ILC Bunch Compressor Simulations

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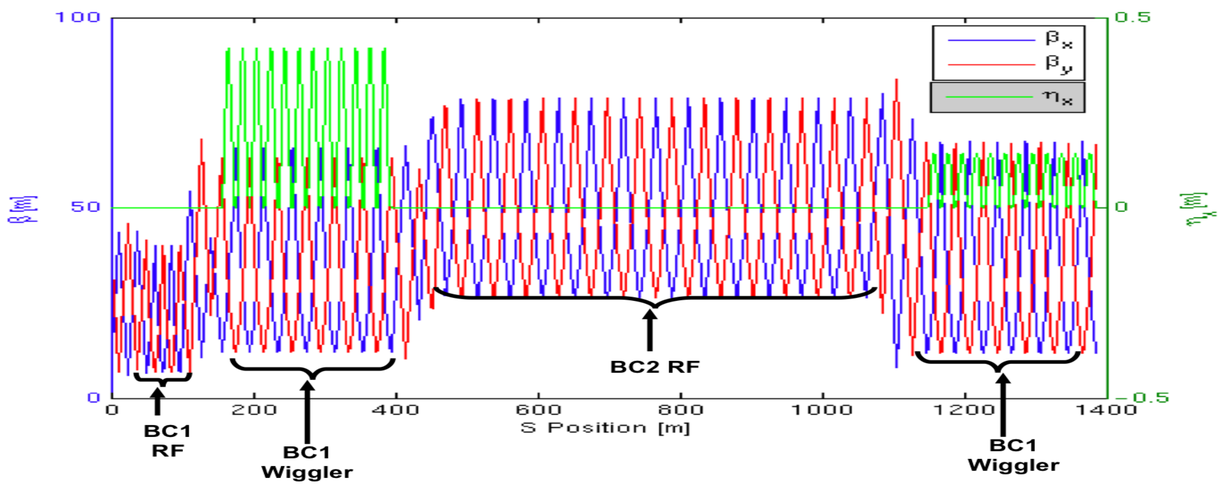
- Sources of emittance growth (misalignments, couplers' transverse kicks)
- Mitigation techniques: BBA + girder pitch optimization
- Emittance preservation in BC1+BC2
- Emittance presentation in BC1S
- Conclusions and future steps

Two-Stage Bunch Compressor

Design ILC2007b

- **BC Stage 1**:
  - Start bunch length = 6 mm / 9 mm
  - End bunch length ≈ 1 mm
  - Start energy = 5 GeV
  - End energy = less than 5 GeV
  - Start energy spread = 0.15 %
  - End energy spread = 2.5 %

- **BC Stage 2**:
  - Start bunch length ≈ 1 mm
  - End bunch length = 0.3 mm / 0.15 mm
  - Start energy = less than 5 GeV
  - End energy = 15 GeV
  - Start energy spread = 2.5 %
  - End energy spread = 1.07 %



⇒ An alternative design for a **single-stage bunch compressor**, 6 mm → 0.3 mm, is being proposed

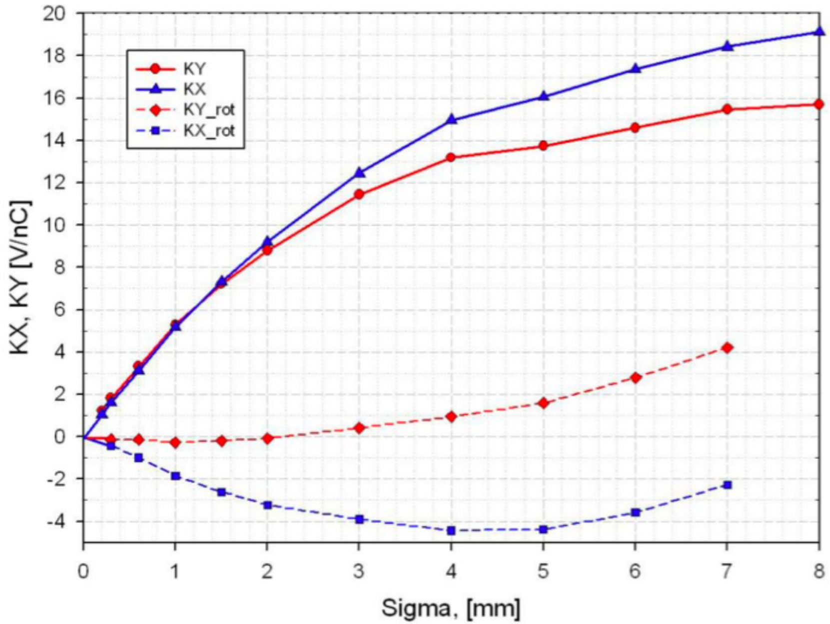
Sources of Emittance Dilution in the RTML

- **Synchrotron radiation**
  - From DRX arc, turnaround, BC wigglers
- **Beam-ion instabilities**
- **Beam jitter**
  - From DR
  - From stray fields
- **Dispersion**
  - DR extraction
  - Misaligned quads
  - Rolled bends
- **Collimator Wakefields**
- **Coupling**
  - DR extraction septum
  - Rolled quads
  - Misaligned bends
  - Quad strength errors in spin rotator
- **Pitched RF cavities (BC)**
  - Produce time-varying vertical kick
- **RF phase jitter (BC)**
  - Varies IP arrival time of beams
- **Beam halo formation**
- **Couplers**
  - RF-Kick
  - Wakefields

$\Rightarrow$ Most critical for BC : misalignments (dispersive and chromatic effects), couplers' transverse kicks (bunch blow up)

Wakefields due to the Couplers

- Coupler wakefields depend on the bunch length:
  - for short bunches it depends linearly on the bunch length
  - for longer bunches it depends (about) on the square root of the bunch length



- Numerical calculation using GdfidL by A.Lunin

⇒ for a 6 mm long bunch the wake-kick is about 10 times larger than for 0.3 mm (ML)

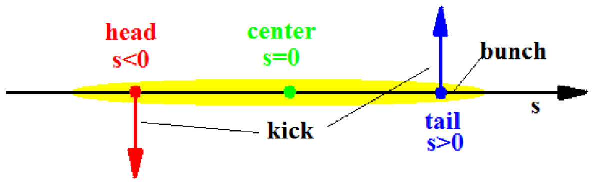
RF-Kick due to the Couplers

- Couplers' asymmetry induces a transverse RF-kick:

$$\Delta \vec{V}_{RF} = (k_{\text{real}} + i k_{\text{imag}})\, G L\, e^{-i(\phi_{RF} + ks)}$$

where $\vec{k} \simeq (-7.3 + 11\, i) \times 10^{-6}$ (HFSS calculations by A.Lunin).

- Kick has opposite sign at the head and the tail of the bunch



$$\Delta \vec{V}_{RF} = V_{\text{real}} \cos(ks) \;-\; V_{\text{imag}} \sin(ks)$$

- **Emittance growth** due to RF-Kick (V. Yakovlev's analytical estimation) is

$$\Delta\epsilon \approx \frac{(F')^2 \sigma^2 \beta^3 \gamma_0}{2 U_0^2} \left(1 - 2 \sqrt{\frac{\gamma_0}{\gamma(z)}} \cos(z/\beta) + \frac{\gamma_0}{\gamma(z)} \right)$$

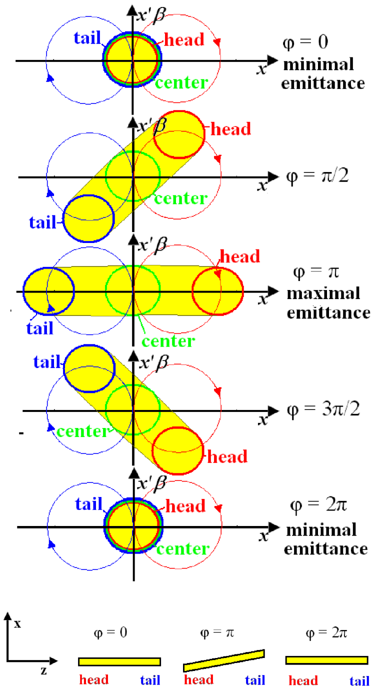
where ϵ_0 is the initial emittance, F' is the first derivative of the kick for $z = 0$, σ is the bunch length, β is the betatron amplitude, U_0 is the initial energy and γ_0 the corresponding relativistic factor.

