INTERNATIONAL LINEAR COLLIDER
SLAC

ILC BDS Beam-Based Alignment and Tuning

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Overview

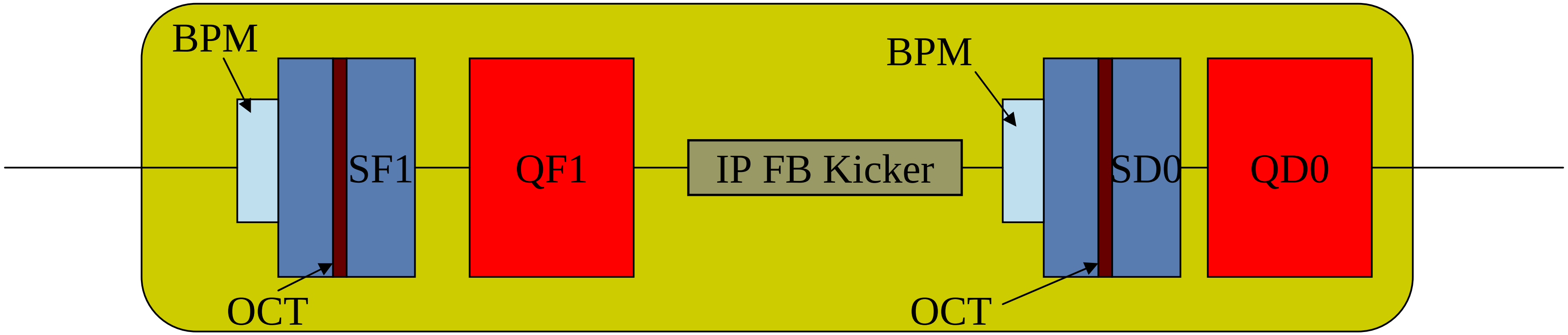
- Demonstrate can tune-up ILC BDS from expected post initial survey conditions to nominal luminosity.
- Try and “keep it real”.
- Simulation models:
  - Magnet – BPM alignment.
  - Beam-Based alignment using magnet movers.
  - Luminosity tuning using Sextupole multi-knobs.
  - 5-Hz trajectory feedback to maintain orbit in FFS Sextupoles.
  - Only 1 side of BDS modeled here.

Simulation Model

- Use Matlab + Lucretia. (ILC2006c lattice)
- Beam model:
  - Single bunch tracking, 80,000 macro-particles.
  - Single ray used where possible.
  - Tuning performed on luminosity calculated by colliding bunch with itself with GUINEA-PIG.
- 5-Hz Feedback:
  - 5 x- and y- sextupole BPMs + 6 correctors.
  - ~50-pulse convergence gain.
  - Error sources from BPM + kicker resolutions (no GM).
- Initial beam:
  - Beam enters BDS on-axis with 10um/34nm horizontal/vertical normalised emittances (6nm vertical emittance-growth budget).

Final Doublet Model

- The final Quad/Sext/Oct doublet (Final Cryomodule String FCMS) is modeled here thus:



- Octupoles modeled as thin lenses within Sextupoles (actually co-wound).
- FCMS misaligned & relative misalignment of magnets within also.
- FCMS is aligned with the 2 BPMs shown using external movers on the whole assembly.
- In alternate scenario, this can be split in two (not modeled here), in which case SF1/QF1 and SD0/QD0 could be independently moved.

Error Parameters

Initial Quad, Sext, Oct x/y transverse alignment	**200 um**
Quad, Sext, Oct roll alignment	**300 urad**
Initial BPM-magnet field center alignment	**30 um**
dB/B for Quad, Sext, Octs (RMS)	**1e-4**
Mover resolution (x & y)	**50 nm**
BPM resolutions (Quads)	**1 um**
BPM resolutions (Sexts)	**100 nm**
Power supply resolution	**14 - bit**
FCMS: Assembly alignment	**200 um / 300urad**
FCMS: Relative internal magnet alignment	**10um / 100 urad**
FCMS: BPM-magnet initial alignment (i.e. BPM-FCMS Sext field centers)	**30 um**
FCMS: Oct – Sext co-wound field center relative offsets and rotations	**10um / 100urad**
Corrector magnet field stability (x & y)	**0.1 %**
Luminosity (pairs measurement or x/y IP sigma measurements)	**~ 1 %**

