Simulations of Orbit Response Matrix Analysis at KEK-ATF

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Orbit Response Matrix Analysis

ORM Analysis is a well-established technique for tuning the linear optics, including coupling, in a storage ring.

We have applied the technique at intervals at ATF, in an attempt to reduce the vertical emittance to below 5 pm.

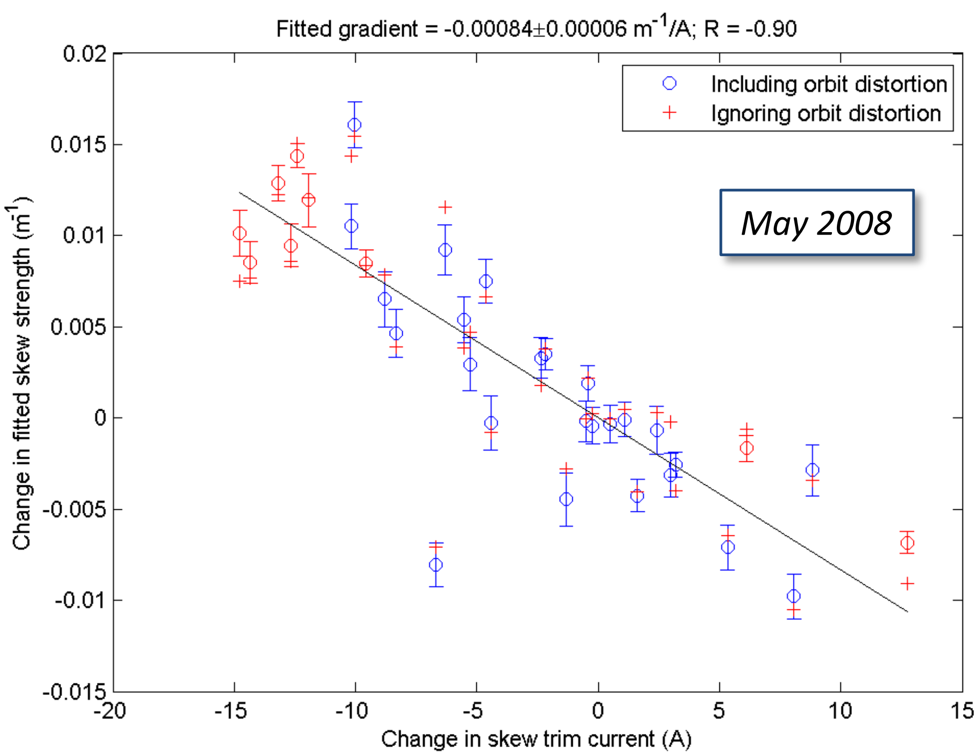
- Measure the closed orbit change at 96 horizontal and 96 vertical bpms, in response to changes in strength in each of 50 horizontal and 51 vertical orbit corrector magnets.
- Measure the horizontal and vertical dispersion.
- Fit a range of lattice parameters (100 quadrupole strengths, kick amplitudes, bpm gains and couplings, 34 skew quadrupole strengths) in a model to reproduce the measured orbit response matrix and the measured dispersion. Note: closed orbit distortion (with the correctors at their "regular" settings) is not included in the model.
- Use the fitted skew quadrupole strengths to determine the correction needed to minimize the vertical emittance in the real machine.

We can achieve a good correlation between known changes in skew quadrupole strengths, and the change determined from fits to two sets of ORM data…

…but we have had limited success in minimizing the vertical emittance. *Why?*

ORM "calibration"

1. Take an ORM data set, and fit the skew quad strengths.
2. Change the skew quad currents in the real machine.
3. Take a second ORM data set, and fit the skew quad strengths.
4. Plot the changes in fitted skew strengths vs the changes in skew currents.