$\Rightarrow$ Note that: when $z/\beta = 2\,\pi\, n$ and there is no acceleration : $\Delta\epsilon = 0$

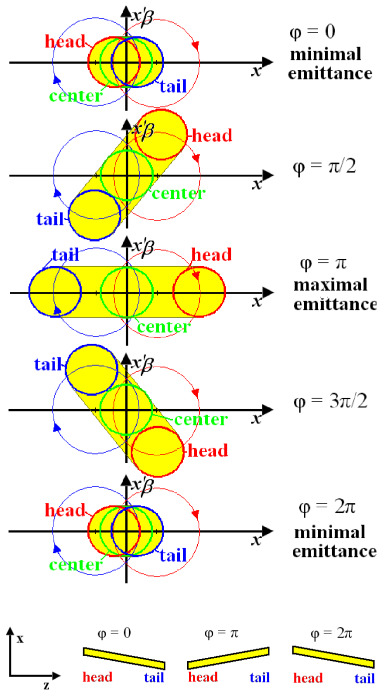
Emittance Growth due to RF-Kick

- Emittance growth behavior is different w/ or w/o acceleration:

$$\Delta\epsilon \approx \frac{(F')^2\sigma^2\beta^3\gamma_0}{2U_0^2}\left(1 - 2\sqrt{\frac{\gamma_0}{\gamma(z)}}\cos(z/\beta) + \frac{\gamma_0}{\gamma(z)}\right)$$



(no acceleration)



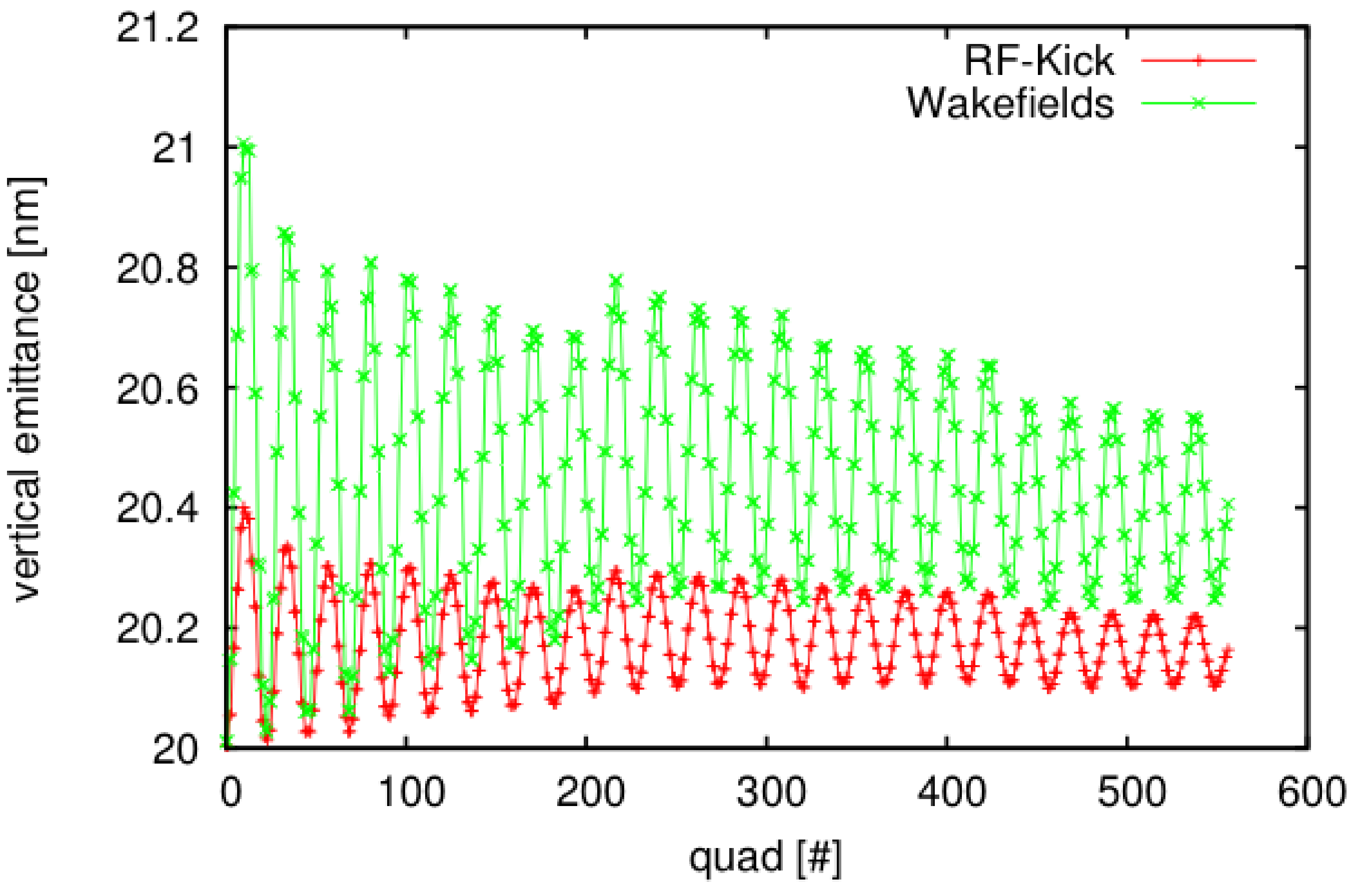
(acceleration)

⇒ Emittance growth is minimum when $z/\beta = 2\pi n$

⇒ this induces an emittance growth that cannot be corrected by basic BBA techniques

Emittance Growth due to RF-Kick and Wakes

- ..in the Main Linac: the effect of the bunch rotation in the phase space is visible



Simulation Setup

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

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

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

  $\Rightarrow$ impact and cure using beam-based alignment

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

  $\Rightarrow$ impact and cure using beam-based alignment

- Effect of **element misalignments** <u>and</u> **couplers RF-Kick and Wakes**

Alignment Procedure

1) **1-to-1 Correction**

2) **Dispersion Free Steering**

- a phase offset is applied to the RF cavities of the BC1S (BC1) in order to generate the energy difference for the DFS's test beams

  (in BC1S the test beams are synchronized to the PRE-LINAC's RF phase at its entrance)

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

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

3) **Dispersion Bumps**

- we used two *dispersion* bumps η, η' as global correctors

$$\begin{cases} y_i \Leftarrow y_i + \eta \frac{E_i - E_0}{E_0} \\ y'_i \Leftarrow y'_i + \eta' \frac{E_i - E_0}{E_0} \end{cases}$$

- two dispersion *knobs*: tune dispersion at entrance to minimize the final vertical emittance

4) **Girder Pitch Optimization** $\boxed{\textit{new!}}$

Girder Pitch Optimization

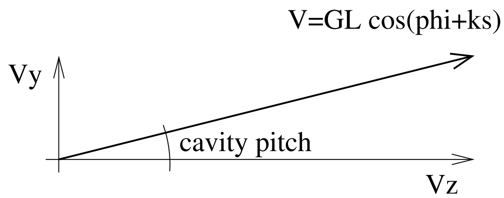
- The idea behind **Girder Pitch Optimization** is that Cavity Pitch kick can compensate RF-kick and coupler wakes

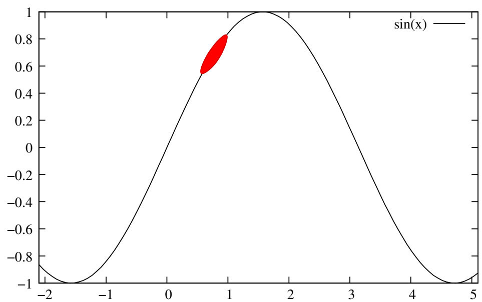
$$\Delta\vec{V}_{RF} = \underbrace{\vec{k}\, GL\, e^{-i(\phi_{RF}+ks)}}_{\text{RF}-\text{Kick}}$$

resulting in

$$\Delta\vec{V}_{RF} = V_{\text{real}}\cos(ks) \; - \; \underbrace{V_{\text{imag}}\sin(ks)}_{\sim\, GL\cos(\phi_{RF})\,\sigma_{\text{PITCH}}\,ks}$$

⇒ Like RF-kick, cavity pitch gives two contributions:

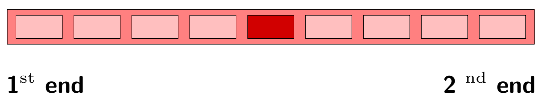




- an average kick to all the entire bunch and

- a slope along the bunch, proportional to the phase

⇒ Rotation must occur around the central quadrupole:



Girder Pitch Optimization

- Estimation for BC1S-PreLinac's cryomodules ($GL = 31.5$ MV, $\psi = 5.3^o$, $n = 8$ cavities):

  - Misalignment: average kick spread along the bunch, due to cavity pitch $\sigma_{y'} = 300$ μrad

  $$< \Delta\vec{p} > \;\propto\; 31.5\ [\mathrm{MV}] \times \cos(5.3^o) \times 300\ [\mu\mathrm{rad}] \times \sqrt{8} \times (k\,\sigma_z) \;=\; \boxed{26.6\ \mathrm{kV} \times (k\,\sigma_z)}$$

  - RF-kick spread: for $V_o/V_a = 11.7 \cdot 10^{-6}$

  $$< \Delta\vec{p} > \;\propto\; 11.7 \cdot 10^{-6} \times 31.5\ [\mathrm{MV}] \times 8 \times (k\,\sigma_z) \;=\; \boxed{2.9\ \mathrm{kV} \times (k\,\sigma_z)}$$

  $\Rightarrow$ The two contributions are about of the same order

$\Rightarrow$ We can estimate the girder pitch angle θ necessary to compensate the RF-kick:

$$GL \cdot \theta \cdot \cos\psi \cdot N = \; 2.9\ \mathrm{kV} \quad \Rightarrow \quad \boxed{\theta = \frac{2.9\ [\mathrm{kV}]}{31.5\ [\mathrm{MV}] \cdot \cos(5.3^o) \cdot 8} \approx 11.6\ \mu\mathrm{rad}}$$

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
- **Lattice**: ILC2007b and new design of single-stage bunch compressor
- **Tracking Setup**
  - PLACET simulation code

