Update on Beam Based Alignment Methods for the CLIC Main Linac

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CLIC Meeting - November 3^{rd}, 2006

- Introduction
- Beam-Based Alignment Methods
- Bunch Compressor and Dispersion Free Steering
- Simulation Results
- Case of the ILC
- Conclusions and To Do List

Introduction

- the luminosity depends strongly on the vertical emittance at the interaction point
- in CLIC:

  - structure misalignment $\longrightarrow$ **strong transverse wakefields** (due to the high RF frequency)

  - quadrupole misalignment $\longrightarrow$ **dispersion effects**

  are the most important sources of emittance growth
- the **tiny vertical emittance** of the CLIC beam make it very sensitive to these effects

- beam-based alignment is necessary

Trajectory Correction Strategy

- **preliminary alignment** by means of a sophisticated system of wires

  - after that the position of all the linac elements will be randomly scattered around the *pre-alignment line*

  - averaged misalignment amplitudes are estimated of the order of:
    - 10 μm RMS for BPMs and cavities and
    - 50 μm RMS for quadrupoles

    (this accuracy is critical for BPMs and accelerating structures, but not for quadrupoles)

  this is not enough to preserve the vertical emittance

- **beam-based alignment** is necessary. It will proceed through four steps :

  1. 1-to-1 correction : alignment of the quadrupoles (robust, but may introduce dispersion)
  2. dispersion free steering : dispersion free correction (multidim. minimization, it might not converge)
  3. RF alignment : alignment of the cavities
  4. emittance-tuning bumps : minimization of the emittance at some measurement station

  or, alternatively :

  1. **ballistic alignment**, followed by emittance-tuning bumps (not usable for a curved machine)

$\Rightarrow$ We need to use Dispersion Free Steering

The Idea Behind 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:

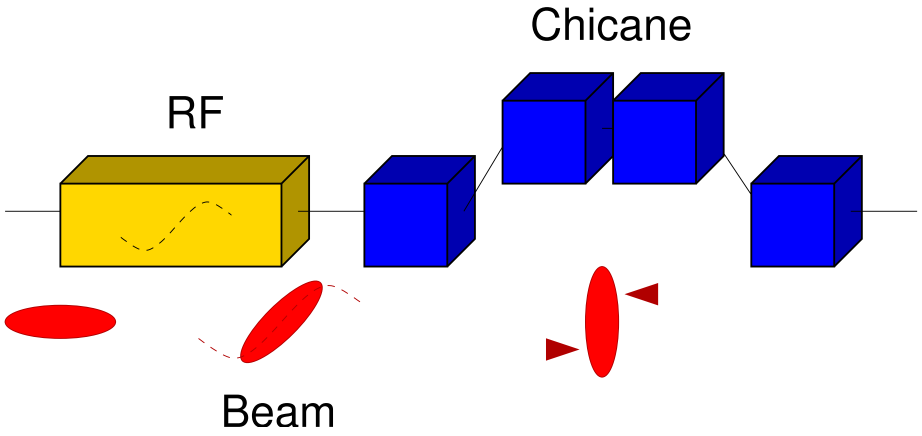
$$\chi^2 = \sum_{i=1}^{n} \omega_{1,i}\, y_{0,i}^2 + \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_{2,j} \left(y_{j,i} - y_{0,i}\right)^2 + \sum_{k=1}^{p} \omega_{3,k}\, c_k^2$$

$i = 1..n$	BPMs	$y_{i,j}$	position of beam j in BPM i
$j = 0..m$	beams ($j = 0$ for nominal beam)	c_k	strength for the corrector k
$k = 1..p$	correctors	$\omega_{1,i}$, $\omega_{2,j}$, $\omega_{3,k}$	weights for orbit, difference and correction terms

- We want to use the Bunch Compressor to generate the energy difference.

Principles of Bunch Compression

- In order to compress a bunch longitudinally we need to impress a "rotation" in the longitudinal phase space
- this is achieved by two *pseudo*-rotations :

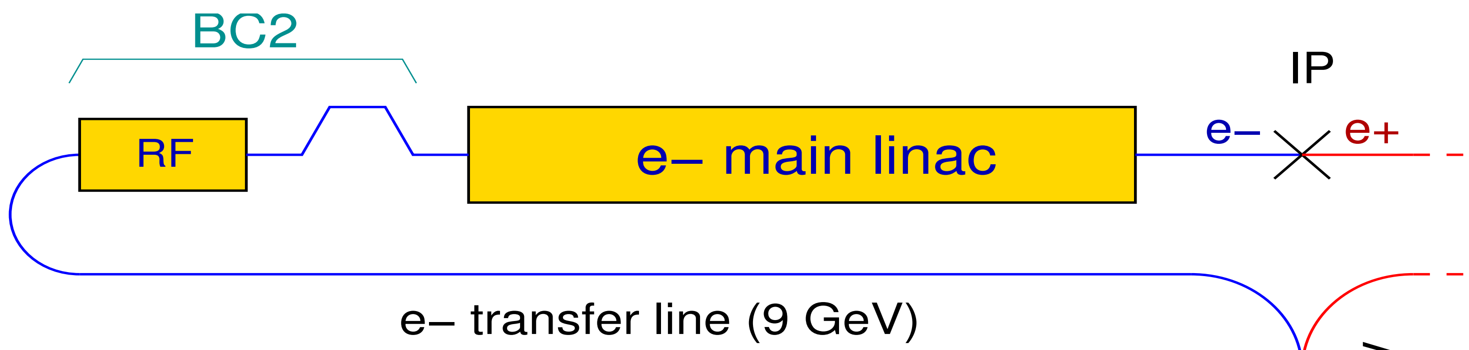


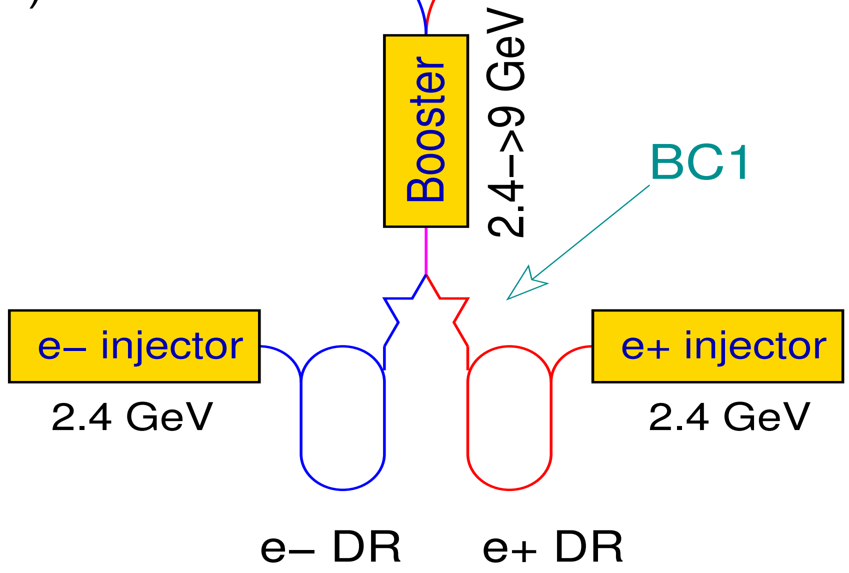
for which we need :

