ILC Single Stage Bunch Compressor Studies

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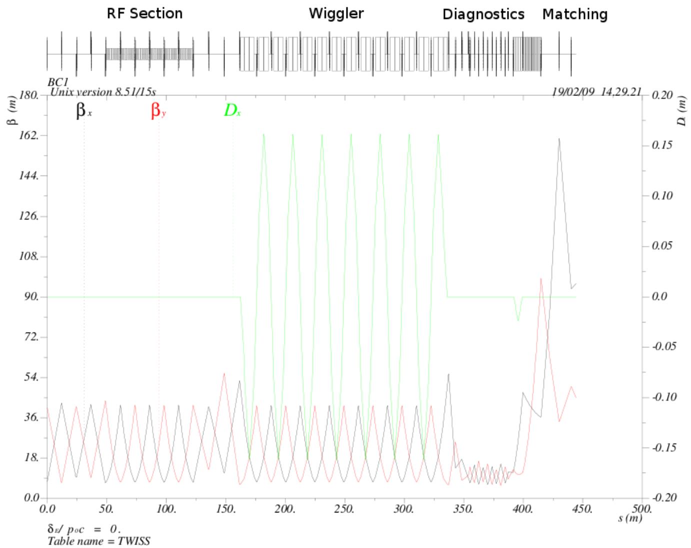
ILC LET Beam Dynamics - Phone Meeting

- Summary of BC1S Design and Status
- Beam Dynamics Case: impact of misalignments, coupler kicks
- Emittance Preservation Techniques: BBA, girder pitch, crab cavities correction
- Conclusions and Future Plans

BC1S - Optics and General Description

- Based on the original design at 5 GeV by PT in April 2005:

`http://www-project.slac.stanford.edu/ilc/acceldev/LET/BC/OneStageBC.html`



- six cryomodules for RF acceleration

- 6-cells *Raubenheimer-type* wiggler: a *single bend magnet* between quads in a *6-cells FODO lattice*

⇒ NEW sections added:

(1) beam diagnostics and extraction, adapted from BC2

(2) booster linac from 5 to 15 GeV

Design Characteristics

- The beam properties at injection are:

Charge	2e10 (3.2 nC)
Energy	5 GeV
Energy spread	0.15% (actually 0.13% from Damping Ring)
Bunch Length	6 mm

- Properties of the bunch compressor are:

Integrated voltage	1275.2 MV @ 1.3 GHz
Cavity gradient	≈25.6 MV/m
Accelerating Structures	48 (6 cryomodules; old-type : quadrupole is at the END)
Phase	-119.5 degrees
Energy Loss	627.9 MeV
R_{56}	-147.5 mm
Total length	434 m

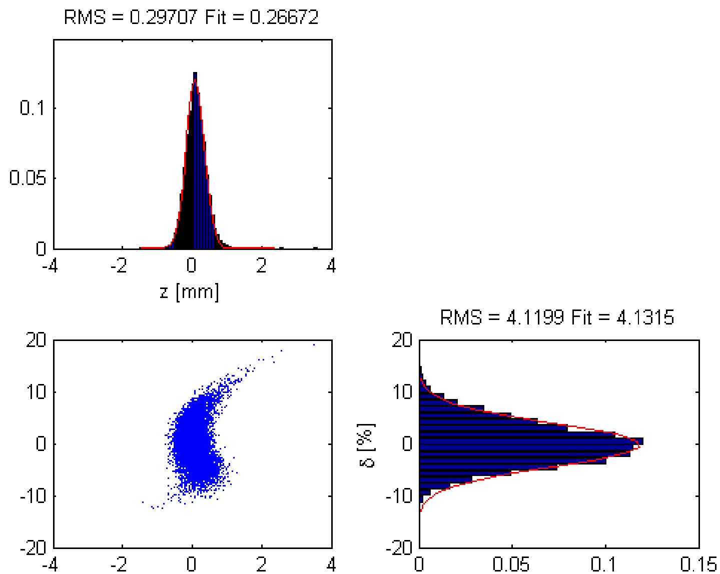
⇒ Desired final bunch length : 0.3 mm

⇒ Desired energy spread at ML entrance (baseline): 1.07%

Design Beam Profile and Optimization

- Nominal beam parameters at exit
  - blength $= 266\ \mu$m ($300\ \mu$m)
  - energy $= 4.3797$ GeV
  - espread $= 4.13$ %

$\Rightarrow$ espread @ 15 GeV $\simeq 1.2\%$ (1.07%)



- Optimization to reach nominal values at ML entrance
  - simplex on (1) **rf gradient**, (2) **rf phase**, (3) **wiggler** R_{56}
  - minimization of the following merit function

$$M = \left(1 - \frac{\Delta E/E}{1.07\%}\right)^2 + \left(1 - \frac{\sigma_z}{300\mu\mathrm{m}}\right)^2 + 10 \cdot \mathrm{corrcoeff}(\{\mathrm{E}\},\{\mathrm{z}\})^2$$