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

  $\Rightarrow$ incoherent synchrotron radiation is turned off

  $\Rightarrow$ full 6d tracking in the whole bunch compressor(s)
- **Simulation Procedure**

  $\Rightarrow$ Studied both BC1S and BC1+BC2

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

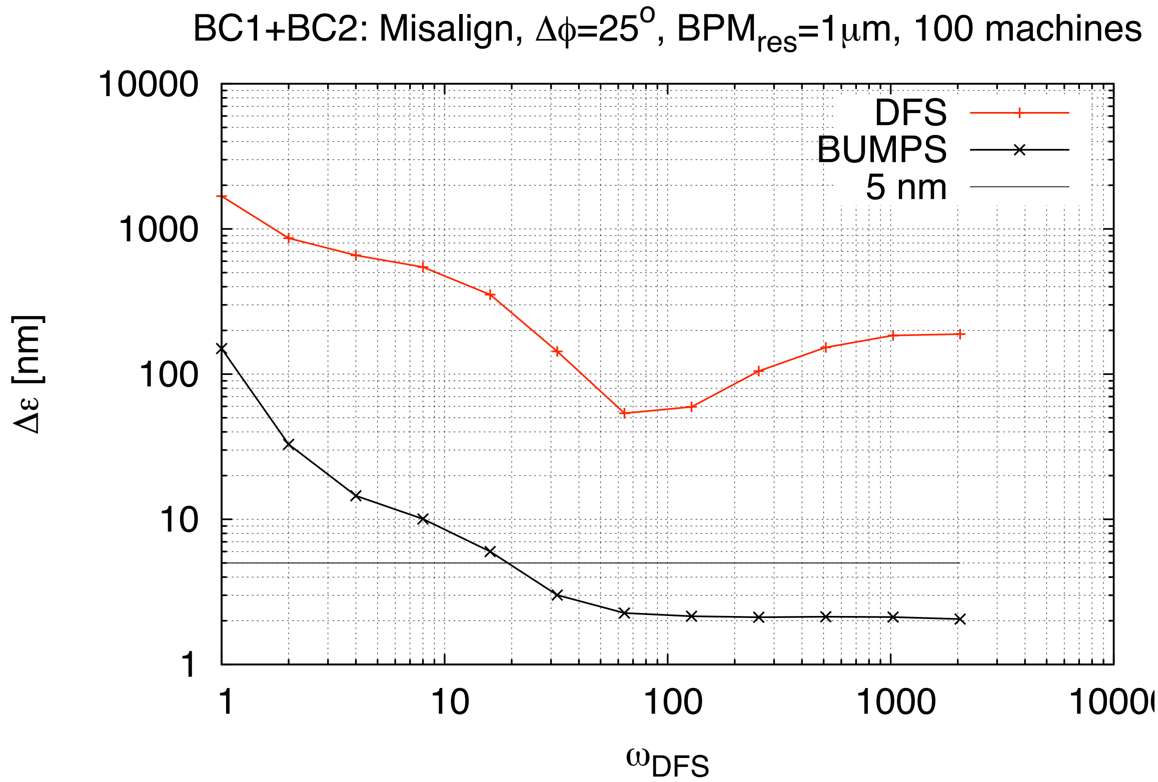
  $\Rightarrow$ 100 machines (i.e. random seeds) have been simulated for each case (when possible)

Beam-Based Alignment in BC1+BC2

- Misaligmments are 300 μx, BPM resolution is 1 μm
- RF-Kick and couplers wakes are considered
- Dispersion Free Steering
  - two test beams
    - Case A: no Couplers. $\Delta\phi = \pm 25^o$ phase offset in both the RF sections of BC1+BC2
    - Case B: Couplers
      $\Rightarrow$ $\Delta\phi = \pm 25^o$ phase offset in the RF section of BC1 (no phase offset in BC2)
      $\Rightarrow$ phase synchronization at entrance of BC2 is necessary
      $\Rightarrow$ otherwise RF-Kicks completely spoils the test beams, due to the large phase difference (10 $\sigma_z \approx 1$ cm)
- Dispersion bumps optimization
  - minimize the final dispersion-corrected emittance by changing the dispersion at entrance
- Girder Pitch optimization
  - using 3 CM in BC1
  - using 4 CM in BC2, out of 45

$\Delta\epsilon_y$ due to Misalignments in BC1+BC2

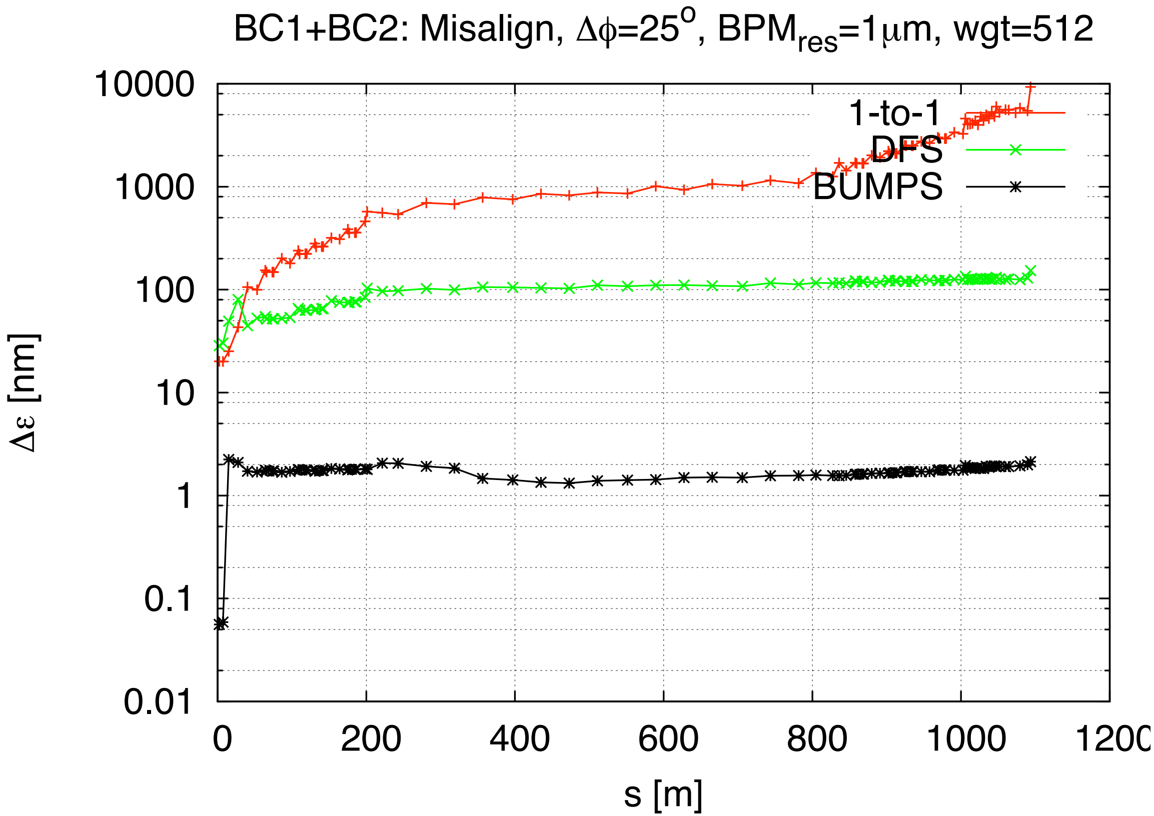
- Case A. Final vertical emittance growth as a function of ω



$\Rightarrow$ Minimal vertical emittance growth $\boxed{\Delta\epsilon = 2.1 \text{ nm}}$

$\Delta\epsilon_y$ due to Misalignments in BC1+BC2

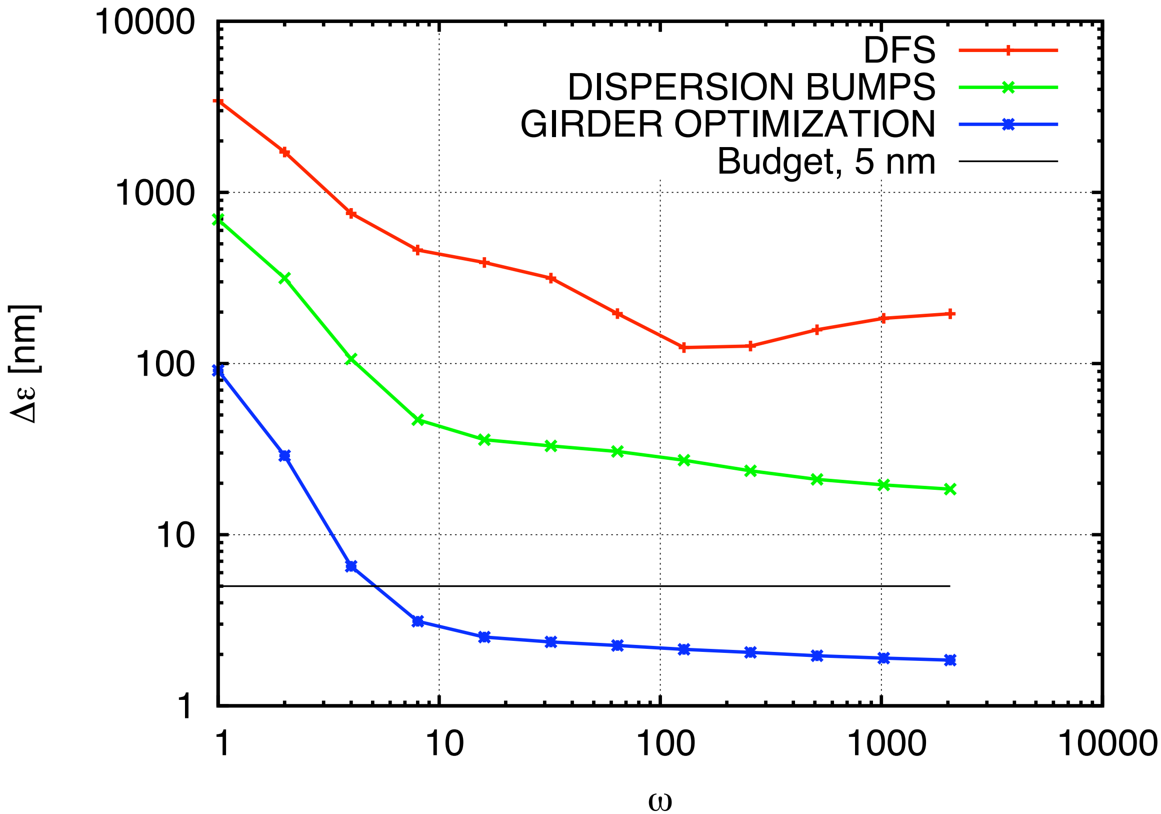
- Case A. Emittance Growth **along the beamline**, average of 100 machines



