Beam-Based Alignment of the ILC RTML “Front End” - An Update

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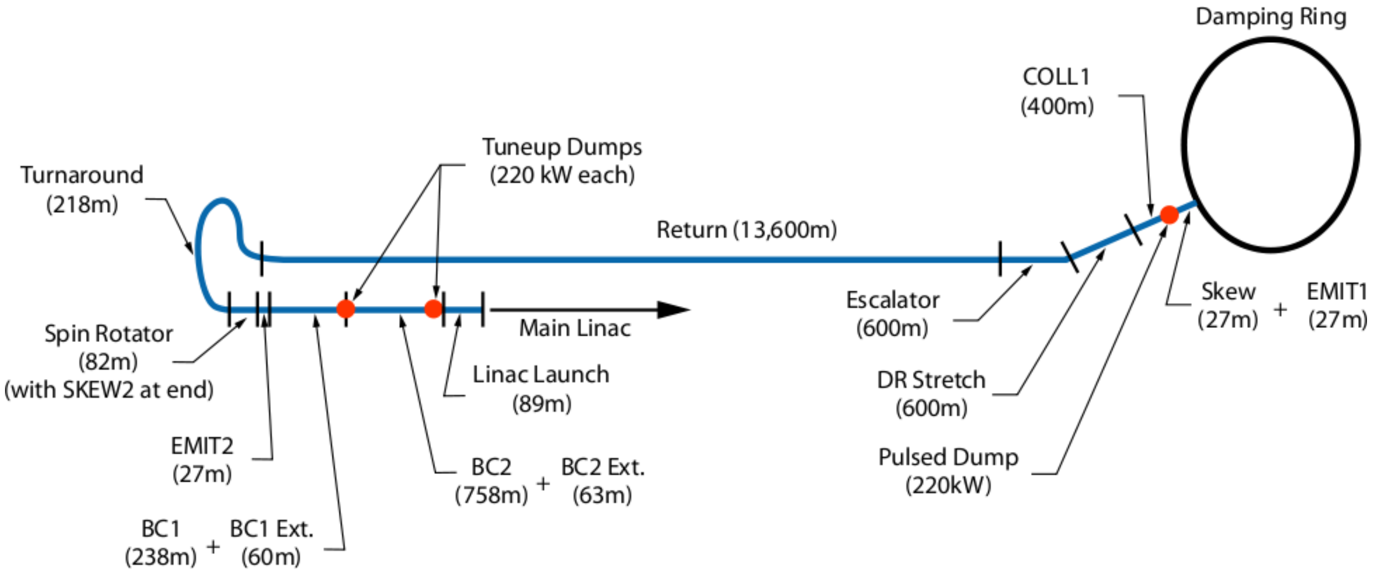
ILC RTML "Front End"



- The "Front End" of the RTML constitutes the sections of the RTML which are upstream of the first RF cavity of the first bunch compressor
- The Return line is the long FODO lattice which transports the beam backwards through the main linac tunnel to the turnaround
- The Turnaround's main purpose, as the name implies, is to reverse the direction of travel of the beam

ILC RTML Return Line

- The Return line optics is a weak focusing system with 45/45 phase advance

- The Return line is about 11.3 km long

- Most of the Return line is vertically curved to follow a gravitational equipotential.

- The beam is steered to follow this line by the dipole correctors which are located near the quads

- The dispersion matching and suppression is accomplished with correctors in the first 7 and last 7 cells of the curved section

- It is just a FODO lattice but its alignment is tricky, because:
  - the beamline is curved to follow the earth curvature
  - the downstream turnaround fixes the energy

Quad-Shunting and other BBA techniques

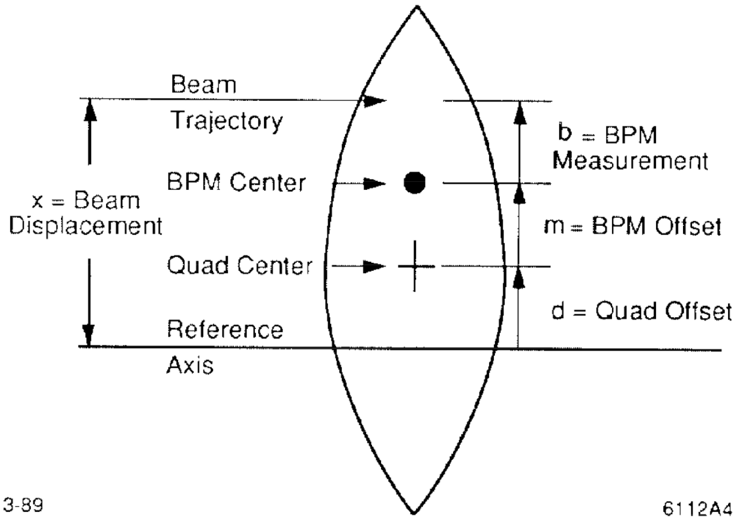
- **Quad-shunting technique** is used to measure the BPM-to-quad offset
- **BPM-to-quad** offset tells approximately where the magnetic center of each quad is located

- **Minimum emittance growth** does not occur when the beam passes through the magnetic center of each quads, but when the trajectory is straight in an absolute sense.

