INTERNATIONAL LINEAR COLLIDER
SLAC

BDS BBA, Tuning and Beam Dynamics

Glen White / SLAC

ILC LET Workshop - SLAC

Dec 2007

Overview

- Demonstrate can tune-up ILC BDS from expected post initial survey conditions to nominal luminosity.
  - Magnet – BPM alignment.
  - Beam-Based alignment using magnet movers.
  - Luminosity tuning using Sextupole multi-knobs.
  - Single-sided fully dynamic simulation
    - A.S. Liar GM model ‘B’ + 5Hz feedback + 25nm RMS magnet jitter
  - 2-sided ‘static’ simulation.
- Final doublet jitter effects.
- Opportunities for code testing on new fast parallel analogue supercomputer in 2008.

Simulation Model

- Use Matlab + Lucretia.
- Beam model:
  - Single bunch tracking, 80,000 macro-particles.
  - Single ray used where possible.
  - Beam-beam physics with GUINEA-PIG (beam-beam kick, pair creation & lumi calculation).
- 5-Hz Feedback:
  - 5 x- and y- sextupole BPMs + 6 correctors.
  - ~50-pulse convergence gain.
- Initial beam:
  - Beam enters BDS on-axis with 10um/34nm horizontal/vertical normalised emittances (6nm vertical emittance-growth budget).

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 % (ATF2 SM ~5%)**

Alignment and Tuning Steps

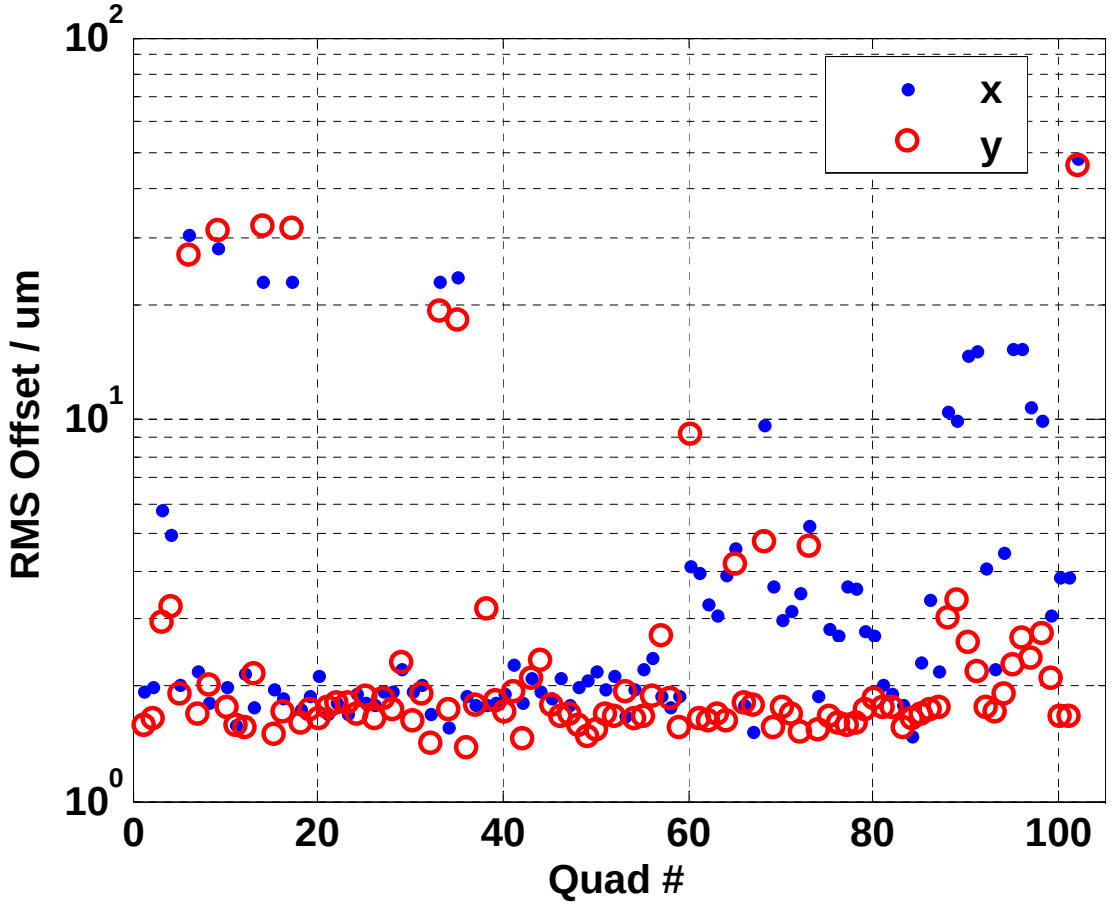
- Switch off Sextupoles and Octupoles.
- Perform initial BBA using Quad movers and BPMs -> beam through to IP.
- Quadrupole BPM alignment.
- Perform Quadrupole BBA (DFS).
- Align Sextupole BPMs.
- Move FCMS to minimize FCMS BPM readings.
- Align tail-folding Octupole BPMs.
- Activate and align sextupole and octupole magnets.
- Rotate whole BDS about first quadrupole to pass beam through nominal IP position.
- Apply sextupole multiknobs to tune-out IP aberrations and maximise luminosity.
- 5-Hz feedback system used throughout to maintain orbit whilst tuning.

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 fit to downstream BPM readings based on model transfer functions:

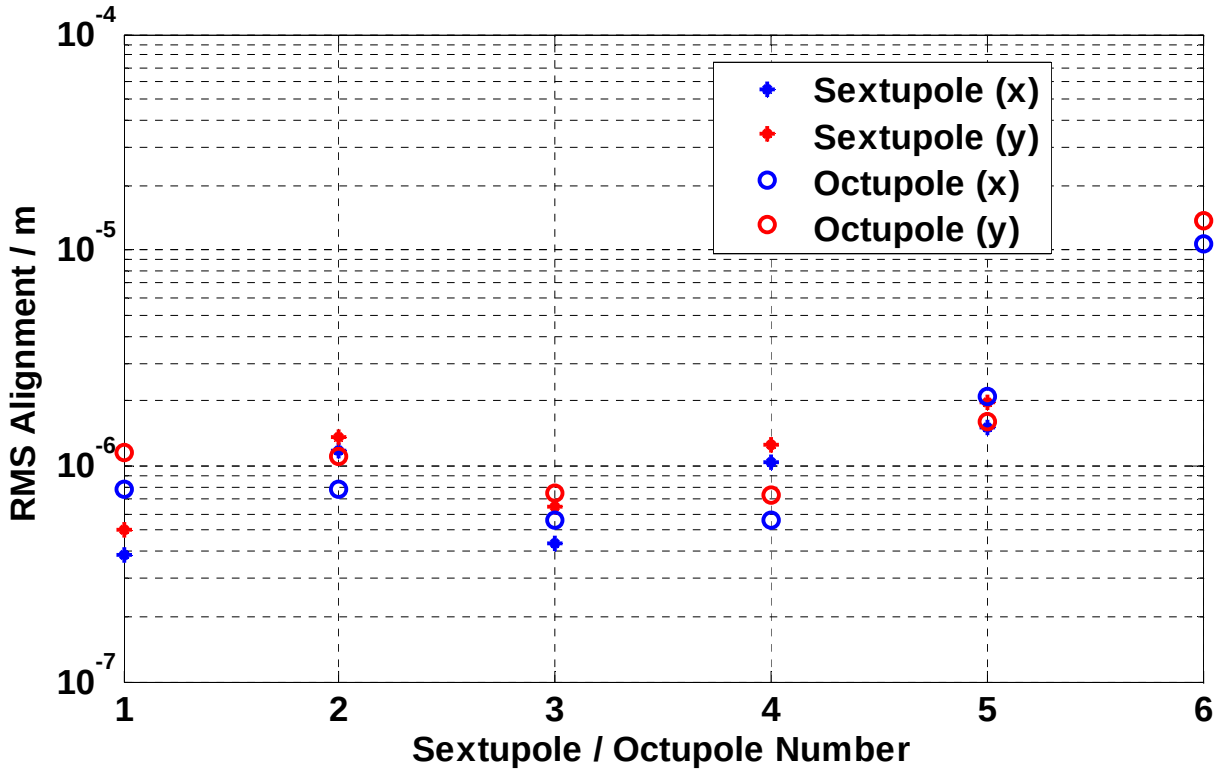
$$x_{Quad} = \Delta x_{BPM} / \left(\Delta R_Q(1,1) * R(1,1) + \Delta R_Q(2,1) * R(1,2) \right)$$