$\Rightarrow$ Final vertical emittance growth is $\boxed{\Delta\epsilon = 2.1 \text{ nm}}$

$\Delta\epsilon_y$ due to Misalignments+Couplers in BC1+BC2

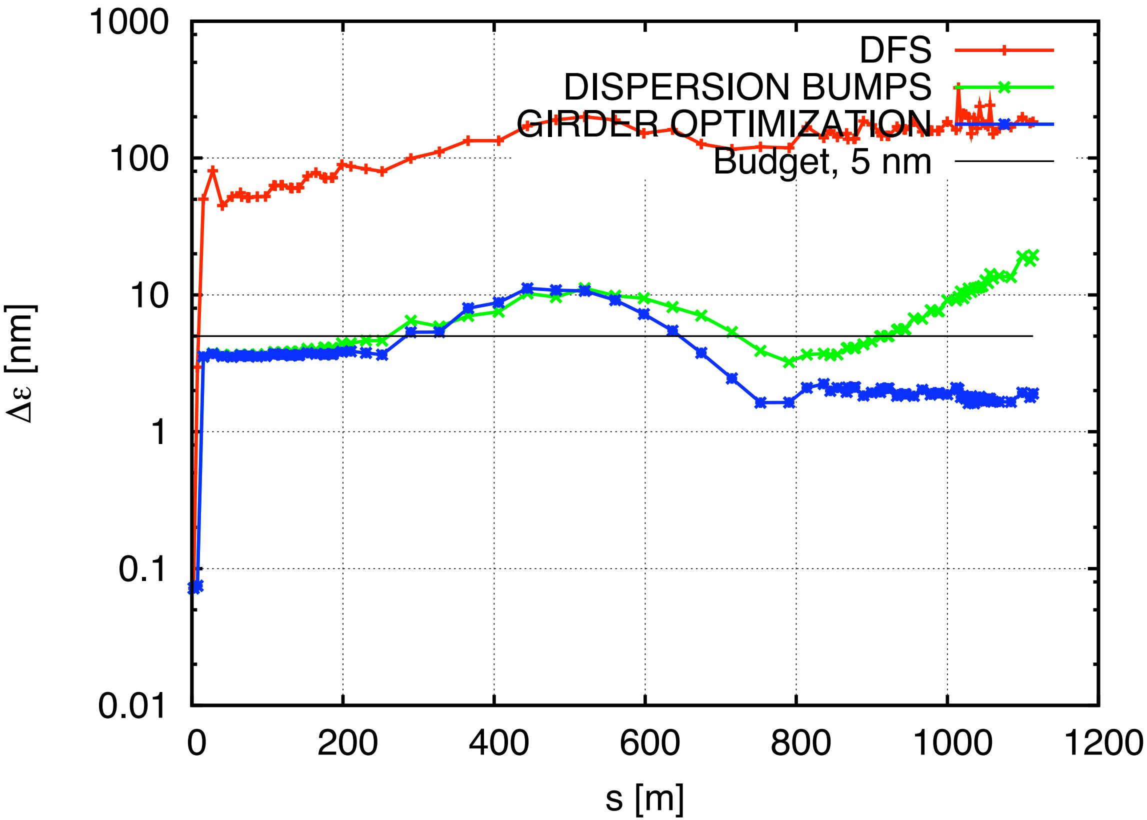
- Case B. Final vertical emittance growth as a function of ω



$\Rightarrow$ Minimal vertical emittance growth $\boxed{\Delta\epsilon = 1.8 \text{ nm}}$ at $\omega = 2048$

$\Delta\epsilon_y$ due to Misalignments+Couplers in BC1+BC2

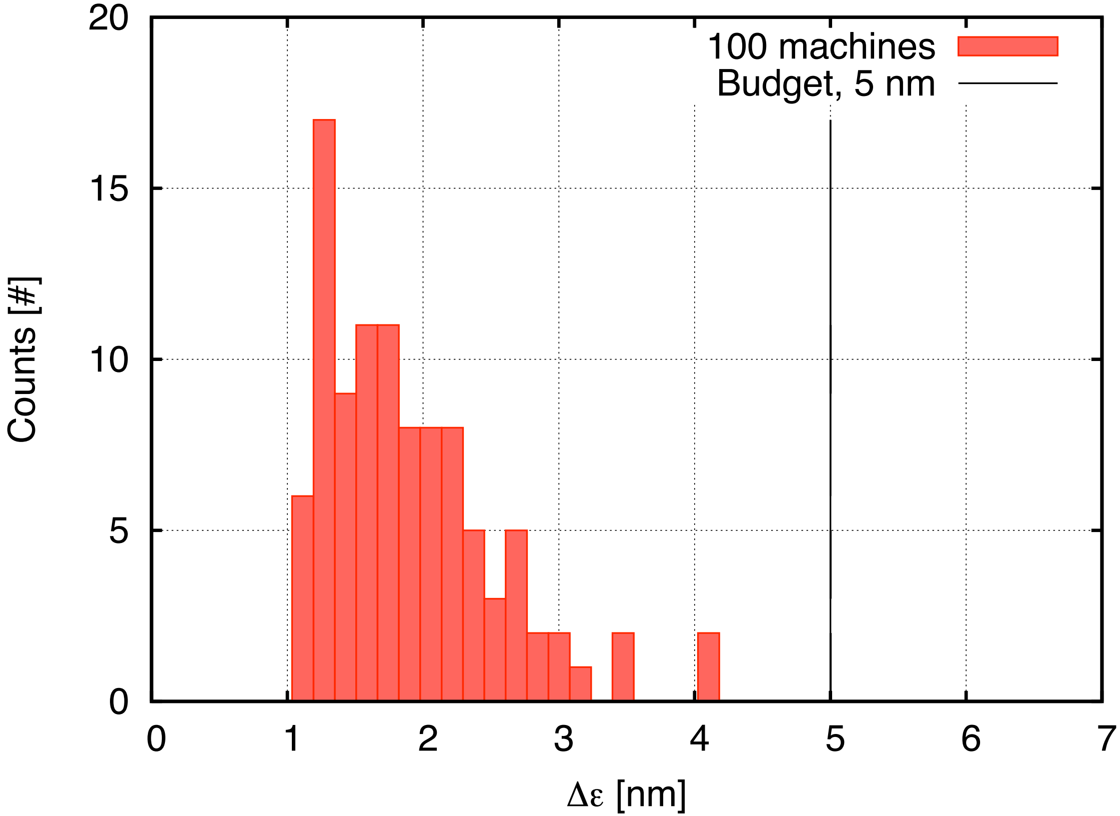
- Case B. Emittance Growth along the beamline, for 100 machines, at $\omega = 2048$



$\Rightarrow$ Final vertical emittance growth is $\boxed{\Delta\epsilon = 1.8 \text{ nm}}$

$\Delta\epsilon_y$ due to Misalignments+Couplers in BC1+BC2

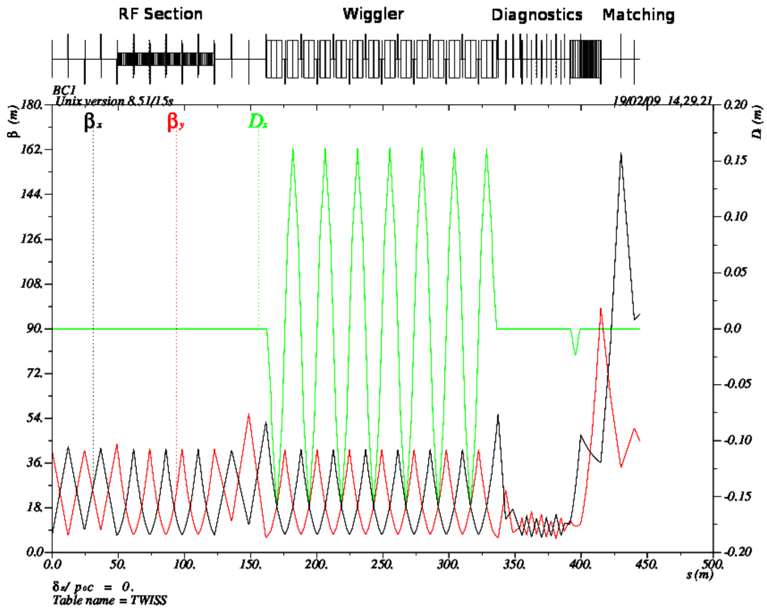
- Case B. Histogram with the emittance Growth for 100 machines, at $\omega = 2048$



