ILC Beam Dynamics Studies Using PLACET

Andrea Latina (CERN)

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John Adams Institute for Accelerator Science - Oxford (UK)

- Introduction
- Simulations Results
- Conclusions and Outlook

PLACET Physical Highlights

- PLACET is a tracking code that simulates **beam transport** and **orbit correction** in linear colliders
- it implements **synchrotron radiation emission**
- it takes into account **collective effects** such as:
  - short/long range wakefields in the accelerating structures / in the crab cavities,
  - multi-bunch effects and beam loading,
  - geometric and resistive wall wakes in the collimators
- it can track the longitudinal phase space
- it can track **sliced beams** as well as beams of **single particles**, and can switch between them during tracking

⇒ It can simulate: bunch compressor, main linac, drive beam, beam delivery system (including crab cavities and instrumentation), interaction point (using Guinea-Pig) and soon : post collision line

PLACET Technical Highlights

- It is -relatively- easy to use
- It is fully **programmable** and **modular**, thanks to its **Tcl/Tk** interface and its external modules:
  - it allows the simulation of feedback loops
  - ground motion effects are easy to include
  - external MPI parallel tracking module (limited tracking)
- It is **open** to other codes:
  - it can read **MAD/MAD-X** deck files, as well as **XSIF** files
  - can be easily interfaced to Guinea-Pig
  - it can use other codes to perform beam transport
- It has a **graphical** interface
- [NEW] it embeds **Octave**, a mathematical toolbox like MatLab (but *free*)
  - rich set of numerical tools
  - easy to use optimization / control system tool-boxes

Emittance Preservation and ILPS

- In future linear colliders, $e^{\pm}$ emittances will be very small $\Rightarrow$ *flat beams*

- Small emittances are critical

$$\mathsf{L} \propto \frac{1}{\sqrt{\beta_x^* \, \beta_y^* \, \epsilon_x \, \epsilon_y}}$$

- Sources of Emittance Degradation:

  $\Rightarrow$ Static:

  - $\Rightarrow$ Synchrotron radiation
  - $\Rightarrow$ Collective effects: *wakefields*, *space charge*, ...
  - $\Rightarrow$ Residual gas scattering
  - $\Rightarrow$ Accelerator errors:
    - beam jitter
    - field errors
    - x-y couplings
    - magnet alignment errors

  $\Rightarrow$ Dynamic:

  - $\Rightarrow$ *element jitters, power supplies ripples, ground motion, ...*

Beam Based Alignment

- preliminary alignment
  - after that, all linac elements will be randomly scattered around the *pre-alignment line*
  - averaged misalignment amplitudes are estimated of the order of
    - 300 μm RMS for BPMs, cavities and quadrupoles position and
    - 300 μrad RMS cavity pitch

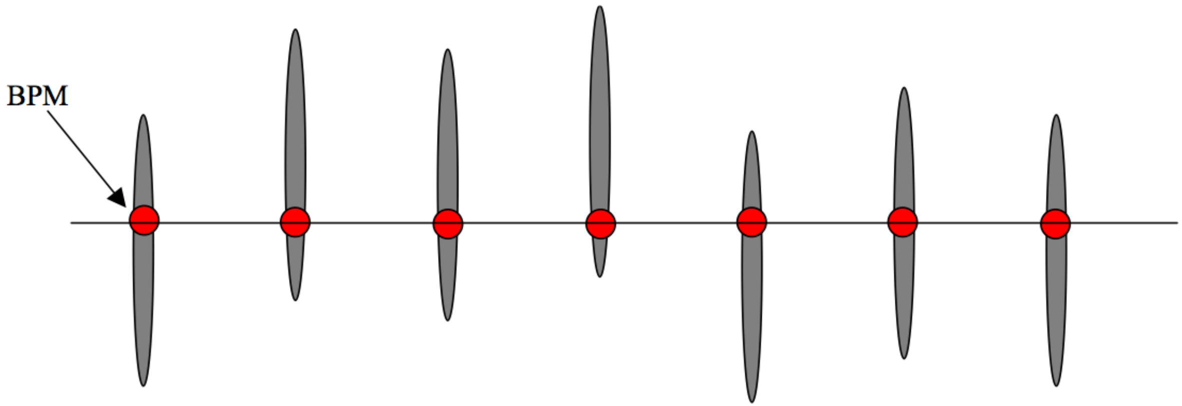
  this is not enough to preserve the vertical emittance

- static misalignments will be cured by beam-based alignment
  1. 1-to-1 correction
  2. dispersion free steering
  3. tuning bumps

- dynamic effects will be cured by several feedback loops

One-to-One Correction: Scenario 1

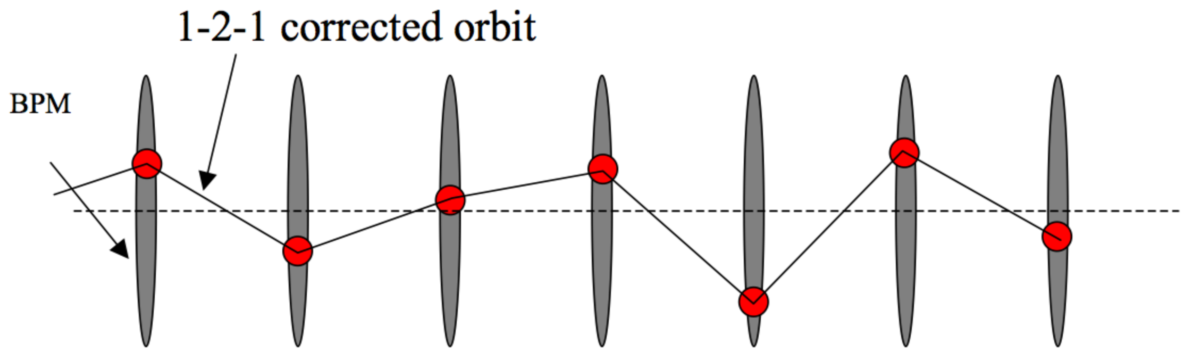
- Quadrupoles offset but BPMs aligned



- One-to-one correction steers the beam to the center of the BPMs
- Assuming:
  - a BPM adjacent to each quadrupole
  - a *steerer* at each quad ⇒ where *steerer* can be
    - quadrupole mover
    - dipole corrector

One-to-One Correction: Scenario 2

- Quadrupoles aligned but BPMs offset



- One-to-one correction is **bad**!
  - the resulting orbit is not dispersion free
- Reality is a mix of Scenario 1 and Scenario 2
- We need to find a reference line for the BPMs ⇒ Dispersion Free Steering

Dispersion Free Steering

DFS attempts to correct dispersion and trajectory at the same time

⇒ A *nominal beam* + one or more *test beams* with different energies are used to determine the dispersion along the linac.