Alignment Results



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

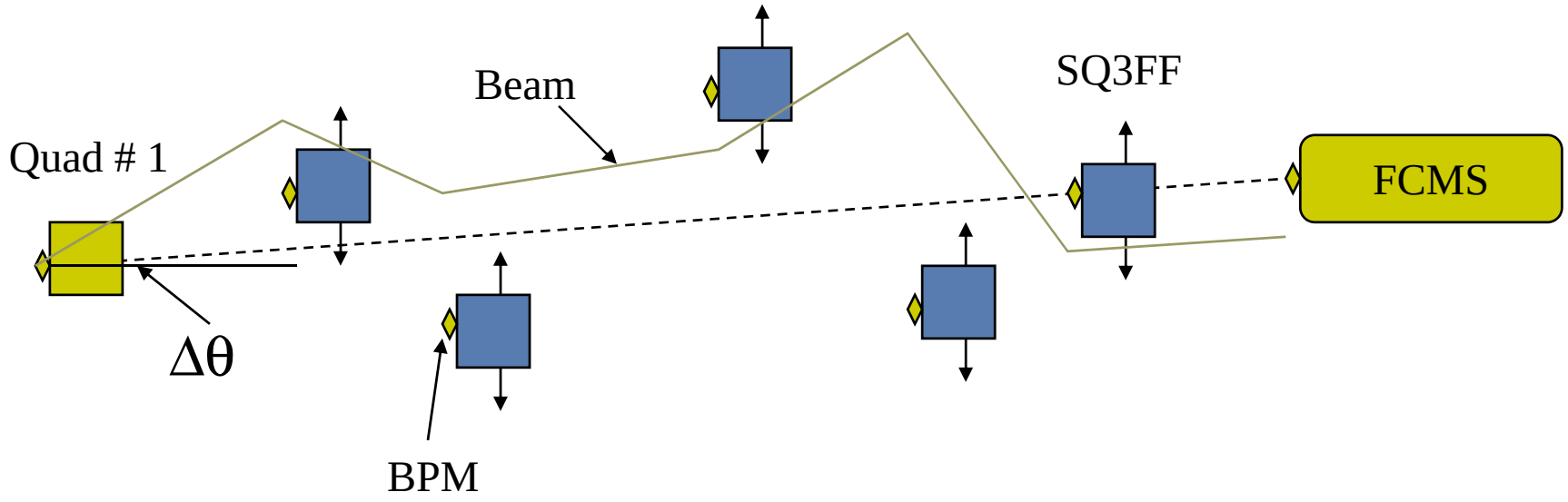
Sextupole/Octupole BPM Alignment



- 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.
- 6th 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.

