Wake field effects in LHeC ERL

LHeC workshop 2015

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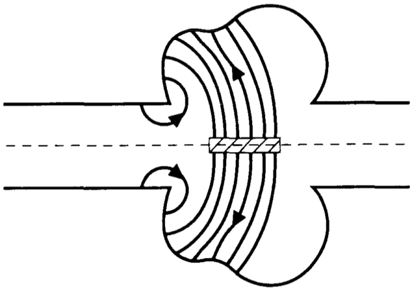
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Summary

- Wake Field Physics and Modelling:
  - Short-Range Wake Fields;
  - Long-Range Wake Fields.
- The Tool: PLACET2.
- End-to-End Tracking;
- Single Bunch effects:
  - Full Optics, Short-Range Wakes, Synchrotron Radiation, Beam-Beam.
- Multi-Bunch Tracking:
  - Long-Range Wakes and Beam Break Up studies.

Wake Fields



Short Range:

Generate energy losses along the bunch;
Transverse kick to the bunch tail.

Long Range:

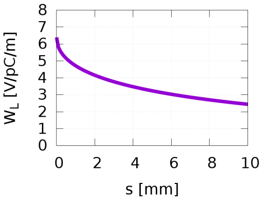
With big Q values the field persists;
Later bunches are kicked.

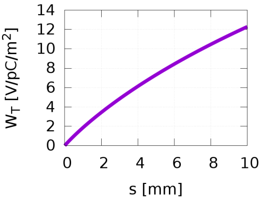
Modeling of Short-Range Wake Fields

1. *Wake Function*:
   - Tells the electric potential felt by a test charge following an exciting charge at a given distance;
   - Depends on the cavity geometry;
   - Can be computed numerically, but analytical approximations exist[1].

$$W_L(s) = \frac{Z_0 c}{\pi a^2} \exp\left(\sqrt{\frac{s}{s_{00}}}\right),$$

$$W_T(s) = \frac{4 Z_0 c s_{00}}{\pi a^4} \left[1 + - \left(1 + \sqrt{\frac{s}{s_{00}}}\right) \exp \sqrt{\frac{s}{s_{00}}}\right].$$





[1] K. Bane, SLAC-PUB-9663, 2003

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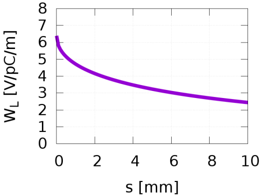

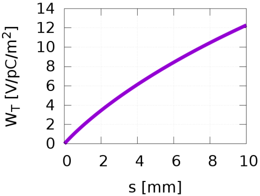

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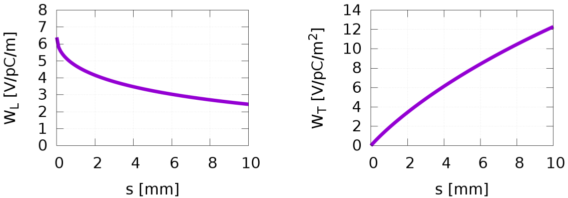

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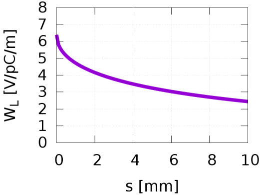

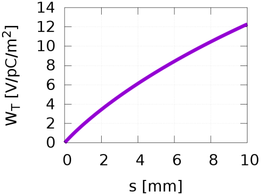

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Recent addition in PLACET2, some work is still in progress!

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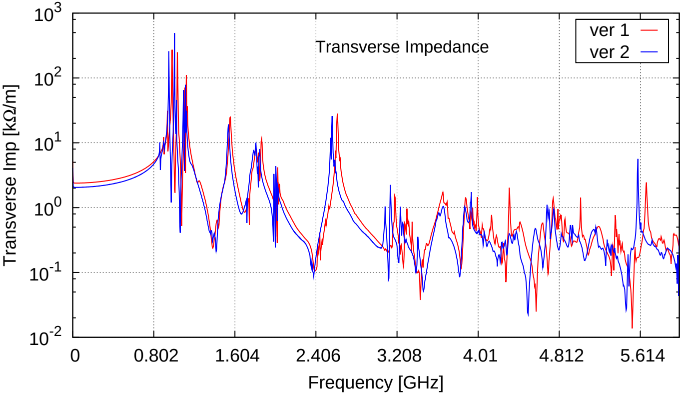
Origin of Long-Range Wake Fields

