Magnet Alignment Sensitivities in ILC DR Configuration Study Lattices

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2: Equilibrium vertical emittance in ILC DR must be < 2 pm

Required equilibrium emittance is determined by injected emittance, damping time and specified extracted emittance.

$$\varepsilon(t) = \varepsilon(0)\exp(-2t/\tau) + \varepsilon(\infty)[1 - \exp(-2t/\tau)]$$

Lattice	**Circumference [m]**	**Energy [GeV]**	**Cell Style**	**Equilibrium geometric vertical emittance [pm]**
KEK-ATF	138	1.28	FOBO	~ 4.5 (achieved)
PPA	2824	5.0	PI	2.04
OTW	3223	5.0	TME	2.04
OCS	6114	5.066	TME	2.00
BRU	6333	3.74	FODO	2.52
MCH	15935	5.0	FODO	1.69
DAS	17014	5.0	PI	1.67
TESLA	17000	5.0	TME	1.45

3: Very small vertical emittances are difficult to measure

Measurements at KEK-ATF are made with a laser-wire.

Beam size at 4.5 pm is around 5 μm, and comparable to the size of the laser-wire itself.

Measurements do not allow for beam jitter, but this should be small.

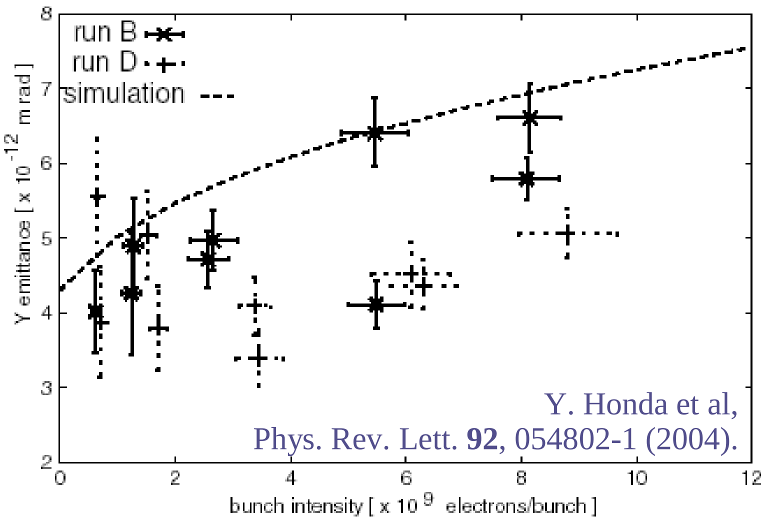


FIG. 2. Current dependence of the vertical emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

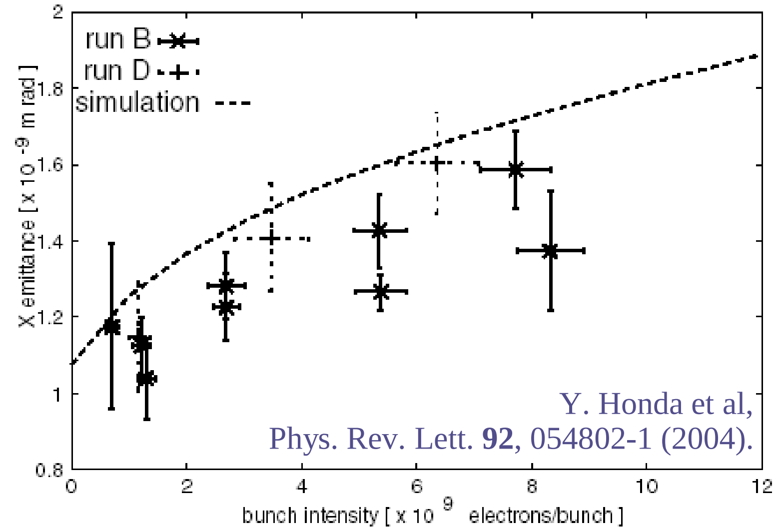


FIG. 3. Current dependence of the horizontal emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

4: Vertical emittance is generated by various sources

Vertical opening angle of radiation excites some vertical emittance.

Generally, this is ~ 5% of the specified emittance in the damping rings.

Vertical steering generates vertical dispersion.

We will require rms vertical dispersion < few mm, at least in wiggler sections.

Typical rms residual vertical dispersion in storage rings ~ cm.

Horizontal dispersion is coupled into the vertical plane.

Primary sources are vertical orbit offsets in sextupoles and quadrupole tilts.

Betatron coupling transfers horizontal excitation into vertical plane.

Primary sources are vertical orbit offsets in sextupoles and quadrupole tilts.

Synchrobetatron coupling: longitudinal emittance is transferred to vertical.

Resonances may be driven by, for example, vertical dispersion in RF cavities.

5: A first step is to estimate alignment sensitivities

Vertical orbit offsets in sextupoles and quadrupole tilts tend to be dominant sources of vertical emittance in many cases.

For the ILC damping rings, 2 pm vertical emittance is generated by:

- few 10s of μm orbit offset in sextupoles
- few 10s or 100s of μrad quadrupole tilts

The required vertical emittance cannot be achieved simply by survey and alignment: orbit, dispersion and coupling correction are essential.

Many emittance tuning schemes are possible. A detailed study of different schemes is an important part of the analysis of any damping ring lattice…

…but simple sensitivity estimates can give an indication of the difficulty of achieving the required emittance, and its stability.

Simple analytical estimates of sensitivities can be made, but these need to be supported by simulations.

We performed simulations in Merlin, calculating emittance using Chao's method.