1. a RF system, working at a phase equal to $k\pi$, that linearly correlates the momentum with the z-position of the particles in the bunch

2. a magnetic chicane that provides a convenient R_{56}. The magnetic chicane consists of two pairs of rectangular dipoles, one being the mirror image of the other, separated by a drift space (see Frank Stulle's talk, CLIC Meeting, October 6, 2006)

Bunch Compressors in the CLIC Main Linac





- there is not yet a complete design
- beam at the exit of the damping ring:

energy	2.424 GeV
no. of particles per bunch	$2.56 \cdot 10^9$
bunch length	$1550\ \mu$m
uncorrelated energy spread	0.13%

- beam at main linac injection:

energy	9 GeV
no. of particles per bunch	$2.56 \cdot 10^9$
bunch length	$30\ \mu$m
uncorrelated energy spread	2%

- CLIC requires **two** bunch compressors

$\Rightarrow$ I focused my attention on the BC stage 2, at the entrance of the ML

CLIC BC2 (1/2)

- BC1 is not yet designed and BC2 is only partially designed (magnetic chicane seems OK, but what about the RF structures? problem of beam-loading)
- I used the information contained in
  - the "CLIC design report" (2000)
  - the "Updated CLIC Parameters" (2005)
  - the results achieved at PSI for the chicane, see Frank Stulle's talk

⇒ Beam parameters:

	unit	entrance of Bunch Compressor 2	entrance of Main Linac
energy	[GeV]	9	9
unc. energy spread	%	2.0	2.0
no.of particles	[#]	$2.56 \cdot 10^9$	$2.56 \cdot 10^9$
charge	[nC]	0.41	0.41
sigmaz	[μm]	250	30
h. norm. emittance	[nm·rad]	570	680
v. norm. emittance	[nm·rad]	4	5

CLIC BC2 (2/2)

$\Rightarrow$ BC2 Parameters:

- Magnetic chicane:

$\mathbf{R_{56}}$ =	-14 mm
norm. $\mathbf{s-E}$ corr. =	-70.5 1/m

geometry: dipoles length 2m, bending angle 1.17deg, distance between the middle dipoles 1m, total length 40m

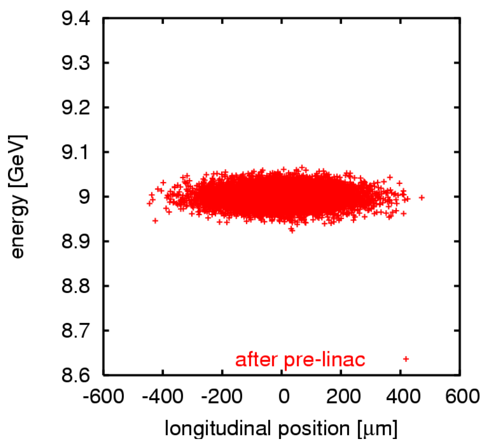
- RF system:

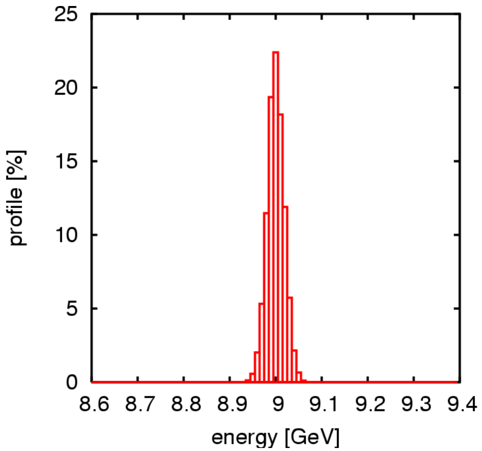
$V =$	1009.14 MV	integrated voltage (*)
$\Phi =$	$k\pi$	phase
$f =$	30 GHz	frequency

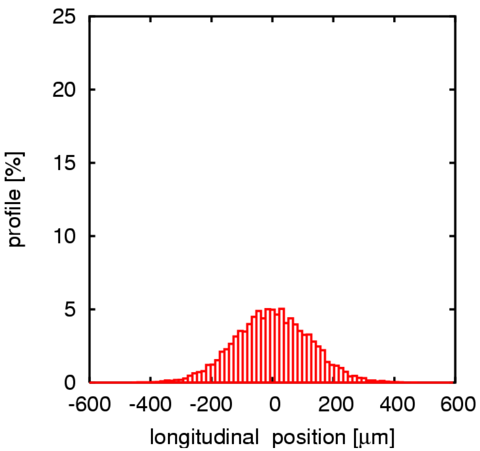
(*) the value estimated in the "CLIC design report" (2000) was 1026 MV

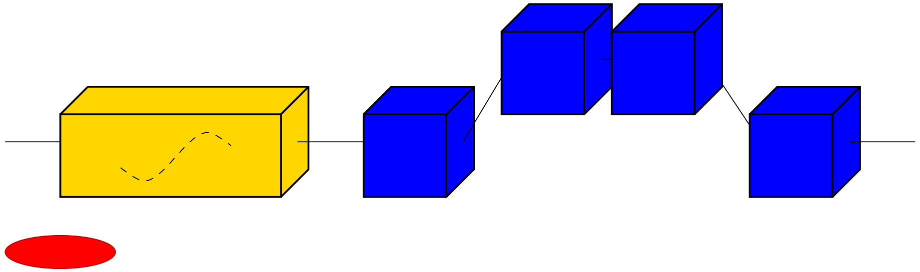
- Notice that: the turn-round loop, at 9 GeV, imposes the beam conditions at the entrance of the BC2 (this limits the energy difference we can obtain from the BC) and somehow controls the BC2 design

CLIC BC2 Simulation (1/3)

