Beam-Based Alignment of the ILC RTML "Front End"

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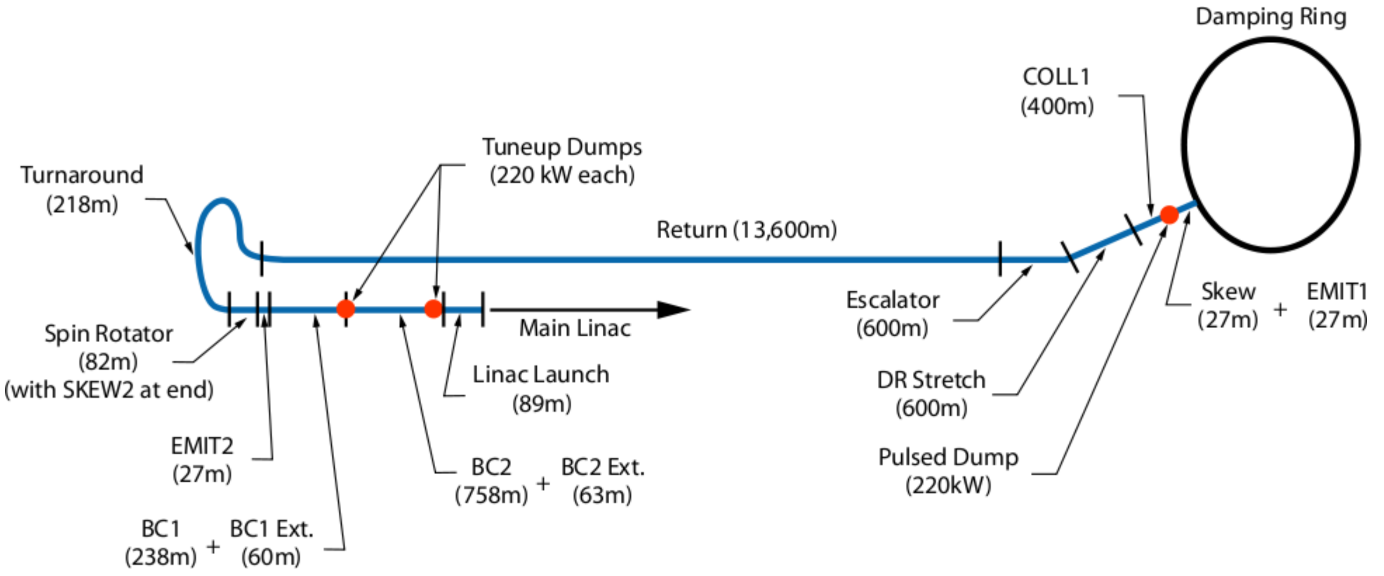
ILC RTML "Front End"



- 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 trunaround fixes the energy

Quad-Shunting and other BBA techniques

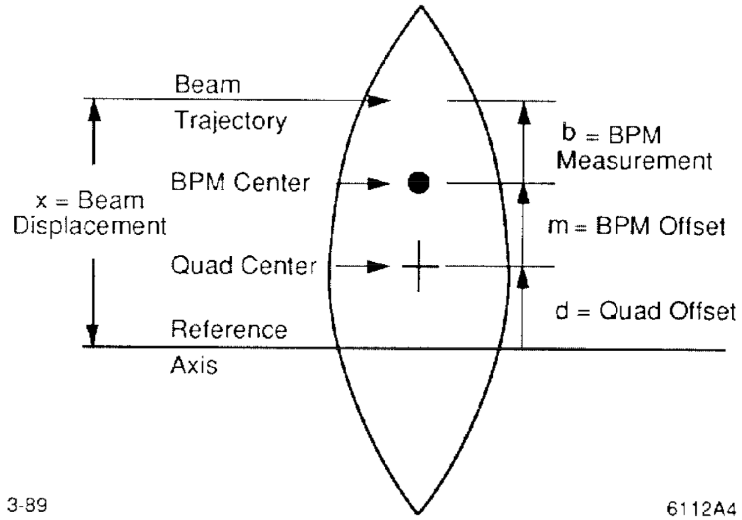
- **Quad-shunting technique** is used to measure the BPM-to-quad offset
- **BPM-to-quad** offset tells approximatively where the magnetic center of each quad is located

