Multi-Bunch Tracking

in Recirculating Machines

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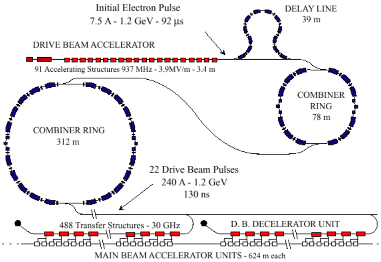
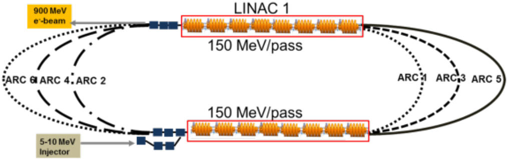
Feb 6, 2015

Recirculating Machines

- Recirculating machines are a special class of particle accelerators in which the beam circulates a few times in the same elements.
- The bunch train is often modified during operation (non-fixed bunch spacing and/or ordering).
- Neither linac nor ring codes are fully suited.
- Multibunch effects in these machines are typically handled with small, *ad hoc* codes.





Many different and complex topologies!

RPL: Recirculating Placet

Why a code designed to handle such machines?

Fundamental reason: compute the impact of multibunch effects with beam recirculation:

- *Long Range Wakefields - Higher Order Modes*,
- ion/electron clouds,

...on top of a full 6D tracking with a number of single particle/single bunch effects:

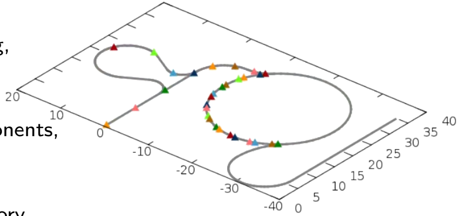
- *Incoherent* and Coherent *Synchrotron Radiation*,
- Short Range Wakefields and Impedances,

Corollary benefits:

- Clearer and easy-to-maintain scripts (no multiple definition of the same element, lattice unrolling, ...),
- Misalignments and timing errors correctly applied and propagated to the whole machine,

What does RPL ask you?

- Definition of one or more *injectors*:
  - create and store bunches for tracking,
  - define the initial beam structure.
- Definition of one or more *beamlines*:
  - standard, simple sequences of components,
  - include "beam instrumentation".
- Definition of one or more *dumps*:
  - delete the bunches, freeing the memory,
  - provide additional instrumentation.



- Connect together injectors, beamlines and dumps to create a *machine*:
  - complete description of the accelerator,
  - possible to adjust/edit properties after the previous definitions.

- Run the machine to obtain beam data!

What does RPL do for you?

- Tracks all the bunches determining their path in the machine at runtime,
- In case of many bunches, guarantees that each of them enters each beamline in the correct order,
- Handles all the time dependencies in the machine (element phases, HOMs damping, ...),
- Collects beam properties at the desired locations, bunch after bunch,
- Allows to follow a bunch along its path collecting many observables (Twiss, orbit, transport matrix/higher order tensors, losses, ...).

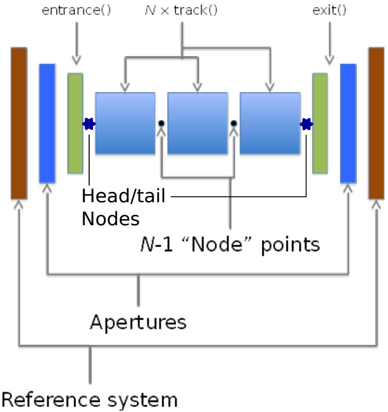
What is there behind the curtain?

RPL is a full 6D tracking code:

- entirely written in modern C++ from scratch,
- embedded into Placet featuring a SWIG-generated Tcl interface,
- designed to be easily expanded (add more beam models, more elements, more physics effects...),
- benefits A LOT from the experience maturated with the operation and maintaining of Placet,
- the interface is mostly compatible with PLACET, featuring a set of richer and more flexible new commands (e.g. beam creation, element slicing, machine topology definition, ...),
- in a good state of development, under constant expansion, already being tested in real-life cases (CTF3 measurements, LHeC design validation, ...).

Three insights on the RPL mechanisms

Structure of the element: an embedded integrator



Element as a collection of kicks:

- Misalignment/Aperture/Fringe fields;
- Sliced *thick* core (drift, dipole, quadrupole, RF cavity...);
- *Thin* kicks added between the slices to import physical effects (Radiation, wakefields, multipolar component, stray fields...).

Huge flexibility:

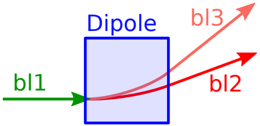
- Select which effects to add in each element;
- Split an effect over multiple kicks.