⇒ The nominal trajectory is steered and the differences between the nominal and the off-energy trajectories are minimized:

$$\chi^2 = \sum_{i=1}^{n} y_{0,i}^2 + \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_{1,j} \left(y_{j,i} - y_{0,i} - \Delta_i\right)^2 + \sum_{k=1}^{p} \omega_{2,k}\, c_k^2$$

$i = 1..n$	BPMs	$y_{i,j}$	position of beam j in BPM i
$j = 0..m$	beams ($j = 0$, nominal beam)	Δ_i	target dispersion at BPM i
$k = 1..p$	correctors	c_k	strength for the corrector k
$\omega_{1,i}$, $\omega_{2,j}$	weights for dispersion and correction terms		

- The beamline is divided into bins of BPMs and correctors
- We propose to use the Bunch Compressor to generate the test beams

Recent Simulation Results

- **Bunch Compressor** (BC)
  - Alignment
- **Main Linac** (ML)
  - Static alignment strategies for a laser-straight and a curved layout
    - use of BC to align the ML
    - impact of BPM calibration errors and quadrupole power supply ripples
  - Dynamic Effects
    - jitter during alignment
    - orbit feedback to cure ground motion
- **Beam Delivery System** (BDS)
  - Feedback Studies
  - Crab Cavity Simulation
  - Collimator Wakefields and Halo Particles

Main Linac Simulations

- Main Linac Alignment Strategy
  - 1-to-1 correction
  - dispersion free steering
  - dispersion bumps optimization

- **Simulation Setup**
  - XSIF ILC2006e version of the lattice
  - Standard ILC misalignments:

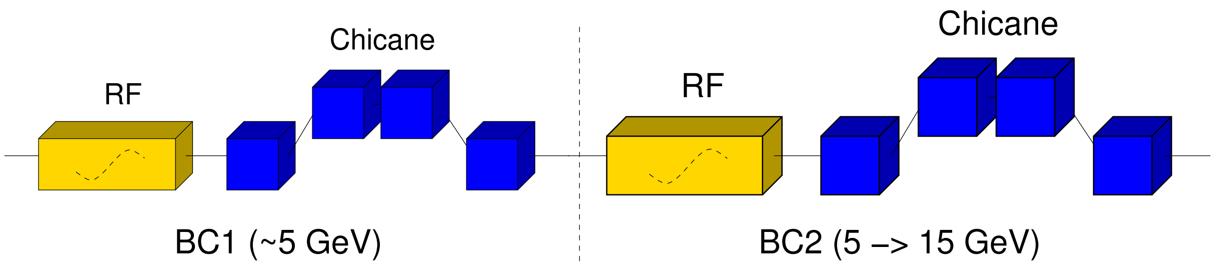
quadrupole position	300 μm
quadrupole tilt	300 μrad
quadrupole roll	300 μrad
cavity position	300 μm
cavity tilt	300 μrad
bpm position	300 μm

  - BPM resolution $= 1\mu$m
  - Curved layout obtained introducing small angles between the cryo-modules (KICKs)
  - Undulators section represented using *EnergySpread* elements

All results are the average of 100 seeds

Bunch Compressor

- ILC BC is composed of two accelerating stages and two magnetic chicanes



- Simulation Setup:
  - Misalignments : "COLD" model

σ_{quad}	=	300 μm	quadrupole position error
$\sigma_{\mathrm{quad\ roll}}$	=	300 μrad	quadrupole roll error
σ_{cav}	=	300 μm	cavity position error
$\sigma_{\mathrm{cav\ angle}}$	=	300 μrad	cavity angle error
$\sigma_{\mathrm{sbend\ angle}}$	=	300 μrad	sbend angle error
σ_{bpm}	=	300 μm	bpm position error

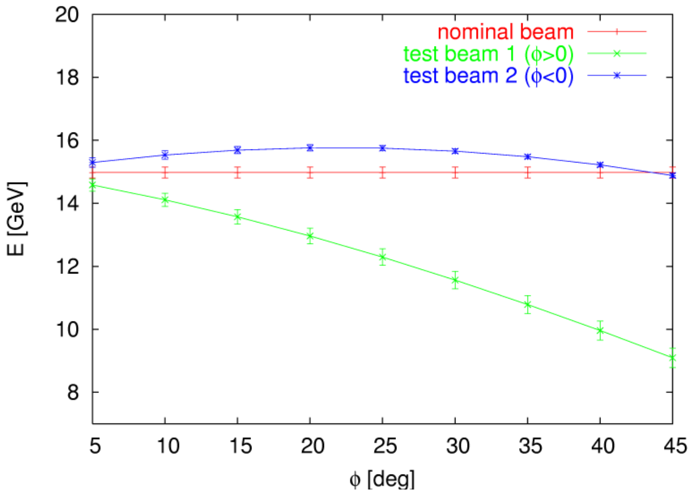
  - BPM resolution : $\sigma_{\mathrm{bpm\ res}} = 1\ \mu$m

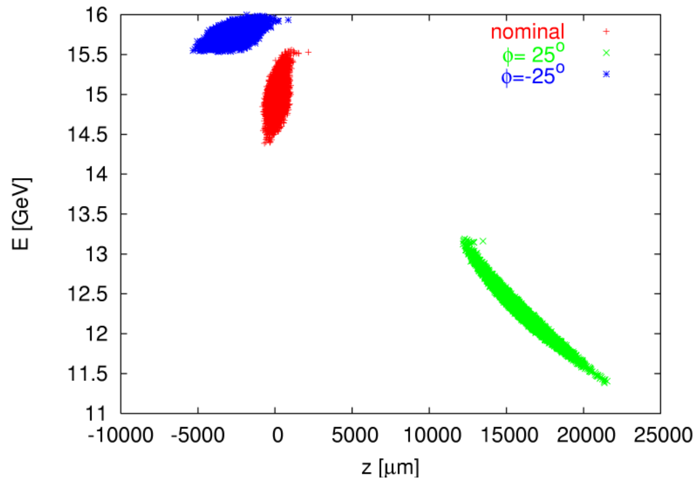
$\Rightarrow$ Wakefields of the cavities are taken into account

Bunch Compressor for Main Linac Alignment

- Compression of off-phase beams

  ⇒ they get different energy with respect to the nominal one and can be used for DFS in the Main Linac

