Ultra-low Emittance Coupling, method and results from the Australian Synchrotron Light Source

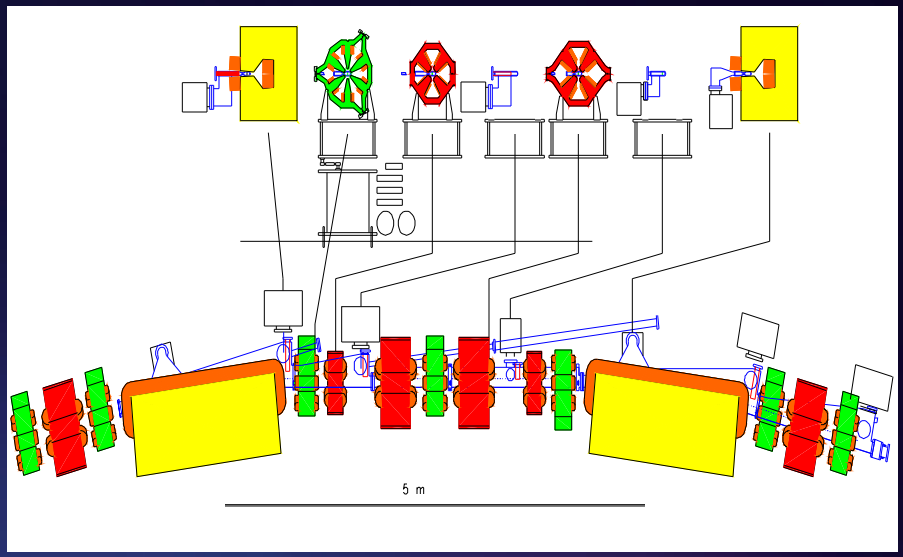
Rohan Dowd
Accelerator Physicist
Australian Synchrotron

Overview

- Lattice and diagnostics overview
- Alignment and orbit correction
- Linear Optics from Closed Orbits (LOCO)
- Vertical Emittance Minimisation
- Measurements
- Conclusions

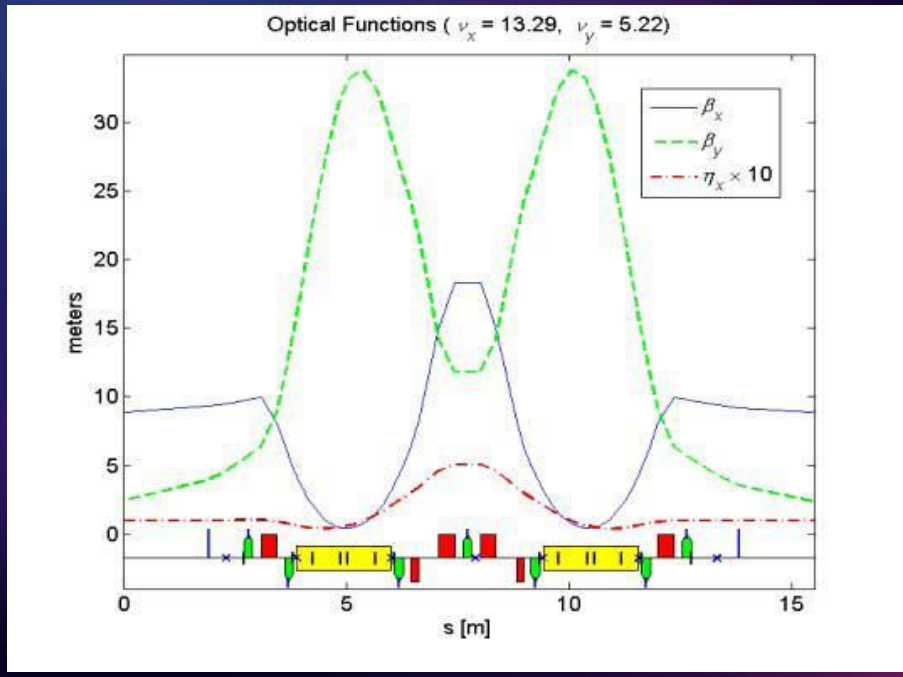
Lattice overview

- Double bend achromat
- 14 Unit cells
- Combined function dipoles
- Corrector and skew quad coils on sextupoles.
- Horizontal emittance varied with dispersion.