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

Kick Minimization

- Kick Minimization is a steering method which balances 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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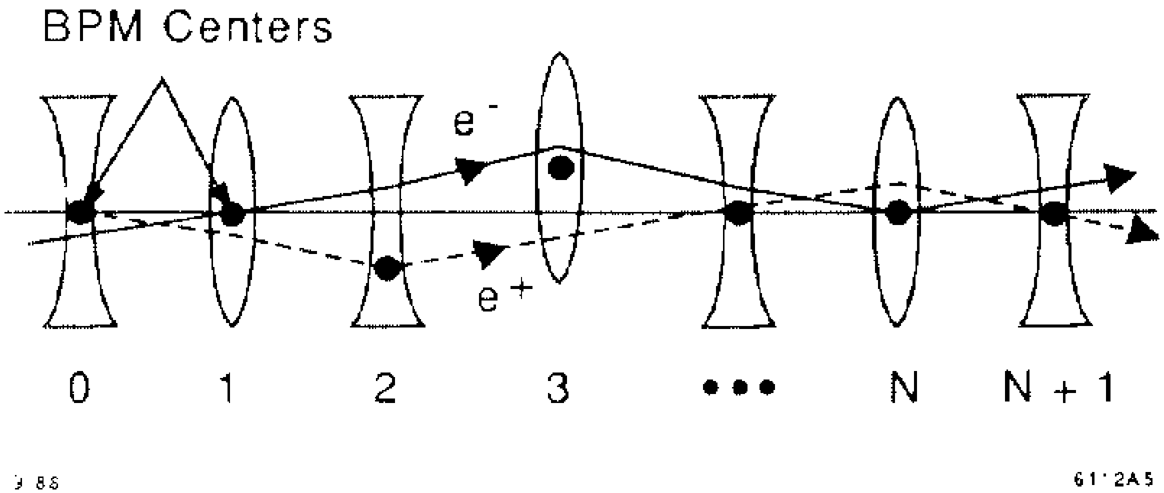


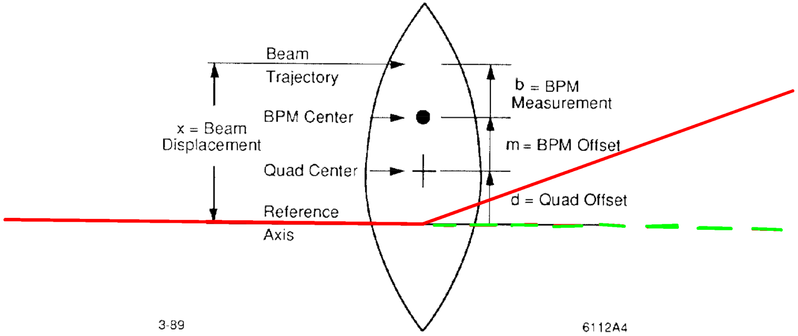
The displacement of the beam from the reference axis is $x = d + b + m$.

⇒ 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 trajctory 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

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

- The system of equations is

$$\begin{pmatrix} b_x \\ b_y \\ c_x \\ c_y \end{pmatrix} = \begin{pmatrix} M_{xx} & 0 \\ 0 & M_{yy} \\ N_{xx} & 0 \\ 0 & N_{yy} \end{pmatrix} \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \end{pmatrix}$$

- Where b is the vector of the BPM readings; M_{xx} is the usual response matrix; N_{xx} is defined as follows:

$$N_{xx,ij} = \begin{cases} M_{xx,ij} \pm \dfrac{1}{KL_i}, & i = j \\ M_{xx,ij}, & i \neq j \end{cases}$$

and

$$c_x = b_x \pm \frac{\theta_x}{KL}$$

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

$$\begin{pmatrix} b_x \\ b_y \\ c_x \\ c_y \end{pmatrix} = \begin{pmatrix} M_{xx} & 0 \\ 0 & M_{yy} \\ N_{xx} & 0 \\ 0 & N_{yy} \end{pmatrix} \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} b_x \\ b_y \\ c_x \\ c_y \end{pmatrix} = \begin{pmatrix} M_{xx} & 0 \\ 0 & M_{yy} \\ I & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \end{pmatrix}$$

- Where $b =$ the vector of the BPM readings; $M_{xx} =$ the response matrix; $I =$ **identity matrix**.
- The observable c is now defined as

$$\boxed{c_x = \theta_x + M_{xx}^{-1} b_x}$$

and replaces

$$c_x = b_x \pm \frac{1}{KL} \theta_x$$

Comparison

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

$\Rightarrow$ 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.

$\Rightarrow$ KM minimization tries to minimize c. When c is $\rightarrow$ zero

$$\boxed{\boldsymbol{\theta} = -M_{xx}^{-1}\mathbf{b}}$$

i.e. the correctors compensate the quadrupole kicks

$\Rightarrow$ 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.

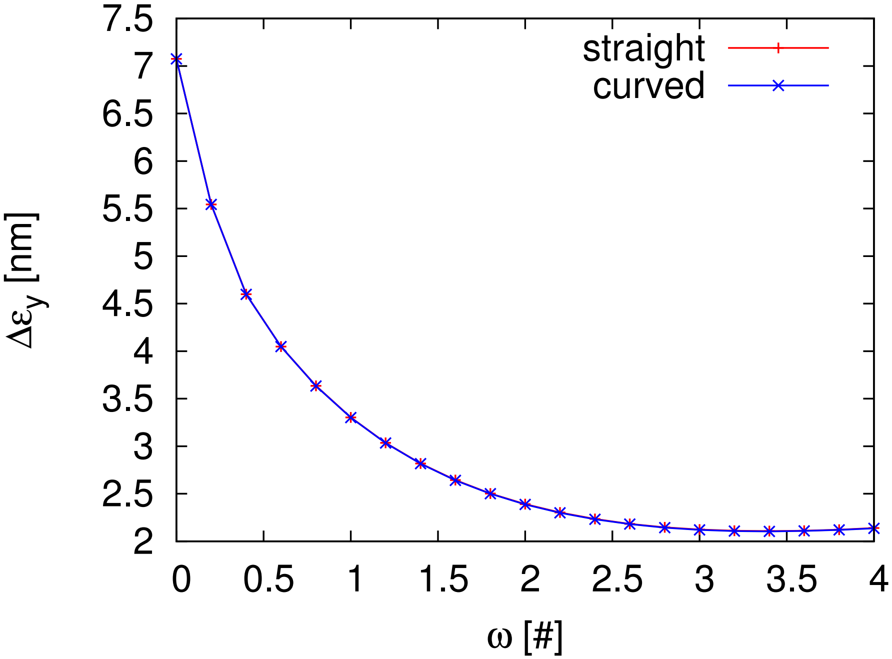
- The actual system of equations that must be solved is