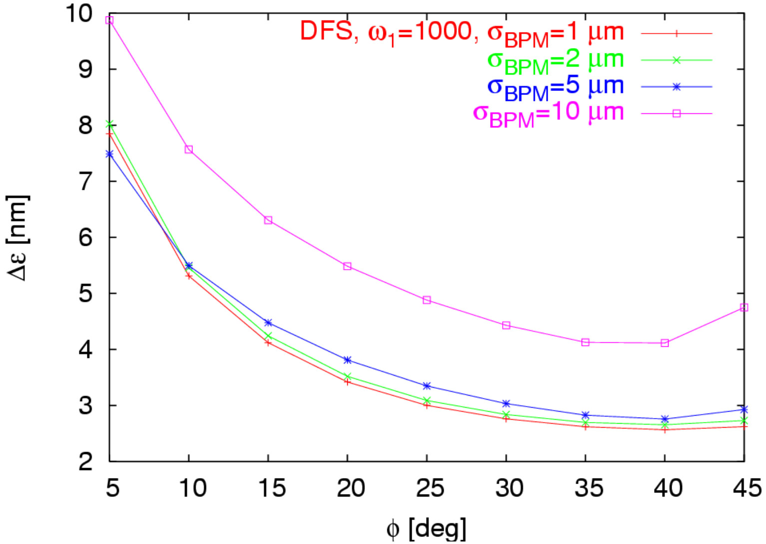


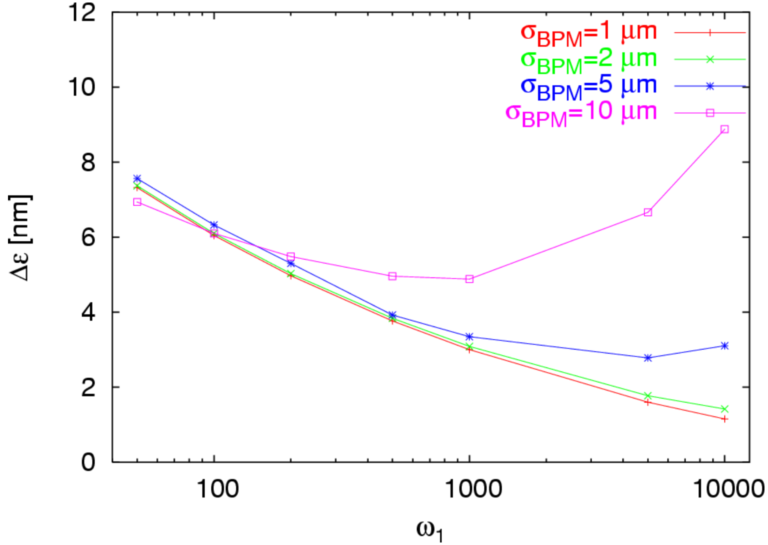


- the longitudinal phase space changes

⇒ their phase must be synchronized with the ML accelerating phase

Final Emittance Growth as a function of Φ and ω





- left hand plot : ω_1 =1000, scan of the phase offset
- right hand plot : Φ=25^o, scan of the weight

\- each point is the average of 100 machines

$\Rightarrow$ there is an optimum (which seems to depend on the weight)

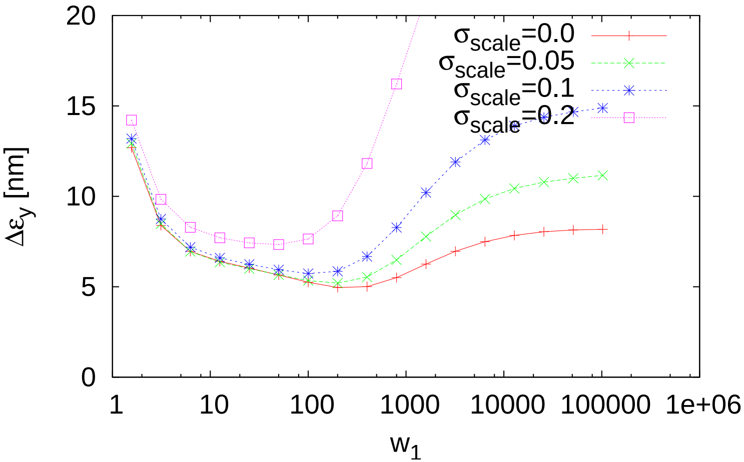
Main Linac

BPM Calibration Error

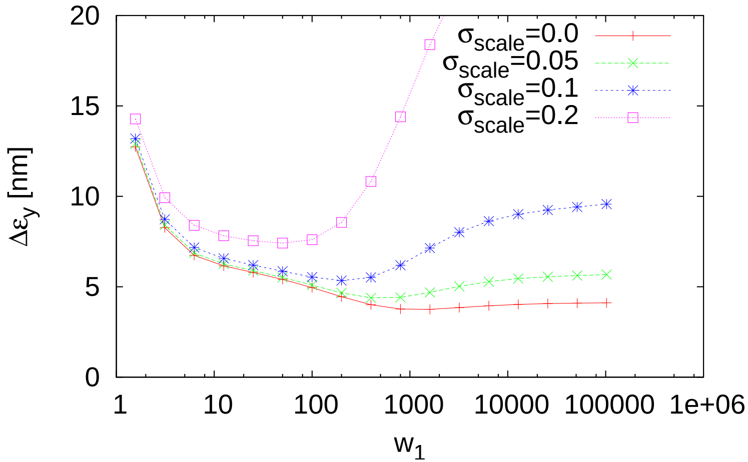
- Emittance growth as a function of the weight ω_1 ($\omega_0 = 1$) for different calibration errors σ_a

$$X_{meas} = (1 - a)\, X_{real}$$

- We used one test beam with an energy 20% below the nominal energy



(BPM resolution 10 μm)

