

# Emittance Preservation in the ILC RTML

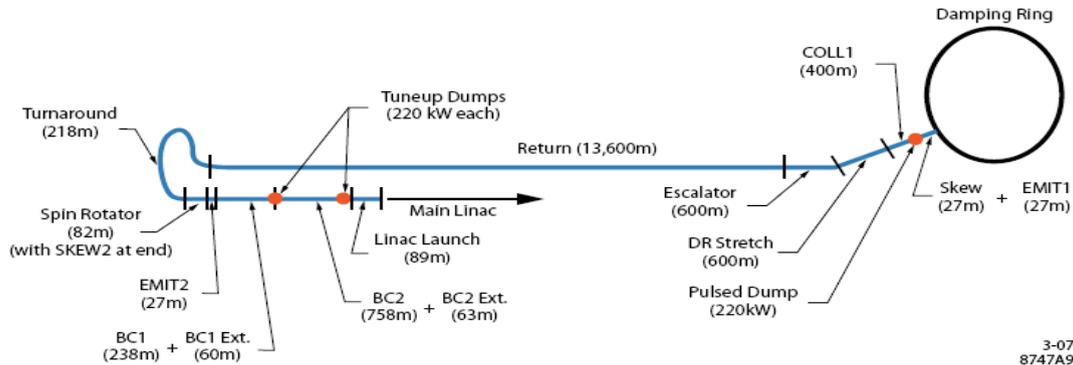
Andrea Latina, A. Lunin, N. Solyak, V. Yakovlev (FNAL)

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**ILC/CLIC Beam Dynamics Workshop, CERN**

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

# 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)

# ILC Bunch Compressor Baseline Design

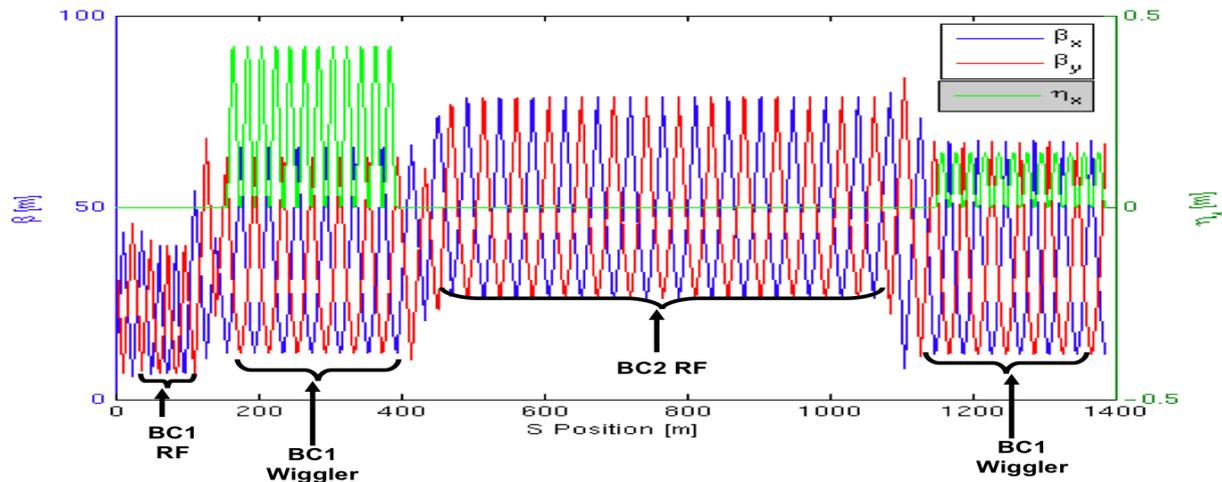
## Two-stage compression

### • BC Stage 1:

- Start bunch length = 6 mm / 9 mm
- End bunch length  $\approx$  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  $\approx$  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  $\rightarrow$  0.3 mm, is being studied

# Sources of Emittance Growth in 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**

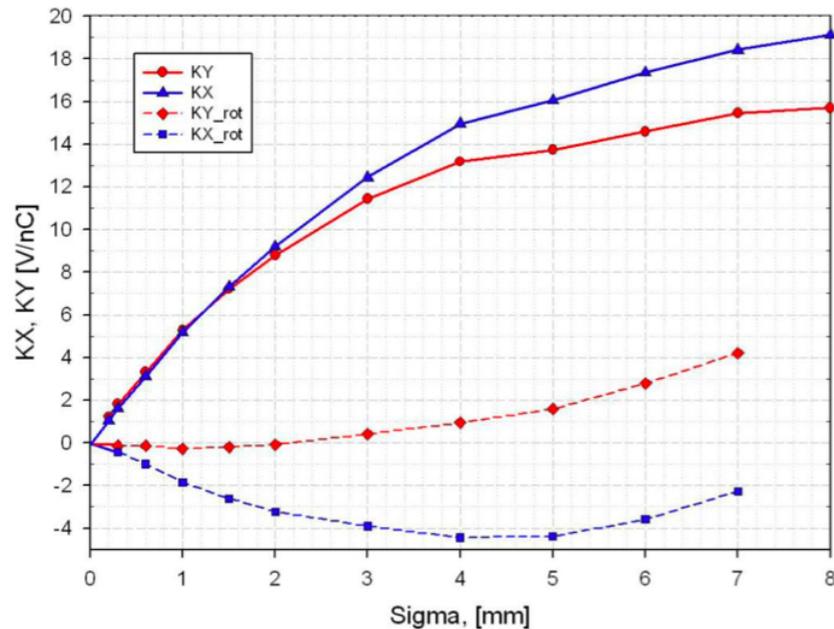
- **Couplers**

- RF-Kick
- Wakefields

⇒ Most critical : misalignments (dispersive and chromatic effects), couplers' transverse kicks (bunch blow up)

# Coupler Wakefields

- 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)

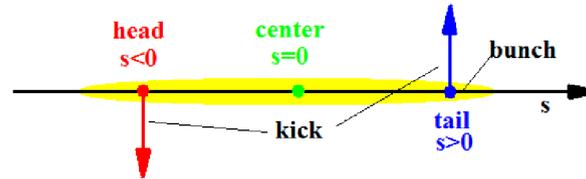
# Coupler RF-Kick

- Couplers' asymmetry induces a transverse RF-kick:

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

where  $\vec{k} \simeq (-7.2 + 11i) \times 10^{-6}$  (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

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

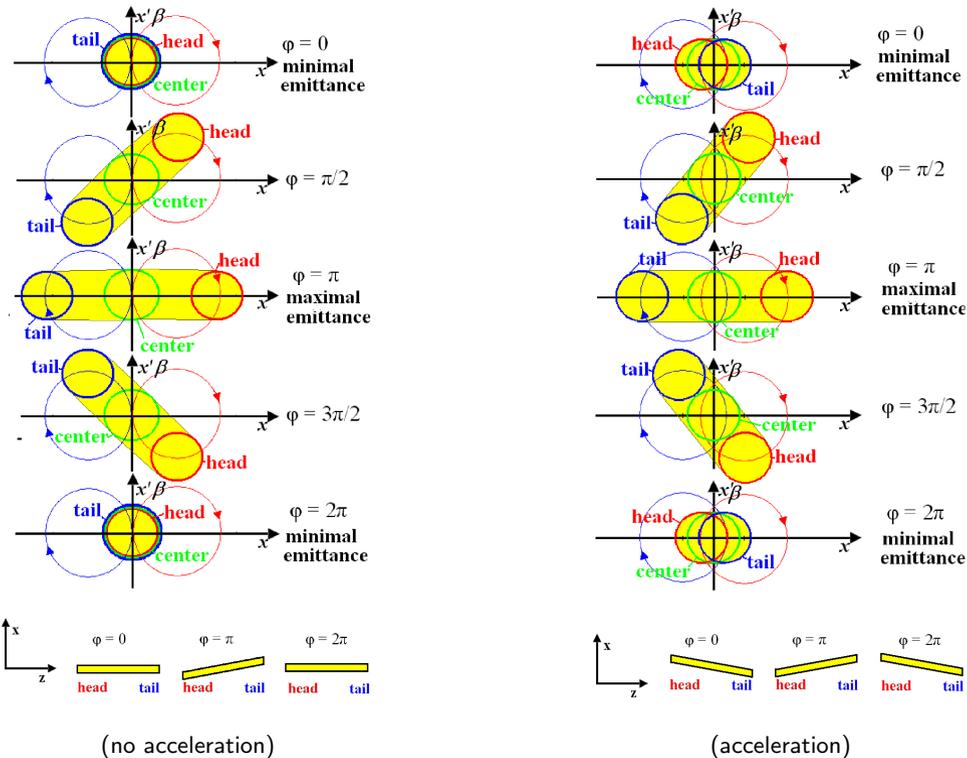
where  $\epsilon_0$  is the initial emittance,  $F'$  is the first derivative of the kick for  $z = 0$ ,  $\sigma$  is the bunch length,  $\beta$  is the betatron amplitude,  $U_0$  is the initial energy and  $\gamma_0$  the corresponding relativistic factor.

