Strategies on Coupling and Dispersion Tuning for Low Vertical Emittance Rings

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SLAC, Jan. 26th 2008

Emittance growth mechanisms for low vertical emittance rings

- Three effects dominate the contributions to the vertical emittance:
  - non-zero vertical opening angle of the synchrotron radiation in dipole magnetic fields excites vertical betatron motion of particles as they “recoil” from photon emission,
  - vertical dispersion from steering errors generates vertical emittance, in the same way that horizontal dispersion from the bending magnets determines the horizontal emittance of the beam,
  - betatron coupling from skew quadrupole errors leads to a transfer of horizontal betatron motion (and hence horizontal emittance) into the vertical plane.
- The first of these effects, places a fundamental lower limit on the vertical emittance that can be achieved in any storage ring; this can be calculated for a given lattice design. In most rings, including *SuperB*, the lower limit is a fraction of a picometer, and is significantly smaller than the specified vertical emittance.

Emittance growth mechanisms for low vertical emittance rings (cont)

- Effects of vertical dispersion and betatron coupling, which arise from magnet alignment and field errors, dominate the vertical emittance
- Reducing the vertical emittance in *SuperB* to the value required to achieve the specified luminosity requires highly precise initial alignment of the machine, followed by careful tuning and error correction
- The lowest vertical emittance achieved in an operating storage ring is 2 pm in the DIAMOND synchrotron radiation source in UK (presented at EPAC ’08)
- *SuperB* rings are specified to operate at 4 and 7 pm, so the alignment and tuning issues require attention

Comparison of design and achieved beam emittances

Comparison of rings with similar beam energy and ATF, SLS (* achieved)

	E (GeV)	C (m)	Gamma	ε_x (nm)	$\gamma\varepsilon_x$ (μm)	ε_y (pm)	$\gamma\varepsilon_y$(nm)
Spring-8	8	1430	15656	6	94	5	78
ILC-DR	5	6400	9785	1	10	2	20
Diamond*	3	561	5871	2.7	16	2	29
ATF*	1.28	138	2524	1	3	4	10
SLS*	2.4	288	4700	6	28	3.2	15
SuperB LER	4	1800	7828	2.8	22	7	55
SuperB HER	7	1800	13699	1.6	22	4	55

A range of tuning techniques and algorithms have been tested in simulations and experiments on the ATF and on the other electron storage rings to achieve such small emittances

Emittance growth mechanisms for low vertical emittance rings (cont)

- Theoretical and simulation studies suggest that 2 pm vertical emittance is a realistic goal for the ILC damping rings. Significant effort has already been devoted to understanding the alignment and tuning requirements in these systems
- How the difficulty of achieving 4 pm in *SuperB* compares with the difficulty of achieving 2 pm in the ILC-DR ?
- We may characterize the behavior of the vertical emittance in a given lattice by calculating the vertical emittance generated by a variety of magnet alignment errors. The principal errors to consider, all of which generate unwanted skew quadrupole components, are:
  - vertical sextupole misalignments,
  - rotations or tilts of quadrupoles around the beam axis,
  - closed orbit distortion generated by vertical misalignments of the quadrupoles, which results in vertical beam offsets in the sextupoles with the same consequences as vertical misalignments of the sextupoles themselves.

Coupling and Dispersion Tuning for Low Vertical Emittance Rings

- Estimates of the sensitivity of a lattice to these errors can be made using analytical formulae involving the magnet strengths and lattice functions; it is usually found that simulations support the results of these analytical calculations
- Sensitivity to a particular error: rms misalignment that, averaged over a large number of seeds will generate a specified vertical emittance.
- Table (from *SuperB* CDR, by A. Wolski) shows the results of analytical estimates of the sensitivity of *SuperB* rings to various alignment errors, compared to the ATF and the baseline design for the ILC-DR
- Results in Table are statistical: they represent the mean over many different sets of random errors; the spread in the response of a lattice to a given set of alignment errors is large, usually 100% of the mean