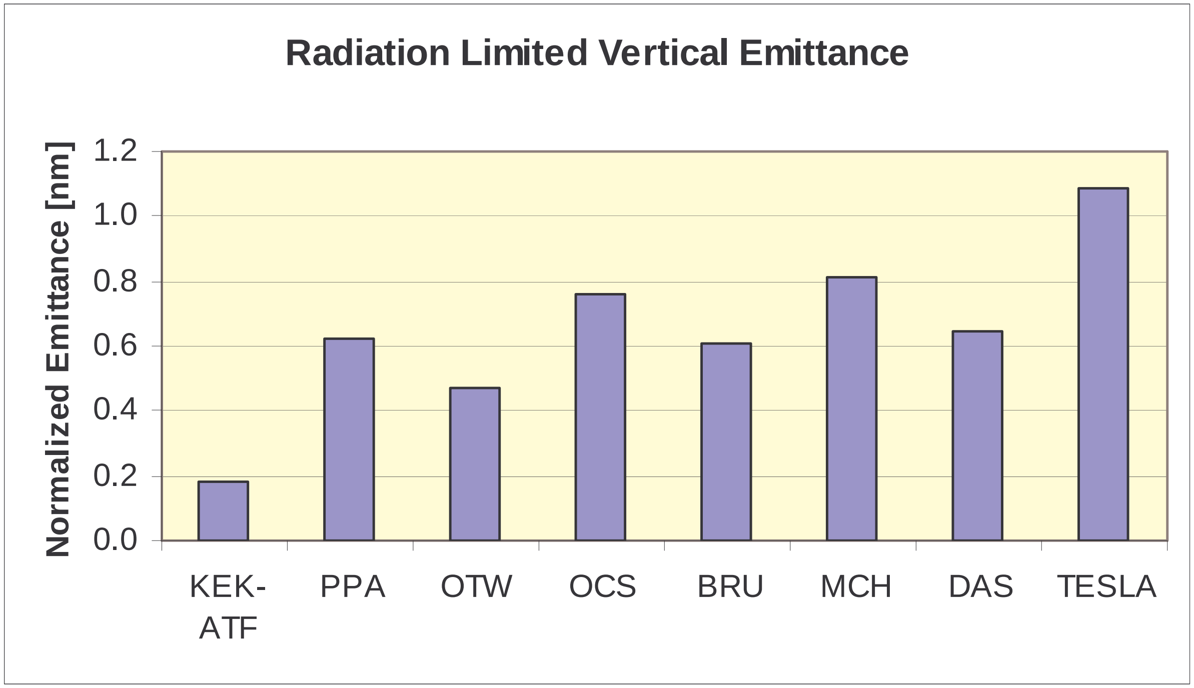
"Split" elements in the lattices were recombined before performing the simulations.

6: SR vertical opening angle is not *completely* negligible

Specified equilibrium vertical normalized emittance is 20 nm.

In most lattices, vertical opening angle of radiation contributes < 1 nm

$$\varepsilon_{y,SR} = \frac{13}{55}\frac{C_q}{J_y I_2}\oint \frac{\beta_y}{|\rho|^3}\,ds$$



7: Quadrupole misalignment generates orbit distortion

Moving the quadrupoles vertically results in vertical steering.

Vertical steering generates vertical dispersion.

Vertical orbit offset in sextupoles leads to vertical dispersion and betatron coupling.

We can characterize sensitivity to quad alignment by an "orbit amplification factor":

vertical orbit rms = amplification factor × quadrupole vertical misalignment rms

We can estimate analytically the amplification factor:

$$\text{amplification factor} \approx \sqrt{\frac{\langle \beta_y \rangle \Sigma_{1O}}{8 \sin^2(\pi \nu_y)}}$$

where

$$\Sigma_{1O} = \sum_{quads} \beta_y (k_1 L)^2$$

There is a wide distribution of orbit rms for a given quadrupole misalignment rms.

8: Example: quadrupole misalignment in PPA lattice

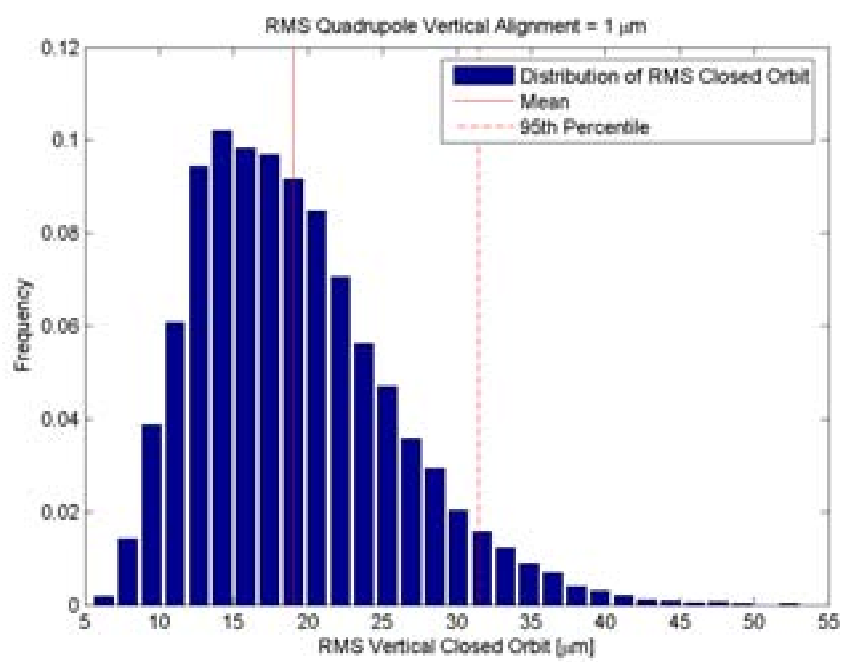
We take a "perfect" lattice, and apply random alignment errors to all quadrupoles.

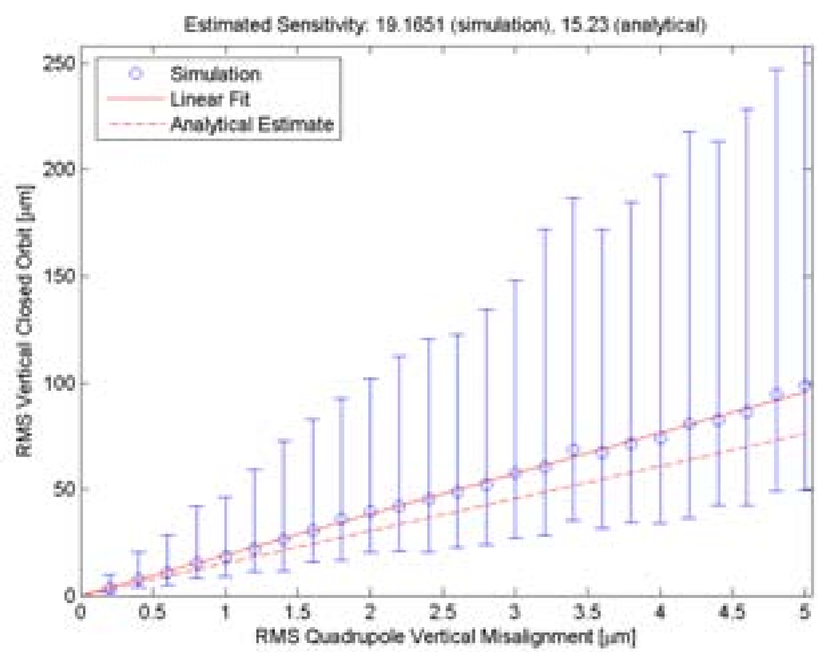
- Alignment errors have a normal distribution, with a cut-off at 3σ.

