Main Linac Simulations

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ILC LET Beam Dynamics Workshop

Overview

- **Bunch Compressor**

- **Main Linac**

  ⇒ Static alignment strategies for a laser-straight and a curved layout

  - use of BC to align the ML
  - weight scan for DFS with two test beams
  - emittance tuning bumps
  - impact of BPM calibration errors

  ⇒ Dynamic effects

  - quadrupole jitter during alignment
  - ripples of the RF gradient
  - luminosity loss due to quadrupole jitter
  - MICADO in the main linac

Main Linac Simulations

- **Simulation Setup**
  - All simulations made using PLACET
  - 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

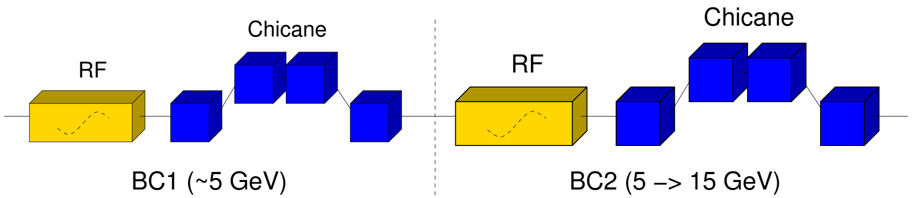
  - BPM resolution $= 1\mu$m
  - Curved layout obtained introducing small angles between the cryo-modules (KICKs)

- **Alignment Procedure**
  - 1-to-1 correction
  - dispersion free steering
  - emittance tuining bumps (dispersion / wakefields bumps)

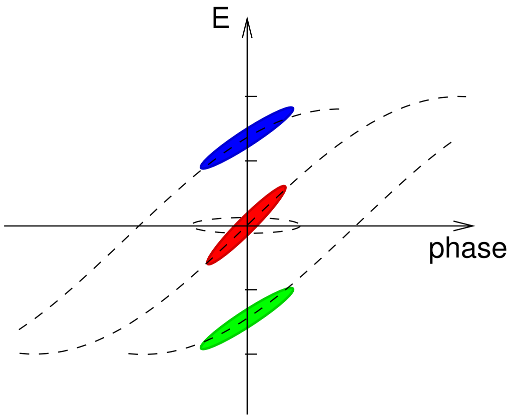
All results are the average of 100 seeds

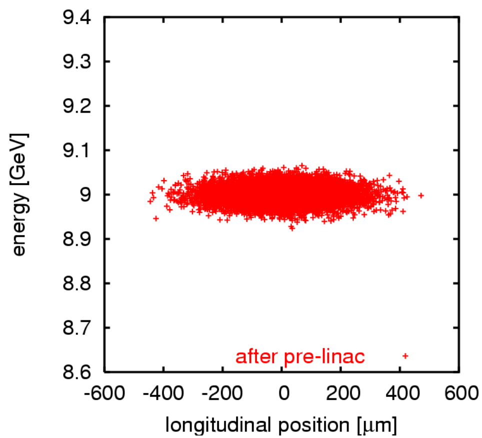
Bunch Compression for Dispersion Free Steering (1/3)

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



- in order to generate the energy difference for the DFS test beams, we introduce a *phase delay* in the BC's RF structure

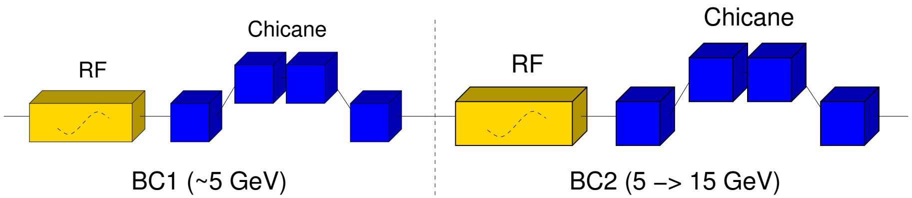




$\Rightarrow$ the nominal beam is not accelerated. whereas the test beams, whose relative phase is $\pm\Delta\phi$, get an acceleration

Bunch Compression for Dispersion Free Steering (2/3)

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



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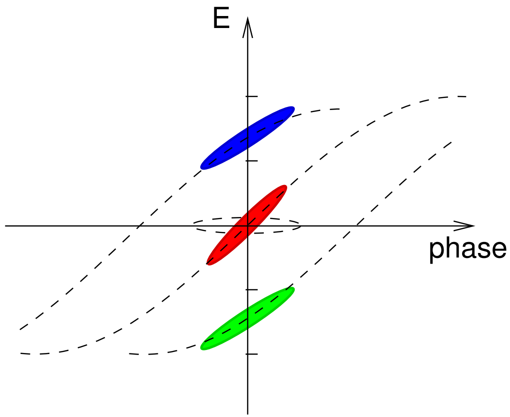

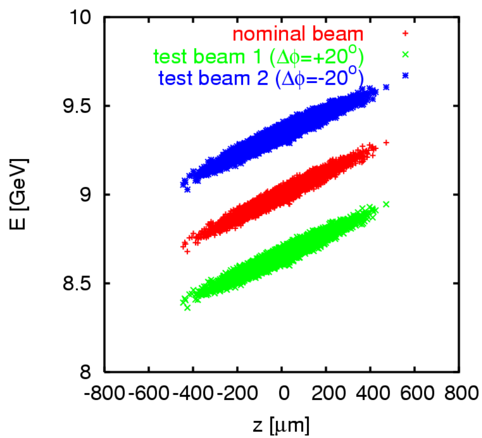

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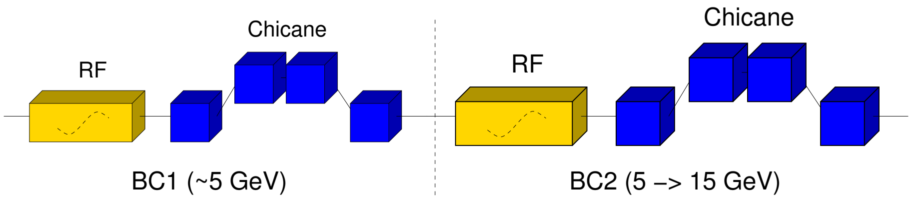
Bunch Compression for Dispersion Free Steering (3/3)

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



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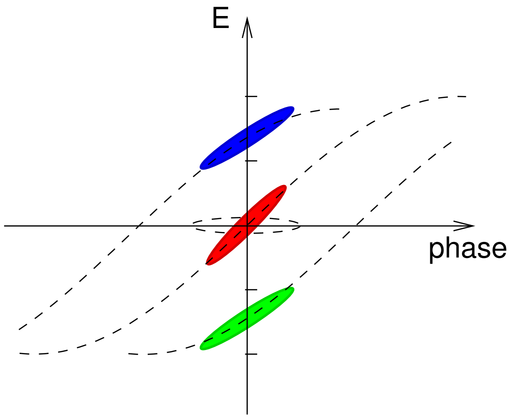
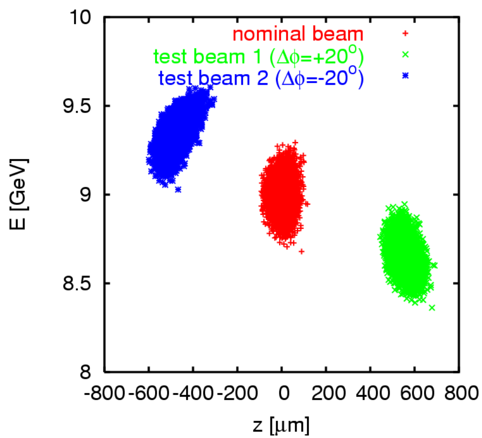