⇒ 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:

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

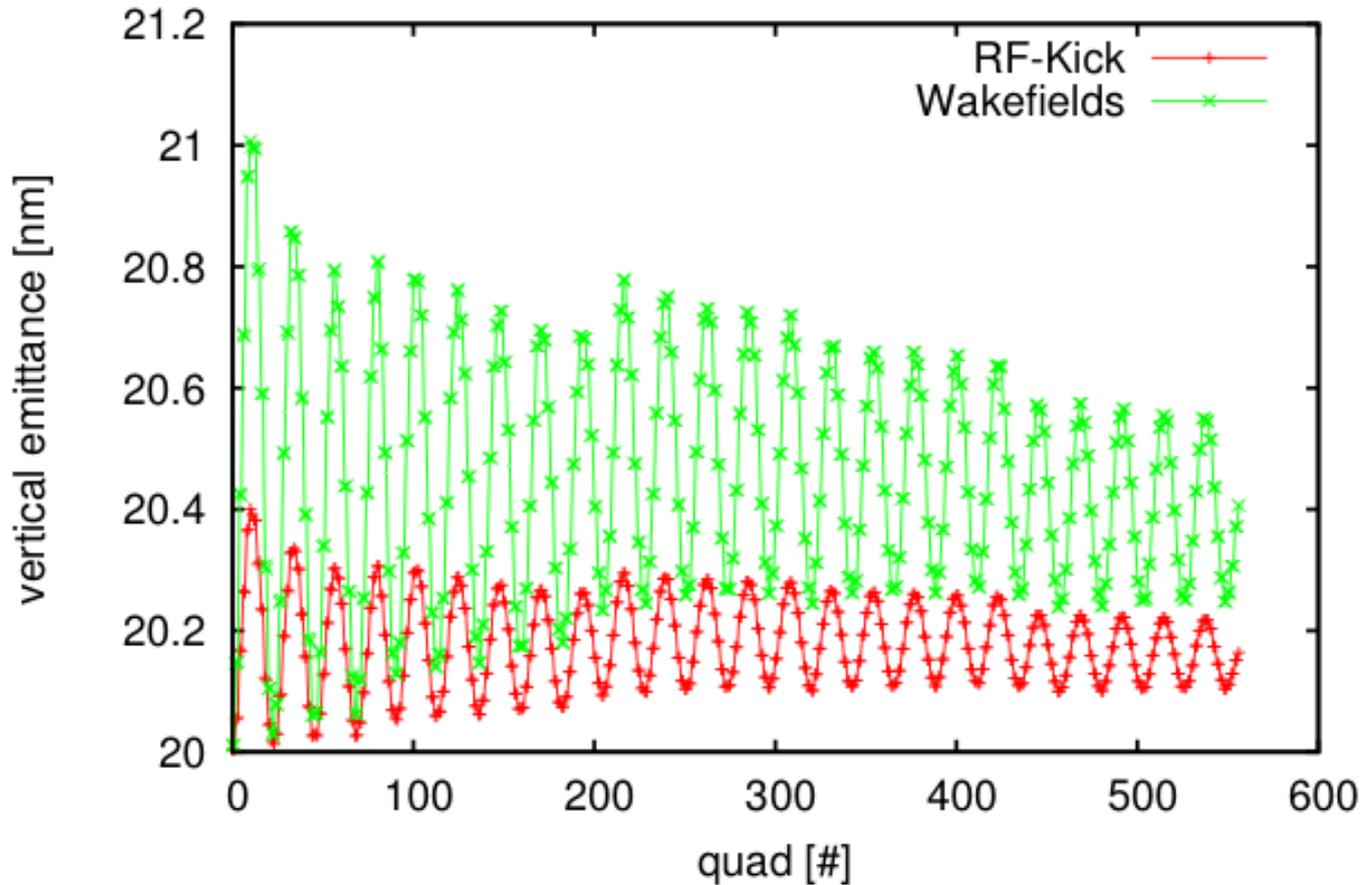


$\Rightarrow$  Emittance growth is minimum when  $z/\beta = 2\pi n$

$\Rightarrow$  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



# Study Cases

- Effect of **element misalignments** and correction

- “COLD” model

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

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

⇒ impact and cure using beam-based alignment

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

⇒ impact and cure using beam-based alignment

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

# Beam-Based Alignment

- **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)

- 3) Dispersion bumps optimization

- we used two *dispersion* bumps  $\eta, \eta'$  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) new Girder pitch optimization / Crab cavity compensation

⇒ **Dispersion Free Steering**

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

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

# Girder Pitch Optimization

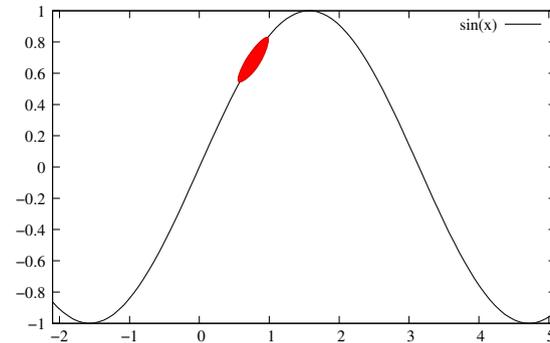
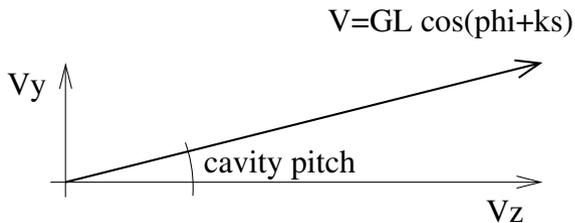
- The idea behind **Girder Pitch Optimization** is that Cavity Pitch kick can compensate RF-kick and coupler wakes

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

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

# Girder Pitch Optimization

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

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

$$\langle \Delta \vec{p} \rangle \propto 31.5 \text{ [MV]} \times \cos(5.3^\circ) \times 300 \text{ [\mu rad]} \times \sqrt{8} \times (k \sigma_z) = \boxed{26.6 \text{ kV} \times (k \sigma_z)}$$

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

$$\langle \Delta \vec{p} \rangle \propto 11.7 \cdot 10^{-6} \times 31.5 \text{ [MV]} \times 8 \times (k \sigma_z) = \boxed{2.9 \text{ kV} \times (k \sigma_z)}$$

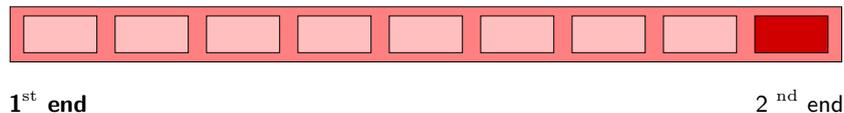
$\Rightarrow$  The two contributions are about of the same order

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

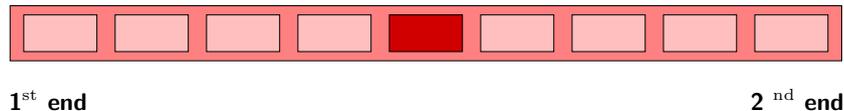
$$GL \cdot \theta \cdot \cos \psi \cdot N = 2.9 \text{ kV} \Rightarrow \boxed{\theta = \frac{2.9 \text{ [kV]}}{31.5 \text{ [MV]} \cdot \cos(5.3^\circ) \cdot 8} \approx 11.6 \text{ \mu rad}}$$

# 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. **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



⇒ Quadrupoles **must be** the **pivot** of the rotation

⇒ We used a simplex optimization. To simplify its implementation, we used only:

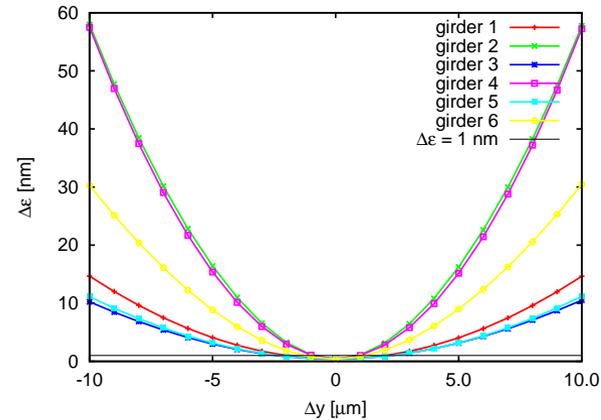
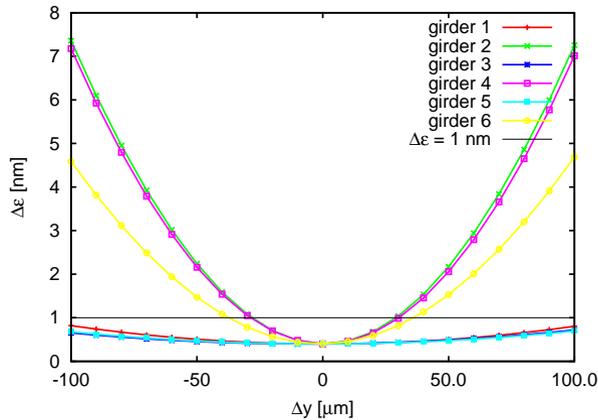
- **BC1S**: 3/6 CM in the RF section of BC1S and 3/36 CM in the pre-linac accelerating section
- **BC1+BC2**: 3/3 CM in the RF section of BC1 and 4/45 CM in the RF section of BC2

# Girder Pitch Sensitivity

⇒ Emittance growth depend on the square of the pitch angle

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

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



1<sup>st</sup> end

2<sup>nd</sup> end

- Maximum allowed vertical displacement in  $\mu\text{m}$  that causes  $\Delta\epsilon_y \Rightarrow 1 \text{ nm}$

Girder	1	2	3	4	5	6
1 <sup>st</sup> end	±120	±28	±145	±29	±144	±36
2 <sup>nd</sup> 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

- **Lattice:** ILC2007b

- **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**

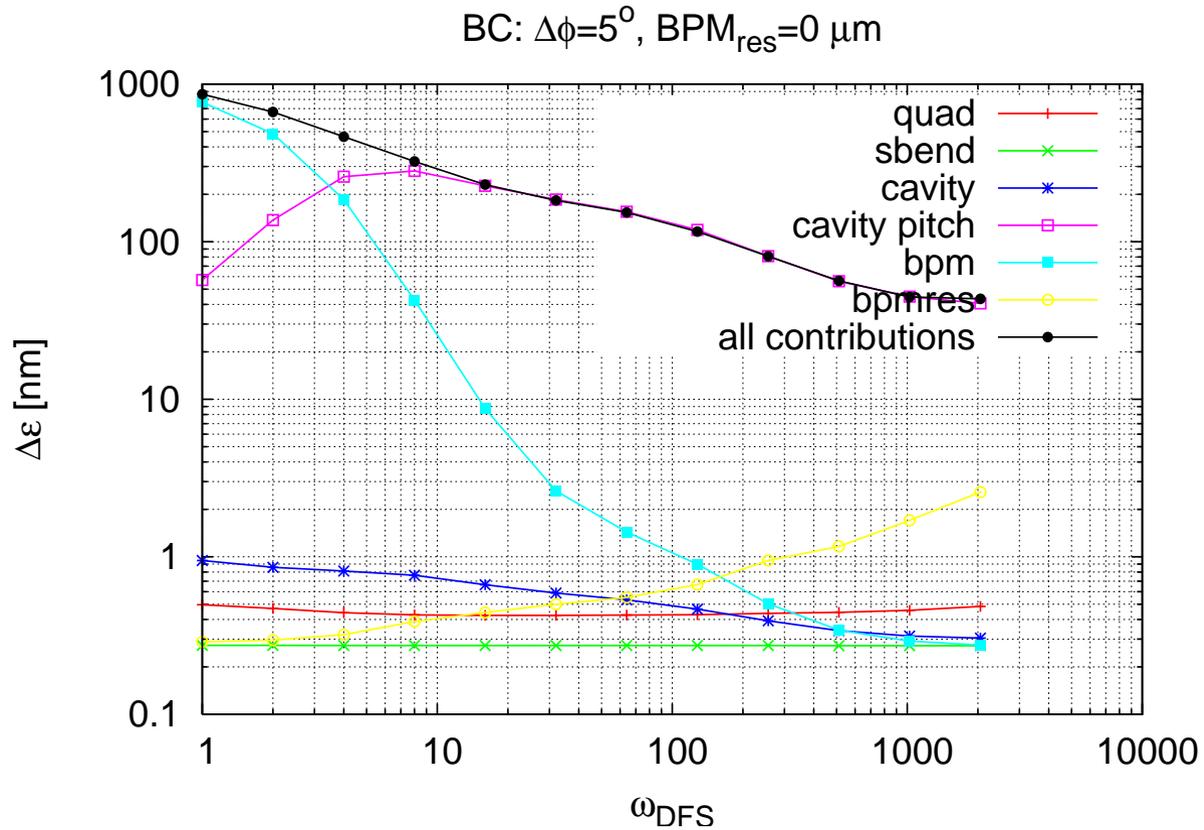
- ⇒ Studied both BC1S and BC1+BC2
- ⇒ scan of the DFS's weight  $\omega$
- ⇒ 100 machines (i.e. random seeds) have been simulated for each case (when possible)