Generalised kicks: they do not necessary "kick" the beam but can:

- transform the beam (match Twiss, phase advance, generate offsets, ...);
- collect the required properties of the passing bunches.

Beamlines connections and bunch routing

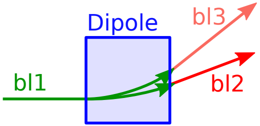
Example: dipole splitter



Routing according to energy:

- Beamline 1 ends at the dipole;
- Beamline 2 and 3 have two dipoles tuned at different energies.

```
Mac link -in bl1 -out bl2 -cmd {abs([bunch getd energy] - 20)}
Mac link -in bl1 -out bl3 -cmd {abs([bunch getd energy] - 10)}
```



Routing according to offset:

- Beamline 1 contains the dipole, bunches at different energies end up with different positions;
- Beamline 2 and 3 start after the dipole.

```
Mac link -in bl1 -out bl2 -cmd {abs([bunch getd cx] - 2e-3)}
Mac link -in bl1 -out bl3 -cmd {abs([bunch getd cx] - 1e-3)}
```

- The *bunch* keyword in the interface, becomes the actual bunch object being tracked by the C++ core: you can call its member functions (*getd* for instance)!
- The bunch proceeds in the beamline whose command evaluates to the *smaller* value.
- Beamlines merges are simpler: do not require to specify a routing criterion.

Machine operation and Synchronisation

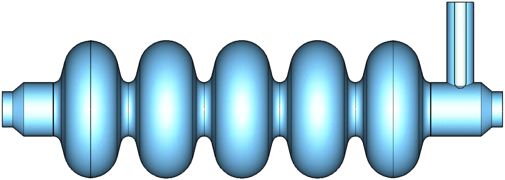
- The machine owns *global timer* used for synchronisation → increases at small steps;
- Each bunch owns an *internal timer* → increases as bunch travels through thick elements;
- Bunches travel straight down beamlines, their timer can be greatly increased,
- but are forced to wait at the subsequent joints until the global timer exceeds their internal one.

- Global timer steps smaller than shortest beamline ⇒ bunch order is preserved;
- Elements always see bunches in the correct time sequence ⇒ element time is the being-tracked bunch time.

Long-Range Wakefields

Higher Order Modes and Long-Range Wakefields

- The field in a cavity has many Higher Order Modes (*HOMs*) of oscillation.
- HOMs are excited by bunches passing through the cavity and affect the followings $\Rightarrow$ long-range wakefields.
- Dipolar modes are particularly bad as they are strong and easily excited by orbit displacements.



- SPL cavities: 5 cells design at 720 MHz.
- List of HOMs from M. Schuh, all Q-values at TESLA worst.

#	f [GHz]	A [V/C/m²]	Q
1	0.9151	9.323	1e5
2	0.9398	19.095	1e5
3	0.9664	8.201	1e5
4	1.003	5.799	1e5
5	1.014	13.426	1e5
6	1.020	4.659	1e5
7	1.378	1.111	1e5
8	1.393	20.346	1e5
9	1.408	1.477	1e5
10	1.409	23.274	1e5
11	1.607	8.186	1e5
12	1.666	1.393	1e5
13	1.670	1.261	1e5
14	1.675	4.160	1e5
15	2.101	1.447	1e5
16	2.220	1.427	1e5
17	2.267	1.377	1e5
18	2.331	2.212	1e5
19	2.338	11.918	1e5
20	2.345	5.621	1e5
21	2.526	1.886	1e5
22	2.592	1.045	1e5
23	2.592	1.069	1e5
24	2.693	1.256	1e5
25	2.696	1.347	1e5
26	2.838	4.350	1e5

Long-Range Wakefield in Complex Topologies

Goal $\rightarrow$ Reduction to a local problem: interaction bunch-mode in a single cavity

HOMs are represented as complex numbers: $z = \rho e^{i\theta}$

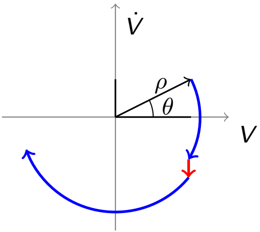
- Time evolution: $z(t+dt) = z(t)\underbrace{\exp\left(-\frac{\omega}{2Q}dt\right)}_{\text{damping}}\underbrace{\exp\left(i\omega dt\right)}_{\text{rotation}}$

- Bunch $\rightarrow$ mode interaction:

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

- Mode $\rightarrow$ bunch interaction:

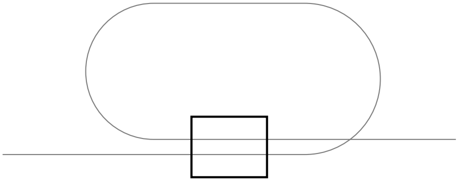
  $x' = x'_0 + \dfrac{e\,\Re(z)}{\gamma\,m_e\,c^2}$



Iterated over all the HOMs of the cavity.