From the ERLF cavity design[2]

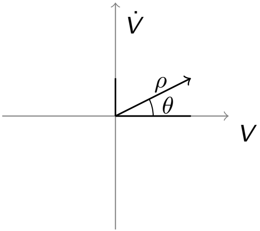


- Some modes can have big Q value and slow damping;
- Dipole modes are particularly strong and easy excited by orbit displacements;
- With many bunches, modes can build up leading to Beam Break Up.

[2] R. Calaga, CERN-ACC-NOTE-2015-015, 2015

Modeling of Long-Range Wake Fields

The status of a mode is represented with a complex numbers: $z = \rho e^{i\theta}$



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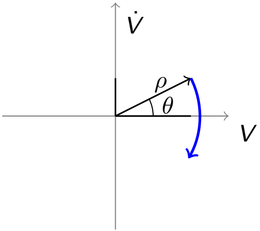

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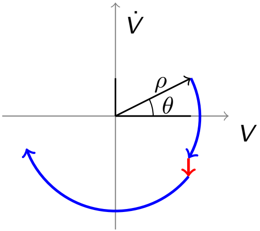
  $\Im(z) = \Im(z_0) + Ne\,A\,L_{cav}\,\delta x$



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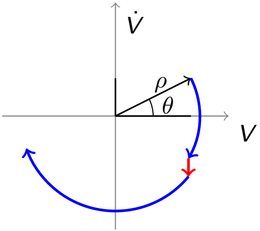
- Mode $\rightarrow$ bunch interaction (kick):

  $x' = x'_0 + \frac{e\,\Re(z)}{\gamma\, m_e\, c^2}$

Iterated over all the HOMs of the cavity.



A Complication: Beam Recirculation

The kicks received from a passage are fed back to the HOMs in the next passages.
In single-pass, single-cavity, single-mode ERLs can estimate the *threshold current*:

$$I_{th} = \frac{2c^2}{eR\omega} \frac{1}{T_{12} \sin(\omega t)}$$

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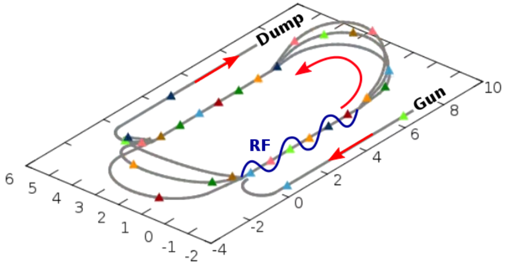
- In the LHeC the beam is *recirculated six times*, 576 cavities per linac, many HOMs;
- *Non fixed train structure*: at every passages some bunches are dumped and replaced with fresh bunches;
- *Coupling with other effects* such as beam-beam.



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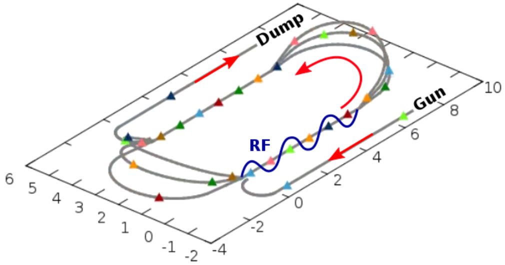


Need to setup a tracking simulation!

PLACET2

New version of the tracking code PLACET equipped with the *recirculation module*. Full 6D tracking code, allows to simulate the simultaneous propagation of many bunches in recirculating lattices.

- Description of multiple *beamlines* as standard sequences of elements;
- Creation of *links* between them with runtime-evaluated routing criteria;
- Introduction new elements: *injectors* and *dumps*.