The distribution (left-hand plot below) shows 10000 seeds, each with 1 μm rms.

The right-hand plot shows the calculated rms closed-orbit distortion for alignment errors between 0 and 5 μm rms.

- 100 seeds for each value of rms alignment error.
- Error bars are between the 5th and 95th percentiles.





9: Sextupole misalignment generates dispersion and coupling

Vertical sextupole misalignment is equivalent to inserting a skew quadrupole.

We can estimate analytically the vertical emittance generated by a given rms of sextupole vertical misalignment:

$$\frac{\varepsilon_y}{\langle Y_{sext}^2 \rangle} \approx \boxed{\frac{J_x\left[1-\cos(2\pi\nu_x)\cos(2\pi\nu_y)\right]}{4J_y\left[\cos(2\pi\nu_x)-\cos(2\pi\nu_y)\right]^2}\Sigma_{2C}\varepsilon_x} + \boxed{\frac{J_z\sigma_\delta^2}{4\sin^2(\pi\nu_y)}\Sigma_{2D}}$$

coupling dispersion

where

$$\Sigma_{2C} = \sum_{sexts} \beta_x \beta_y (k_2 L)^2 \qquad \Sigma_{2D} = \sum_{sexts} \beta_y \eta_x^2 (k_2 L)^2$$

10: Example: sextupole misalignments in PPA lattice

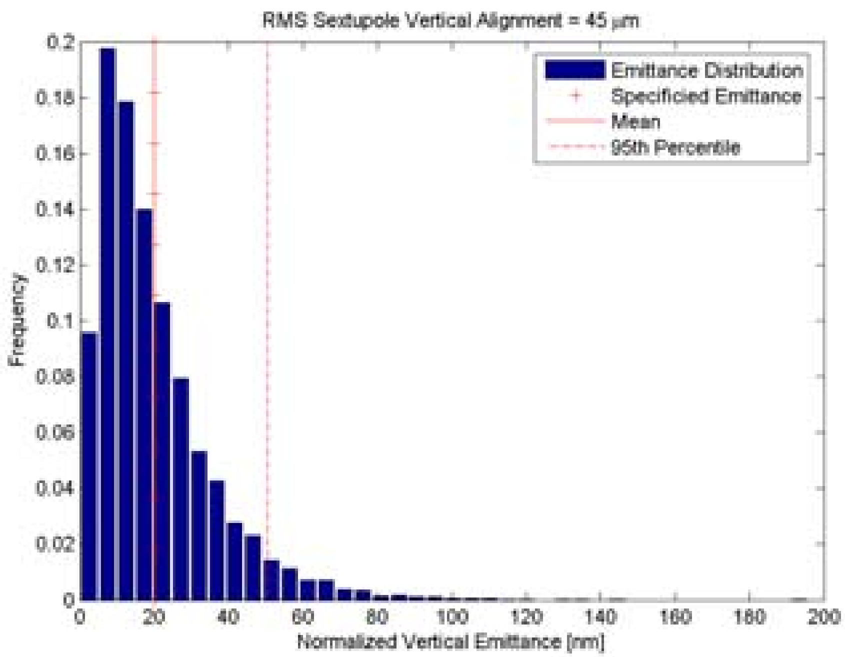
We take a "perfect" lattice, and apply random vertical alignment errors to all sextupoles.

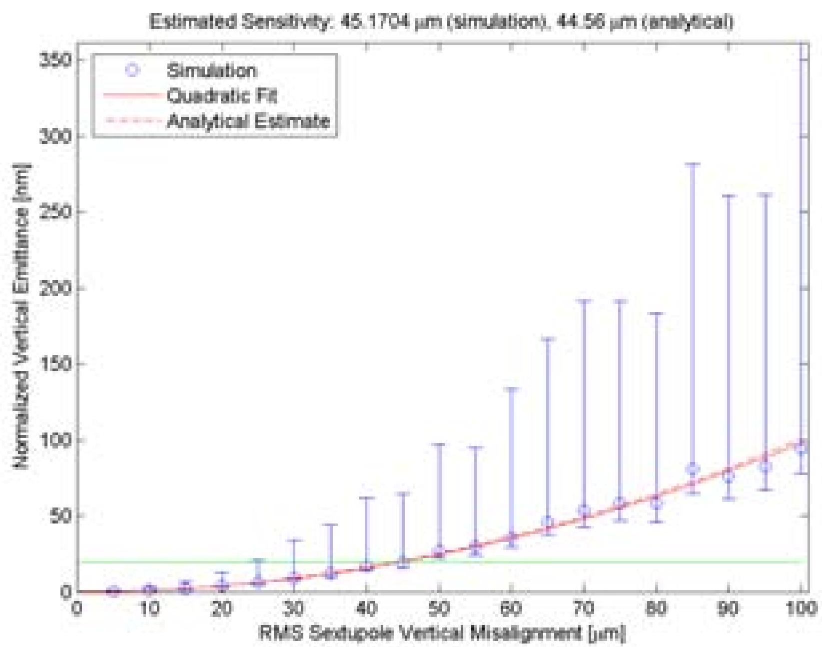
- Alignment errors have a normal distribution, with a cut-off at 3σ.

The distribution (left-hand plot below) shows 10000 seeds, each with 45 μm rms.

The right-hand plot shows the calculated rms normalized vertical emittance for sextupole alignment errors between 0 and 100 μm rms.

- 100 seeds for each value of rms alignment error.
- Error bars are between the 5th and 95th percentiles.