$\Rightarrow$ Average final vertical emittance growth is $\boxed{\Delta\epsilon = 1.8 \text{ nm}}$

Single-Stage Bunch Compressor

- Bunch compression from 6 mm to 0.3 mm
- Based on the original design at 5 GeV by PT in April 2005



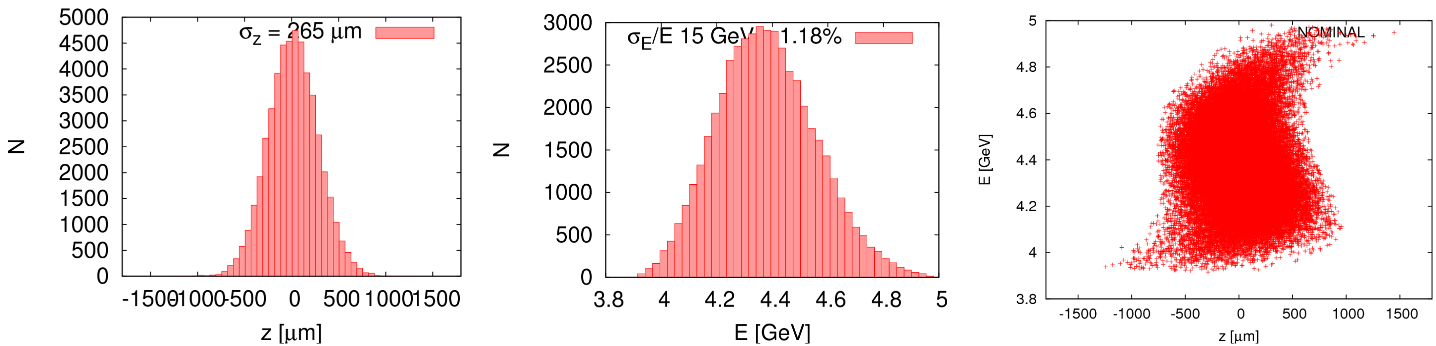
Lattice is modified to improve performance:

- Type-3 cryomodules replaced by **Type-4**
- **Wiggler** by PT/Seletskiy presented at PAC 2007
- beam **diagnostics** from BC2 (4 laserwires, LOLA cavities)
- new **extraction line** (see talk by Seletskiy)
- **pre-linac** to boost the beam from 5 to 15 GeV

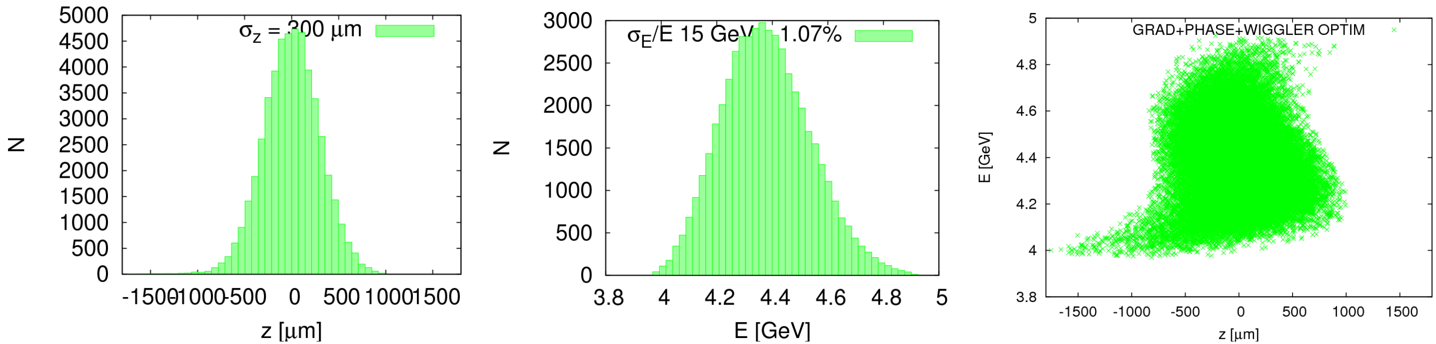
Optimization of BC1S

- 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-Based Alignment in BC1S

- Misaligmments are 300 μx, BPM resolution is 1 μm
- RF-Kick and wakes

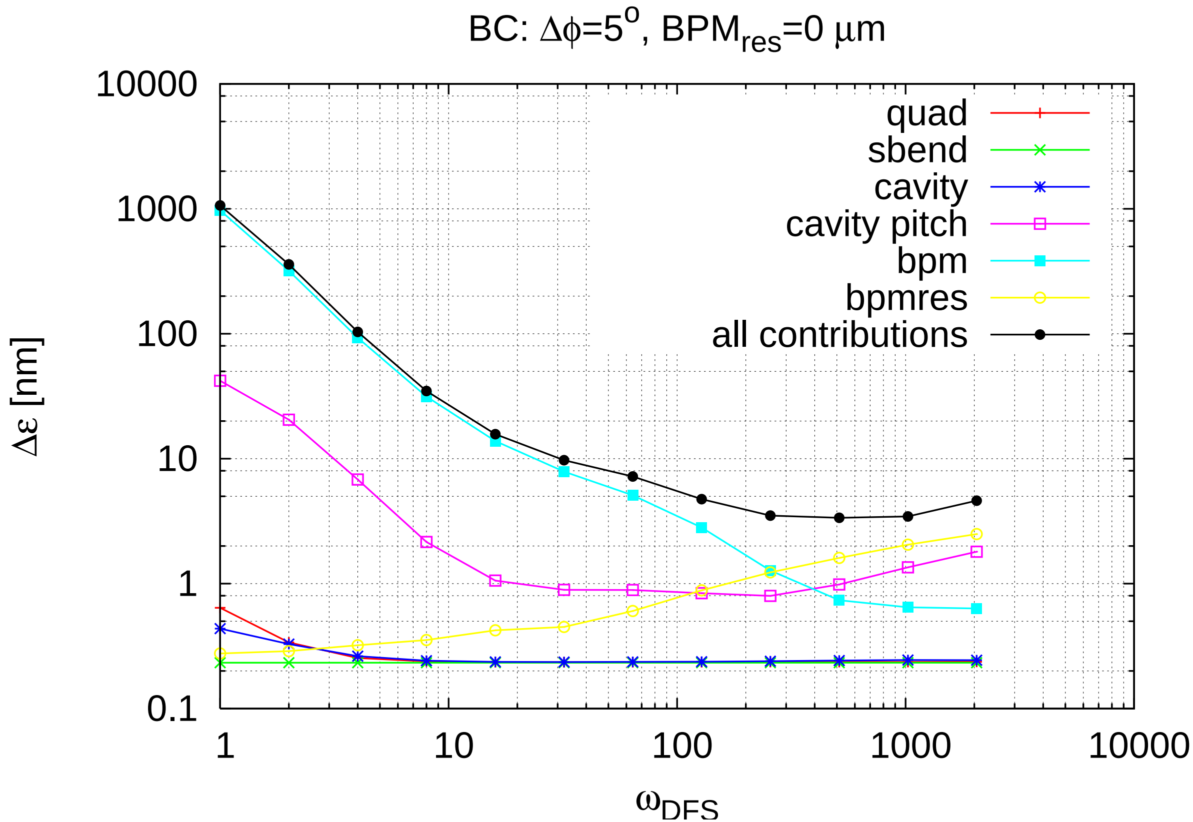
- Dispersion Free Steering
  - two test beams
  - $\Delta\phi = \pm 5^o$ phase offset in the RF section of BC1
  - phase synchronization at entrance of Pre-Linac is necessary
    $\Rightarrow$ otherwise RF-Kicks spoils the test beams, due to the large phase difference (6 $\sigma_z \approx 6$ mm)

- Dispersion bumps optimization
  - minimize the final dispersion-corrected emittance by changing the dispersion at entrance

- Girder Pitch optimization
  - using 3 CM in BC1S, out of 6
  - using 3 CM in BC1S pre-linac, out of 36