$$\begin{pmatrix} \mathbf{b} \\ \omega \cdot \mathbf{c} \end{pmatrix} = \begin{pmatrix} \mathbf{M} \\ \omega \cdot \mathbf{I} \end{pmatrix} \begin{pmatrix} \Delta\theta_x \\ \Delta\theta_y \end{pmatrix}$$

⇒ 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 $\epsilon_y = 22.11$ nm

Simulation Setup

- A number of simulations were performed with different sets of errors

- 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
  - $\sigma_{\text{quad roll}} = 300\ \mu$rad RMS w.r.t. design orbit
  - $\sigma_{\text{bpm res}} = 1\ \mu$m

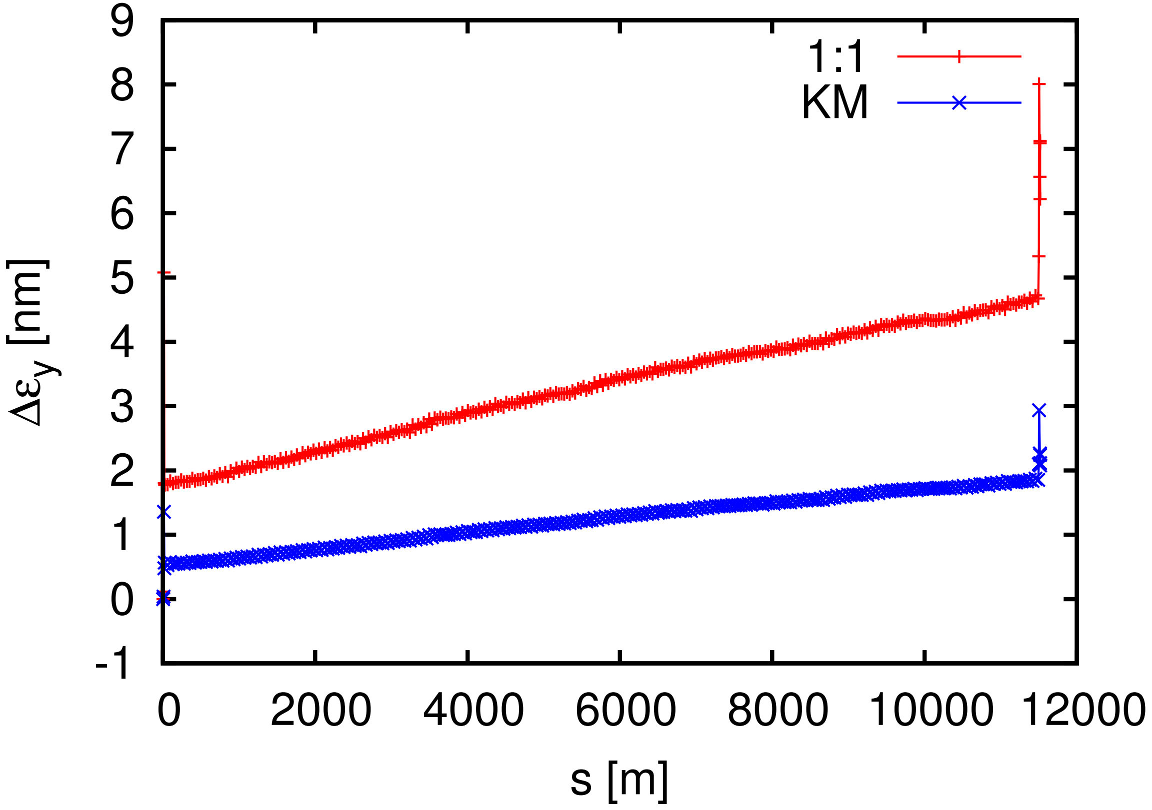
- Strength errors
  - $\sigma_{\text{quad strength}} = 0.25\%$ RMS
  - $\sigma_{\text{bend strength}} = 0.5\%$ RMS

