not captured by the FODO's periodic solution

Solving the losses issue

- By making a small shift in the initial reference energy $E_{\text{ref}} \to (1-\delta)E_{\text{ref}}$ we ensure all particles are captured by the FODO



Emittance-Dependency

The longitudinal spillage is ”static” but if it depends on the amplitude of oscillations. What is the effect of transverse emittance on it?

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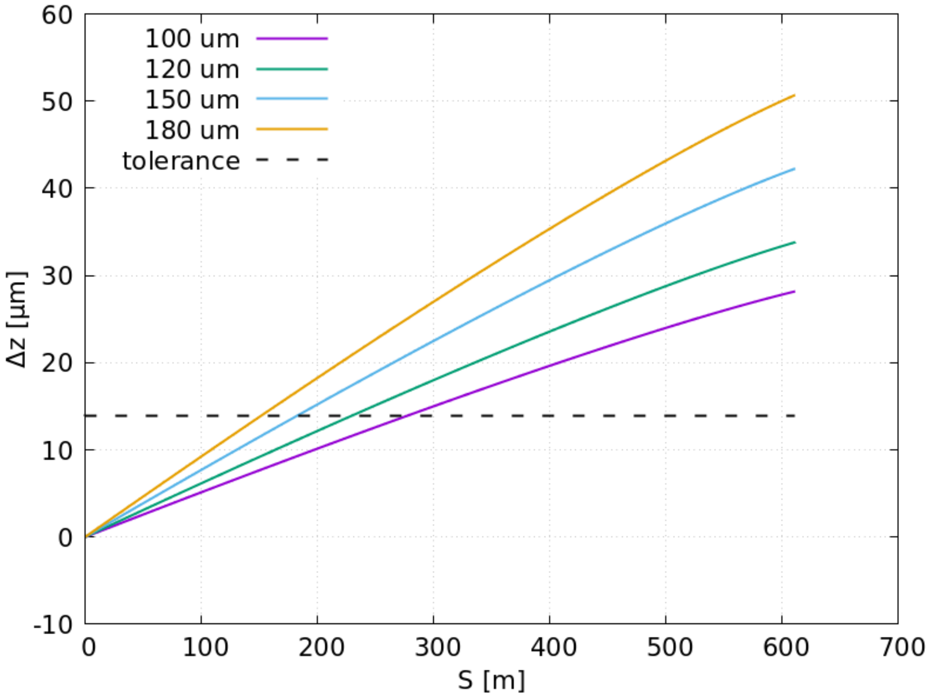
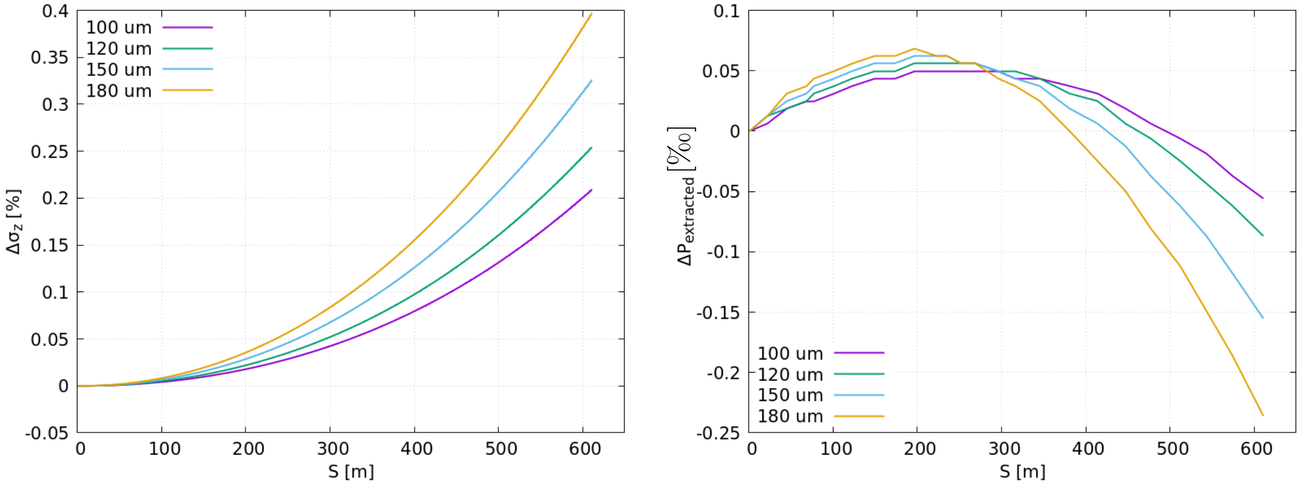


Consequence: changes in transverse emittance (even improvements) may require re-tuning of the RF coupling to the main linac

Emittance-Dependency



Changes to σ_z and $P_{\text{Extracted}}$ are within the tolerance

Conclusions

- We produced the new CLIC 380GeV decelerator lattices
- Quadrupole matching needs to take into account the energy spread at injection
- Betatron-induced longitudinal slippage is a non-negligible effect
- The power output of the PETS is within tolerances
- The longitudinal slippage greatly affects the RF phase of the PETS
- Even though this is a static effect that should be correctable in the RF system, changes to transverse emittance could nulify said correction

Outlook

- We can now use power extraction directly as a merit figure
- Matching the injection to the vertical dogleg, the feed-forward chicane and the turnaround loop (and eventually the entire complex)
- Applying injection errors and misalignments
- Applying periodic bunch errors matching the recombination complex different pathways