11: Quadrupole tilts generate dispersion and coupling

A quadrupole tilt (around the beam axis) is equivalent to inserting a skew quadrupole.

We can estimate analytically the vertical emittance generated by a given rms of sextupole vertical misalignment:

$$\frac{\varepsilon_y}{\left\langle \Theta_{quad}^2 \right\rangle} \approx \underbrace{\boxed{\frac{J_x\left[1-\cos(2\pi\nu_x)\cos(2\pi\nu_y)\right]}{4J_y\left[\cos(2\pi\nu_x)-\cos(2\pi\nu_y)\right]^2}\Sigma_{1C}\varepsilon_x}}_{\text{coupling}} + \underbrace{\boxed{\frac{J_z\sigma_\delta^2}{4\sin^2(\pi\nu_y)}\Sigma_{1D}}}_{\text{dispersion}}$$

where

$$\Sigma_{1C} = \sum_{quads} \beta_x\beta_y(k_1L)^2 \qquad \Sigma_{1D} = \sum_{quads} \beta_y\eta_x^2(k_1L)^2$$

12: Example: quadrupole tilts in PPA lattice

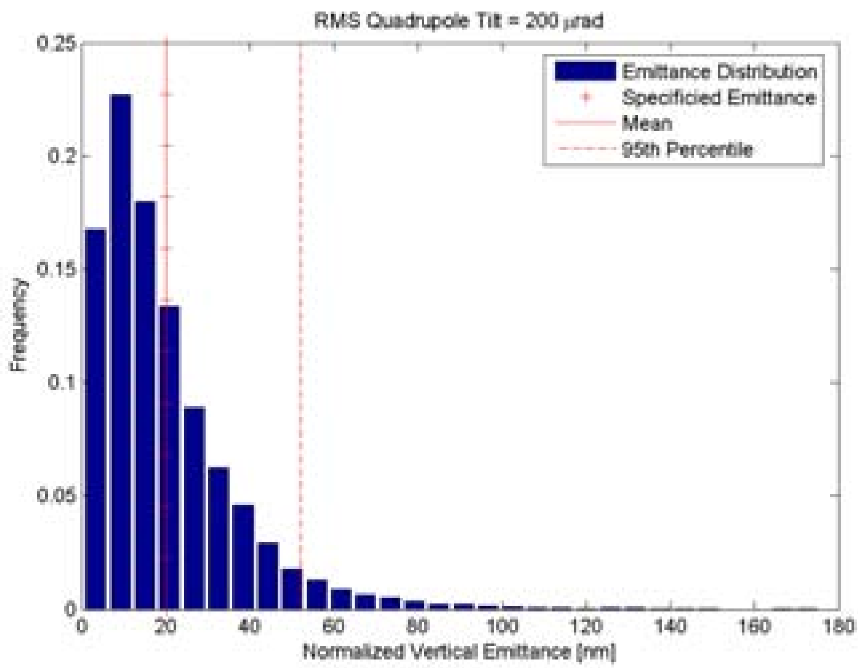
We take a "perfect" lattice, and apply random tilt errors to all quadrupoles.

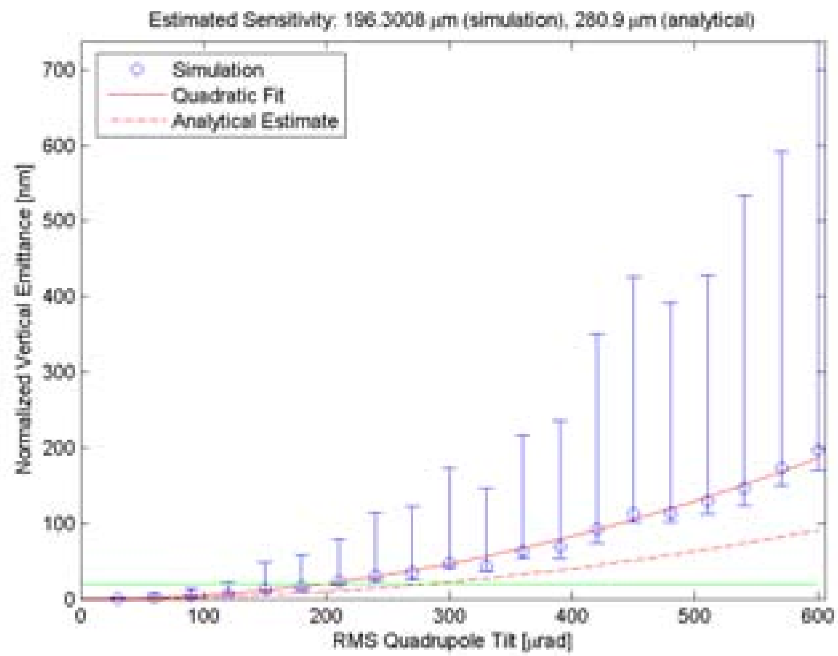
- Tilt errors have a normal distribution, with a cut-off at 3σ.

The distribution (left-hand plot below) shows 10000 seeds, each with 200 μrad rms.

The right-hand plot shows the calculated rms normalized vertical emittance for quadrupole tilt errors between 0 and 600 μm rms.