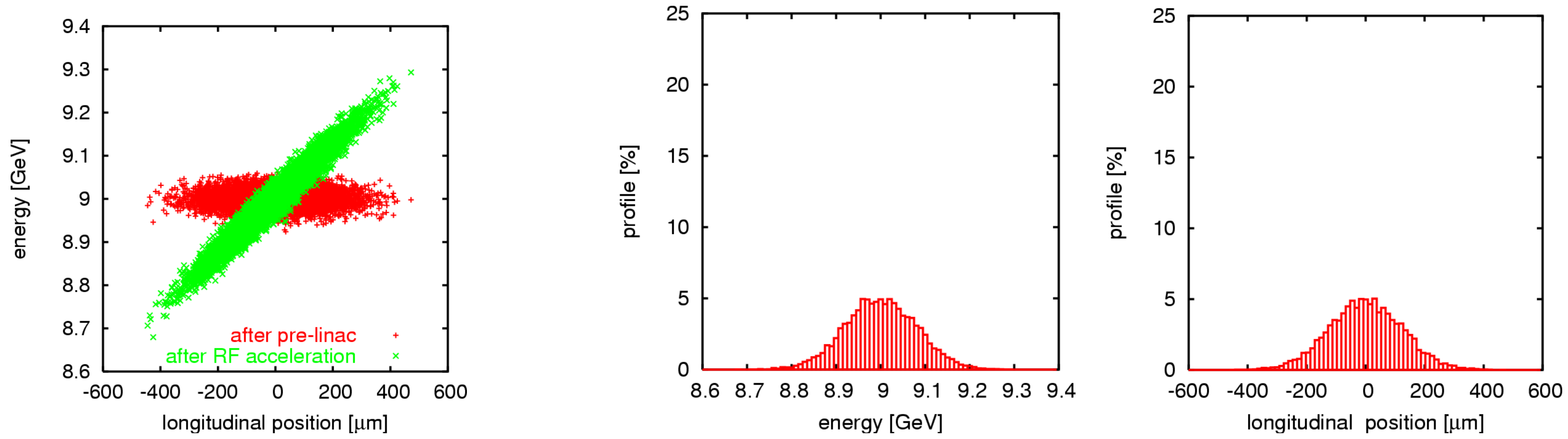


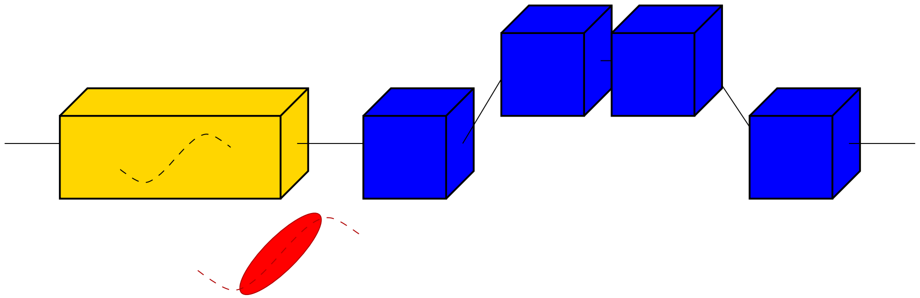




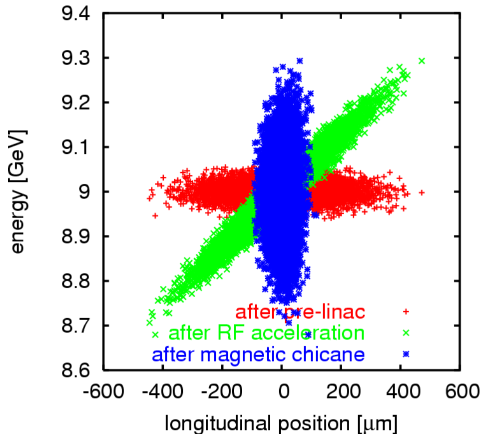


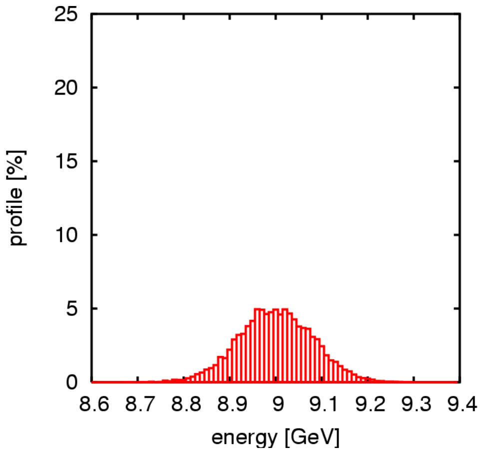
CLIC BC2 Simulation (2/3)

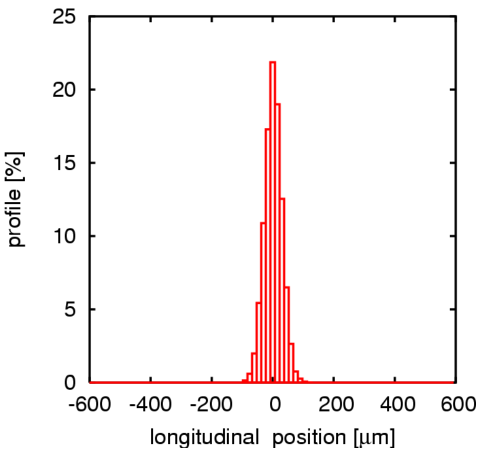


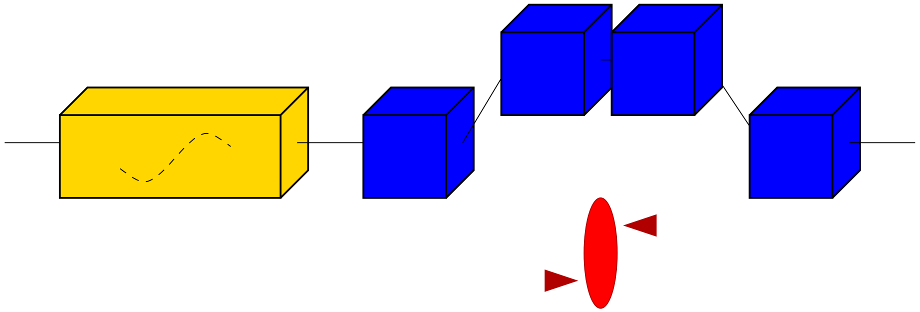


CLIC BC2 Simulation (3/3)