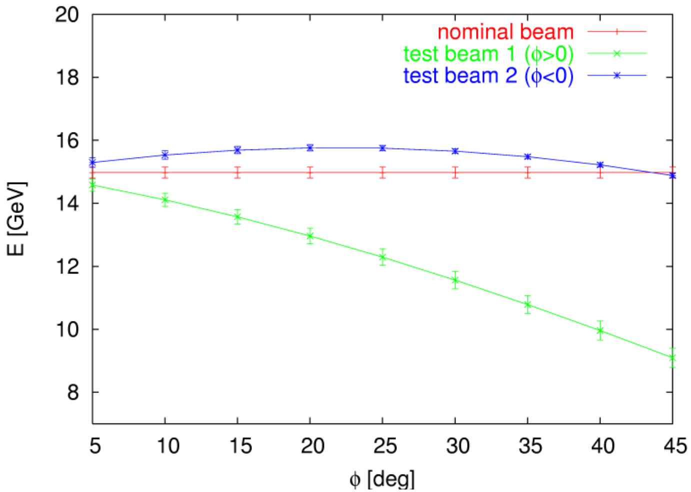


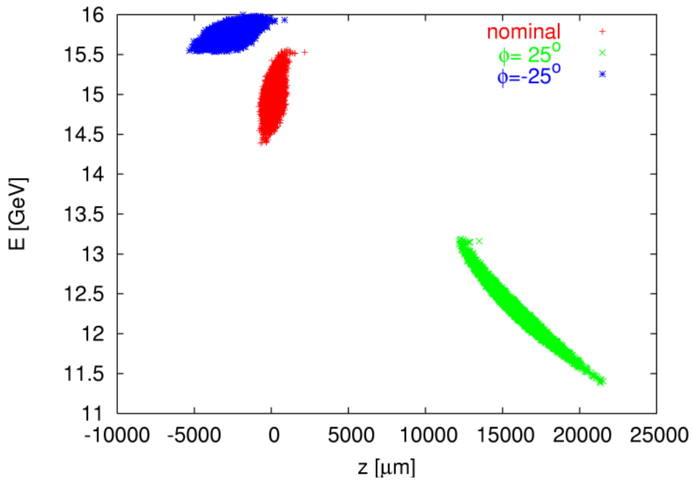
⇒ the nominal beam is not accelerated. whereas the test beams, whose relative phase is $\pm\Delta\phi$, get an acceleration

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





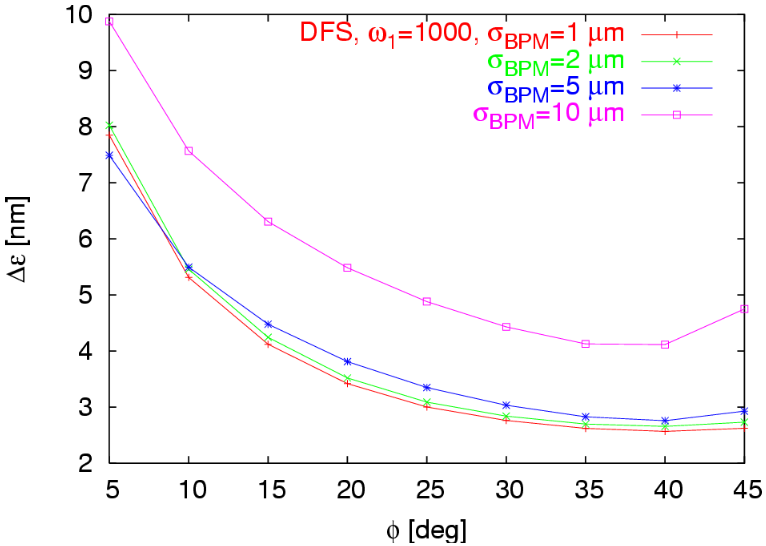
- the longitudinal phase space changes

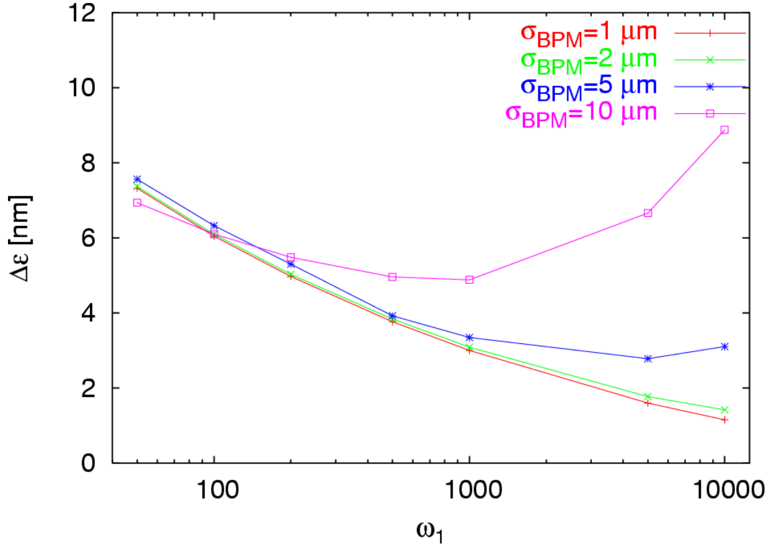
⇒ their phase must be synchronized with the ML accelerating phase

Final Emittance Growth as a function of Φ and ω

- Emittance growth after DFS:

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





- 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

$\Rightarrow$ emittance growth is recovered.

Test Beams for DFS

- We use two 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

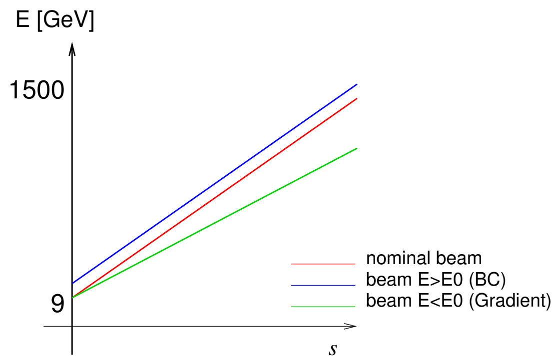
  $\Rightarrow$ **we need both.**

- DFS formula:

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

we have three contributions:

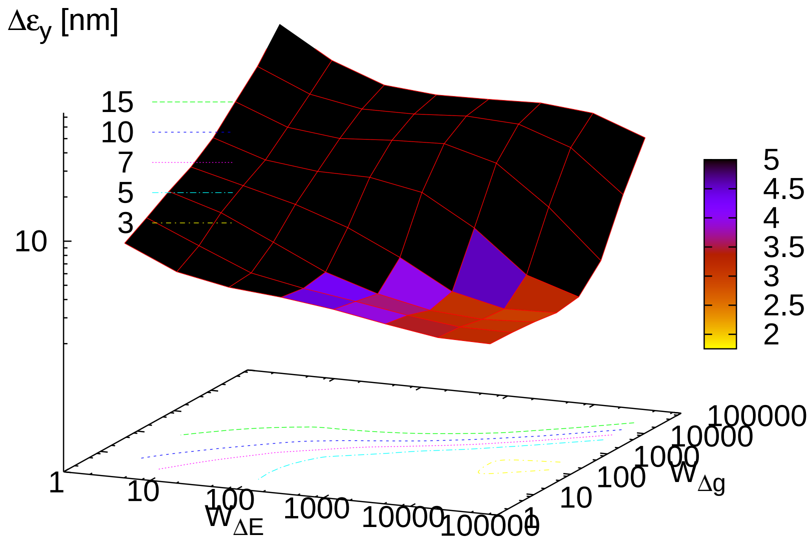
1. nominal beam steered to the nominal trajectory
2. test beams steered to the nominal beams
3. balancing term