- Common **BBA techniques** include: 1:1 correction, Dispersion Free Steering, Kick Minimization, Ballistic Alignment
  - ⇒ 1:1 can be used, but it is not sufficient to recover the emittance blow up
  - ⇒ Dispersion Free Steering cannot be used, as it is not possible to send test beams with energy $E \neq E_0$ to measure the dispersion
  - ⇒ Kick Minimization is the object of this presentation
  - ⇒ Ballistic Alignment cannot be used, because the Return Line follows a gravitational equipotential

Kick Minimization

- Kick Minimization is a steering method which tries to balance two optima:
  - minimization of the RMS measured orbit, 1:1 term
  - minimization of the corrector strength, KM term
- General situation: quadrupole offset d, BPM offset m and BPM measurement b:



The displacement of the beam from the reference axis is $x = d + b + m$.

⇒ BPMs are aligned to quadrupoles using quad-shunting

⇒ After quad-shunting the quad-bpm offsets are close to zero: $\boxed{m \simeq 0}$

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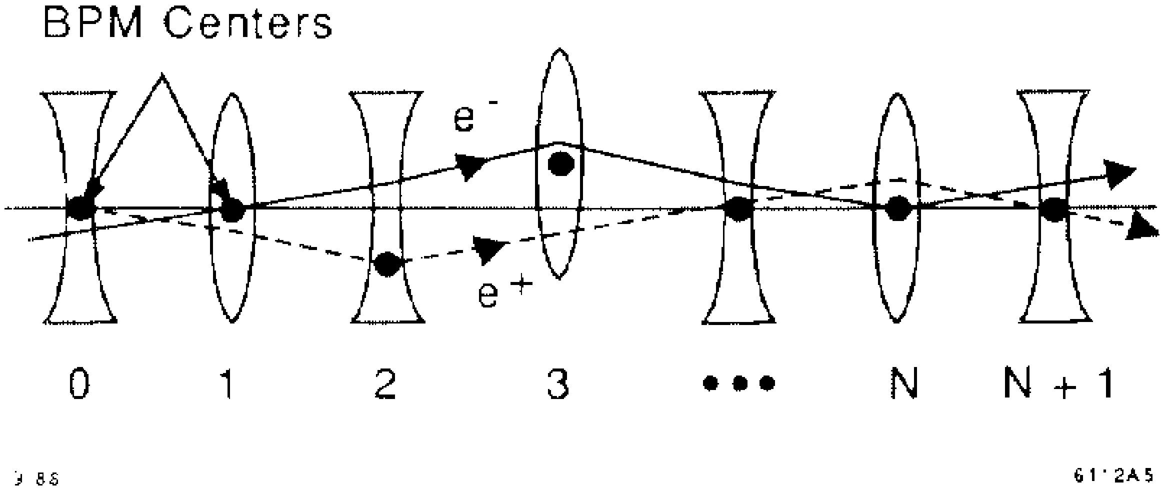


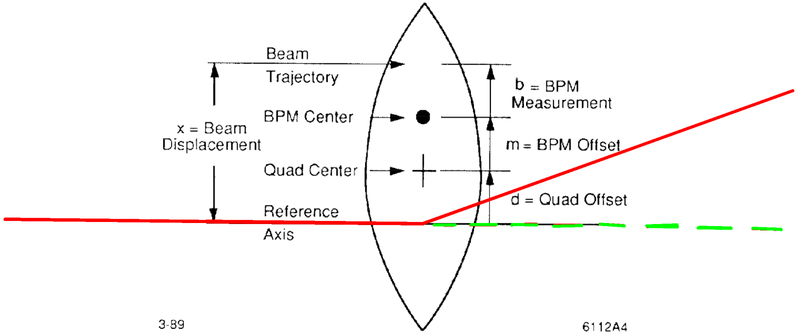
The displacement of the beam from the reference axis is $x = d + b + m$.

⇒ BPMs are aligned to quadrupoles using quad-shunting

⇒ After quad-shunting the quad-bpm offsets are close to zero: $\boxed{m \simeq 0}$

Kick Minimization

- Case of misaligned quads and bpms:



1:1 alone would introduce dispersion, thus emittance growth

⇒ Kick Minimization attempts to make use of the additional information $m \simeq 0$.

For a quad with nonzero bpm reading b, the beam is kicked by the quad by:

$$\Delta\theta = KL \cdot b$$

where KL is the integrated strength of the quadrupole expressed in m^{-1}.

⇒ If the corrector gives an **opposite kick** the beam will pass the quadrupole **unkicked**.