Alignment and Tuning Strategy

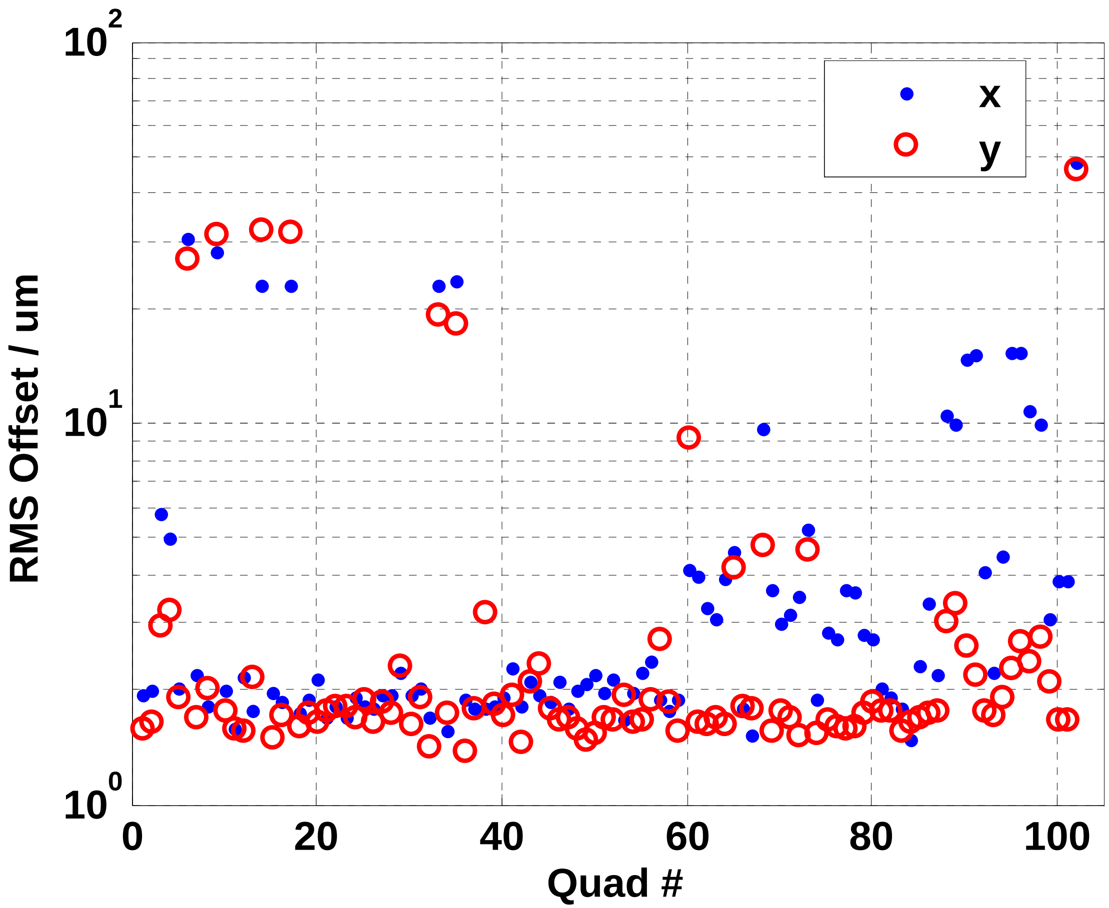
- Switch off Sextupoles and Octupoles.
- Perform initial BBA using Quad movers and BPMs -> beam through to IP.
- Quadrupole BPM alignment.
- Perform Quadrupole BBA (DFS-like algorithm).
- Align Sextupole BPMs.
- Move FCMS to minimize FCMS BPM readings.
- Align tail-folding Octupole BPMs.
- Activate and align sextupole and octupole magnets.
- Rotate whole BDS about first quadrupole to pass beam through nominal IP position or iteratively move FCMS and re-apply DFS BBA.
- Set reference orbit for 5 Hz feedback.
- Apply sextupole multiknobs to tune-out IP aberrations and maximise luminosity.
- 5-Hz feedback system used throughout to maintain orbit whilst tuning. Errors are from finite BPM res. + lumi measurement, no GM or magnet jitter.

Quadrupole BPM Alignment

- Nulling Quad-Shunting technique:
  - To get BPM-Quad offsets, use downstream 10 Quad BPMs for each Quad being aligned (using ext. line BPMs for last few Quads).
  - Quad dK 100-80 %, use change in downstream BPM readouts to get Quad offset.
  - Move Quad and repeat until detect zero-crossing.
  - For offset measurement, use weighted-fit to downstream BPM readings based on model transfer functions:

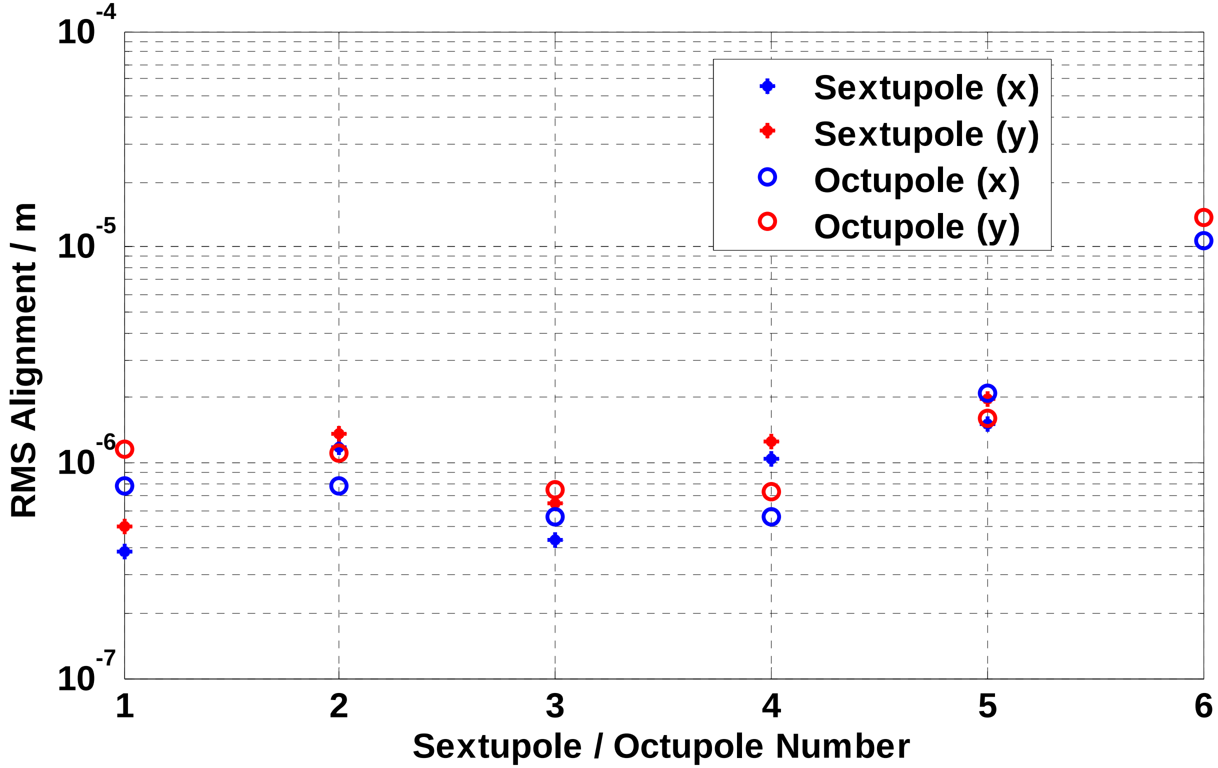
$$x_{Quad} = \Delta x_{BPM} / \left(\Delta R_Q(1,1) * R(1,1) + \Delta R_Q(2,1) * R(1,2) \right)$$

Alignment Results



- RMS BPM-Quadrupole field center alignments (100 seeds).

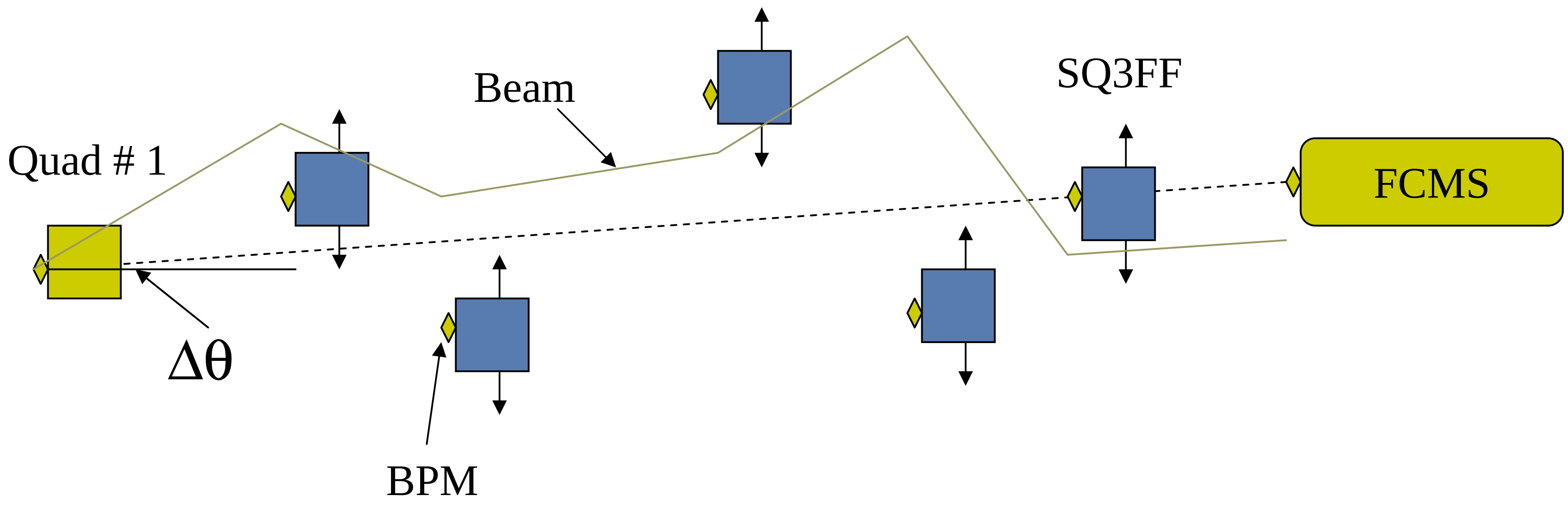
Sextupole/Octupole BPM Alignment



- Use x-, y-movers on magnets and fit 2nd, 3rd order polynomials to downstream BPM responses.
- Alignment is where 1st, 2nd derivative is 0 from fits.
- 6^{th} Octupole can only be aligned by increasing its field strength by a factor of 10, so is left with the initial alignment in the simulation.

