RTML Beam Dynamics

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"Rings to Main Linac" section

- must transport the beam from the exit of the Damping Rings to the entrance of the Main Linac

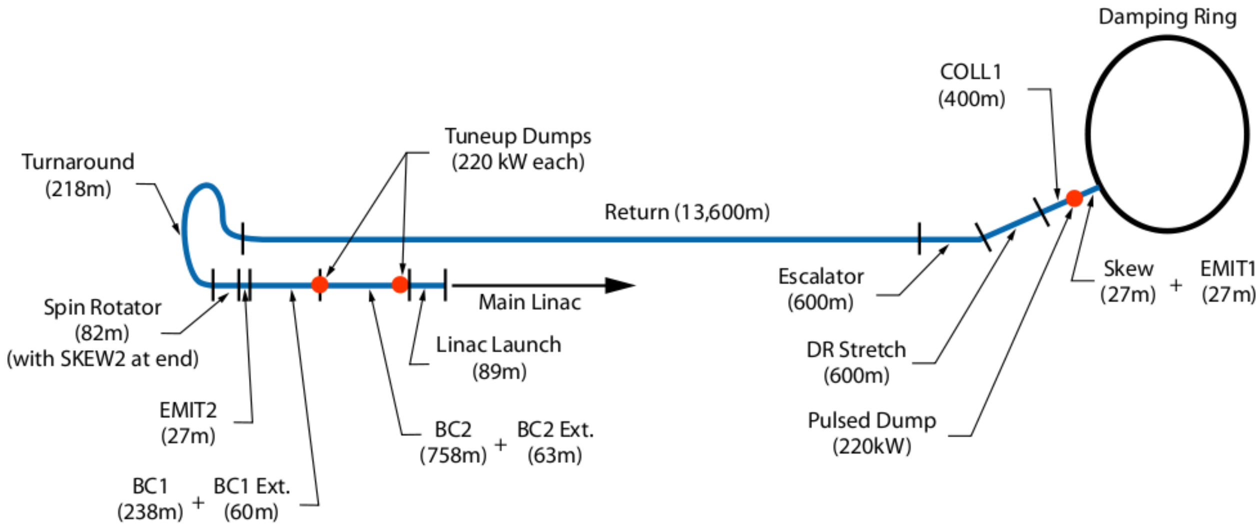
- must modify the beam phase space, in several respects

  $\Rightarrow$ increase the beam energy, compress the length, set the polarization

  $\Rightarrow$ connect different beamlines, geometry stretch

  $\Rightarrow$ diagnose the beam parameters, and dump the beam when necessary

RTML Sketch



- it is composed by several sub-systems:
  - getaway and stretcher, long return line, turnaround, spin rotator, 2× bunch compressors, 3× dump lines
- its total length is about 13 km ⇒ with the long return line curved to follow the curvature of the earth
- in the literature, it is referred to as divided in two parts:
  1. "Front End": all what preceeds the bunch compressors
  2. the bunch compressors

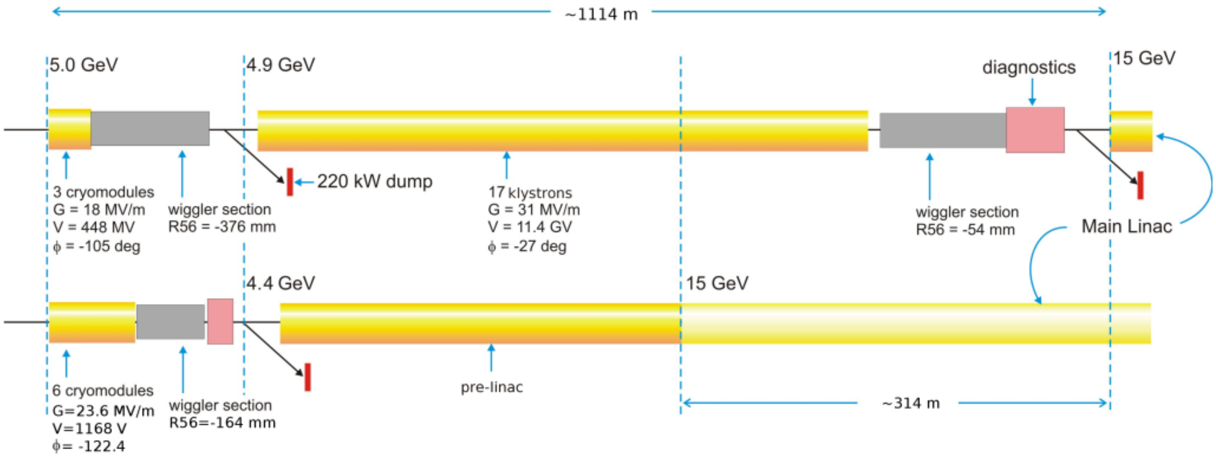
RTML in the RDR and in SB2009

From two-stage bunch compressor (BC1-BC2) $\Rightarrow$ single-stage bunch compressor (BC1S)

- **ILC Baseline: Two-Stage Bunch Compressor**
  - Bunch length at damping rings extraction: 6/9 mm, compression down to 200/300 μm at main linac entrance (compression ratio: up to $\sim$45)
  - * **Pro**: more flexibility
  - * **Cons**: two diagnostics sections, two extraction lines

- **Minimum cost machine: Single-Stage Bunch Compressor**
  - New design of the damping rings allows 6 mm bunch length with a smaller radius
  - Compression factor can be fixed to $\sim$20
  - * **Pro**: Shorter beamline and associated tunnel length (314 meters); Removal of the second 220 kW/15 GeV beam dump and extraction line components; Removal of one section of beam diagnostics
  - * **Cons**: Less flexibility; Larger energy spread at BC exit; Possible emittance preservation issues (see DFS in the main linac)

Single-Stage Bunch Compressor (BC1S)



- **What do we gain**
  - Reduction in beamline and associated tunnel length (314 meters)
  - Removal of the second 220 kW/15 GeV beam dump and extraction line components
  - Removal of one section of the beam diagnostics
- **What do we loose**
  - Less flexibility
  - Larger energy spread at BC exit
  - Emittance preservation and additional tuning issues (see DFS in the main linac)

RDR Beam Parameters

⇒ Bunch length at Damping Rings exit can be either 6 or 9 mm

⇒ Two stages of bunch compression ⇒ final bunch length can be 150 or 300 μm

⇒ Main Linac start at 15 GeV

- Damping Ring exit

Property	Symbol	Value	Unit
Energy	E_0	5	GeV
Bunch charge	Q_0	3.2	nC
RMS bunch length	σ_0	6 / 9	mm
RMS energy spread	σ_E/E_0	0.15	%
Normalized emittance	$\epsilon_{\eta,x}$	10'000	nm
	$\epsilon_{\eta,y}$	20	nm

- Main Linac entrance

Property	Symbol	Value	Unit
Energy	E_0	15	GeV
Bunch charge	Q_0	3.2	nC
RMS bunch length	σ_0	150 / 300	μm
RMS energy spread	σ_E/E_0	1.07	%
Normalized emittance	$\epsilon_{\eta,x}$	$<$ 12'000	nm
	$\epsilon_{\eta,y}$	$<$ 25	nm

SB2009 Beam Parameters

⇒ Damping Ring exit bunch length is fixed to 6 mm

⇒ Single-Stage Bunch Compressor ⇒ final bunch length fixed to 300 μm

⇒ Main Linac starts at 4.4 GeV ⇒ need a Pre-Linac to bring the beam to 15 GeV

- Dampig Ring exit

Property	Symbol	Value	Unit
Energy	E_0	5	GeV
Bunch charge	Q_0	3.2	nC
RMS bunch length	σ_0	6	mm
RMS energy spread	σ_E/E_0	0.15	%
Normalized emittance	$\epsilon_{\eta,x}$	10'000	nm
	$\epsilon_{\eta,y}$	20	nm