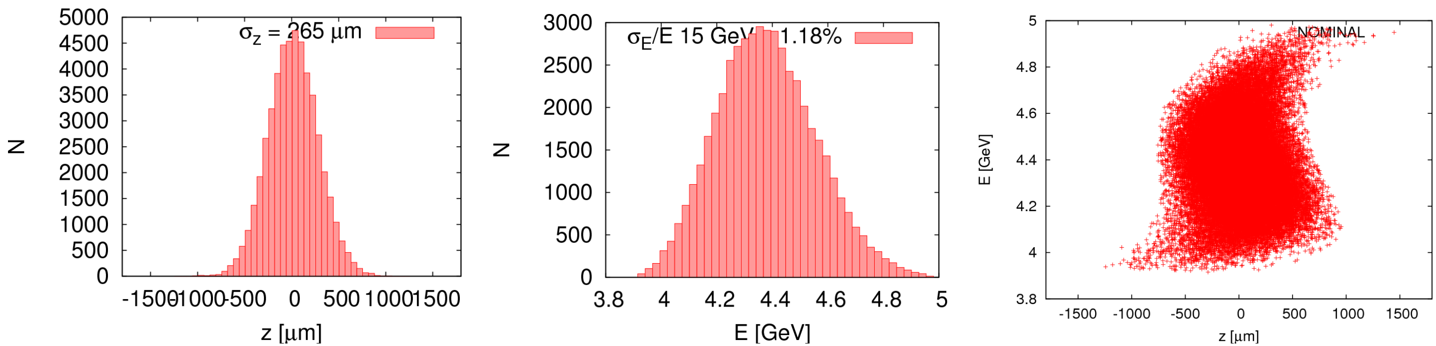
$\Rightarrow$ convergence is *good* $\rightarrow$ we played with the coefficient of correlation

Phase Space Before and After Optimization

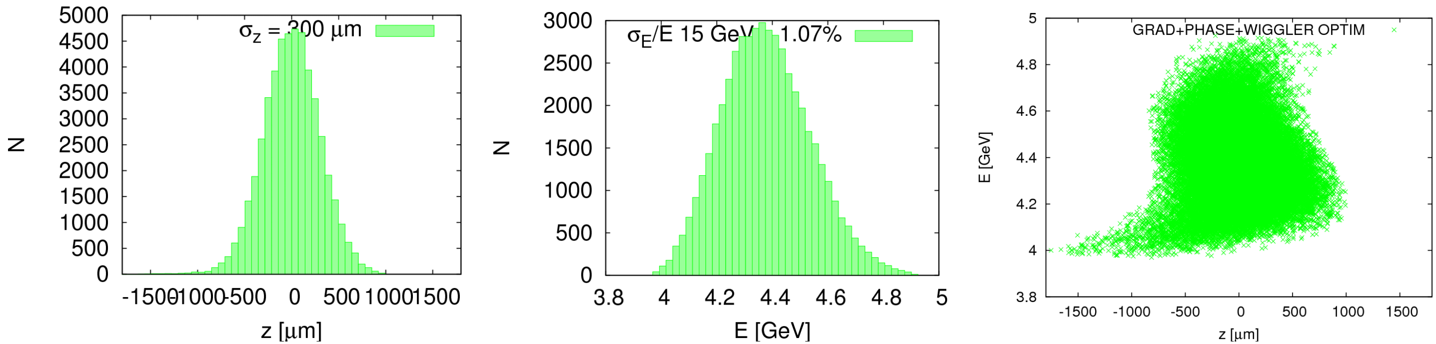
- Before optimization
  - Bunch length = 265 μm
  - energy spread = 4.13 %
  - energy spread @ 15 GeV = 1.18 %

- After optimization
  - Bunch length = 300 μm
  - energy spread = 3.54 %
  - energy spread @ 15 GeV = 1.07 %

$\Rightarrow$ Before



$\Rightarrow$ After



Beam Dynamics Study Cases

- Effect of **element misalignments** and correction
  - "COLD" model

$$
\begin{array}{lcll}
\sigma_{\mathrm{quad}} & = & 300\ \mu\mathrm{m} & \text{quadrupole position error} \\
\sigma_{\mathrm{quad\ roll}} & = & 300\ \mu\mathrm{rad} & \text{quadrupole roll error} \\
\sigma_{\mathrm{cav}} & = & 300\ \mu\mathrm{m} & \text{cavity position error} \\
\sigma_{\mathrm{cav\ pitch}} & = & 300\ \mu\mathrm{rad} & \text{cavity pitch error} \\
\sigma_{\mathrm{sbend\ angle}} & = & 300\ \mu\mathrm{rad} & \text{sbend angle error} \\
\sigma_{\mathrm{bpm}} & = & 300\ \mu\mathrm{m} & \text{bpm position error}
\end{array}
$$

  - Bpm resolution error: $\sigma_{\mathrm{bpmres}} = 1\ \mu\mathrm{m}$

  $\Rightarrow$ Two cases have been studied:
    - all misalignments applied at the same time
    - each individual contribution at once