A Single Cavity Case

A bunch sees an RF deflector a few times in a Combiner Ring.



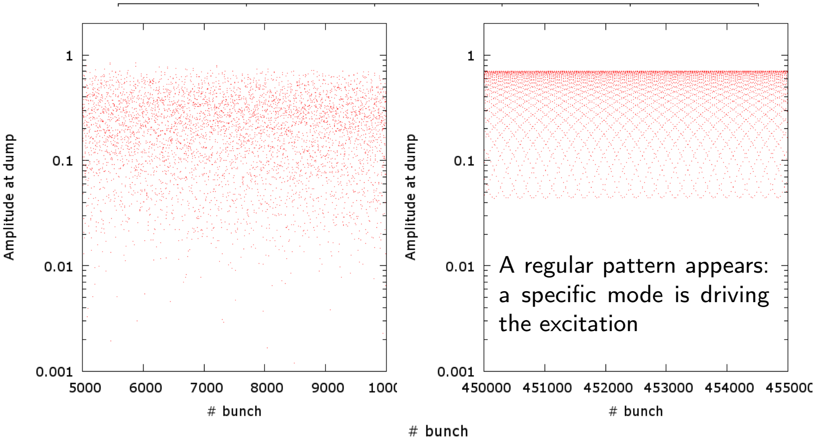
- Bunches establish a feedback system: the orbit excitation collected at the first passage, interacts with the modes at the second passage.
- Can a *positive feedback* take place?

  Simplified formula for threshold current estimation: $I_{th} = \dfrac{2pc^2}{e\omega \frac{R}{Q} Q} \dfrac{1}{T_{12} \sin(\omega t_r)}$

- Simulation technique:
  1. Inject a bunch with some offset $\rightarrow$ modes excitation.
  2. Inject many centred bunches $\rightarrow$ look at their orbit excitation (amplitude at dump).

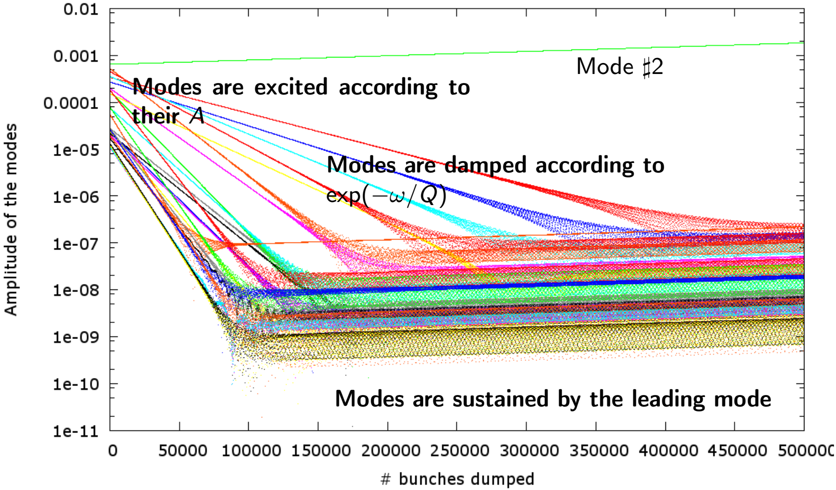
Evolution of the excitation

A misaligned bunch is injected, followed by many centred bunches. The first bunch excite the modes, the excitation is sustained by the following bunches. The amplitude of bunches coming out from the machine is observed:



A look at the modes

The amplitude of the 26 modes of the cavity is plotted over the same timespan of the previous slide.

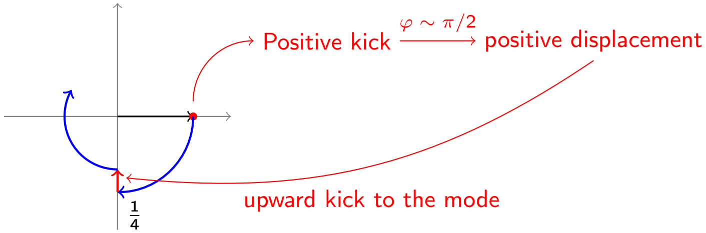


Mitigation of a single mode

- Match the length of the arc so that at the second passage the interaction beam-mode reduces the amplitude of the latter.
- The condition for the mitigation of the worst mode is given by a relation between periods:

$$\left(n \pm \frac{1}{4}\right) T_{HOM} = T_{arc}$$

The sign is $+$ for phase advance between 0 and π (positive kick $\rightarrow$ positive offset)
The sign is $-$ for phase advance between π and 2π (positive kick $\rightarrow$ negative offset)