- Main Linac entrance

Property	Symbol	Value	Unit
Energy	E_0	4.4	GeV
Bunch charge	Q_0	3.2	nC
RMS bunch length	σ_0	300	μm
RMS energy spread	σ_E/E_0	3.54 (1.07*)	%
Normalized emittance	$\epsilon_{\eta,x}$	$<$ 12'000	nm
	$\epsilon_{\eta,y}$	$<$ 25	nm

* at 15 GeV

Status of the L.E.T. Simulations

- Static misalignment in the whole RTML has been studied
  - Emittance growth budget: 10 nm

- Dynamic studies have to be performed

- Stray fields, previous studies stated that:
  - to limit the resulting vertical beam jitter at the feed-forward to about 10% of the beam size, the RMS of the stray fields should not exceed about 2 nT.
  - there is another limit, which is that a beam with a bad orbit in the turnaround will get emittance growth from dispersion. The limit on this appears to be looser, more like 7.5 nT RMS.

Simulation of Static Effects

- Wakefields in the AccCavities, ISR emission in the bends
- Alignment Errors:
  - Standard "COLD" model for crymodules
  - Standard "WARM" model
  - Bpm resolution: $\sigma_{\mathrm{bpmres}} = 1\ \mu$m
- RF-Kick and Wakes due to Couplers of the RF structures
  - See:

    N. Solyak et al., "Final Results on RF- and Wake- Kicks Caused by the Couplers in the ILC Cavity" presented ICAP 2009

    A. Latina et al., "Emittance Dilution Caused by the Couplers in the Main Linac and in the BC of the ILC", presented PAC 09
- PLACET tracking code

Simulation Setup in the Warm Regions

- Warm Region: RTML "Front End" (i.e. RTML without RF the sections)
- 1000 random seed were simulated, with Gaussian distributed misalignments
  - X/Y element offsets
    - $\sigma_{\text{quad offset}} = 150\ \mu$m RMS w.r.t. design orbit
    - $\sigma_{\text{bpm offset}} = 7\ \mu$m RMS w.r.t. quadrupole center
    - $\sigma_{\text{bpm res}} = 1\ \mu$m
  - Strength errors
    - $\sigma_{\text{quad strength}} = 0.25\%$ RMS
    - $\sigma_{\text{bend strength}} = 0.5\%$ RMS
  - Roll errors
    - $\sigma_{\text{quad roll}} = 300\ \mu$rad RMS w.r.t. design orbit
    - $\sigma_{\text{sbend roll}} = 300\ \mu$rad RMS w.r.t. design orbit
- Bunches of 50000 macro-particles
- ILC2007b lattice

Simulation Setup in the Cold Regions

- Cold Region: Bunch Compressors (i.e. regions with cryomodules)
- 1000 random cases were simulated, with Gaussian distributed misalignments
  - X/Y element offsets
    - $\sigma_{\text{quad offset}} = 300\ \mu$m RMS w.r.t. design orbit
    - $\sigma_{\text{bpm offset}} = 300\ \mu$m RMS w.r.t. design orbit
    - $\sigma_{\text{bpm res}} = 1\ \mu$m
  - Strength errors
    - $\sigma_{\text{quad strength}} = 0.25\%$ RMS
    - $\sigma_{\text{bend strength}} = 0.5\%$ RMS
  - Roll errors
    - $\sigma_{\text{quad roll}} = 300\ \mu$rad RMS w.r.t. design orbit
    - $\sigma_{\text{sbend roll}} = 300\ \mu$rad RMS w.r.t. design orbit
- Bunches of 50000 macro-particles
- ILC2007b / SB2009 lattice

Cases Studied (1/2)

1) **Getaway + Escalator + Return Line**

- Only X/Y misalignments
- Add Quadrupole and Sbend strength errors
- Add Quadrupole and Sbend roll errors

$\Rightarrow$ Correction technique:

- 1:1 + Kick Minimization
- Dispersion Tuning Knobs
- Skew Coupling Correction

2) **Turnaround + Spin Rotator** (Solenoids <u>OFF</u> and <u>ON</u>)

- Only X/Y misalignments
- Add Quadrupole and Sbend strength errors
- Add Quadrupole and Sbend roll errors

$\Rightarrow$ Correction technique:

- 1:1 + Kick Minimization
- Dispersion Tuning Knobs

Cases Studied (2/2)

3) **Getaway + Escalator + Return Line + Turnaround + Spin Rotator**

- Only X/Y misalignments
- Add Quadrupole and Sbend strength errors
- Add Quadrupole and Sbend roll errors

⇒ Correction technique:

- 1:1 + Kick Minimization
- Dispersion Tuning Knobs
- Skew Coupling Correction

4) **Bunch Compressors**

- Only X/Y misalignments
- Coupler Effects

⇒ Correction technique:

- 1:1 + Dispersion Free Steering
- Dispersion Tuning Knobs
- Girder Pitch Optimization

Beam-Based Alignment in the "Front End"

1) **1-to-1 Correction**: orbit correction

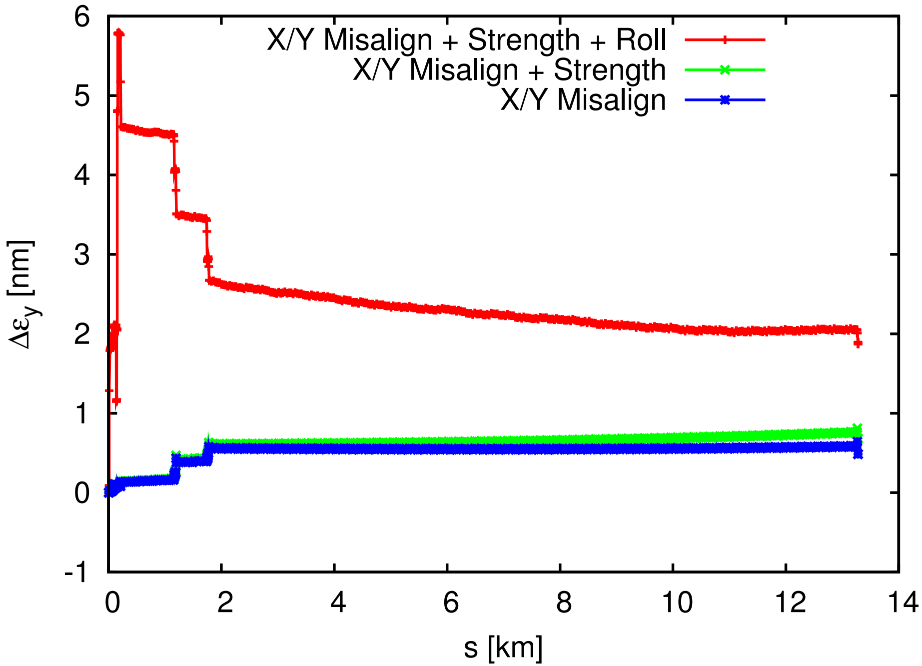
2) **Kick Minimization**: orbit correction after quad-shunting

3) **Dispersion Bumps**: two bumps, to minimize the emittance

4) **Coupling Correction**: using appropriate skew quadrupoles

1) Getaway + Escalator + Return Line

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps + Coupling Correction
- Emittance growth along the line for 1000 seeds:



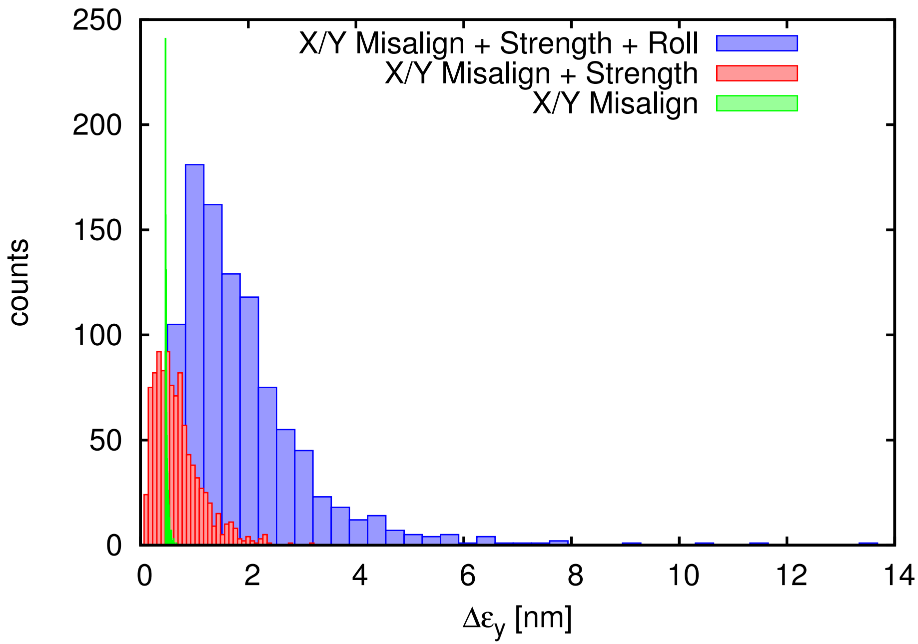
⇒ X/Y Offsets: Final average emittance growth is 0.48 nm (0.52 nm 90% c.l.)

⇒ Add Quad/Sbend Strength: Final average emittance growth is 0.68 nm (1.25 nm 90% c.l.)

⇒ Add Quad/Sbend Roll: Final average emittance growth is 1.87 nm (3.23 nm 90% c.l.)

1) Getaway + Escalator + Return Line

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps + Coupling Correction
- Histogram of final emittance growth for 1000 seeds:



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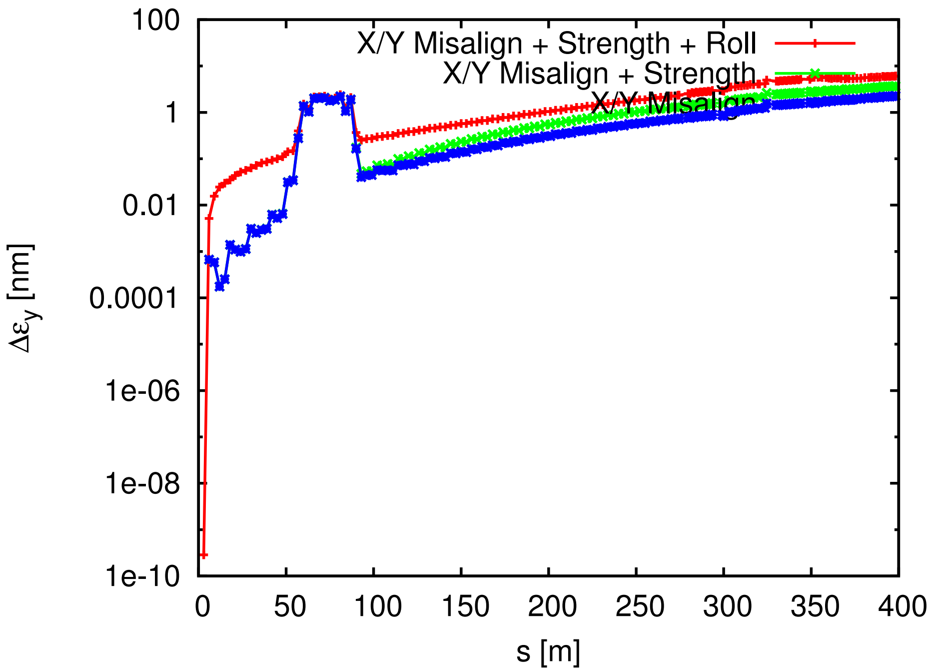
2) Turnaround + Spin Rotator (Solenoids OFF)

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps
- Emittance growth along the line for 1000 seeds:



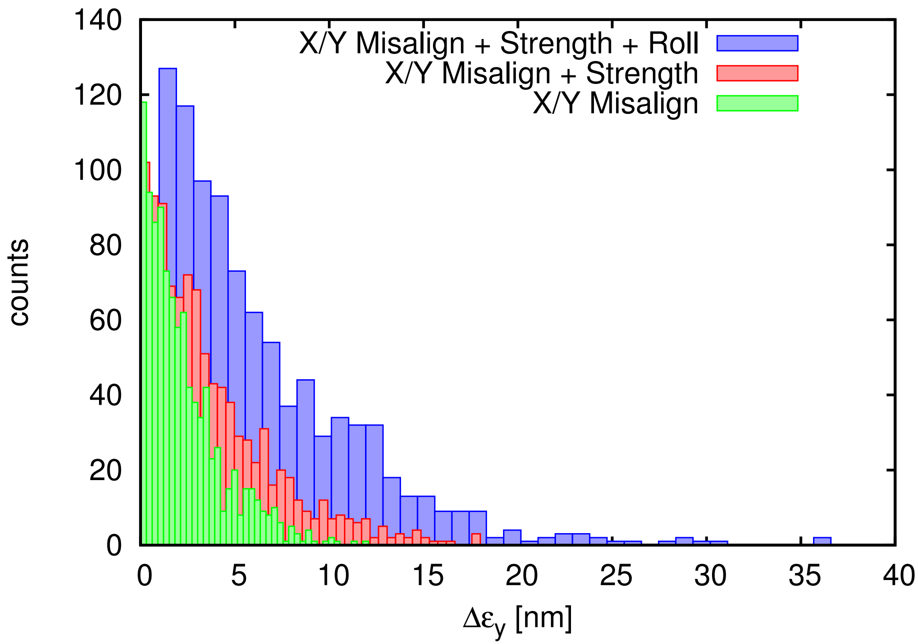
⇒ X/Y Offsets: Final average emittance growth is 2.26 nm (5.33 nm 90% c.l.)

⇒ Add Quad/Sbend Strength: Final average emittance growth is 3.69 nm (8.12 nm 90% c.l.)

⇒ Add Quad/Sbend Roll: Final average emittance growth is 6.11 nm (12.73 nm 90% c.l.)