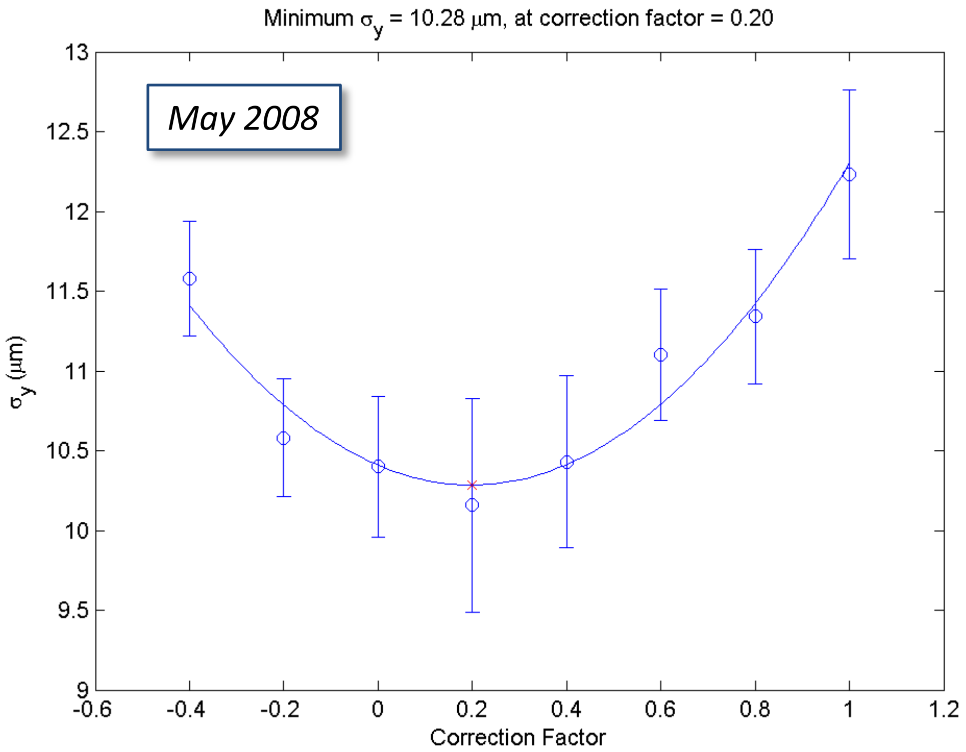
A good correlation indicates that the skew quadrupole strengths we obtain from a given fit have some physical meaning.

Typical results of coupling "correction"

We applied a correction determined from ORM analysis in steps, and observed the vertical beam size on the x-ray SR monitor.

The reduction in vertical beam size was smaller than we had hoped for: and the minimum did not occur at the nominal optimum correction.

A vertical beam size of 10 μm corresponds to an emittance of around 20 pm.



Why is ORM analysis not effective for reducing ε_y?

There are many possible explanations, for example:

- The vertical emittance may be dominated by vertical dispersion generated by vertical orbit distortion.
  - There is some evidence this may be the case: we have had a little more success on previous occasions, when ORM was applied following beam-based alignment.
  - However, to generate 20 pm emittance in ATF, the vertical rms dispersion would need to be around 1 cm: a few mm is more typical.
- The quality of the fit is not sufficiently good to enable a precise determination of the coupling correction required.
  - Fits to the ORM typically have χ^2/N of around 3.5 (in units of bpm resolution).
  - The scatter in the correlation plot (see previous slide) is not sufficiently large to explain the "limit" of 20 pm – though it certainly makes some contribution.
- There may be some degeneracy in the ORM fit between the skew quadrupole strengths, and "fake" coupling errors, e.g. bpm couplings, that do not really generate vertical emittance.

Investigating degeneracies

If we attempt to correct a "fake" coupling, then we risk *adding* to the coupling in the machine, instead of correcting the coupling.

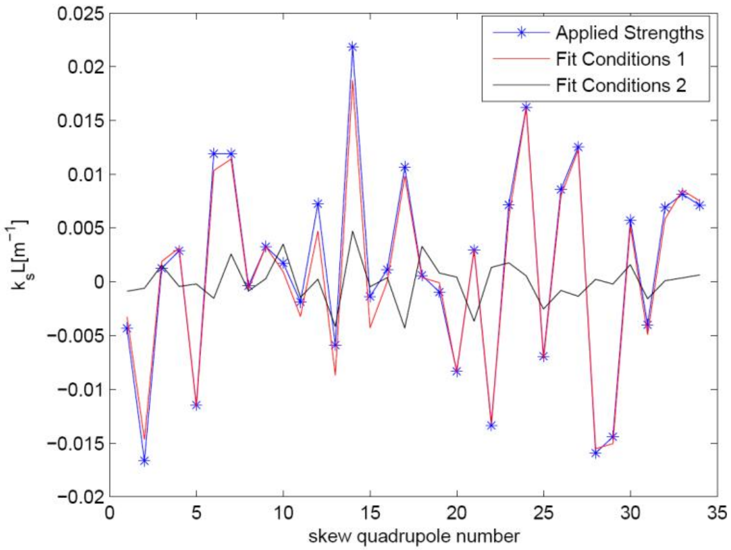
We can investigate degeneracies in simulation:

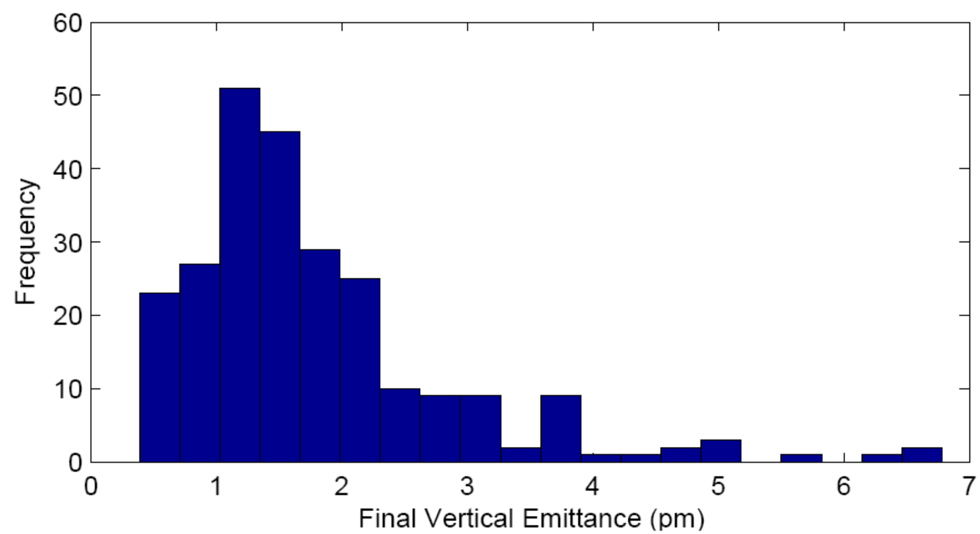
- Apply a set of errors (e.g. bpm couplings) to an otherwise perfect machine.
- Generate a set of ORM data.
- Fit the ORM data using the skew quadrupole strengths as variables.
- Apply the skew quadrupole strengths determined from the fit to the model, and calculate the vertical emittance.
- If the skew quadrupole strengths determined in this way generate significant vertical emittance, then degeneracy between the applied errors and skew quadrupole strengths may be a potential limitation in coupling correction using ORM analysis.

Investigating degeneracies

First, we optimize the fitting routine so that we can determine the skew quadrupole strengths in simulation with good precision (where skew quadrupoles are the only errors present).

The residuals to the fit are sufficient to generate typically less than 2 pm vertical emittance.