Specified vertical emittance in SuperB, ATF, ILC-DR, with sensitivity indicators

A. Wolski, *SuperB* CDR

	Super$B$ LER	Super$B$ HER	ILC DRs	KEK ATF
Vertical emittance (pm)	4	4	2	4.5
Orbit amplification factor	46	44	32	21
Quadrupole jitter sensitivity (nm)	209	217	221	227
Sextupole alignment sensitivity (μm)	95	87	70	50
Quadrupole tilt sensitivity (μrad)	166	183	79	800

Now 7 pm

With the exception of the quadrupole tilts, these values indicate that tuning *SuperB* to achieve 4 pm should not be significantly more difficult than tuning ATF to achieve the already-demonstrated emittance of 4 pm, or tuning the ILC-DR to achieve 2 pm vertical emittance.

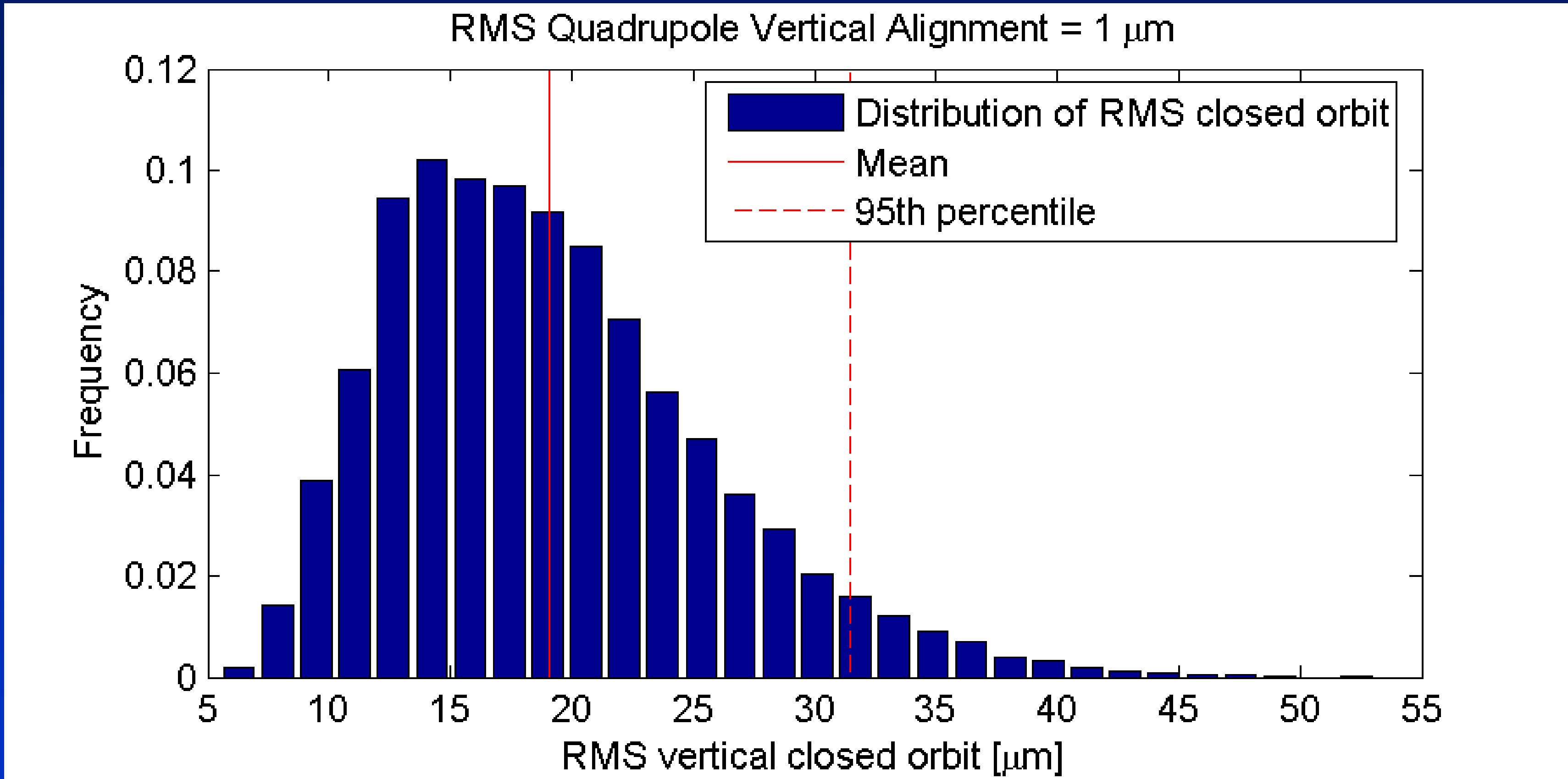
Specified vertical emittance in SuperB, ATF, ILC-DR, with sensitivity indicators (cont)