2) Turnaround + Spin Rotator (Solenoids OFF)

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps
- Histogram of final emittance growth for 1000 seeds:



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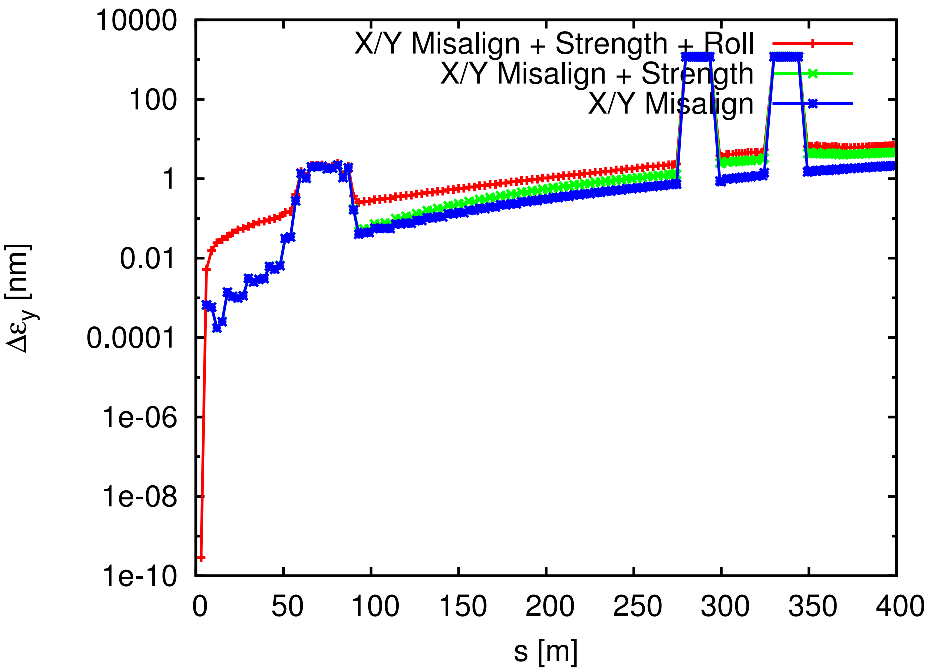
⇒ Add Quad/Sbend Roll: Final average emittance growth is 6.11 nm (12.73 nm 90% c.l.)

2) Turnaround + Spin Rotator (Solenoids ON)

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps
- Emittance growth along the line for 1000 seeds:



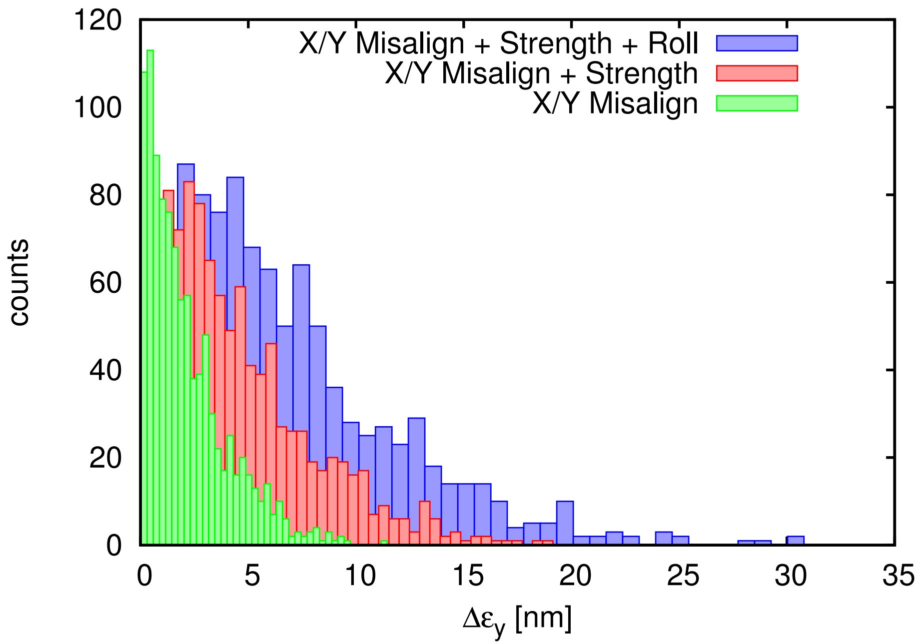
⇒ X/Y Offsets: Final average emittance growth is 2.14 nm (4.83 nm 90% c.l.)

⇒ Add Quad/Sbend Strength: Final average emittance growth is 4.63 nm (9.42 nm 90% c.l.)

⇒ Add Quad/Sbend Roll: Final average emittance growth is 6.86 nm (13.66 nm 90% c.l.)

2) Turnaround + Spin Rotator (Solenoids ON)

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps
- Histogram of final emittance growth for 1000 seeds:



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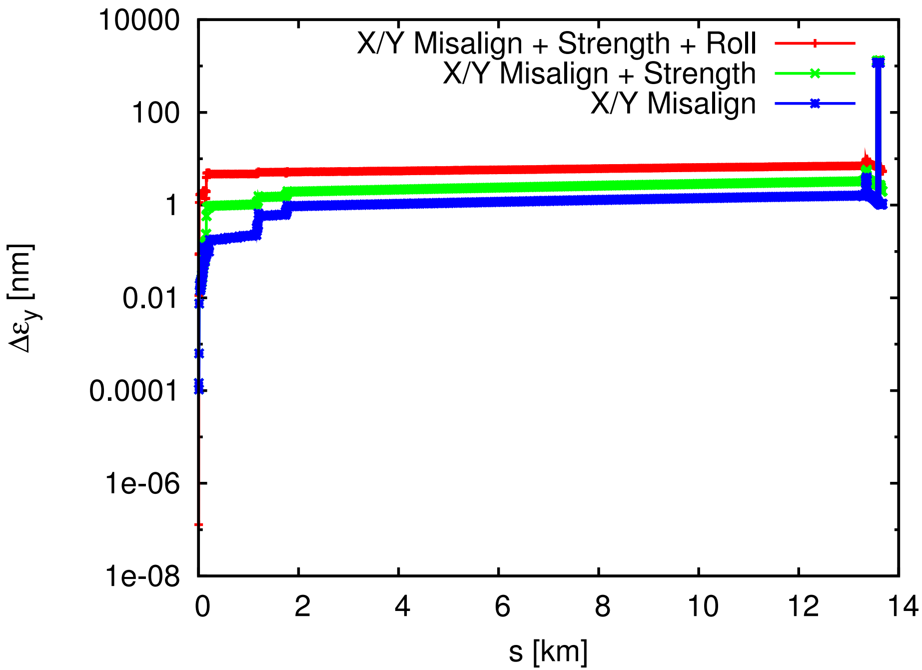
⇒ Add Quad/Sbend Roll: Final average emittance growth is 6.86 nm (13.66 nm 90% c.l.)

3) Entire "Front End"

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps + Coupling Correction
- Emittance growth along the line for 1000 seeds:



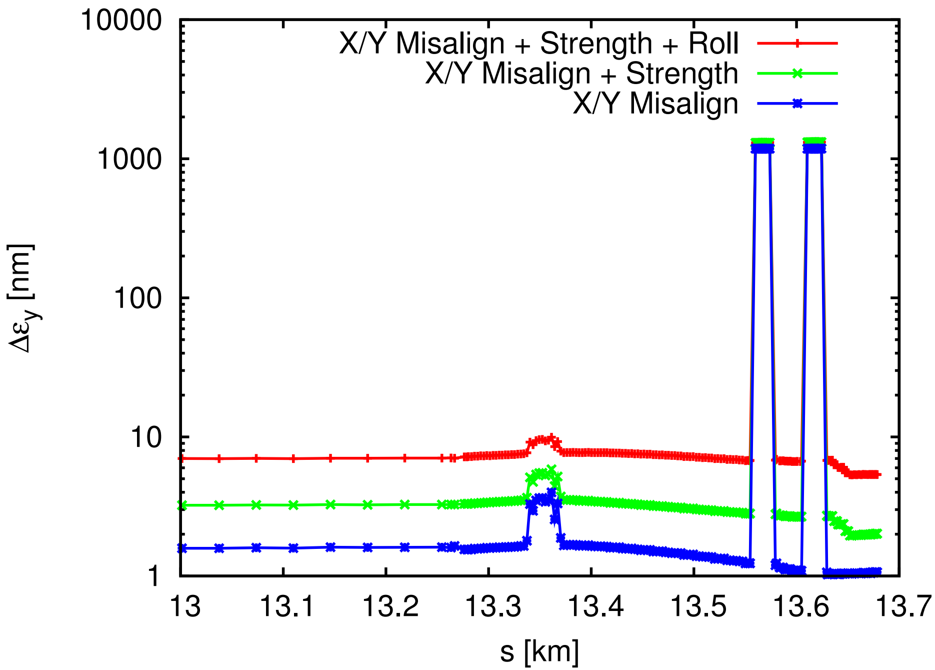
⇒ X/Y Offsets: Final average emittance growth is 1.06 nm (1.58 nm 90% c.l.)