# Beam-Based Alignment in BC1+BC2

- Misalignments are  $300 \mu\text{x}$ , BPM resolution is  $1 \mu\text{m}$
- RF-Kick wakes
- Dispersion Free Steering
  - two test beams
    - Case A: no Couplers.  $\Delta\phi = \pm 25^\circ$  phase offset in both the RF sections of BC1+BC2
    - Case B: Couplers
      - $\Rightarrow \Delta\phi = \pm 25^\circ$  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 ( $10 \sigma_z \approx 1 \text{ cm}$ )
- 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

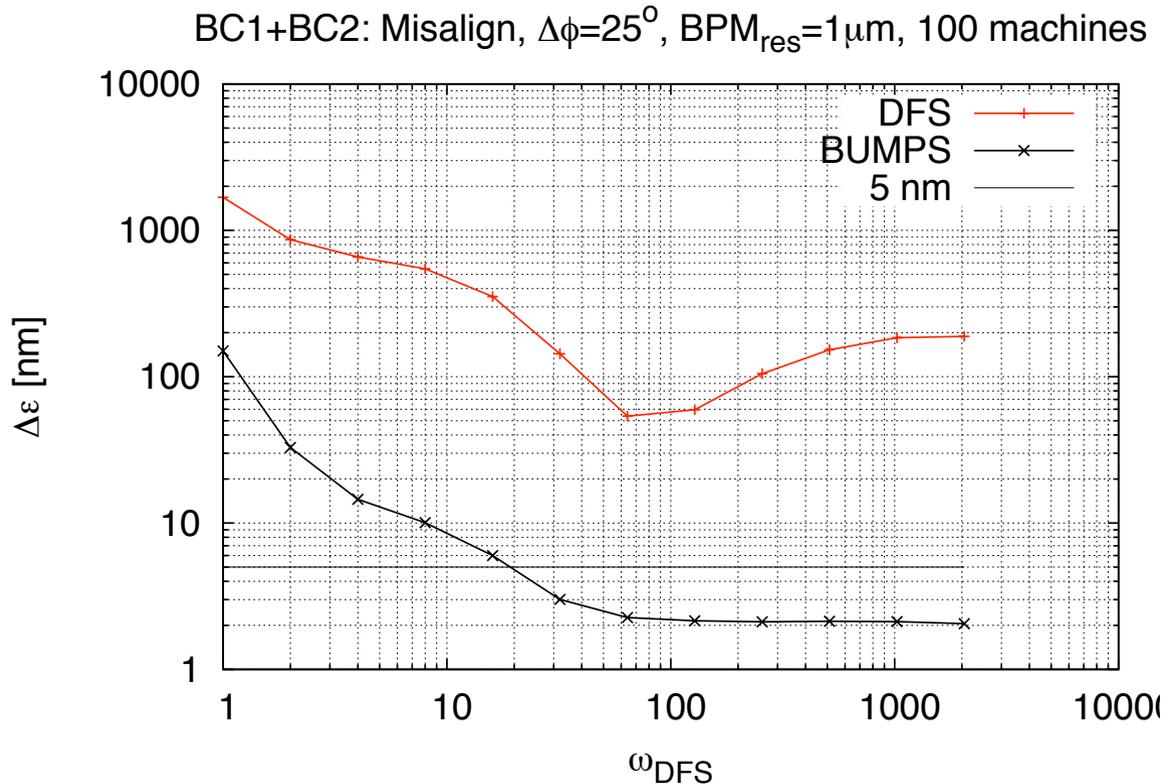
# Emittance Growth due to Misalignments in BC1+BC2

- Case A. Final vertical emittance growth as a function of  $\omega$ , individual misalignments



# Emittance Growth due to Misalignments in BC1+BC2

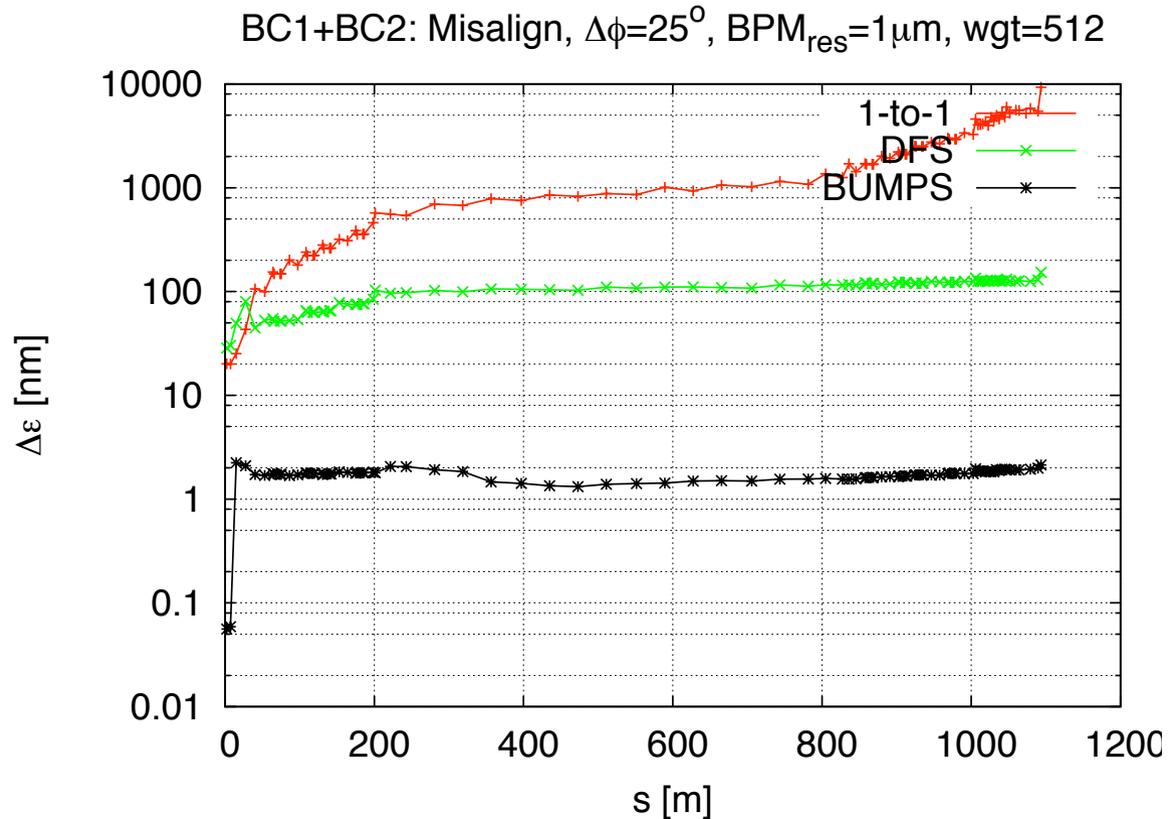
- Case A. Final vertical emittance growth as a function of  $\omega$



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

# Vertical Emittance Growth along BC1+BC2

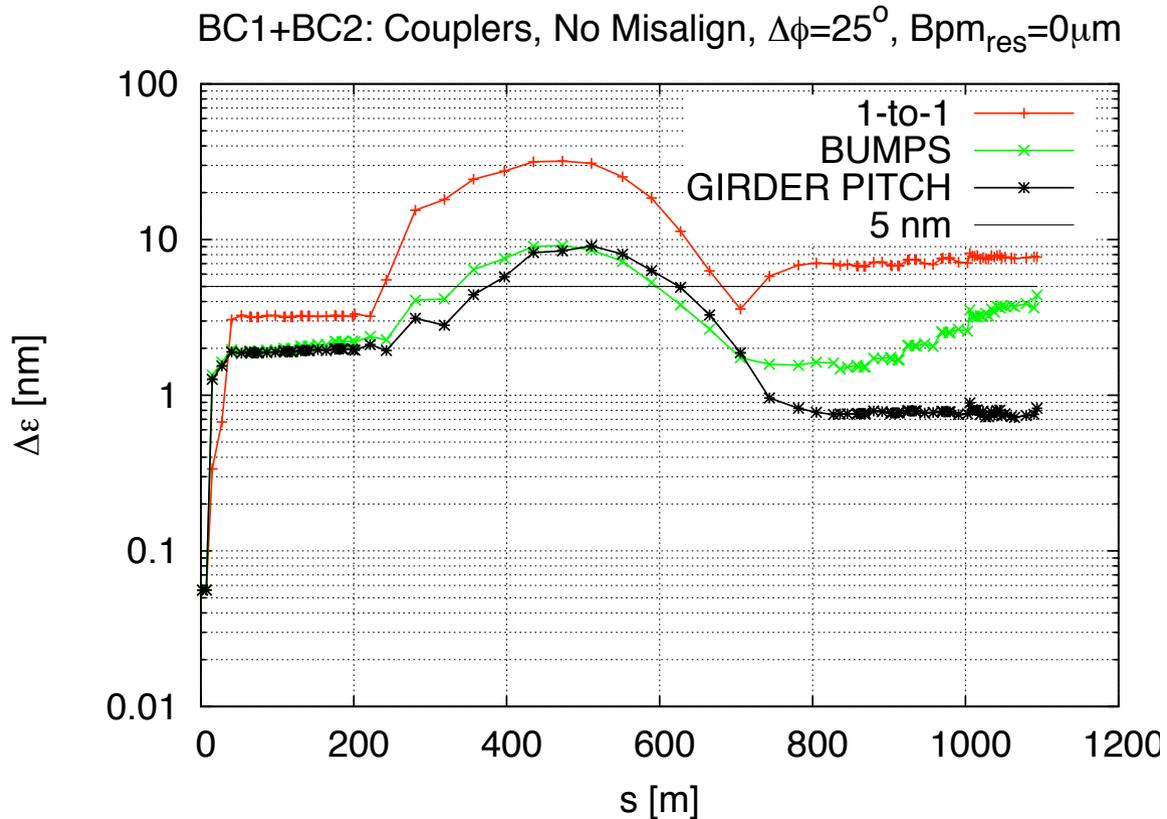
- Case A. Emittance Growth along the beamline, average of 100 machines