- 100/1000 seeds

- All simulations have been peformed using PLACET

Only Misalignment Errors

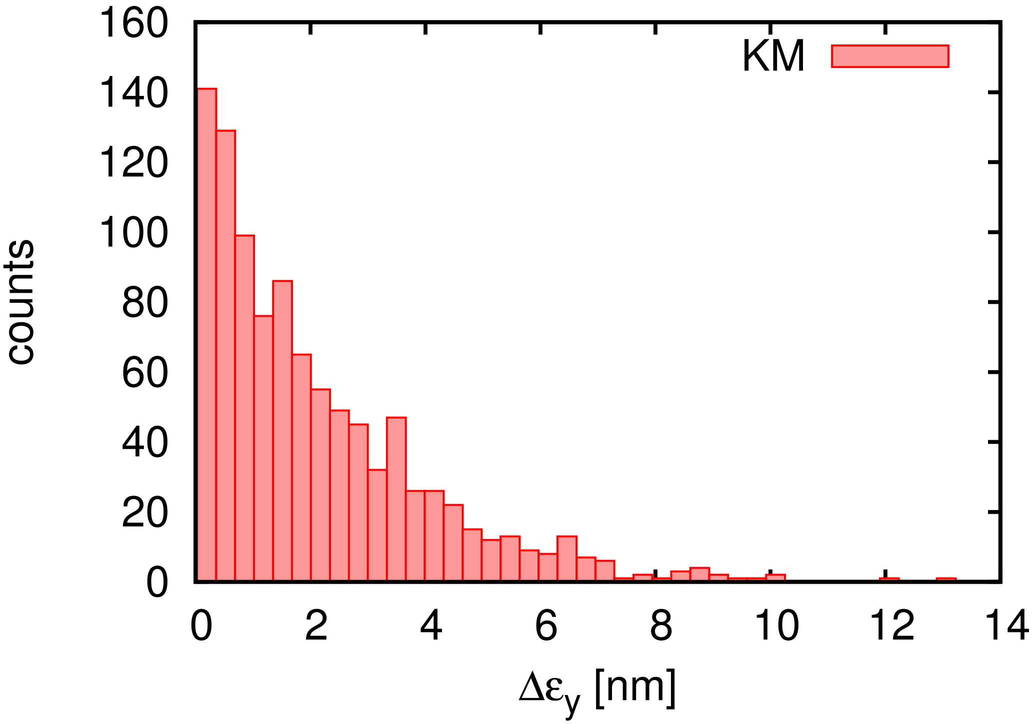
- Emittance growth along the line for 1000 seeds:



⇒ Final vertical emittance growth 2.11 nm.

Only Misalignment Errors

- Histogram with the final emittance growths for 1000 seeds:

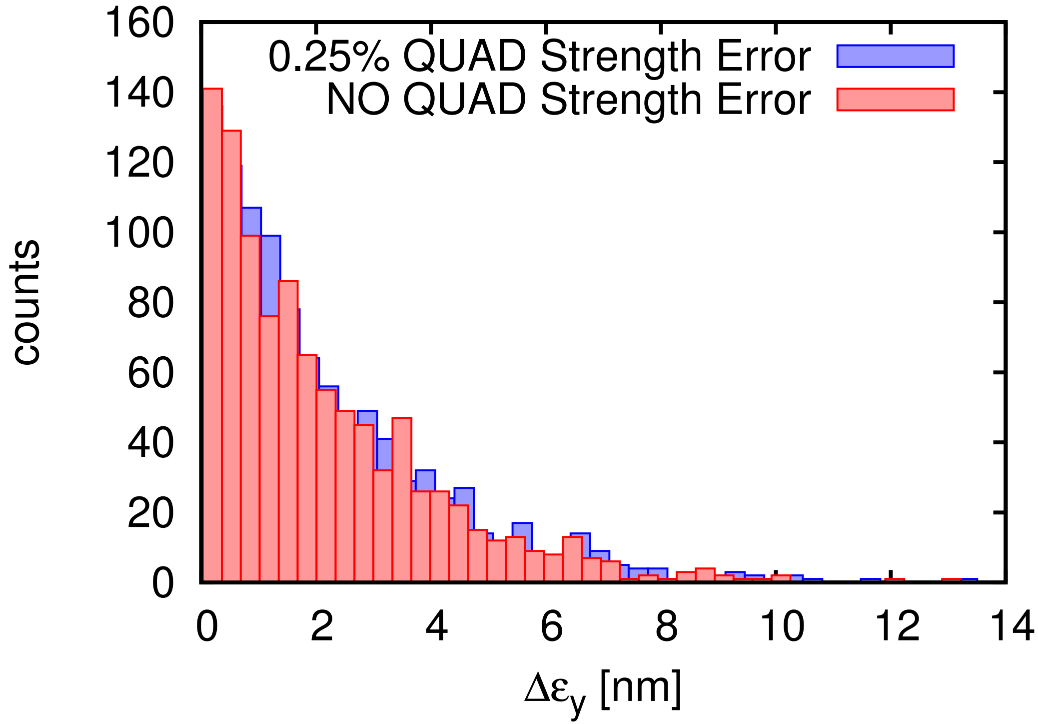


⇒ Final vertical emittance growth 2.11 nm.

⇒ Final vertical emittance growth 90% confidence level 4.67 nm.

Misalignments + Quad Strength Errors

- 0.25% RMS quad Strength error has been added



⇒ Final average emittance growth is 2.14 nm

⇒ 90% confidence level vertical emittance growth is 4.74 nm

Rolls: Getaway + Escalator + Return Line

- Getaway and Escalator have been added to the simulation in order to use the skew quadrupoles for the coupling correction
- Roll errors have been added

- Dispersion bumps are run after KM

\- 4 skew quadrupoles are located in the GetAway for coupling correction.