⇒ Nevertheless, you still need to have a 1:1 correction term to keep the trajectory straight

Kick Minimization by PT

- In the SLAC-Tech-Note 07-002,
- PT explained his implementation of KM: if $\theta_{\text{quad}} = KL \cdot b$ and $\theta_{\text{corr}} = -\theta_{\text{quad}}$, then the emittance growth is minimized if the following equations are satisfied

$$\boldsymbol{\theta}_{\text{quad}} = KL \cdot b \quad \Rightarrow \quad \boldsymbol{\theta}_{\text{corr}} = -\boldsymbol{\theta}_{\text{quad}} \quad \Rightarrow \quad b + \frac{\theta_{\text{corr}}}{KL} \approx 0$$

- The system of equations is

$$\begin{pmatrix} \mathbf{b}_{\text{x}} \\ \mathbf{b}_{\text{y}} \\ \mathbf{c}_{\text{x}} \\ \mathbf{c}_{\text{y}} \end{pmatrix} = \begin{pmatrix} \mathbf{M}_{\text{xx}} & 0 \\ \mathbf{0} & \mathbf{M}_{\text{yy}} \\ \mathbf{N}_{\text{xx}} & 0 \\ \mathbf{0} & \mathbf{N}_{\text{yy}} \end{pmatrix} \begin{pmatrix} \Delta\boldsymbol{\theta}_{\text{x}} \\ \Delta\boldsymbol{\theta}_{\text{y}} \end{pmatrix}$$

\- Where b is the vector of the BPM readings; $\mathbf{M}_{\text{xx}}$ is the usual response matrix; $\mathbf{N}_{\text{xx}}$ is defined as follows:

$$\mathbf{N}_{\text{xx,ij}} = \begin{cases} \mathbf{M}_{\text{xx,ij}} \pm \dfrac{1}{KL_{\text{i}}}, & i = j \\ \mathbf{M}_{\text{xx,ij}}, & i \neq j \end{cases}$$

and

$$\mathbf{c}_{\text{x}} = \mathbf{b}_{\text{x}} \pm \frac{1}{KL} \boldsymbol{\theta}_{\text{x}}$$

Kick Minimization by Me

- Kick Minimization by PT manifests some limitation
  - You need to have an equal number of quadrupoles / correctors / bpms ⇒ this is not always the case
  - it is a **local** correction
- New system of equations

$$\begin{pmatrix} \mathbf{b}_\mathsf{x} \\ \mathbf{b}_\mathsf{y} \\ \mathbf{c}_\mathsf{x} \\ \mathbf{c}_\mathsf{y} \end{pmatrix} = \begin{pmatrix} \mathbf{M}_\mathsf{xx} & 0 \\ \mathbf{0} & \mathbf{M}_\mathsf{yy} \\ \mathbf{N}_\mathsf{xx} & 0 \\ \mathbf{0} & \mathbf{N}_\mathsf{yy} \end{pmatrix} \begin{pmatrix} \Delta\boldsymbol{\theta}_\mathsf{x} \\ \Delta\boldsymbol{\theta}_\mathsf{y} \end{pmatrix} \Rightarrow \begin{pmatrix} \mathbf{b}_\mathsf{x} \\ \mathbf{b}_\mathsf{y} \\ \mathbf{c}_\mathsf{x} \\ \mathbf{c}_\mathsf{y} \end{pmatrix} = \begin{pmatrix} \mathbf{M}_\mathsf{xx} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_\mathsf{yy} \\ \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{pmatrix} \begin{pmatrix} \Delta\boldsymbol{\theta}_\mathsf{x} \\ \Delta\boldsymbol{\theta}_\mathsf{y} \end{pmatrix}$$

- Where b = the vector of the BPM readings; M_xx = the response matrix; I = **identity matrix**.
- The observable c is now defined as

$$\boxed{\mathbf{c}_\mathsf{x} = \boldsymbol{\theta}_\mathsf{x} + \mathbf{M}_\mathsf{xx}^{-1}\,\mathbf{b}_\mathsf{x}}$$

and replaces

$$\mathbf{c}_\mathsf{x} = \mathbf{b}_\mathsf{x} \pm \frac{1}{KL}\boldsymbol{\theta}_\mathsf{x}$$

Comparison

⇒ In PT's implementation c has a unit of length, and it's meant to be a "correction" applied to each BPM reading

⇒ In my implementation c has a unit of kick and accounts for the difference between the kick given by the correctors and the kick given by all downstream quadrupoles.

⇒ KM minimization tries to minimize c. When c is → zero

$$\boxed{\boldsymbol{\theta} = -\mathbf{M}_{\mathsf{xx}}^{-1}\mathbf{b}}$$

i.e. the correctors compensate the quadrupole kicks

⇒ The matrix N is not really necessary: when c is defined as described and N is replaced by the identity matrix, each single line accounts for the balance of each single corrector, that is sufficient at our purpose

Tuning of Kick Minimization

- KM tries to balance 1:1 correction with minimization of the quadrupole kicks.