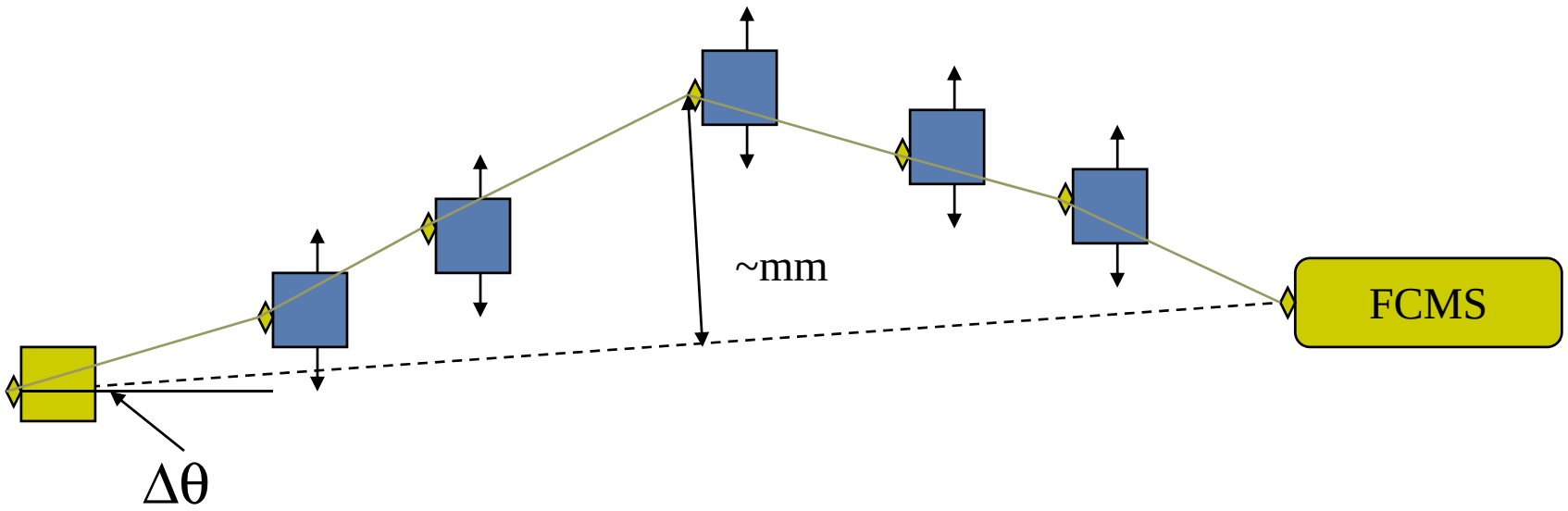
Beam-Based Alignment of Quads

- 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 $\Delta\theta$



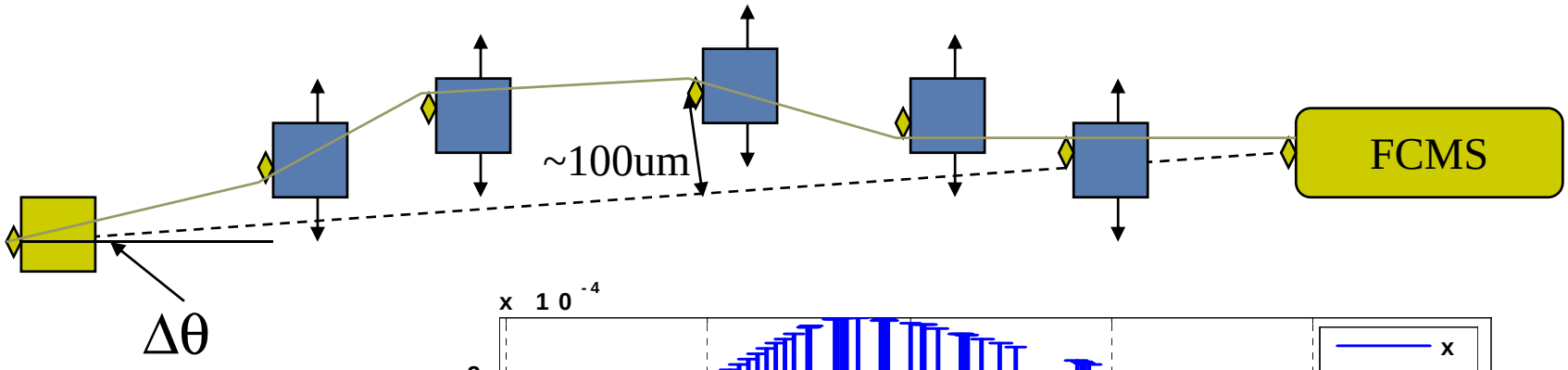
Beam-Based Alignment of Quads

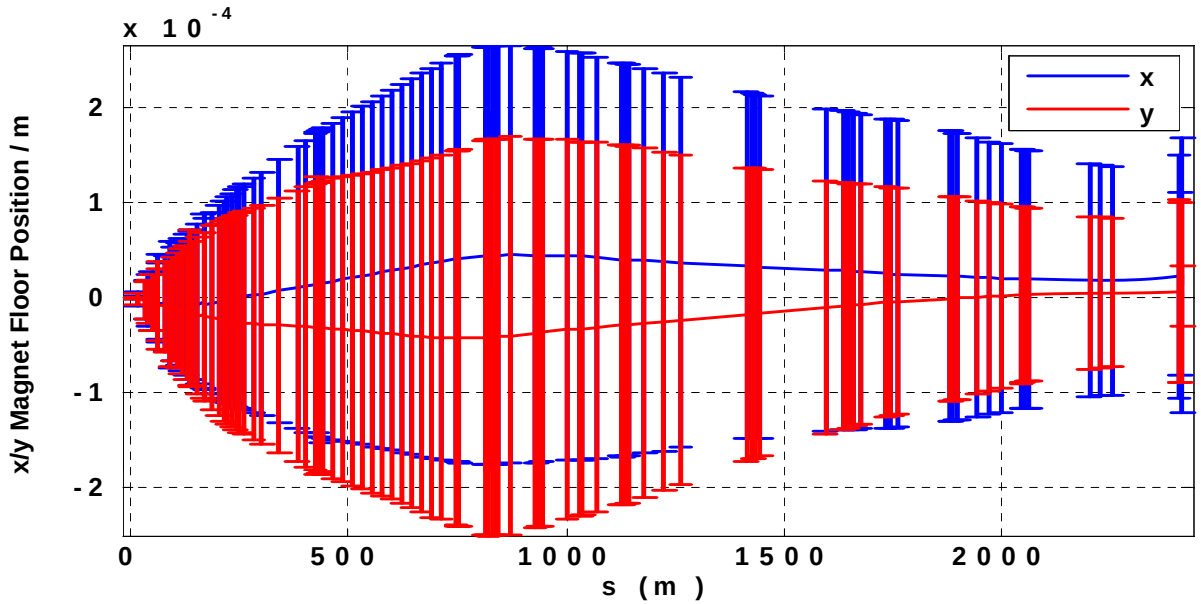
- Simple 1-1 style solution constrains BPM readings well but causes large deviation from straight-line.
  - Large dispersive growth of beamsize + possibly moves out of mover range.



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

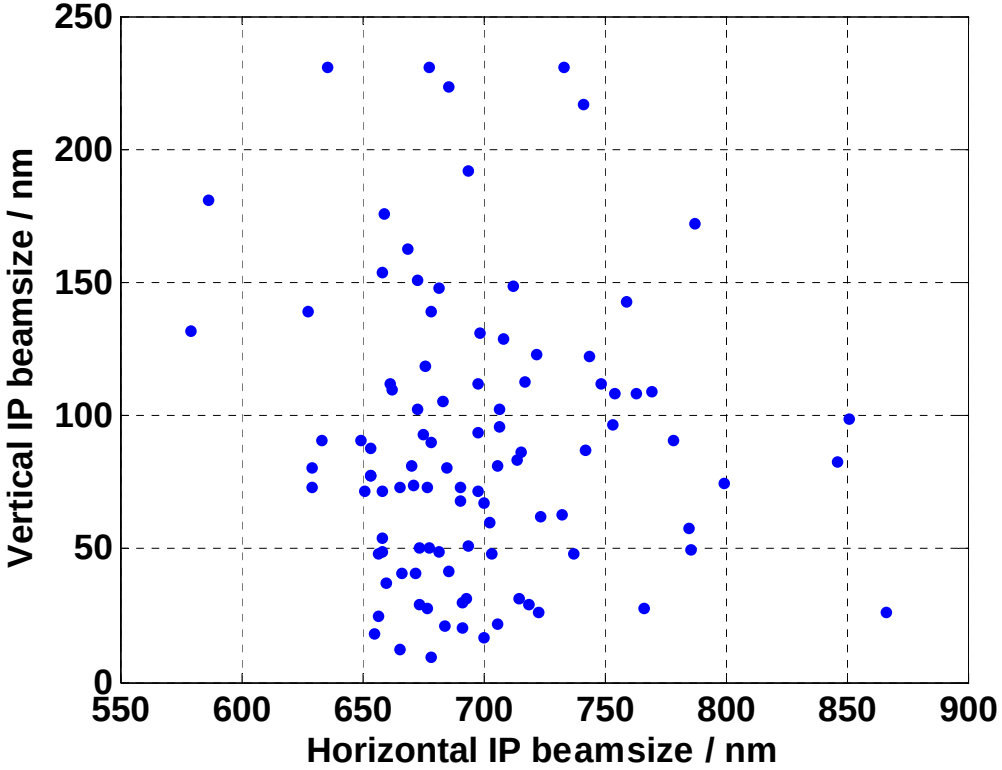
- DFS + mover minimisation solution, use Matlab lscov to solve in a least-squares sense, A*c=b with weight vector, ie. minimise: (b- A*c)'*diag(1/w^2)*(b - A*c), where:

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

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

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

Beam Conditions Post-BBA



- IP beamsizes (100 seeds) after BPM alignment and BBA.
- Significant aberrations present at IP- coupling, dispersion, waist + higher order terms.
- 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: $\Delta s_{x,y} \sim \Delta x . K_2^s L \beta_{x,y}^s \beta_{x,y}^* \cos(2.\mu)$

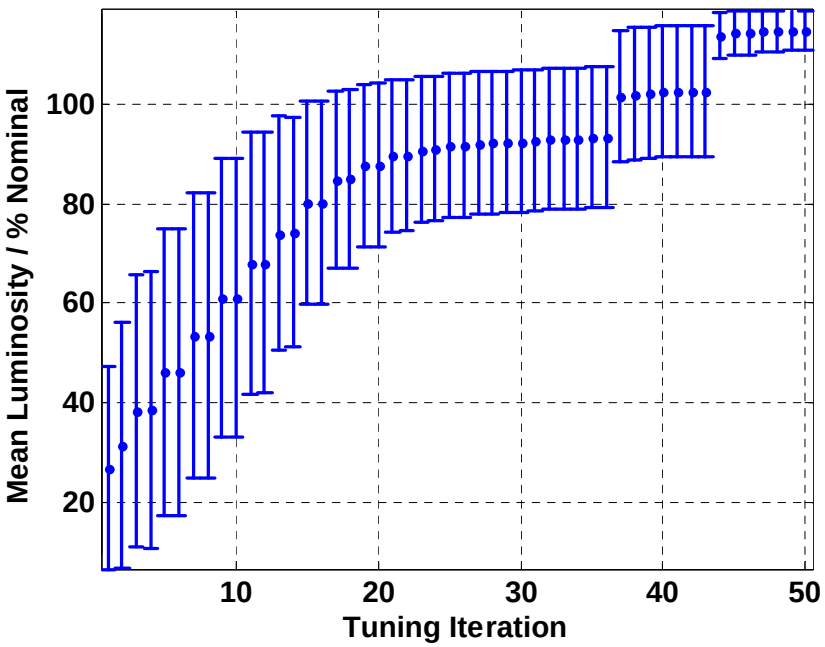
$$\Delta \eta_{x,y}^* \sim \Delta(x,y) . K_2^s L \eta_{x,y}^s \sqrt{\beta_{x,y}^s \beta_{x,y}^*} \sin(\mu)$$

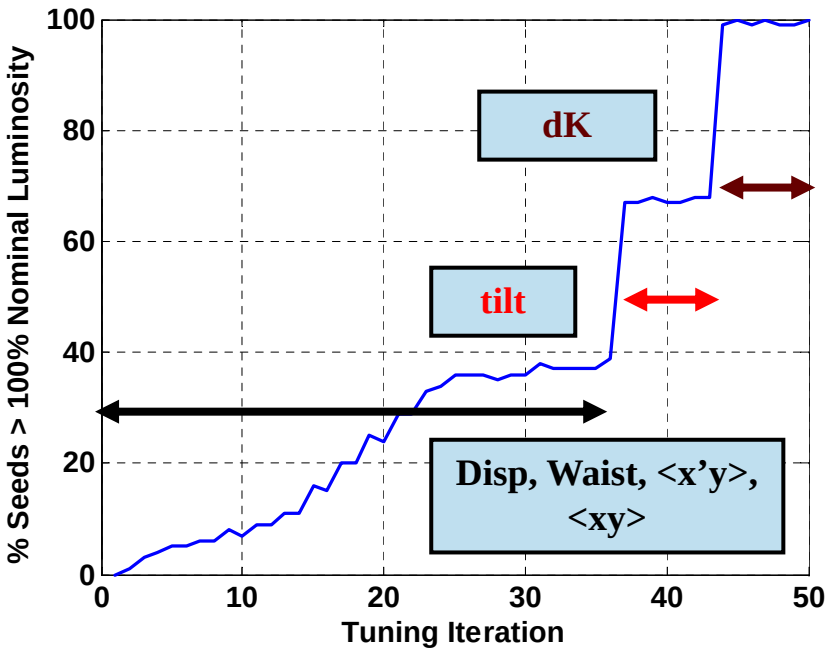
- Orthogonal knobs are computed by inverting the sextupole move -> IP aberration matrix formed by scanning the sextupoles in turn and measuring the IP terms.
- The dominant IP coupling term <x'y> is tuned-out using SQ3FF.
- The 4 skew quads in the BDS coupling correction system are iteratively scanned 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.
- The strengths of the 5 sextupoles are also scanned.