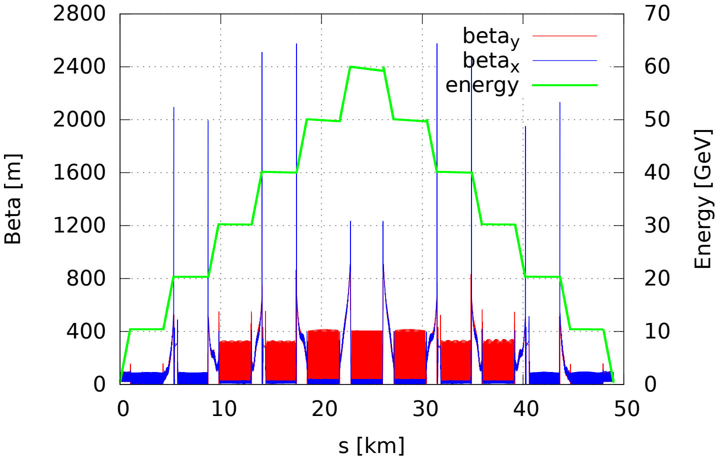
- Injectors release bunches in the machine at the right time;
- Each bunch keep track of its time-of-flight, elements can read it to update themselves, a global timer allows the synchronisation.

Each beamline sees the *correct sequence of bunches* even when the train is recombined → Can compute *multibunch effects* in a realistic operational scenario.

Flexible design: can integrate a number of physics effect in a single code and verify their interplay!

End-to-end Optics

PLACET2 extracts the optics parameters from the particles distribution. A test bunch is followed from the injector to the dump. Basic validation of the setup.



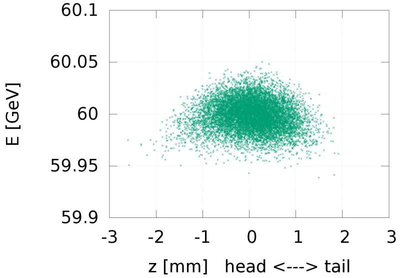
Notable: the energy loss due to synchrotron radiation in Arc 6, the different average β in the arcs, the recovery of the mismatch generated in the linacs.

Beam at the IP

Higgs Factory Parameters - $L = 10^{34}$

Injection/Dump Energy	500 MeV
Bunch Spacing	25 ns
Particles per bunch	$4 \times 10^9 = 640\,\text{pC}$
Normalised RMS Emittance	$50\,\mu$m
IP β function	0.032 m

Longitudinal phase space at IP

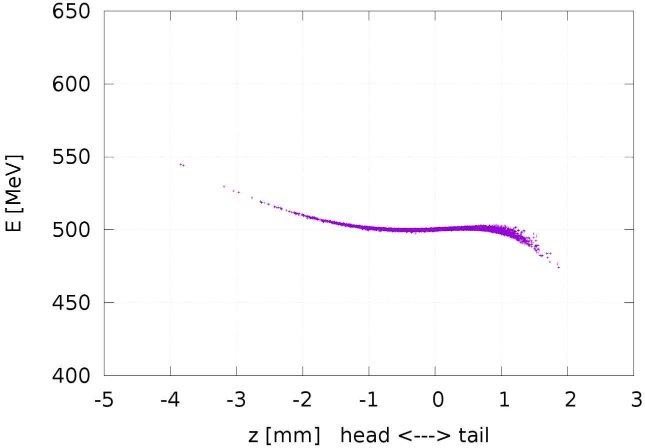


	initial/CDR	IP
ε_x [μm]	50	57.4
ε_y [μm]	50	50.8
δ	0.0020	0.0026
RMS x [μm]	7.20	7.66
RMS y [μm]	7.20	7.21
RMS z [mm]	0.600	0.601
RMS e [MeV]	-	15.4

- The beam at the IP maintains a very good quality, still need to verify imperfections and stability;
- The acceleration mitigates many effects, but the deceleration amplifies them...

Longitudinal Phase Space at Dump (I)

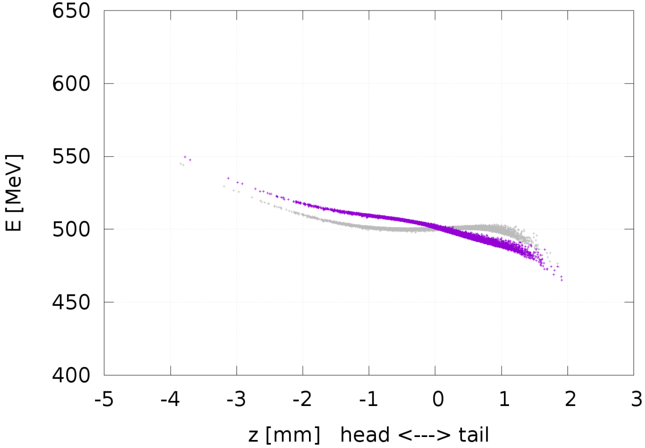
Optics only:



Non perfect isochronicity together with the RF curvature.