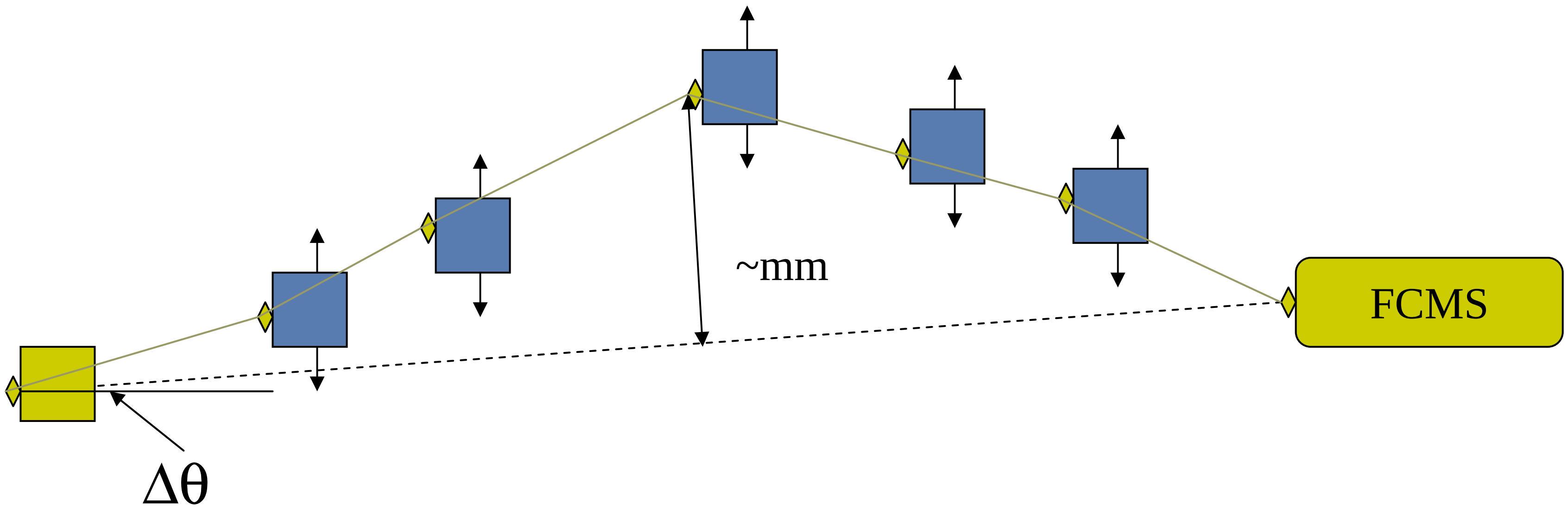
Beam-Based Alignment of Quads

- Use movers on quadrupoles to steer beam through quad BPM centers assuming upstream alignment procedure has put beam through center of BPM in quad 1.
  - Move quads 2 -> SQ3FF to center beam in BPMs 2 -> FCMS.
  - Also move quad 1 to provide Δθ