Application of Multi-Knobs

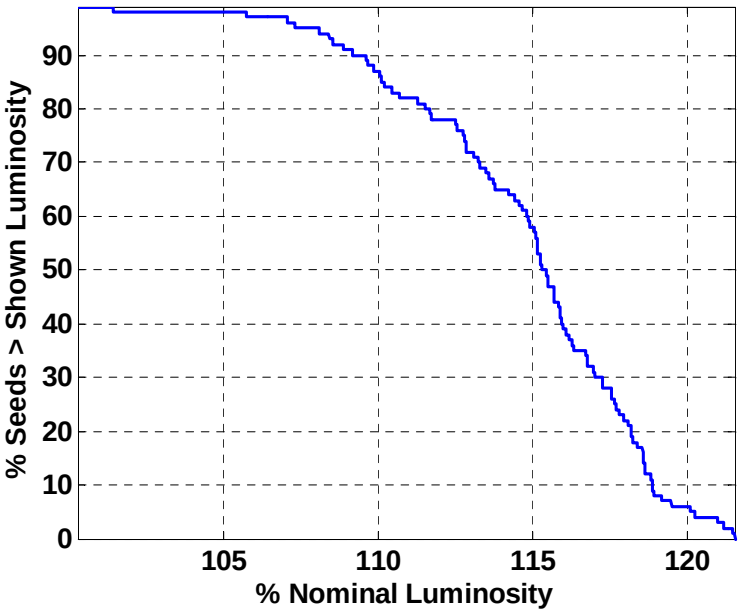




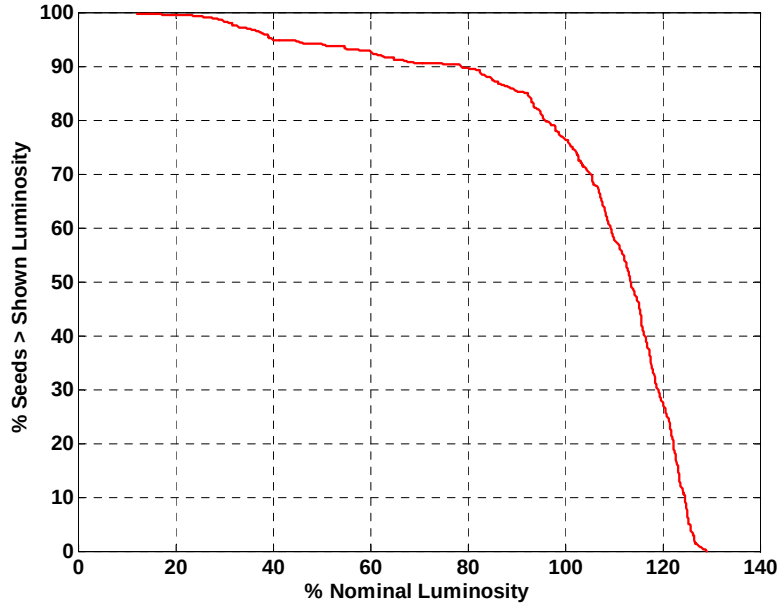
- Single-sided simulation (100 seeds).
- The linear sextupole knobs are applied until convergence, then the sextupole tilts and strengths are tuned on.

Achieved Luminosity

Single-Sided Sim

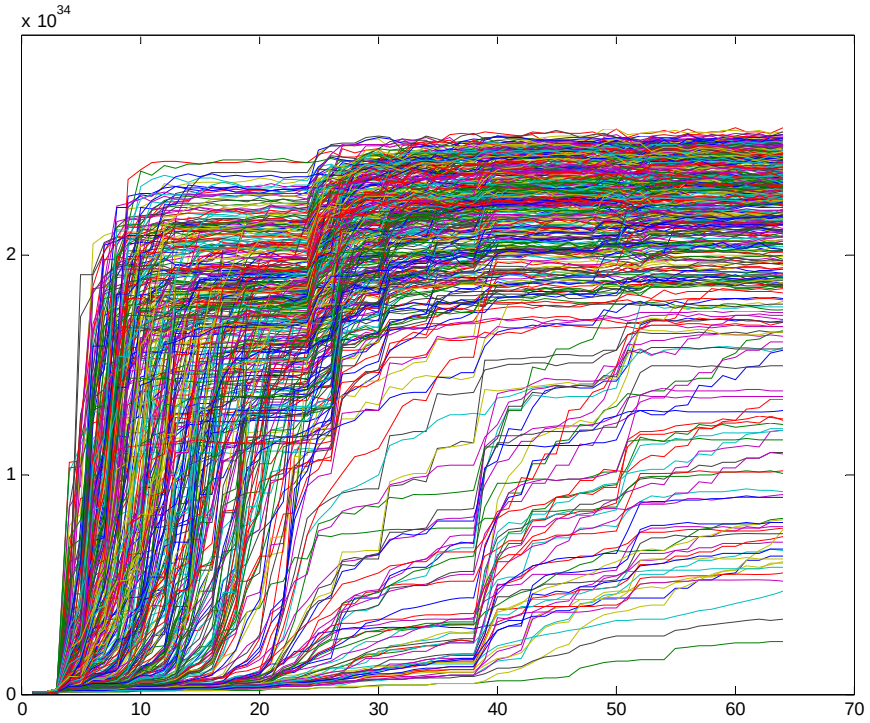


2-Sided Sim



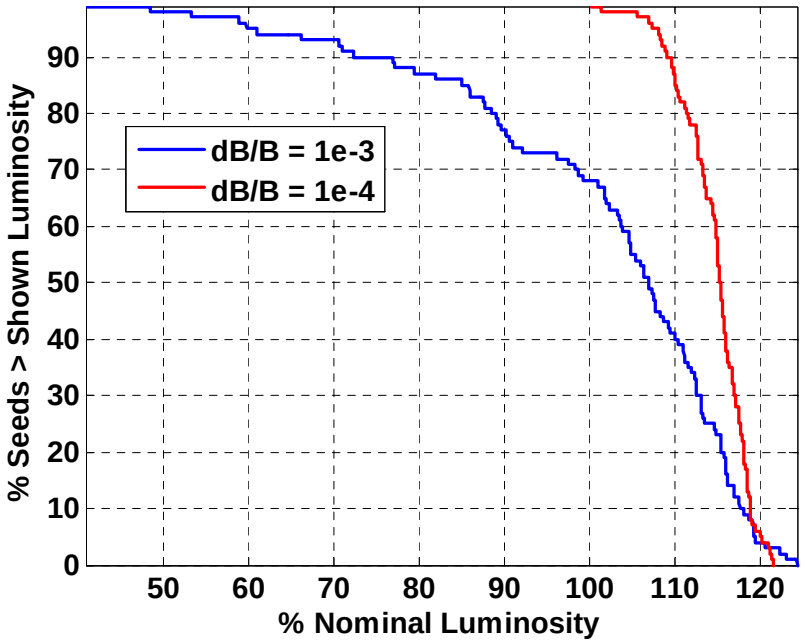
- Median lumi overhead ~15% in both cases
- When simulating both sides 25% of seeds fail to meet design luminosity.