Mitigation of a single mode

$$\left(n+\frac{1}{4}\right)T_{HOM}=T_{arc}\equiv\left(m+\frac{1}{2}^{\star}\right)T_{RF}$$

m represents the number of buckets in the return arc.
* is required to go from acceleration to deceleration in the second passage.
The condition is verified for m such that:

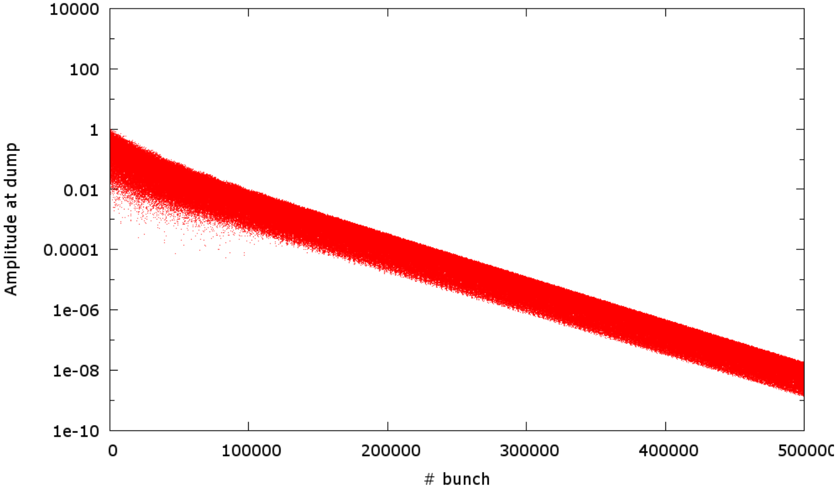
$$n=\frac{f_{HOM}}{f_{RF}}\left(m+\frac{1}{2}\right)-\frac{1}{4}$$

is (close to) an integer.
For $f_{RF}=802$ MHz and $f_{mode\sharp 2}=939.8$ MHz:

m	n
15	17.914
16	19.085
21	24.945
33	39.007
39	46.038
...	...

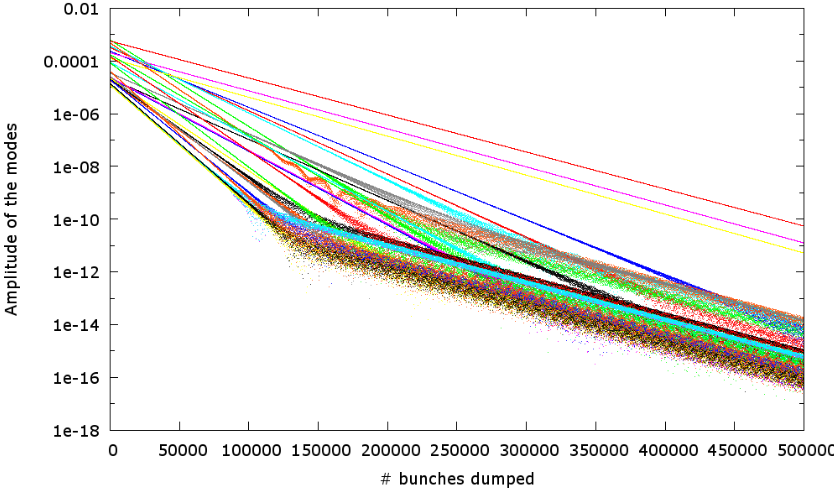
Mitigation of mode $\sharp$ 2 for $m = 33$

bunches amplitudes



Mitigation of mode $\sharp$ 2 for $m = 33$

modes amplitudes



Mitigation of instabilities: other suggestions

Optic optimisations:

- Reduce the β function: beam offset will be reduced and so the excitation of HOMs;
- Stay away from $(n + 1/2)\pi$ phase advances: the kick received in the first passage does not result in a dangerous displacement that can match to some of the HOMs in the second passage.

Interventions on the cavity design:

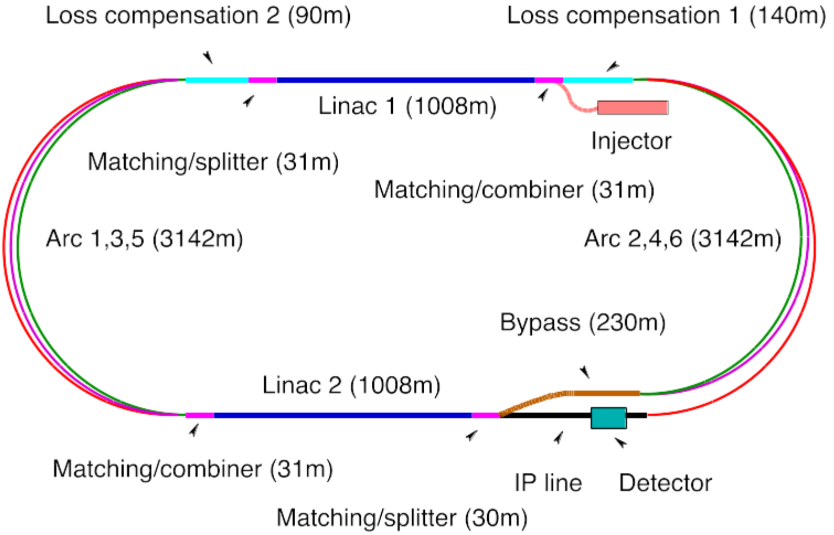
- Keep low Q-values $\Rightarrow$ faster damping;
- Try to avoid big mode amplitudes $\Rightarrow$ less bunch-to-mode excitation;

Detuning of mode frequencies in different cavities helps when many cavities are present.

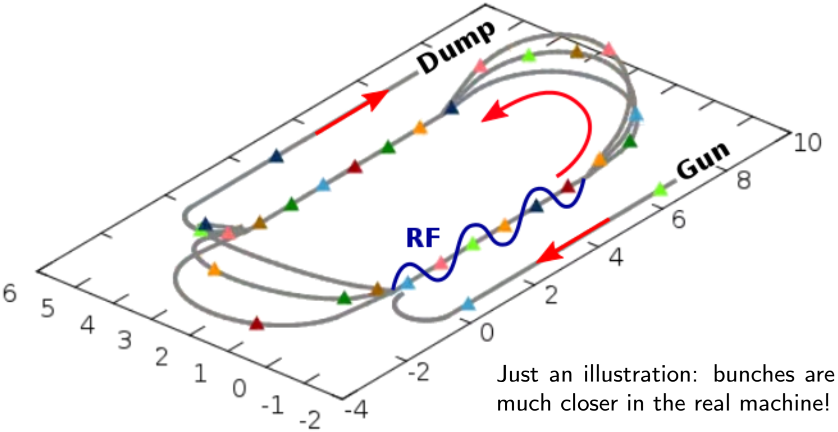
Applications to the LHeC

Large Hadron-electron Collider

Baseline Design



Continuous Wave (CW) operation



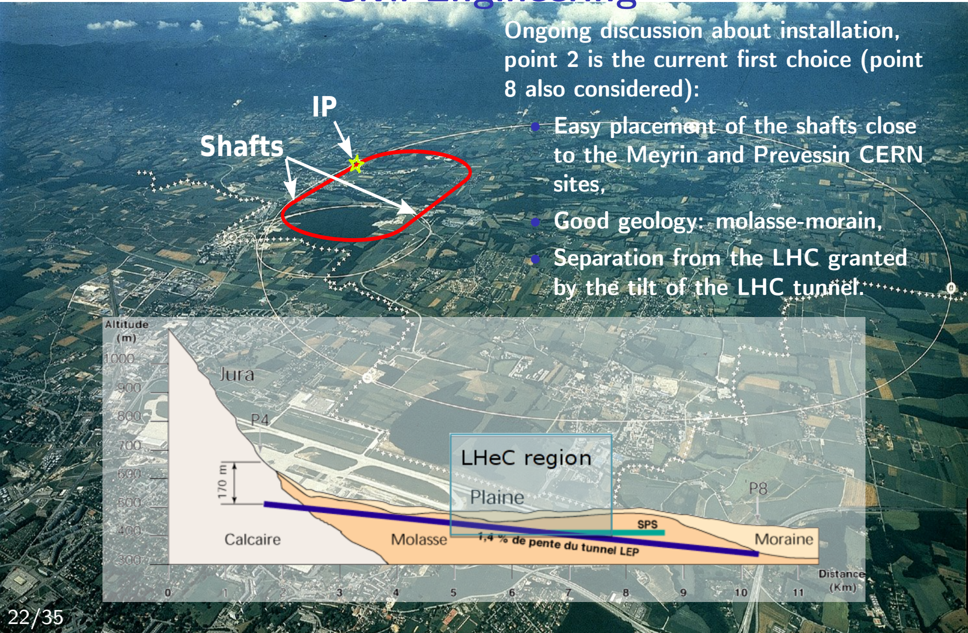
Just an illustration: bunches are much closer in the real machine!

- New bunches are continuously injected and spent bunches are continuously dumped,
- In the linacs bunches at different turn numbers and energies are interleaved.