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

# Emittance Growth due to Couplers in BC1+BC2

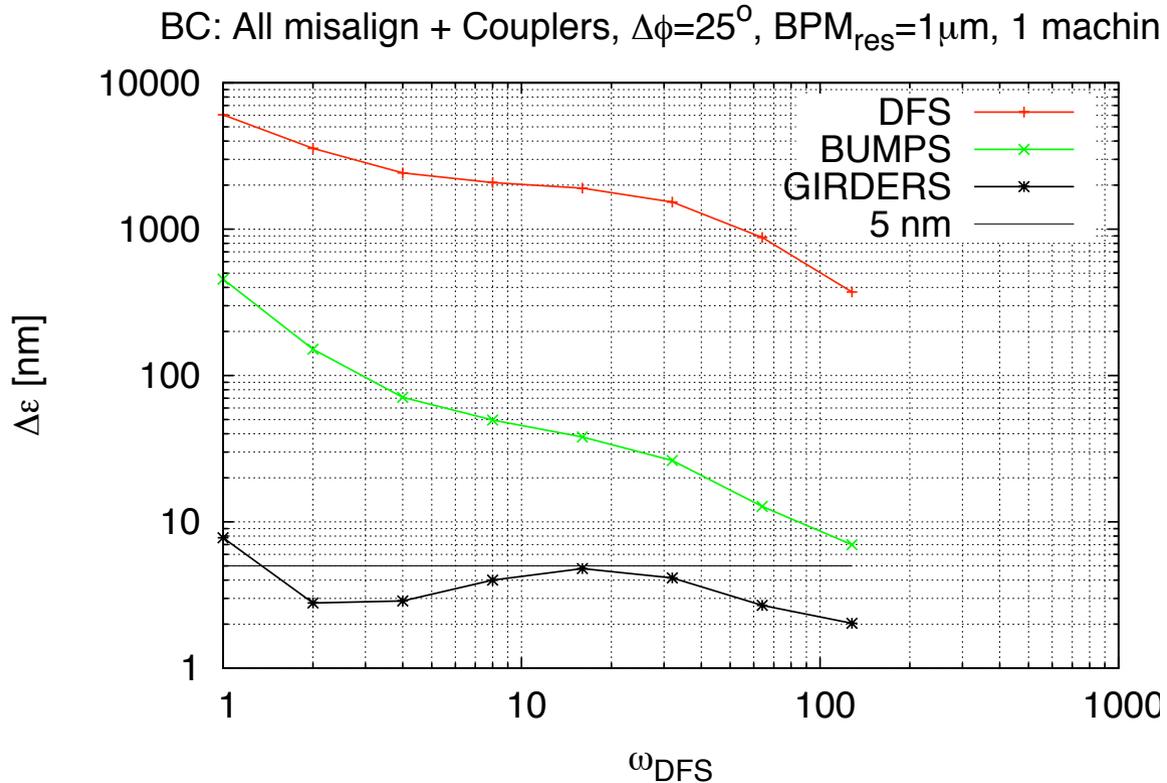
- Case B. Vertical emittance growth after correction (no misalignments, bpm resolution 0)



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

# Emittance Growth due to Misalignments + Couplers in BC1+BC2

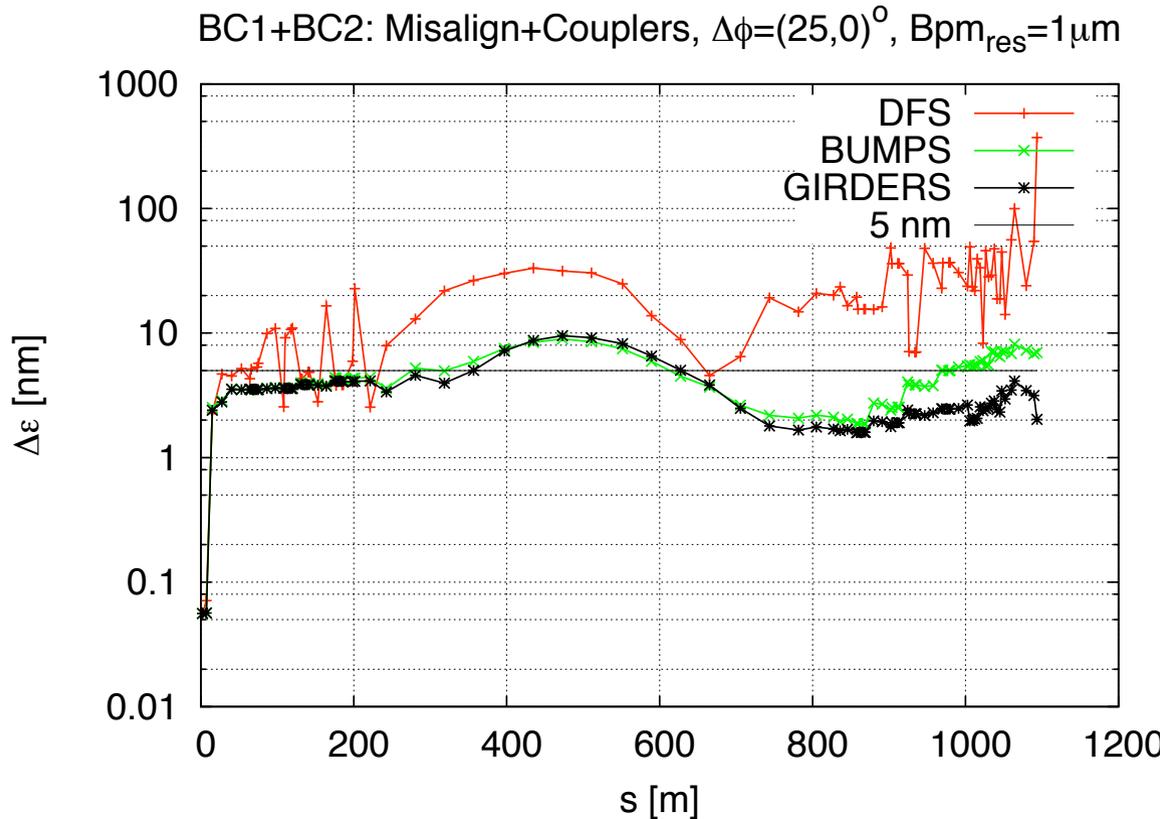
- Case B. Final vertical emittance growth as a function of  $\omega$



