Australian Synchrotron
Turning bright ideas into brilliant outcomes

Beam based techniques as tools for magnet alignment

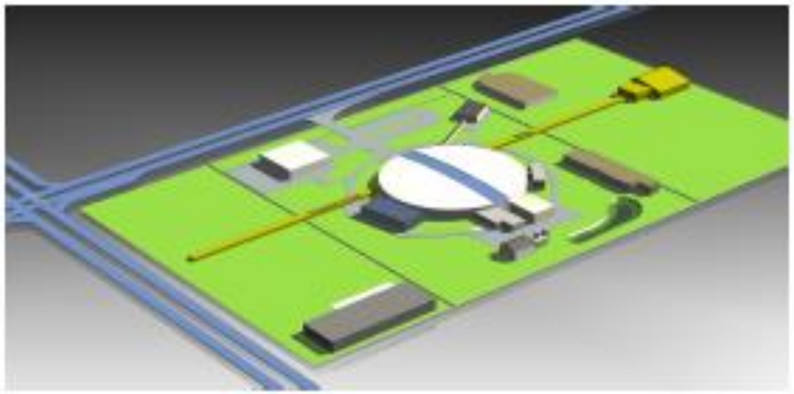
Rohan Dowd
Senior Accelerator Physicist, Australian Synchrotron

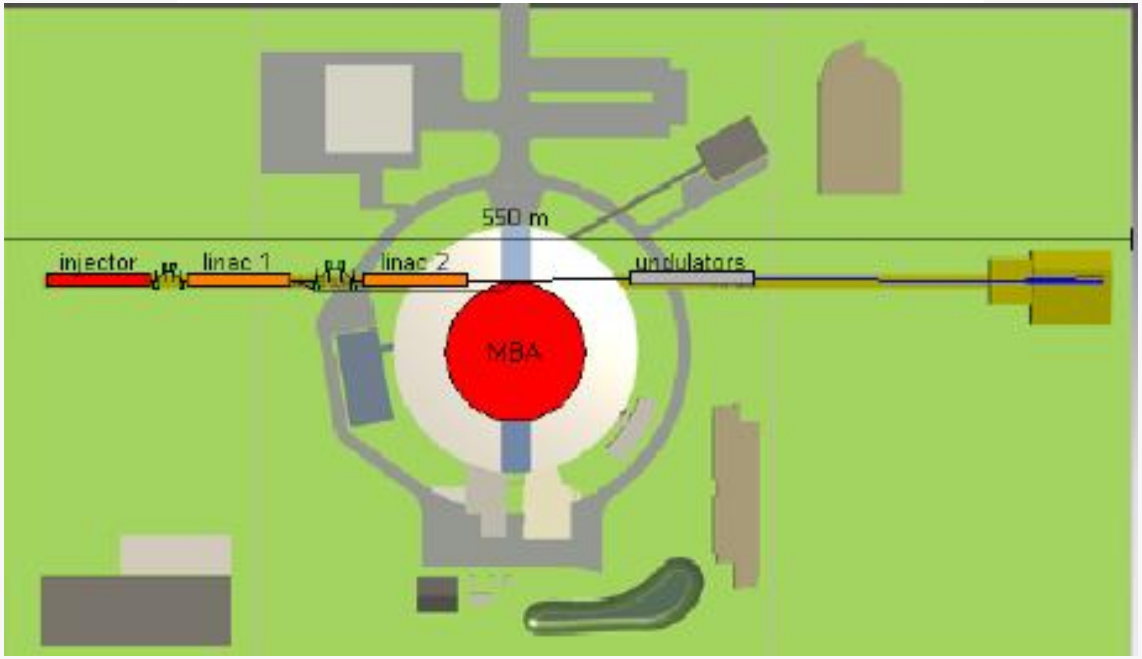
Overview

- Introduction to AXXS
- Low Emittance rings - mechanical alignment considerations
- Beam based alignment techniques
- Conclusions

AXXS (Australian X-band X-ray Source)

