BC Alignment Issues

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GDE Main Linac & Beam Dynamics

- Study Case: impact of misalignments, coupler kicks
- Emittance Preservation Techniques: BBA, girder pitch, crab cavities correction
- Conclusions and Future Plans

Emittance Growth in RTML

Region	BBA method	Dispersive or Chromatic mean Emittance Growth	Coupling mean emittance Growth
Return Line	Kick Minimization and feed-forward to remove beam jitter	0.15 nm	2 nm (without correction)
Turnaround and spin rotator	Kick Minimization and Skew Coupling Correction	1.52 nm (mostly chromatic)	0.4 nm (after correction)
Bunch Compressor	KM or DFS and Dispersion bumps	greater than 4.9 nm (KM + bumps) 2.68 nm (DFS and bumps)	0.6 nm (without correction)
Total		~5 nm almost all from BC	3 nm (without complete correction)

Beam Dynamics Study Cases

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

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

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

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

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

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

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

Alignment Procedure

- **Beam-Based Alignment**

  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

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

  3) Dispersion bumps optimization

     - as there are no skew quadrupoles in the lattice, we used two *ideal* bumps η, η'

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

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

  4) *new* Girder pitch optimization / Crab cavity compensation

- **Reminder**: Dispersion Free Steering

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

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

Girder Pitch Optimization

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

- Like RF-kick, cavity pitch gives two contributions: an average kick and a slope along the bunch, proportional to the RF phase. This slope can be used to compensate RF-kick and coupler wakes's slope

- Estimation for BC1S-PreLinac's cryomodules ($G = 31.5$ MV, $\psi = 5.3^o$, $n = 8$ cavities):
  - Misalignment: average kick spread along the bunch, due to cavity pitch $\sigma_{y'} = 300$ μrad

$$< \Delta\vec{p} > \;\propto\; 31.5\ [\mathrm{MV}] \times \sin(5.3^o) \times 300\ [\mu\mathrm{rad}] \times \sqrt{8} \times (k\,\sigma_z) \;=\; \boxed{2.4\ \mathrm{kV} \times (k\,\sigma_z)}$$

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

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

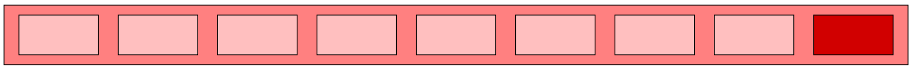
  $\Rightarrow$ The two contributions are of the same order

$\Rightarrow$ Therefore, the girder pitch angle α necessary to compensate RF-kick is

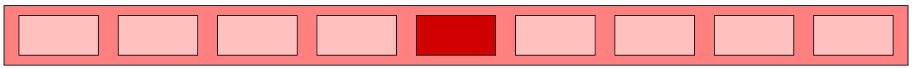
$$G \cdot \alpha \cdot \sin\psi \cdot N = \;2.9\ \mathrm{kV} \quad\Rightarrow\quad \boxed{\alpha = \frac{2.9\ [\mathrm{kV}]}{31.5\ [\mathrm{MV}] \cdot \sin(5.3^o) \cdot 8} \approx 125\ \mu\mathrm{rad}}$$

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. 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



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

$\Rightarrow$ We used a simplex optimization. To speed it up we used only:

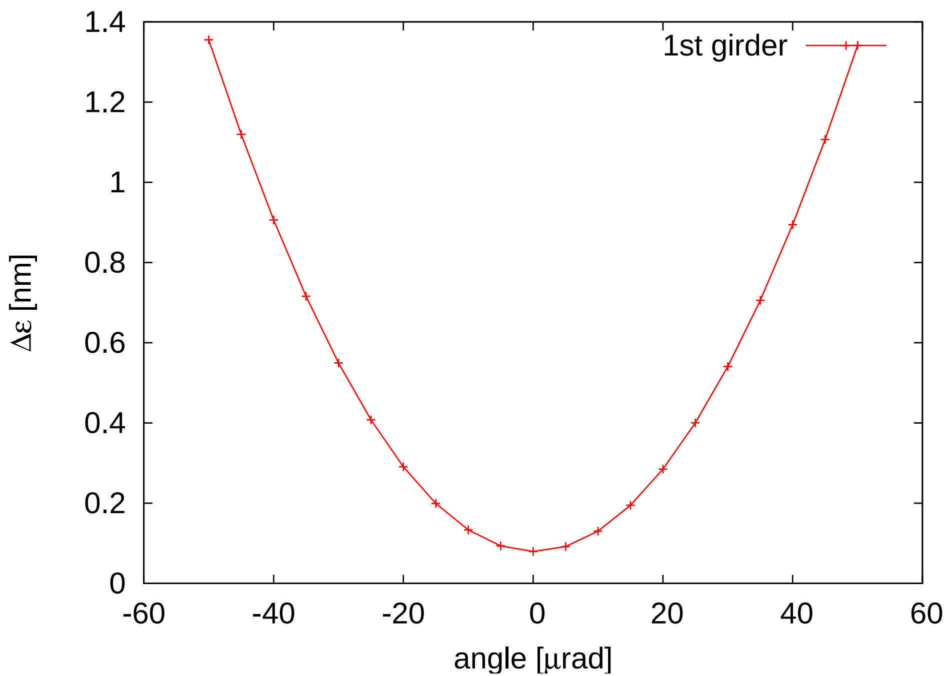
- **BC1S**: 3/6 CM in the RF section of BC1S and 3/36 CM in the pre-linac accelerating section
- **BC1+BC2**: 3/3 CM in the RF section of BC1 and 4/45 CM in the RF section of BC2