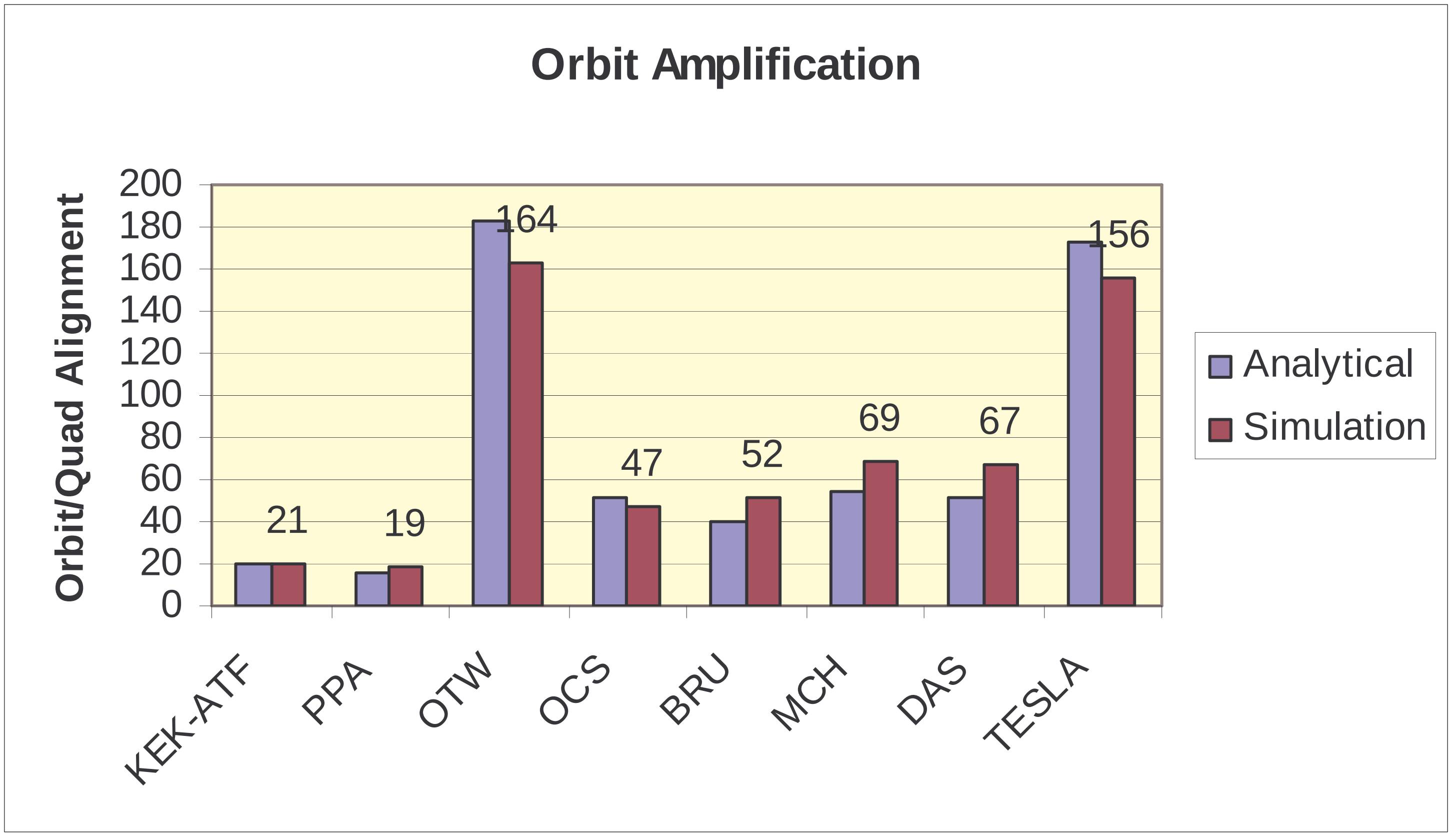
- 100 seeds for each value of rms tilt error.
- Error bars are between the 5th and 95th percentiles.





13: Comparison of orbit amplification factors

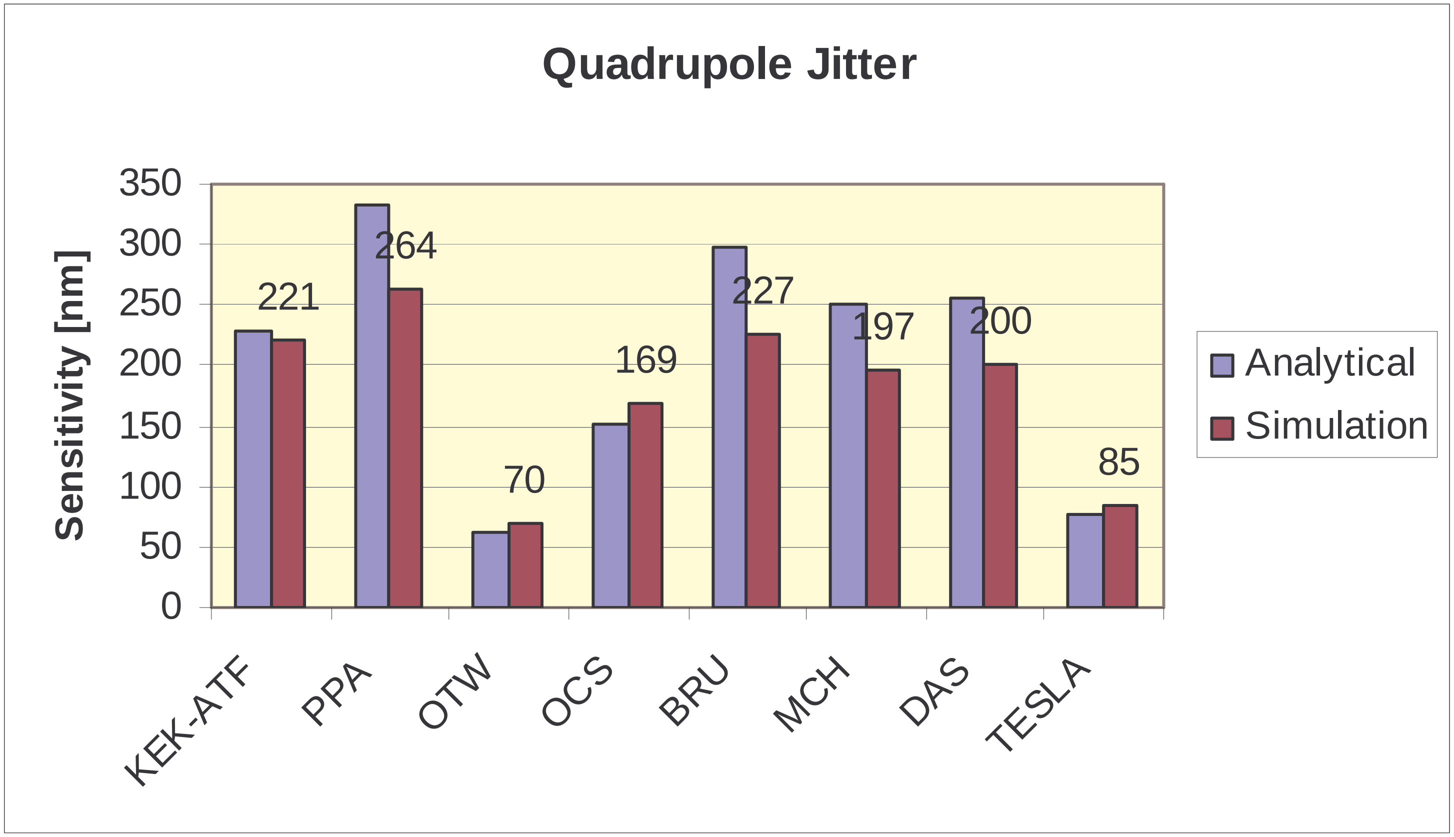
The orbit amplification factor is the ratio between the rms vertical closed-orbit distortion and the rms quadrupole vertical alignment error.