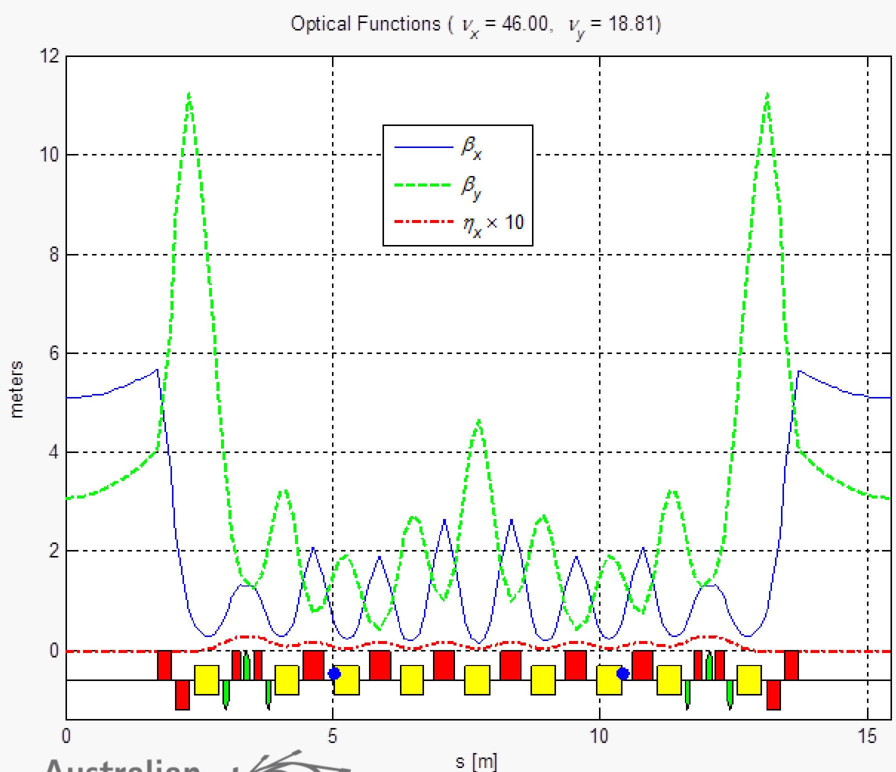
- Upgrade proposal for ~2025
- 3 GeV X-band injector for storage ring
- Low emittance (0.2 nm ε_H) MBA storage ring
- Second Linac for 6 GeV FEL facility.
- Injector based on CLIC X-band structures, in collaboration with XbFEL project.

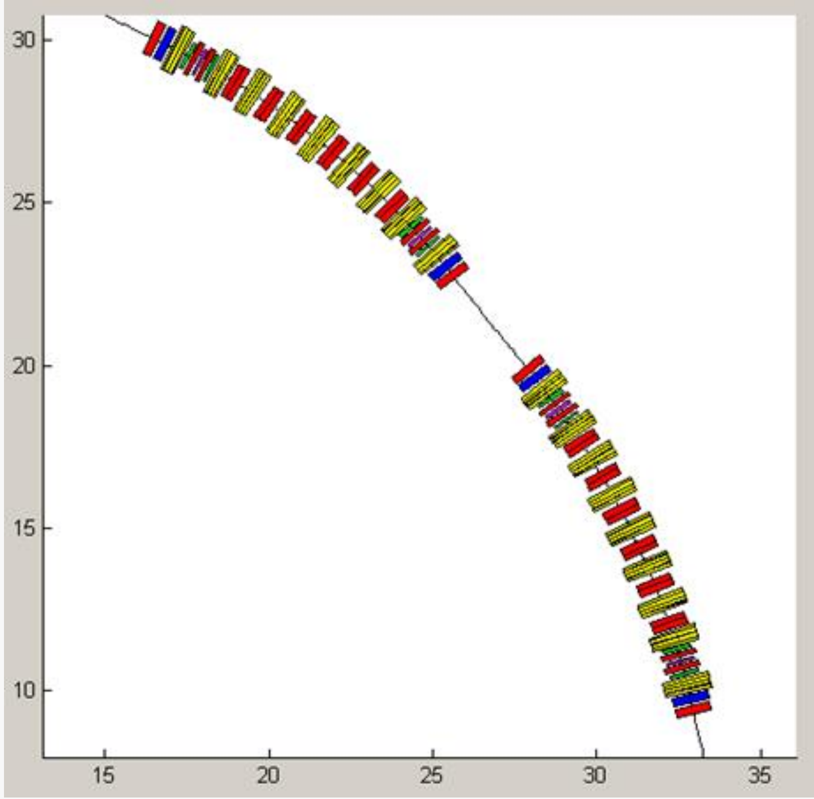




AXXS – MBA lattice

- 9 Bend Achromat, 3.0 GeV
- Horizontal emittance 0.2 nm
- Same source points as existing AS storage ring, 14 cells.
- 3.4m straights





Low Emittance Rings – Alignment Requirements

- Ultra low emittance storage rings have very tight magnet tolerances.