⇒ Add Quad/Sbend Strength: Final average emittance growth is 2.01 nm (3.51 nm 90% c.l.)

⇒ Add Quad/Sbend Roll: Final average emittance growth is 5.36 nm (9.94 nm 90% c.l.)

3) Entire "Front End" (last 700 meters)

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps + Coupling Correction
- Emittance growth along the line for 1000 seeds:



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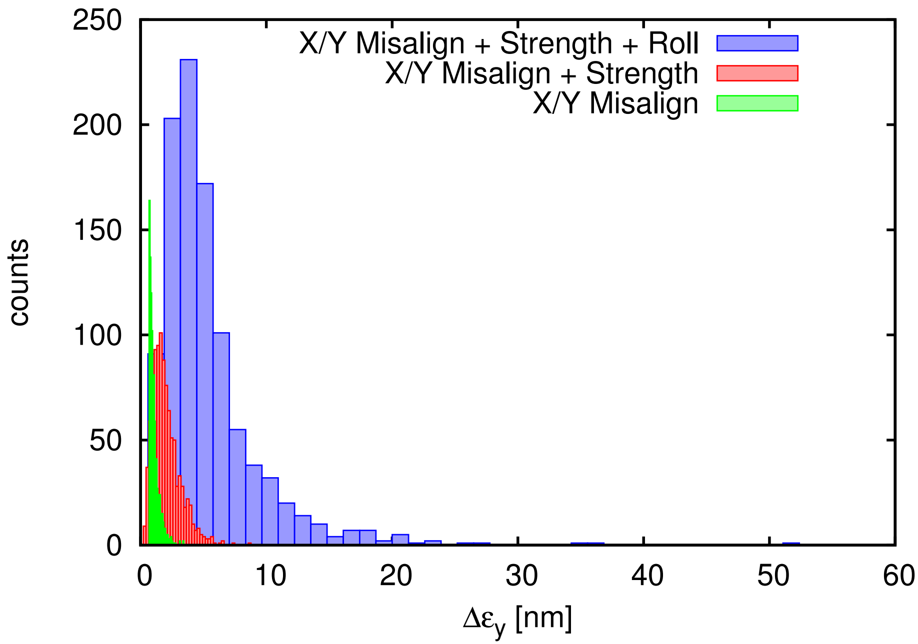
⇒ Add Quad/Sbend Roll: Final average emittance growth is 5.36 nm (9.94 nm 90% c.l.)

3) Entire "Front End"

- Correction: 1-TO-1 + Kick Minimization + Dispersion Bumps + Coupling Correction
- Histogram of final emittance growth for 1000 seeds:



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⇒ Add Quad/Sbend Strength: Final average emittance growth is 2.01 nm (3.51 nm 90% c.l.)

⇒ Add Quad/Sbend Roll: Final average emittance growth is 5.36 nm (9.94 nm 90% c.l.)

Summary Tables for the "Front End"

- These simulations:

Region	Errors	Emittance Increase (nm)		Correction
		average	90% CL	
Escalator + Getaway + RL	X/Y Offsets	0.48	0.52	KM + knobs + CC
	+ Quad Strength	0.68	1.25	KM + knobs + CC
	+ Quad/Sbend Roll	1.87	3.23	KM + knobs + CC
Turnaround + Spin Rotator (OFF)	X/Y Offsets	2.26	5.33	KM + knobs
	+ Quad/Sbend Strength	3.69	8.12	KM + knobs
	+ Quad/Sbend Roll	6.11	12.73	KM + knobs
Turnaround + Spin Rotator (ON)	X/Y Offsets	2.14	4.83	KM + knobs
	+ Quad/Sbend Strength	4.63	9.42	KM + knobs
	+ Quad/Sbend Roll	6.86	13.66	KM + knobs
Entire "Front End"	X/Y Offsets	1.06	1.58	KM + knobs + CC
	+ Quad/Sbend Strength	2.01	3.51	KM + knobs + CC
	+ Quad/Sbend Roll	5.36	9.94	KM + knobs + CC

Older Summary Tables for the "Front End"

- PT's summary table

  SLAC-Tech-Note-07-002:

Table 1:

Errors	After KM	After KM + Knobs
X/Y Offsets	2.13 nm	0.37 nm
Add Quad Strength	5.36 nm	3.20 nm
Add Bend Strength	6.12 nm	3.25 nm
Add Quad Rolls	23.22 nm	7.60 nm
Add Bend Rolls	23.31 nm	7.61 nm

Beam-Based Alignment in the Bunch Compressors

- Dispersion Free Steering can be used

- Other effects must be taken into account:
  - Couplers: RF-Kick, Wakefields

Beam-Based Alignment in the Bunch Compressors

1) **1-to-1 Correction**: orbit correction

2) **Dispersion Free Steering**: dispersion correction

- 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**: emittance minimization

- 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**: correction of intra-bunch effects

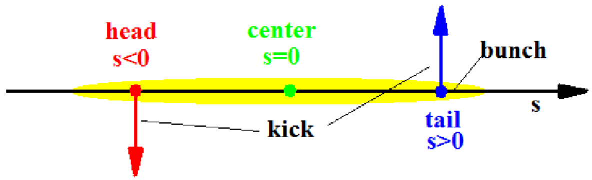
Coupler RF-Kick

- Couplers' asymmetry induces a transverse RF-kick:

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

where $\vec{k} \;\simeq\; (-7.2 + 11\; i) \times 10^{-6}$ (HFSS calculations by A.Lunin).

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



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

- **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 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 $z/\beta = 2\,\pi\, n$ <u>and</u> there is no acceleration : $\Delta\epsilon = 0$

Girder Pitch Optimization

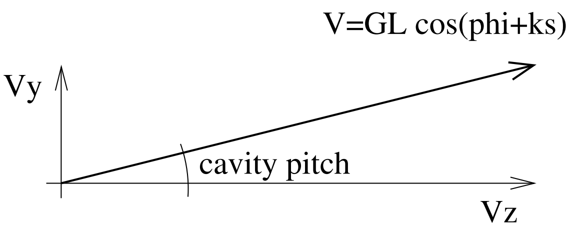
- The idea behind **Girder Pitch Optimization** is that Cavity Pitch kick can compensate RF-kick and coupler wakes

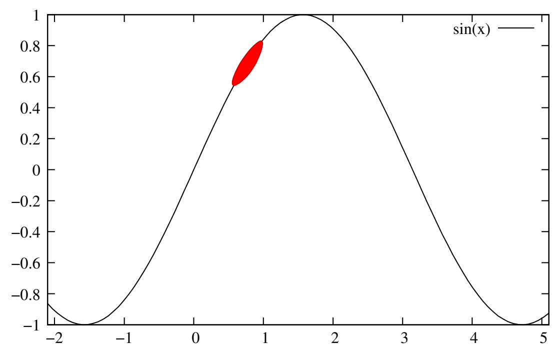
$$\Delta\vec{V}_{RF} = \underbrace{\vec{k}\,GL\,e^{-i(\phi_{RF}+ks)}}_{\text{RF}-\text{Kick}}$$