- They are pairwise located $-\mathbf{I}$ from each other and are used as two dispersion tuning knobs

⇒ The first dispersion tuning knob has coefficients

$$\left[\begin{array}{cccc} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{array} \right]$$

⇒ The second dispersion tuning knob, that is orthogonal to the first, has coefficients

$$\left[\begin{array}{cccc} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{array} \right]$$

Rolls: Getaway + Escalator + Return Line

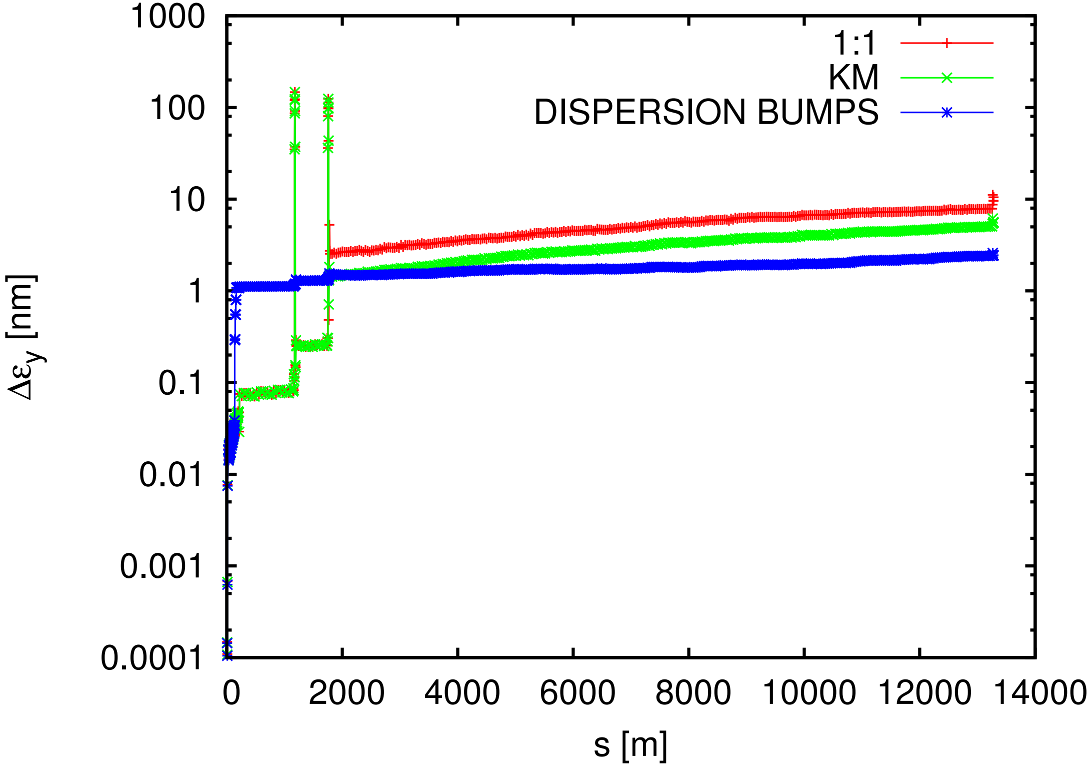
- Misalignments
  - $\sigma_{\text{quad offset}} = 150\ \mu$m RMS w.r.t. design orbit
  - $\sigma_{\text{bpm offset}} = 7\ \mu$m RMS w.r.t. quadrupole center
  - $\sigma_{\text{quad roll}} = 300\ \mu$rad RMS w.r.t. design orbit
  - $\sigma_{\text{bpm res}} = 1\ \mu$m

- Strength errors
  - $\sigma_{\text{quad strength}} = 0.25\%$ RMS
  - $\sigma_{\text{bend strength}} = 0.5\%$ RMS