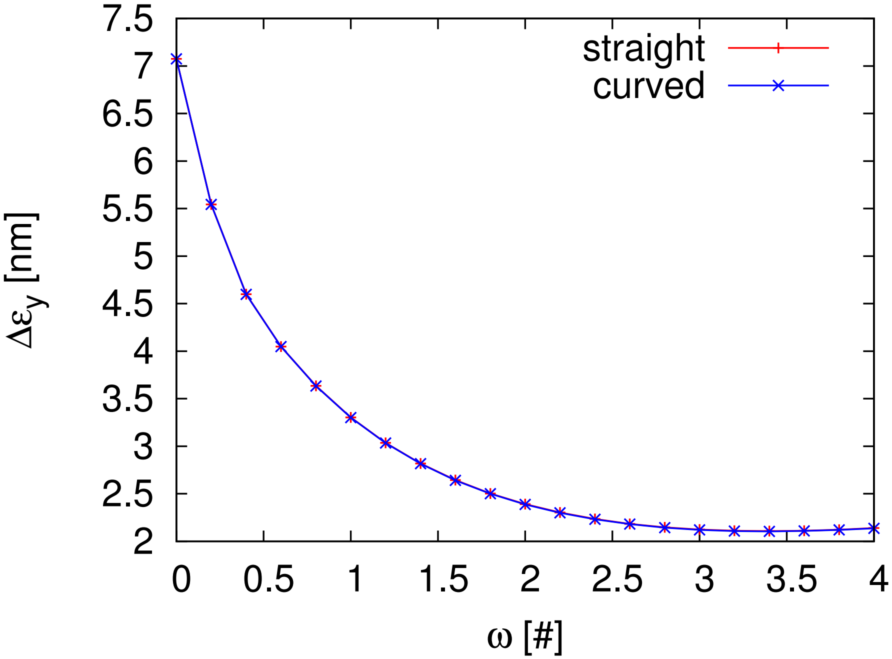
- The actual system of equations that must be solved is

$$\begin{pmatrix} \mathbf{b} \\ \omega \cdot \mathbf{c} \end{pmatrix} = \begin{pmatrix} \mathbf{M} \\ \omega \cdot \mathbf{I} \end{pmatrix} \begin{pmatrix} \Delta\boldsymbol{\theta}_{\mathrm{x}} \\ \Delta\boldsymbol{\theta}_{\mathrm{y}} \end{pmatrix}$$

⇒ We need to find the optimum of the parameter ω.

Tuning of Kick Minimization

⇒ Using the standard sources of errors (see next slides) we performed a scan of the emittance growth as a function of ω:



Each point is the average of 100 seeds

⇒ The minimum is found for $\omega = 3.35$ at $\epsilon_{\mathrm{y}} = 22.11$ nm

Coupling Correction

Coupling is corrected in two ways:

1) Modifying the Kick Minimization system of equations to include $\mathbf{M}_{\mathsf{xy}}$ and $\mathbf{M}_{\mathsf{yx}}$

$$\begin{pmatrix} \mathbf{b}_{\mathsf{x}} \\ \mathbf{b}_{\mathsf{y}} \\ \omega\mathbf{c}_{\mathsf{x}} \\ \omega\mathbf{c}_{\mathsf{y}} \end{pmatrix} = \begin{pmatrix} \mathbf{M}_{\mathsf{xx}} & \mathbf{M}_{\mathsf{xy}} \\ \mathbf{M}_{\mathsf{yx}} & \mathbf{M}_{\mathsf{yy}} \\ \omega\mathbf{I} & \mathbf{0} \\ \mathbf{0} & \omega\mathbf{I} \end{pmatrix} \begin{pmatrix} \Delta\boldsymbol{\theta}_{\mathsf{x}} \\ \Delta\boldsymbol{\theta}_{\mathsf{y}} \end{pmatrix}$$

2) Using 4 skew quadrupoles located in the Getaway

⇒ Simplex optimization of the final emittance

Simulation Setup

- A number of simulations were performed with different sets of errors
  - X/Y Misalignments
    - $\sigma_{\text{quad offset}} = 150\ \mu$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

- 1000 seeds

- All simulations have been performed using PLACET

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

⇒ 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

⇒ Correction technique:

  - 1:1 + Kick Minimization
  - Dispersion Tuning Knobs

Cases Studied (2/2)

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

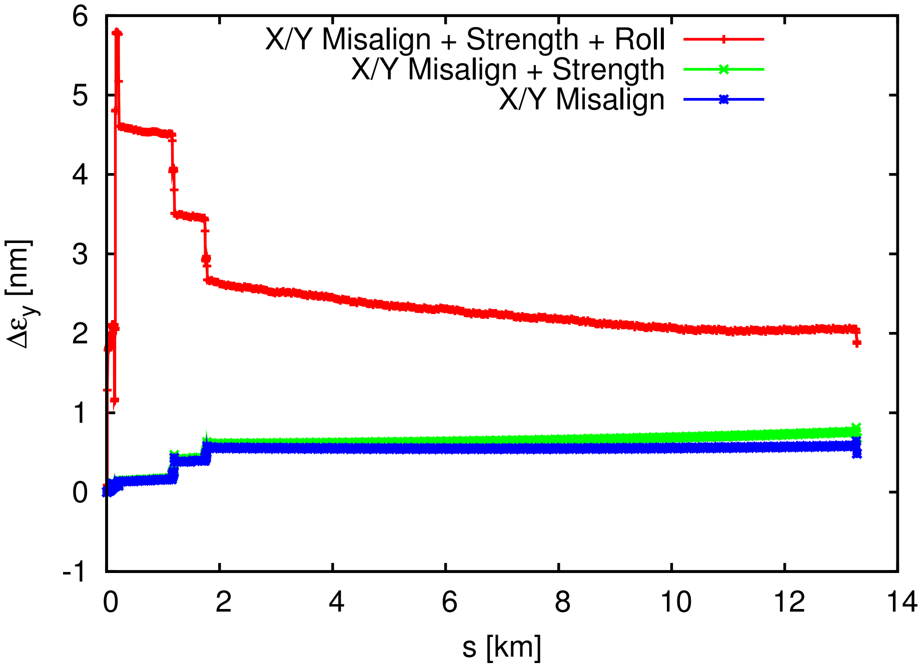
- Only X/Y misalignments
- Add Quadrupole and Sbend strength errors
- Add Quadrupole and Sbend roll errors