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

# Vertical Emittance Growth along BC1+BC2

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

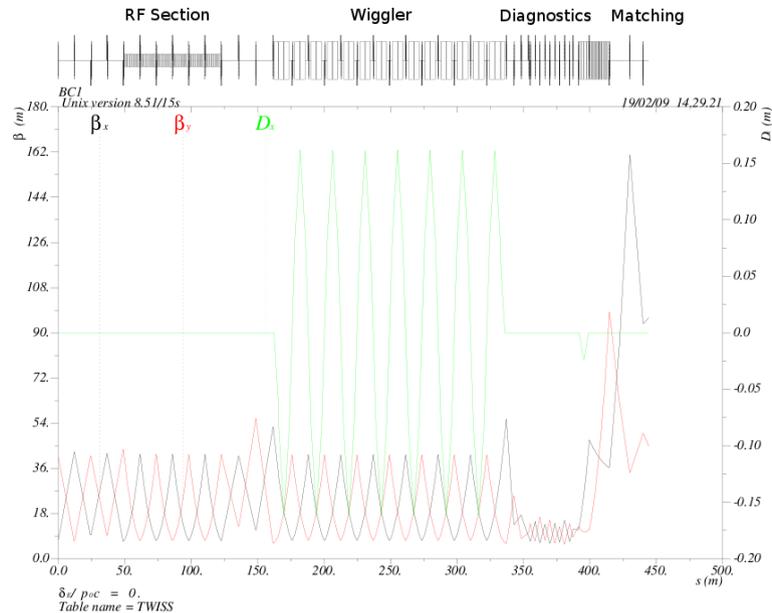


⇒ Final vertical emittance growth is  $\Delta\epsilon = 2.0 \text{ nm}$

# 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:

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



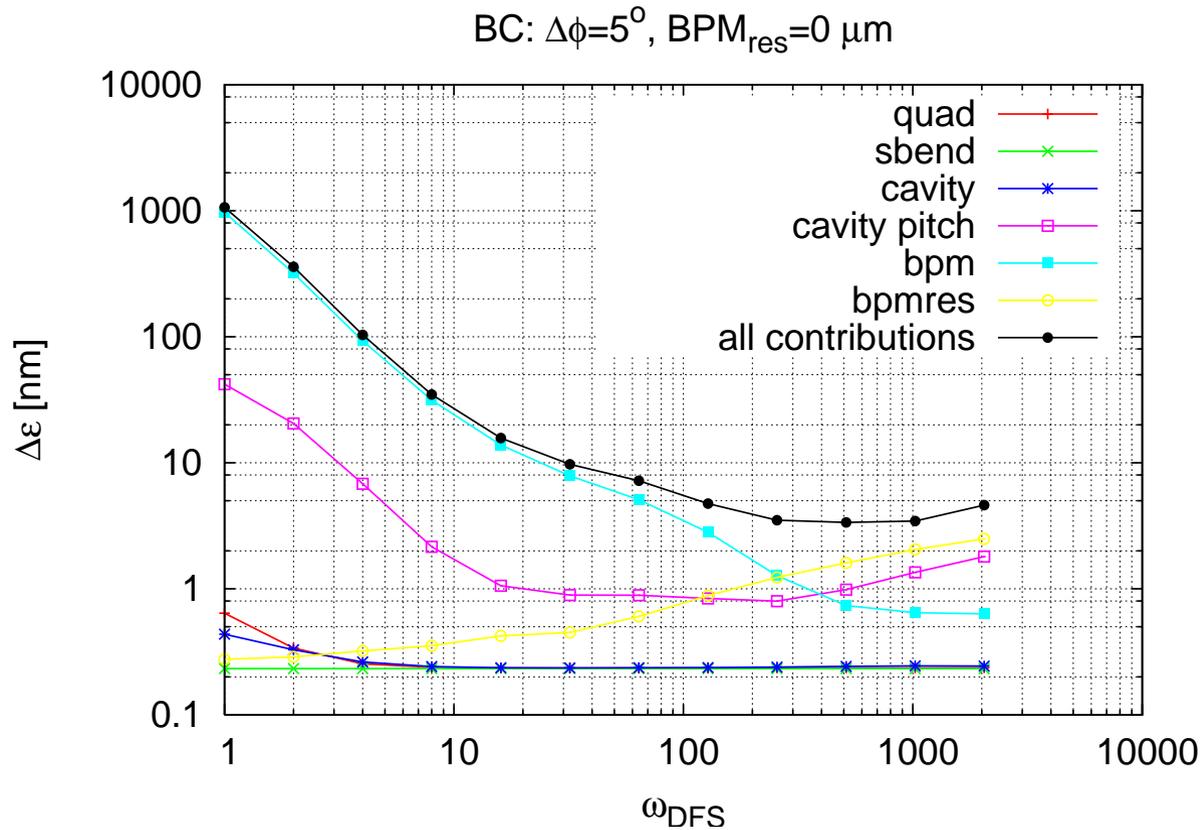
- Six Type-3 cryomodules for RF acceleration
  - 6-cells *Raubenheimer-type* wiggler: a *single bend magnet* between quads in a *6-cells FODO lattice*
- ⇒ NEW sections added:
- (1) beam **diagnostics** and **extraction** adapted from BC1
  - (2) **pre-linac** to rise the energy from 5 to 15 GeV

# Beam-Based Alignment in BC1S

- Misalignments are  $300 \mu\text{x}$ , BPM resolution is  $1 \mu\text{m}$
- RF-Kick and wakes
- Dispersion Free Steering
  - two test beams
  - $\Delta\phi = \pm 5^\circ$  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 ( $6 \sigma_z \approx 6 \text{ mm}$ )
- 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

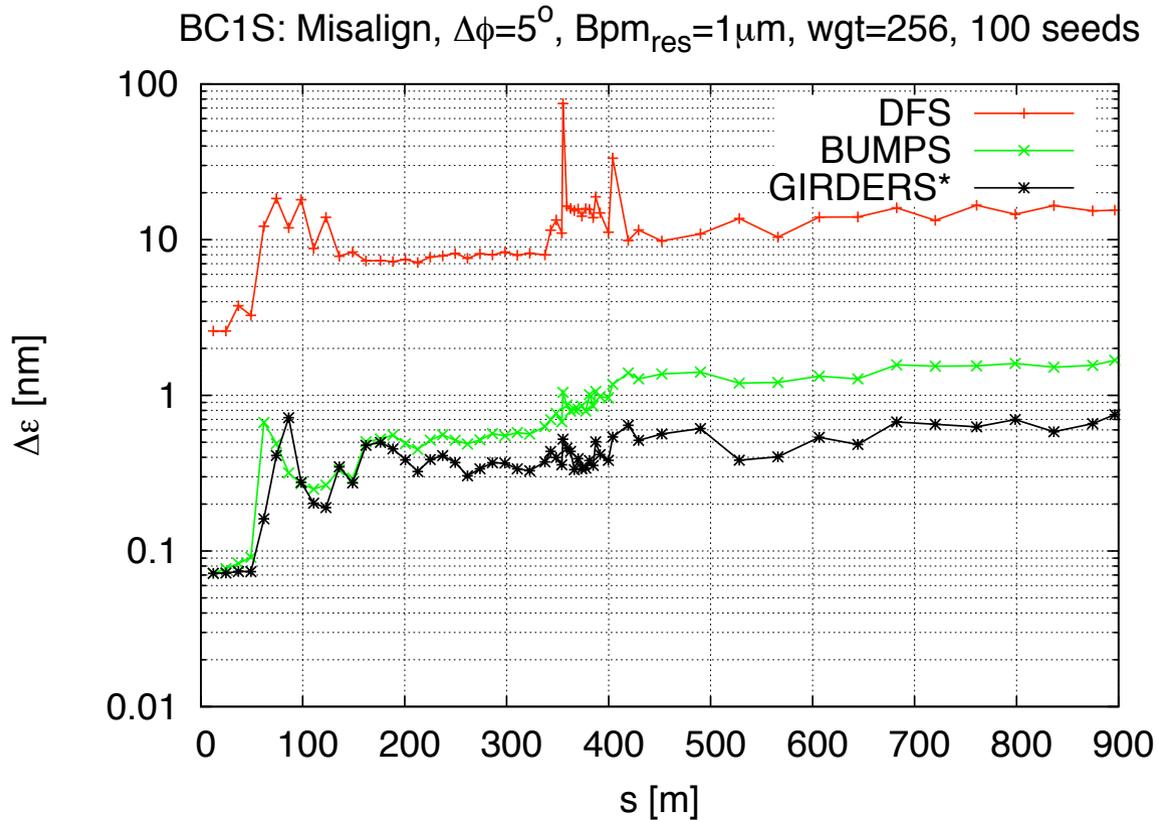
# Emittance Growth due to Misalignments in BC1S

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



# Emittance Growth due to Misalignments in BC1S

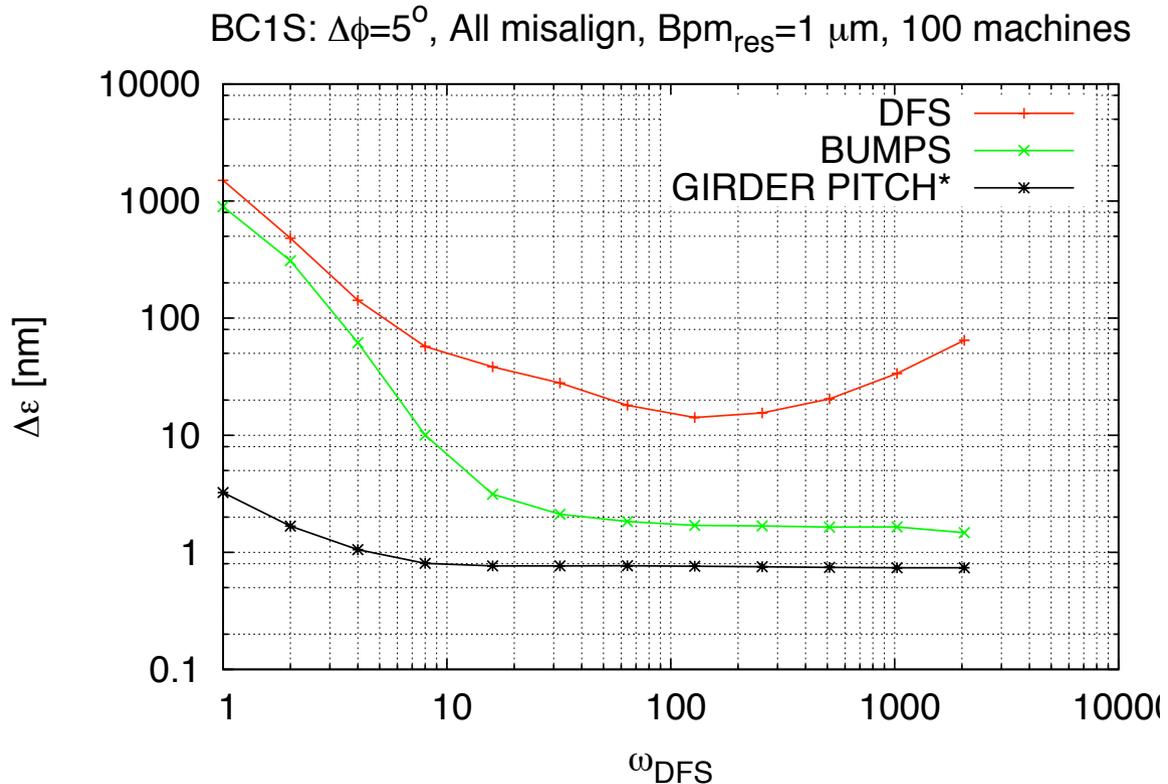
- Emittance Growth along the beamline, average of 100 machines



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

# Emittance Growth due to Misalignments in BC1S

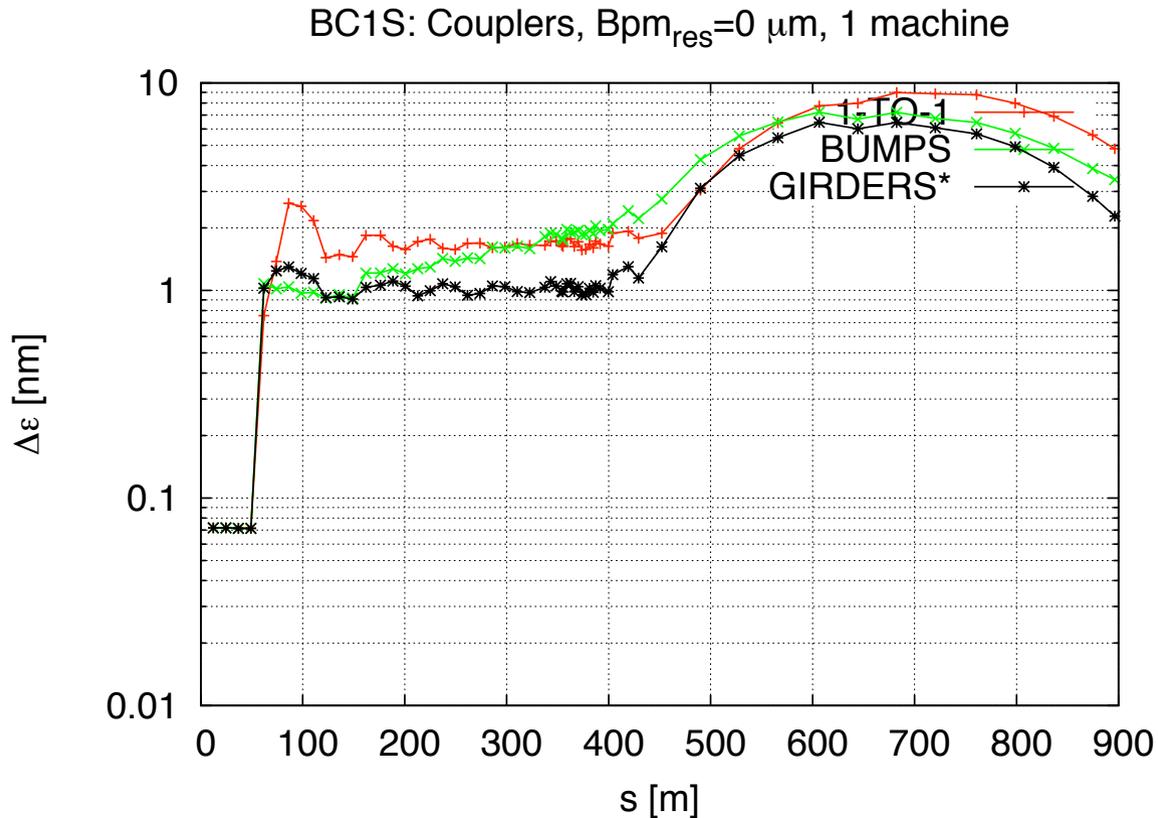
- Final vertical emittance growth as a function of  $\omega$