- Smaller values indicate a greater sensitivity to quadrupole tilts, and larger values are more desirable
- These sensitivity indicators should not be taken as alignment tolerances: they simply indicate the mean response of the beam to errors of a given magnitude
- Generally, alignment of the magnets will be significantly worse than the indicated sensitivities, but coupling correction and tuning techniques can be used to achieve the specified vertical emittance
- The sensitivity values may be taken to indicate the difficulty of implementing the tuning successfully, and the frequency with which tuning might be required to maintain the specified emittance

BPMs errors

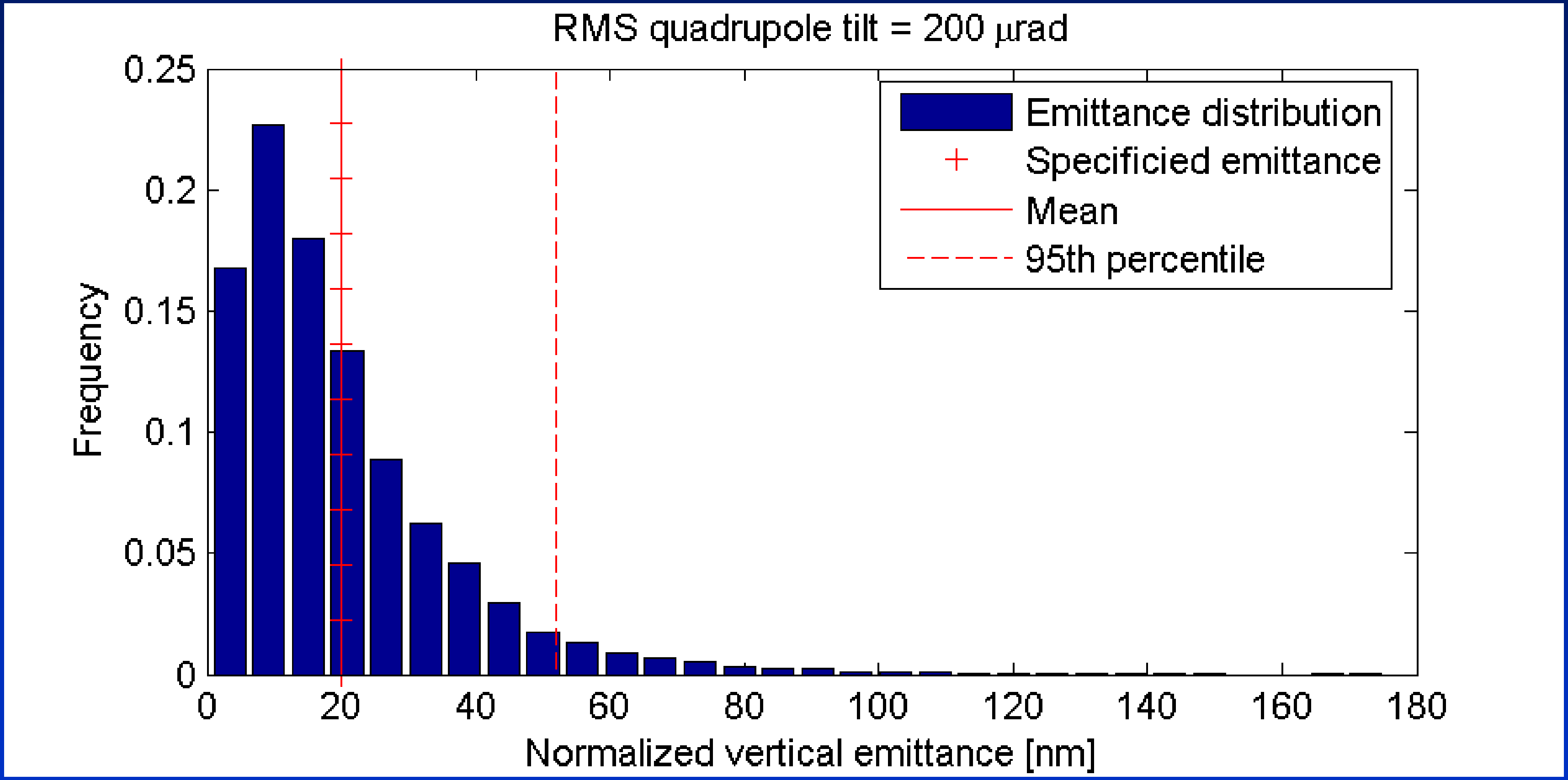
- A further difficulty in estimating the emittance growth is also due to BPMs, where measurements, and simulations, are performed
- In order to consider BPM misalignments and calibration errors in BPM electronics, each BPM must be assumed to have a random (gaussian) offset and rotation errors, indipendent from the quadrupole ones
- This adds variables to the game