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:



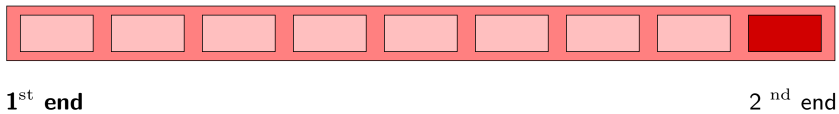


- an average kick to all the entire bunch and

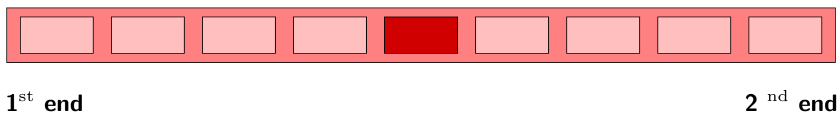
- a slope along the bunch, proportional to the phase

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:

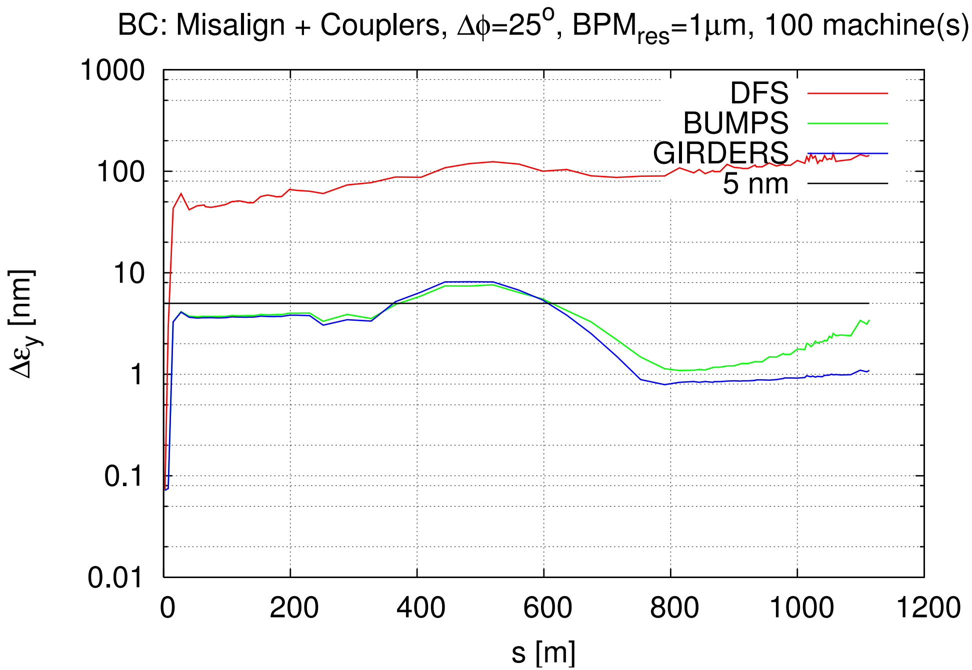
- **BC1S**: 3/6 CM in the RF section of BC1S and 3/36 CM in the pre-linac accelerating section
- **BC1+BC2**: 3/3 CM in the RF section of BC1 and 4/45 CM in the RF section of BC2

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

4) BC1+BC2, misalignment and couplers

- Correction: 1:1 + DFS + Dispersion Bumps + Girder Optimization
- Emittance growth along the line for 100 seeds:



⇒ Minimum of the emittance is at $\omega = 2048$

⇒ Average of final vertical emittance growth is 1.09 nm (1.48 nm 90% c.l.)

4) BC1+BC2, misalignment and couplers

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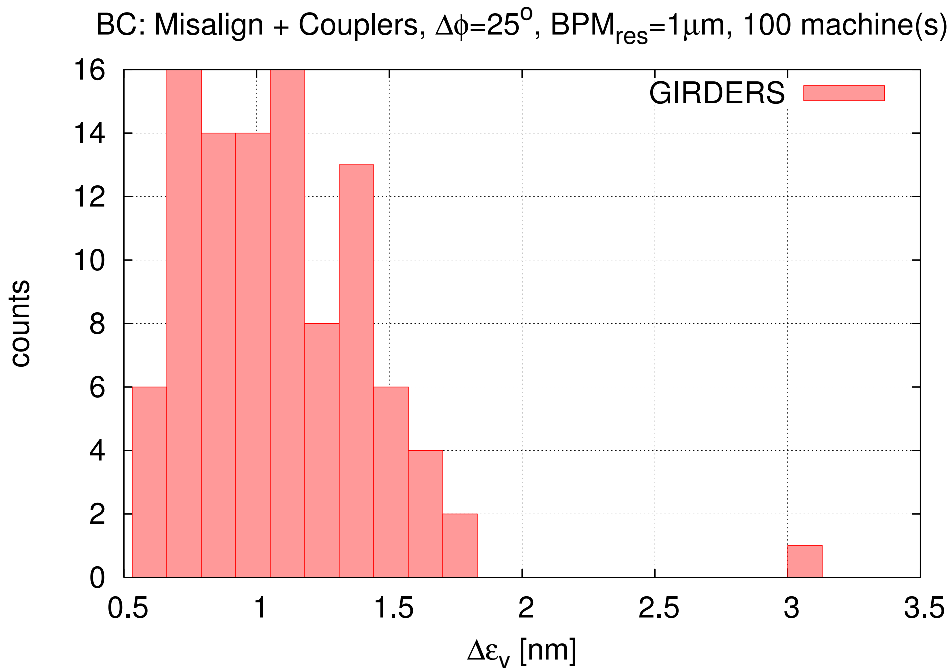


⇒ Minimum of the emittance is at $\omega = 2048$

⇒ Average of final vertical emittance growth is 1.09 nm (1.48 nm 90% c.l.)