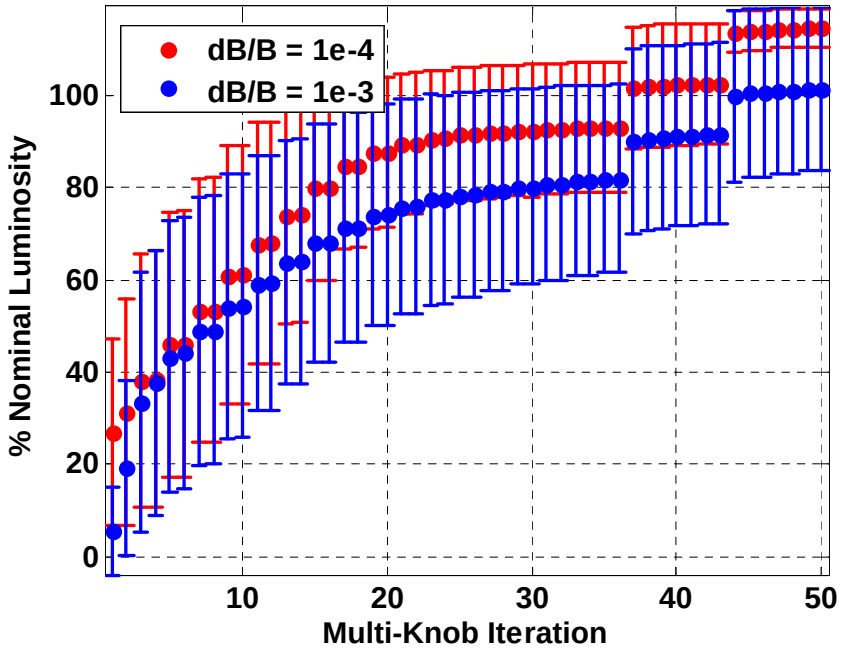
2-beam Simulation



- Some seeds slower to converge in 2-sided simulation case. (450 seeds simulated).
- In 2 beam-simulation:
  - Rotate 2 beamlines to bring beams into collision
  - Added tuning iterations – perform a tuning scan on e-, then e+ beam – in 1-beam simulation, effectively colliding beam with self- here against a larger beam- effects pair stats.

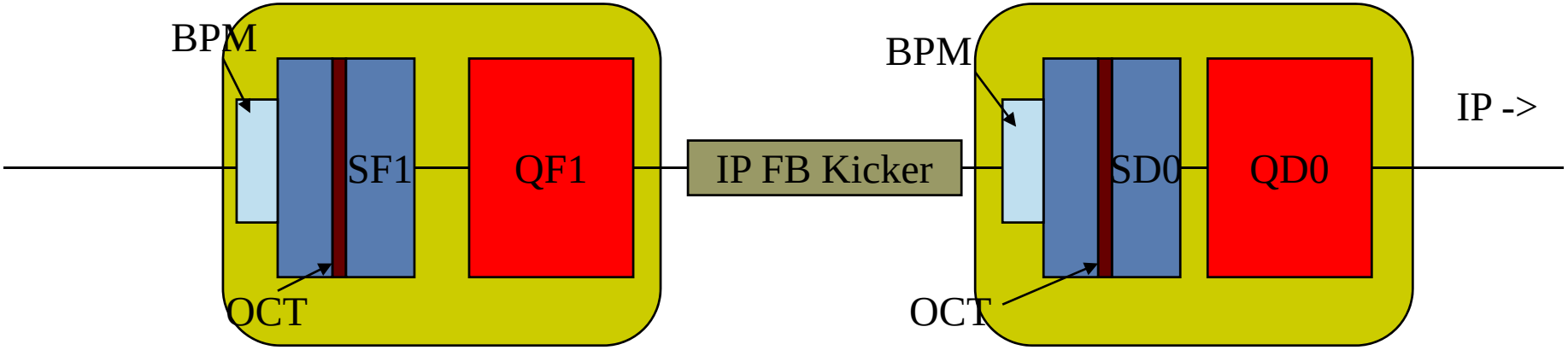
Magnet Strength Error Comparison





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

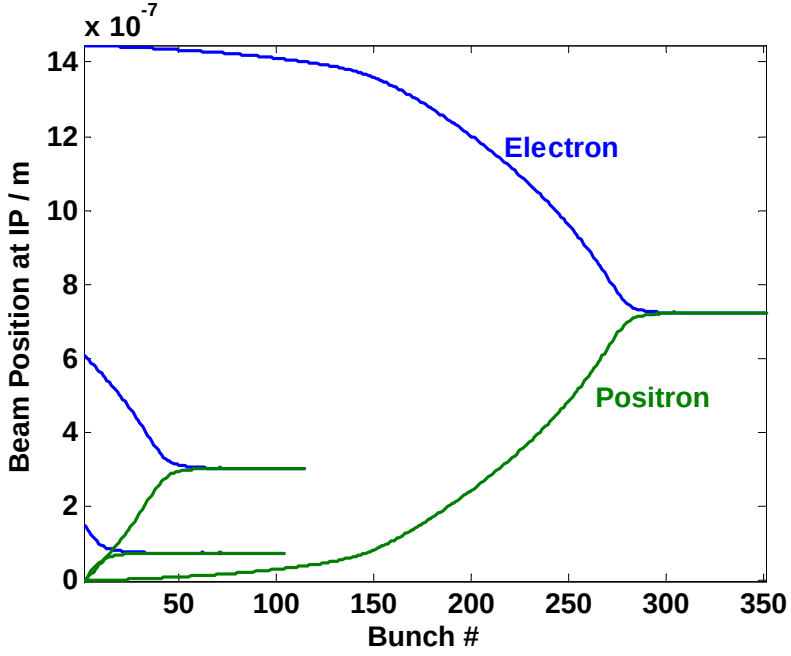
Final Doublet Jitter Study

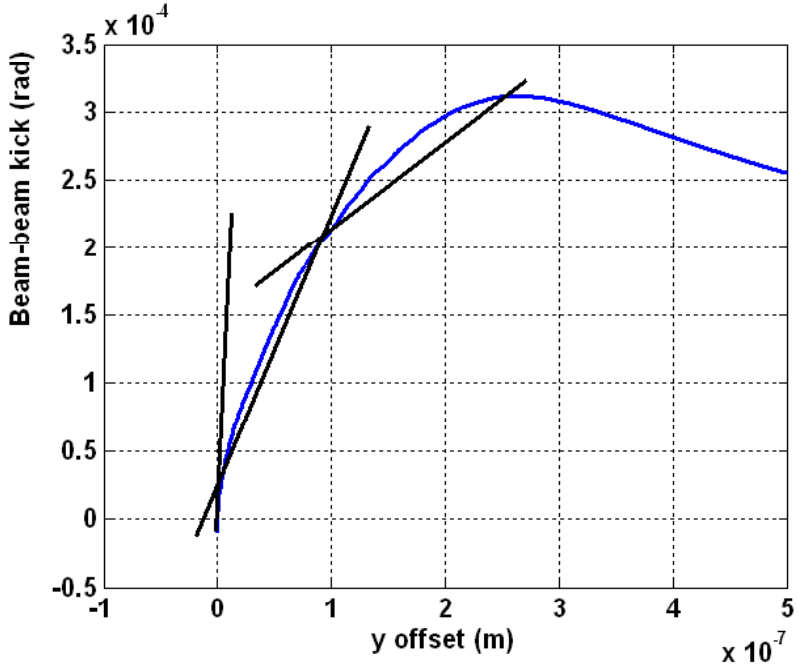


- IP FFB kicker in ~1m gap between 2 cryomodules near IP.
- Distance of kick from SD0 face effects lumi as beam is kicked off-center going through SD0.
- Advantage to using shorter kicker?