- These tolerances arise from:
  - The need to create as large as possible lattice dynamic aperture to allow for successful injection and capture of the beams.
  - At such low emittance, small magnet errors will have relatively large effects on the beam emittance (via orbit distortions)..

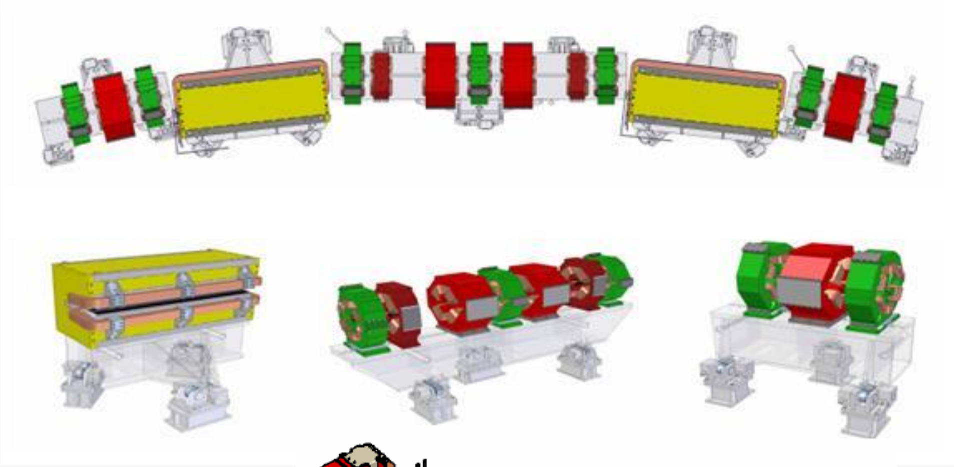
- Example: Tolerances for NSLS II:
  - 30 micron offset, magnet to magnet.
  - 0.2 mrad roll angle

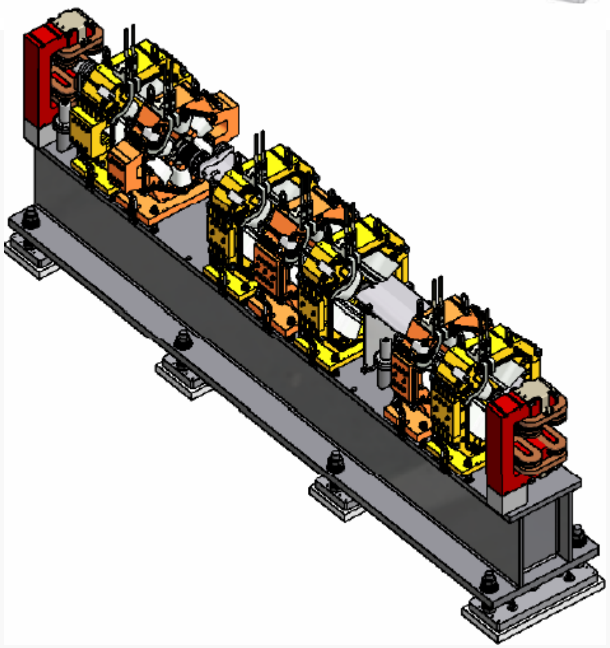
Alignment Methods - Examples

- AS uses laser tracker and magnet fiducials. Magnet to magnet resolution ~ 25-50 micron (but magnetic centre somewhat uncertain).

- NSLS II employs a vibrating wire measurement. Resolution of finding magnetic centre is 5-10 micron. Locked onto girder then installed. Overall magnet to magnet positioning claimed < 30 micron (15-20?),

- What about Beam based Alignment?





Motivation for Beam Based Magnet Alignment at AS

- Research was being conducted into minimising the x-y coupling of beam motion in our storage ring, to achieve the quantum limit of vertical emittance.