- Effect of **couplers RF-Kick and Wakes**

  $\Rightarrow$ impact and cure using
    - beam-based alignment
    - girder pitch optimization
    - crab cavity calibration

Emittance Preservation Procedure

- **Beam-Based Alignment**
  - 1-to-1 Correction
  - Dispersion Free Steering
    - a $\pm 5^o$ phase offset is applied to the RF cavities of the BC1S in order to generate the energy difference for the DFS's test beams
    - the test beams are synchronized to the BOOSTER's RF phase at the BOOSTER entrance
  - [*in progress*] Girder pitch optimization / Crab cavity compensation
  - Dispersion bumps optimization
    - two dispersion bumps: one at the entrance and the other at the exit of BC1S
    - as there are no skew quadrupoles in the lattice (yet), we used two *ideal* bumps

$$y_{i(\mathrm{new})} = y_{i(\mathrm{old})} + \underline{\eta} \frac{E_i - E_0}{E_0}$$

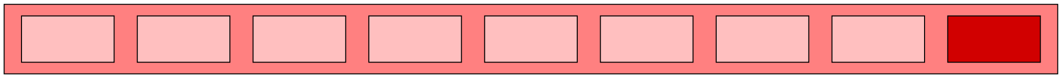
- **Reminder**: Dispersion Free Steering

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

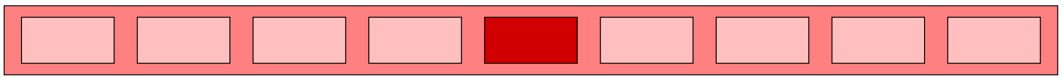
$\Rightarrow$ we make a scan of the weight $\omega_{1,j}$ to find the optimum

Girder Pitch Optimization

- Compensate the emittance growth by rotating the girders in the plane $yz \rightarrow$ tilted cavities induce a transverse kick that is used to correct
- We deal with two cryomodule designs
  1. Old, like in the current design of BC1S: quadrupole at the end



  2. New, like in the design of BC1+BC2: quadrupole in the middle

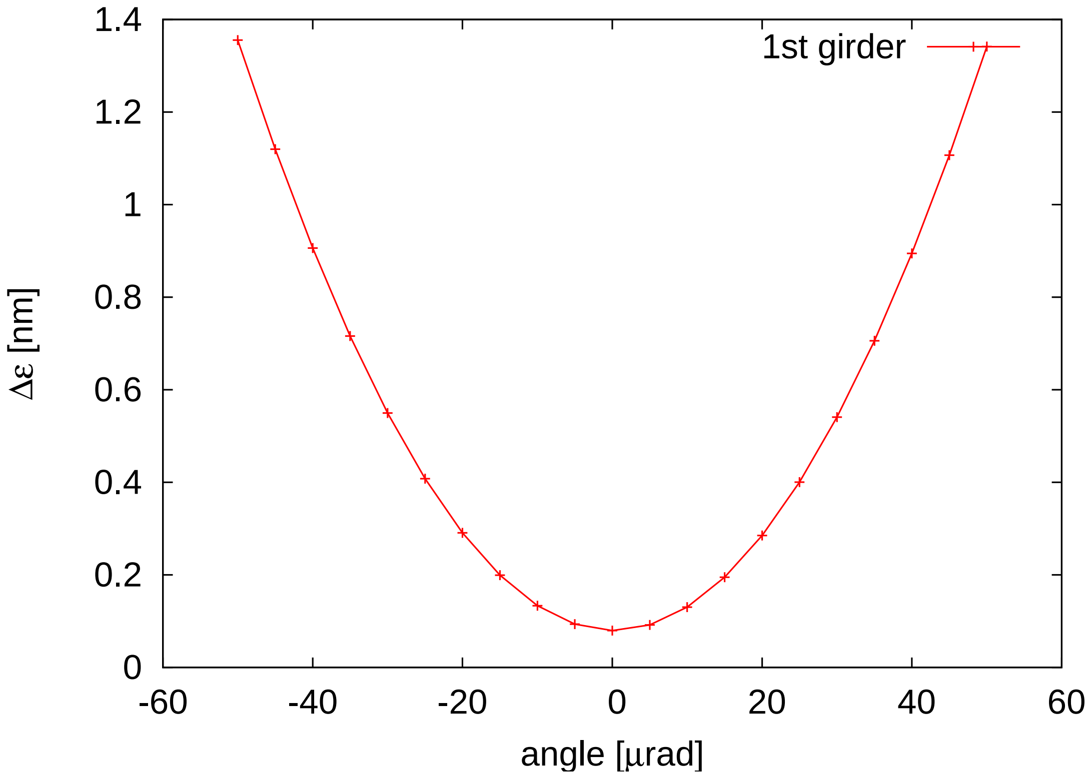


$\Rightarrow$ Rotation must happen **around** the quadrupole

$\Rightarrow$ It is a non-local compensation. Emittance is measured and minimized at the end of the line.

Vertical Emittance as a Function of the Girder Pitch

⇒ Example: final vertical emittance in BC1S for a perfectly aligned line, as a function of the 1st girder rotation



⇒ it might work..