Longitudinal Phase Space at Dump (II)

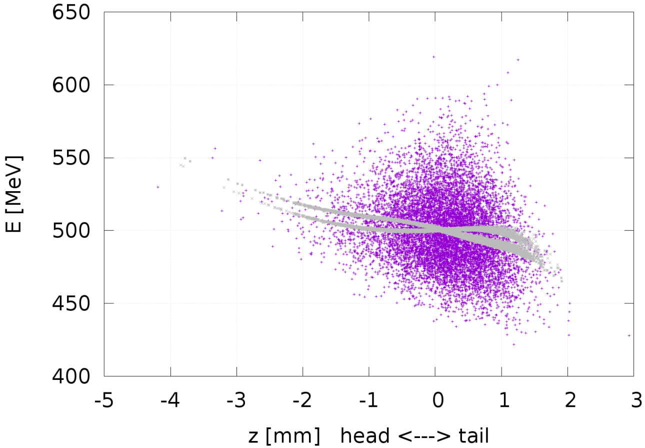
Short Range Wake Fields:



Second harmonic RF losses compensation (no RF curvature from it).

Longitudinal Phase Space at Dump (III)

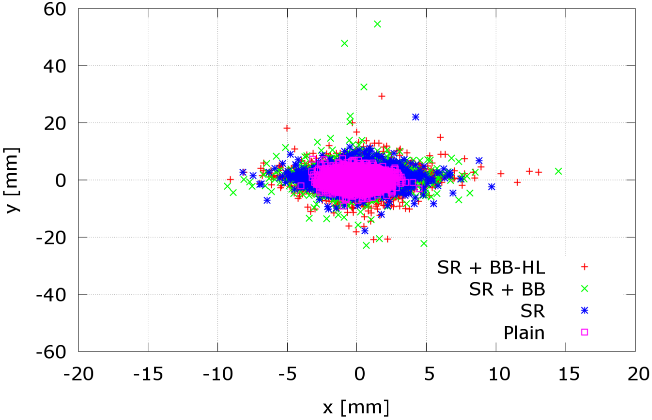
Short Range Wake Fields + Synchrotron Radiation:



Big energy spread from quantum excitation, structures from optics and sr wakes disappeared!

Transverse Plane at Dump

Synchrotron Radiation and Beam-Beam



- Iris radius of the cavity > 50 mm;
- Short-range wakefields not included.

Long-Range Wake Fields with Multi-Bunch Tracking

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- Fill the machine with perfectly centred (single particle) bunches,
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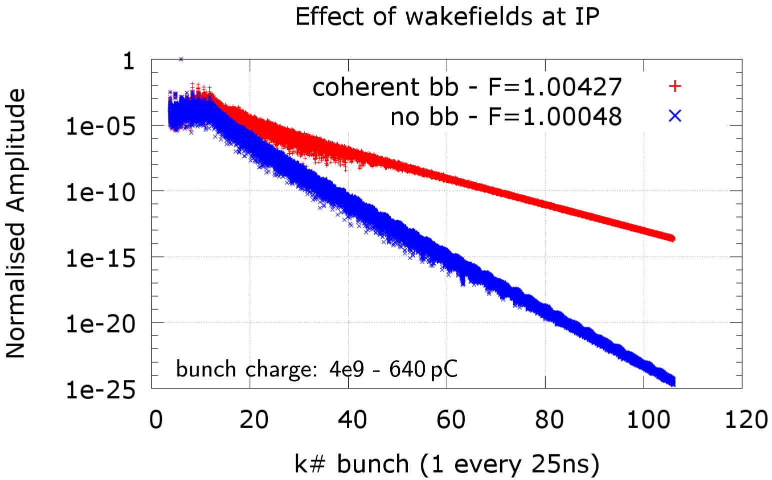
Used 26 transverse dipole modes of the SPL cavity, scaled to 802 MHz.