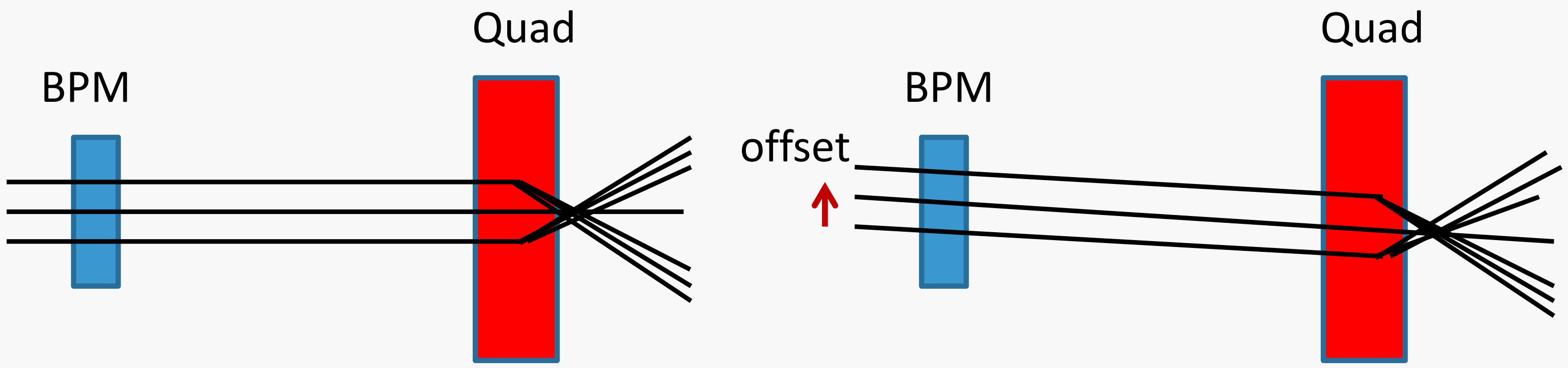
- Coupling terms in multipole magnets rise from quadrupole rolls and sextupole vertical offsets.

- Ring re-alignment based with laser tracker often made coupling worse
  - Alignment survey positioning doesn't tell you what is happening at the magnetic centre.
  - The beam is very similar to a vibrating wire

- Beam orbit response matrix analysis should allow you to find the sextupole offsets. (Eg. V. Sajaev, A Xiao, IPAC10) It can also be extended to other alignment errors .

Beam Based Alignment – Standard Use

- Commonly used to calibrate BPMs to quad centres.
- Shunting the quadrupole strength will deflect any beam that doesn't pass through the centre of the magnet.
- Systematic offsets can occur if the closed orbit passes through the quad centre at an angle.
- Therefore closed orbit should be well corrected to start with and the BPM should be close to the quad.
- Typical accuracy ~ 10 um



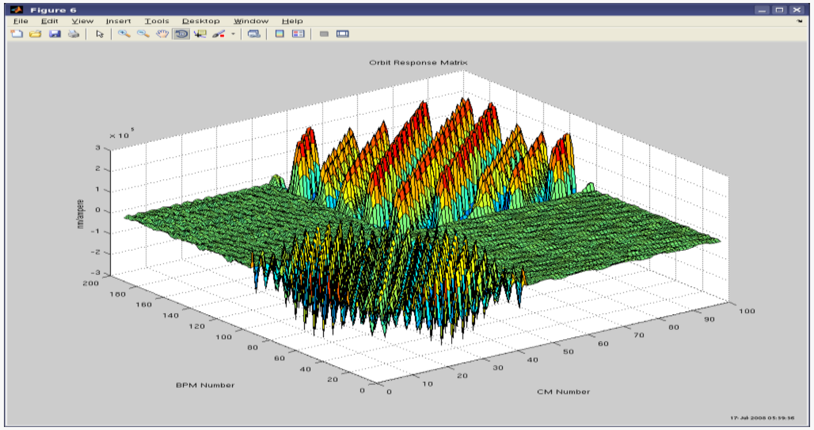
Ideal case: no angle, undisturbed beam will give the centre of the BPM

Some angle: undisturbed beam will be offset in the BPM, leading to a systematic error

LOCO method – a quick overview

- LOCO – Linear Optics from Closed Orbits.