14: Comparison of quadrupole jitter sensitivities

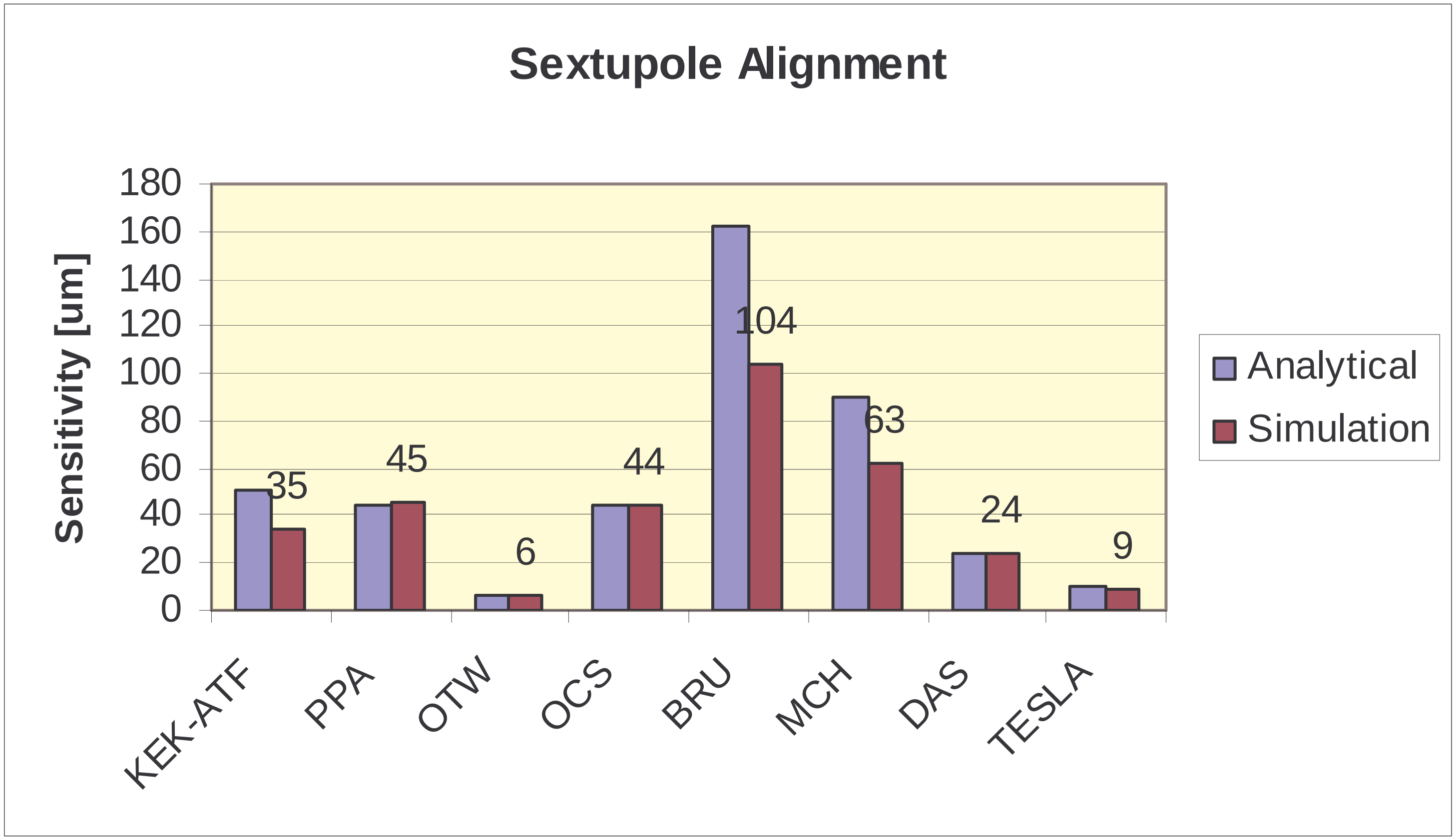
Jitter sensitivity is the rms quadrupole vertical alignment error that will generate a closed orbit distortion equal to the beam size.

The jitter sensitivity is significant in the context of the extracted beam stability.