Vertical Emittance as a Function of the Girder Pitch

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

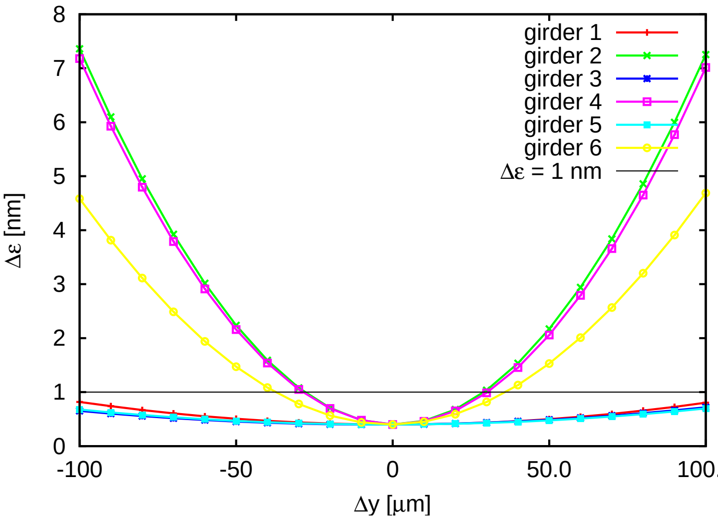
⇒ Emittance growth depend on the square of the pitch angle

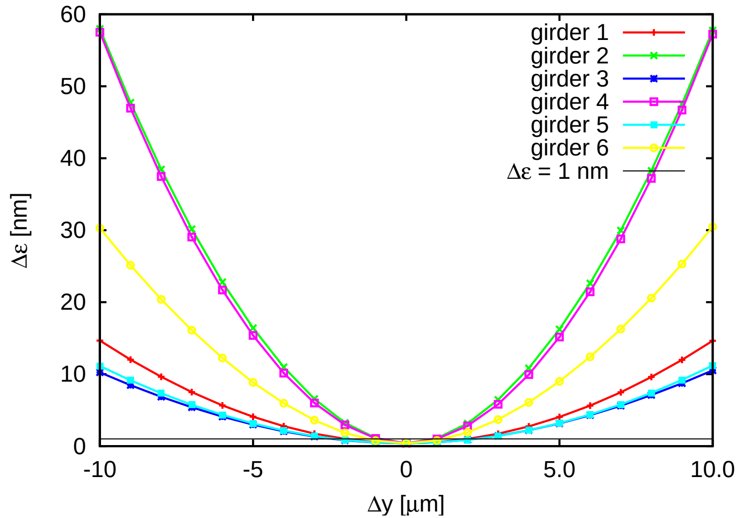
$$\epsilon = \sqrt{<x><x'> - <xx'>}; \quad x' = x'_0 + \Delta\phi; \quad \Delta\epsilon \propto \Delta\phi^2$$

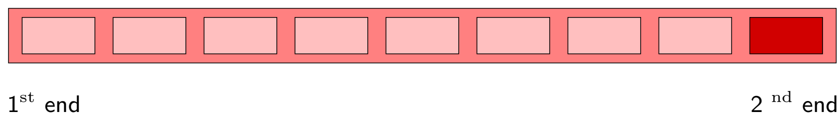


Girder Pitch Sensitivity

- 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







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

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

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**
  - PLACET simulation code

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

  ⇒ incoherent synchrotron radiation is turned off

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

  ⇒ Studied both BC1S and BC1+BC2

  ⇒ scan of the DFS's weight ω

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

  ⇒ in all results, dispersion-corrected emittance is shown

Summary of BBA Setup in BC1S

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

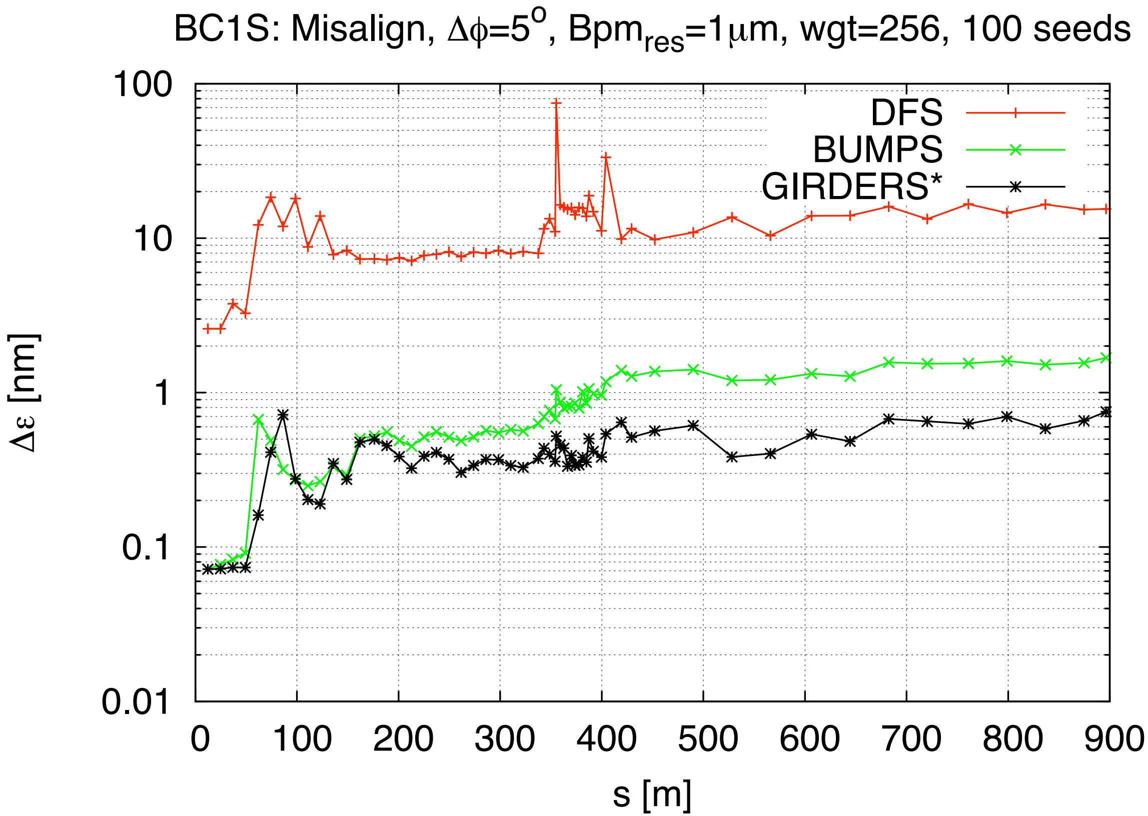
- Dispersion Free Steering
  - two test beams
  - $\Delta\phi = \pm 5^o$ phase offset in the RF section of BC1
  - phase syncronization at entrance of Pre-Linac is necessary
    $\Rightarrow$ otherwise RF-Kicks spoils the test beams, due to their large phase difference (6 $\sigma_z \approx 6$ mm)