⇒ Dispersion Bumps have been applied after KM

Rolls: Getaway + Escalator + Return Line

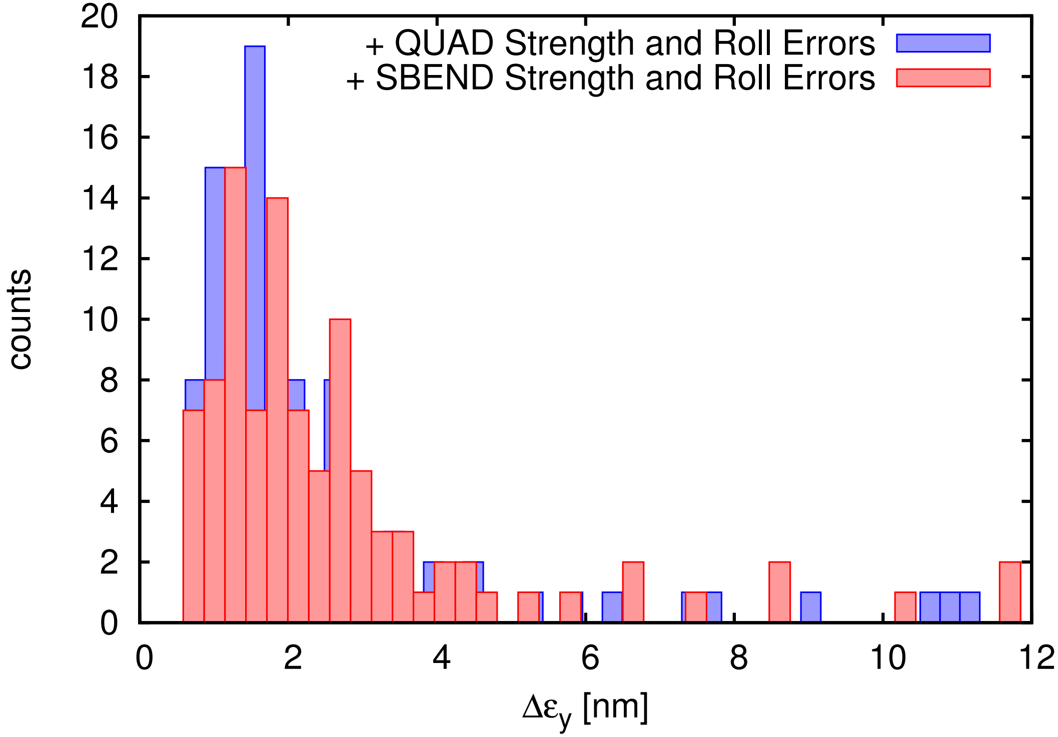
- Emittance growth along the line for 100 seeds



⇒ Final average emittance growth is 2.68 nm

Rolls: Getaway + Escalator + Return Line

- Emittance growth along the line for 100 seeds



⇒ Final average emittance growth is 2.68 nm

⇒ 90% confidence level vertical emittance growth is 4.58 nm

Turnaround + Spin Rotator

- 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
  - $\sigma_{\text{quad roll}} = 300\ \mu$rad RMS w.r.t. design orbit
  - $\sigma_{\text{bpm res}} = 1\ \mu$m

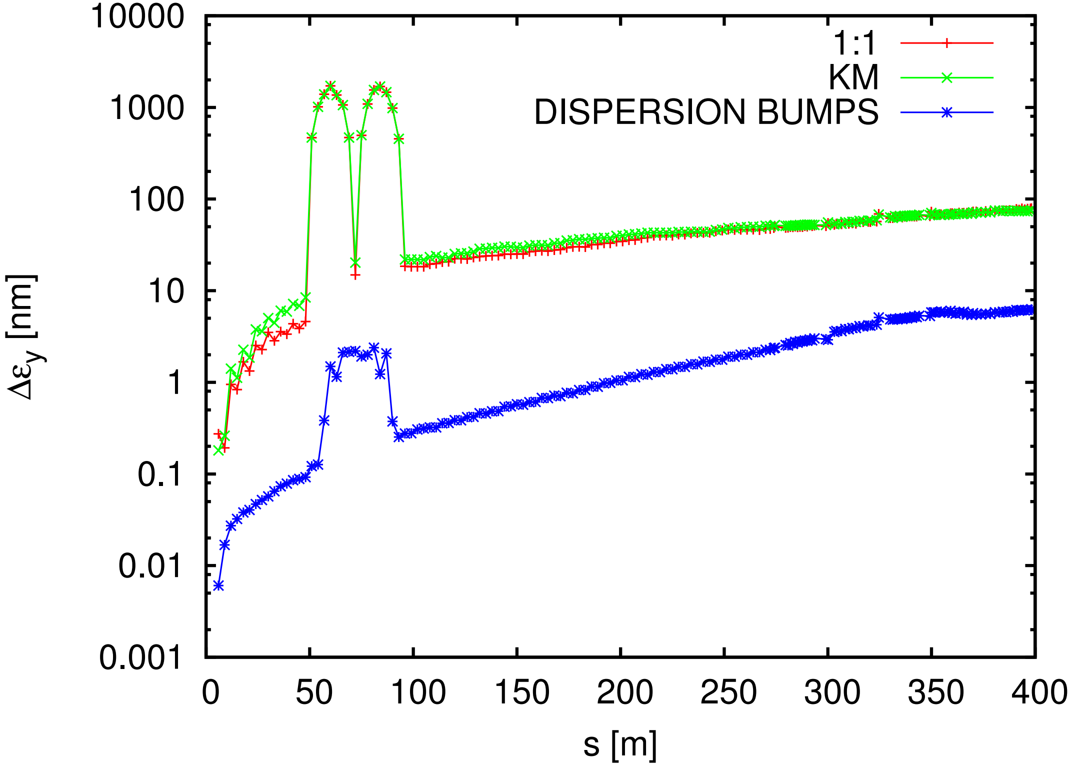
- Strength errors
  - $\sigma_{\text{quad strength}} = 0.25\%$ RMS
  - $\sigma_{\text{bend strength}} = 0.5\%$ RMS

- Solenoids OFF and ON (but not misaligned)