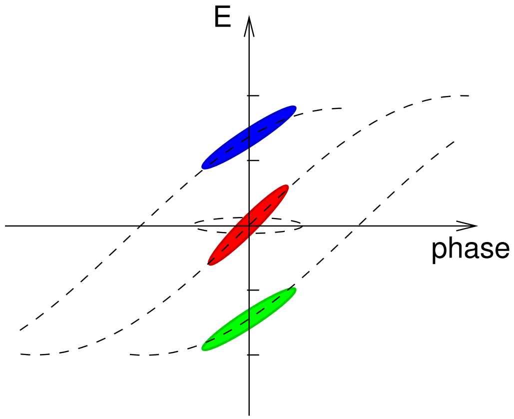


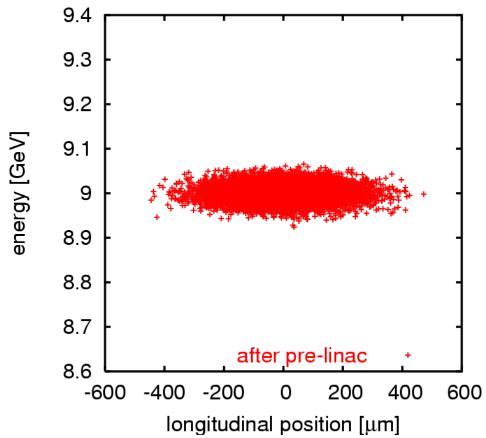


Bunch Compression for Dispersion Free Steering (1/3)

- in order to create the energy difference for the DFS test beams, we introduce a *phase delay* in the BC's RF structure
- we want to have:
  - one nominal beam : i.e. the *in phase beam*, which is fully compressed, nominal energy
  - two test beams obtained by offsetting the *phase* :
    $\phi_1 = \phi_0 + \Delta\phi_1$ and
    $\phi_2 = \phi_0 - \Delta\phi_2$

  we chose $\Delta\phi_1 = \Delta\phi_2$ but this is not necessary.





- the nominal beam is not accelerated. whereas the test beams, whose relative phase is $\pm\Delta\phi$, get an acceleration

Bunch Compression for Dispersion Free Steering (2/3)

- in order to create the energy difference for the DFS test beams, we introduce a *phase delay* in the BC's RF structure
- we want to have:
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  - two test beams obtained by offsetting the *phase* :
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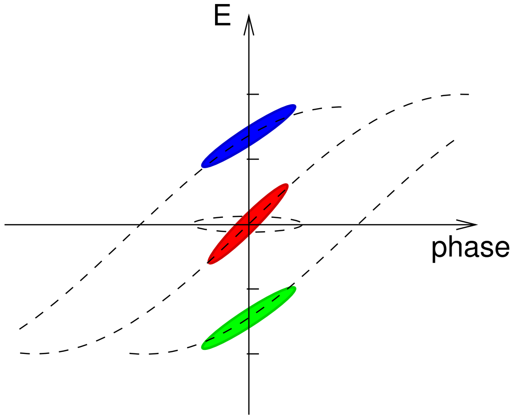

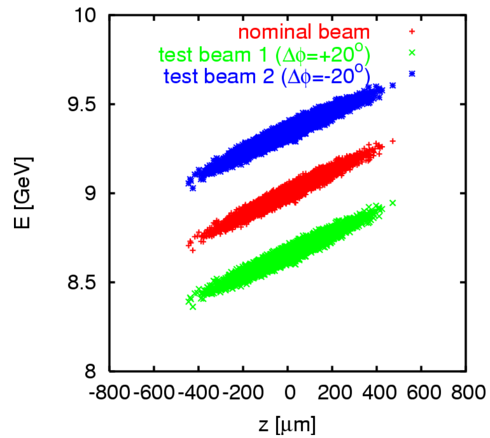

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Bunch Compression for Dispersion Free Steering (3/3)

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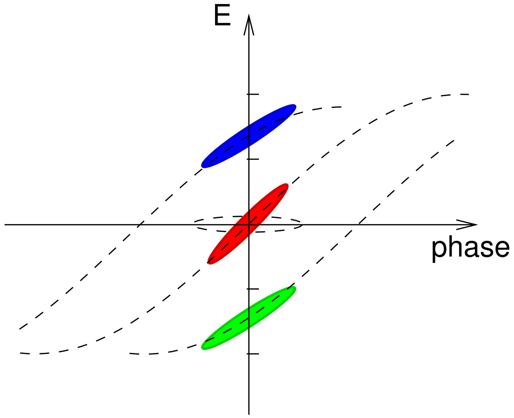
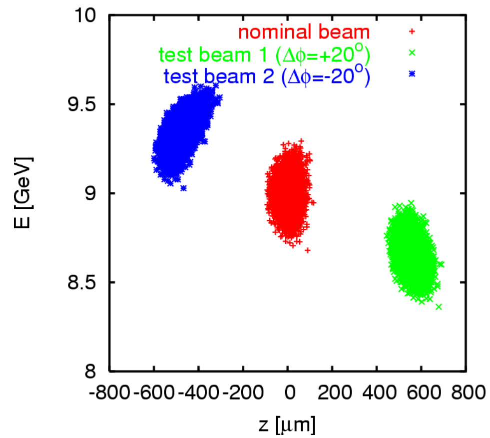
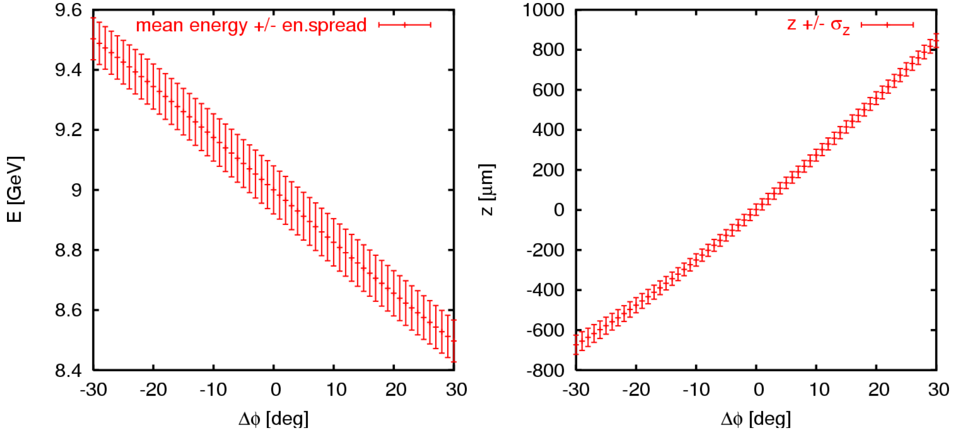