Summary of BBA Setup in BC1S

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

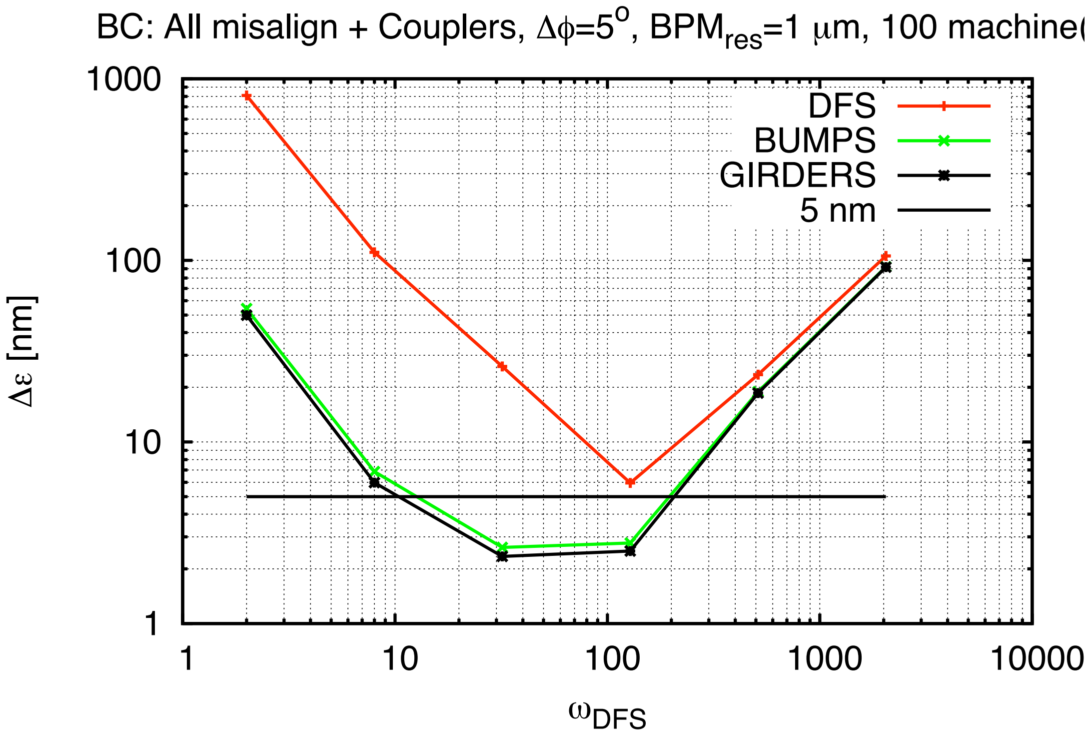
- Dispersion Free Steering
  - two test beams
  - $\Delta\phi = \pm 5^o$ phase offset in the RF section of BC1
  - phase syncronization at entrance of Pre-Linac is necessary
    $\Rightarrow$ otherwise RF-Kicks spoils the test beams, due to their large phase difference (6 $\sigma_z \approx 6$ mm)

- 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 CM (out of a total of 36 CM)

4) BC1S, misalignment and couplers

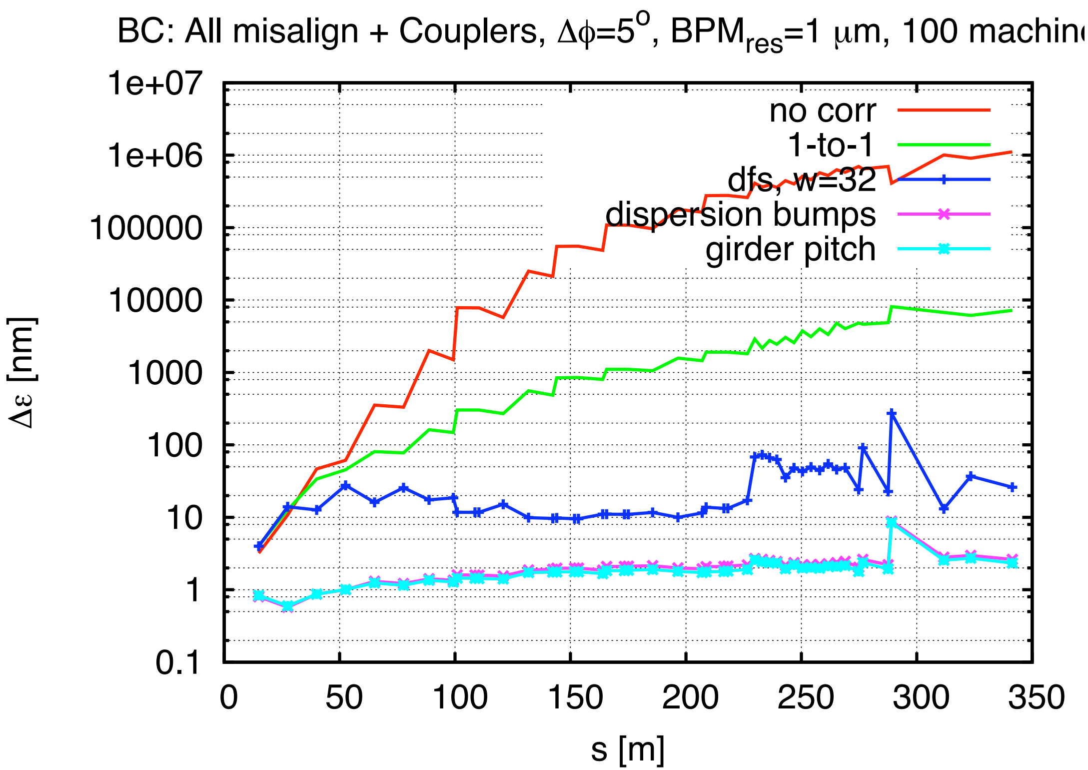
- Vertical emittance along BC1S in case of misalignments
- Couplers kicks are considered



⇒ final emittance growth is 2.3 nm (3.0 with 90% CL)

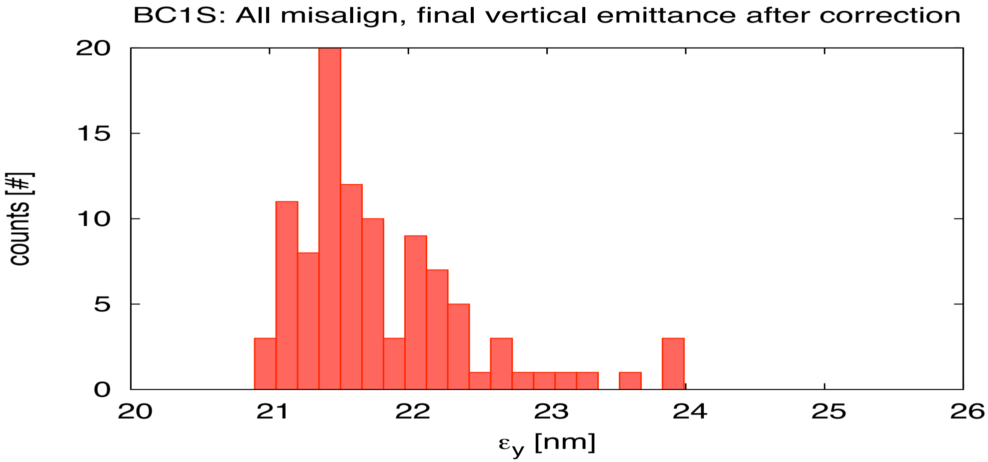
4) BC1S, misalignment and couplers

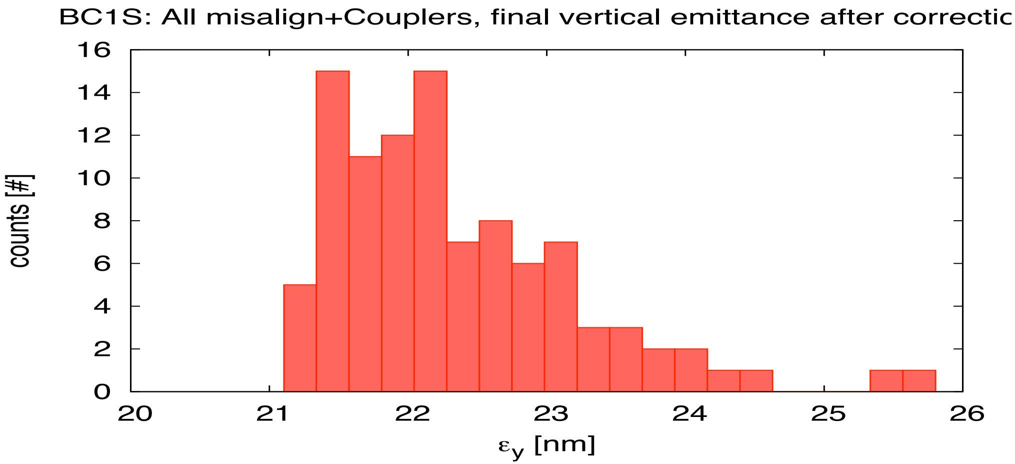
- Vertical emittance along BC1S in case of misalignments
- Couplers kicks are considered