Crab Cavity Optimization

- We inserted a thin Crab Cavity at the end of each cryomodule
  - 6 crab cavities in total
- Each Crab Cavity provides two knobs:
  - voltage
  - phase
- It seems a natural solution → RF-Kicks are simulated using a Crab Cavity

⇒ It is a non-local compensation. Emittance is measured and minimized at the end of the line.

⇒ 12 knobs to optimize

- The effect might be equivalent to the previous method but
- notice: this is only a *feasibility test*!
  - an actual implementation of this method would require the modification of the entire RF section of the BC1S

  ⇒ because each cryomodule should host a crab cavity at the cost of one accelerating cavity and we would need an additional cryomodule

Simulation Setup and Results

- **Beam properties** at injection are:
  - Charge: 2e10 (3.2 nC)
  - Energy: 5 GeV
  - Energy spread: 0.15%
  - Bunch Length: 6 mm
  - Beam model : 50000 single-particles
- **Tracking Setup**

  $\Rightarrow$ short-range wakefields in the cavities are taken into account

  $\Rightarrow$ bending magnets are simulated with 100 thin lenses (because of the strong non linearity)

  $\Rightarrow$ incoherent synchrotron radiation is turned on

  $\Rightarrow$ full 6d tracking in whole bunch compressor
- **Simulation Procedure**

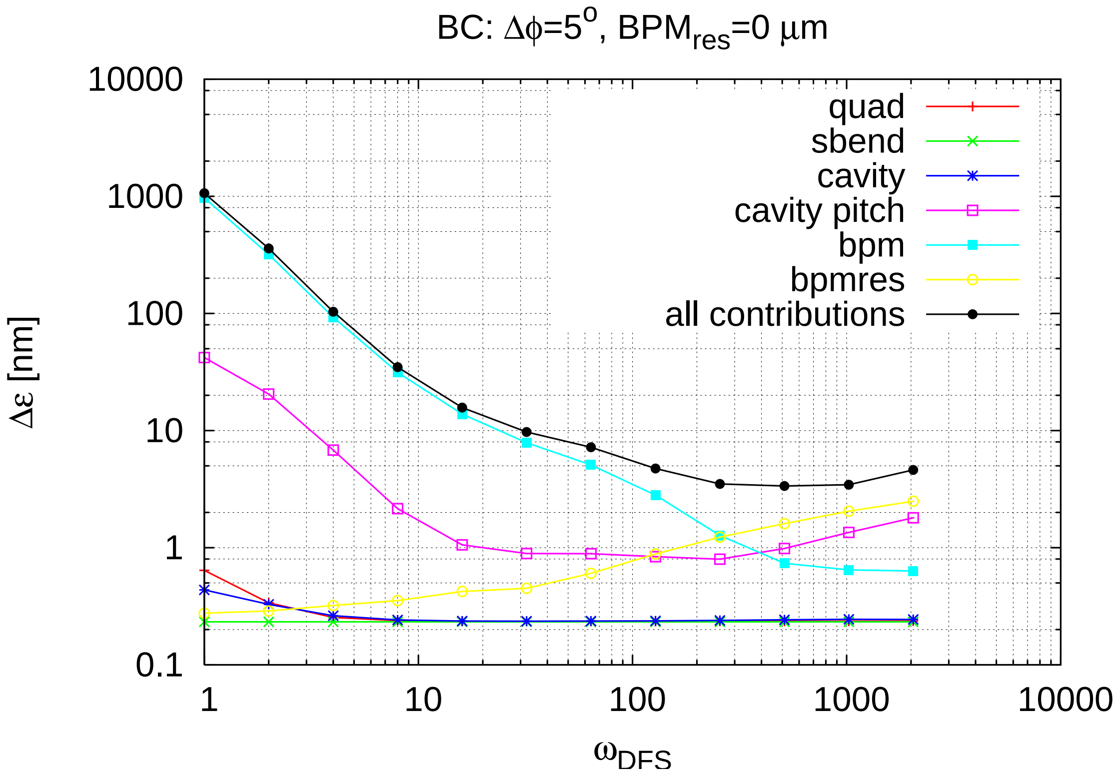
  $\Rightarrow$ misalignments applied to BC1S+BOOSTER