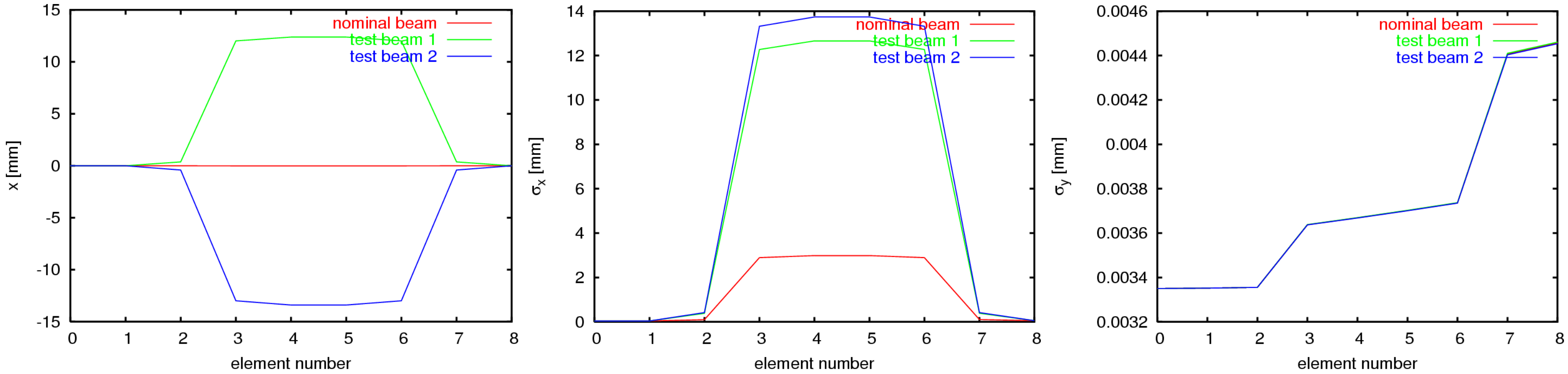
- the nominal beam is not accelerated. whereas the test beams, whose relative phase is $\pm\Delta\phi$, get an acceleration

Off-phase Bunch Compression

- Mean energy and mean longitudinal position as a function of the phase offset before (left) and after (right) the chicane:



- Beam size in the magnetic chicane for $\Delta\Phi_{1,2} = \pm 20^o$:



Energy Difference and Dispersion Free Steering

- There are (at least) **two ways** to create the energy offset of the test beams:
  1. creating an initial energy difference before the man linac (using the BC)
  2. reducing the gradient of the main linac accelerating structures

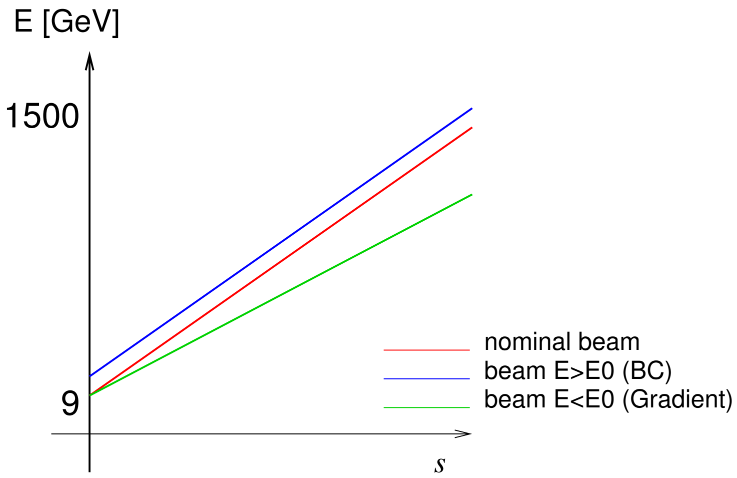
  $\Rightarrow$ **we need to use them both.**

- Let's consider the DFS formula:

$$\chi^2 = \sum_{i=1}^{n} \omega_{1,i}\, y_{0,i}^2 + \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_{2,j} \left(y_{j,i} - y_{0,i}\right)^2 + \sum_{k=1}^{p} \omega_{3,k}\, c_k^2$$

  we have three contributions:

  1. nominal beam steered to the nominal trajectory
  2. test beams steered to the nominal beams
  3. balancing term



Summary of the Simulation Parameters

- bunch compressor:
  - incoherent synchrotron radiation emission considered
  - 2^{nd} order longitudinal tracking
  - assumed : no wakefields in the BC cavities, perfectly aligned BC
- main linac misalignment model:
  - $\sigma_{quad} = 50\,\mu\mathrm{m}$ Quadrupole position error
  - $\sigma_{cav} = 10\,\mu\mathrm{m}$ Cavity position error
  - $\sigma'_{cav} = 10\,\mu\mathrm{rad}$ Cavity angle error
  - $\sigma_{BPM} = 10\,\mu\mathrm{m}$ BPM position error
  - $\sigma_{res} = 0.1\,\mu\mathrm{m}$ BPM resolution
- DFS:
  - $\Phi_0 = 0$, nominal beam
  - $\Phi_{1,2} = \pm\Delta\Phi$, help beams
  - $\omega_{1,i} = 1$, orbit correction
  - $\omega_{2,k} = 100$, difference of the trajectories (test value, can be optimized)

