ILC Single Stage Bunch Compressor Studies

Andrea Latina (FNAL)

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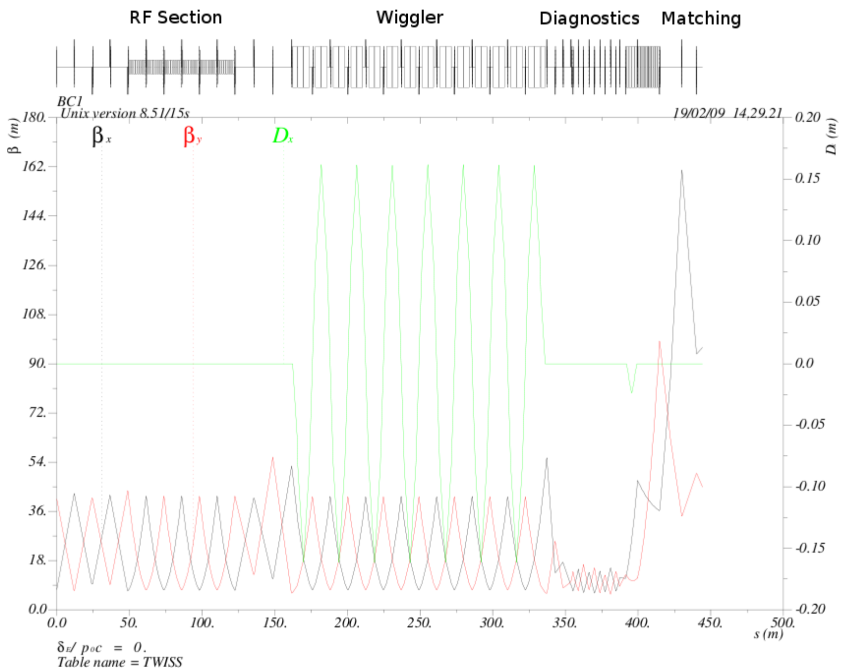
ILC LET Beam Dynamics - Phone Meeting

- Description of BC1S and Update
- Beam Dynamics Simulations (misalignments, coupler kicks)
- Conclusions and Work Plan

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

⇒ **NEW!** beam diagnostics section and extraction kickers, adapted from BC2 + 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)
  - Phase: -119.5 degrees
  - Energy Loss: 627.9 MeV
  - R_{56}: -147.5 mm

$\Rightarrow$ Desired final bunch length: 0.3 mm

$\Rightarrow$ Energy spread at ML entrace (baseline): 1.07%

BC1S Single Stage Schematics

- AHEAD : turnaround, spin rotator, emittance measurement station, beam diagnostics
- BC1S is composed by the following consecutive parts
  - **BC0** : entrance
  - **BC1 RF** : RF section, 6 CM, 48 accelerating structures, $\sim$ 75 meters
  - **BC1 RF2WIG** : matching section from RF to wiggler
  - **BC1 WIGGLER** : 6-cells, $\sim$ 24 meters long each

  - **BC1WIG2DIAG** : matching section to diagnostics
  - **BC2 DIAG** : 4 laserwires, phase monitor, bunch length monitor (LOLA cavity)
  - **BC2 ML_1** : kickers to the extraction line
  - **BC2_ML_2** : matching section to main linac FODO

  - **BC1BOOSTER** : accelerating section from 5 to 15 GeV, adapted from ML ILC2007b

$\Rightarrow$ Total length is now : 896.34 m

BC1S vs BC1+BC2

BC1S: total length = 896.34 m

BC1STAGE	number	unit	total
units	2	-	2
gradient	25.6 MV/m	-	-
cryo-modules	2×(CMQ-CMQ-CMQ)	-	6
quadrupoles	45	-	45
bpms	45	-	45
acc structures	2×(8+8+8)	-	48
length	433.37	m	433.37

BC1S_BOOSTER	number	unit	total
units	12	-	12
gradient	31.5 MV/m	-	-
cryo-modules	12×(CM-CMQ-CM)	-	36
quadrupoles	12	-	12
bpms	12	-	12
acc structures	12×(9+8+9)	-	312
length	462.97	m	462.97

BC1+BC2: total length = 1093.5 m

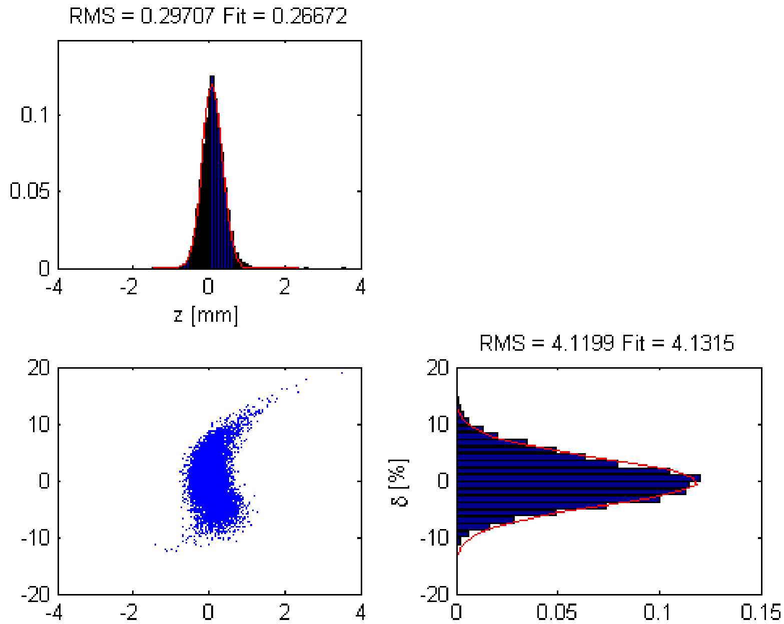
BC1	number	unit	total
units	1	-	1
gradient	18.0 MV/m	-	-
cryo-modules	(CMQ-CMQ-CMQ)	-	3
quadrupoles	29	-	29
bpms	27	-	27
acc structures	$(8+8+8)$	-	24
length	221.8	m	221.8