Beam Stability with the Higgs Factory Params



Note the amplification due to the beam-beam kick!

Long-Range Wakes investigations

- Cavity Detuning;
- Bunch Recombination Pattern;
- Phase Advance in the IP line.

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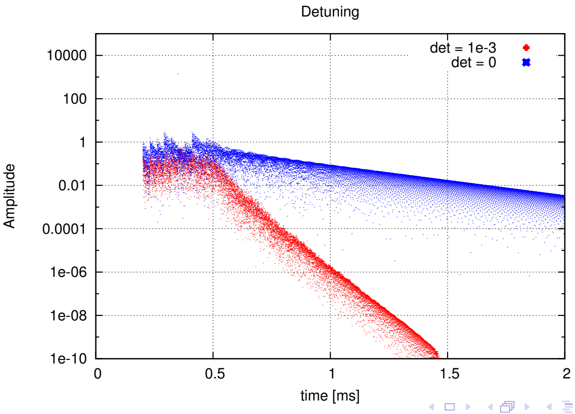
- Cavity Detuning;
- Bunch Recombination Pattern;
- Phase Advance in the IP line.

Sudies done with an injection/dump energy of 300 MeV and $2e9$ electrons per bunch.

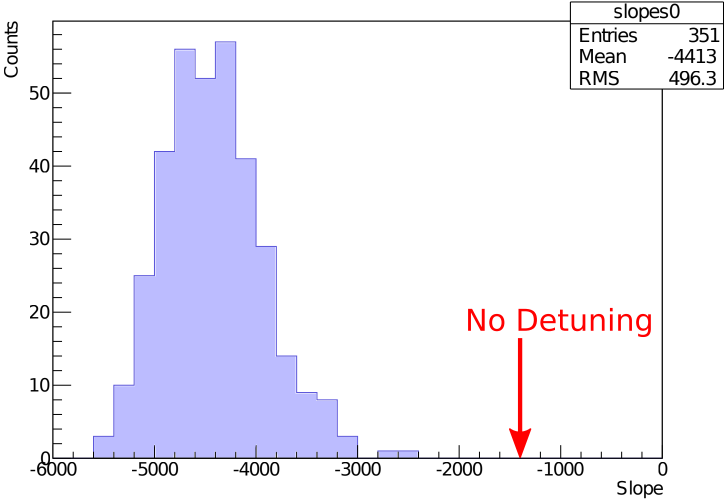
Detuning of the cavities

- Small imperfection in the manufacturing of the cavities leads to slightly different frequencies for the HOMs;
- The same modes in different cavities decohere and their effect can be mitigated;
- The frequencies of the HOMs of the cavities are picked from a Gaussian distribution with: $\sigma = \delta f / f = \text{det}$.



Impact of Detuning

- 351 machines with a detuning factor of 1 ‰ have been simulated.
- The distribution of the slopes of the amplitudes is shown:

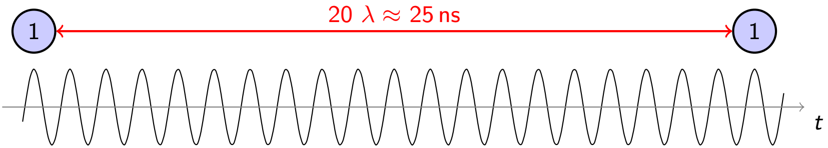


Recombination Pattern

Multi-bunch effects are enhanced by the value of:

$\int_{\text{linacs}} \frac{\beta}{E} ds \rightarrow$ low energy particles are more susceptible.

The filling of the RF buckets of the LHeC can be controlled tuning the lengths of the arcs $\rightarrow$ maximise the separation between the bunches at first and sixth turn.