- 100 seeds

Turnaround + Spin Rotator - Solenoids OFF

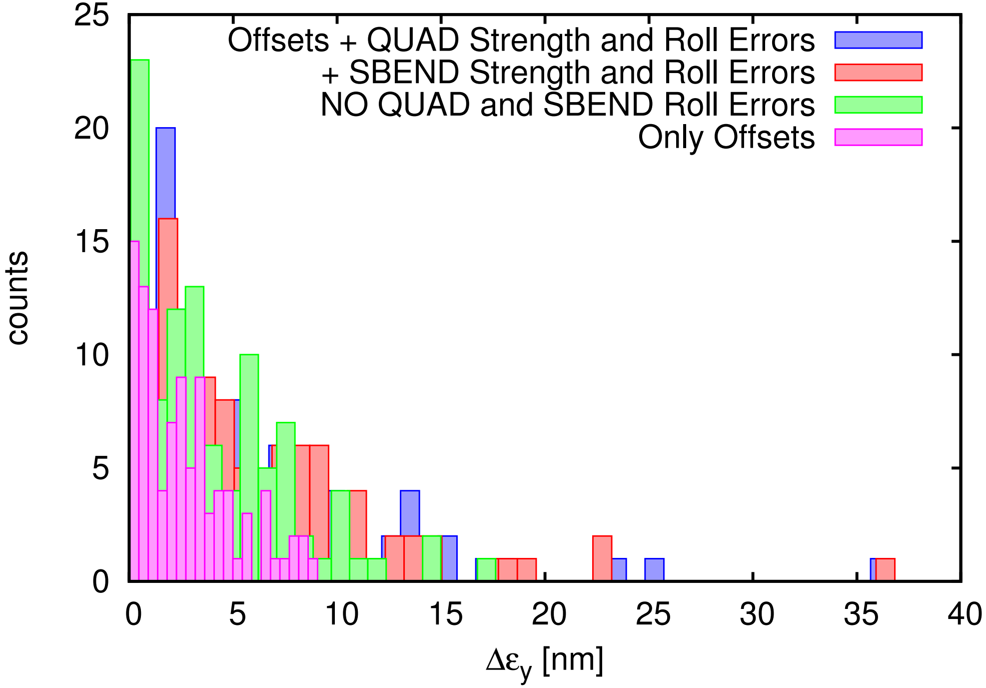
- Emittance growth along the line for 100 seeds



⇒ All misalignments: Final average emittance growth is 6.23 nm

Turnaround + Spin Rotator - Solenoids OFF

- Emittance growth along the line for 100 seeds



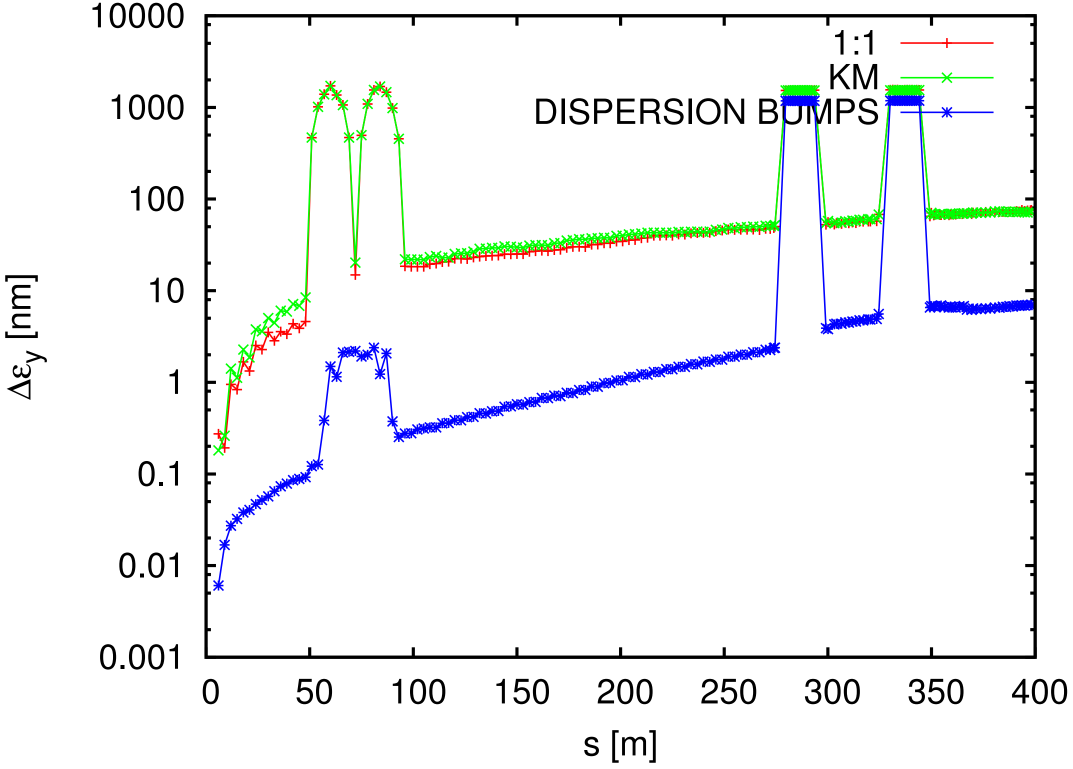
⇒ X/Y Offsets: Final average emittance growth is 2.67 nm (6.43 nm 90% c.l.)