BC2	number	unit	total
units	15	-	15
gradient	30.2 MV/m	-	-
cryo-modules	15×(CM-CMQ-CM)	-	45
quadrupoles	29	-	29
bpms	27	-	27
acc structures	$15\times(9+8+9)$	-	390
length	871.66	m	871.66

Design Beam Profile

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

$\Rightarrow$ espread @ 15 GeV $\simeq$ 1.2%



$\Rightarrow$ Notice that the nominal value of the energy spread at the entrance of the ML is 1.07%

Beam Profile Optimization

- Nominal beam parameters at exit
  - blength $= 266\ \mu$m $\Rightarrow$ we would like 300 μm
  - energy $=$ 4.3797 GeV
  - espread $=$ 4.13 %
  - espread @ 15 GeV $=$ 1.2 % $\Rightarrow$ we would like 1.07 %

  $\Rightarrow$ 300 μm and 1.07 % correspond to the beam parameters for the baseline design

- Cavities' *phase* and *gradient* as well as *wiggler's* R_{56} were scanned to optimize the beam profile at the entrance of the main linac
- Optimization was run to match the following characteristics:
  1. 300 μm bunch length
  2. 1.07% energy spread
  3. minimal correlation coefficient in the longitudinal phase space $E - z$

$\Rightarrow$ Simplex on rf gradient (1), rf phase (2), wiggler angle (R_{56}) (3) to minimize:

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

Beam Profile Optimization Results

- Initial Parameters
  - gradient = 25.6 MV/m
  - espread = 0.15 %
  - blength = 6 mm
  - wiggler angle = 0.03935 rad

- Nominal exit parameters
  - blength = 268.88 μm
  - energy = 4.3797 GeV
  - espread = 4.13 %
  - espread @ 5 GeV = 3.6 %

$\Rightarrow$ Optimization 1

- wiggler not changed
- blength = 301.18 μm
- energy = 4.2897 GeV
- rf gradient = 25.517 MV/m
- rf phase = -124.45
- espread = 3.88789 %
- espread @ 5 GeV = 3.33559 %
- espread @ 15 GeV = 1.11 %

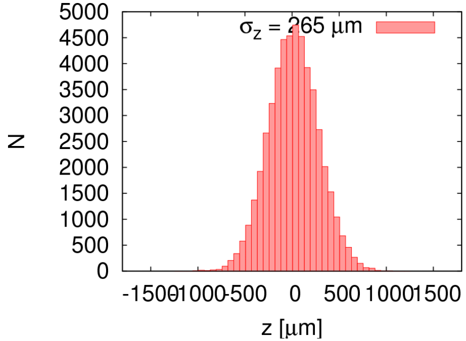
$\Rightarrow$ Optimization 2

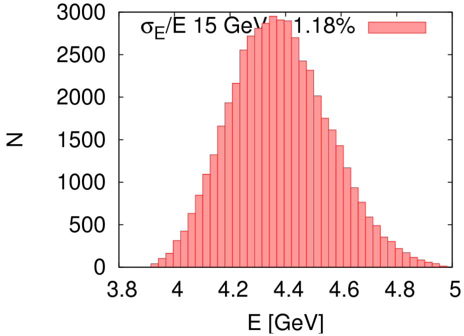
- blength = 301.20 μm
- energy = 4.4143 GeV
- rf gradient = 23.580 MV/m
- rf phase = -122.38
- wiggler angle = 0.042207 rad
- espread = 3.5452 %
- espread @ 5 GeV = 3.12989 %
- espread @ 15 GeV = <u>1.07 %</u>

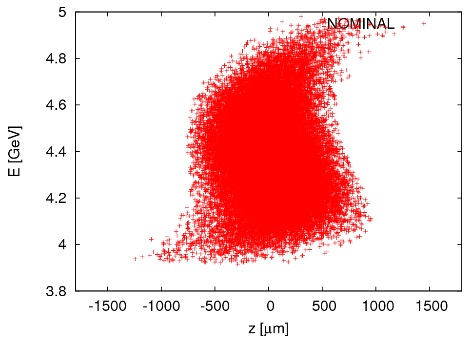
Longitudinal Phase Space Before and After Optimization