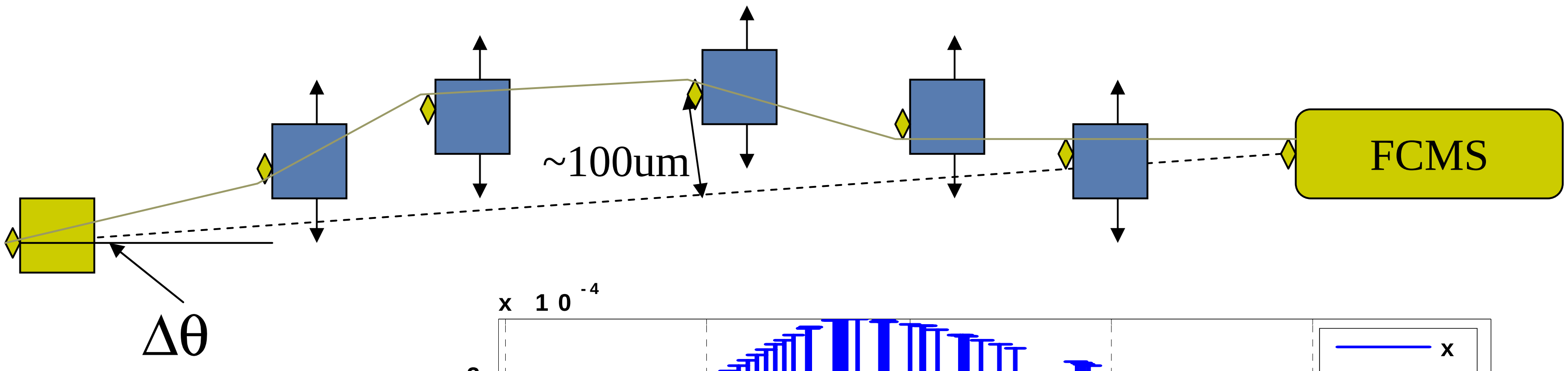
Beam-Based Alignment of Quads

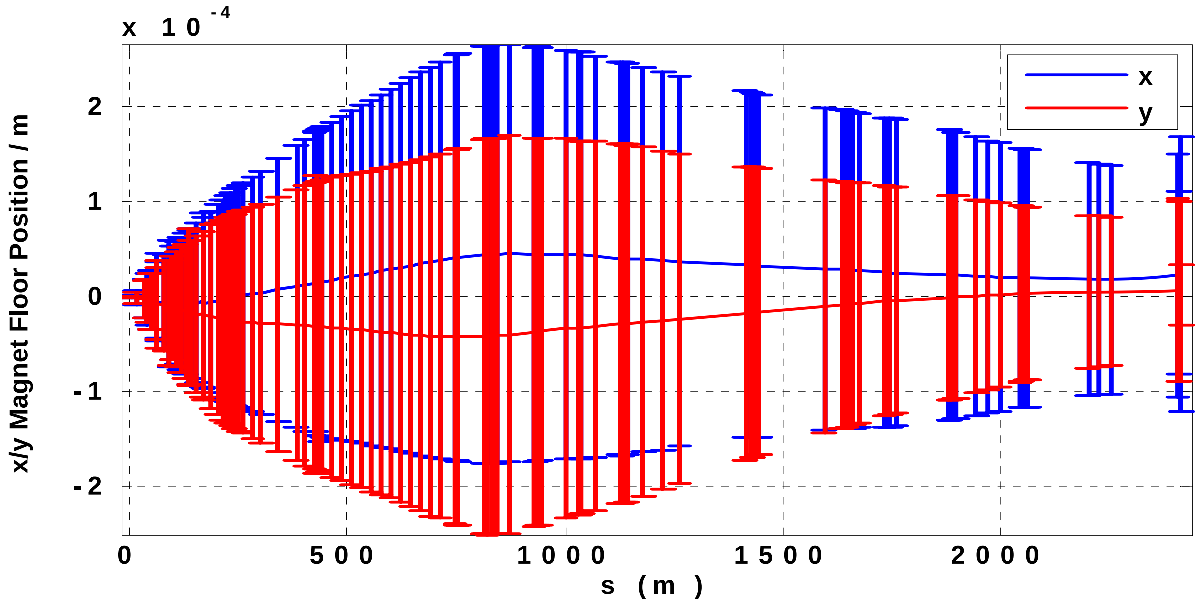
- Simple 1-1 style solution constrains BPM readings well but causes large deviation from straight-line.
  - Large dispersive growth of beamsize + possibly moves out of mover range.



Beam-Based Alignment of Quads

- Use mover minimisation and DFS constraints to limit the mover motion.
- Weights used in minimisation algorithm constrain how far movers move, this trades-off final mover positions against accuracy of BPM orbit.





•Results simulation.

•RMS Quad floor positions shown (100 seeds).

BBA Algorithm

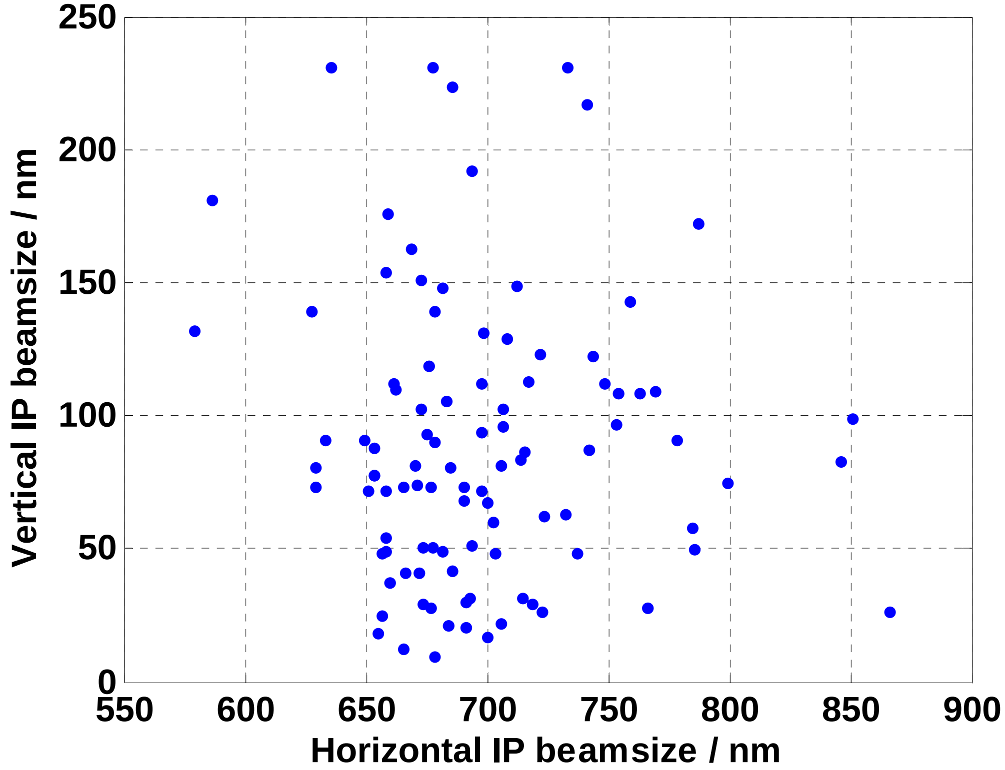
- DFS + mover minimisation solution, use Matlab lscov to solve in a least-squares sense, A*c=b with weight vector, ie. minimise: (b- A*c)'*diag(1/w^2)*(b - A*c), where:

$$b=\begin{pmatrix} B_x^0 \\ B_y^0 \\ B_x^- \\ B_y^- \\ B_x^+ \\ B_y^+ \\ c \end{pmatrix} \quad B=\begin{pmatrix} b_2 \\ b_3 \\ \vdots \\ b_n \end{pmatrix} \quad A=\begin{pmatrix} T^0 \\ T^- \\ T^+ \\ diag(1) \end{pmatrix}$$

$$\begin{aligned}
M_{i,j}^{XX} &= R_i^q(2,1).R_{i,j}(1,2)+\left(R_i^q(1,1)-1\right).R_{i,j}(1,1)+R_i^q(3,1).R_{i,j}(1,3)+R_i^q(4,1).R_{i,j}(1,4) \\
M_{i,j}^{XY} &= R_i^q(2,3).R_{i,j}(1,2)+R_i^q(1,3).R_{i,j}(1,1)+\left(R_i^q(3,3)-1\right).R_{i,j}(1,3)+R_i^q(4,3).R_{i,j}(1,4) \\
M_{i,j}^{YY} &= R_i^q(1,3).R_{i,j}(3,1)+R_i^q(2,3).R_{i,j}(3,2)+\left(R_i^q(3,3)-1\right).R_{i,j}(3,3)+R_i^q(4,3).R_{i,j}(3,4) \\
M_{i,j}^{YX} &= \left(R_i^q(1,1)-1\right).R_{i,j}(3,1)+R_i^q(2,1).R_{i,j}(3,2)+R_i^q(3,1).R_{i,j}(3,3)+R_i^q(4,1).R_{i,j}(3,4)
\end{aligned}$$

$$T=\begin{pmatrix}
-1 & 0 & 0 & \cdots & \cdots & R_{1,2}(1,2) & 0 & 0 & 0 & \cdots & \cdots & R_{1,2}(1,4) \\
M_{2,3}^{XX} & -1 & 0 & \cdots & \cdots & R_{1,3}(1,2) & M_{2,3}^{XY} & 0 & 0 & \cdots & \cdots & R_{1,3}(1,4) \\
M_{2,4}^{XX} & M_{3,4}^{XX} & -1 & \cdots & \cdots & R_{1,4}(1,2) & M_{2,4}^{XY} & M_{3,4}^{XY} & 0 & \cdots & \cdots & R_{1,4}(1,4) \\
\vdots & \vdots & \ddots & \ddots & \ddots & \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\
M_{2,n}^{XX} & M_{3,n}^{XX} & M_{4,n}^{XX} & \cdots & M_{n-1,n}^{XX} & R_{1,n}(1,2) & M_{2,n}^{XY} & M_{3,n}^{XY} & M_{4,n}^{XY} & \cdots & M_{n-1,n}^{XY} & R_{1,n}(1,4) \\
0 & 0 & 0 & \cdots & \cdots & R_{1,2}(3,2) & -1 & 0 & 0 & \cdots & \cdots & R_{1,2}(3,4) \\
M_{2,3}^{YX} & 0 & 0 & \cdots & \cdots & R_{1,3}(3,2) & M_{2,3}^{YY} & -1 & 0 & \cdots & \cdots & R_{1,3}(3,4) \\
M_{2,4}^{YX} & M_{3,4}^{YX} & 0 & \cdots & \cdots & R_{1,4}(3,2) & M_{2,4}^{YY} & M_{3,4}^{YY} & -1 & \cdots & \cdots & R_{1,4}(3,4) \\
\vdots & \vdots & \ddots & \ddots & \ddots & \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\
M_{2,n}^{YX} & M_{3,n}^{YX} & M_{4,n}^{YX} & \cdots & M_{n-1,n}^{YX} & R_{1,n}(3,2) & M_{2,n}^{YY} & M_{3,n}^{YY} & M_{4,n}^{YY} & \cdots & M_{n-1,n}^{YY} & R_{1,n}(3,4)
\end{pmatrix}
\quad c=\begin{pmatrix} q_2^x \\ q_3^x \\ \vdots \\ q_{n-1}^x \\ k_1^x \\ q_2^y \\ q_3^y \\ \vdots \\ q_{n-1}^y \\ k_1^y \end{pmatrix}$$

Beam Conditions Post-BBA



- IP beamsizes (100 seeds) after BPM alignment and BBA.
- Significant aberrations present at IP- coupling, dispersion, waist + higher order effects from non-linear optics.
- Use sextupole multi-knobs to tune these out and arrive at nominal ILC luminosity parameters.