DFS with Two Test Beams

Emittance growth as a function of the weights after DFS, using two test beams :

1) ΔE=0.2 $\rightarrow E_{\text{initial}} = 80\%\, E_{0,\text{initial}}$
2) Δg=0.2 $\rightarrow E_{\text{final}} = 80\%\, E_{0,\text{final}}$



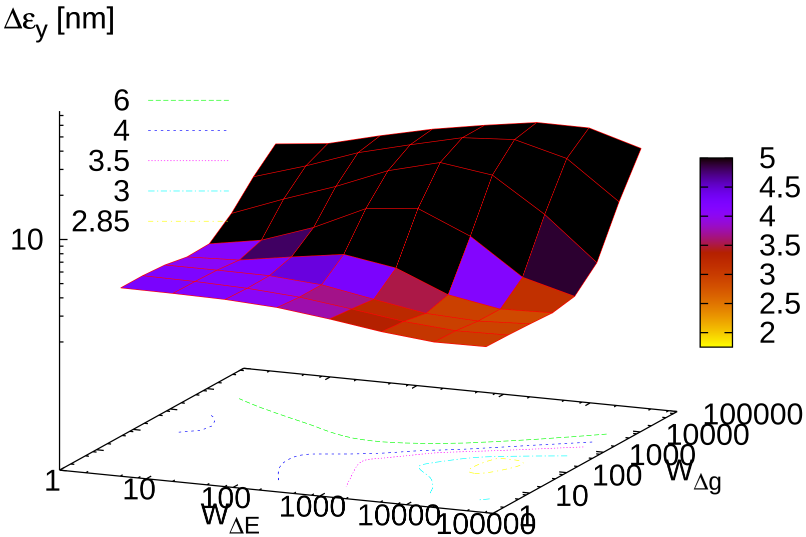
(black means $\Delta\epsilon > 5nm$)

$\Rightarrow$ Optimum: $\boxed{w_\Delta E\text{=12800, } w_\Delta g\text{=200}}$

DFS with Two Test Beams + Emittance Bumps

Emittance growth as a function of the weights after dispersion bumps :

1) ΔE=0.2 $\rightarrow E_{\text{initial}} = 80\%\ E_{0,\text{initial}}$
2) Δg=0.2 $\rightarrow E_{\text{final}} = 80\%\ E_{0,\text{final}}$

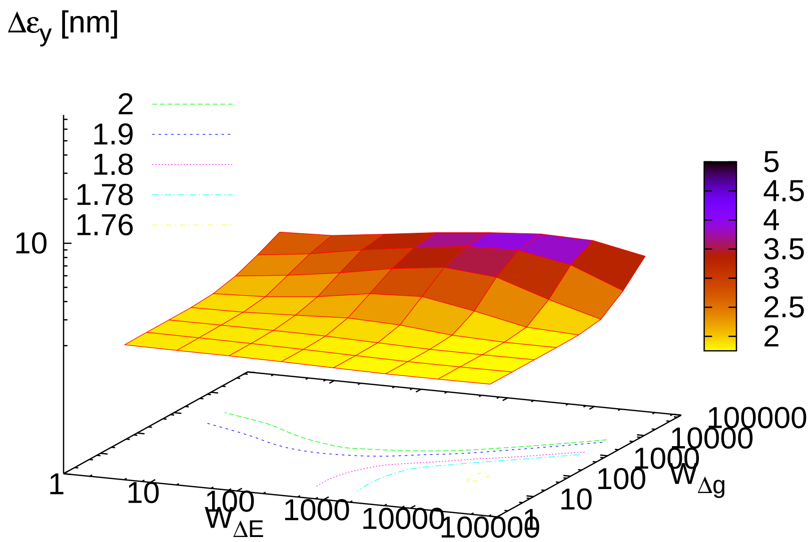


$\Rightarrow$ Residual emittance growth after the correction procedure is $\boxed{\Delta\epsilon = 2.85 \text{ nm}}$

DFS with Two Test Beams + Emittance Bumps

Emittance growth as a function of the weights after dispersion bumps and wakefields bumps:

1) ΔE=0.2 $\rightarrow E_{\text{initial}} = 80\%\ E_{0,\text{initial}}$
2) Δg=0.2 $\rightarrow E_{\text{final}} = 80\%\ E_{0,\text{final}}$

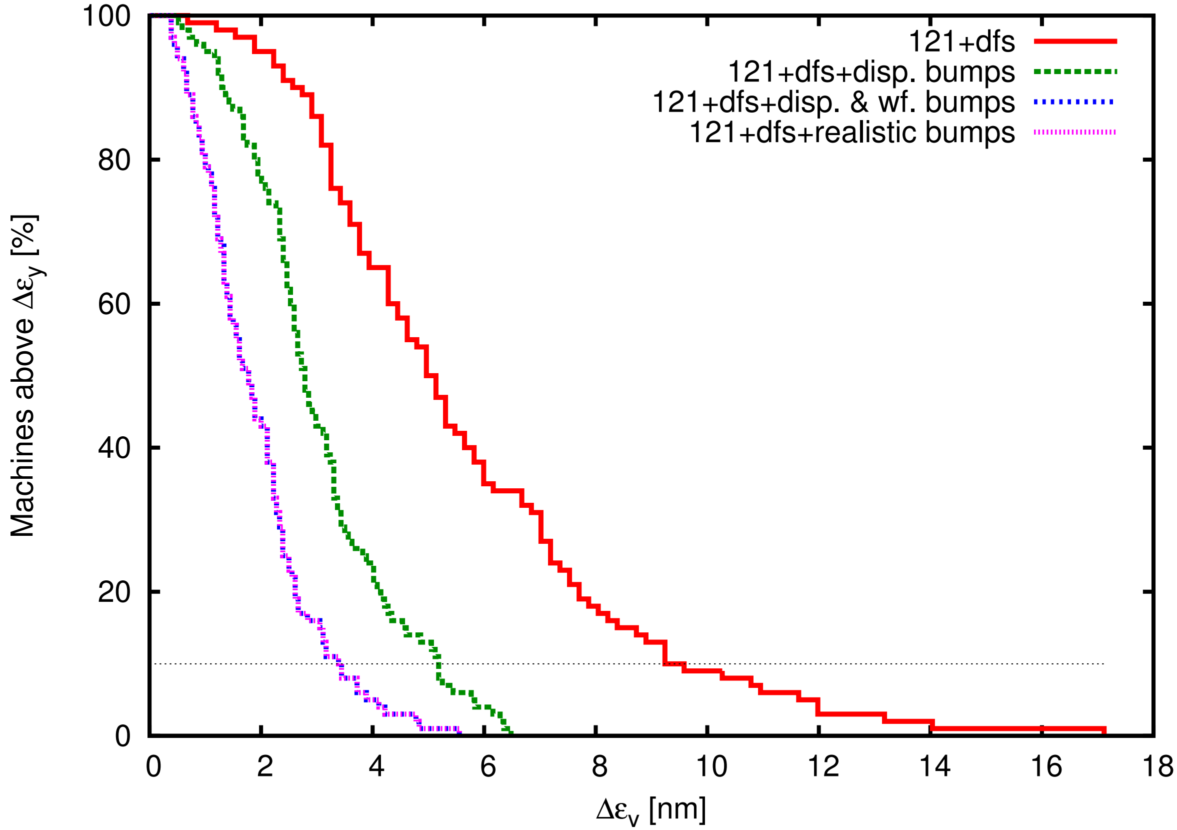


⇒ Residual emittance growth after the correction procedure is $\boxed{\Delta\epsilon = 1.7 \text{ nm}}$