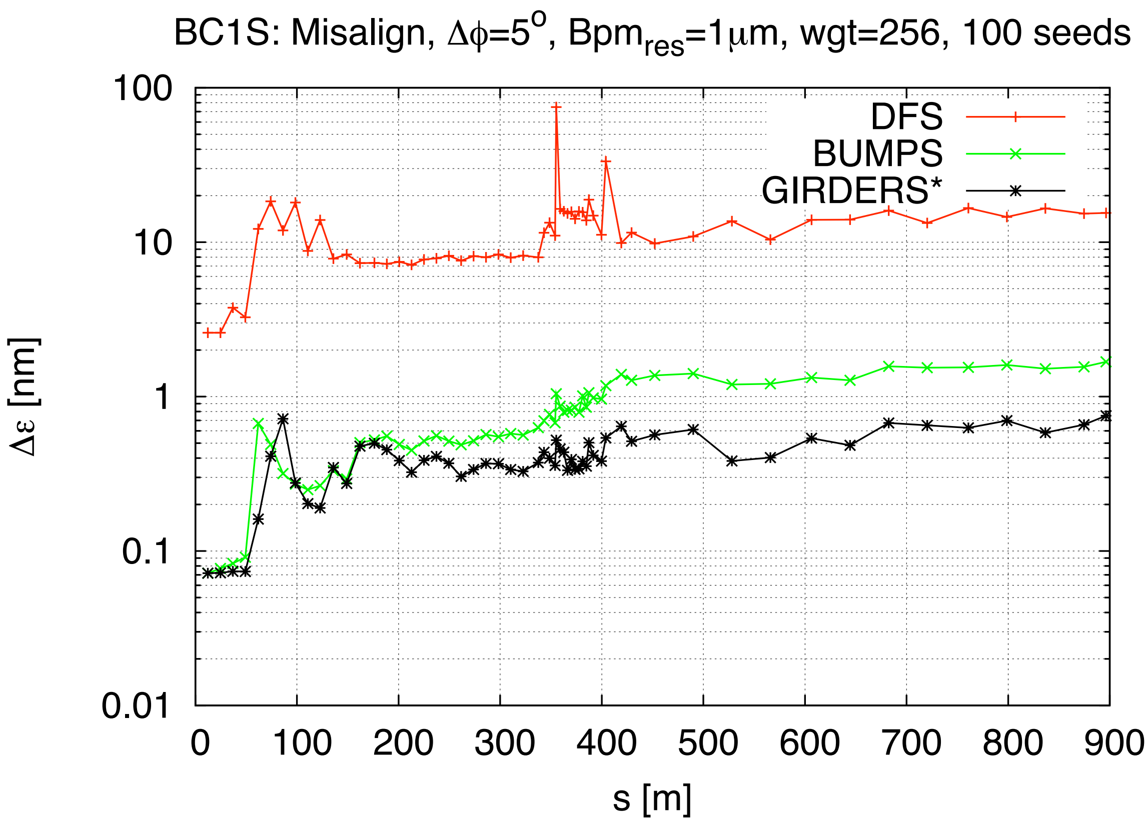
Emittance Growth due to Misalignments in BC1S

- Emittance Growth along the beamline, average of 40 machines, individual misalignments
- DFS results



Emittance Growth due to Misalignments in BC1S

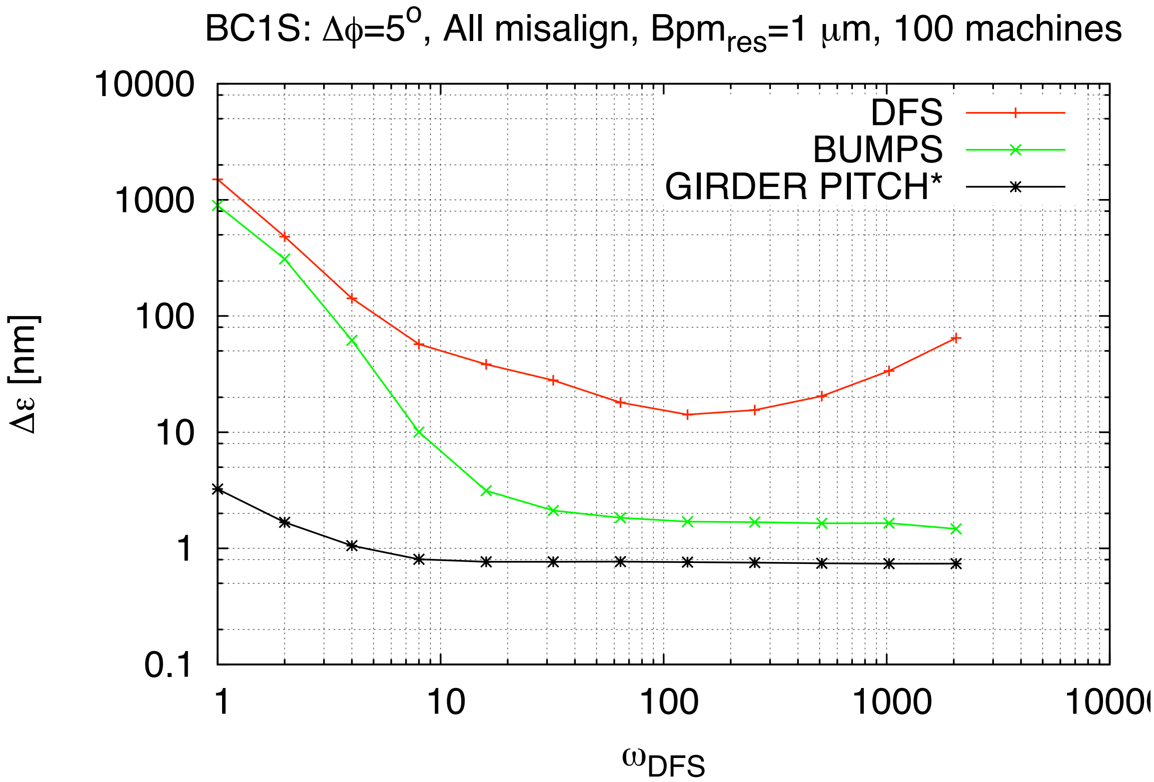
- Emittance Growth along the beamline, average of 100 machines



$\Rightarrow$ Final vertical emittance growth is $\boxed{\Delta\epsilon = 0.8 \text{ nm}}$

Emittance Growth due to Misalignments in BC1S

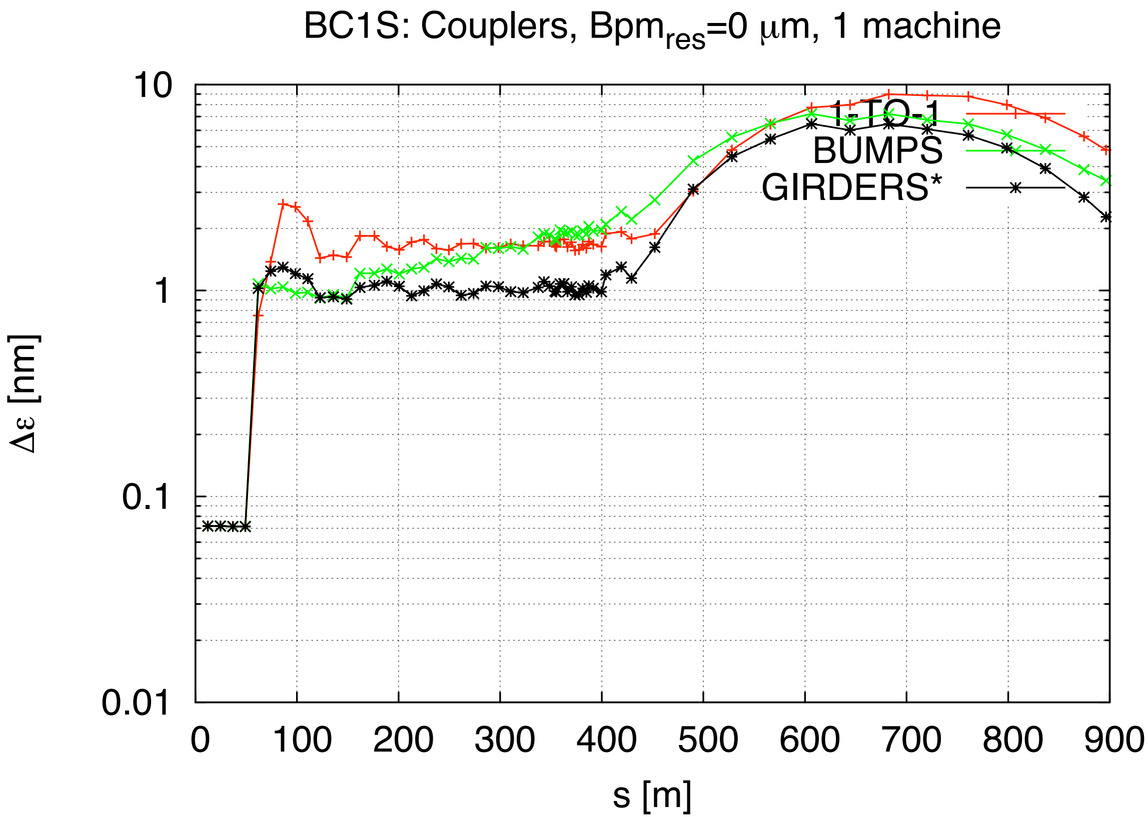
- Final vertical emittance growth as a function of ω



$\Rightarrow$ Minimal vertical emittance growth $\boxed{\Delta\epsilon = 0.8\text{ nm}}$