Sextupole Multi-Knobs

- Deliberately offsetting the beam orbit using the first 3 FFS sextupoles in an orthogonal way provides tuning knobs for dispersion and waist-shift at the IP through: $\Delta s_{x,y} \sim \Delta x.K_2^s L \beta_{x,y}^s \beta_{x,y}^* \cos(2.\mu)$

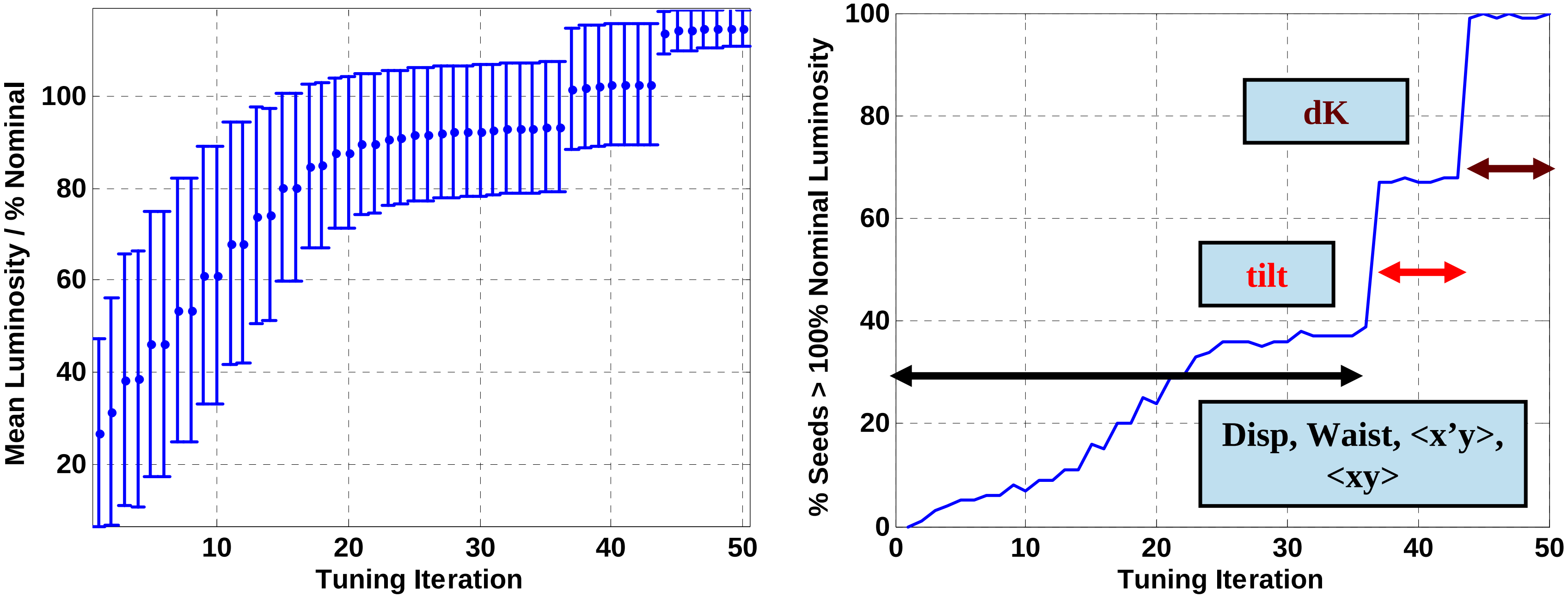
$$\Delta \eta_{x,y}^* \sim \Delta(x,y).K_2^s L \eta_{x,y}^s \sqrt{\beta_{x,y}^s \beta_{x,y}^*} \sin(\mu)$$

- Orthogonal knobs are computed by inverting the sextupole move -> IP aberration matrix formed by scanning the sextupoles in turn and measuring the IP terms.
- The dominant IP coupling term <x'y> is tuned-out using SQ3FF.
- The 4 skew quads in the BDS coupling correction system are iteratively scanned to remove any <xy>.

Higher-Order Sextupole Multi-Knobs

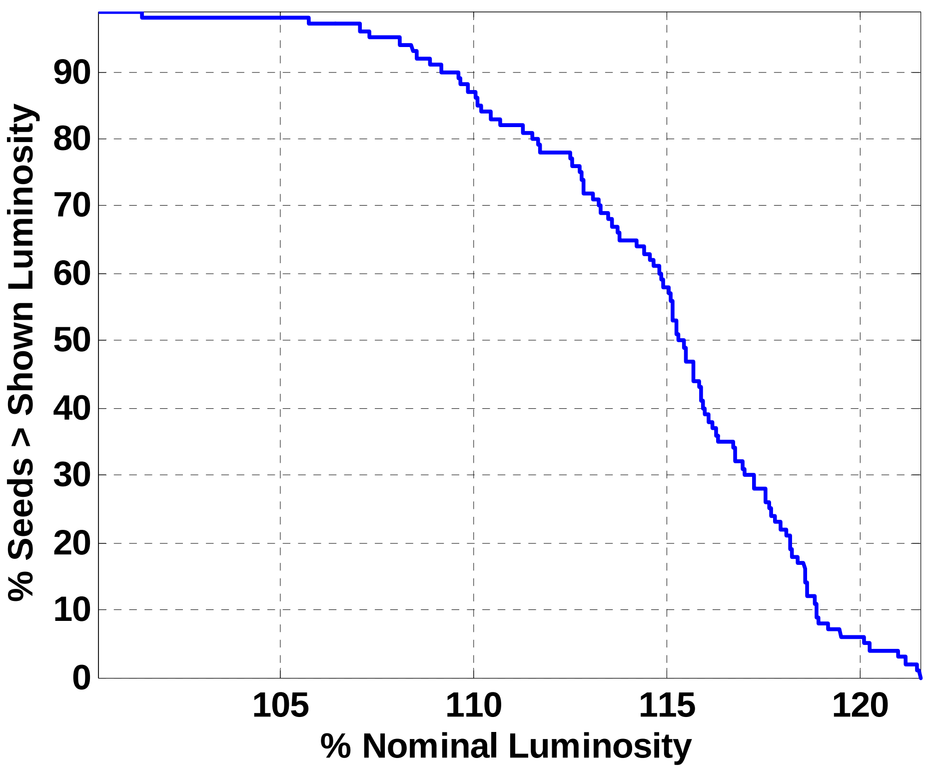
- Due to sextupole tilt and strength errors, and due to non-linear fields as the beam passes off-center in the sextupoles, higher-order aberrations also exist at the IP.
- These are corrected for by iterating through sextupoles 1-3 using the tilt dof. on the movers to maximise luminosity after the linear knobs have converged.
- If necessary, the strengths of the 5 sextupoles are also scanned.