⇒ final emittance growth is 2.3 nm (3.0 with 90% CL)

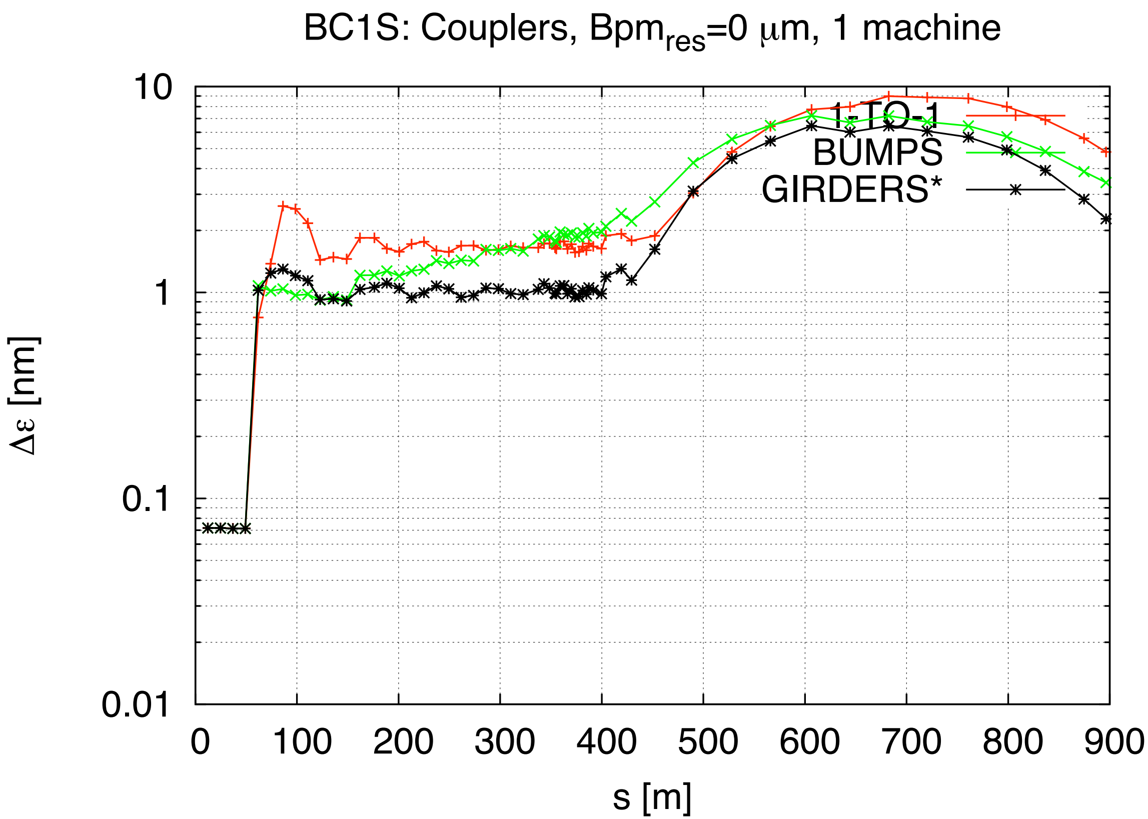
4) BC1S, misalignment and couplers





5) BC1S + Pre-Linac

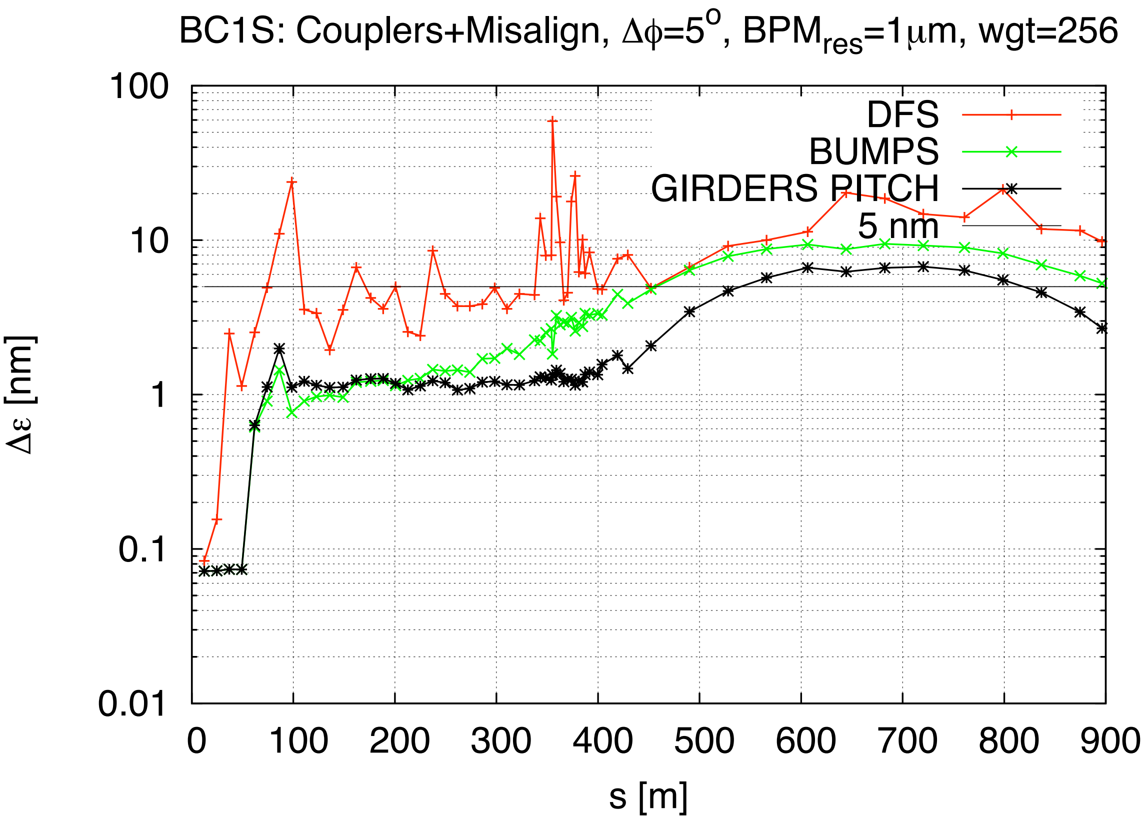
- Vertical emittance growth after correction (no misalignments, bpm resolution 0)



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

5) BC1S + Pre-Linac

- Emittance Growth along the beamline, 1 machine



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

Summary Tables for the Bunch Compressors

- These simulations:

Region	Errors	Emittance Increase (nm)		Correction
		average	90% CL	
BC1+BC2	X/Y/X'/Y' Offsets	0.98	1.6	DFS + knobs + Girders
	+ Quad Strength	-	-	DFS + knobs + Girders
BC1+BC2 w/Couplers	X/Y/X'/Y' Offsets	1.09	1.48	DFS + knobs + Girders
	+ Quad Strength	-	-	DFS + knobs + Girders
BC1S w/Couplers	X/Y/X'/Y' Offsets	2.3	3.0	DFS + knobs + Girders
	+ Quad Strength	-	-	DFS + knobs + Girders

Conclusions

- Performances of the entire RTML have been evaluated

- Performance of "Front End" have been evaluated
- Performances of BC1S are comparable to BC1+BC2

- The two configurations perform similarly

⇒ full integrated simulations of the entire RTML including bunch compressor should be performed

⇒ dynamic simulations should be performed