⇒ Correction technique:

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

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

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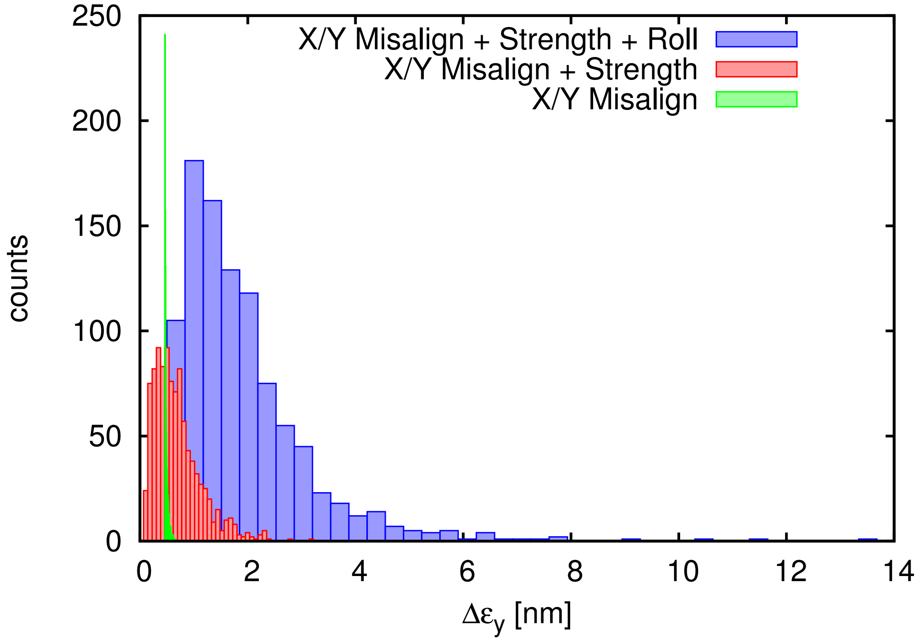

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2) Turnaround + Spin Rotator (Solenoids OFF)

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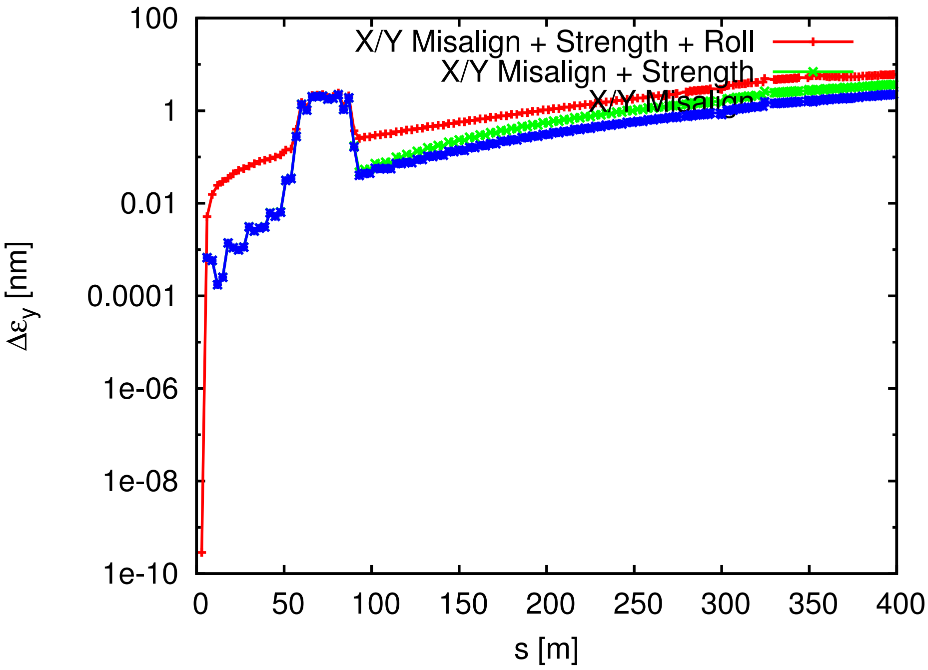

⇒ X/Y Offsets: Final average emittance growth is 2.26 nm (5.33 nm 90% c.l.)