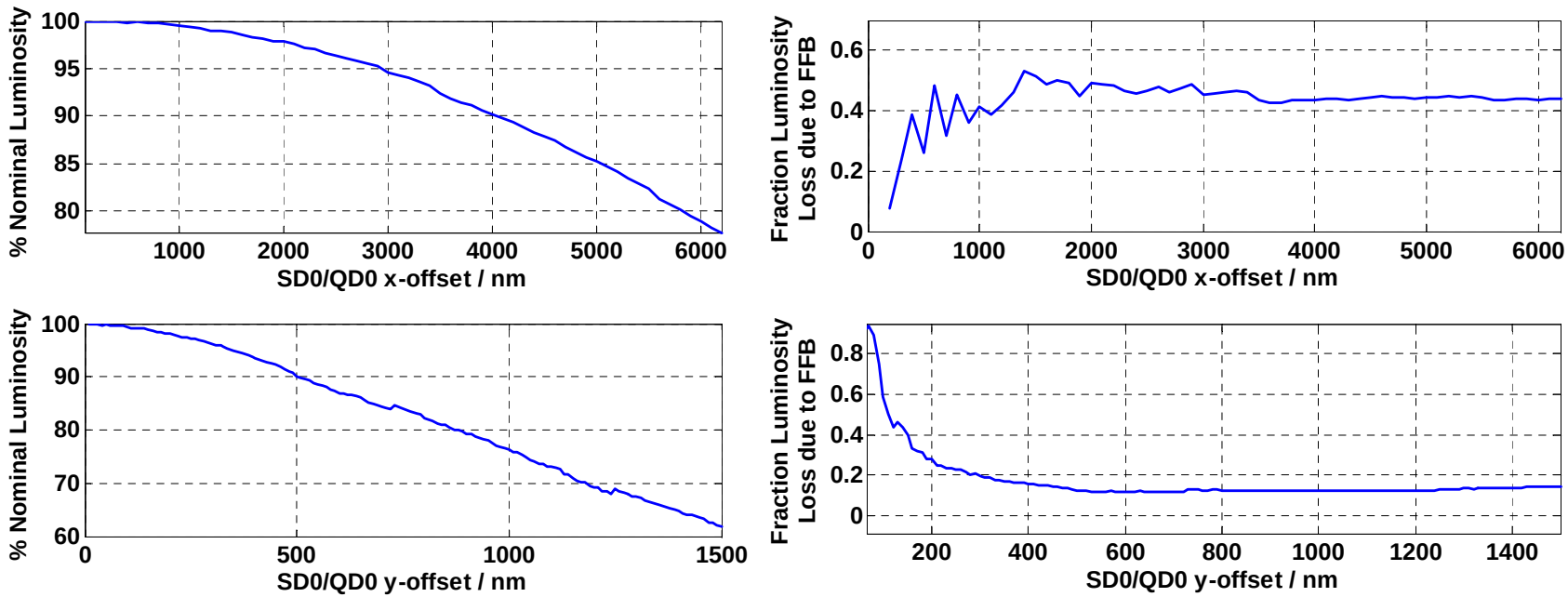
IP Fast-Feedback

- Use ILC IP FFB, tuned for 'noisy' conditions
  - Less than 5% lumi-loss with GM 'K' + 25nm component vibration (pulse-pulse) & ~ 0.1 sigma intra-bunch uncorrelated beam jitter.
- Assume BDS-entrance FFB has perfectly flattened beam train (flat trajectory into Final Doublet).
- No 'banana' effect on bunches.
- Calculate Luminosity from measured bunches, with mean of last 50 weighted to account for the rest of the beam train (2820 bunches).



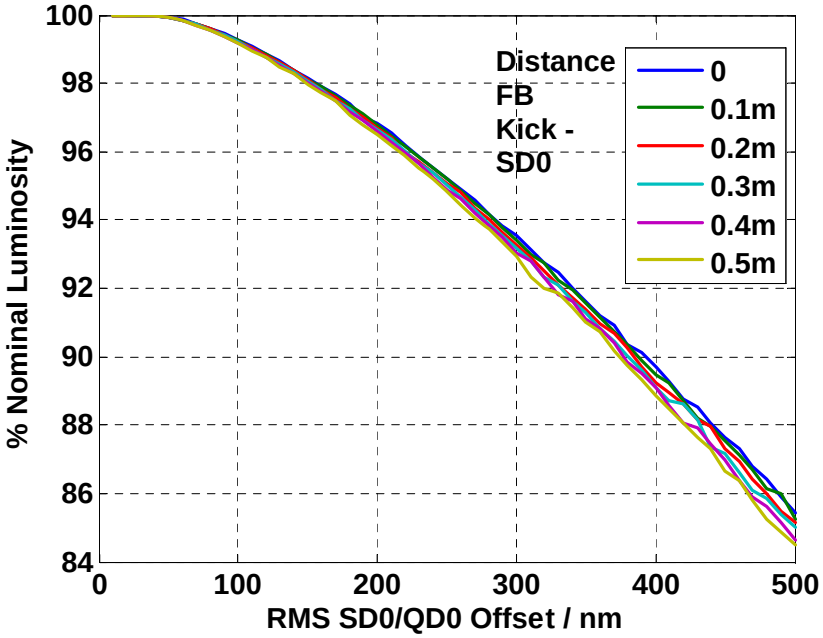


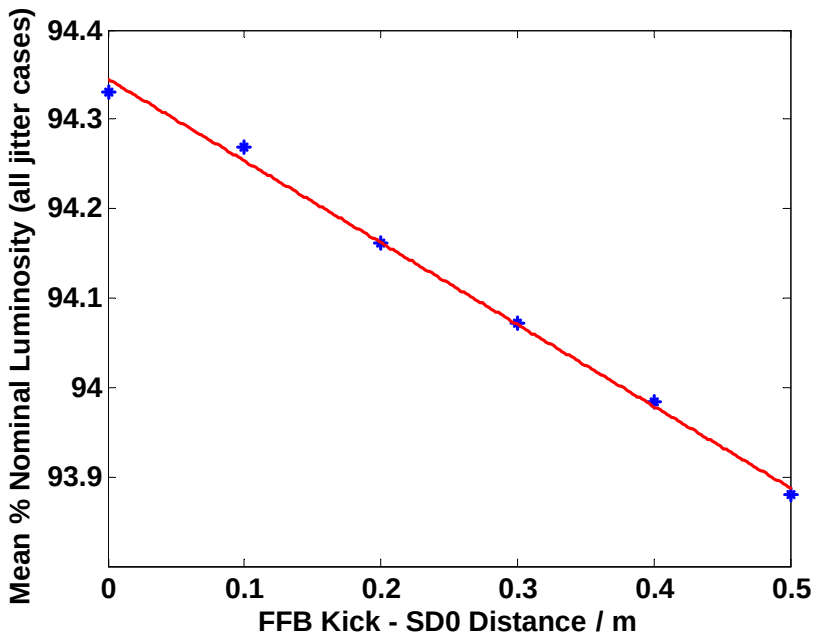
Effect of SD0/QD0 Offset



- Luminosity loss as a function of SD0/QD0 offset and relative importance of offset through SD0 vs. IP offset.
- Shows beam size growth through offset SD0 dominant over FFB beam offset conversion time (more so in vertical plane).
  - e.g. for y at 500nm offset, ~85% of luminosity loss through beamsize growth effect, 15% through conversion time of FFB system.