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

- Girder Pitch optimization
  - using 3 CM in BC1S, 1 every 2
  - using 3 CM in BC1S pre-linac, 1 every 12

Emittance Growth due to Misalignments in BC1S

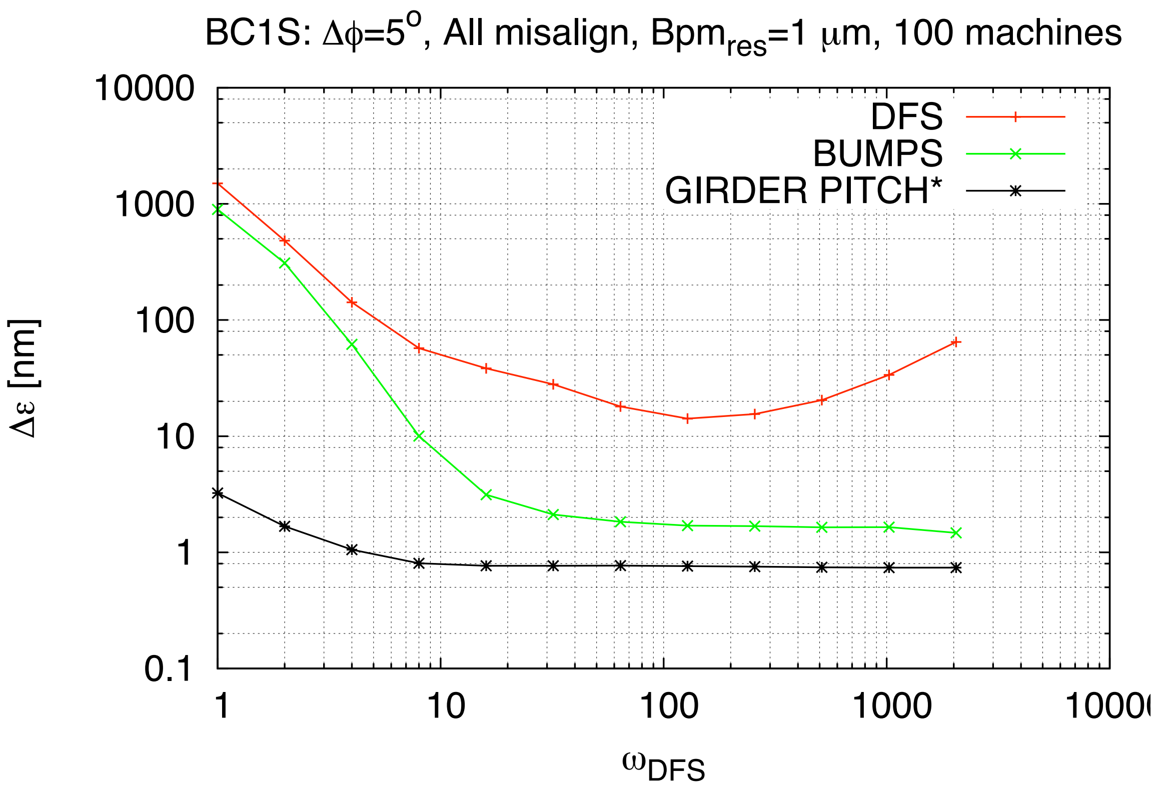
- Emittance Growth along the beamline, average of 100 machines



⇒ 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



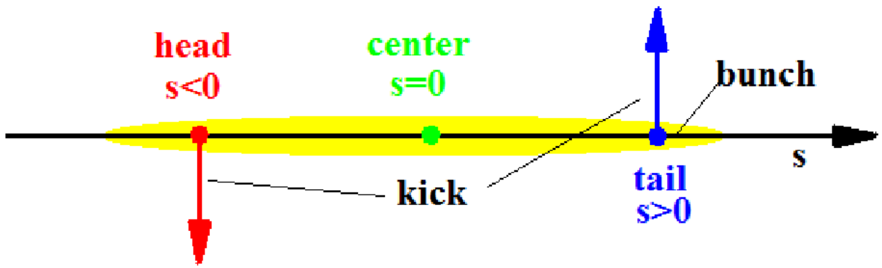
$\Rightarrow$ Minimal vertical emittance growth $\boxed{\Delta\epsilon = 0.8 \text{ nm}}$

Emittance Growth due to Couplers in BC1S

- Couplers induce transverse RF-kick and wakefields
- Emittance growth due to RF-Kick (V. Yakovlev's analytical estimation) is

$$\varepsilon \approx \varepsilon_0 + \frac{(F')^2 \sigma^2 \beta^3 \gamma_0}{2U_0^2} \left(1 - 2\sqrt{\frac{\gamma_0}{\gamma(z)}} \cos(z/\beta) + \frac{\gamma_0}{\gamma(z)} \right).$$

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

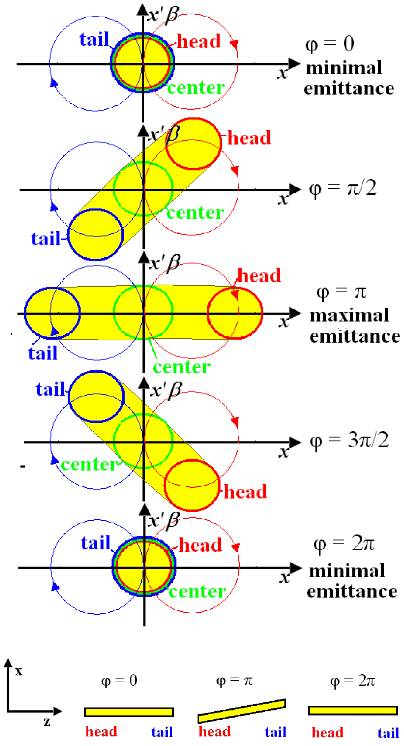


⇒ this affects the emittance growth behavior

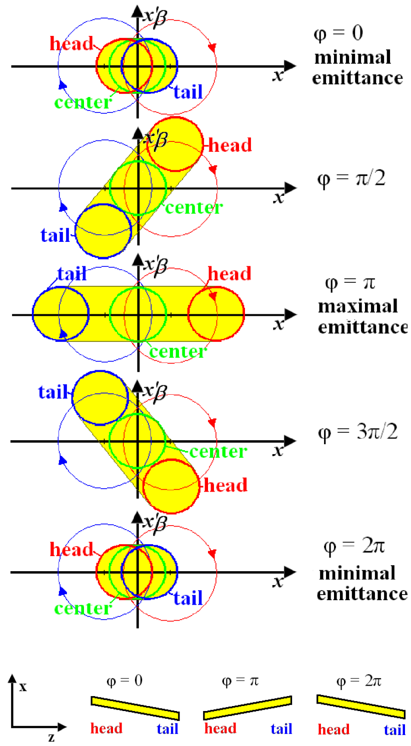
⇒ when $z/\beta = 2\pi n$ and there is no acceleration $\Delta\epsilon = 0$