(quadrupole roll is not corrected)

Emittance Growth Histogram

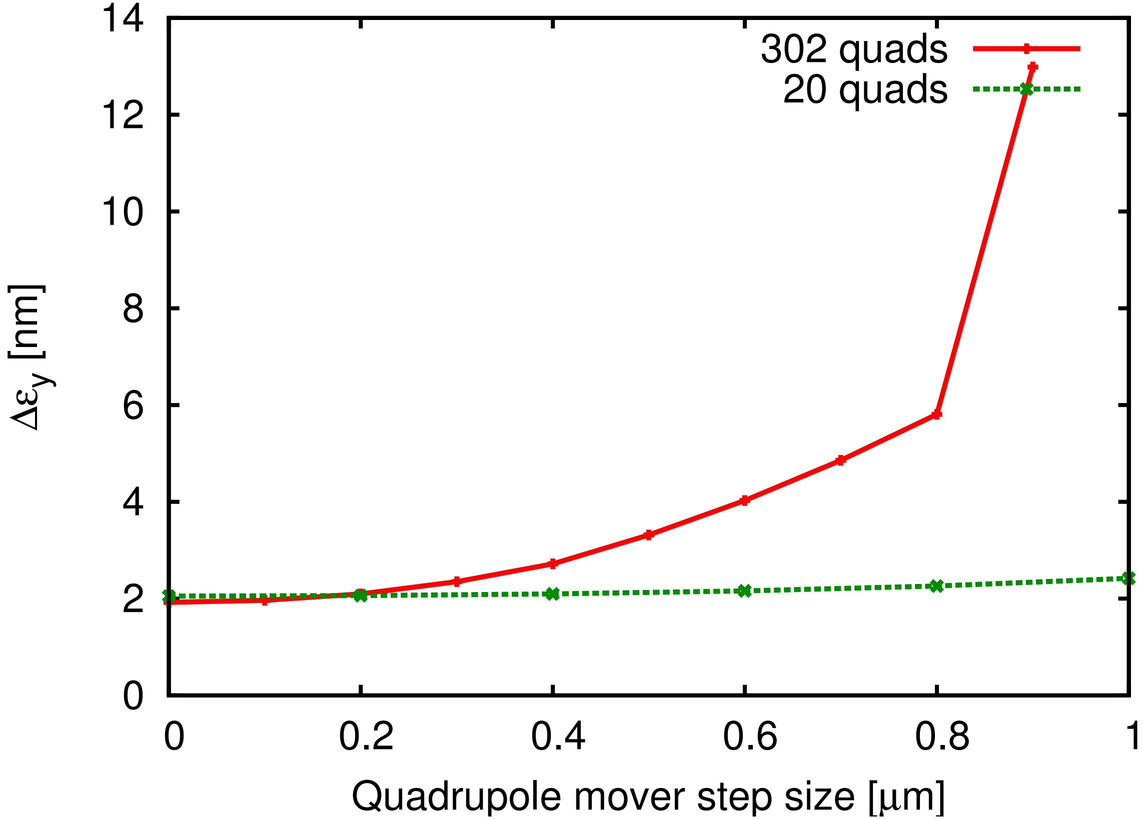
- Emittance growth within 90% confidence limit



Selection of Optimal Correctors

- If all quadrupoles are used to construct knobs the tuning gets sensitive to the mover step size.

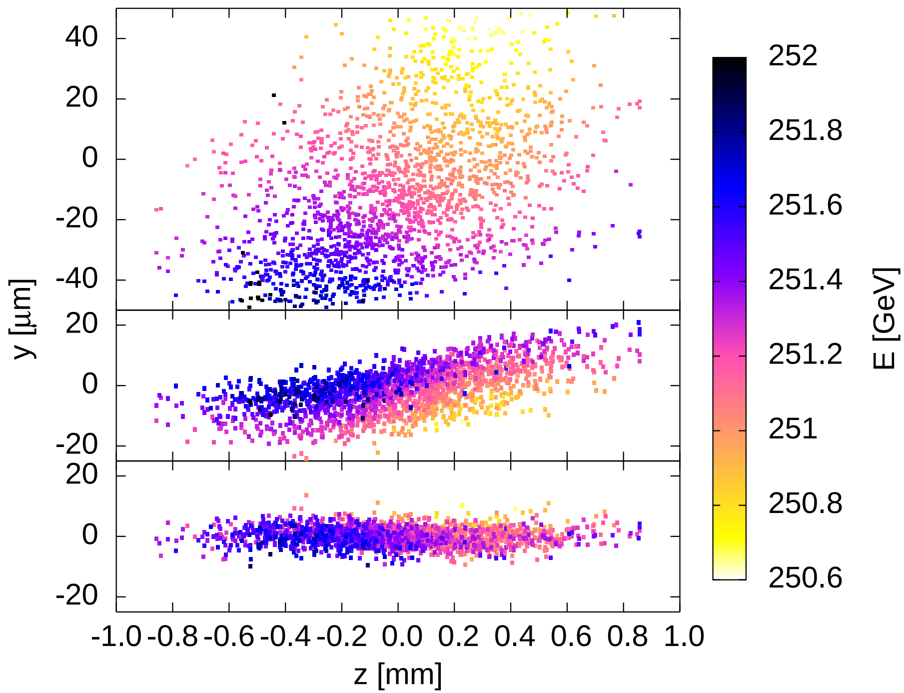
$\Rightarrow$ We must choose the "optimal" correctors (P.Eliasson)



Tuning Bumps in the ILC Linac

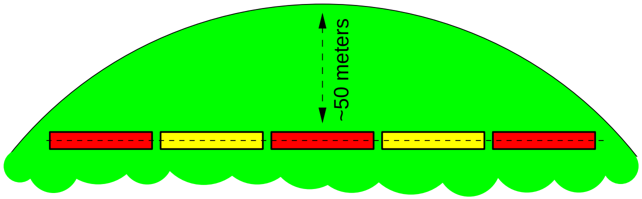
Beam portrait in the $z - y$ plane, the color corresponds to the energy

- top: beam after 1-to-1 correction
- middle: beam after DFS
- bottom: beam after emittance tuning bumps

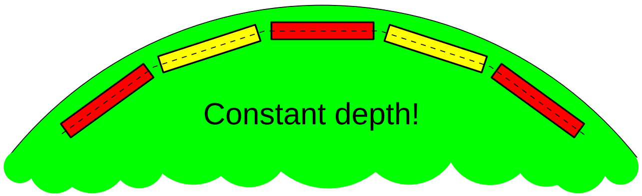


Linac that Follows the Earth's Curvature

- Laser-Straight vs. Curved Layout



- Dispersion Free Steering



- Target Dispersion Steering

- main linac lattice is the same in case of a laser straight or a curved linac
- cryogenic modules are straight and a small angle is introduced between each pair of modules to follow the earth curvature