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

# Emittance Growth due to Couplers in BC1S

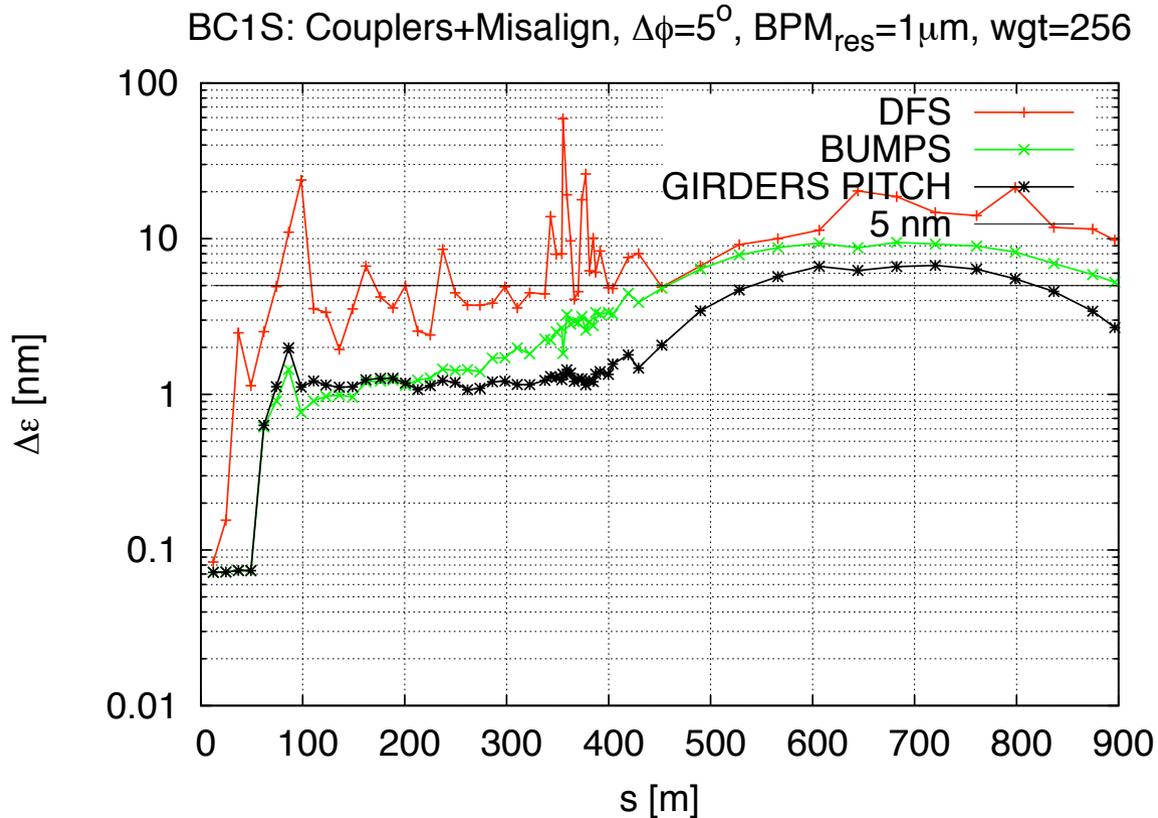
- Vertical emittance growth after correction (no misalignments, bpm resolution 0)



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

# Emittance Growth due to Misalign+Couplers in BC1S

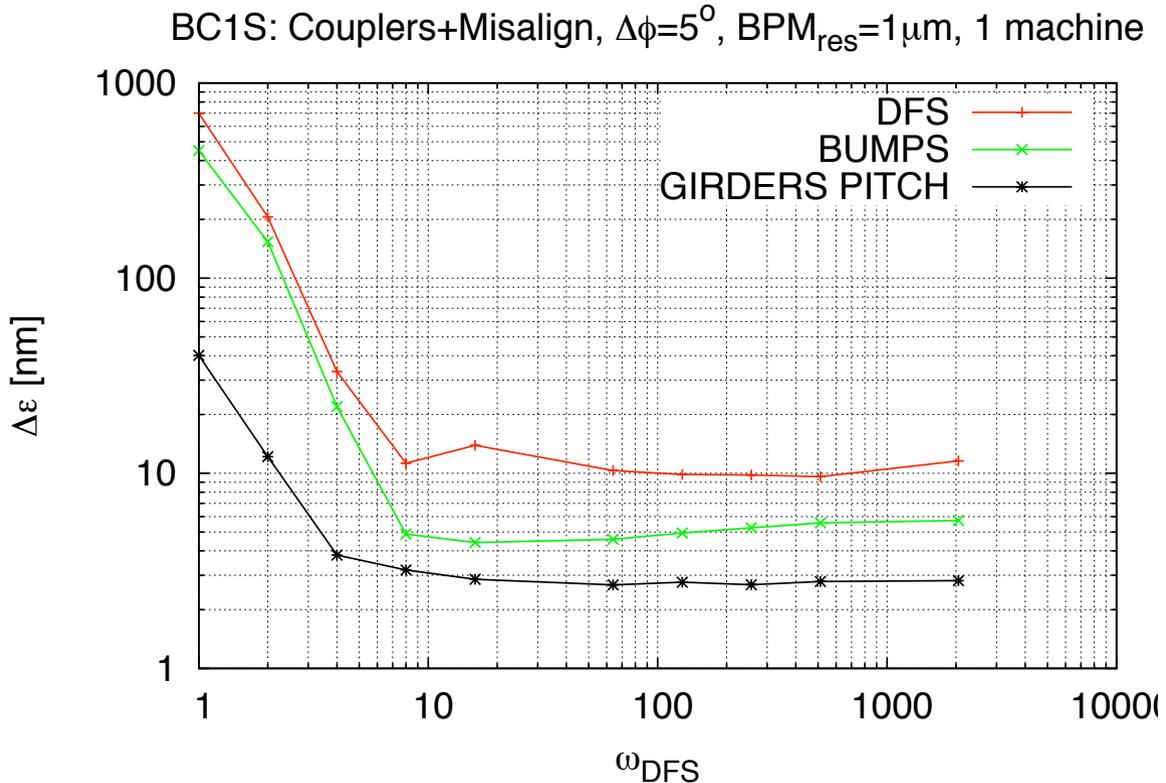
- Emittance Growth along the beamline, 1 machine



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

# Emittance Growth due to Misalign+Couplers in BC1S

- Final vertical emittance growth as a function of  $\omega$



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

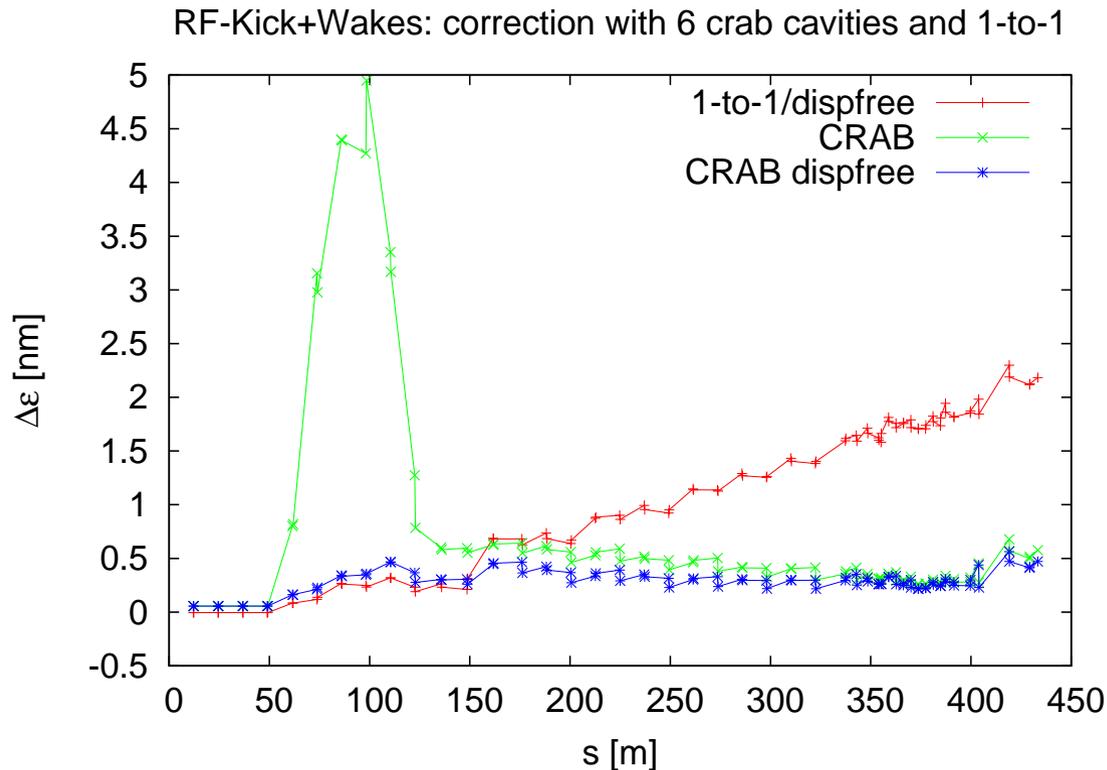
# Crab Cavity Optimization in BC1S

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

- 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
- Note that:
    - 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

- Two-stage bunch compressor

Method	RF	Wakes	RF+Wakes
no correction	28.0	6.9	23.4
1-to-1	2.1	3.4	7.8
1-to-1 disp. corrected	1.6	2.8	5.6
dispersion bumps	1.4	2.4	4.3
girder optimization	0.3	0.5	0.5
crab cavity compensation	0.2	0.3	0.3