Emittance Growth due to RF-Kick

- Emittance growth behavior is different in presence of acceleration:



(no acceleration)



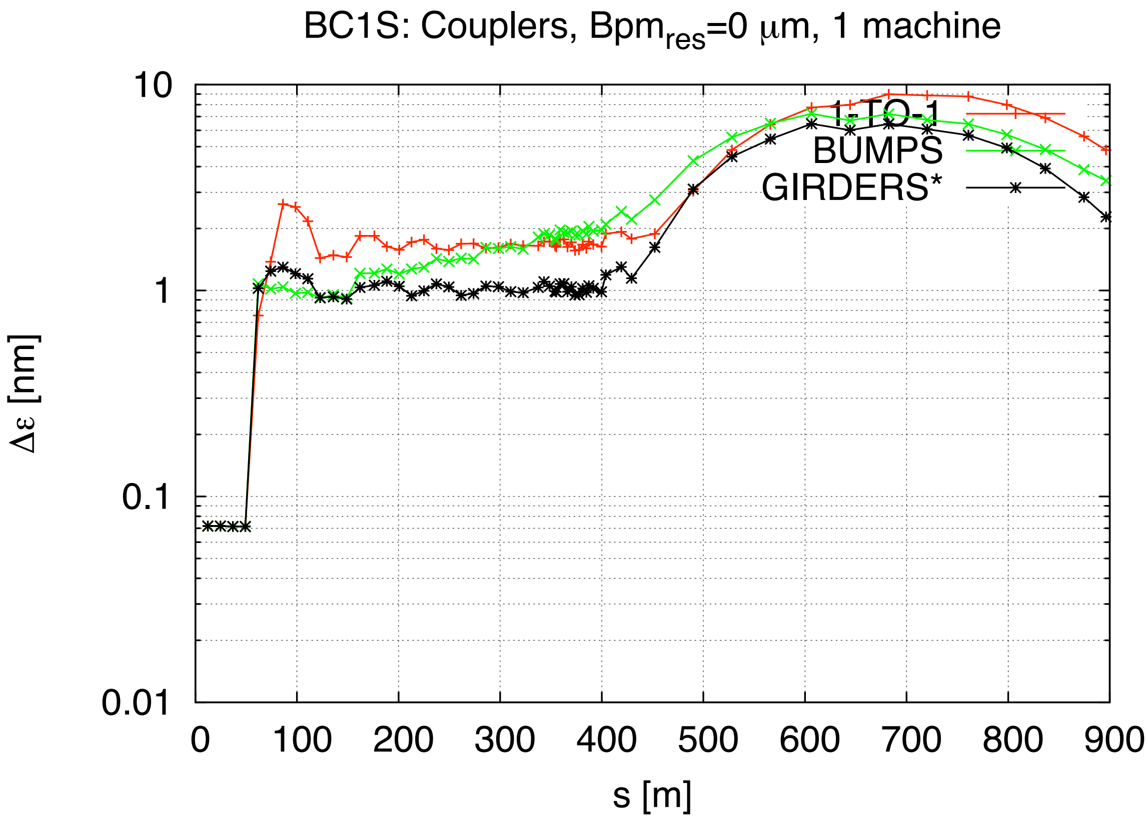
(acceleration)

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

⇒ **Note:** being a systematic effect, simulating one single machine with perfect BPMs is enough

Emittance Growth due to Couplers in BC1S

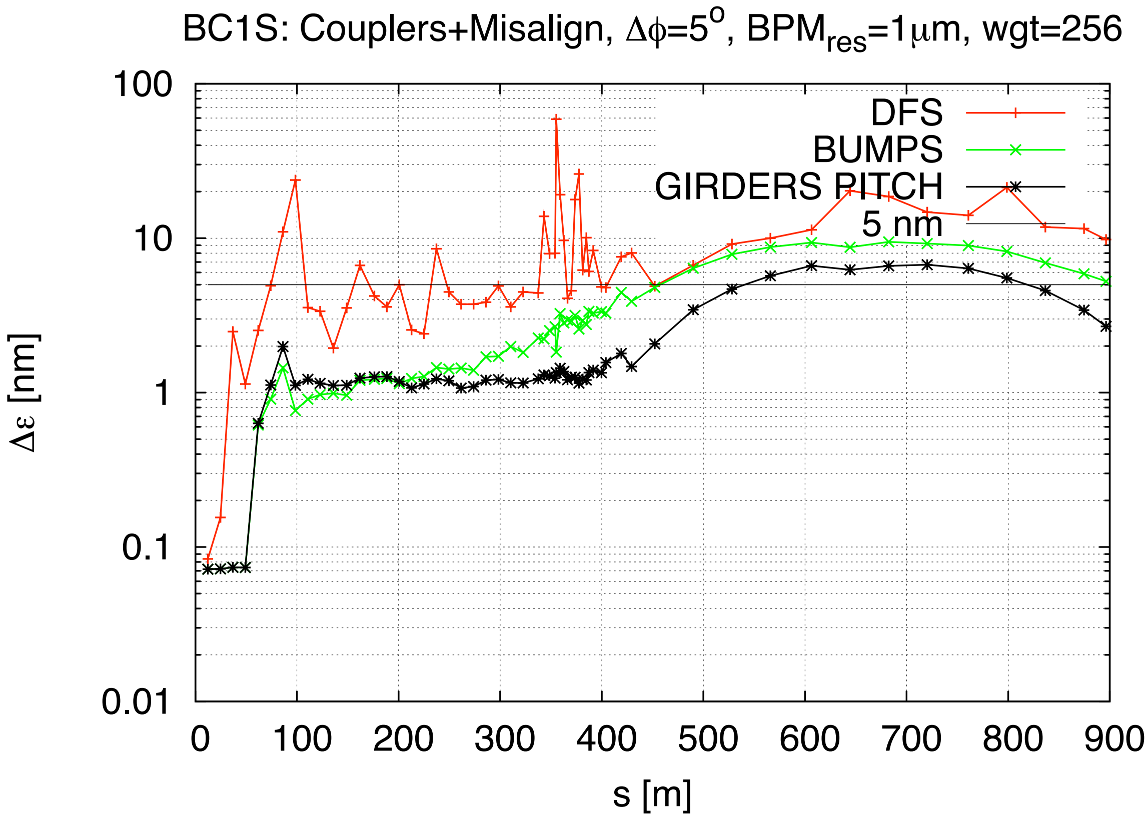
- Vertical emittance growth after correction (no misalignments, bpm resolution 0)