⇒ 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.)

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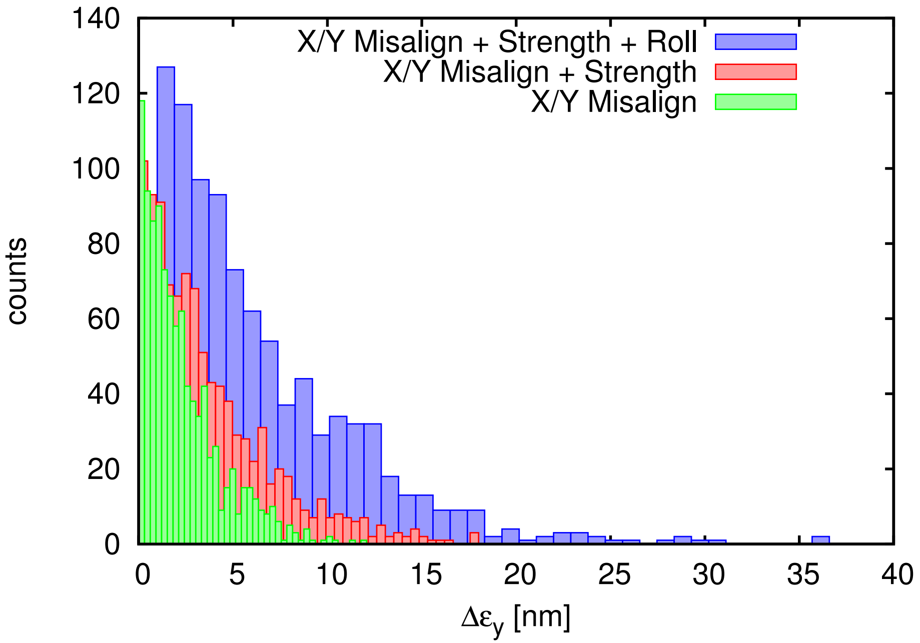

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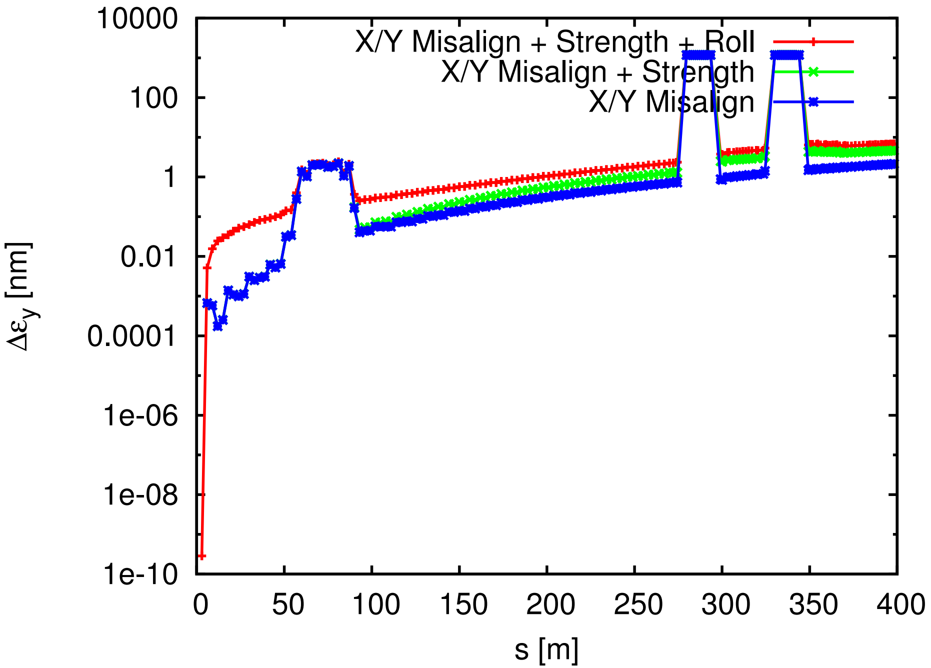
2) Turnaround + Spin Rotator (Solenoids ON)