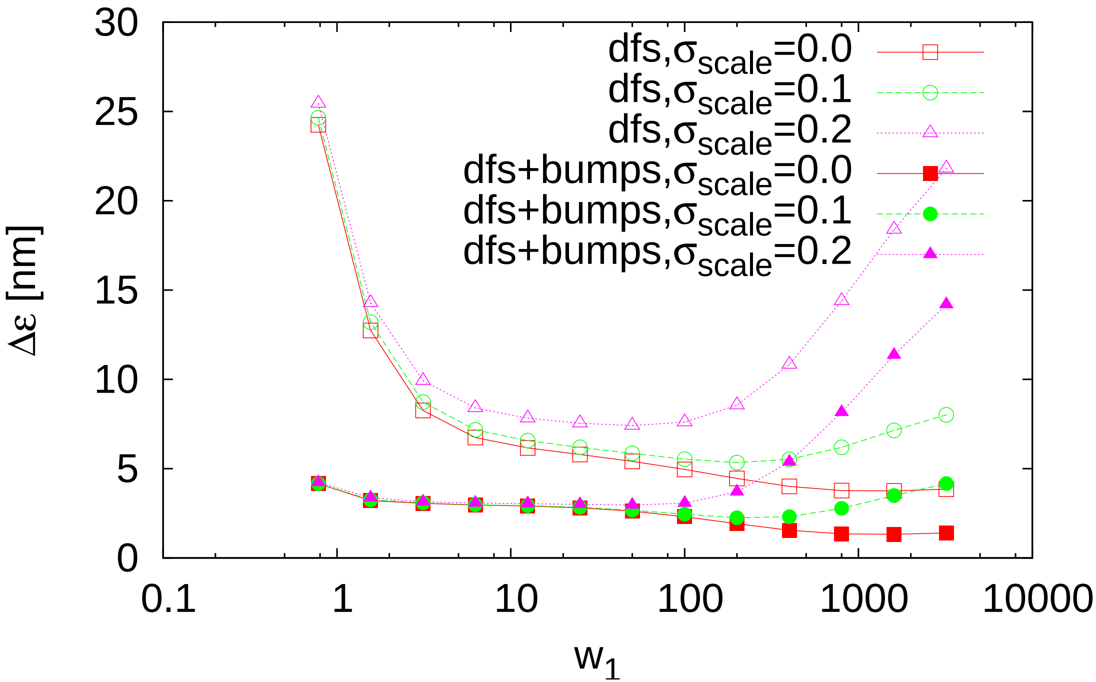


(BPM resolution 1 μm)

⇒ For large scale errors, the curvature does not allow to use large values of ω_1 and thus one does not take full advantage of the good BPM resolution

BPM Calibration Error and Tuning Bumps

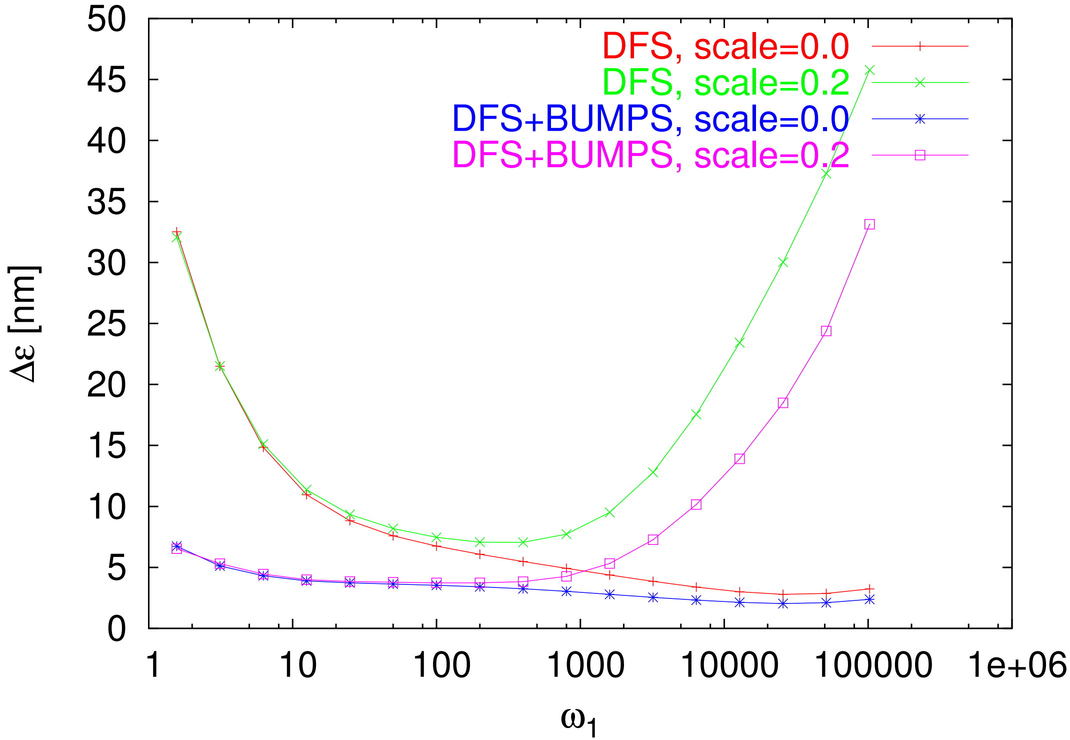
- Emittance tuning bumps can significantly reduce the emittance growthhey are likely required already in the laser-straight linac
- We investigated the impact of one dispersion bump before and one after the main linac



⇒ With zero BPM calibration error the performances are almost identical to those for the laser-straight machine.

BC+DFS and BPM Calibration Error

In a curved linac BPM calibration errors, $x_{\text{reading}} = a\,x_{\text{real}}$, have an impact on the BC+DFS performances:



- Calibration errors prevent from using “big” weights

⇒ We need to use Dispersion Bumps to reduce the emittance growth

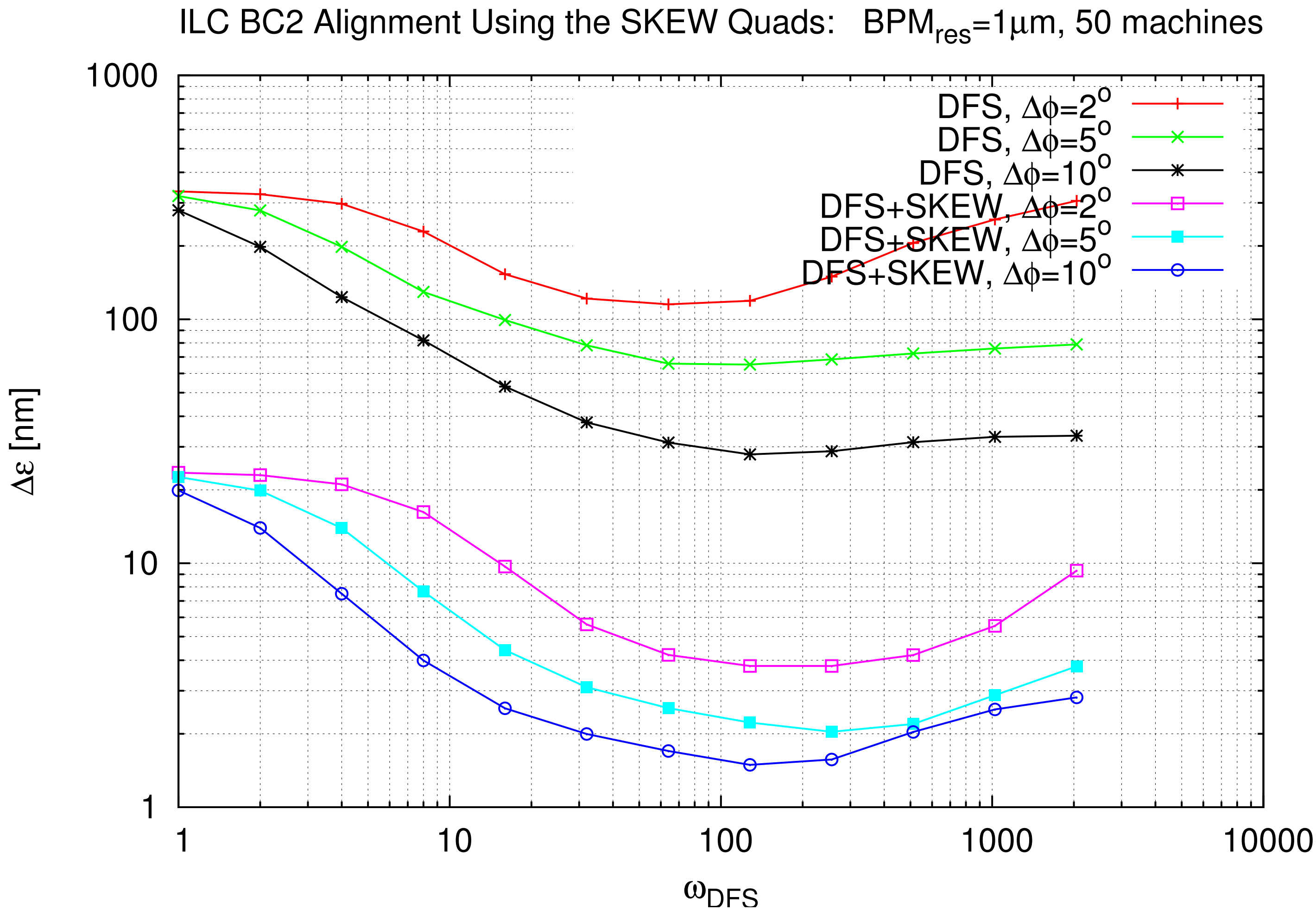
Bunch Compressor 1 used to align Bunch Compressor 2