Emittance Growth due to Couplers in BC1S

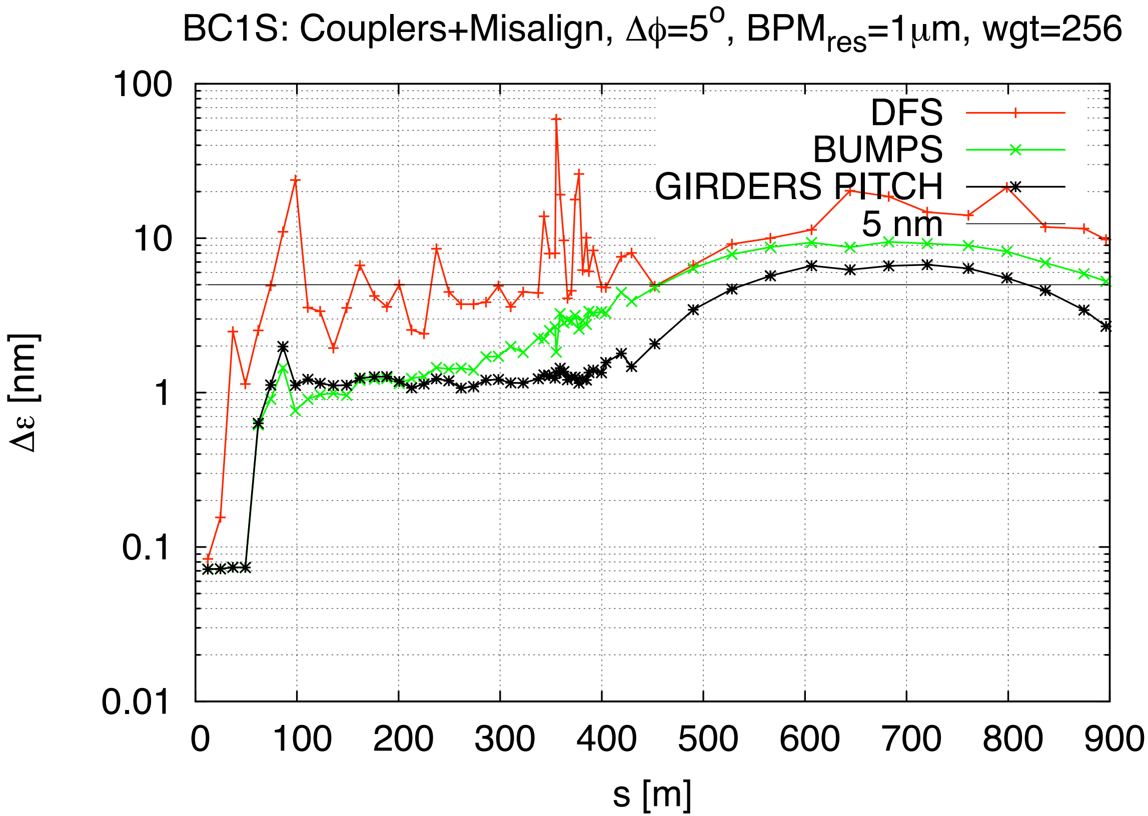
- Vertical emittance growth after correction (no misalignments, bpm resolution 0)



⇒ Final vertical emittance growth is *less than* $\boxed{\Delta\epsilon = 2.2 \text{ nm}}$

Emittance Growth due to Misalign+Couplers in BC1S

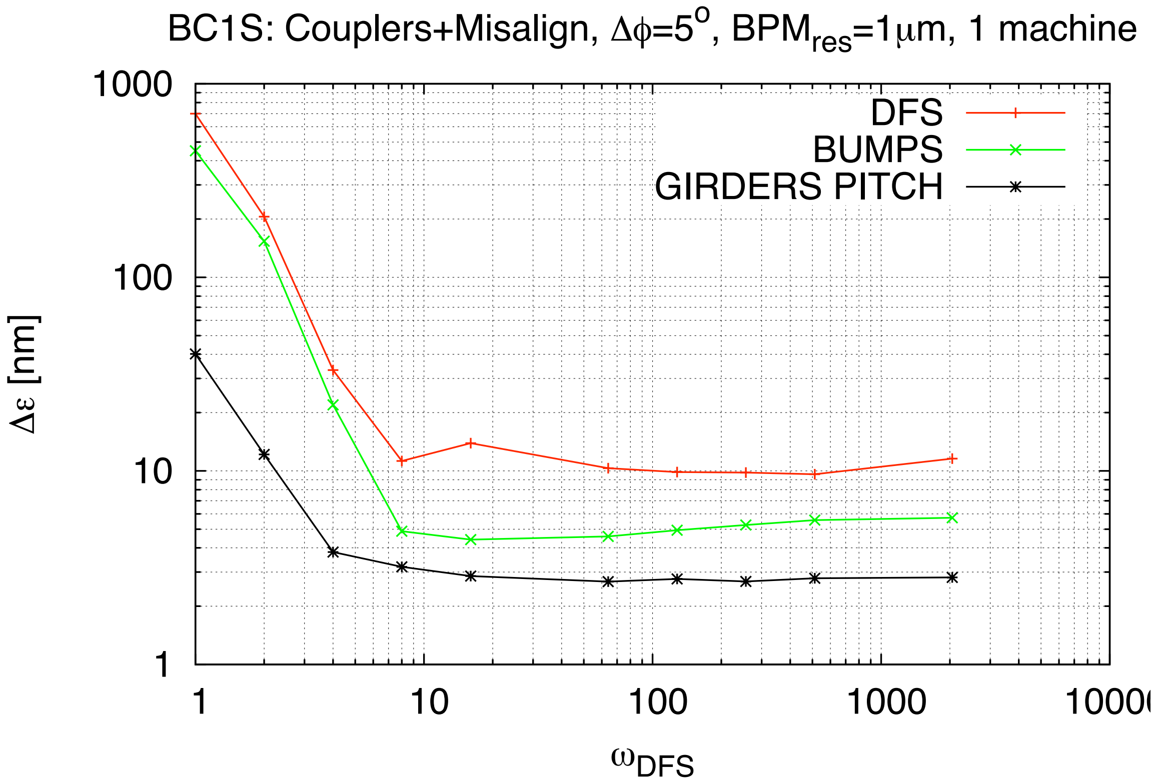
- Emittance Growth along the beamline, 1 machine



$\Rightarrow$ Final vertical emittance growth is *less than* $\boxed{\Delta\epsilon = 2.6 \text{ nm}}$

Emittance Growth due to Misalign+Couplers in BC1S

- Final vertical emittance growth as a function of ω



$\Rightarrow$ Minimal vertical emittance growth is *less than* $\boxed{\Delta\epsilon = 2.6 \text{ nm}}$

Summary Table of Vertical Emittance Growths

- Two-stage bunch compressor

Technique	Misalignments	Couplers$^{(1)}$	Misalign+Couplers
DFS	91.2 nm	7.7 nm	123.0 nm
BUMPS	2.1 nm	4.3 nm	18.0 nm
GIRDER	-	0.5 nm	1.8 nm

- Single-stage bunch compressor

Technique	Misalignments	Couplers$^{(1)}$	Misalign+Couplers
DFS	14.8 nm	4.8 nm	27.0 nm
BUMPS	1.47 nm	3.4 nm	4.6 nm
GIRDER	0.8 $^{(*)}$ nm	2.5 nm	2.6$^{(*)}$ nm

(1) 1 machine

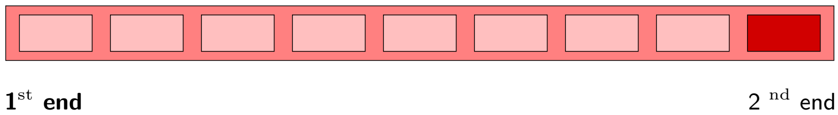
(*) 40 machines

Conclusions and Work Plan

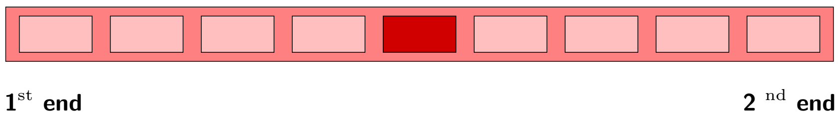
- Emittance growth due to misalignments and couplers seems to be compensated both for BC1S and BC1+BC2
- Girder Pitch optimization is very effective to counteract coupler kicks and misalignments, both for BC1S and BC1+BC2
- To Do List:
  - Beam Tracking through the full RTML is already possible (PLACET)
    $\Rightarrow$ Misalignment simulations and correction in whole RTML
    $\Rightarrow$ Stray fields simulations
    $\Rightarrow$ Multi-bunch effects
    $\Rightarrow$ Dynamic effects and feedback loops

Girder Pitch Optimization

- Compensate the emittance growth by rotating the girders in the plane $yz \rightarrow$ tilted cavities induce a transverse kick, of the same order, that is used to correct
- We deal with two cryomodule designs
  1. **CM Type-3**: eighth cavities and one quadrupole at the end



  2. **CM Type-4**: like in the baseline design of BC1+BC2: quadrupole in the middle



$\Rightarrow$ Quadrupoles **must be** the **pivot** of the rotation

$\Rightarrow$ We used a simplex optimization. To simplify its implementation, we used only:

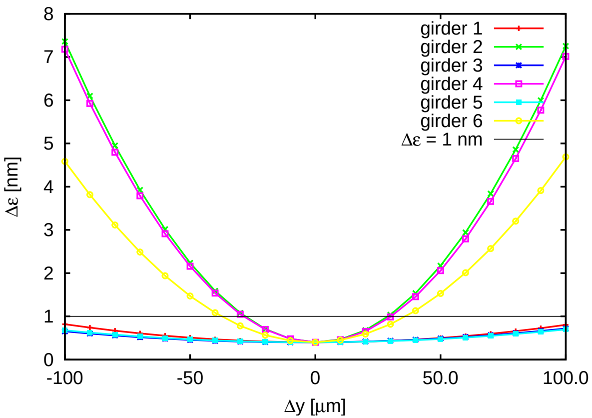
- **BC1S**: 3/6 CM in the RF section of BC1S and 3/36 CM in the pre-linac accelerating section
- **BC1+BC2**: 3/3 CM in the RF section of BC1 and 4/45 CM in the RF section of BC2

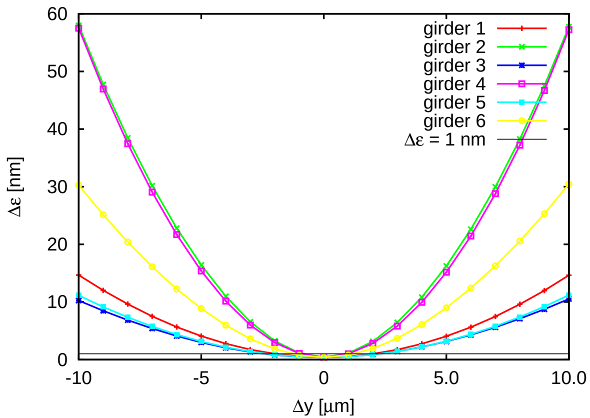
Girder Pitch Sensitivity

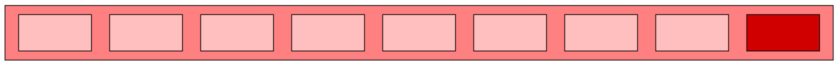
$\Rightarrow$ Emittance growth depend on the square of the pitch angle

$$\epsilon = \sqrt{< x >< x' > - < xx' >}; \qquad x' = x'_0 + \Delta\phi; \qquad \Delta\epsilon \ \propto \ \Delta\phi^2$$

- Starting from the optimum for RF-Kick + Wakes, where $\Delta\epsilon_y = 0.4$ nm
- Each girder's end has been moved individually to see its impact on the emittance growth







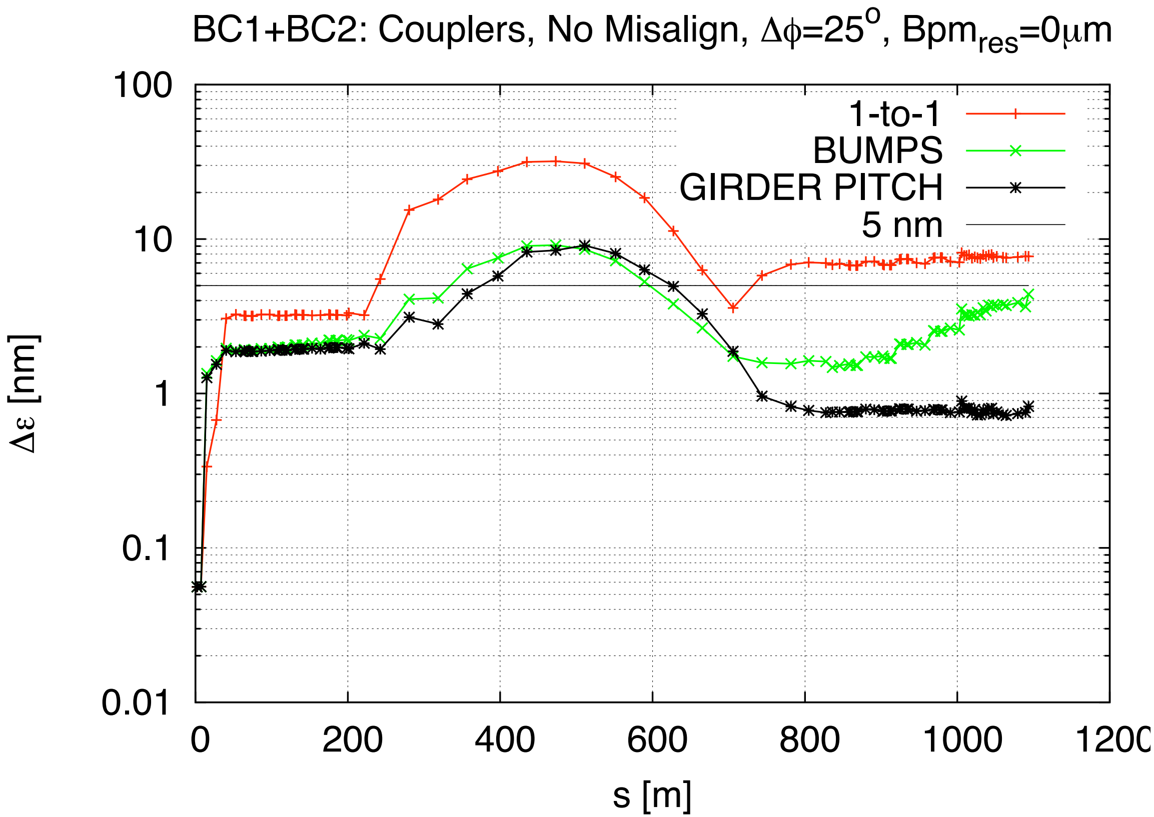
1^{st} end 2^{nd} end

- Maximum allowed vertical displacement in μm that causes $\Delta\epsilon_y \ \Rightarrow$ 1 nm

Girder	1	2	3	4	5	6
1^{st} end	$\pm$120	$\pm$28	$\pm$145	$\pm$29	$\pm$144	$\pm$36
2^{nd} end	$\pm$20	$\pm$9	$\pm$23	$\pm$9	$\pm$23	$\pm$12

Emittance Growth due to Couplers in BC1+BC2

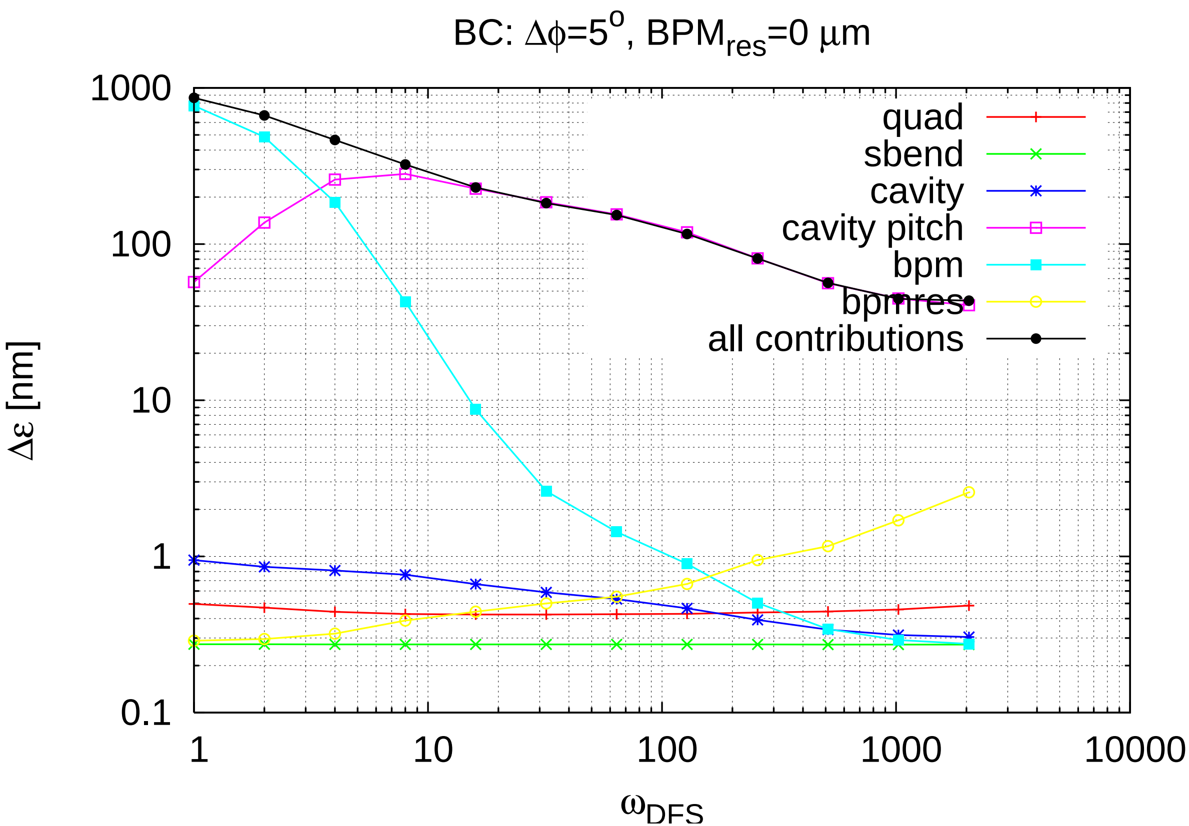
- Case B. Vertical emittance growth after correction (no misalignments, bpm resolution 0)



⇒ Final vertical emittance growth $\boxed{\Delta\epsilon = 0.8 \text{ nm}}$

$\Delta\epsilon_y$ due to Misalignments in BC1+BC2

- Case A. Final vertical emittance growth as a function of ω, individual misalignments



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:

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