- Single-stage bunch compressor

Method	RF	Wakes	RF+Wakes
no correction	72.2	4.6	57.6
1-to-1	2.4	2.4	4.8
1-to-1 disp. corrected	2.0	2.0	4.2
dispersion bumps	1.3	2.0	3.4
girder optimization	0.7	1.1	2.5
crab cavity compensation	0.3	1.6	1.4

# Summary Table of Vertical Emittance Growths

- Two-stage bunch compressor

Technique	Misalignments	Couplers <sup>(1)</sup>	Misalign+Couplers
DFS	91.2 nm	7.7 nm	371.0 nm
BUMPS	2.1 nm	4.3 nm	6.9 nm
GIRDER	-	0.5 nm	2.0 nm

- Single-stage bunch compressor

Technique	Misalignments	Couplers <sup>(1)</sup>	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

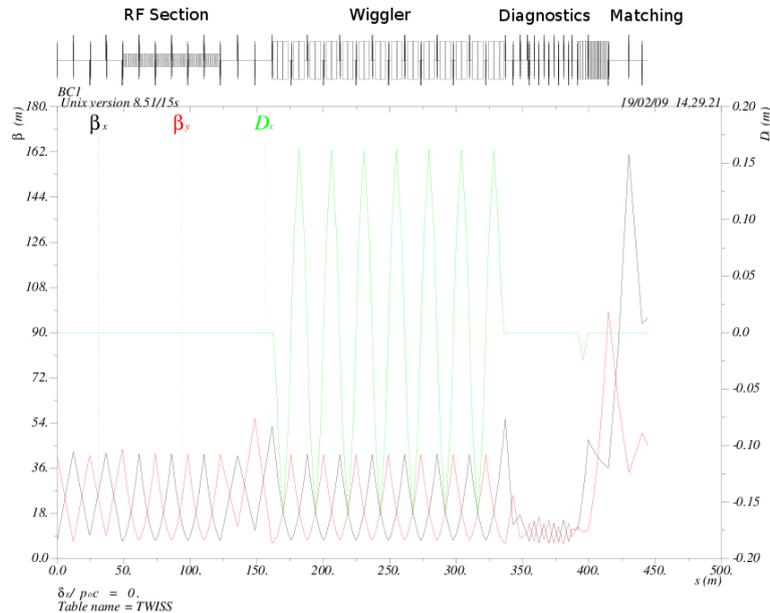
(\*) 40 machines

# BC1S Lattice Update

# 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 Type-3 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 (extraction line to be taken from BC1 ⇒ shorter)
  - (2) **pre-linac** to rise the energy from 5 to 15 GeV

# 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
  
  - **BC1PRELINAC** : accelerating section from 5 to 15 GeV, adapted from ML ILC2007b

⇒ Total length is now : 896.34 m

# 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

- Characteristics of the bunch compressor are:

Integrated voltage	1275.2 MV @ 1.3 GHz
Cavity gradient	$\approx 25.6$ 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 ( $-164.8$ mm)
Total length	$\sim 433$ m ( $\sim 423$ )

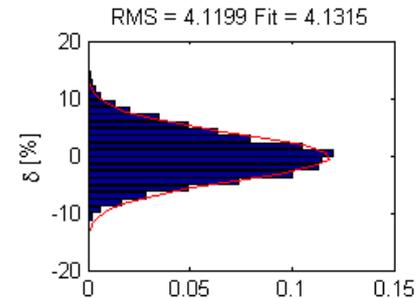
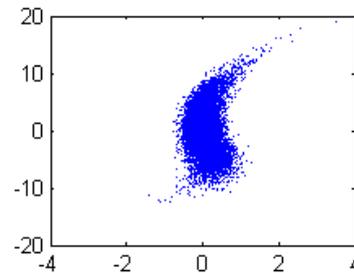
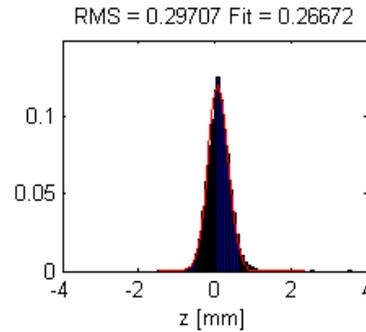
- Pre-Linac Acceleration: 36 CM, same structures used in the ML
- Original design was optimized (RF phase, acc gradient,  $R_{56}$ ) to achieve:
  - $\Rightarrow$  final bunch length : 0.3 mm
  - $\Rightarrow$  energy spread at ML entrance (baseline): 1.07%

# Design Beam Profile

- Nominal beam parameters at exit

- length = 266  $\mu\text{m}$
- 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 =  $266 \mu\text{m}$   $\Rightarrow$  we would like  $300 \mu\text{m}$
- energy =  $4.3797 \text{ GeV}$
- espread =  $4.13 \%$
- espread @  $15 \text{ GeV} = 1.2 \%$   $\Rightarrow$  we would like  $1.07 \%$

$\Rightarrow 300 \mu\text{m}$  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.  $300 \mu\text{m}$  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:

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

# 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  $\mu\text{m}$
- energy = 4.3797 GeV
- espread = 4.13 %
- espread @ 5 GeV = 3.6 %

⇒ Optimization 1

- wiggler not changed
- blength = 301.18  $\mu\text{m}$
- 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 %

⇒ Optimization 2

- blength = 301.20  $\mu\text{m}$
- 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 = 1.07 %

# Beam Profile Before and After Optimization

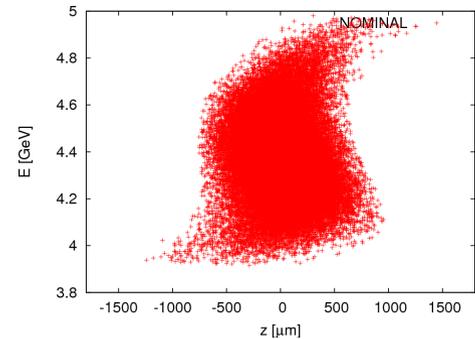
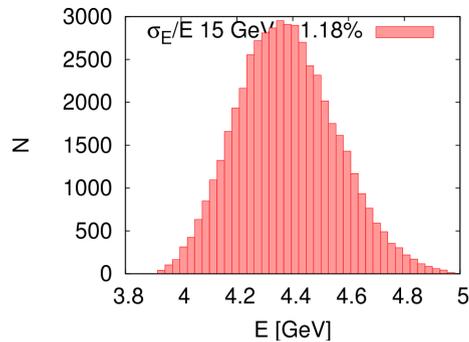
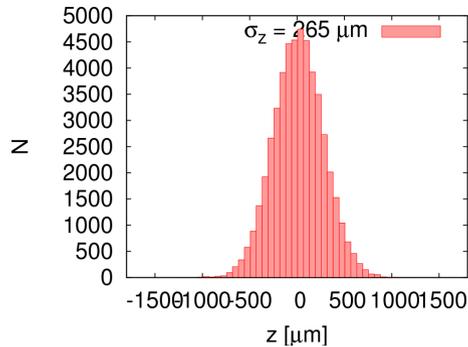
- Before optimization

- Bunch length = 265  $\mu\text{m}$
- energy spread = 4.13 %
- energy spread @ 15 GeV = 1.18 %

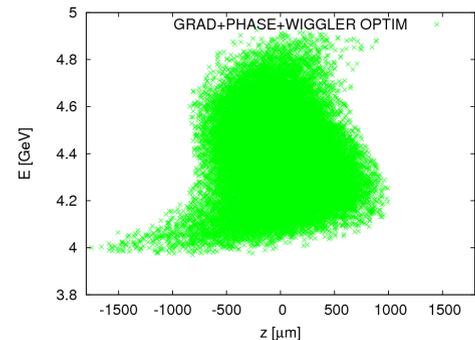
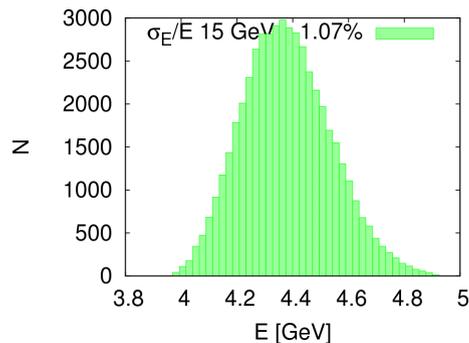
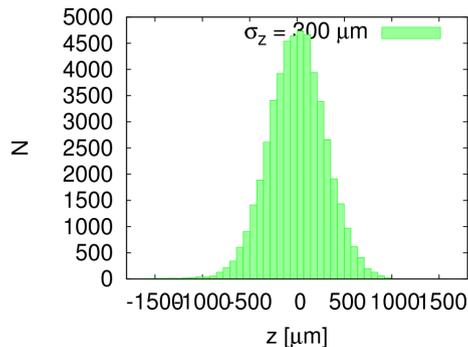
- After optimization

- Bunch length = 300  $\mu\text{m}$
- energy spread = 3.54 %
- energy spread @ 15 GeV = 1.07 %

⇒ Before



⇒ After



# Lattice Upgrade: RF Section and Wiggler

- Changed type of cryomodule from Type-3 to Type-4

1. Type-3 CM: original design of BC1S by PT: quadrupole at the end



2. Type-4 CM: quadrupole in the middle

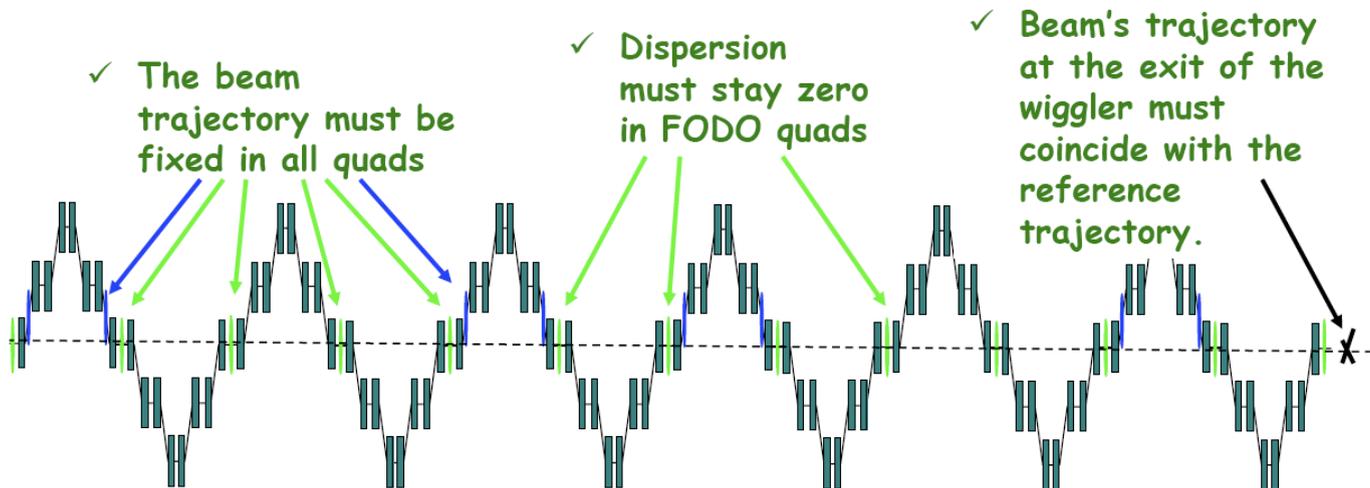


- New design of Wiggler, according to Seletskiy and Tenenbaum's method @ PAC07
  - shorter wiggler