- Alignment Strategy
  - 1-to-1 correction
  - dispersion free steering using two test beams, $\pm\Delta\phi$
  - dispersion bumps optimization using the skew quadrupoles in BC2
- A perfectly aligned BC1 is used to generate the test beams for DFS in BC2
  - an offset of few degrees in the RF phase of the BC1 accelerating structures, leads to an energy difference at the entrance of BC2
  - bunch energy as a function of the RF phase offset

$$\begin{array}{llll} \Delta\phi = +2^o & \Rightarrow & 99.59\%\ E_0; \ \Delta\phi = -2^o & \Rightarrow \quad 100.41\%\ E_0 \\ \Delta\phi = +5^o & \Rightarrow & 98.98\%\ E_0; \ \Delta\phi = -5^o & \Rightarrow \quad 101.04\%\ E_0 \\ \Delta\phi = +10^o & \Rightarrow & 98.01\%\ E_0; \ \Delta\phi = -10^o & \Rightarrow \quad 102.11\%\ E_0 \end{array}$$

$\Rightarrow \phi_0 = 110$ deg

$\Rightarrow E_0 \simeq 4.79$ GeV

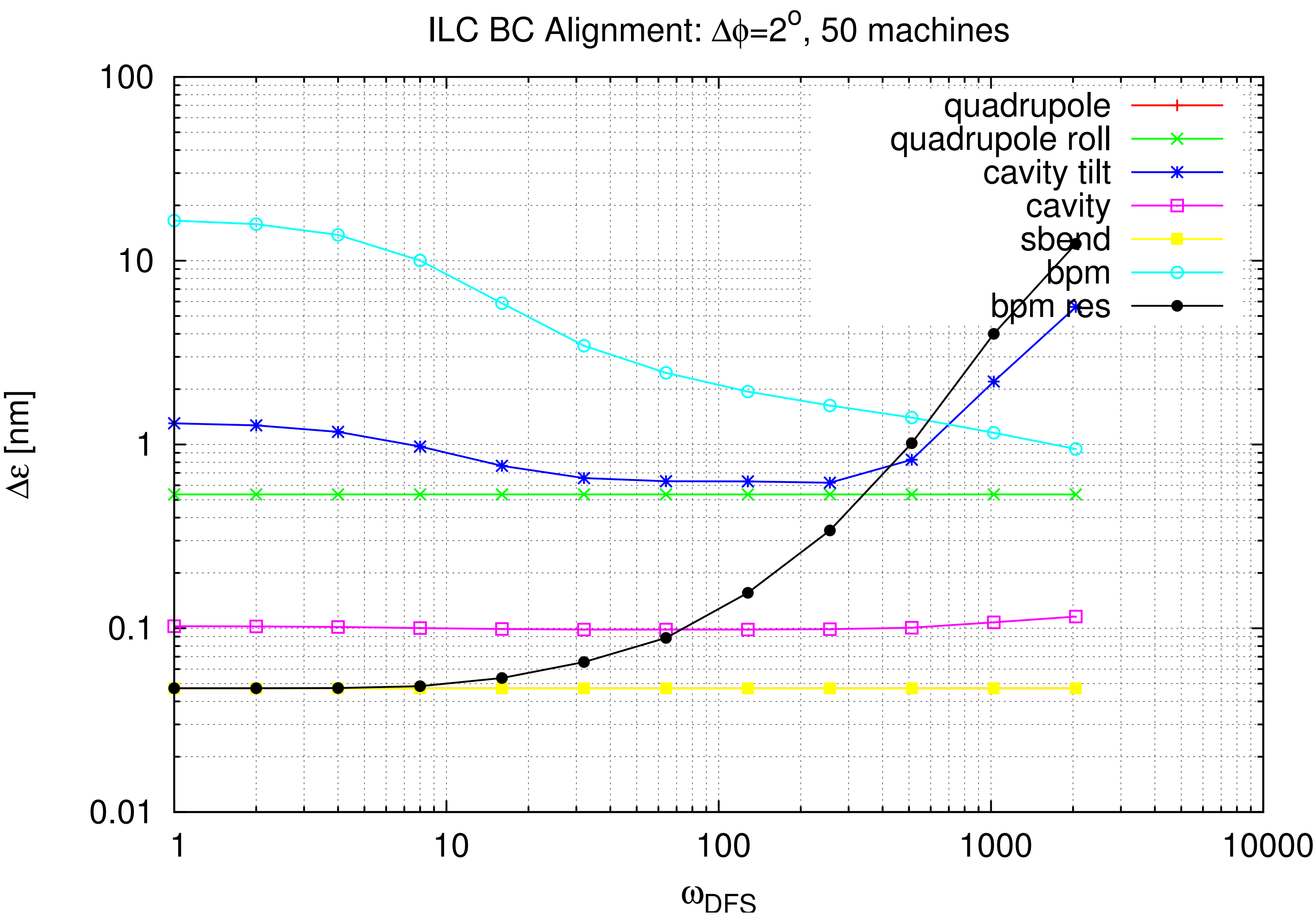


⇒ Final emittance growth after DFS and SKEW quad optimization

$\Delta\phi = \pm 2^o \Rightarrow$ 3.7 nm

$\Delta\phi = \pm 5^o \Rightarrow$ 2.0 nm

$\Delta\phi = \pm 10^o \Rightarrow$ 1.5 nm


ILC BC Alignment: Δφ=2°, 50 machines
100
10
1
0.1
0.01
Δε [nm]
1
10
100
1000
10000
ω_DFS
quadrupole
quadrupole roll
cavity tilt
cavity
sbend
bpm
bpm res