- 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 %

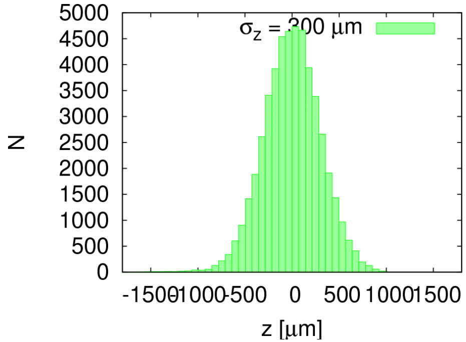
$\Rightarrow$ Before

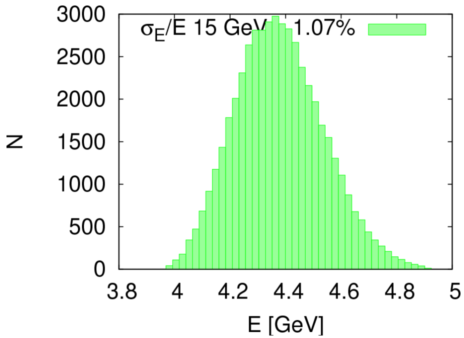


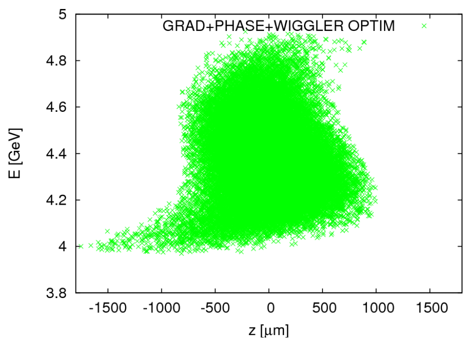




$\Rightarrow$ After

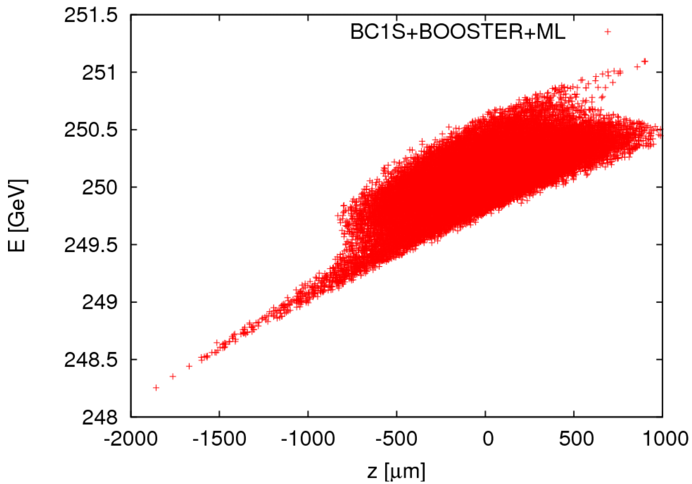


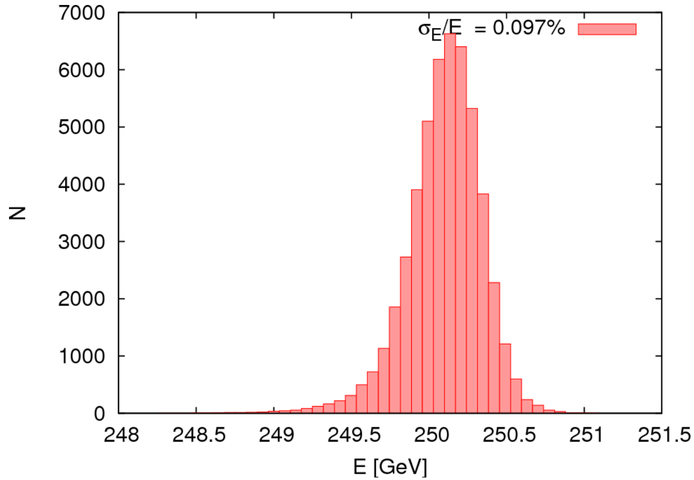