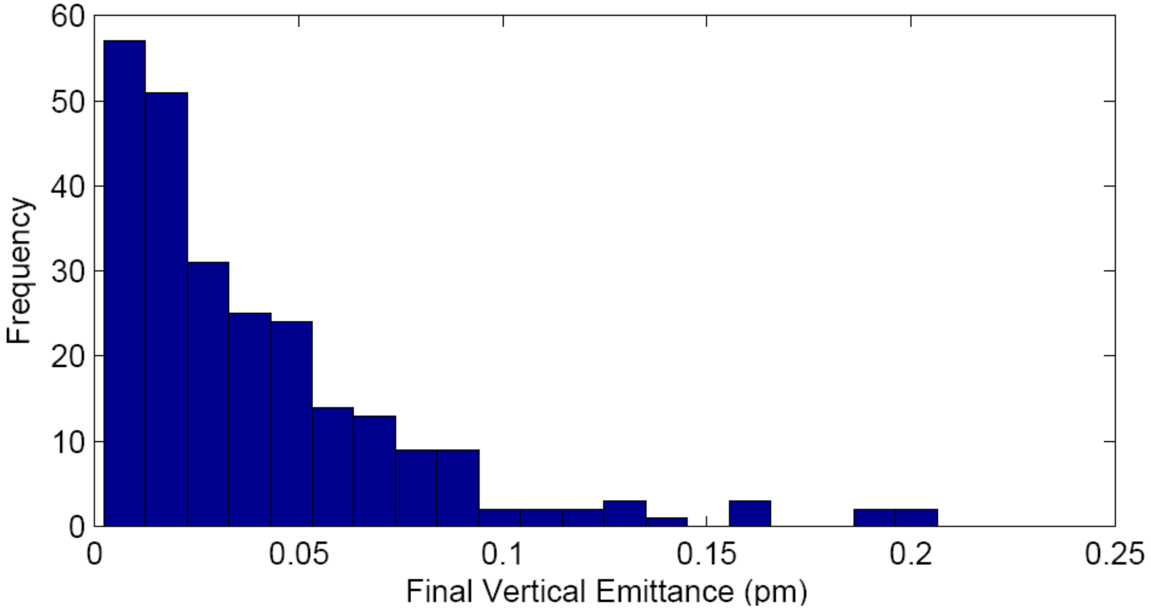




Investigating degeneracies: corrector tilts

Next, we apply tilts to the correctors, and try to fit the simulated ORM using skew quadrupole strengths.

The fitted strengths generate negligible vertical emittance.



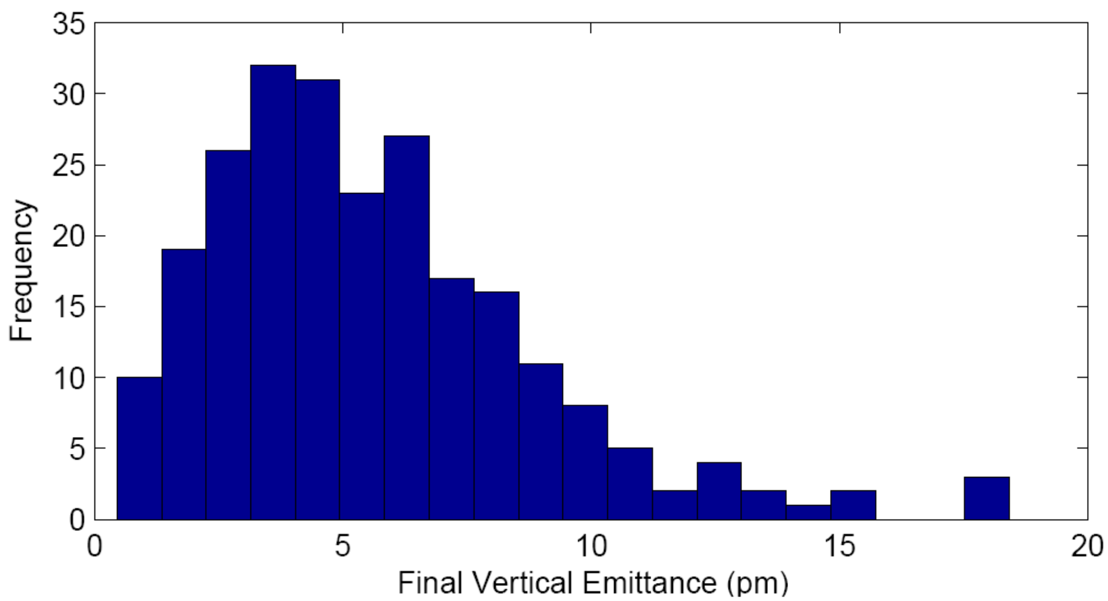
Investigating degeneracies: bpm couplings

Finally, we apply coupling to the bpms, and try to fit the simulated ORM using skew quadrupole strengths.

BPM couplings are applied as deviations (with a realistic rms 0.020) from the identity for each element of the "gain" matrix relating actual to measured beam position:

$$\begin{pmatrix} x_m \\ y_m \end{pmatrix} = \begin{pmatrix} g_{xx} & g_{xy} \\ g_{yx} & g_{yy} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

The fitted strengths generate significant vertical emittance.



Comments and Conclusions

Degeneracies in the ORM fit are somewhat surprising since the fit is (in principle) highly over-constrained…

…but having more constraints than variables does not completely rule out degeneracies.

- For example, in the ATF there are two skew quadrupoles per arc cell (one at each sextupole): these are known to be degenerate for the coupling.

The best we can hope for using ORM analysis in an ATF lattice with *only* skew quadrupole errors, is a vertical emittance of around 2 pm.

If bpm couplings are present, the degeneracy with the skew quadrupole strengths may limit the vertical emittance that could be achieved using ORM analysis to around 5 – 10 pm.

The results are indicative, but further simulations and analysis are needed to arrive at a complete understanding.

Is it possible to design the coupling correction system to avoid degeneracies in the ORM fitting, and thus avoid limitations in the application of ORM analysis?