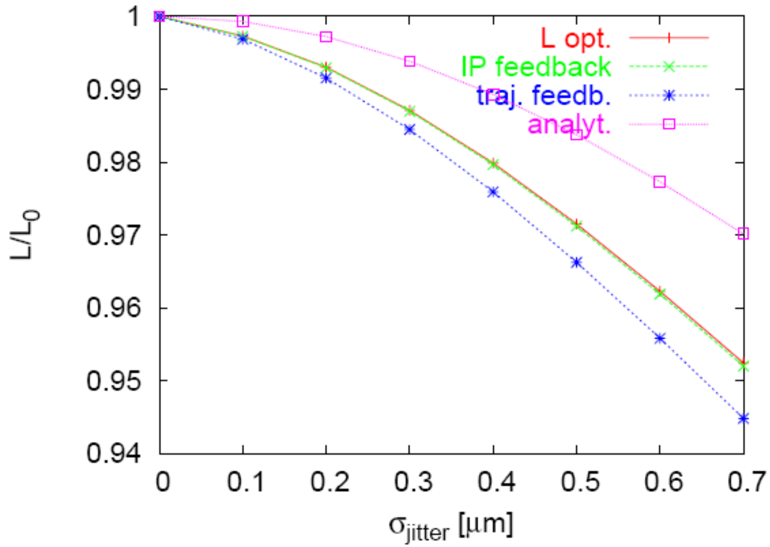
Luminosity Loss Due to Quadrupole Jitter

Simulation parameters:

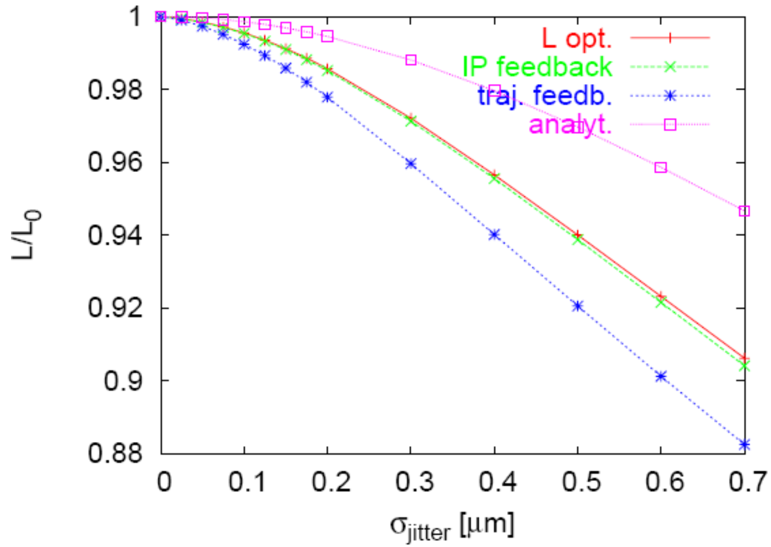
- we used GUINEA-PIG to calculate the luminosity
- a perfect machine has been used in the simulation
- and the end of the linac an **intra-pulse feedback** has been used to remove incoming beam position and angle errors at a single point
- quadrupoles in the electron linac have been scattered, while the ones in the positron linac are kept fixed
- the beam delivery system is represented by a **transfer matrix**: the end-of-linac Twiss parameters are transformed into the ones at the IP

Luminosity Loss Due to Quadrupole Jitter

- The luminosity as a function of the quadrupole jitter in the main linac:



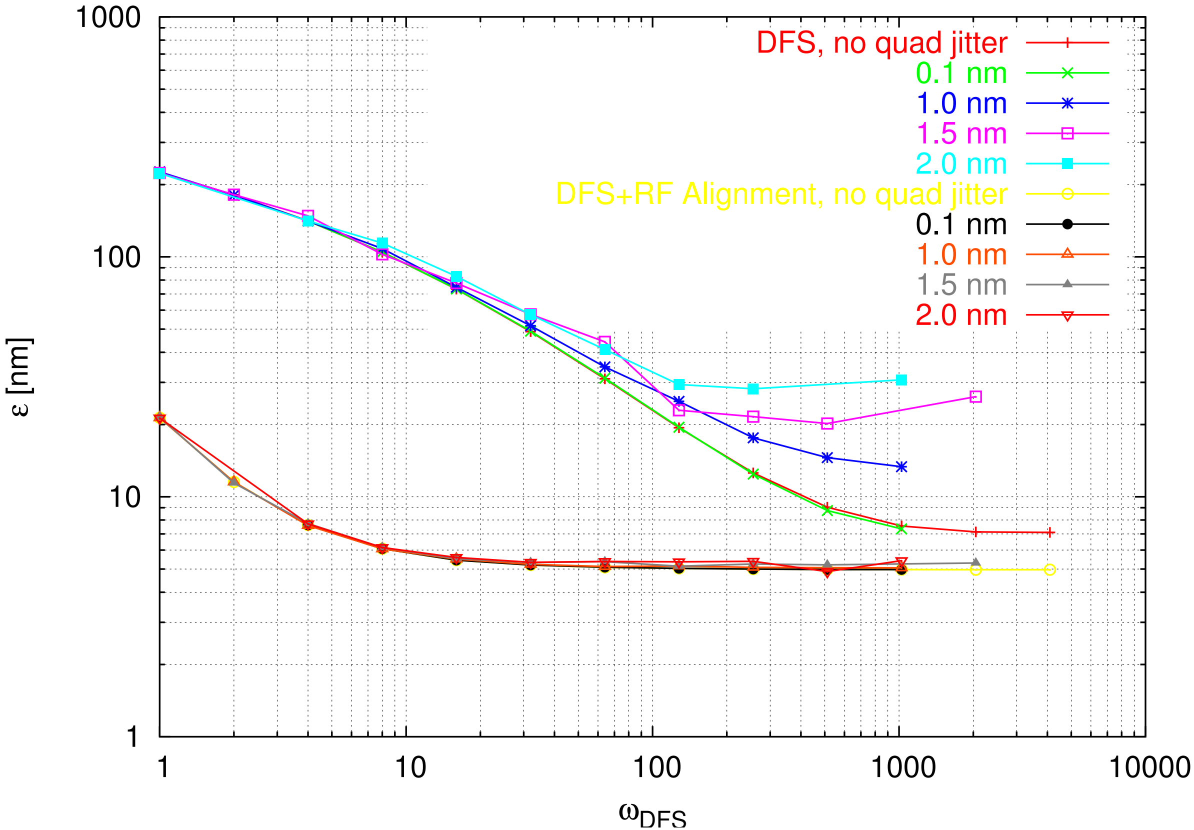
(IP vertical emittance 40 nm)