Application of Multi-Knobs



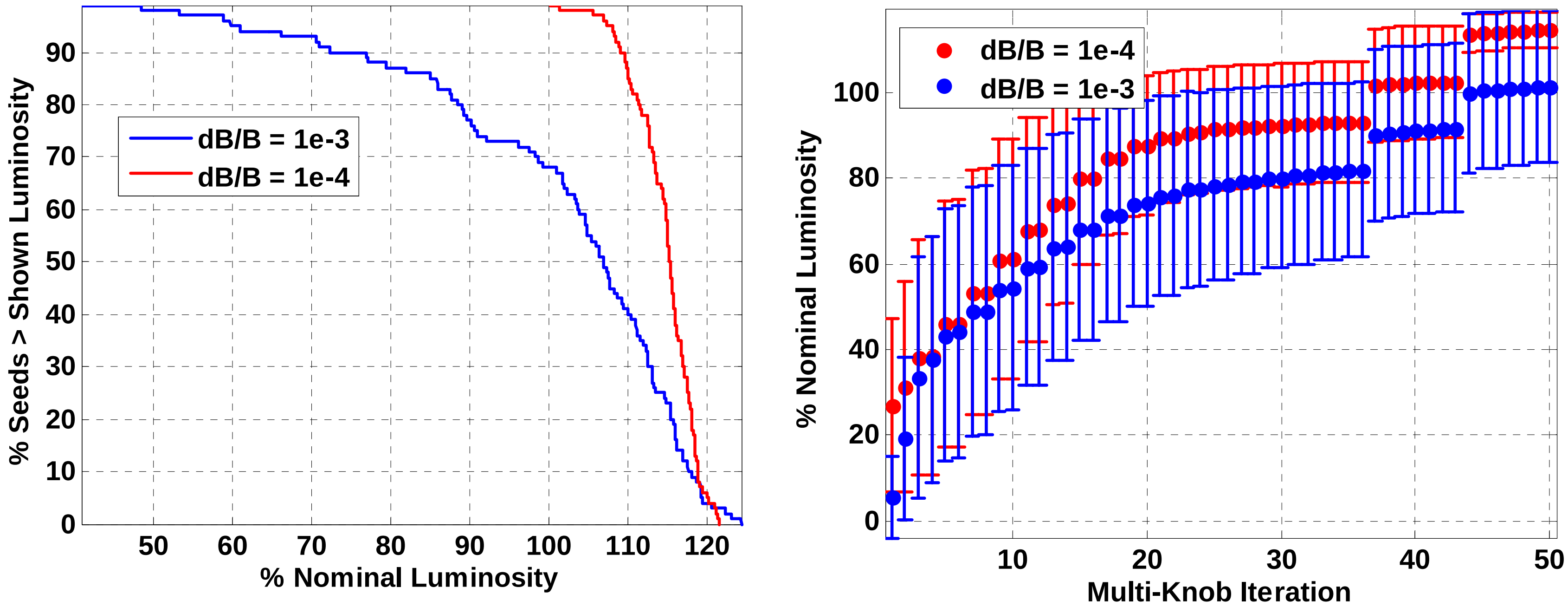
- The linear sextupole knobs are applied until convergence, then the sextupole tilts and strengths are tuned.

Achieved Luminosity



- All the random seeds tuned to give greater than the required nominal luminosity.
- The median result gives a 15% luminosity overhead after tuning.
- This sets the performance requirements for the feedback systems used to maintain luminosity in the presence of ground motion and component vibrations.

Magnet Strength Error Comparison



- Comparison of results with relative absolute RMS errors on all magnets of 1e-3 and 1e-4.

Future Work

- Use 2-beam model.
- Apply GM, component jitter + other error sources (magnetic drift, BPM drift etc.) to tuned beamline. Calculate mean time before re-tuning becomes necassary.
- Incorporate in larger-scale model with RTML+LINAC tuning results.