Civil Engineering

Ongoing discussion about installation, point 2 is the current first choice (point 8 also considered):

- Easy placement of the shafts close to the Meyrin and Prevessin CERN sites,
- Good geology: molasse-morain,
- Separation from the LHC granted by the tilt of the LHC tunnel.



Machine Parameters

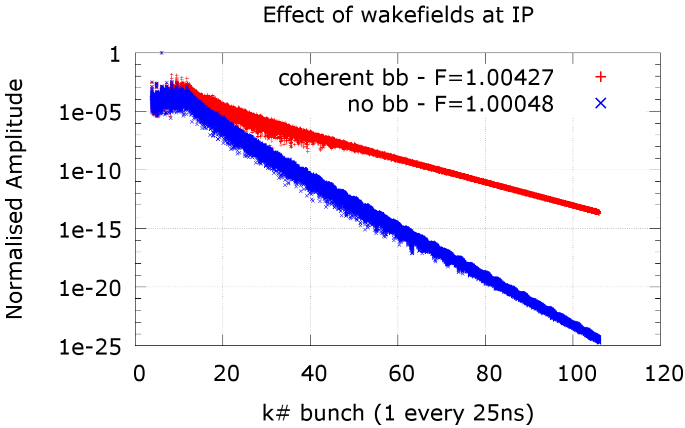
baseline $\rightarrow$ hi-lumi upgrade

	Protons	Electrons
Beam Energy [GeV]	7000	60
Luminosity [10^{33} cm^{-2}s^{-1}]	$1 \rightarrow 10$	
Normalised Emittance [μm]	$3.75 \rightarrow 2$	50 (...16?)
IP beta function $\beta^*_{x,y}$ [m]	0.05	0.032 (...0.1?)
RMS IP beam size $\sigma^*_{x,y}$ [μm]	$7.2 \rightarrow 3.7$	$7.2 \rightarrow 3.7$
Bunch Spacing [ns]	25	25
Bunch Population	2.2×10^{11}	$2.5 - 3.8 \times 10^{9}$
Effective crossing angle	0.0	

- HERA luminosity: 10^{31} (HERA I) upgraded to 4×10^{31} (HERA II) $\rightarrow 10^{33}$ is a HUGE improvement,
- 10^{34} allows to collect ~ 1000 fb^{-1} necessary to study the Higgs in many channels in presence of kinematic cuts ($\sigma_{e+p\rightarrow H+X} \approx 200$ fb).

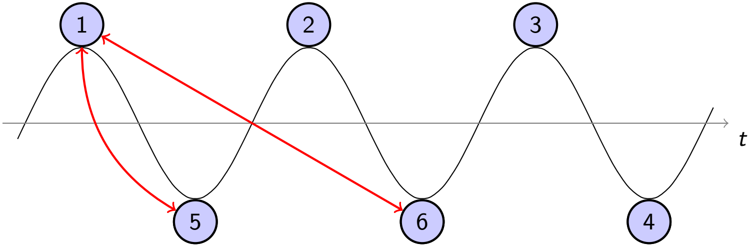
Long Range Wakefields in the LHeC

- Fill the machine with perfectly centred bunches,
- Inject a bunch with some offset,
- Keep injecting perfect bunches and see how they are perturbed.



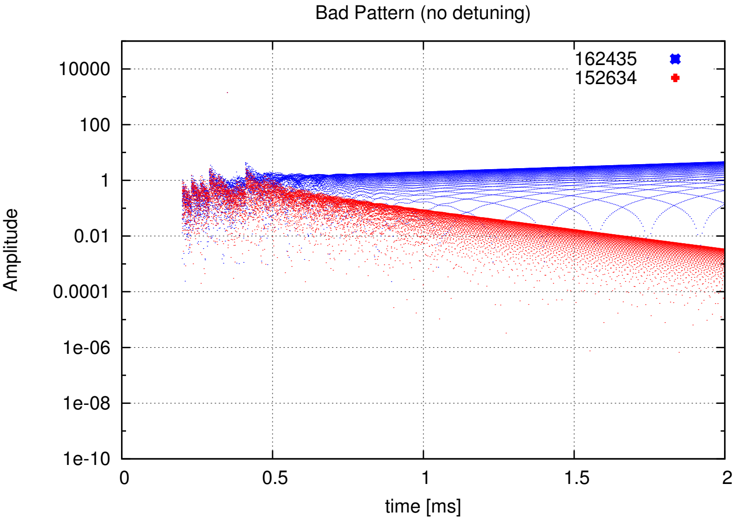
Pattern dependency (I)

- Lowest energy bunches receive the strongest kicks from HOMs: better to keep them separated to maximise the HOMs damping.
- Bunches at different turns can be placed into different RF buckets tuning the lengths of the arcs.