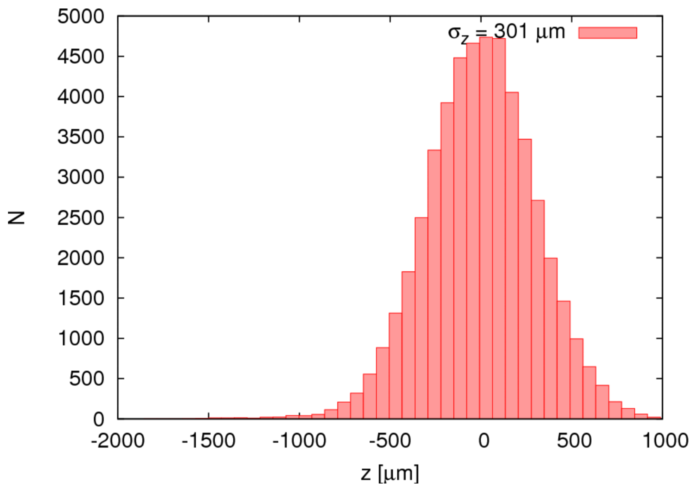


Particle Tracking with Placet

- Beam profile at the end of the Main Linac

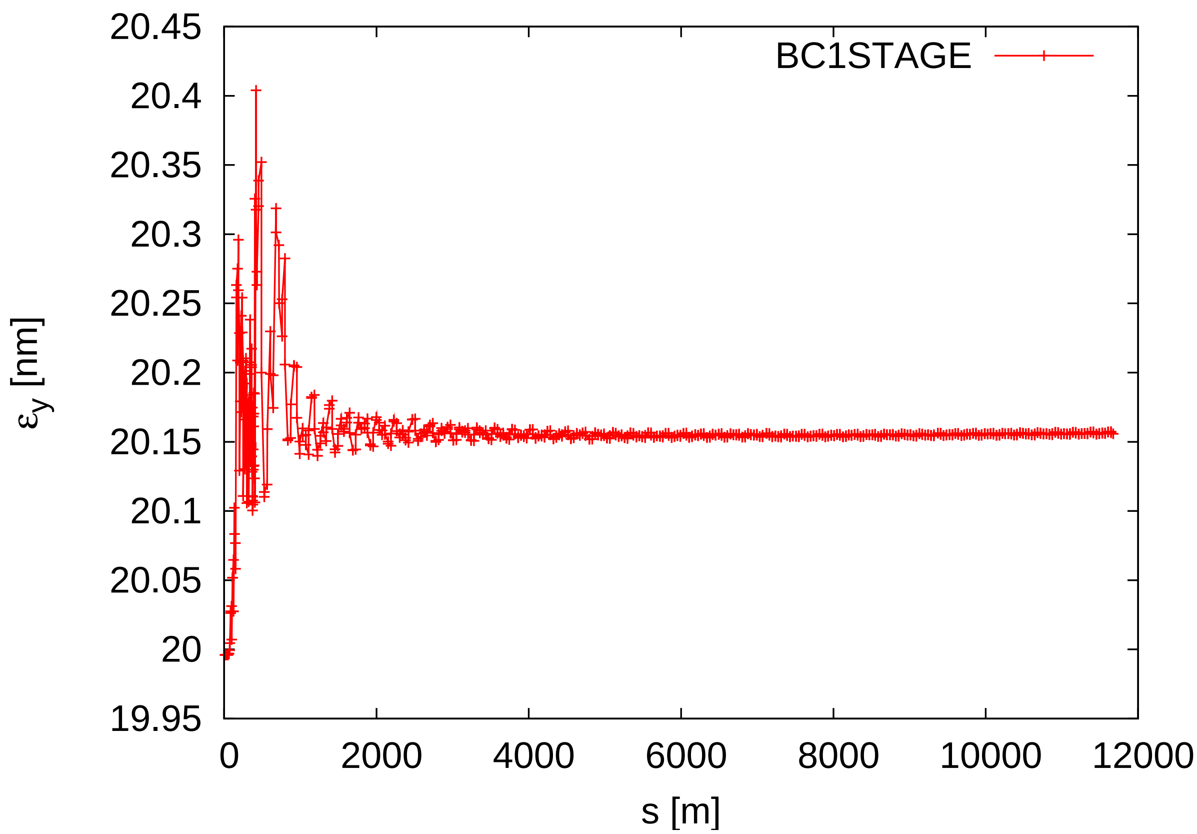






Particle Tracking Using Placet

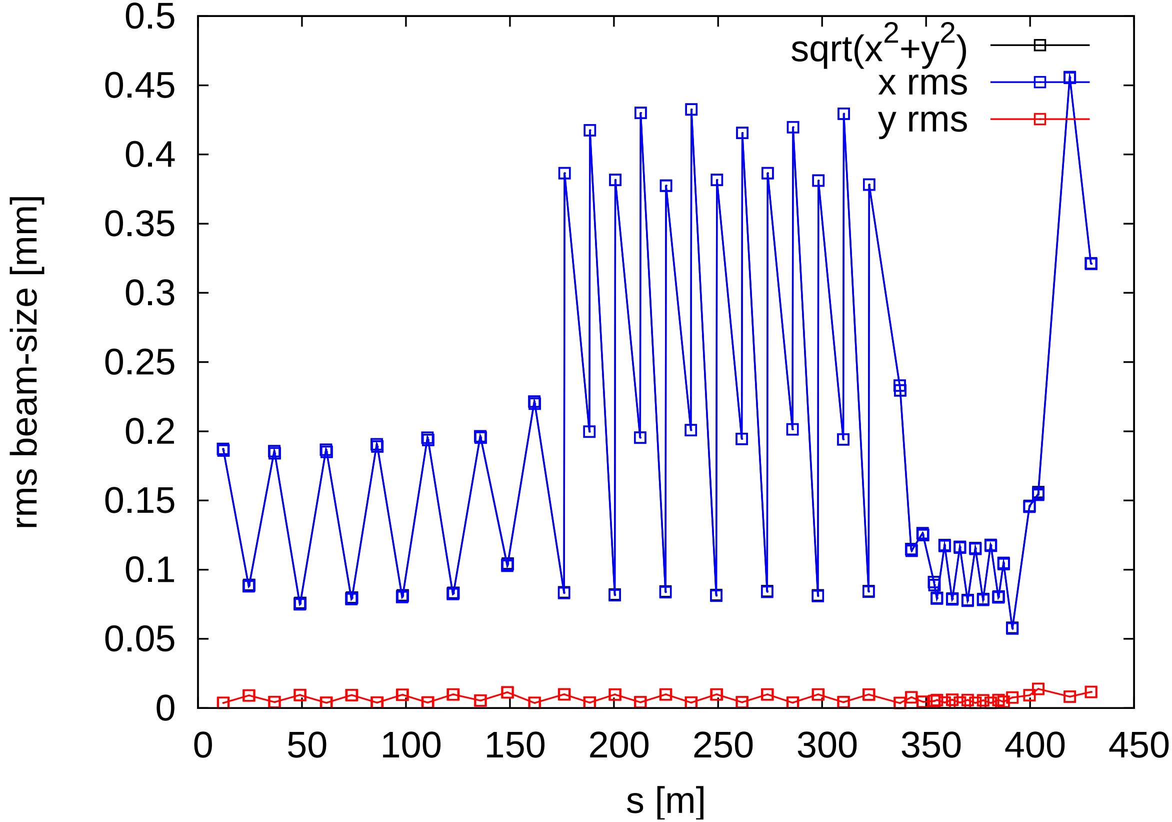
- Emittance along BC1S + BOOSTER + LINAC