(IP vertical emittance 20 nm)

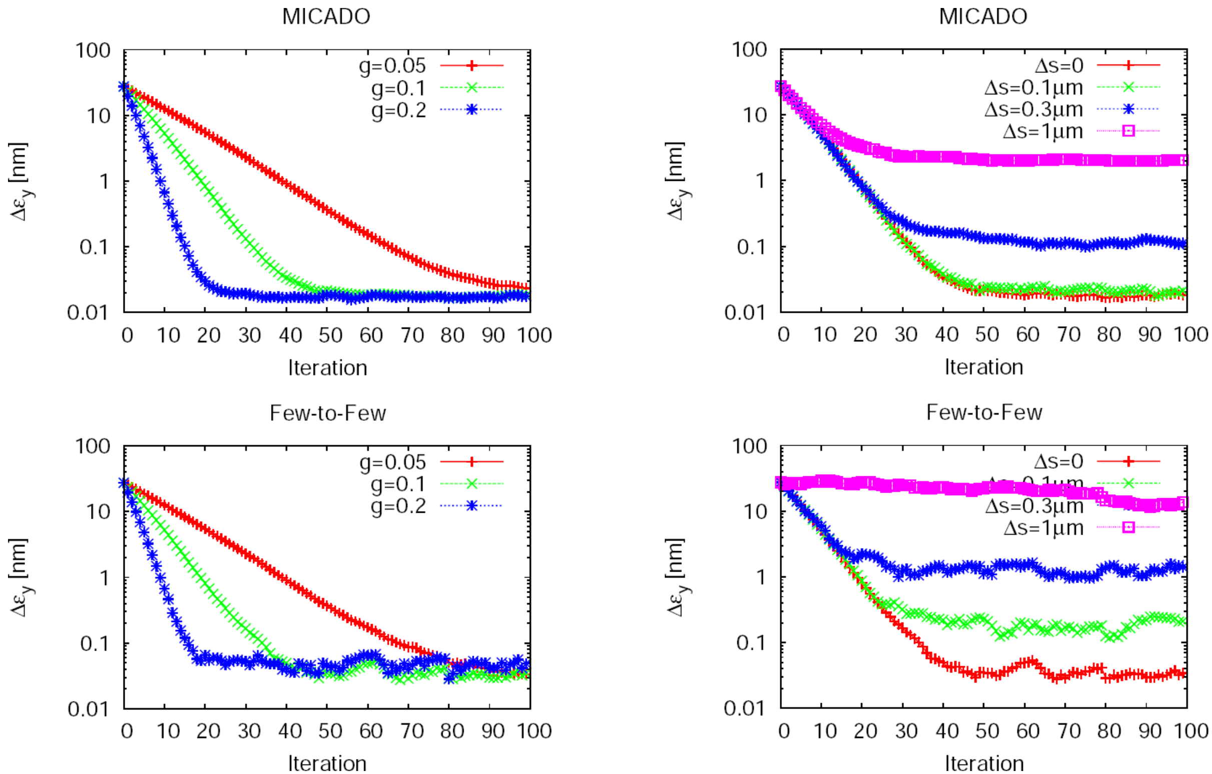
Quadrupole Jitter during Dispersion Free Steering

Alignment of the CLIC Main Linac, with quadrupoles jittering during DFS



Orbit Feedback in the Main Linac

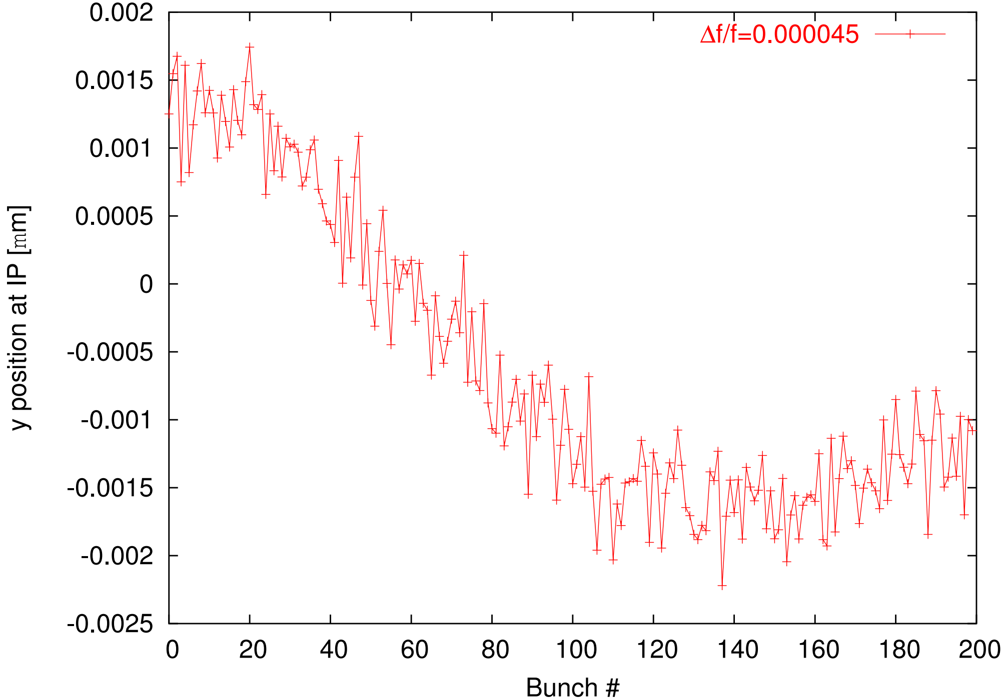
- We start from a perfect machine / to isolate the effect of the BPM noise
- One-to-One Correction vs. MICADO



(function of the gain) (function of the step size)