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

Emittance Growth due to Misalign+Couplers in BC1S

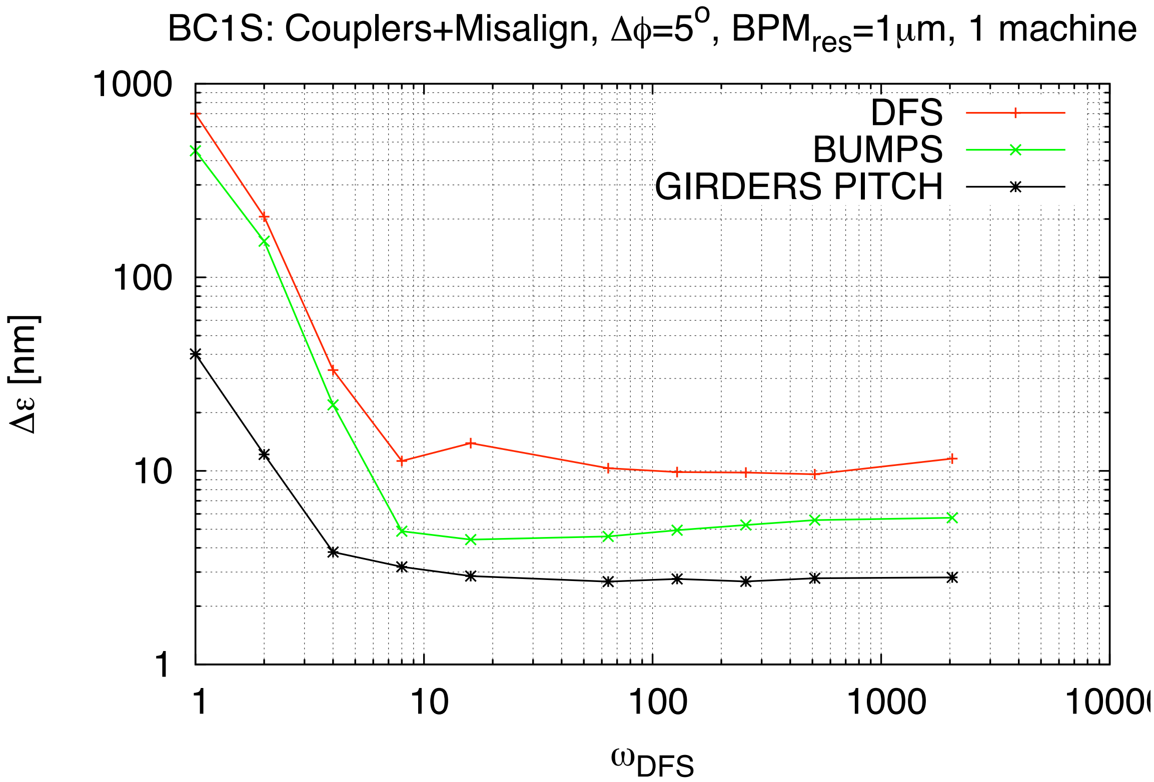
- Emittance Growth along the beamline, 1 machine



⇒ Final vertical emittance growth is $\boxed{\Delta\epsilon = 2.6 \text{ nm}}$

Emittance Growth due to Misalign+Couplers in BC1S

- Final vertical emittance growth as a function of ω



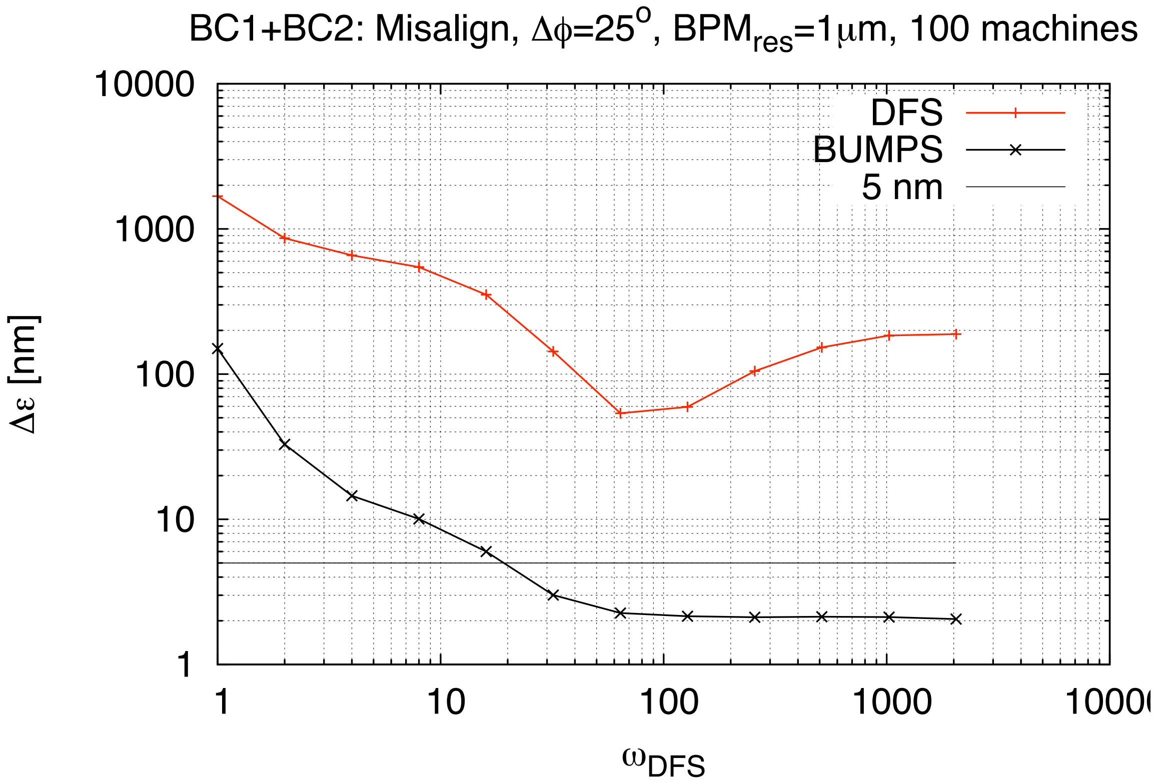
$\Rightarrow$ Minimal vertical emittance growth $\boxed{\Delta\epsilon = 2.6 \text{ nm}}$