  $\Rightarrow$ scan of the DFS's weight ω

  $\Rightarrow$ 40 machines (i.e. random seeds) have been simulated for each case

Emittance Growth due to Misalignments

- Final vertical emittance growth as a function of ω

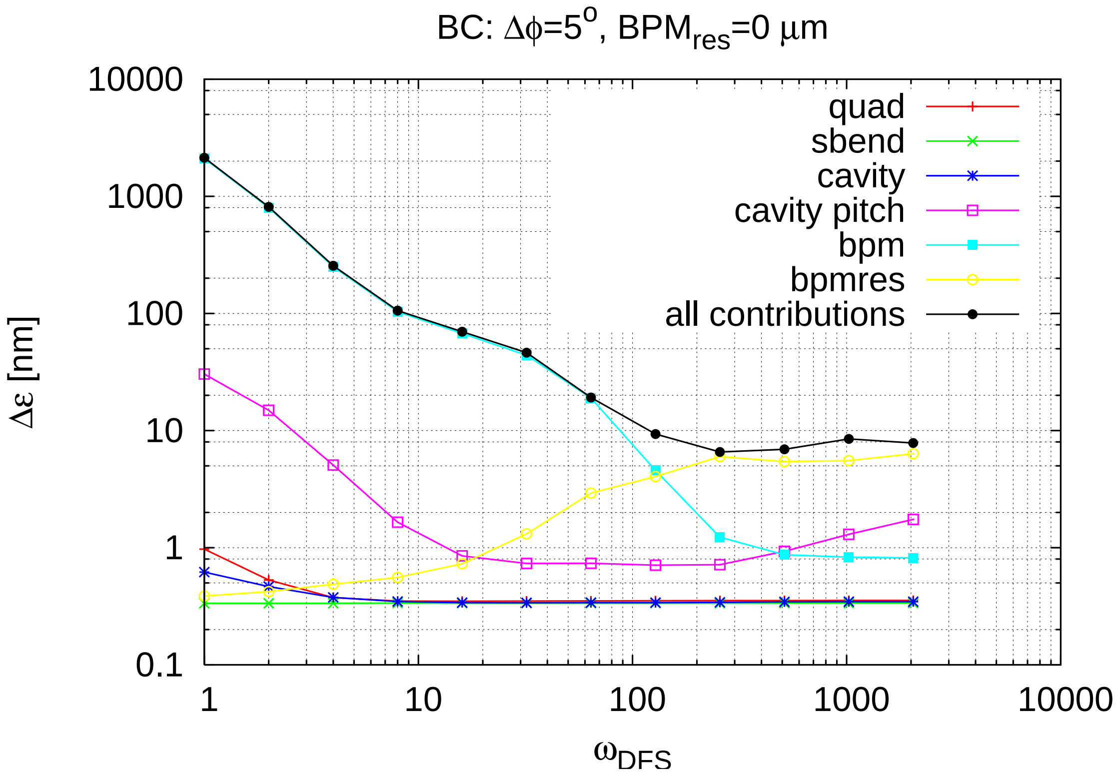


$\Rightarrow$ Minimal vertical emittance growth, for ω=512, $\boxed{\Delta\epsilon = 3.37 \text{ nm}}$