$\Rightarrow$ Practically, no emittance growth $\Rightarrow$ good matching between all sections

Particle Tracking Using Placet

- Beam sizes along BC1S + BOOSTER



Emittance Growth Due to Element Misalignment

- **BC1S** and **BOOSTER** are considered (using 58 correctors and 58 BPMs)
- **Imperfections**
  - Misalignments : "COLD" model

σ_{quad}	$=$	$300\ \mu$m	quadrupole position error
$\sigma_{\text{quad roll}}$	$=$	$300\ \mu$rad	quadrupole roll error
σ_{cav}	$=$	$300\ \mu$m	cavity position error
$\sigma_{\text{cav pitch}}$	$=$	$300\ \mu$rad	cavity pitch error
$\sigma_{\text{sbend angle}}$	$=$	$300\ \mu$rad	sbend angle error
σ_{bpm}	$=$	$300\ \mu$m	bpm position error

  - Bpm resolution error: $\sigma_{\text{bpmres}} = 1\ \mu$m
  - All imperfections are applied to both BC1S and BOOSTER

- **Tracking Setup**

⇒ Short-range wakefields in the cavities are taken into account

⇒ Each bending magnet is simulated with 100 thin lenses (because of strong non linearity)

⇒ Synchrotron radiation is turned off

⇒ full 6d tracking in whole bunch compressor

Emittance Growth due to Element Misalignment

- **Alignment Procedure**
  - 1-to-1 Correction
  - Dispersion Free Steering
    - a 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
  - Dispersion bumps optimization
    - as there are no skew quadrupoles in the lattice (yet), we used two numerical dispersion bumps
    - two dispersion bumps are used: one at the entrance and the other at the exit of BC1S

- **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 relative weights to find the optimum

Simulation Setup

- **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

⇒ Two cases have been studied:

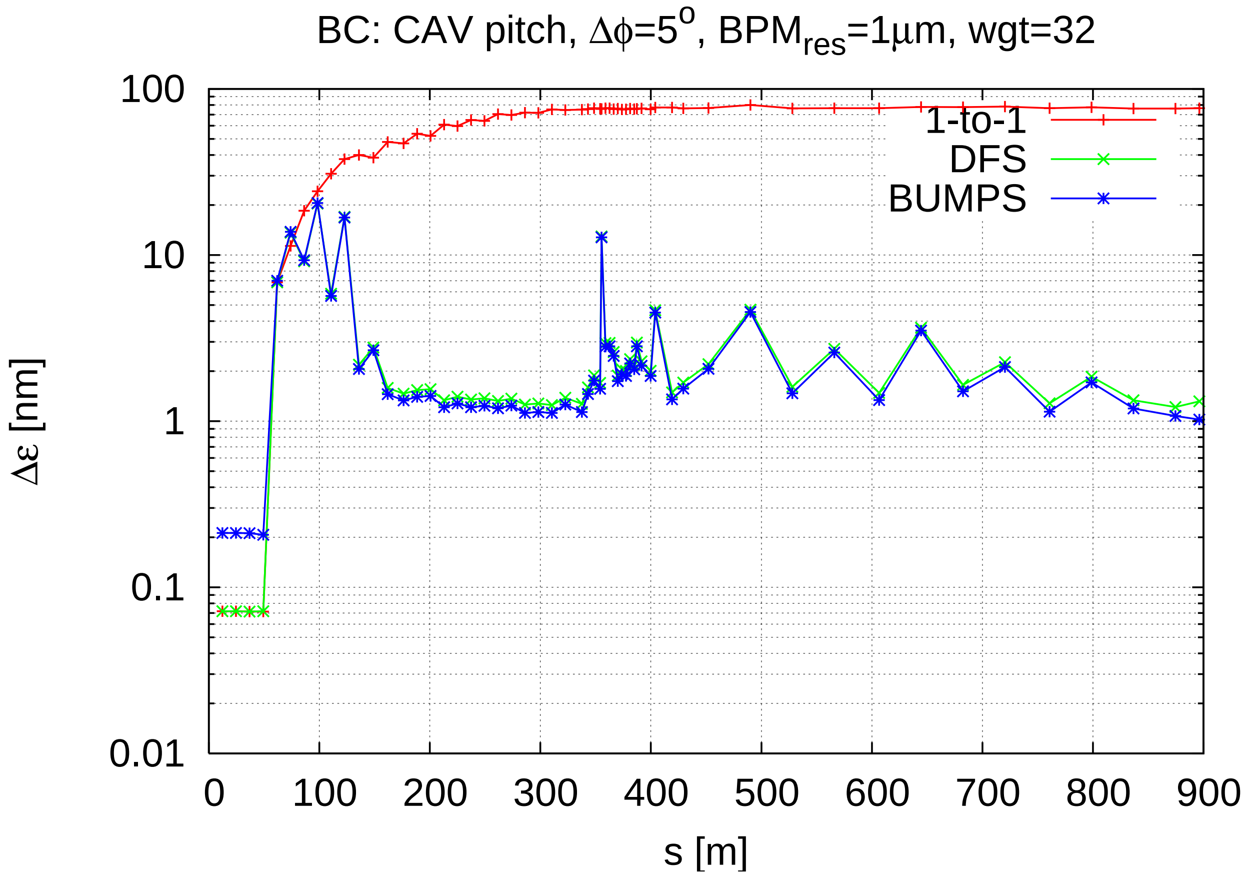
- all misalignments applied at the same time
- each individual contribution at once