Examples for ILC-DR: closed orbit distortion due to quads misalignments



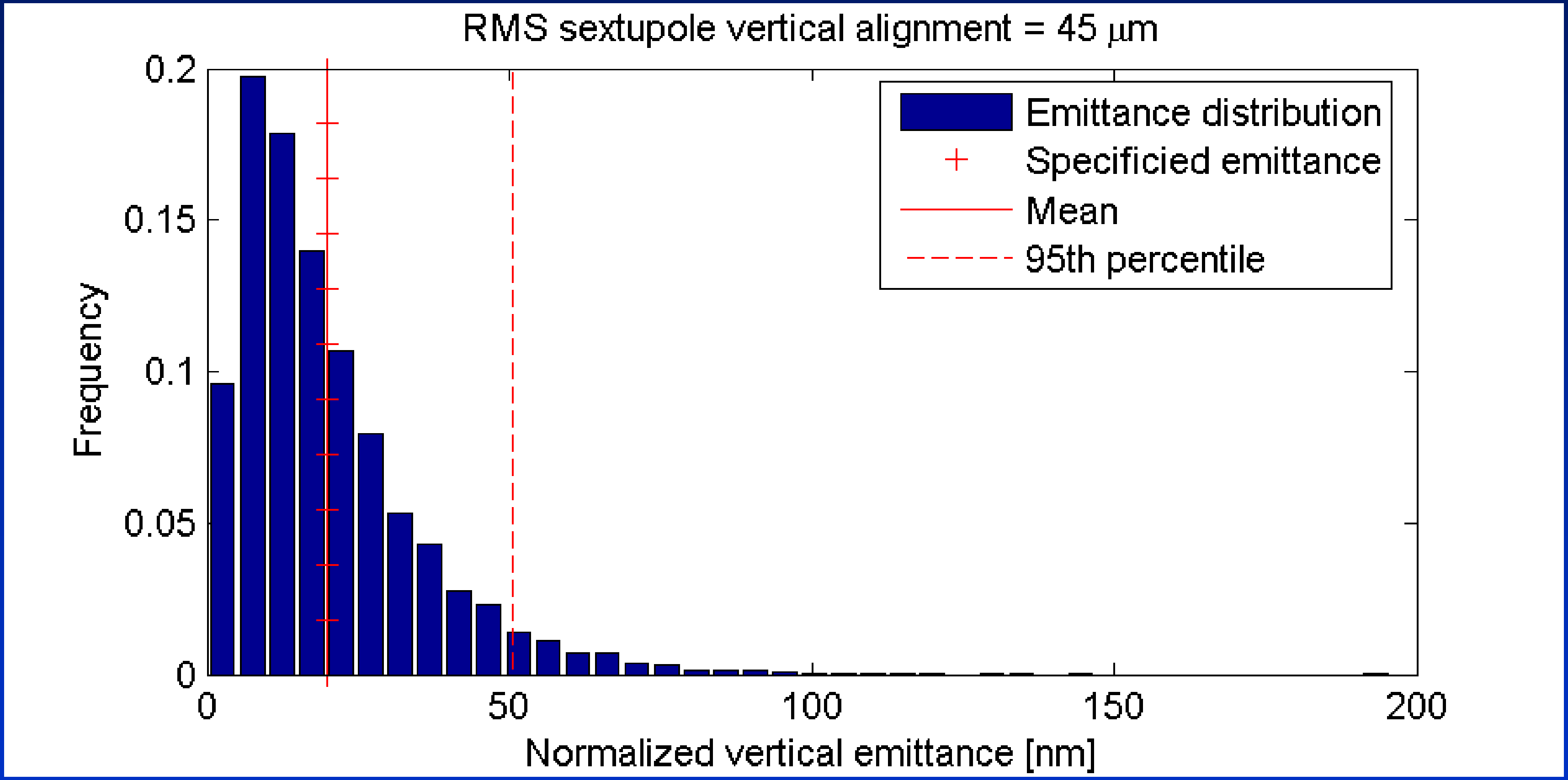
Distribution of rms closed orbit distortion in the PPA lattice, for 10,000 sets of quadrupole misalignments with 1 µm rms.