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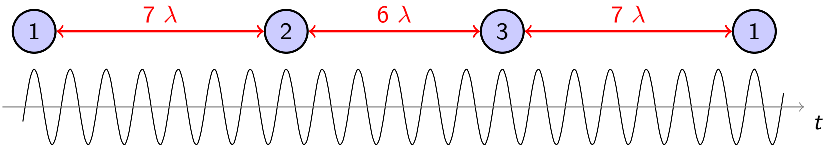

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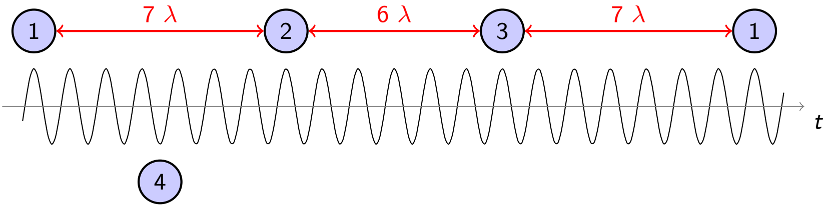

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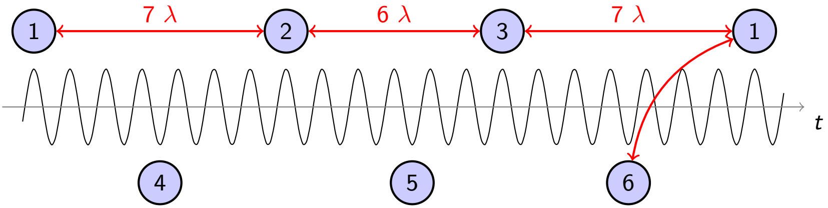

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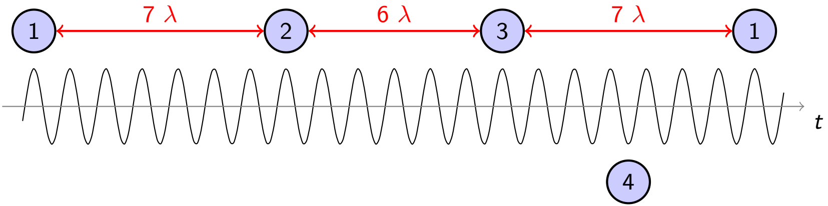

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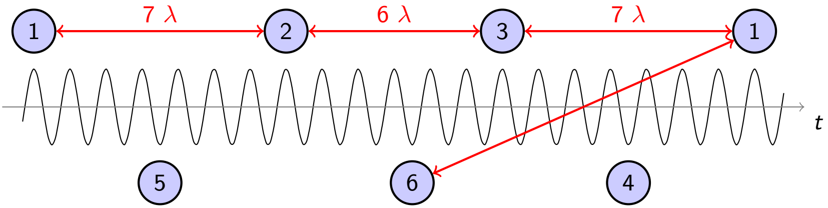
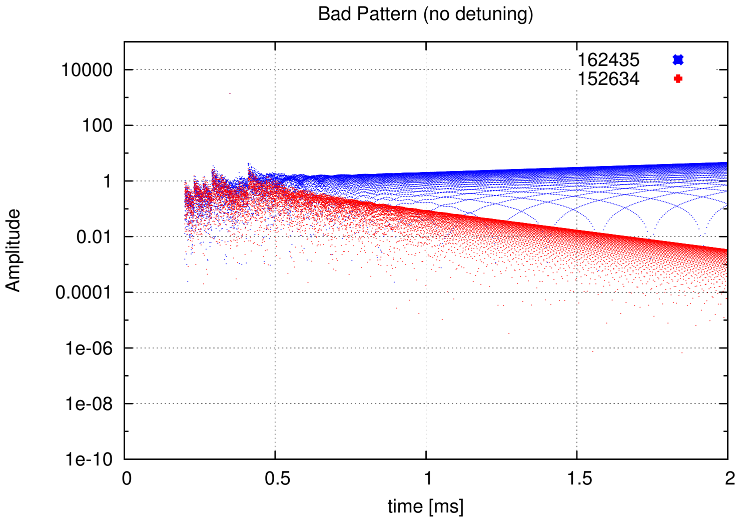


- Pattern 162435 is bad!
- Pattern 152634 is better!