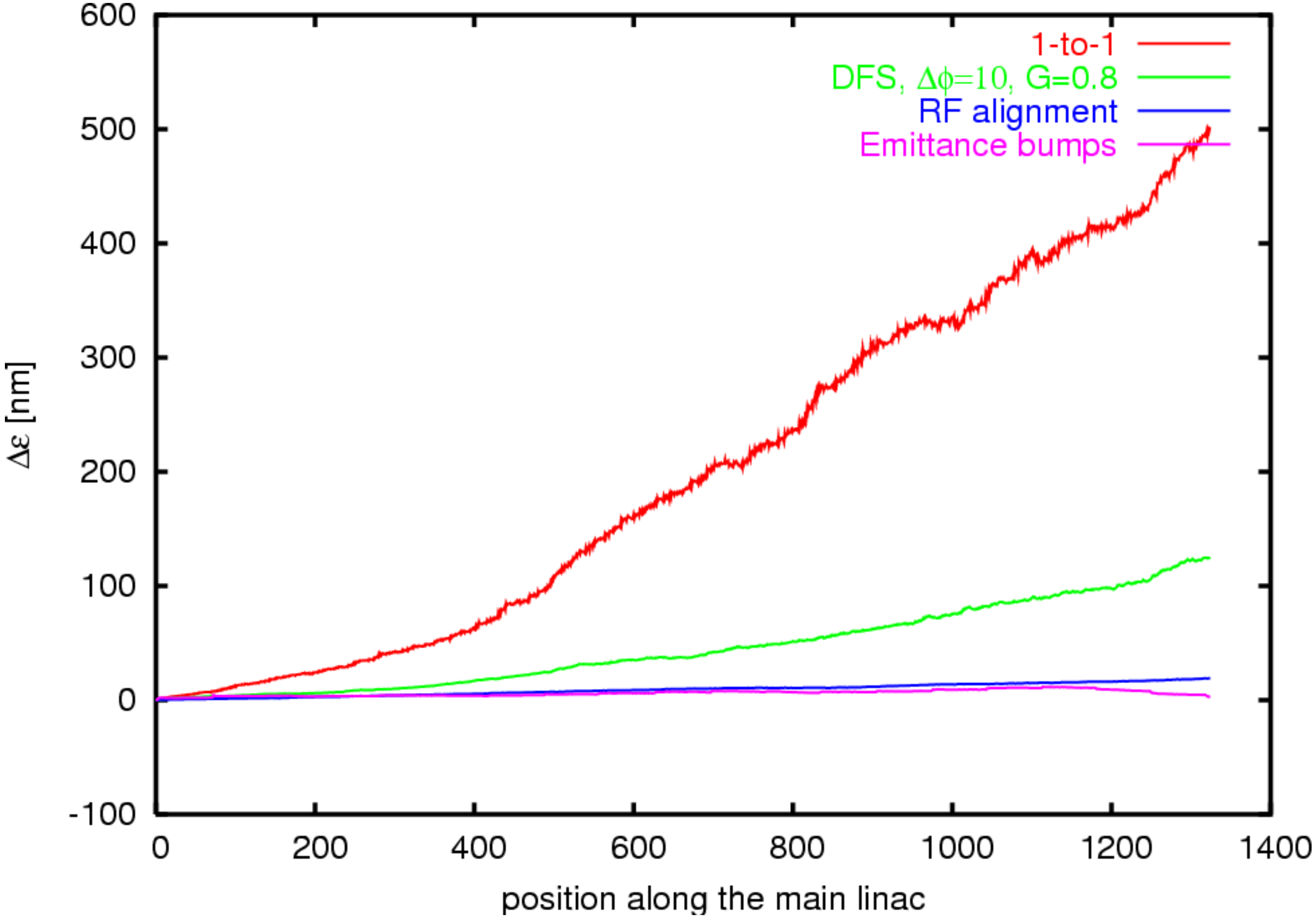
Extensions to PLACET

- in order to perform these simulations, PLACET needed some **extensions** :
  - placet was a 4d-tracking code :

    $\Rightarrow$ a longitudinal tracking module has been created
  - placet was initially written to simulate only LINAC and BDS :
    - beam models: sliced beam for the ML, particles beam for the BDS (SLICES could be converted into PARTICLES but not *vice versa*)

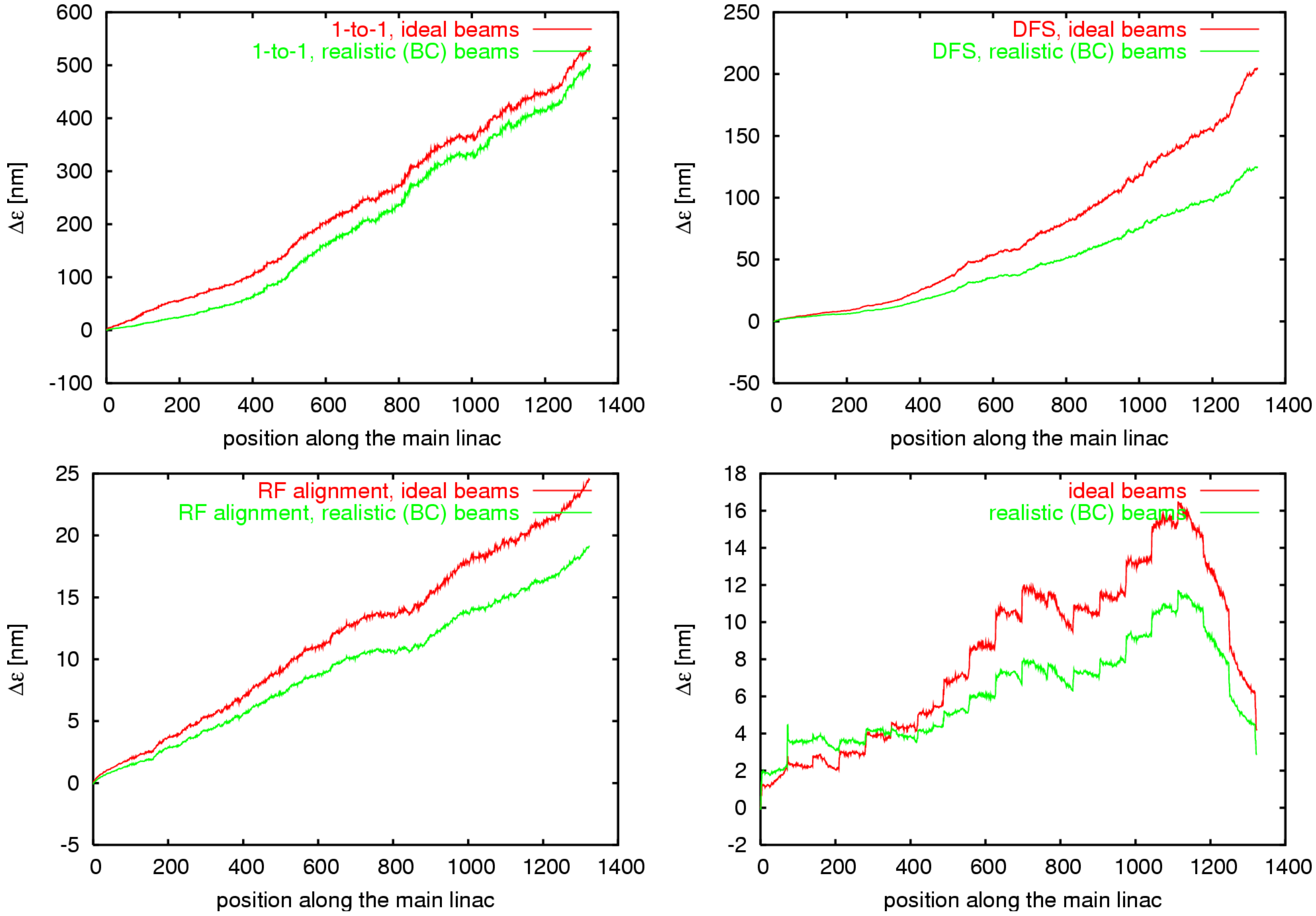
    $\Rightarrow$ the possibility of passing from PARTICLES to SLICES has been added (BC to ML)
  - unexpected improvements and extra features :
    - $\sim$30% faster,
    - a tracking module which uses parallel computer systems has been created