- Adjusts the linear optics in the model to fit the real machine data
- Model response matrix – Machine response matrix = Error. Minimise error by adjusting the model 'fit parameters'



- Fit Parameters normally include:
  - **BPM/Corrector gains and coupling**
  - **Corrector gains and coupling**
  - **Quadrupole strengths**
  - **Skew Quadrupole strengths**

  And these parameters can be placed in any point in the model magnet

- LOCO is a highly over-constrained fit, more accurate that individual measurements.

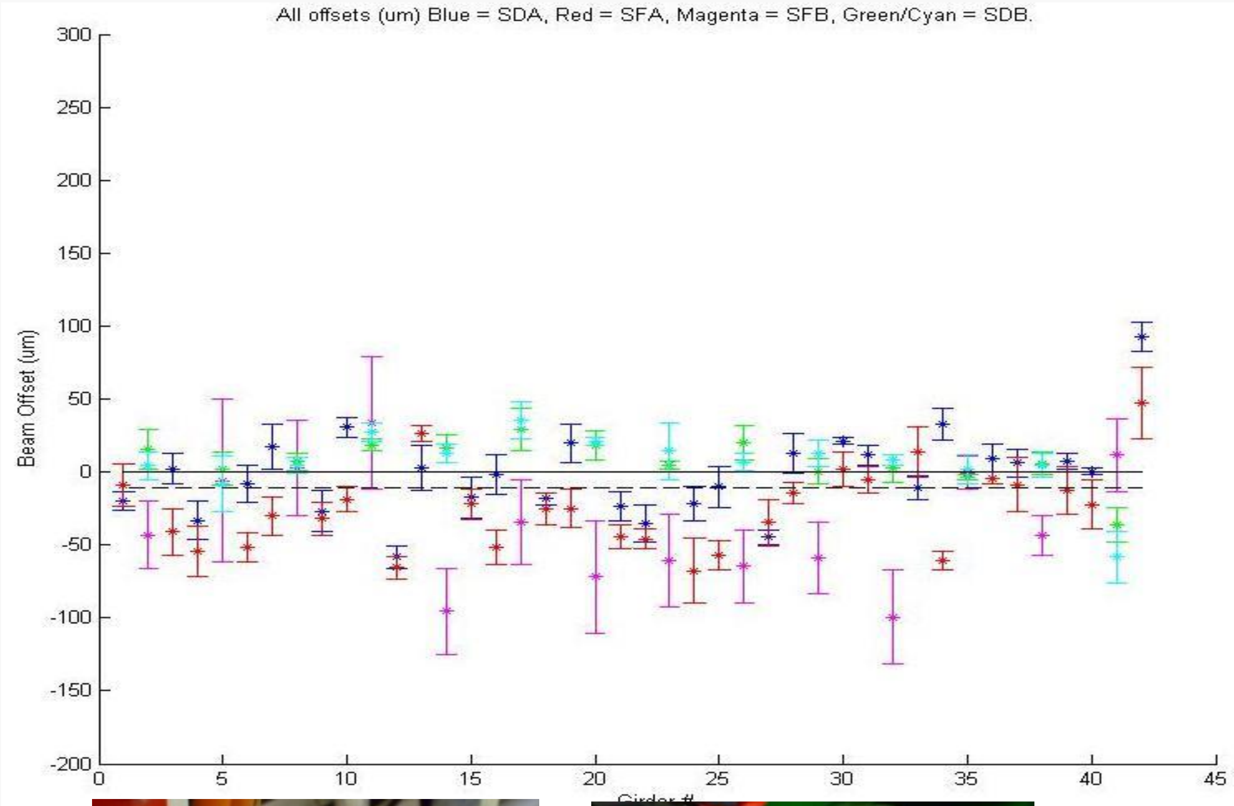
Sextupole Vertical offsets

- Shunt each sextupole magnet family to different strengths and take a response matrix at each point

- Perform LOCO analysis and fit skew quadrupole terms to each sextupole.