- **Procedure**

⇒ Scan of the DFS's weight

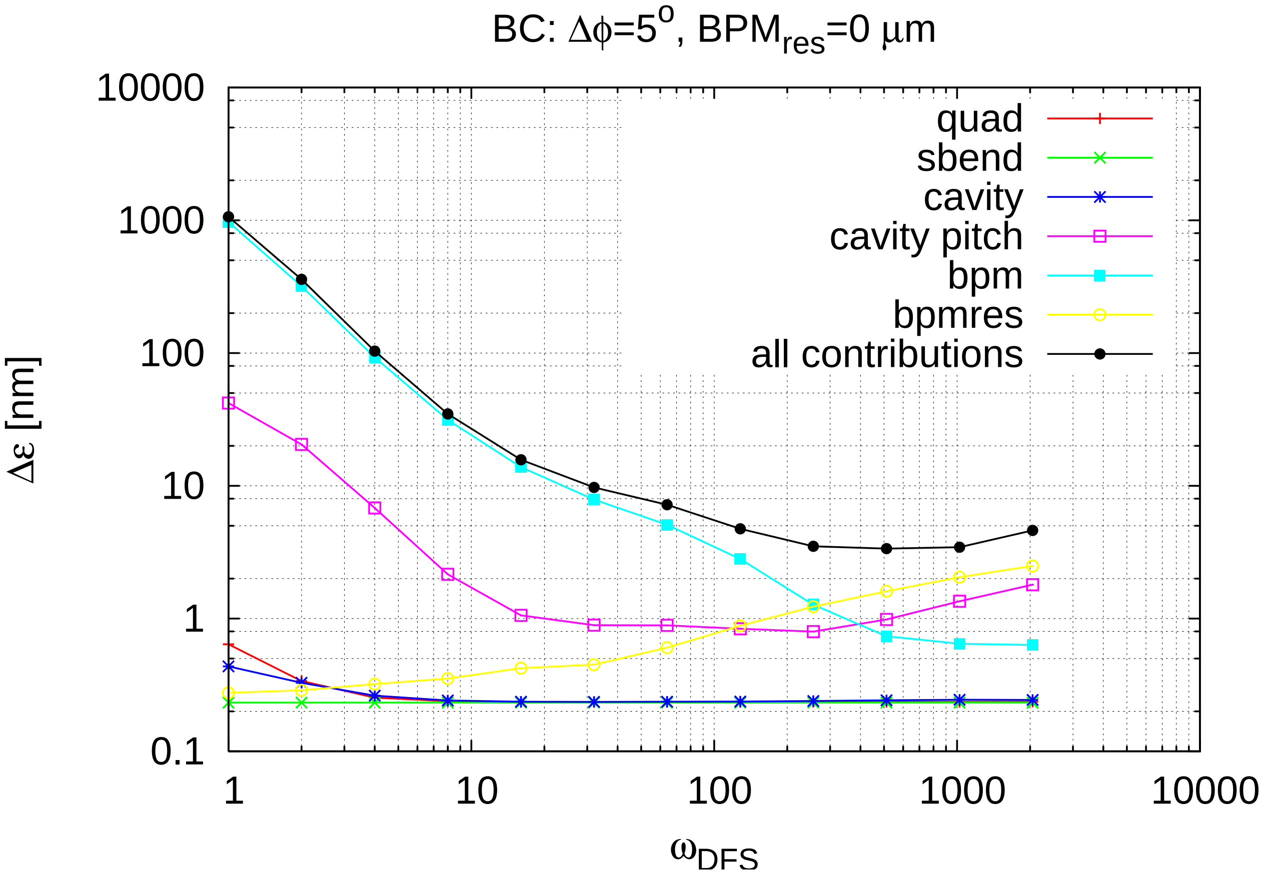
⇒ 40 machines (random seeds) have been simulated for each case