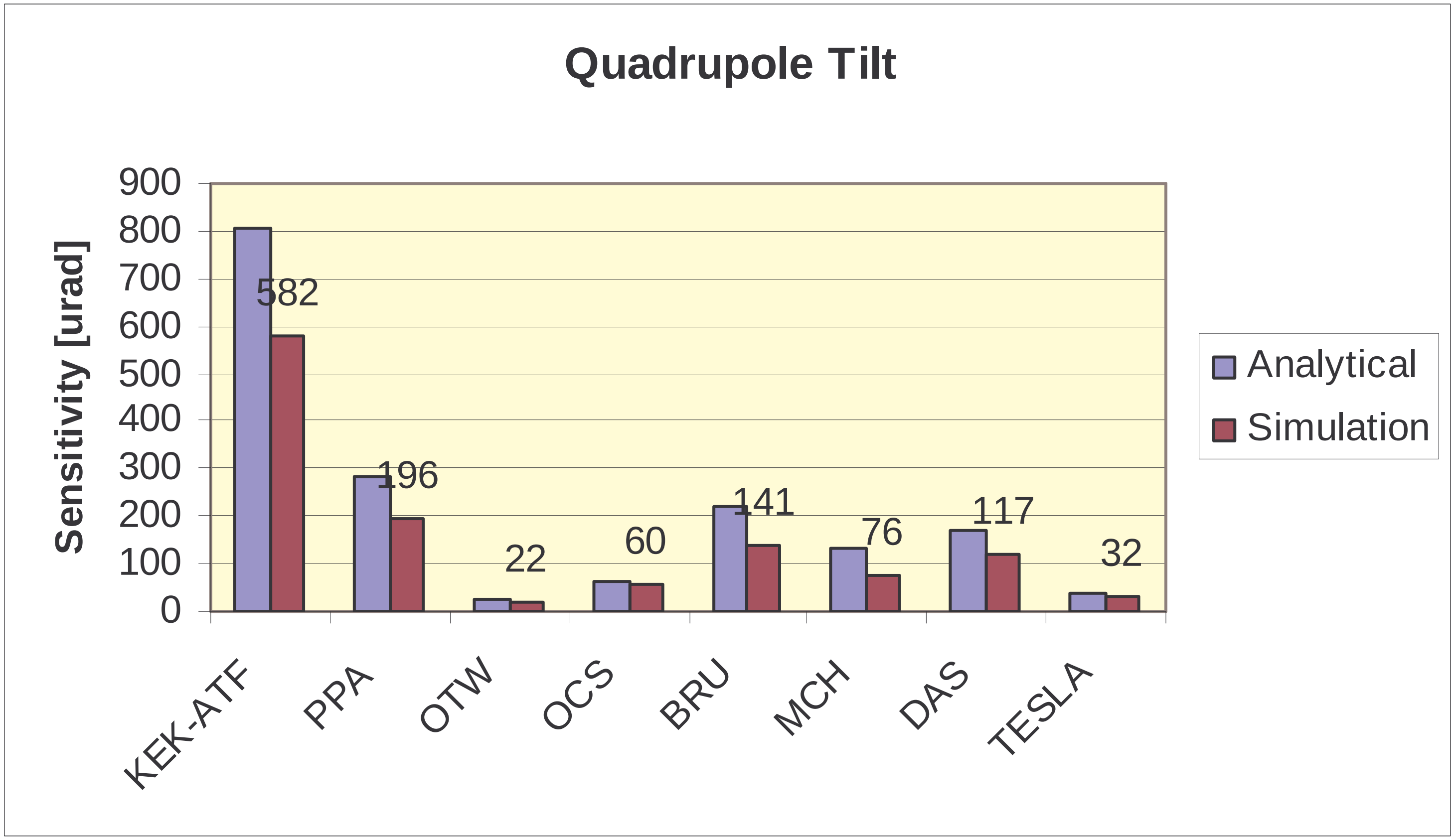
15: Comparison of sextupole alignment sensitivities

The sextupole alignment sensitivity is the rms sextupole vertical alignment error that will generate a vertical emittance equal to the specified equilibrium emittance.



16: Comparison of quadrupole tilt sensitivities

The quadrupole tilt sensitivity is the rms quadrupole tilt error that will generate a vertical emittance equal to the specified equilibrium emittance.



17: Results agree well with simulations by K. Kubo

Kubo-san simulated the same lattices in SAD, looking at emittance generated by:

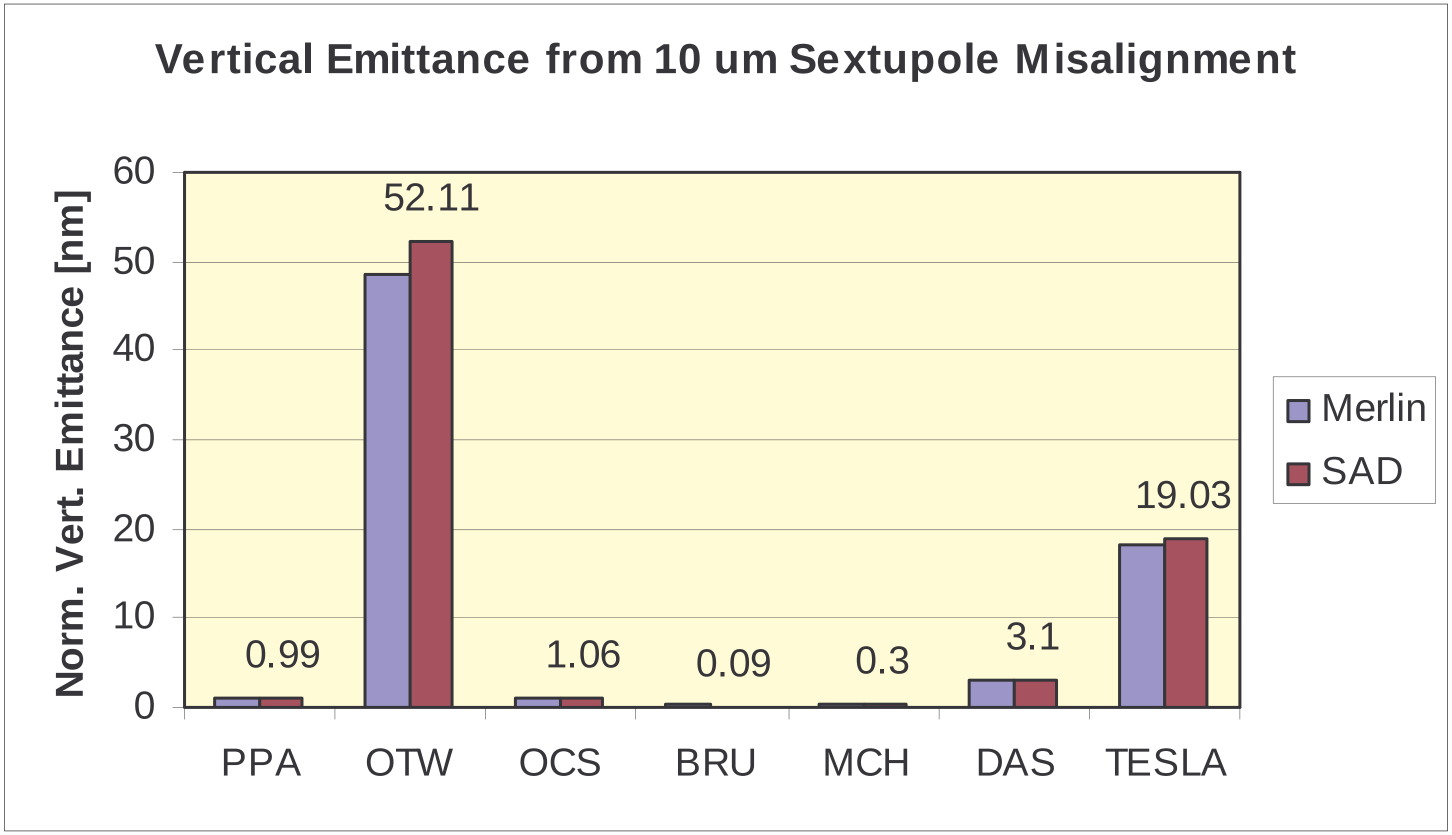
- 10 μm rms sextupole misalignment;
- 30 μrad rms quadrupole tilt;
- 0.4 μm rms misalignment on all elements;
- 10^{-6} Tm rms random magnetic field applied every 100 m.