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

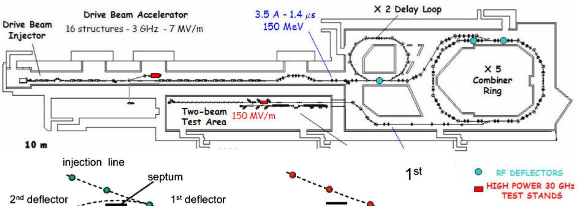
Pattern dependency (II)

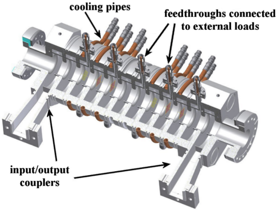


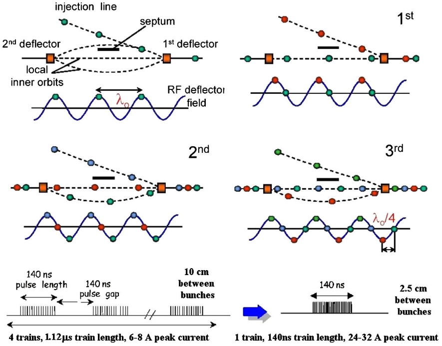
Applications to CTF3

CLIC Test Facility 3

CTF3 RF deflectors

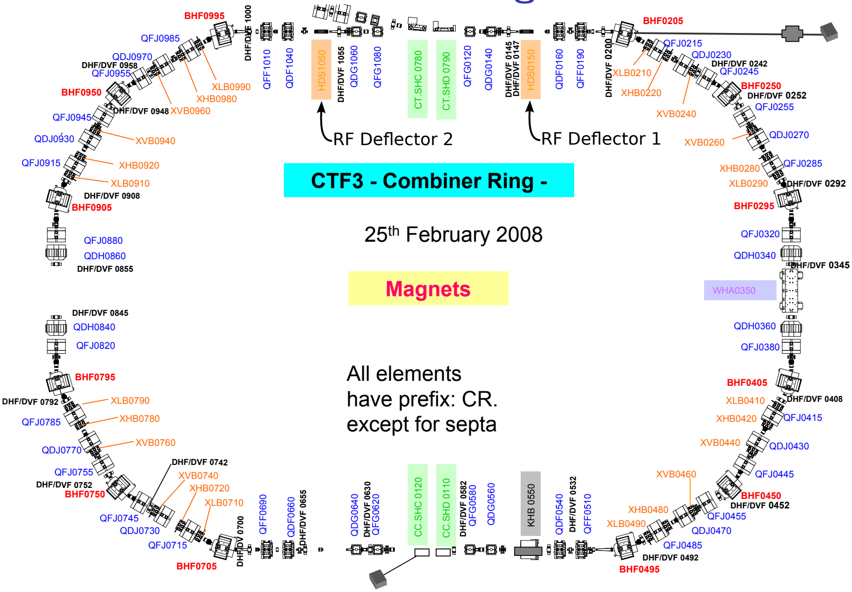






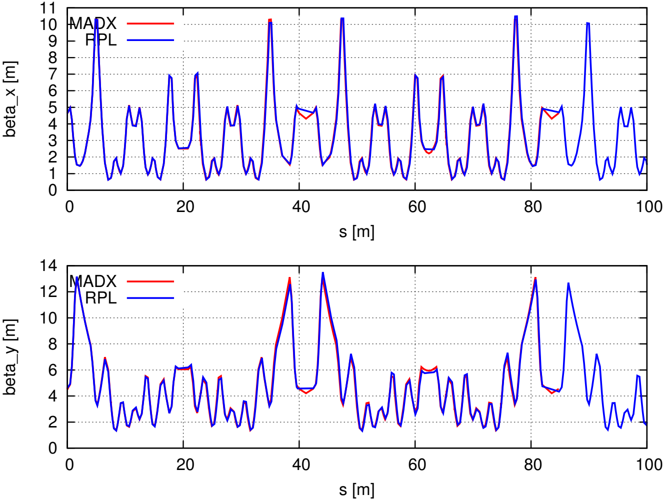
- RF deflector are used to inject in the CR.
- Multiple pulses are merged in four turns.
- Bunches at different turns see different RF phases.