BPM Calibration Error

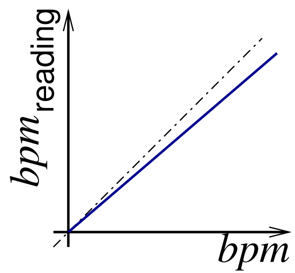
- Let's recall the DFS formula

$$M = \sum_{i=1}^{n} \omega_0 \, y_{0,i}^2 + \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_j \, (y_{j,i} - y_{0,i} - \Delta_i)^2$$

⇒ Erroneous **BPM calibrations** can cause error in evaluating the dispersion, biasing the "target dispersion" steering

- In our model, the BPM readings are linear to the actual measurements but there is a *scale factor* a_i

$$x_{i,\text{reading}} = a_i \, x_i$$



- in the simulations scale factors have a Gaussian distribution with width σ_a around 1

⇒ The estimated error in measuring the dispersion, compared to the BPM resolution, is

$$\sigma_D^2 = \sigma_a^2 \, D^2 + \sigma_{\text{res}}^2 \, (E/\Delta E)^2$$

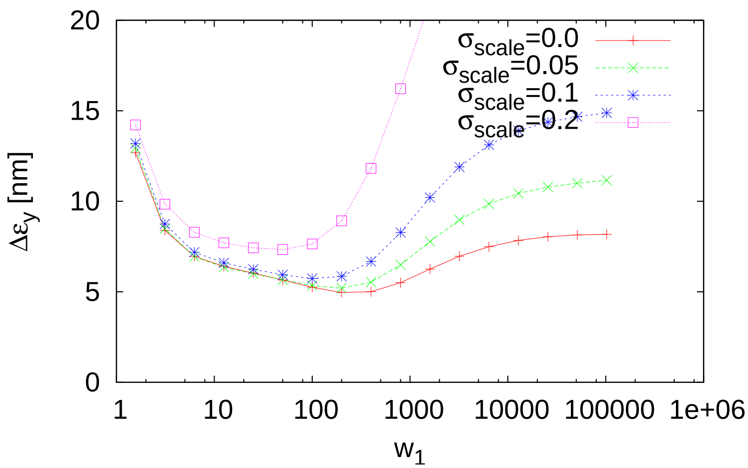
at a given BPM

BPM Calibration Error

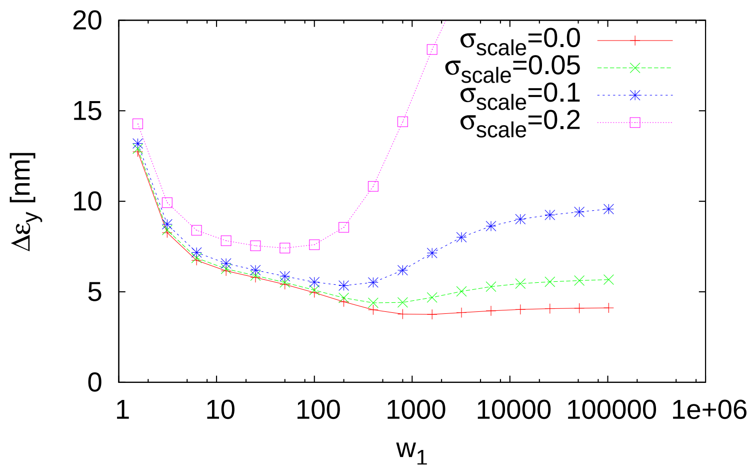
- Emittance growth as a function of the weight ω_1 $(\omega_0 = 1)$ for different calibration errors σ_a

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

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



(BPM resolution 10 μm)

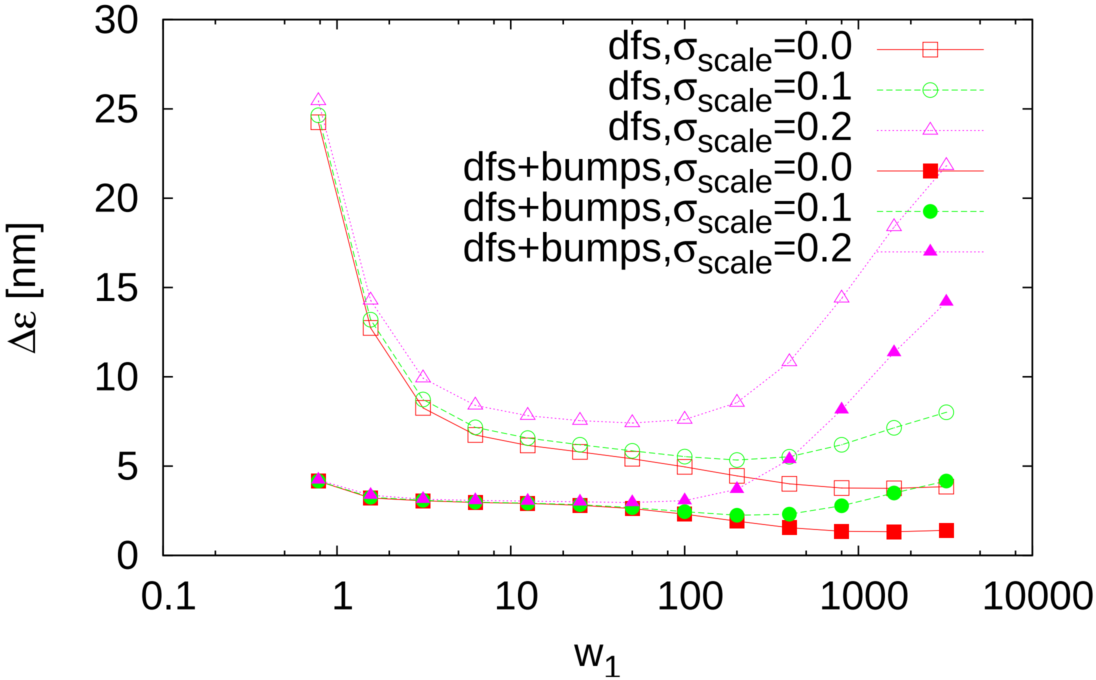


(BPM resolution 1 μm)

$\Rightarrow$ 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

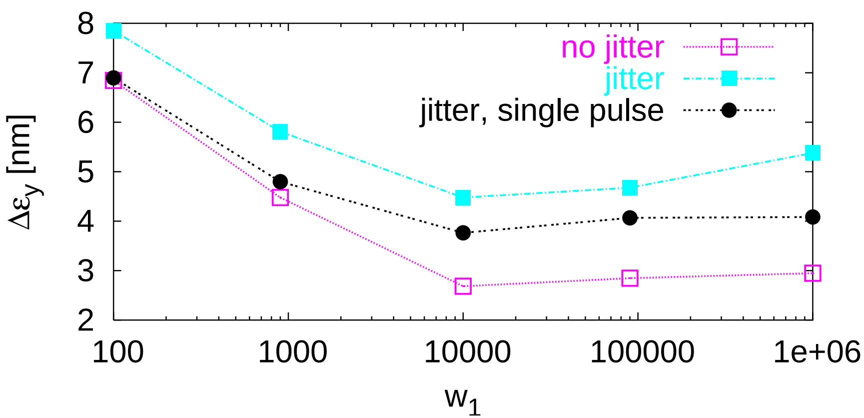
- Emittance tuning bumps can significantly reduce the emittance growthhey are likely required already in the laser-straight linac
- We investigated the impact of one dispersion bump before and one after the main linac