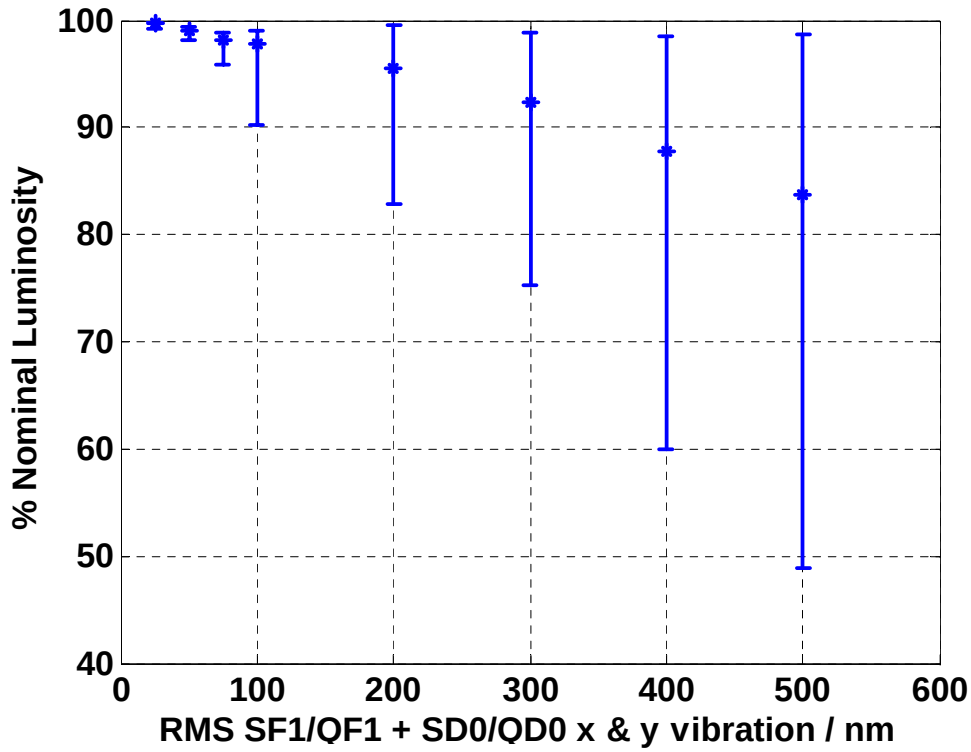
Luminosity vs. QD0/SD0 RMS Jitter and Kick Distance





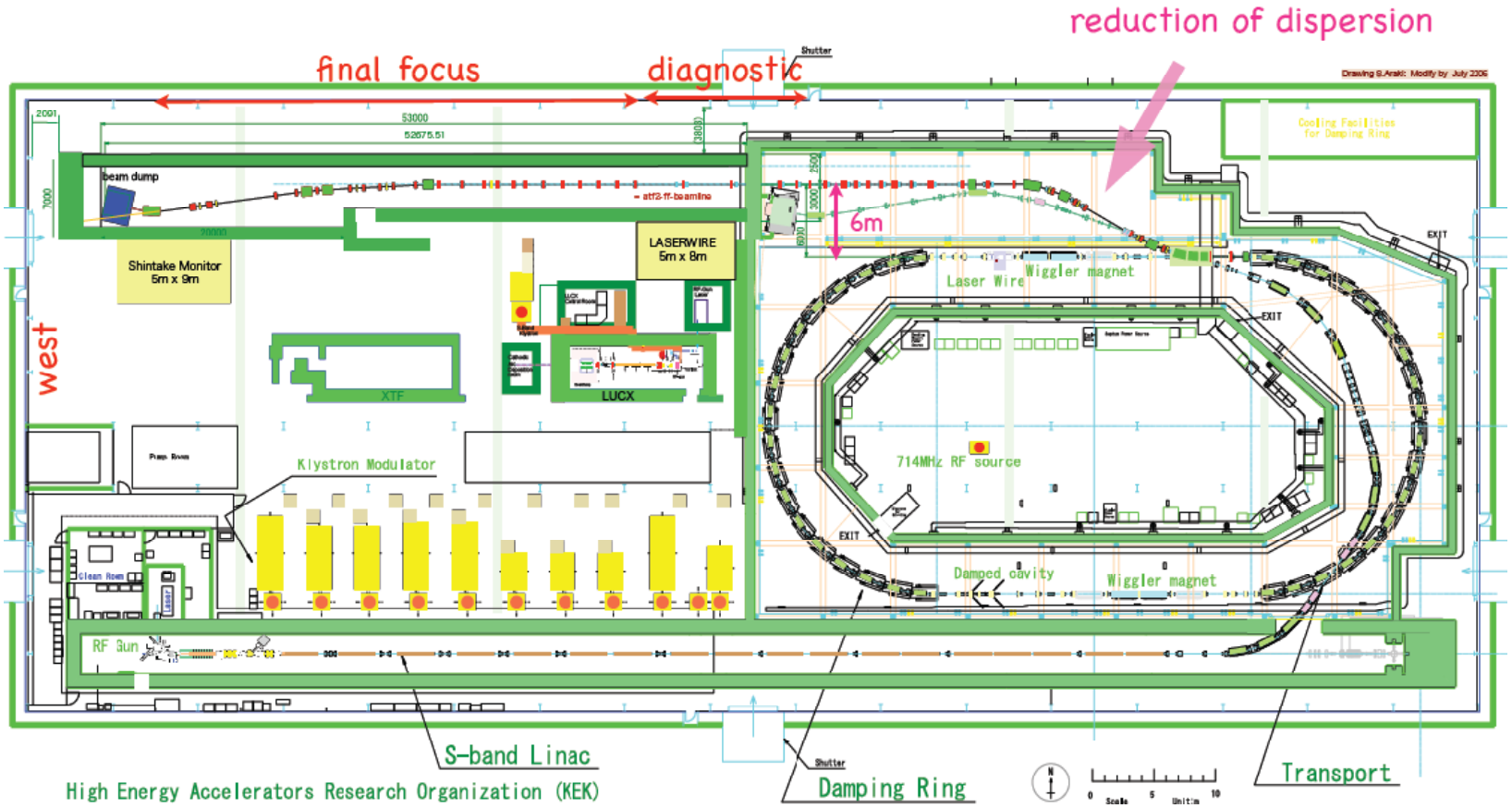
- Calculate Luminosity loss for different jitter / kick distance cases using 'SD0 lumi loss' and 'FFB lumi loss' look-up tables (horizontal + vertical).
- Left plot shows % nominal luminosity with given RMS SD0/QD0 jitter and varying kick-SD0 distance.
- Right plot shows all jitter cases plotted vs. kick distance and shows the expected dependence on kick distance.

Tracking Simulation Results with RMS Offsets of both Final Doublet Cryomodules

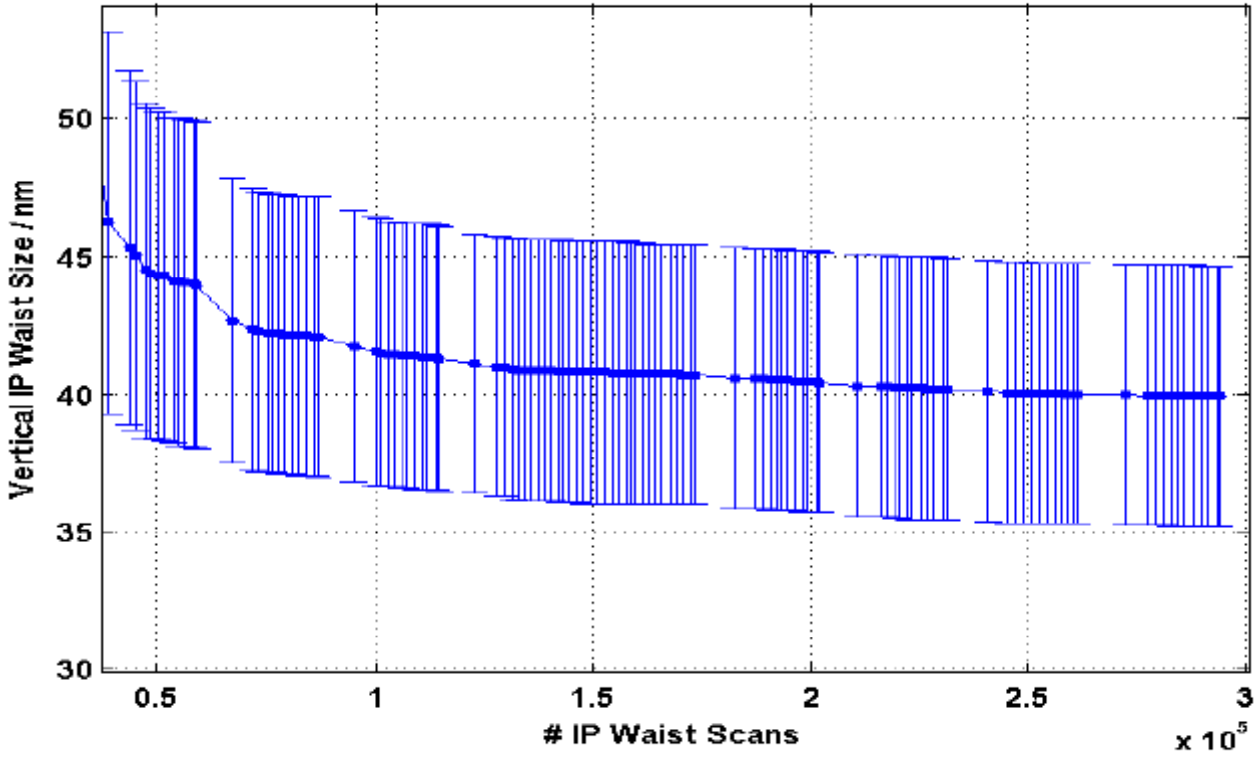


- Track 80K macro particles (e- & e+ side) from QF1 -> IP with RMS SF1/QF1 and SD0/QD0 vibration in horizontal and vertical planes.
- Results show mean and range of luminosities from 100 consecutive pulses.