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



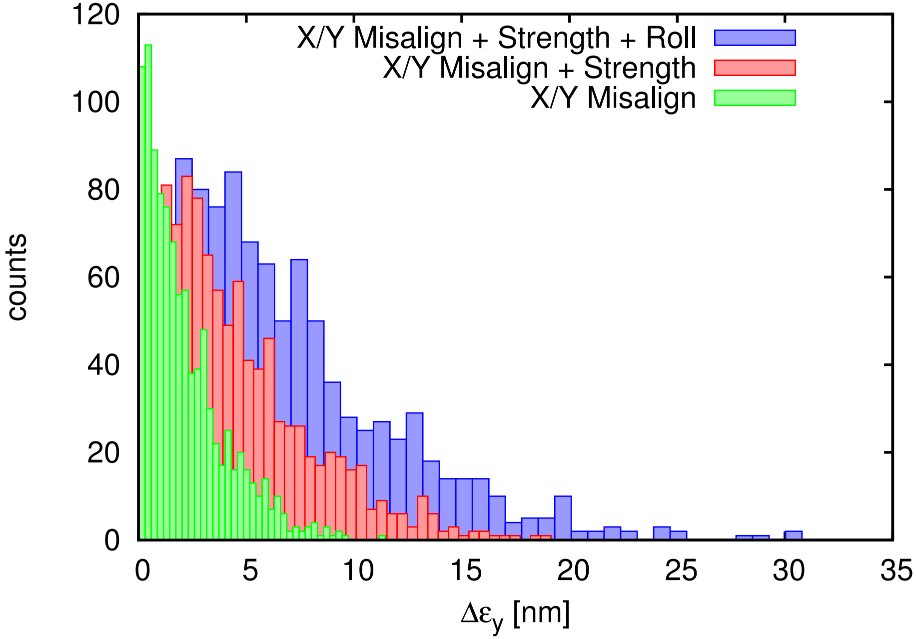
⇒ X/Y Offsets: Final average emittance growth is 2.14 nm (4.83 nm 90% c.l.)

⇒ 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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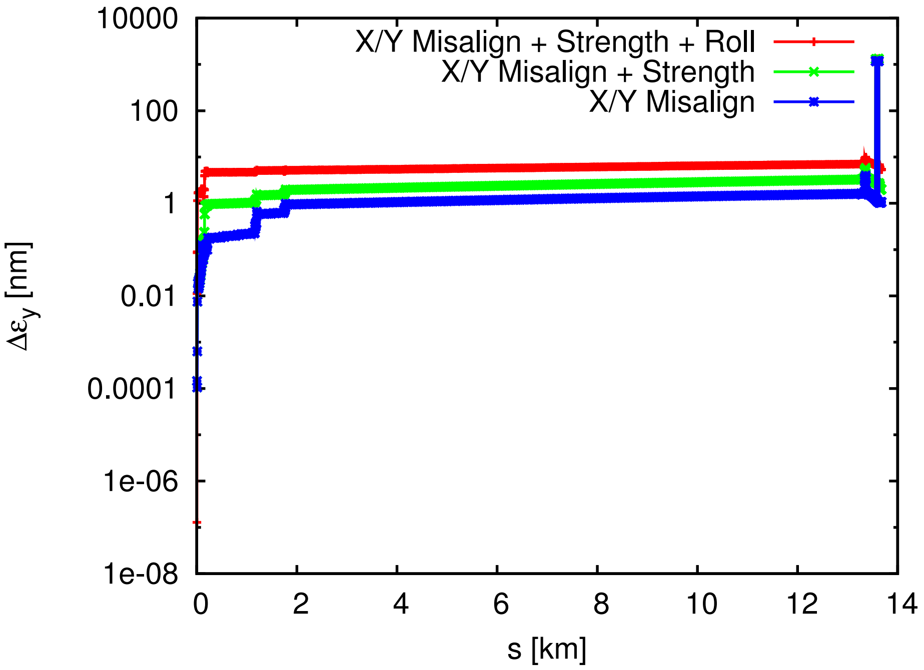
3) Entire “Front End”

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



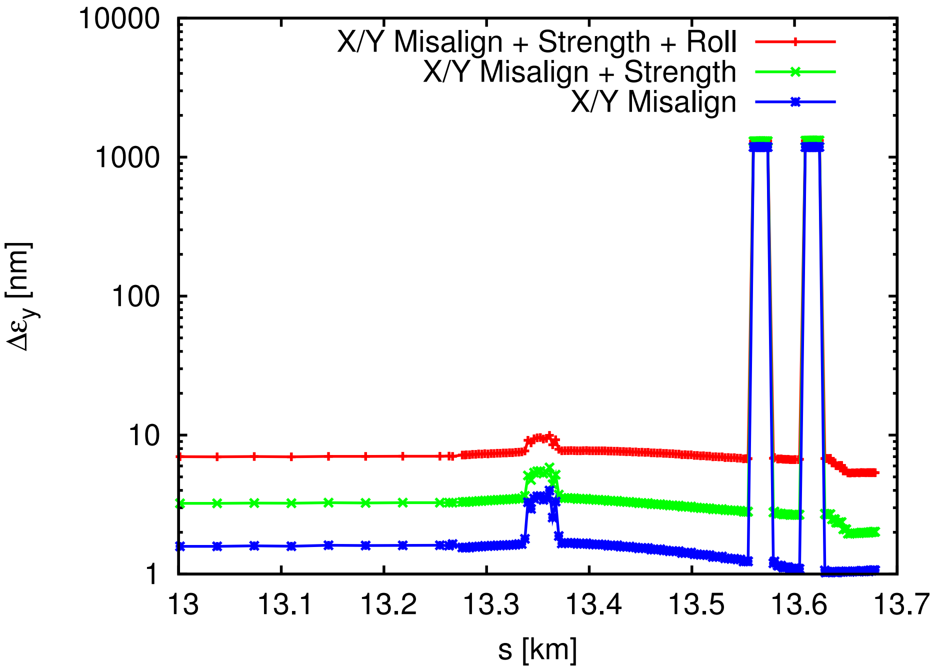
⇒ X/Y Offsets: Final average emittance growth is 1.06 nm (1.58 nm 90% c.l.)