$\Rightarrow$ Large contributions from BPM misalignment and BPM resolution

Emittance Growth due to Misalignments, 100 machines

- Final vertical emittance growth as a function of ω

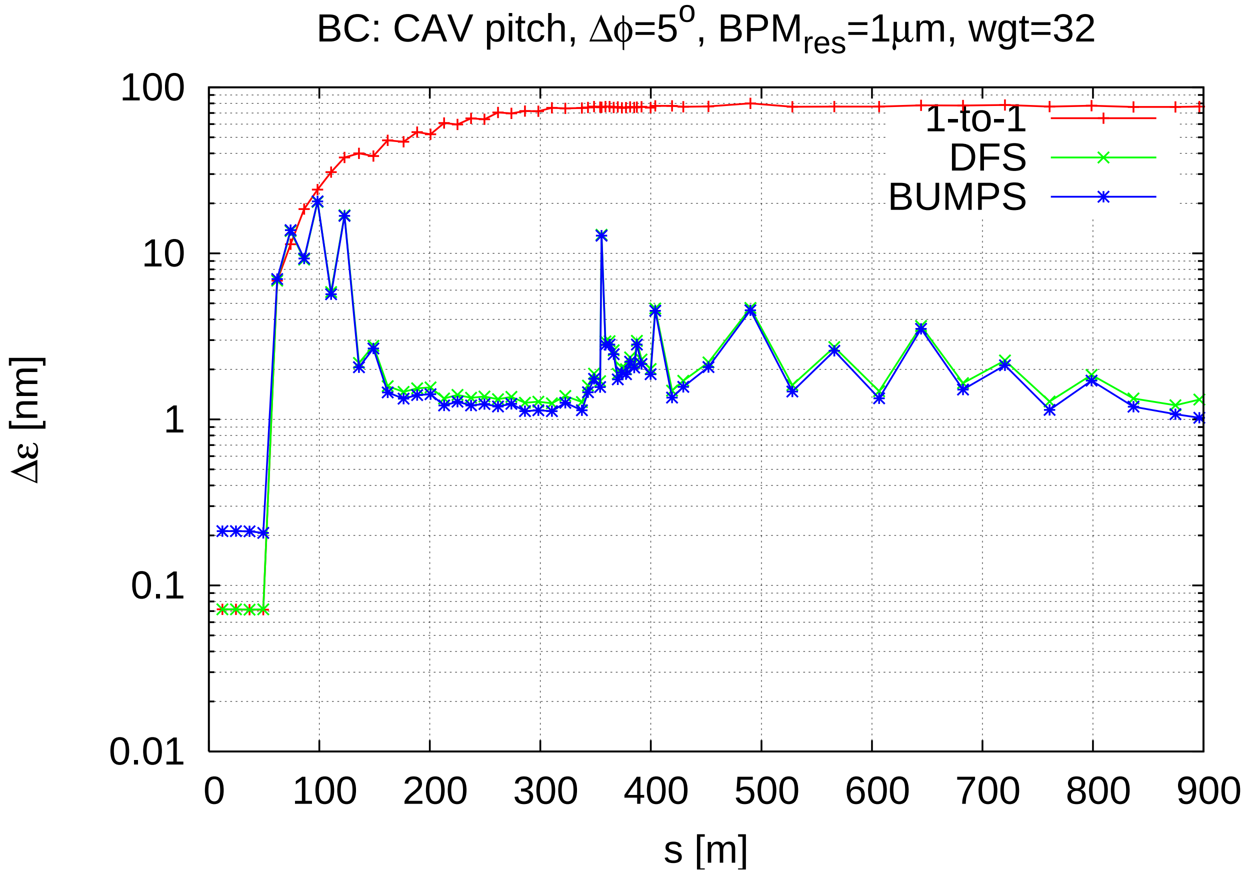


⇒ Minimal vertical emittance growth, for ω=256, $\boxed{\Delta\epsilon = 6.5 \text{ nm}}$

⇒ Large contributions from BPM misalignment and BPM resolution

Vertical Emittance Growth due to Cavity Pitch

- Emittance Growth along the line, average of 40 machines



⇒ In this case, final vertical emittance growth is 1 nm

Summary Table of Vertical Emittance Growths

- For $w = 512$ and each individual misalignment

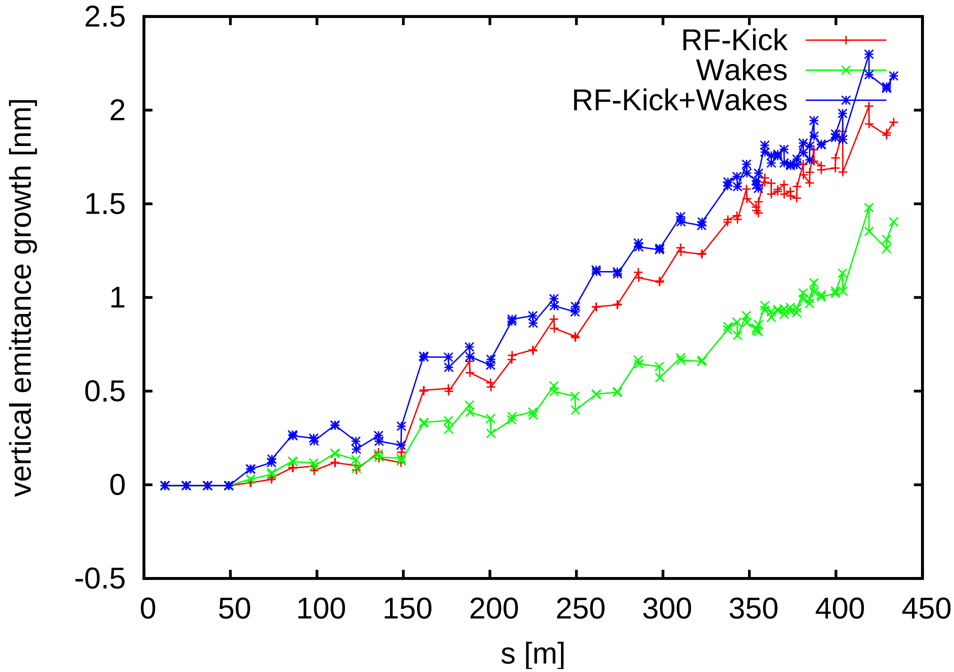
Misalignment	$\Delta\epsilon_y$
bpm position	0.74 nm
cavity position	0.24 nm
quadrupole position	0.24 nm
sbend position	0.23 nm
cavity pitch	0.98 nm
bpm resolution	1.60 nm
TOTAL	**3.37 nm**

$\Rightarrow$ Actually, the SUM of all contributions would be 4.03 nm, not 3.37 nm, but this is an OVERESTIMATION, since it does not include the coupling between all effects