Simulation Results: emittance growth after beam-based alignment



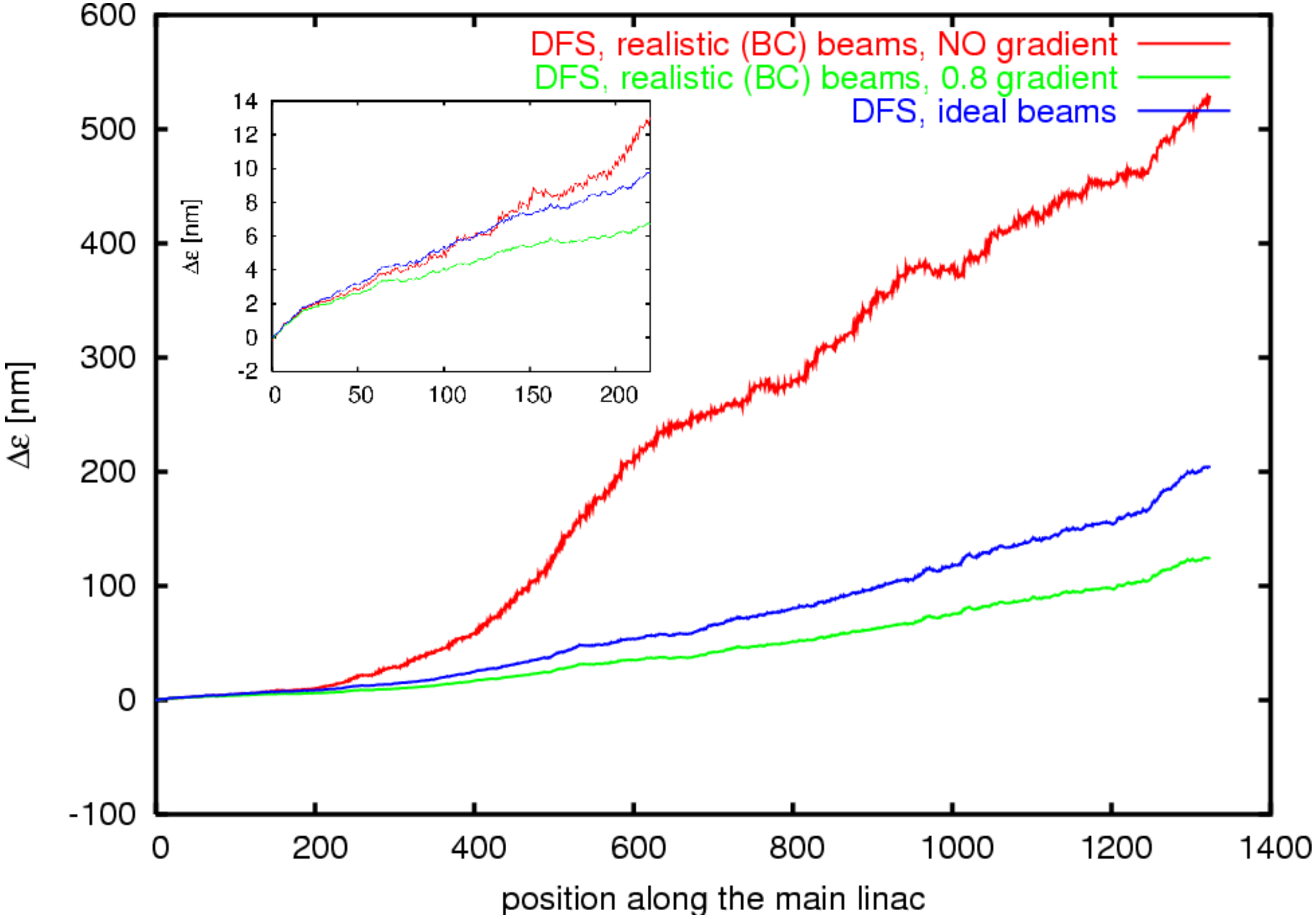
standard average misalignments, 2 test beams, $\Delta\Phi = \pm 10$, $\omega = 100$, $G = 0.8$, average of 50 machines, final emittance growth 2.8 nm

Simulation Results: alignment with *ideal* beams vs. alignment with *realistic* beams



standard average misalignments, 2 test beams, $\Delta\Phi = \pm 10$ / E=0.8,0.9 E_0, $G = 0.8$, $\omega = 100$, average of 50 machines, best final emittance growth 2.8 nm

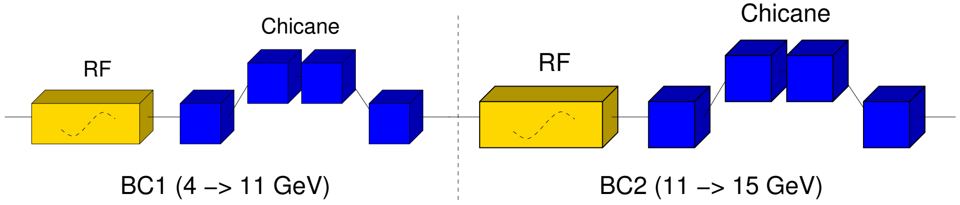
Simulation Results: importance of the gradient



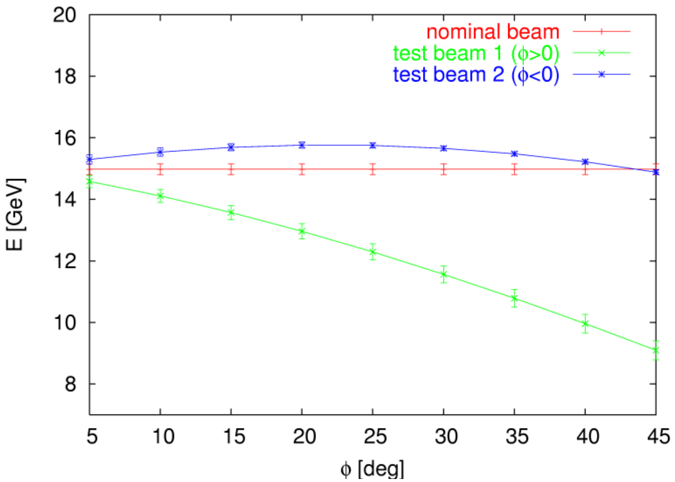
standard average misalignments, 2 test beams, $\Delta\Phi = \pm 10$, $G = 1.0, 0.8$, $\omega = 100$, average of 50 machines