⇒ 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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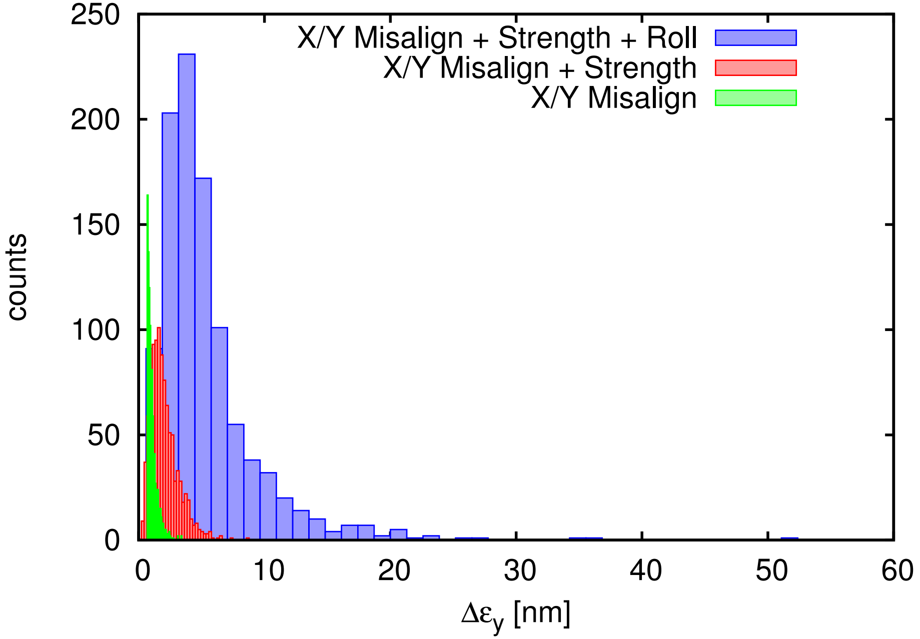
- Histogram of final emittance growth for 1000 seeds:



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Summary Tables

- 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

Summary Tables

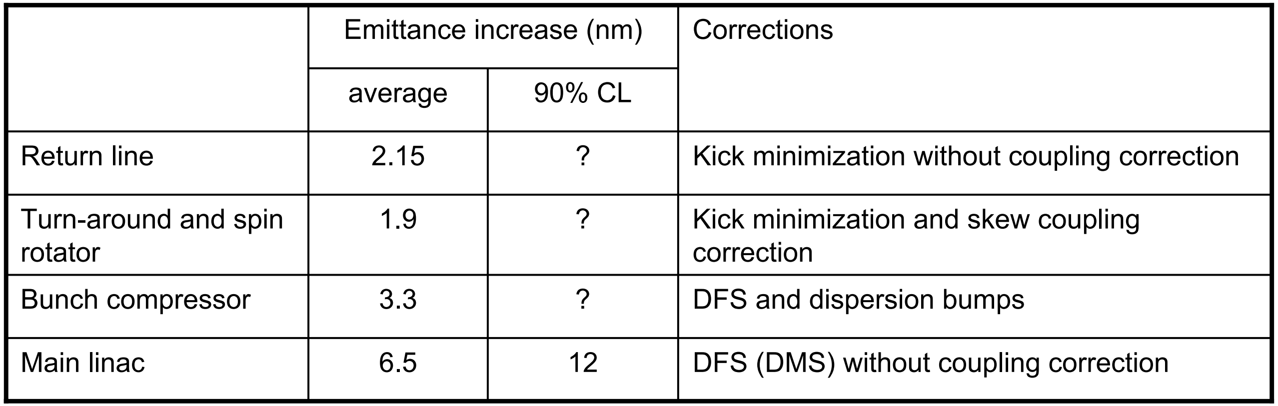
- PT's summary table

  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

- Kiyoshi's table, LCWS2010 Beijing:



	Emittance increase (nm)		Corrections
	average	90% CL	
Return line	2.15	?	Kick minimization without coupling correction
Turn-around and spin rotator	1.9	?	Kick minimization and skew coupling correction
Bunch compressor	3.3	?	DFS and dispersion bumps
Main linac	6.5	12	DFS (DMS) without coupling correction

Conclusions and Next Steps

- RTML "front end" has been studied. It seems "almost" under control

- Performances of return line and turnaround + spin rotator have been evaluated, as well as the entire front end. Are they satisfactory?

⇒ Integrated simulations of the entire RTML, including bunch compressor, must be performed

⇒ 90% CL emittances of the bunch compressors must be evaluated

- Question: which set of errors should we consider "standard" ? Offsets, magnet strength errors, rolls, couplers, . . .
- Question: how the performances can be improved?