Pattern and Long Range Wakefields

The pattern has an influence on the threshold current



Phase Advance in the IP line (I)

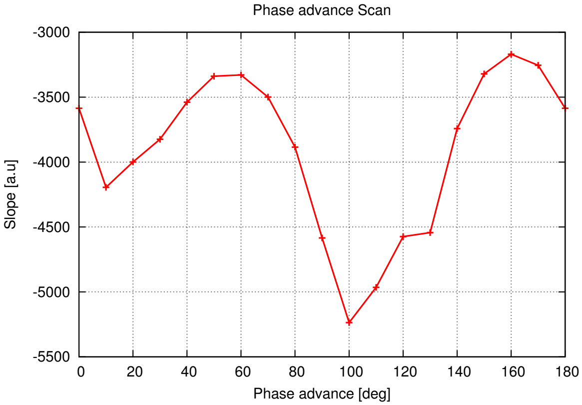
Transport of the beam from the end of Linac 2 to the IP is done with the matrix:

$$\begin{pmatrix} \sqrt{\frac{\beta_{IP}}{\beta_L}}(\cos\psi + \alpha_L \sin\psi) & \sqrt{\beta_{IP}\beta_L}\sin\psi \\ \frac{\alpha_L - \alpha_I P}{\sqrt{\beta_{IP}\beta_L}}\cos\psi - \frac{1+\alpha_{IP}\alpha_L}{\sqrt{\beta_{IP}\beta_L}}\sin\psi & \sqrt{\frac{\beta_L}{\beta_{IP}}}(\cos\psi - \alpha_{IP}\sin\psi) \end{pmatrix}$$

And similar to go back into Arc 6.

- The phase advance ψ does not affect the shape of the beam
- ...but it determines how the centroid offset and angle mix together.
- A scan of this parameter has been done.

Phase Advance in the IP line (II)



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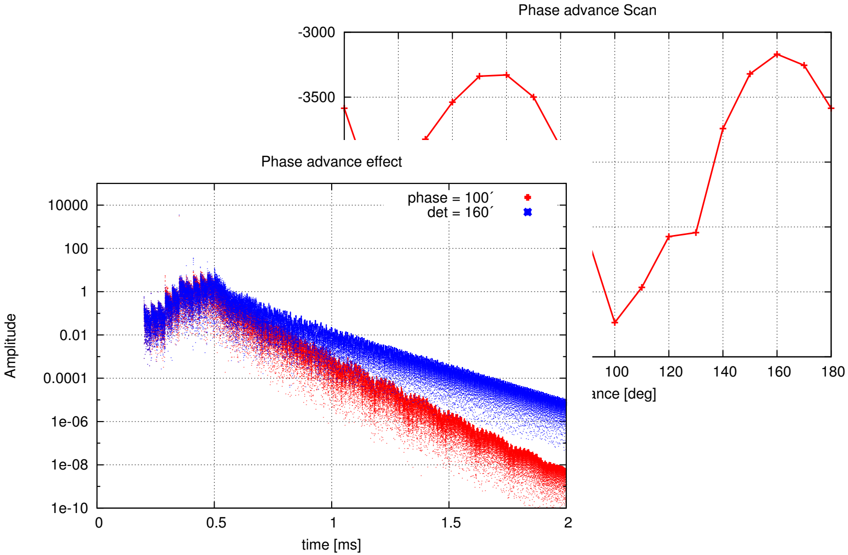

Conclusions

- Introduction:
  - Brief review of Short and Long-Range Wake Fields physics and modelling;
  - PLACET2: simultaneous multi-bunch tracking in recirculating lattices, integration of many physics effects.
- Single-Bunch tracking in the LHeC lattice:
  - *Good beam quality at IP*;
  - Longitudinal phase space affected mostly by synchrotron radiation, other effects are masked;
  - Transverse phase space suffers also from the beam-beam (more details in the Edward's talk);
  - *Can transport the beam to the dump* and possibly reduce the injection/dump energy.
- Multi-Bunch tracking in the LHeC lattice:
  - The LHeC Higgs Factory parameters look *safe for BBU* even with the beam-beam amplification;
  - Further control can come from: Cavities Detuning, Beam Recombination Pattern, Betatron Tune.
- Possible future works:
  - Complete the investigation of Short-Range Wakes;
  - Iterate the BBU studies with the new cavity designs, possibly adding longitudinal modes;
  - Study the Ion-Cloud and its coupling with Wake Fields.

A special thank to Andrea Latina, Daniel Schulte, among the whole LHeC collaboration

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...and to You For Your Attention!