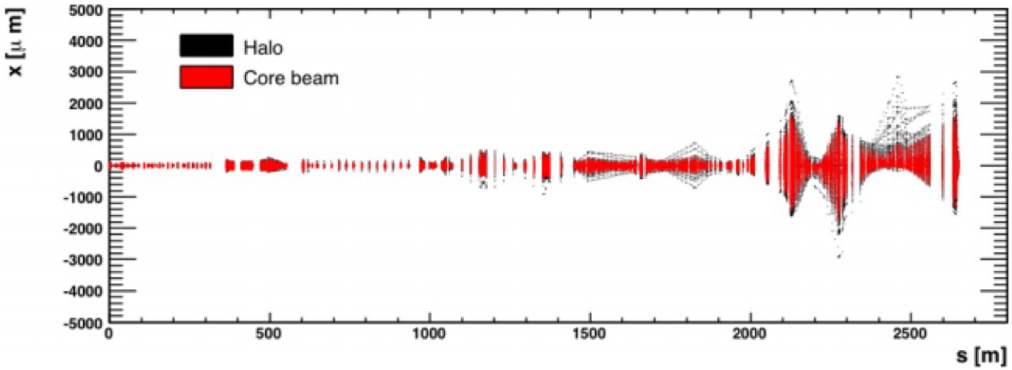
Wakefields in the Crab Cavities

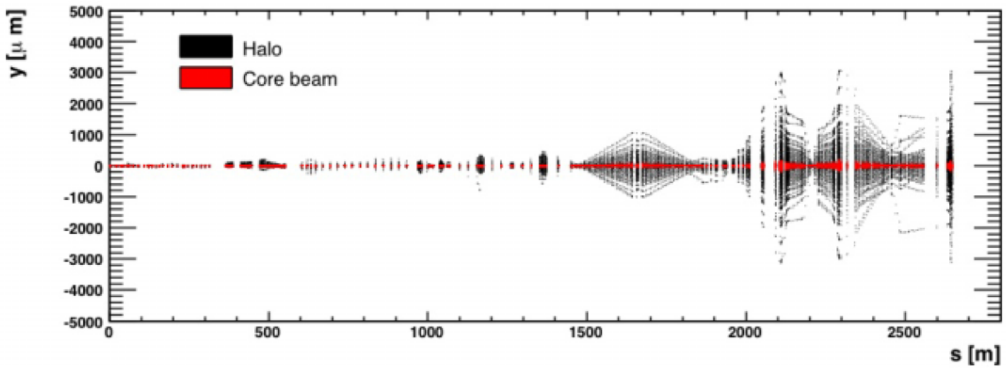
- Wakefields dipole and monopole modes have been calculated at the Cockcroft Institute (Lancaster University) by A.Dexter and G.Burt, using MAFIA
- These values have been put into PLACET to evaluate the vertical offset at the IP due to long-range wakes in case of a frequency dilution of 1.000045



Halo generation and tracking

- The beam gas pressure and apertures can be separately specified for each element
- The particles hitting the beam-pipe are considered lost

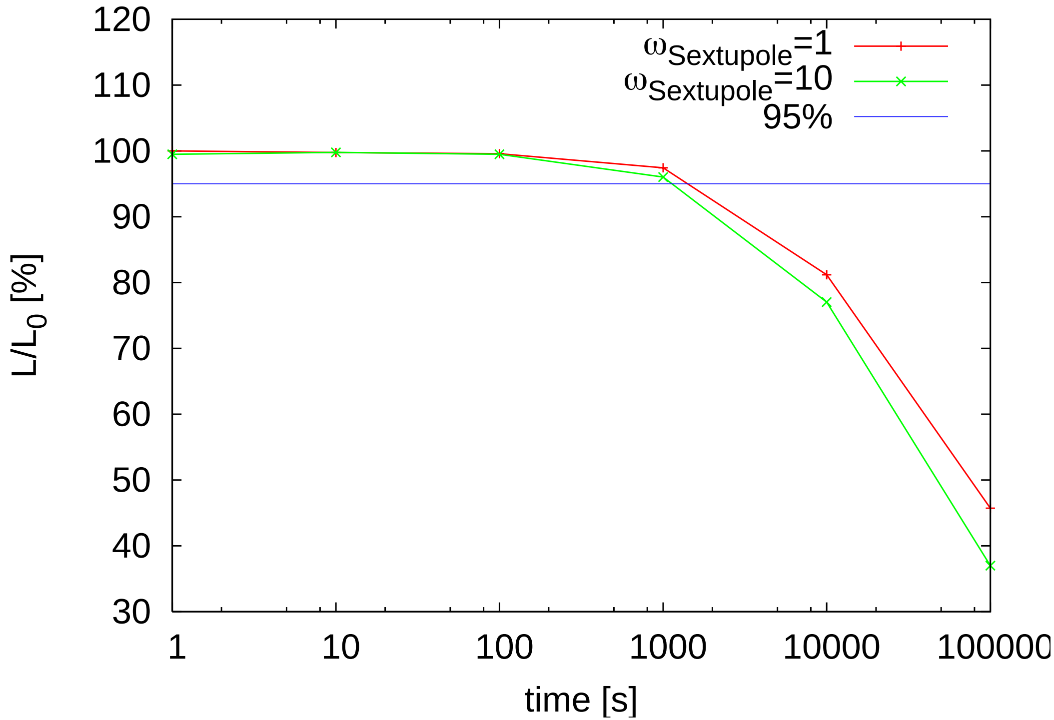




$\Rightarrow$ beam-gas scattering form LINAC and BDS: a fraction of 10^{-4} of the particles impacts on the spoilers

Luminosity Evolution

- ATL ground motion
- pulse-to-pulse orbit feedback
- intra-pulse beam-beam feedback



1-to-1 Correction Using PLACET-Octave

```
#!/home/andrea/bin/placet

source beamline.tcl
source beamdef.tcl
BeamlineSet -name "beamline"

SurveyErrorSet -quadrupole_y 300.0 \
               -quadrupole_roll 300.0 \
               -cavity_y 300.0 \
               -cavity_yp 300.0 \
               -bpm_y 300.0

Octave {
  B = placet_get_number_list("beamline", "bpm");
  C = placet_get_number_list("beamline", "quadrupole");
  R = placet_get_response_matrix("beamline", "beam0", B, C);

  placet_test_no_correction("beamline", "beam0", "Scatter");
  b = placet_get_bpm_readings("beamline", B);
  c = -pinv(R) * b;
  placet_vary_corrector("beamline", C, c);

  placet_test_no_correction("beamline", "beam0", "None");
  [b,S] = placet_get_bpm_readings("beamline", B);
  plot(S, b);
}
```

PLACET Graphical Output

- Longitudinal Beam Profile under the effects of transverse wakefield

Overview and Future Plans...

- PLACET has an extensive set of instructions
- Its Tcl/Tk interface allows to make complex simulations and to invoke easily external tools
- Its modularity and flexibility allow to interact and control the simulation program in several ways
- It has a Graphical Interface
- It can simulate a big fraction of the whole machine

  (Soon also damping rings and post collision line)
- It can be interfaced to external codes : MAD, BDSIM (in progress), Guinea-Pig, ...
- Inclusion of realistic wakepotentials calculated from GdfidL
- You are welcome to use it and contribute to it

http://savannah.cern.ch/projects/placet

⇒ Tutorials:

/afs/cern.ch/eng/sl/lintrack/TEX/PLACET_Tutorials