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

Emittance Growth due to Quadrupole Jitter

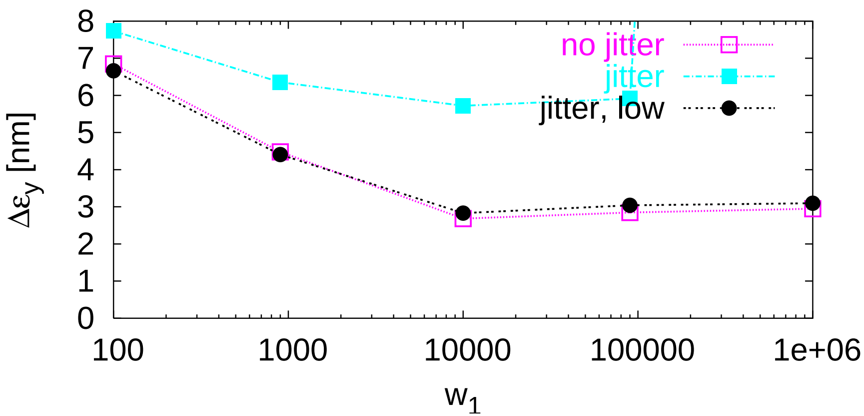
- We expect that the largest impact of dynamics imperfections to arise during DFS
- In this simulation we:
  - used one single test beam
  - assumed that the first three FODO cells were aligned
  - used Dispersion Free Steering
    - 1 test beam, gradient 90%
    - 40 quadrupoles per correction bin, with an overlap of 20
    - each pulse simulated in full detail
- Quadrupole jitter : 500 nm $\Rightarrow$ emittance growth $\boxed{\delta\epsilon_y = 6 \text{ nm}}$



- no jitter = static machine (quadrupole roll gives the largest emittance growth 3 nm - not critical)
- single pulse = gradient changed withing the pulse

Emittance Growth due to RF Gradient Jitter

- We studied the impact of gradient jitter during the acceleration
- We used a -very large- gradient jitter of 5% RMS:
  - for each set of 24 cavities powered by the same klystron
  - gradient error is applied for each beam independently
- Dispersion Free Steering, using the same settings as before
- Additional emittance growth $\boxed{\delta\epsilon_y = 3 \text{ nm}}$



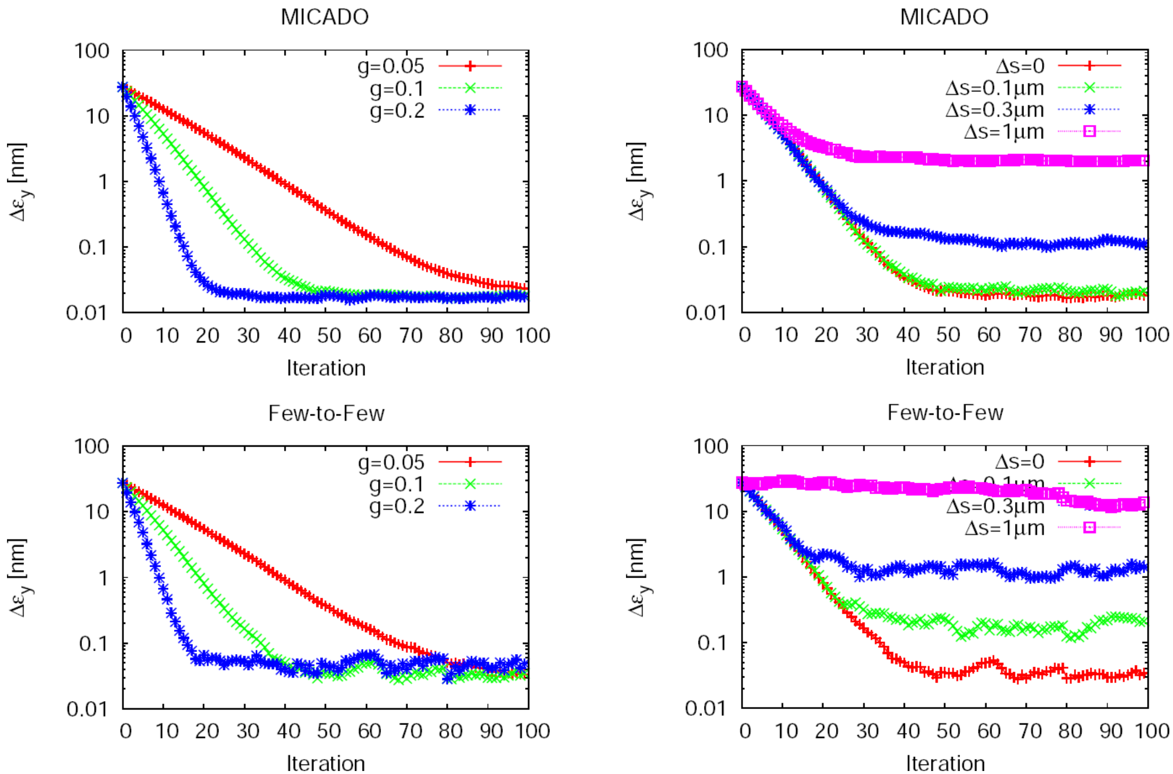
- no jitter = static machine
- low = 1.5 % RMS gradient jitter

$\Rightarrow$ With 1.5 % RMS jitter, the final emittance growth is $\delta\epsilon_y = 0.2$ nm

$\Rightarrow$ the effect is not negligible, but still acceptable

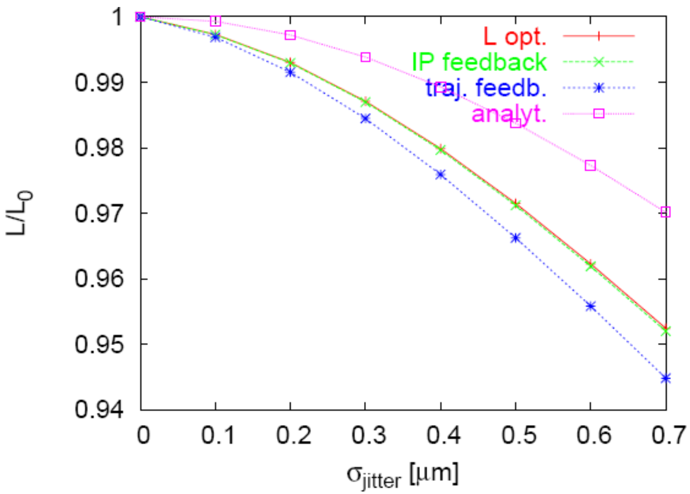
Beam-Based Orbit Correction

- Dynamic imperfections, such as ground motion or vibrations, are cured using BB feedback
- We compare two algorithms for the **orbit correction**:
  - 1-to-1 correction : all correctors and all bpms are used
  - MICADO : a selected number of correctors and bpms is used