Vertical Emittance Growth due to Cavity Pitch



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

Vertical Emittance Growth due to All Misalignments



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

⇒ Large contributions from BPM misalignment and Cavity Pitch

Summary Table of Vertical Emittance Growths

- For $w = 512$ and each individual misalignment

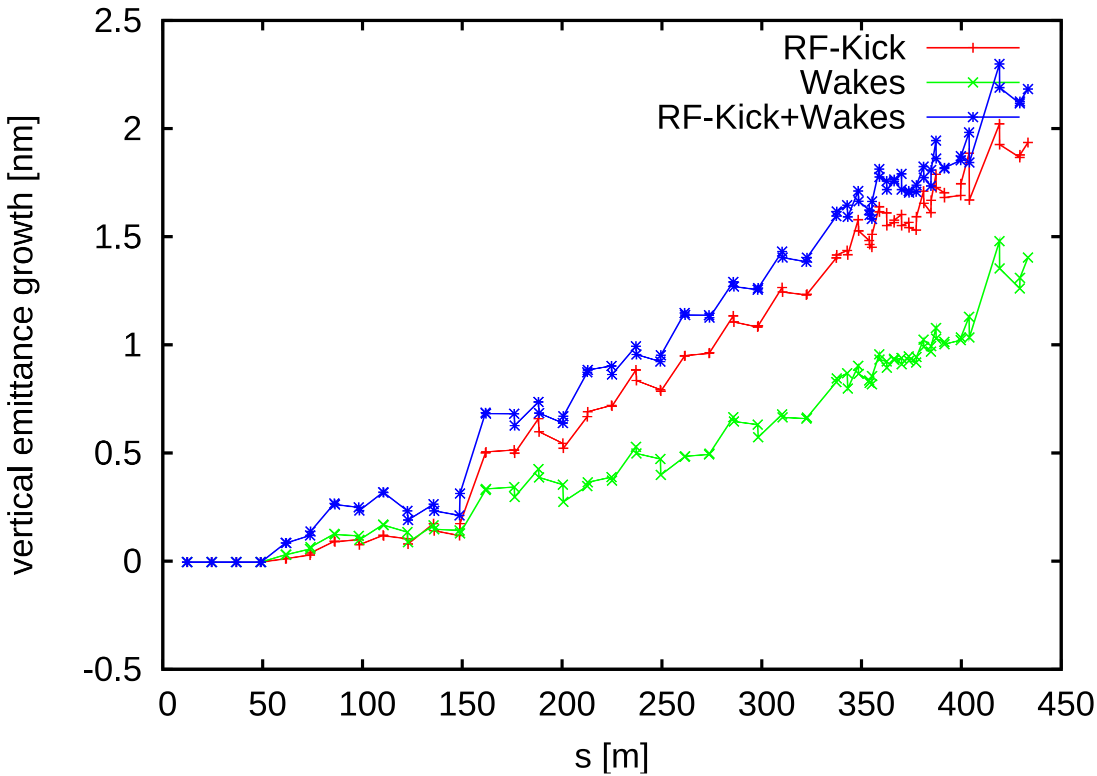
Misalignment	$\Delta\epsilon_y$
bpm position	0.74 nm
cavity position	0.24 nm
quadrupole position	0.24 nm
sbend position	0.23 nm
cavity pitch	0.98 nm
bpm resolution	1.60 nm
TOTAL	**3.37 nm**

$\Rightarrow$ 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 BPM resolution error and elements misalignment

RF-Kick and Wakefields in the Couplers

- We have considered the impact of Couplers' Wakes and RF-Kick in BC1S

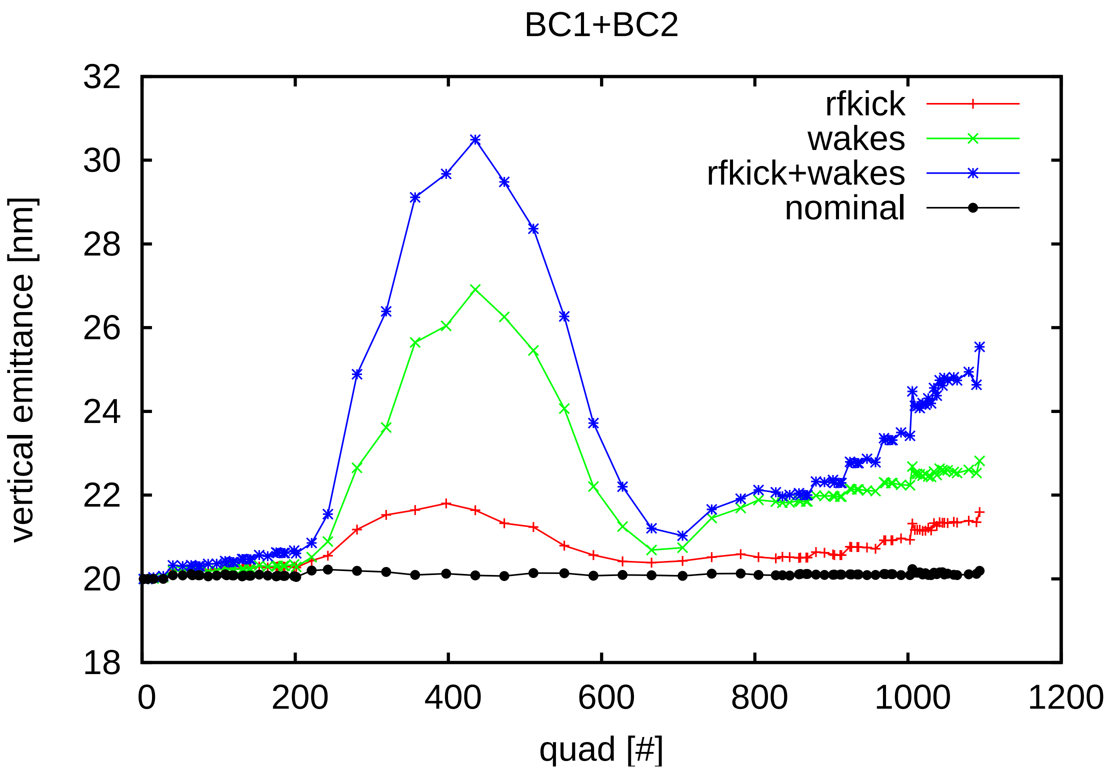
- and its correction using 1-to-1 steering and dispersion bumps