Coupler Kicks: RF-Kick and Wakefields

- We consider the impact of coupler wakes and RF-kick in BC1S

- and its correction using 1-to-1 steering and dispersion bumps

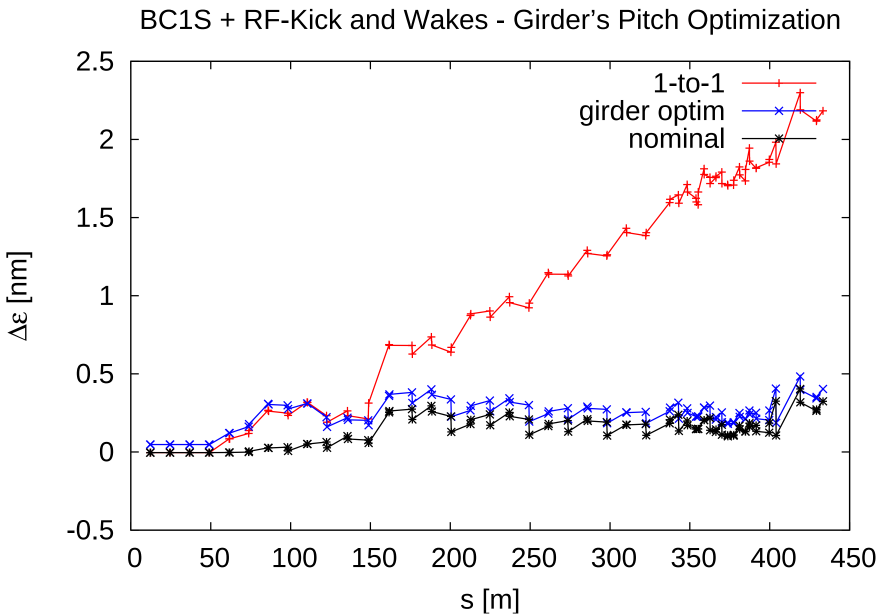


$\Rightarrow$ Final vertical emittance growth is 2.2 nm

$\Rightarrow$ We want to do better $\Rightarrow$ **Girder Pitch Optimization**

Girder Pitch Optimization Result

- All 6 girders are moved at the same time in order to minimize the final emittance



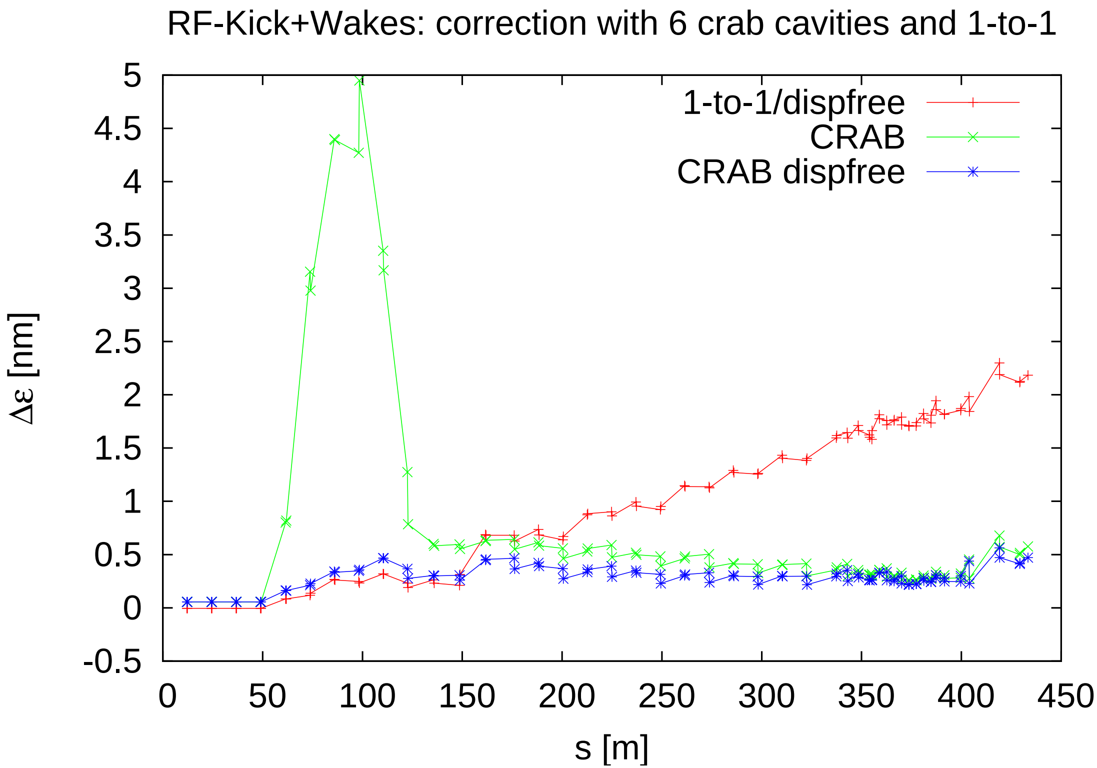
- Angles of the girders (and vertical displacements of the two ends) are the following

girder	1	2	3	4	5	6
angle [μrad]	18.0499	8.8699	25.6944	-2.7834	-29.5327	-1.6109
Δy [μm]	220.209	108.213	313.472	-33.958	-360.299	-19.653

$\Rightarrow$ Final vertical emittance growth is 0.4 nm

CrabCavity Correction Result

- One Crab Cavity is put at the end of each cryomodule
- 1-to-1 correction + Crab Cavity correction (simplex tuning voltage and phase) + dispersion bumps