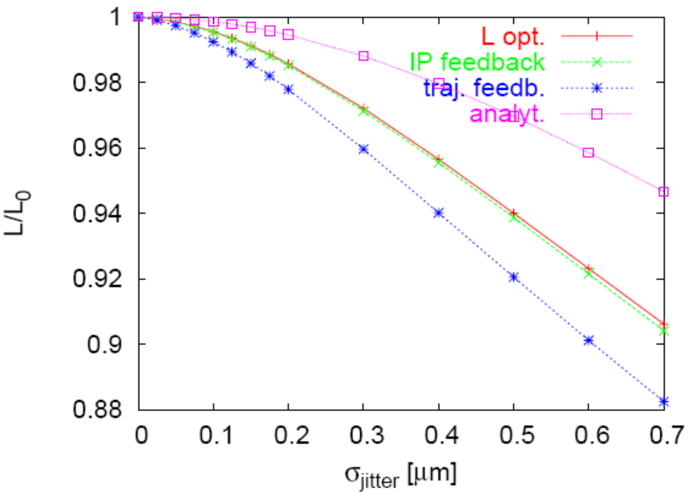


Luminosity Loss Due to Quadrupole Jitter

- 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



(IP vertical emittance 40 nm)



(IP vertical emittance 20 nm)

Conclusions

- PLACET simulations of the ILC main linac have been carried out
- Static Alignment of the LINAC has been performed using beam-based alignment techniques
  - Dispersion Free Steering using the bunch compressor 2 to generate the test beams seems effective both for a curved and laser-straight machine
  - The use of dispersion tuning bumps and wakefields bumps is recommended to achieve the emittance growth goal < 5 nm
  - An optimized set of tuining bumps has been derived using an SVD analysis of the solution space
- Dynamic Effects in the Main Linac have been considered
  - MICADO and 1-to-1 orbit correction algorithms have been compared
  - emittance growth due to quadrupole jitter during the alignment
  - emittance growth due to RF gradient jitter during the alignment
  - luminosity loss due to quadrupole jitter with and without beam-beam feedback correction

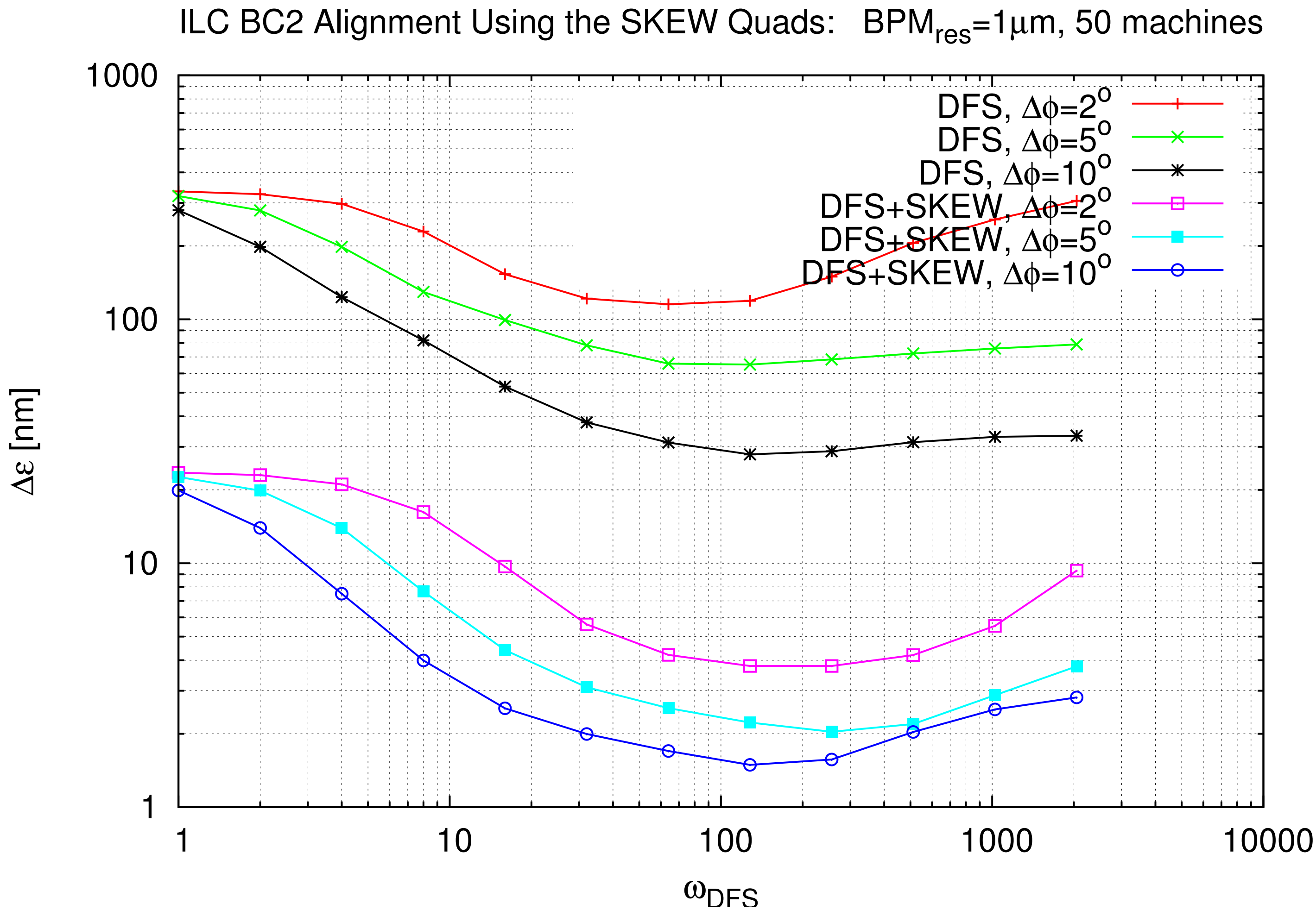
Bunch Compressor 1 used to align Bunch Compressor 2

- 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

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

$\Rightarrow \phi_0 = 110$ deg

$\Rightarrow$ $E_0 \simeq 4.79$ GeV



	$\Delta\phi = \pm 2^o$	$\Rightarrow$	3.7 nm
$\Rightarrow$ Final emittance growth after DFS and SKEW quad optimization	$\Delta\phi = \pm 5^o$	$\Rightarrow$	2.0 nm
	$\Delta\phi = \pm 10^o$	$\Rightarrow$	1.5 nm

Case 2: alignment of BC1 and BC2 at once

- the BC is aligned at once : the phase offset is applied to **all** cavities

  ...using DFS and SKEW quad optimization

  - the RF phase of all accelerating structures is offset by few degrees

    $\Rightarrow$ thus the bunches gain different acceleration $\Rightarrow$ this can be exploited by DFS

    $\Rightarrow$ the energy difference grows along the BC (efficacy of DFS grows along the lattice)