The Combiner Ring Lattice



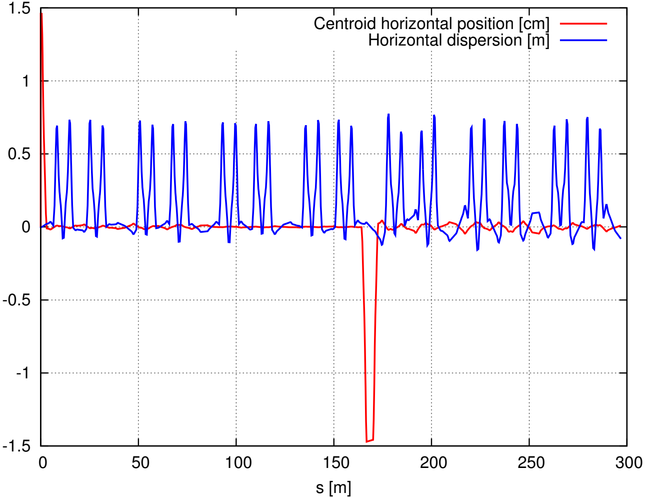
One turn Beta Functions

Optics parameters are collected following a test bunch along its path in the machine. Good agreement with MAD-X computation.



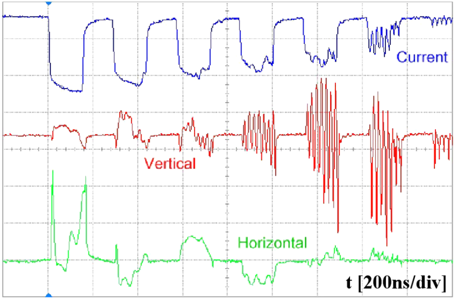
Four turns Orbit and Dispersion

Dispersion and centroid position are collected in the same way across multiple turns, with automatic handling of time dependencies:



Wakefields in the CTF3 RF deflectors

During the commissioning of the combiner ring, an unforeseen vertical instability appeared, limiting the operability to short trains and low charge.



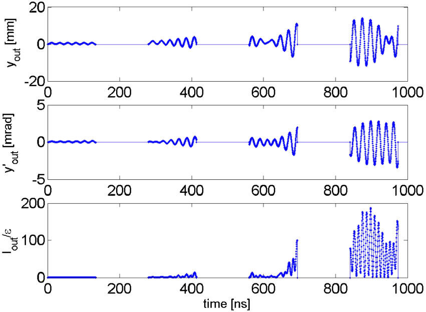
A circulating (not recombined) beam of 400 bunches is subjected to heavy losses due to the excitation of the trapped vertical mode:

Frequency	3.0443 GHz
Impedance	1.6 MΩ
Q-value	11500

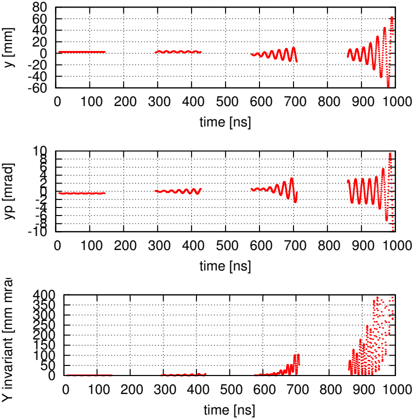
A dedicated tracking code was written by D. Alesini to simulate the excitation (D. Alesini *et al.* Physical Review ST 14 022001, 2011).

Simulations of the vertical instability

Published by Alesini:



RPL:



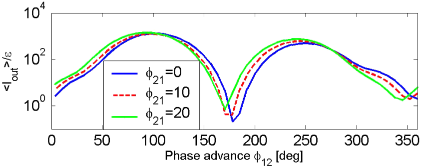
- No perfect agreement is expected (different optics functions, phase advances, ...)

The time scale of the instability is well reproduced!

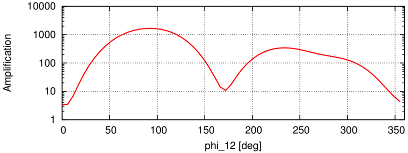
Vertical phase scan

The betatron phase advance in the return loop strongly affects the amplification:

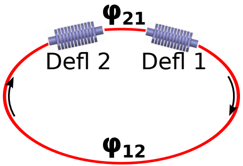
Published by Alesini:

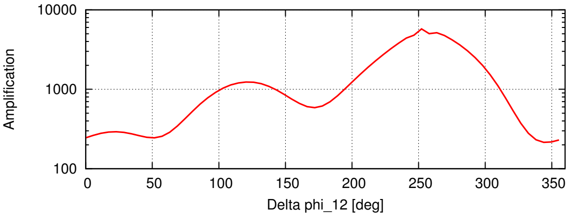


RPL:



Here the phase advance over the septum (ϕ_{21}) is matched to ≈ 0.
The phase advance in the MADX model $\phi_{21} \approx 70^\circ$ gives a different picture:





Vertical Instability: epilogue

- New deflectors with antennas to extract the trapped mode were designed and installed,
- no instability ever appeared again.

Summary

- Overview of the capability and mechanisms of RPL
- Introduction to long-range wakefields and techniques for suppression
- Beam stability in the LHeC
- Vertical instability observed at CTF3

Thank you!