- Gradient of skew field vs sextupole field gives vertical offset.

$$K_2.(y - y_0) \quad = \quad -K_{skew}$$



Initial Accuracy Assessment

Applied BPM Offset	Measure Mean Beam Offset	Difference from zero
+125	234.6 ± 10.6	128.7 ± 18.8
+75	167.7 ± 16.5	61.8 ± 22.6
0	105.9 ± 15.5	0
-75	33.1 ± 17.8	-72.8 ± 23.6
-125	-16.1 ± 21.6	-122 ± 26.6

Magnet	Original Offset (µm)	Applied Shim (µm)	New Offset (µm)	Delta offset (µm)
Sector 9 SFB	-108.4 ± 44.6	150	-249.3 ± 7.2	140.9 ± 45.2
Sector 11 SFB	-56.7 ± 10.0	100	-120.4 ± 56.0	-63.4 ± 57.4
Sector 9 SDA	-14.6 ± 9.9	100	-118.3 ± 8.3	-103.7 ± 14.1

Cross checks show that amplitude of offset is correct and individual magnets can be adjusted accurately.

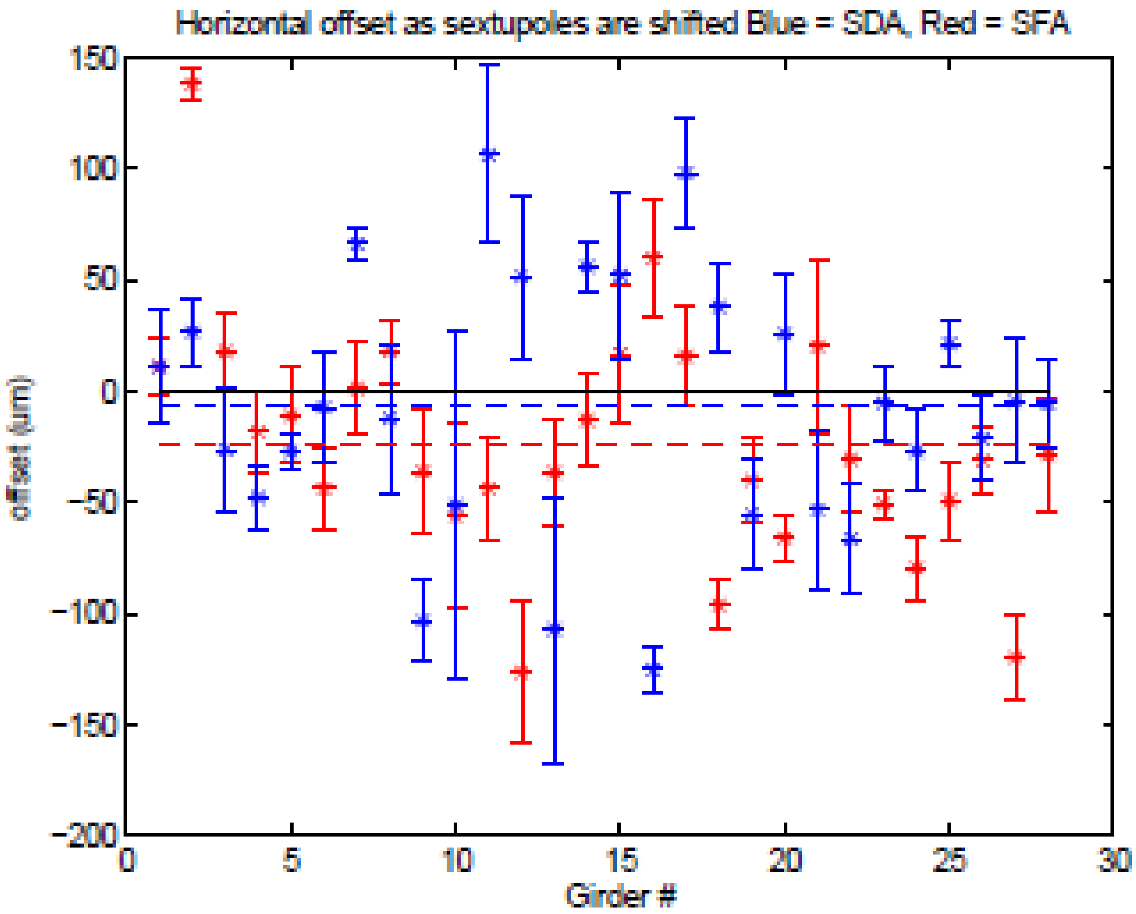
Sextupole Horizontal Offsets

- Similar analysis to vertical offsets, but a horizontal offset will create a normal quadrupole field.