# Requirements to the Wiggler

From Tenenbaum and Seletskiy's presentation at PAC07:

- Each wiggler consists of 6 identical cells
- Wiggler cells are contained in FODO structure with  $90^\circ$  phase advance per cell
- Focusing and defocusing quads are placed in the zero dispersion regions
- There are 4 additional normal quads and 4 skew quads per wiggler (in cells 1,3,4 and 6) that are used for possible dispersion correction without introducing betatron coupling or mismatches
- Sixteen bends allow tuning R56 while preserving beam's trajectory in quads

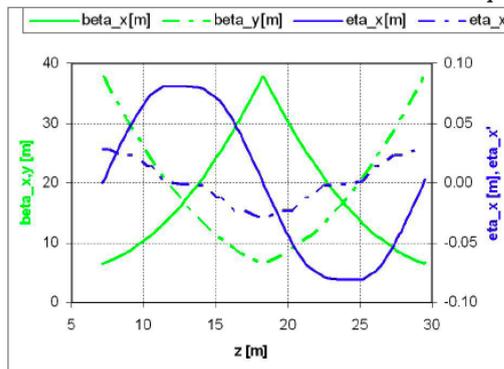




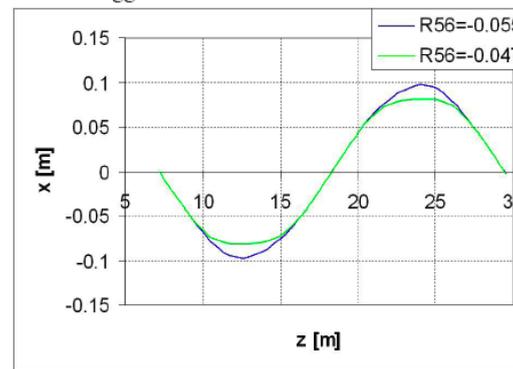
# Wiggler's Design and Optimization

- Wiggler optimization was redone to meet the requirements
  - keep  $\phi_1$ ,  $\phi_8$  and  $\eta'$  constant for different  $R_{56}$ 
    - ⇒ Beam is not moved in quads when wiggler is tuned
  - zero the horizontal trajectory displacement over the half of the cell
    - ⇒ Trajectory at wiggler's exit is fixed to the reference orbit
  - require the mirror symmetry of the first and second halves of the cell
  - require that  $\sum_{i=1}^8 = -2\eta'$ 
    - ⇒ Dispersion in FODO quads is zero;  $\eta'$  at the exit of each cell is equal to its entrance value
  - we explicitly constrain  $R_{56}$  to the required value
- We have 5 bending angles to vary

Cell of the optimized BC2 wiggler



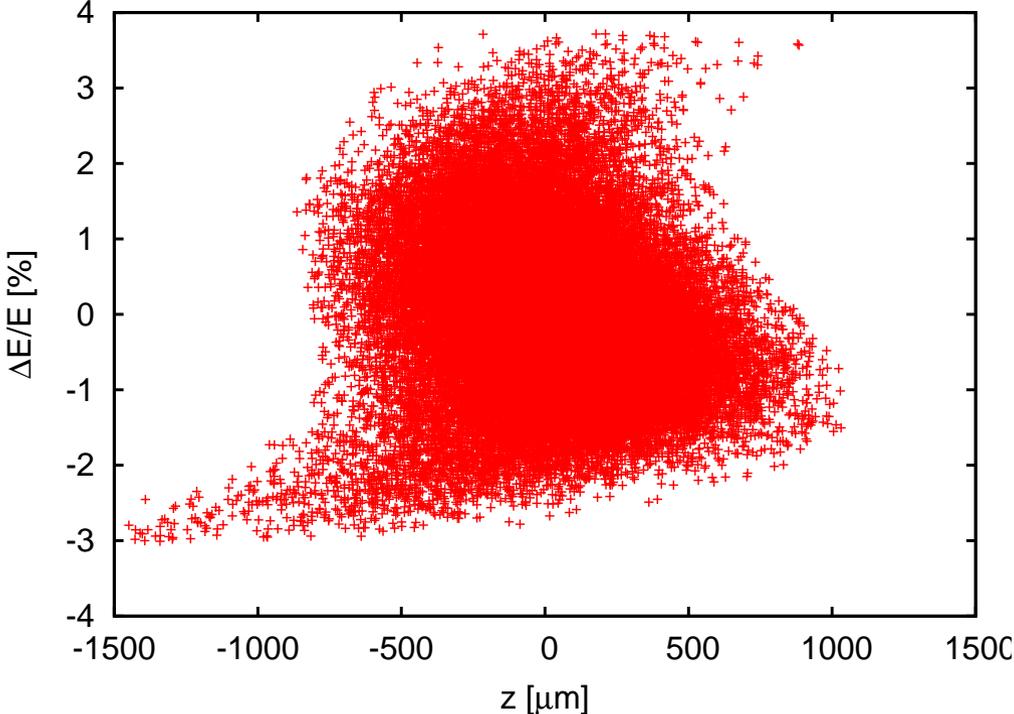
Twiss parameters in BC2 wiggler's cell



Beam trajectory in BC2 wiggler's cell

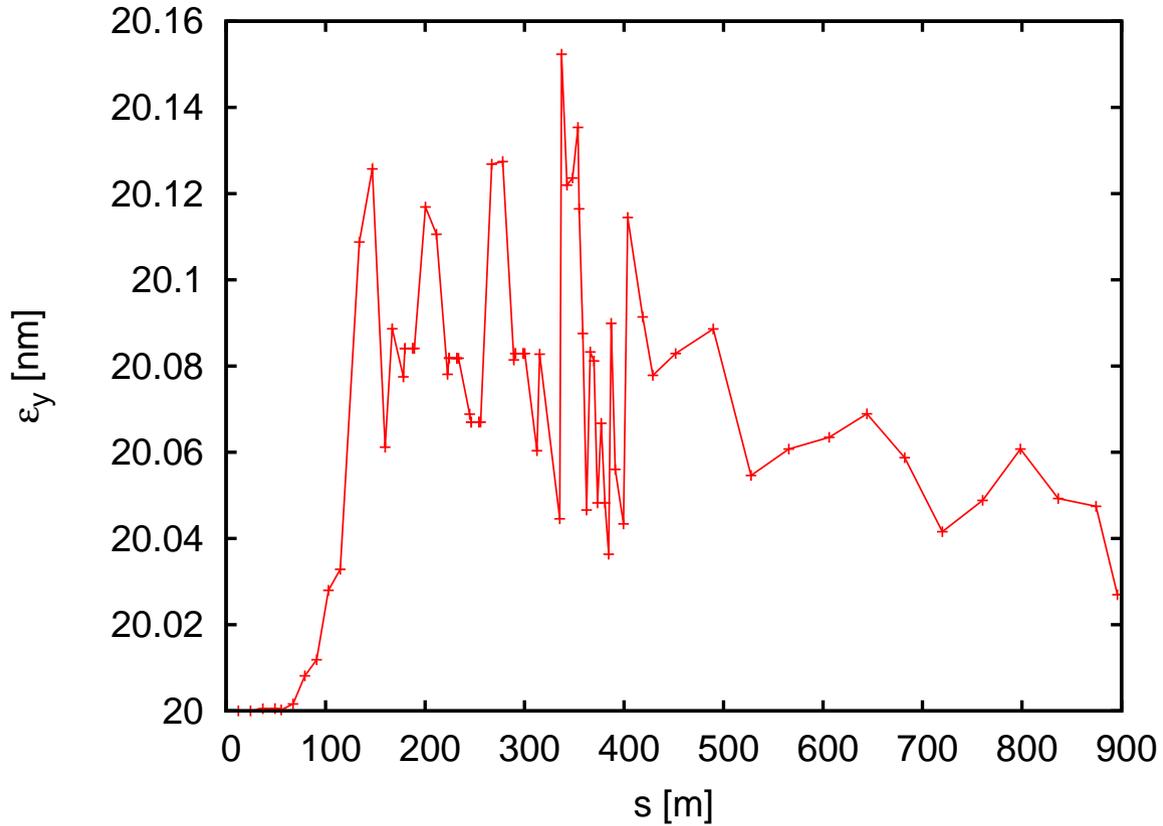
# Particle Tracking with New Design

- Beam profile



# Particle Tracking with New Design

- Vertical emittance after fine rematching optimization



# BC1S Numbers

- Total Length : 896 m (433 + 463)
- Total Number of Elements:
  - Bpms: 66 (54 + 12)
  - Correctors : 133 (49 + 84)
  - Quadrupoles : 76 (64 + 12)
  - Accelerating Structures : 360 (48 + 312)

# BC1S vs BC1+BC2

BC1S: total length = 896.34 m ( $\sim 886$  m with 10 m shorter EXT-LINE)

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 ( $\sim 423$ )

BC1S.PRELINAC	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 × (9 + 8 + 9)	-	390
length	871.66	m	871.66

# Conclusions and Work Plan

- Emittance growth due to mismalignments and couplers seems to be 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:
  - Misalignment and couplers' kicks in BC1S new design (not big differences expected)
  - Beam Tracking through the full RTML is already possible (PLACET)
    - ⇒ Misalignment simulations and correction
    - ⇒ Stray fields simulations
    - ⇒ Multi-bunch effects
    - ⇒ Dynamics effects and feedback loops