Examples for ILC-DR: vertical emittance with quads tilts



Distribution of vertical emittances in the PPA lattice, for 10,000 sets of quadrupole tilts with 200 μrad rms.

Examples for ILC-DR: vertical emittance with sexts misalignments



Distribution of vertical emittances in the PPA lattice, for 10,000 sets of sextupole misalignments with 45 μm rms.

Low emittance tuning in SuperB

- Contributions to ε_y growth in *SuperB* come mainly from:
  - tilts in quadrupoles
  - misaligned sextupoles
  - vertical dispersion
  - beam coupling, also from BaBar detector solenoid and spin rotator solenoids not perfect compensation
  - IBS
- The strong sextupoles and quadrupoles in the Final Focus were omitted from the calculations in CDR: the beam orbit and emittance tend to be particularly sensitive to motion of these elements, which will therefore need special consideration (see stabilization techniques as already studied for ILC at Annecy)

Emittance tuning simulations for SuperB

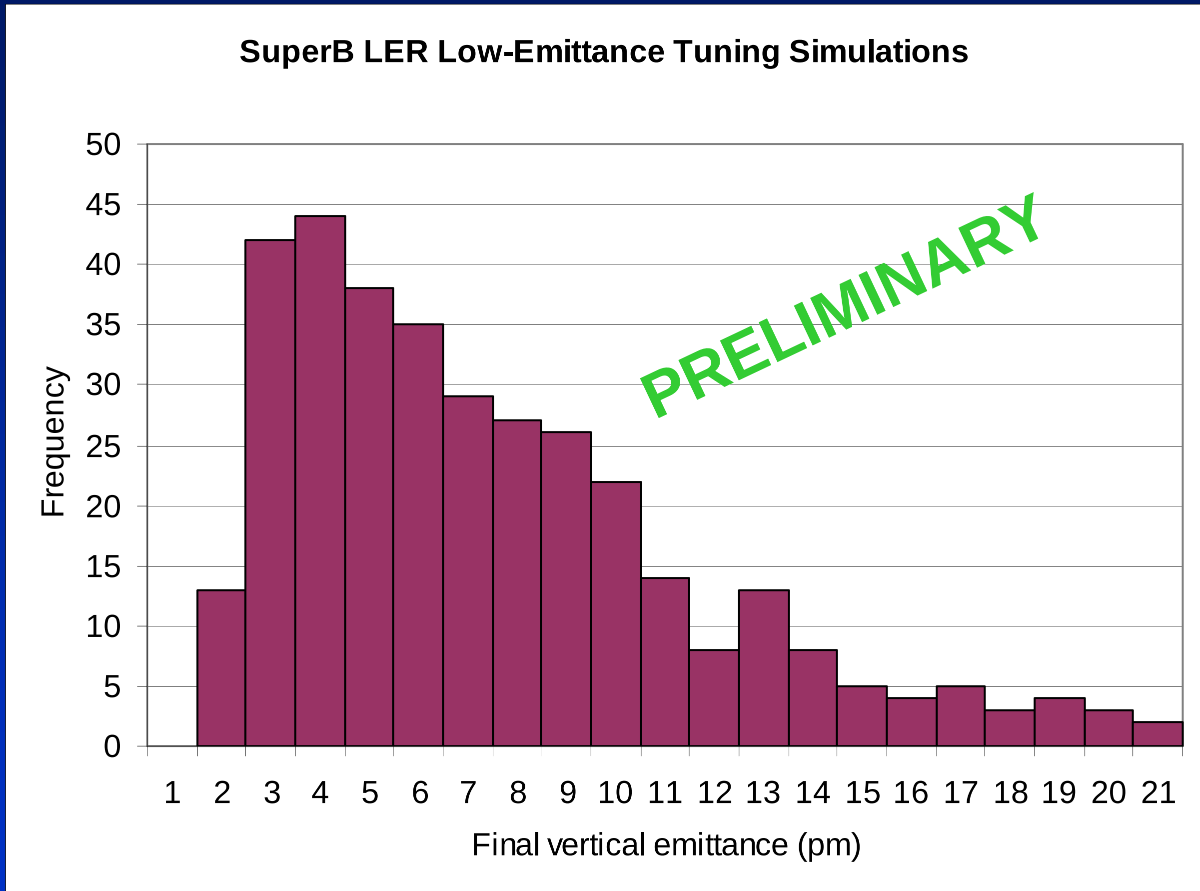
- Code Merlin (C++, N. Walker & A. Wolski) can be used to introduce machine errors (random, systematic)
- Code adapted by A. Wolski to *SuperB* needs
- Procedure:
  - correct orbit at BPMs (response matrix, SVD method)
  - correct coupling with skew quads
  - evaluate vertical emittance after correction
- Simulations started for LER ring

LER vertical emittance with machine systematic and random errors

- Simulated 357 machines with:

rms bpm vertical misalignment	50 µ
rms vertical corrector tilt	500 µrad