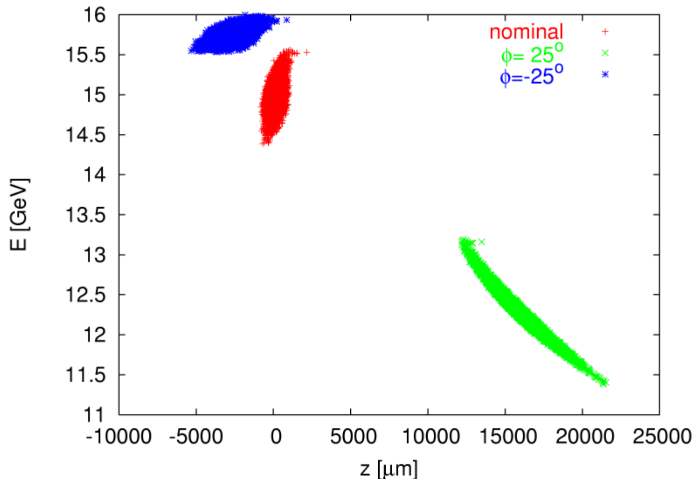
Case of the ILC

- ILC Bunch Compressor : σ_z from 6mm to 300μm



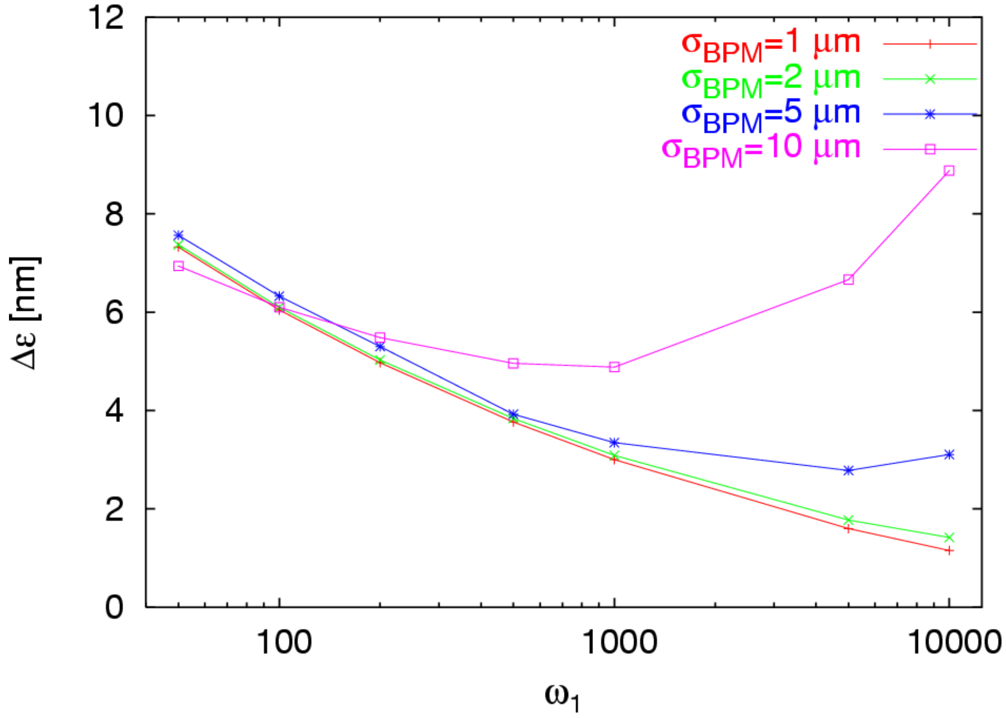
- Bunch Compression of off-phase beams:





Results for a laser-straight ILC

Emittance Growth as a function of the weight, for Φ=25

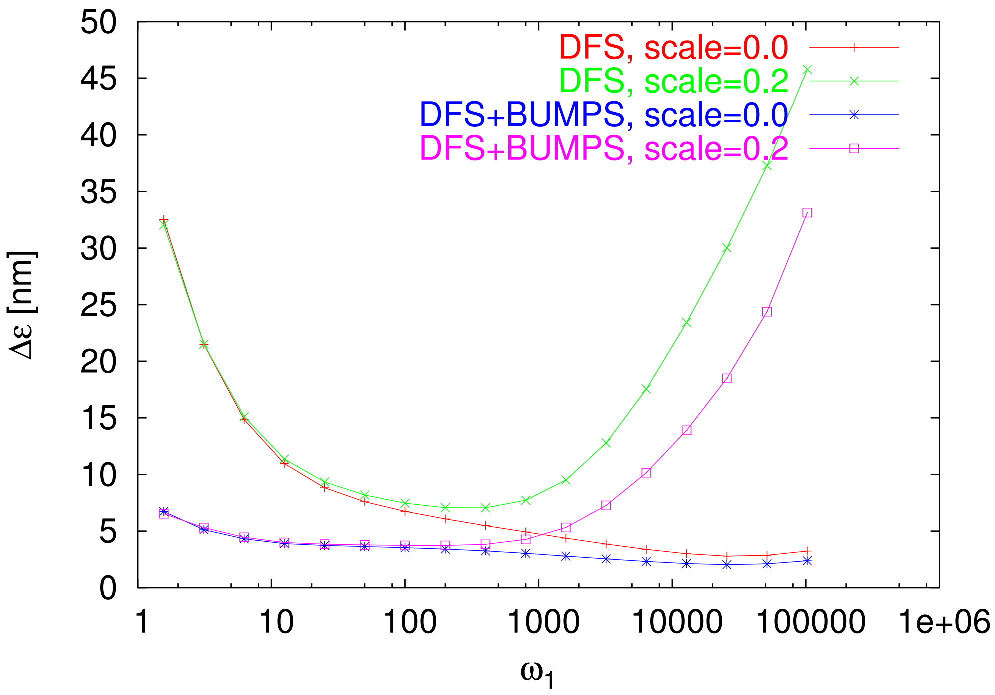


(average of 100 machines)

for a laser-straight linac, DFS (with ω “big”, BPM resolution of 1 μm) leads to excellent results

Results for a curved ILC

In a curved linac, the BPM scale error, $\mathrm{X}_{\mathrm{meas}} = a\, X_{\mathrm{real}}$, has an impact on the DFS performances



- Scale error prevents from using "big" weights

- We need to use dispersion bumps to reduce the emittance growth

Conclusions and To Do List

- BC+DFS seems to work well

  ⇒ now we can simulate CLIC from the Damping Rings to the Interaction Point

- but a lot of work has still to be done:
  - a detailed design of the bunch compressors and the transfer lines
  - simulation:
    - consider coherent synchrotron radiation emission and
    - implement some higher order tracking routine
  - study:
    - how to align the BC2 itself (and BC1 as well)
    - the impact of the wakefields generated in the BC's cavities
    - does the big energy spread in the BC create problems? (apertures, . . .)
    - the case of a curved machine (the results for ILC are already encouraging)
    - study dynamics imperfections (impact on the emittance, beam losses, . . .)