Test of ILC Final Focus Optics @ ATF2

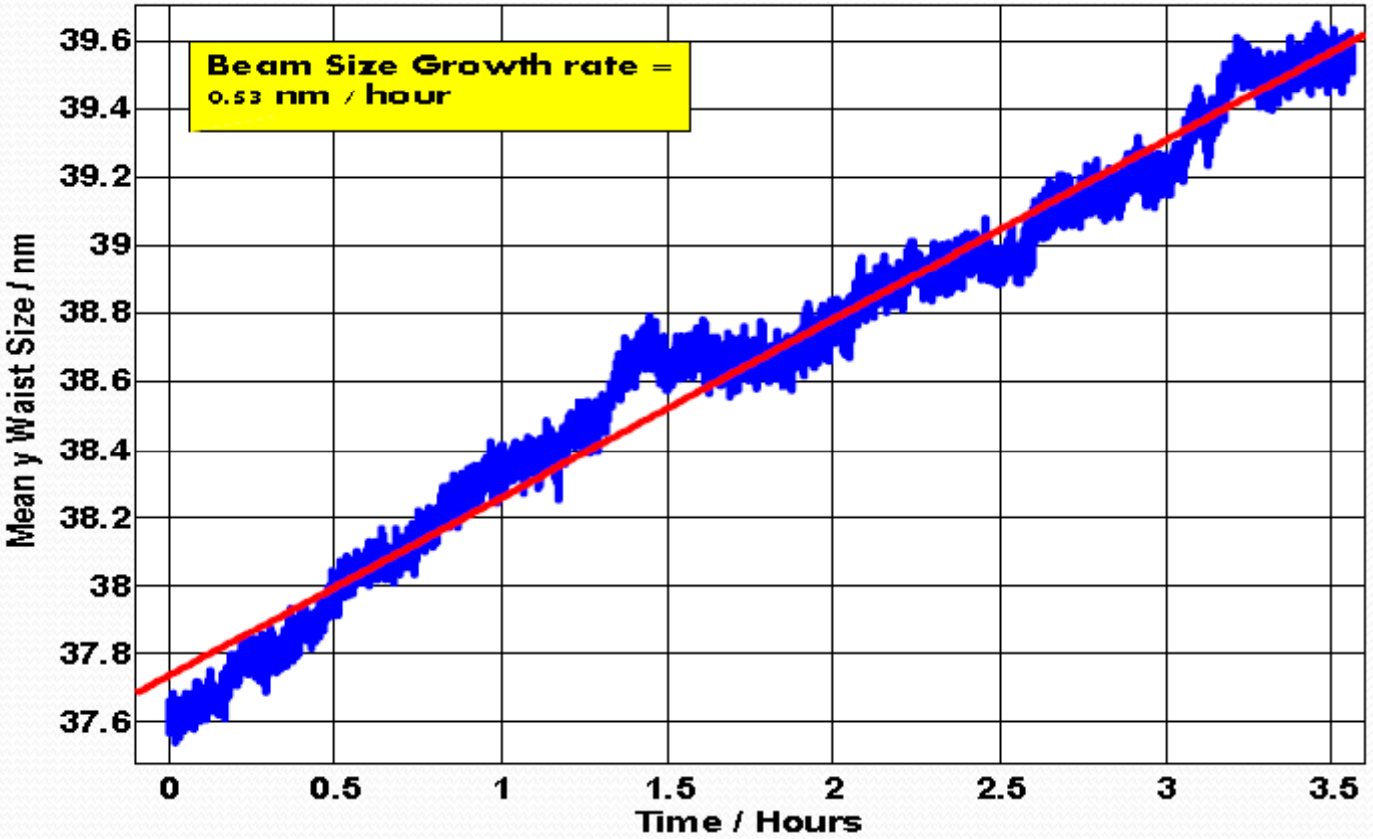


Beam Spot Tuning



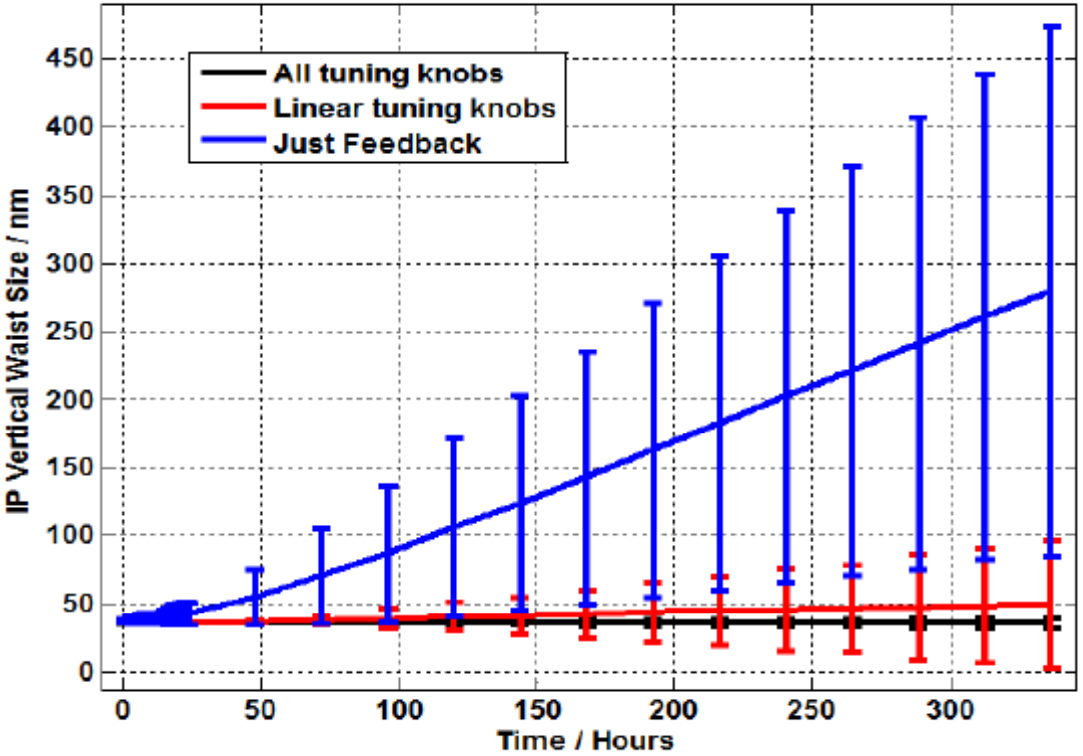
- Tuning Spot size with sextupole knobs and Shintake monitor after Quad+Sext -> Bpm alignment and BBA
- Differences from ILC:
  - Longer to do IP measurements – 1 minute for SM measurement
  - No FFS-phase skew quad for <x'y> correction – use sextupole moves instead

Beam Size Growth After Tuning



- With feedbacks on, y beam size at IP as a function of time
- Mean of 100 seeds shown
- Growth rate ~ 0.5 nm per hour

Long-Timescale Performance



At each point, none, linear (waist, dispersion and coupling) and full tuning knobs (include sextupole strength and tilt scans) applied. For blue, red and black respectively.

- Vertical IP beam size over 2 week period
- Mean and +/- 1 sigma RMS from 100 seeds shown at each point