⇒ Add Quad/Sbend strength: Final average emittance growth is 4.12 nm (8.55 nm 90% c.l.)

⇒ All misalignments: Final average emittance growth is 6.23 nm (12.71 nm 90% c.l.)

Turnaround + Spin Rotator - Solenoids ON

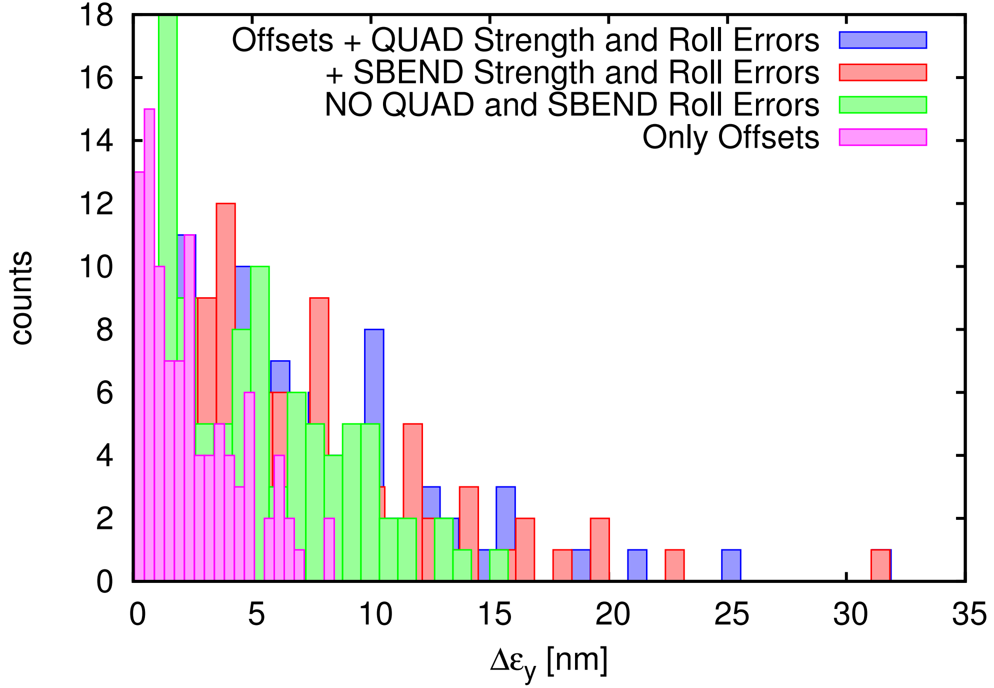
- Emittance growth along the line for 100 seeds



⇒ All Misalignments: Final average emittance growth is 6.67 nm

Turnaround + Spin Rotator - Solenoids ON

- Emittance growth along the line for 100 seeds



⇒ X/Y Offsets: Final average emittance growth is 2.48 nm (5.6 nm 90% c.l.)

⇒ Add Quad/Sbend strength: Final average emittance growth is 4.98 nm (9.8 nm 90% c.l.)

⇒ All misalignments: Final average emittance growth is 6.98 nm (13.76 nm 90% c.l.)

Summary Tables

- These simulations:

Region	Errors	Emittance Increase (nm)		Correction
		average	90% CL	
Return line	X/Y Offsets	2.11	4.67	KM
	+ Quad Strength	2.14	4.75	KM
Escalator + Getaway + RL	+ Quad/Sbend Rolls	2.68	4.58	KM + knobs
Turnaround + spin rotator	X/Y Offsets	2.67	6.43	KM + knobs
	+ Quad/Sbend Strength	4.12	8.55	KM + knobs
	+ Quad/Sbend Rolls	6.23	12.71	KM + knobs
Entire "front end"	no errors	0.75	-	no correction

- PT's summary table

  SLAC-Tech-Note-07-002:

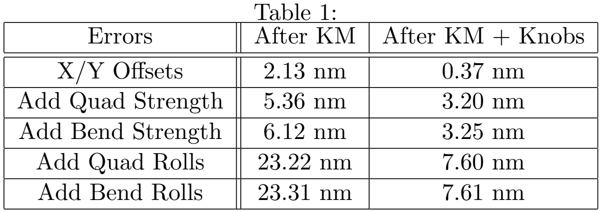
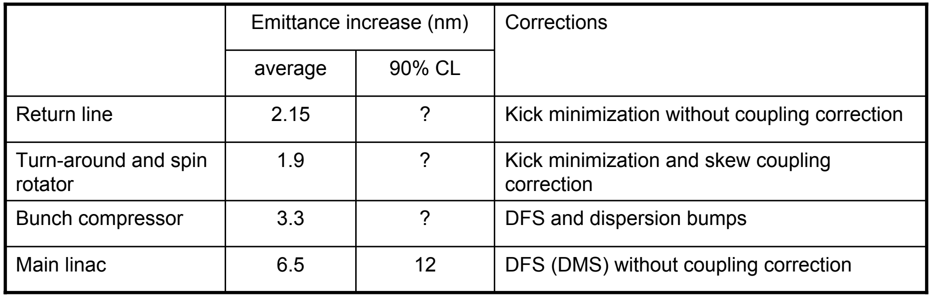


Table 1:

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. 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?