Summary of BBA Setup in BC1+BC2

- Misaligmments are 300 μx, BPM resolution is 1 μm
- RF-Kick wakes
- 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 syncronization at entrance of BC2 is necessary
      $\Rightarrow$ otherwise RF-Kicks completely spoils the test beams, due to their 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, 1 every 12

Emittance Growth due to Misalignments in BC1+BC2

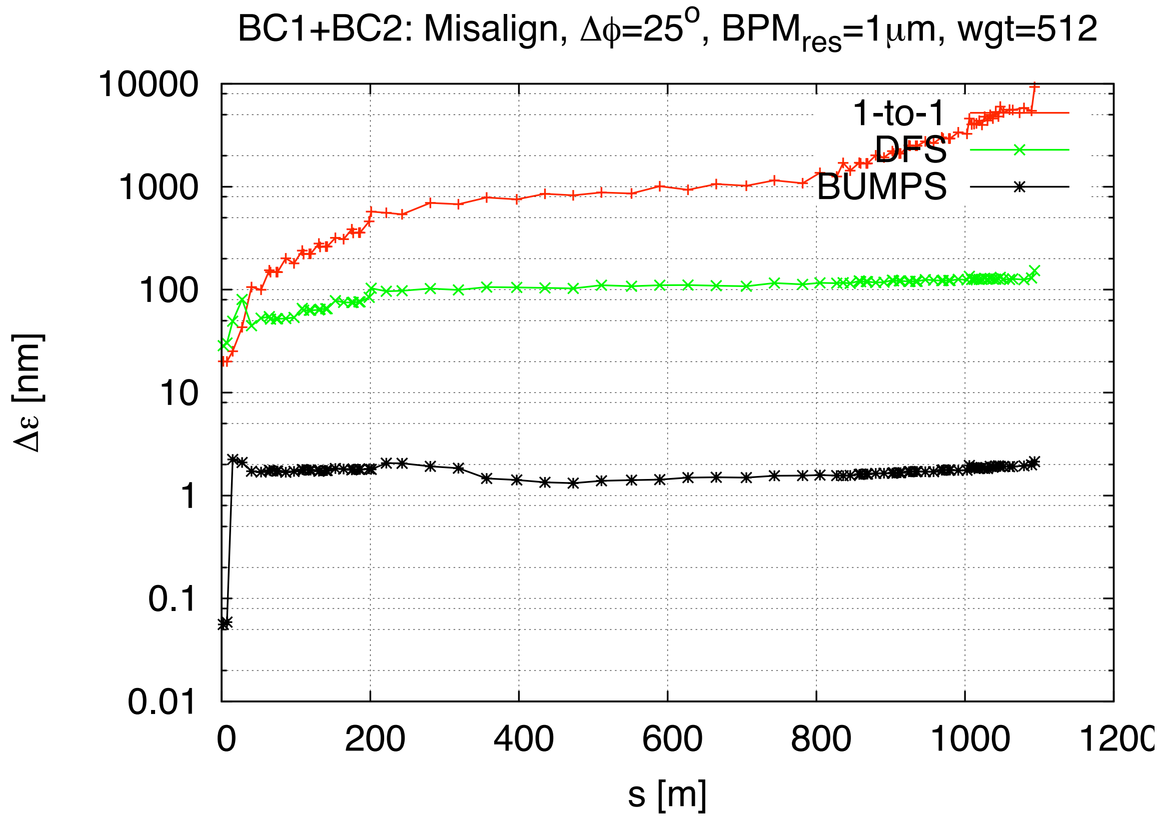
- Case A. Final vertical emittance growth as a function of ω