- Look for changes to the beam focussing as sextupole is shunted

- Preliminary work, but evidence of significant Horizontal offsets in some magnets.

- No way to correct this in-situ.



Australian Synchrotron
Turning bright ideas into brilliant outcomes

Supported by Australian Government State Government Victoria

Quadrupole rolls

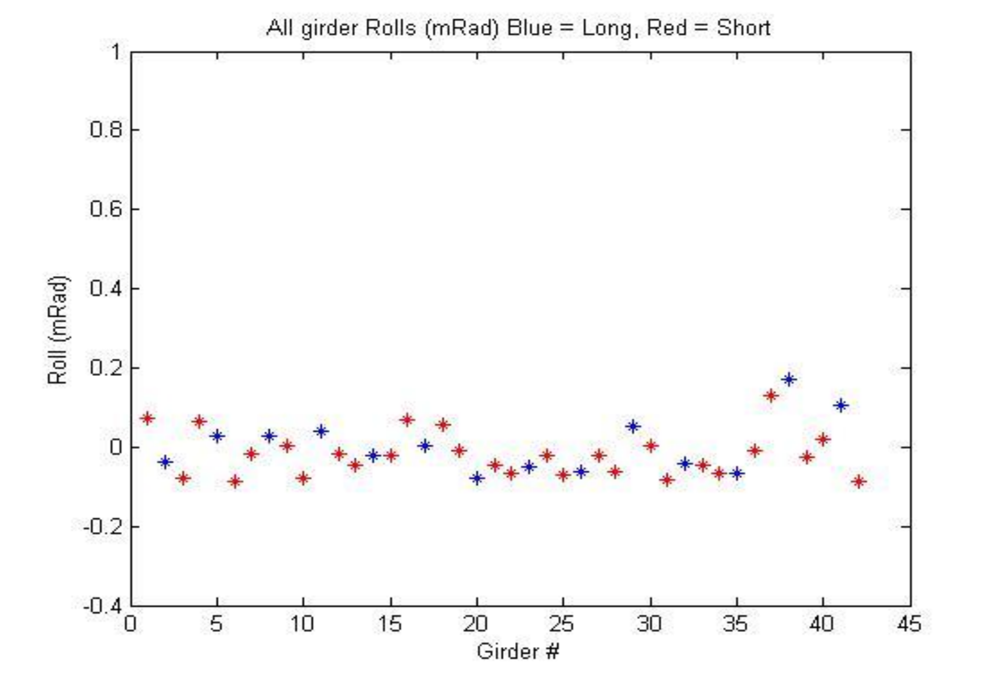
•Turn off Sextupoles and perform LOCO analyis of quadrupoles.

• Unable to roll individual magnets, so whole girder is rolled.

•Roll Girders by the amount indicated in the LOCO analysis and re-measure.

•Method was found to be accurate to ±0.05 mRad. Mechanical precision of setting the girders ±0.1 mRad. Rolls now reduced to < 0.2 mRad.

•May be compensating for other magnet misalignments



Girder roll (mRad) progression over several alignment iterations

Beam based alignment summary

- Sextupole horizontal and vertical offsets can be measured with the beam to a accuracy of 10-50 microns depending on the magnet position. The larger inaccuracies can be reduced with more development of the technique.
- Quadrupole rolls can be measured to 0.05 mrad and corrected down to 0.1 mrad (or less, if girder supports allow).
- Data collection currently takes ~ 1 shift for whole ring measurement. Will take longer for higher accuracy.
- Can measure along with curved paths.
- Using beam based alignment allows you to deliberately misalign to compensate for field errors in other magnets – eg dipoles.

Conclusions

- New low emittance rings have tight alignment tolerances that require a great deal of time and effort to achieve and maintain between bench-top girder assembly and transport and installation in the ring.

- Beam based alignment techniques can potentially achieve **in-situ** measurements of the magnetic centre of magnets to precision comparable to the best bench-top techniques

- You still need good initial alignment to capture and store beam in a new machine. Beam based techniques should be treated as another tool available for alignment.

- Design of magnet supports should give consideration to beam based alignment as a second stage of alignment. The ability to make small adjustments to magnet position after installation should be enabled.

- Thanks to the Australian Synchrotron Mechanical Engineering team for support in these investigation, particularly Jonathan Mckinlay for letting me mess about with his magnet alignments