⇒ Final vertical emittance growth is 0.47 nm

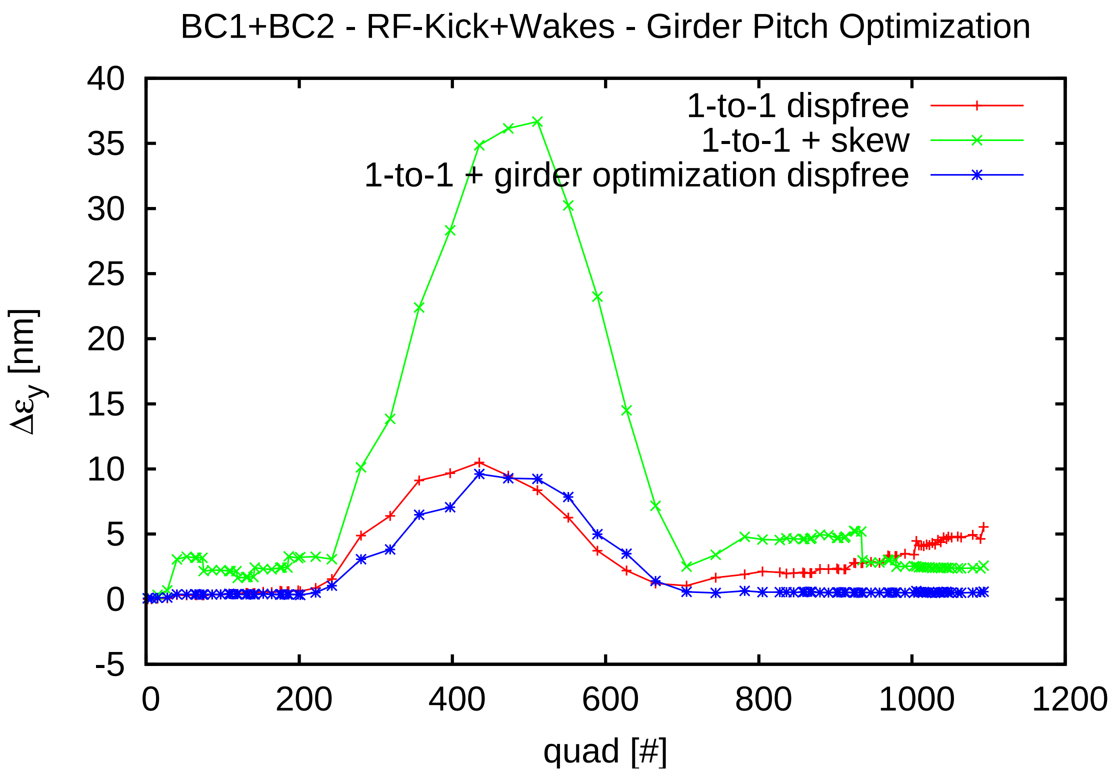
CrabCavity Correction Result

- Voltage and phase of the crab cavities after the optimization are the following

crab cavity [#]	voltage [kV]	phase [deg]
1	-472.5025	0.162373
2	-658.0585	-0.927942
3	240.7833	-0.975989
4	-3.3140	0.032526
5	4.1073	0.773033
6	-10.5209	1.842551

Extra: Girder Pitch Optimization Applied to BC1+BC2

- Girder Pitch Optimization has been applied to BC1+BC2
- optimization with 48 cryomodules, rotation around the center of the cryomodule



⇒ Without optimization the final vertical emittance growth is 5.5 and 2.5 nm, with optimization 0.58 nm

Summary Table of Vertical Emittance Growths

- For RF-Kick and Wakefields induced by the Couplers

⇒ BC1S

Correction algorithm	$\Delta\epsilon_y$ RF-Kick	$\Delta\epsilon_y$ Wakes	$\Delta\epsilon_y$ Total
1-to-1 correction + bumps	1.9 nm	1.4 nm	2.2 nm
crab cavity correction + bumps	-	-	0.47 nm
girder pitch optimization + bumps	-	-	0.4 nm

⇒ BC1+BC2

Correction algorithm	$\Delta\epsilon_y$ RF-Kick	$\Delta\epsilon_y$ Wakes	$\Delta\epsilon_y$ Total
1-to-1 correction / dispersion free	1.59 nm	2.8 nm	5.5 nm
1-to-1 correction + skew quadrupoles	-	-	2.5 nm
girder pitch optimization / dispersion free	-	-	0.58 nm

Conclusions and Work Plan

- Emittance growth due to misalignments seems to be dominated by BPM misalignments and BPM resolution errors, further studies are required

- Girder Pitch optimization is very effective to counteract coupler kicks, both for BC1S and BC1+BC2
- In BC1S, Crab Cavity Option seems to be similarly effective, but it would require a slight redesign of the RF stage

- To Do List:
  ⇒ Replace the current Wiggler with the schema presented by *Seletskiy, Tenenbaum* at PAC 2007
    - they have equivalent cell length ($\sim$ 24 meters) but,
    - at cost of more elements, the new schema allows more flexibility:
    - skew quadrupoles, coupling correction, ...

  ⇒ Replace the crymodules with modern ones

⇒ Detailed Study of Girder Pitch Optimization to cure misalignments