Results for sextupole misalignments and quadrupole tilts are in good agreement between SAD and Merlin.

Simulations for all-element misalignments and random (stray) magnetic fields have not yet been performed in Merlin.

Dogbone lattices look more sensitive to random fields than other lattices.

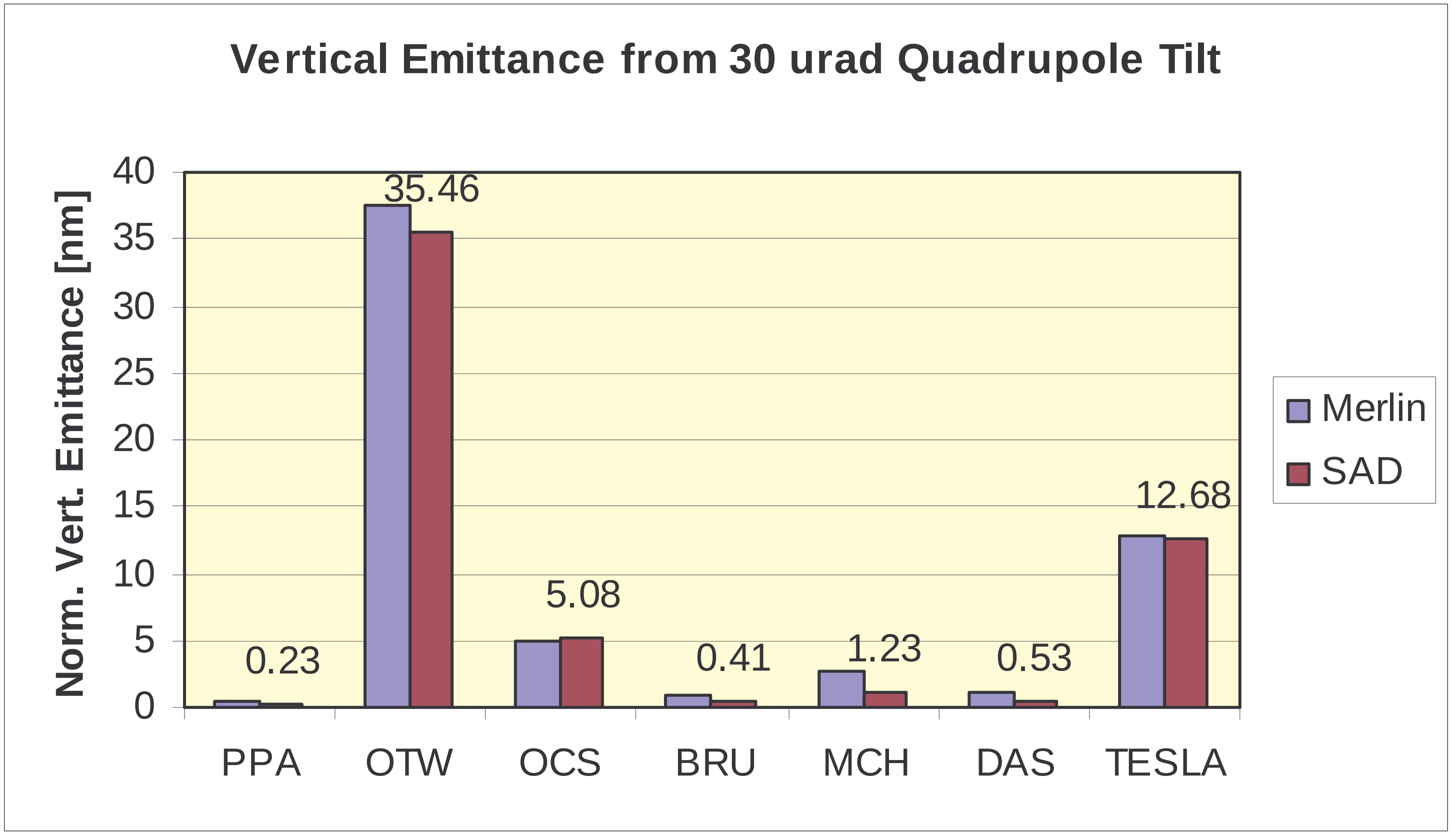
18: SAD and Merlin in good agreement for sext misalignments



Note: values shown above bars are from SAD.

Merlin values are calculated from quadratic fits to simulations with a range of misalignments.

19: SAD and Merlin in good agreement for quad tilts



Note: values shown above bars are from SAD.

Merlin values are calculated from quadratic fits to simulations with a range of misalignments.

20: Summary and conclusions

Alignment sensitivities are a relatively crude way to compare the properties of the different lattices. Simulations of emittance tuning are needed for more significant conclusions to be drawn (and should be performed). Nevertheless…

There is little correlation between lattice size and sensitivity to quadrupole vertical alignment errors, sextupole vertical alignment errors, or quadrupole tilt errors.

The type of lattice does appear to have some effect on the sensitivity to alignment errors:

- The TME lattices (OTW, OCS, TESLA) are the most sensitive to quadrupole jitter.
- The FODO lattices (MCH, BRU) are least sensitive to sextupole vertical alignment error.
- The TME lattices (OTW, OCS, TESLA) are the most sensitive to quadrupole tilt errors.

Compared to the KEK-ATF:

- Some lattices (PPA, OCS, and especially BRU and MCH) are *less* sensitive to sextupole alignment errors.
- All lattices are significantly *more* sensitive to quadrupole tilt errors.

Based on KEK-ATF experience, the specified vertical emittance of 20 nm will not be easy to achieve.