rms quadrupole vertical misalignment	50 µ
rms quadrupole tilt	200 µrad
rms sextupole vertical misalignment	100 µ
bpm horizontal resolution	10 µ
bpm vertical resolution	10 µ
systematic bpm gain error (H/V)	0.01
systematic bpm coupling error	0.01

Vertical emittance after orbit and coupling correction



No errors is FF sextupoles included

Problems...

- Code worked fine until last update of files, then... broke !
- Unable to recover since... (not clear if is Merlin or Visual C++ linker problem)
- Recovery in progress (working with Walker, Wolsky)
- Alternative: create same procedure using MAD8 (time consuming, but maybe useful for comparisons)

Backup slides

Specified vertical emittance in SuperB, ATF, ILC-DR, with sensitivity indicators (cont)

- The sensitivity indicators given in Table should be interpreted as follows:
  - orbit amplification factor = mean rms vertical orbit distortion divided by the rms vertical quadrupole misalignment;
  - quadrupole jitter sensitivity = mean rms quadrupole misalignment required to generate an rms closed orbit distortion equal to the vertical beam size at the specified vertical emittance;
  - sextupole alignment sensitivity = mean rms sextupole vertical misalignment required, in an otherwise perfect lattice, to generate the specified vertical emittance;
  - quadrupole tilt sensitivity = mean rms quadrupole tilt error required, in an otherwise perfect lattice, to generate the specified vertical emittance.

Bibliography

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