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

Vertical Emittance Growth along BC1+BC2

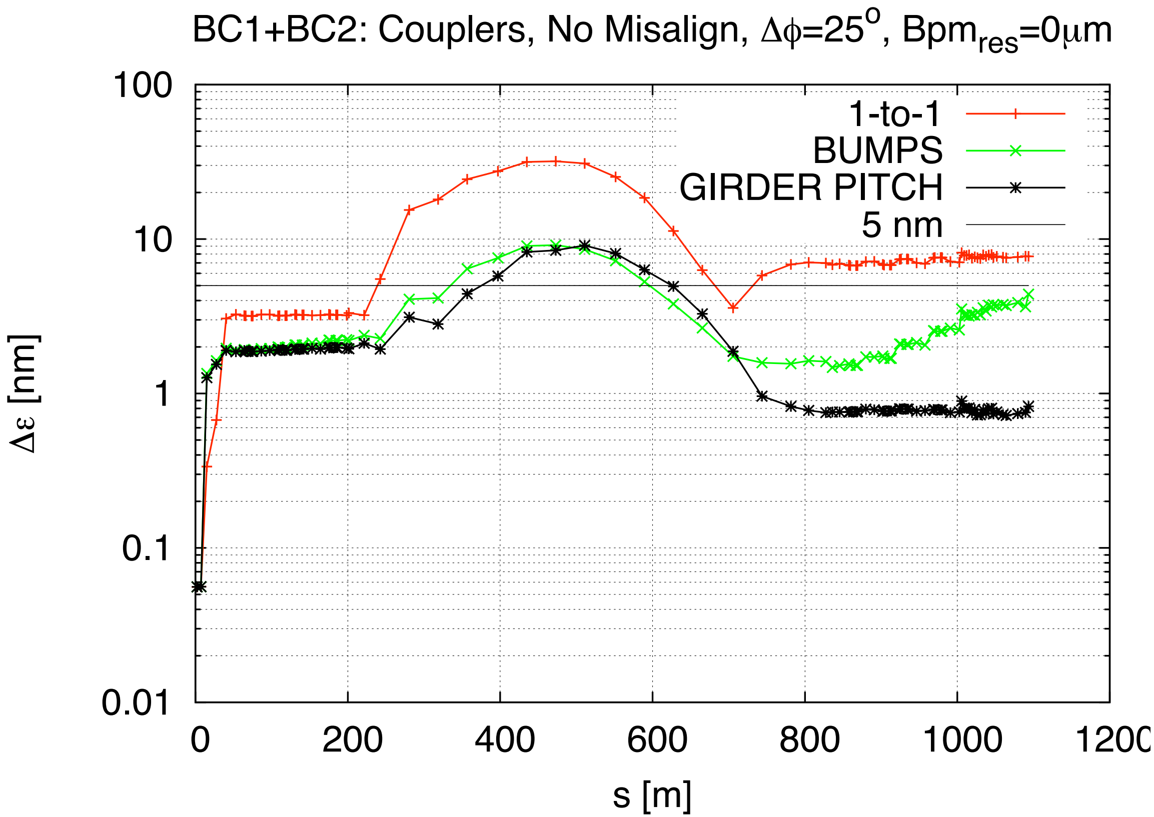
- Case A. Emittance Growth along the beamline, average of 100 machines



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

Emittance Growth due to Couplers in BC1+BC2

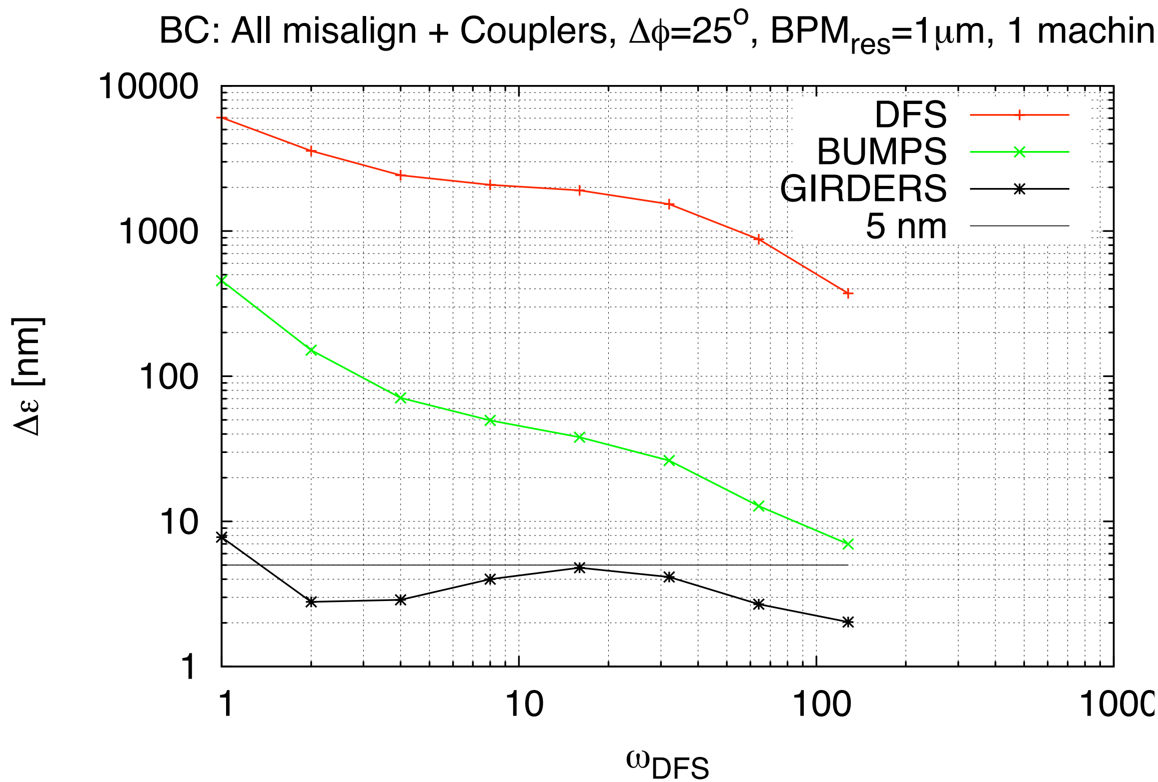
- Case B. Vertical emittance growth after correction (no misalignments, bpm resolution 0)