  - all 4 pairs of SKEW quadrupoles are used for dispersion reduction

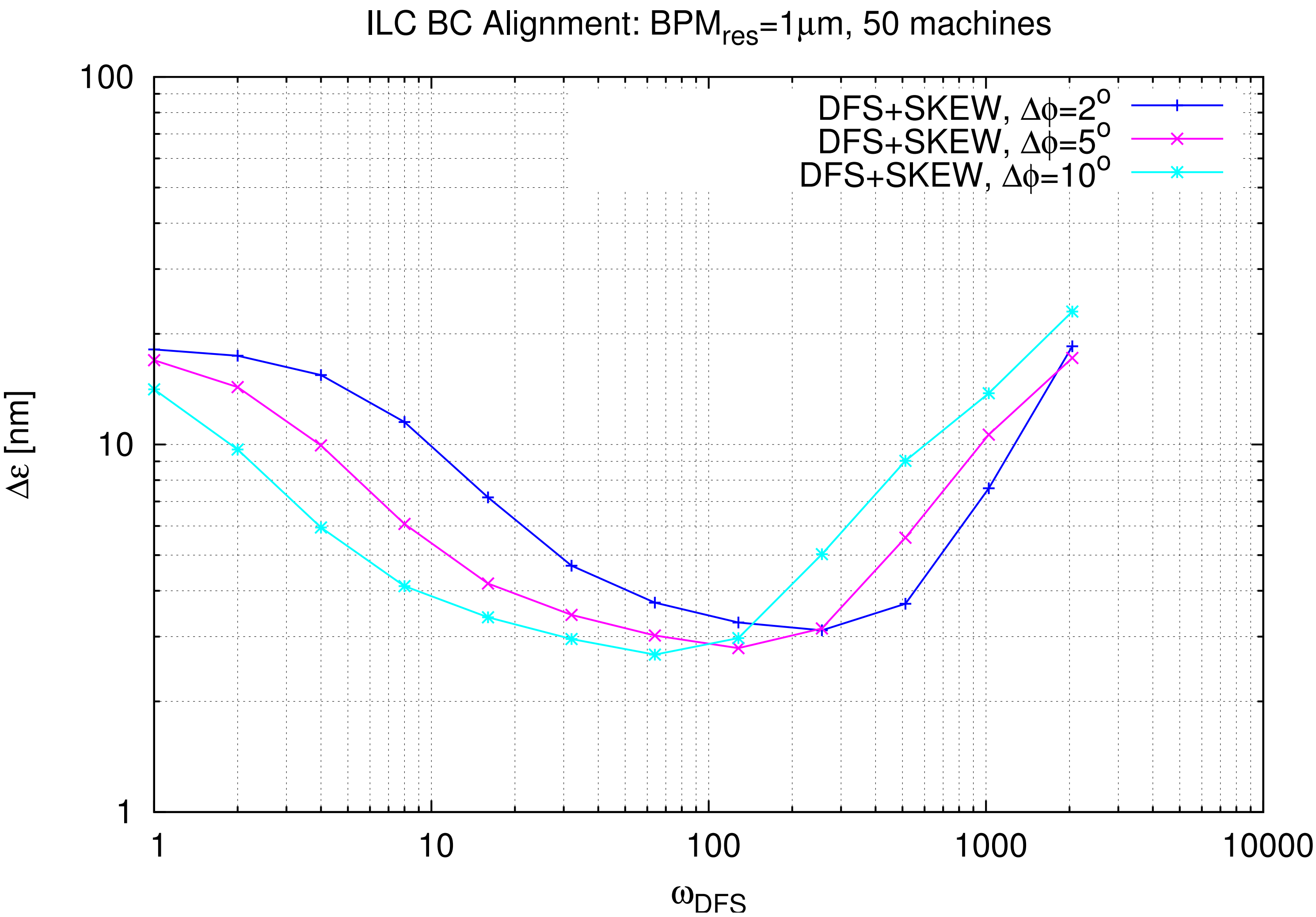
- Results:

  $\Rightarrow$ Final emittance growth after DFS and SKEW quad optimization

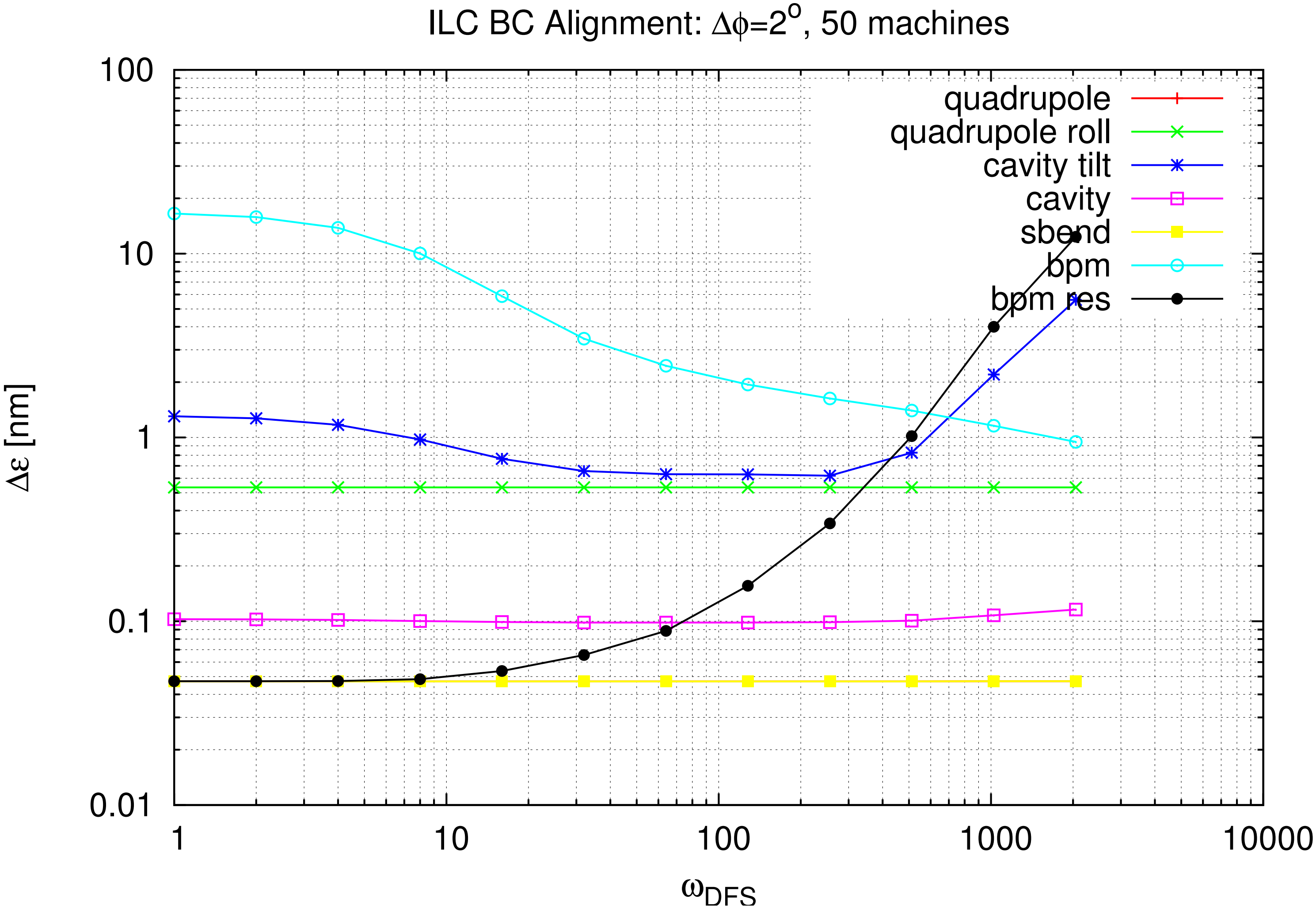
$$
\begin{array}{lcl}
\Delta\phi = \pm 2^o & \Rightarrow & \text{3.12 nm} \\
\Delta\phi = \pm 5^o & \Rightarrow & \text{2.79 nm} \\
\Delta\phi = \pm 10^o & \Rightarrow & \text{2.68 nm}
\end{array}
$$

  $\Rightarrow$ A study of each single source of misalignment was performed

  All results are the average of 50 machines



ILC BC Alignment: BPM$_{res}$=1μm, 50 machines
DFS+SKEW, Δφ=2^o
DFS+SKEW, Δφ=5^o
DFS+SKEW, Δφ=10^o
Δε [nm]
ω_{DFS}
100
10
1
1
10
100
1000
10000



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