$\Rightarrow$ Final vertical emittance growth is 2.2 nm

RF-Kick and Wakefields in the Couplers in BC1+BC2

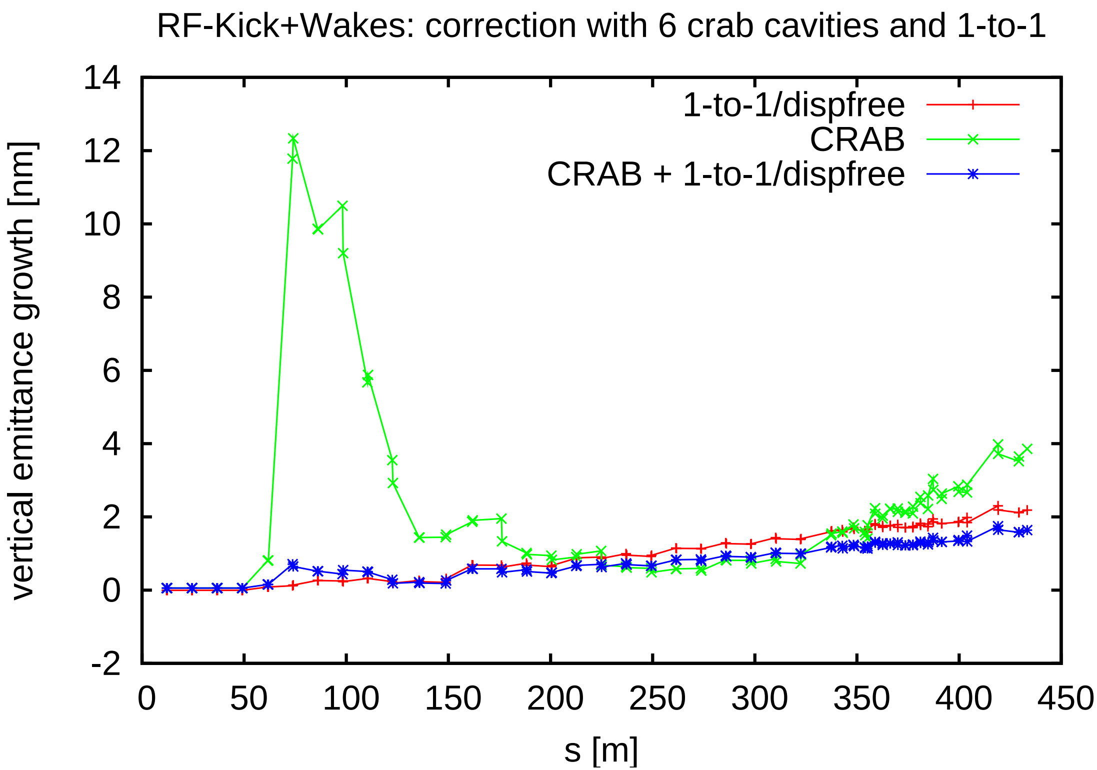
- Let's compare with the impact of these kicks on the baseline design ILC2007b
  $\Rightarrow$ effect in the whole BC: unpublished result!
- Couplers' kicks and their correction using 1-to-1 steering and dispersion bumps



$\Rightarrow$ Final vertical emittance growth is $\Delta\epsilon_y \simeq 5.5$ nm

RF-Kick and Wakes in the Couplers: CrabCavity correction

- One option to counteract these kicks is using a Crab Cavity $\Rightarrow$ we put one per each CM
- CrabCavity Correction (tuning voltage and phase) followed by 1-to-1 and dispersion bumps



$\Rightarrow$ Notice that the final vertical emittance growth is reduced! It's $\boxed{\Delta\epsilon_y = 1.6 \text{ nm}}$ (it was 2.2 nm without CrabCavities)

Summary Table of Vertical Emittance Growths

- For RF-Kick and Wakefields induced by the Couplers

$\Rightarrow$ 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	1.5 nm	0.8 nm	1.6 nm

$\Rightarrow$ BC1+BC2

Correction algorithm	$\Delta\epsilon_y$ RF-Kick	$\Delta\epsilon_y$ Wakes	$\Delta\epsilon_y$ Total
1-to-1 correction + bumps	1.59 nm	2.8 nm	5.5 nm

Conclusions and Work Plan

- 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, ...
- Simulations showed that major contributions to emittance growth come from:
  - Bpm Misalignment for small DFS weights:
    - this requires $\rightarrow$ better alignment (check with respect to the quad centers)
  - Cavity pitches:
    - test the crab cavity correction option
    - introduce a pitch in the cryomodules to compensate it (and the couplers' kicks at the same time)
- Study

  $\Rightarrow$ the impact of the couplers' RF-Kick and wakes in the booster linac

  $\Rightarrow$ the impact of ISR and CSR

  $\Rightarrow$ the impact of a 5 GeV beam with large energy spread (3.54 %) on the extraction line
    - the extraction line might need to be moved right before the ML entrance