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

Emittance Growth due to Misalignments + Couplers in BC1+BC2

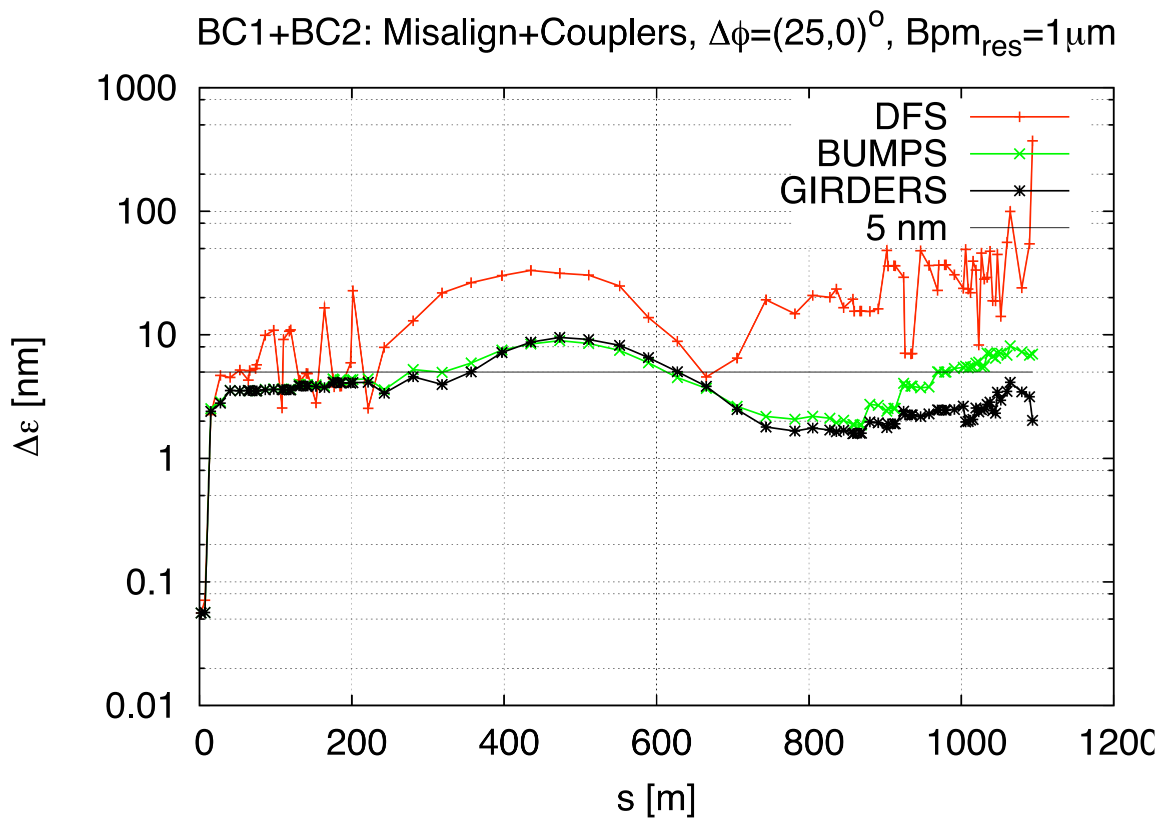
- Case B. Final vertical emittance growth as a function of ω



$\Rightarrow$ Minimal vertical emittance growth $\boxed{\Delta\epsilon = 2.0 \text{ nm}}$

Vertical Emittance Growth along BC1+BC2

- Case B. Emittance Growth along the beamline, 1 machine



⇒ Final vertical emittance growth is $\boxed{\Delta\epsilon = 2.0 \text{ nm}}$

Crab Cavity Optimization in BC1S

- 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.

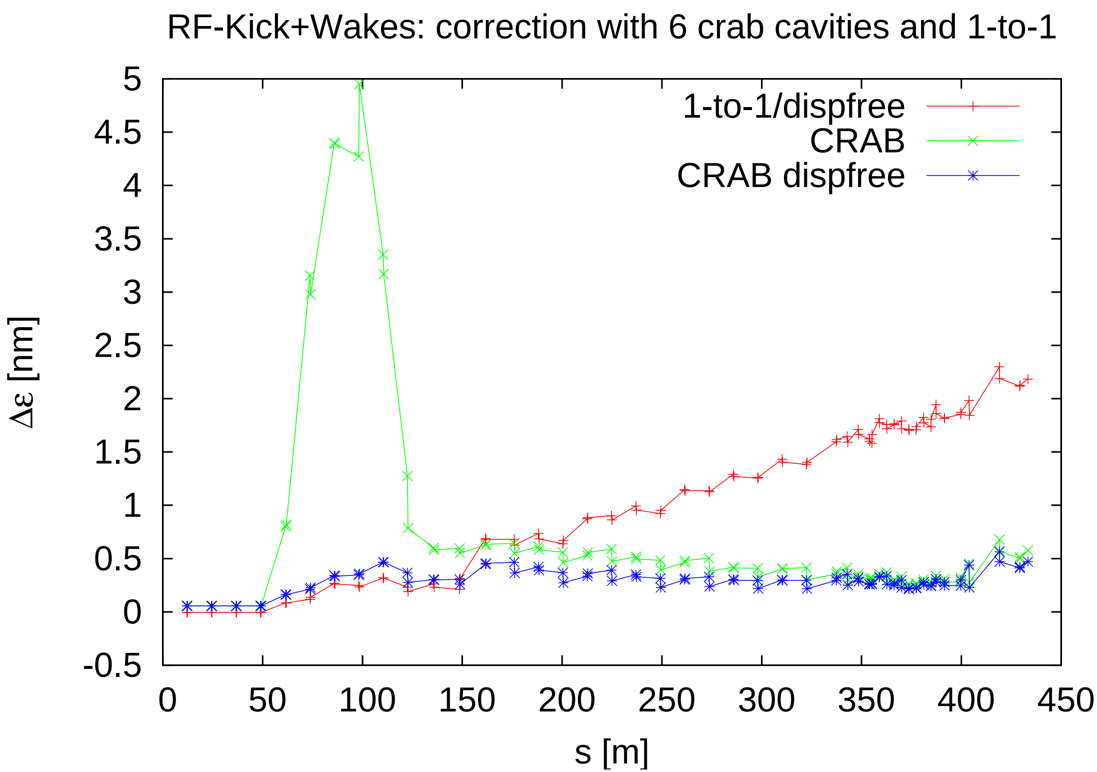
⇒ 12 knobs to optimize

- 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

Crab Cavity 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 (it is 0.4 nm for Girder optimization)

Crab Cavity Correction Result in BC1S

- 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

- Estimate of the sensitivity must be performed...

Summary Table of Vertical Emittance Growths

	Technique	Misalignments	Couplers$^{(1)}$	Misalign+Couplers
BC1S	DFS	14.8 nm	4.8 nm	27.0 nm
	BUMPS	1.47 nm	3.4 nm	4.6 nm
	GIRDER	0.8 $^{(*)}$ nm	2.2 nm	2.6$^{(*)}$ nm

	Technique	Misalignments	Couplers$^{(1)}$	Misalign+Couplers
BC1+BC2	DFS	91.2 nm	7.7 nm	371.0 nm
	BUMPS	2.1 nm	4.3 nm	6.9 nm
	GIRDER	-	0.8 nm	2.0 nm

(1) 1 machine

(*) 40 machines

Conclusions and Work Plan

- Emittance growth due to misalignments and couplers seems to compensated both for BC1S and BC1+BC2

- 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