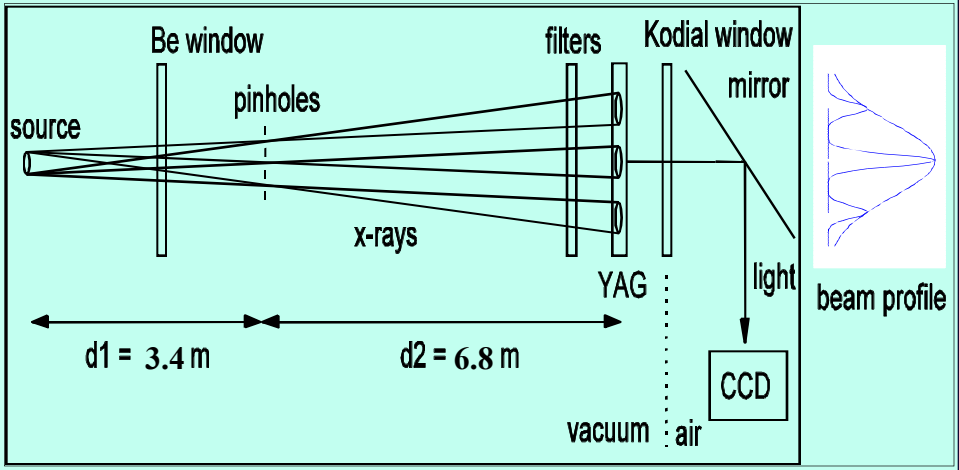
Storage Ring Parameters

Energy	3 GeV
Circumference	216 m
RF Frequency	499.654 MHz
Peak RF Voltage	3.0 MV
Current	200 mA
Betatron Tune (h/v)	13.3/5.2
Momentum Compaction	0.002
ε_x (nominal)	10.4 nm·rad

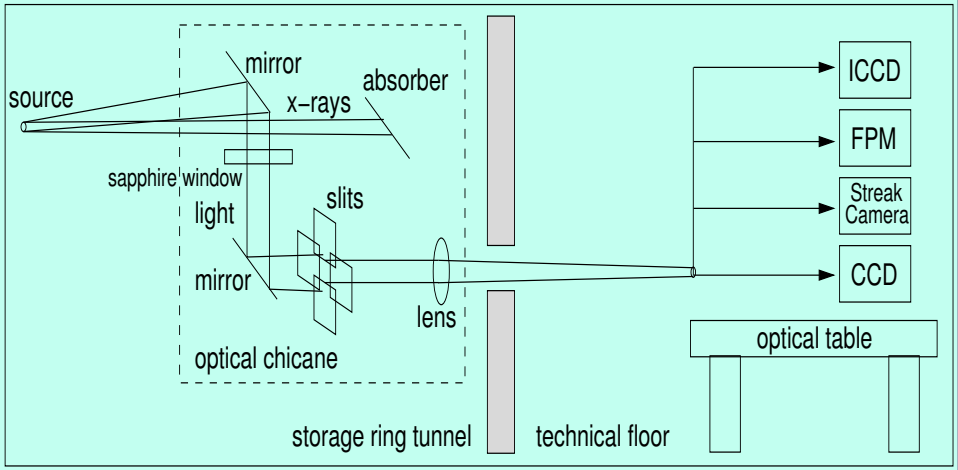


Beam Diagnostics

- 2 diagnostic beamlines: X-ray and optical
- X-ray pinhole used for emittance measurements, but has inherent resolution limit at ~ 10 pm veritcal emittance
- Interferometer developed on Optical Beamline but small front-end vertical aperture has hindered measurements.



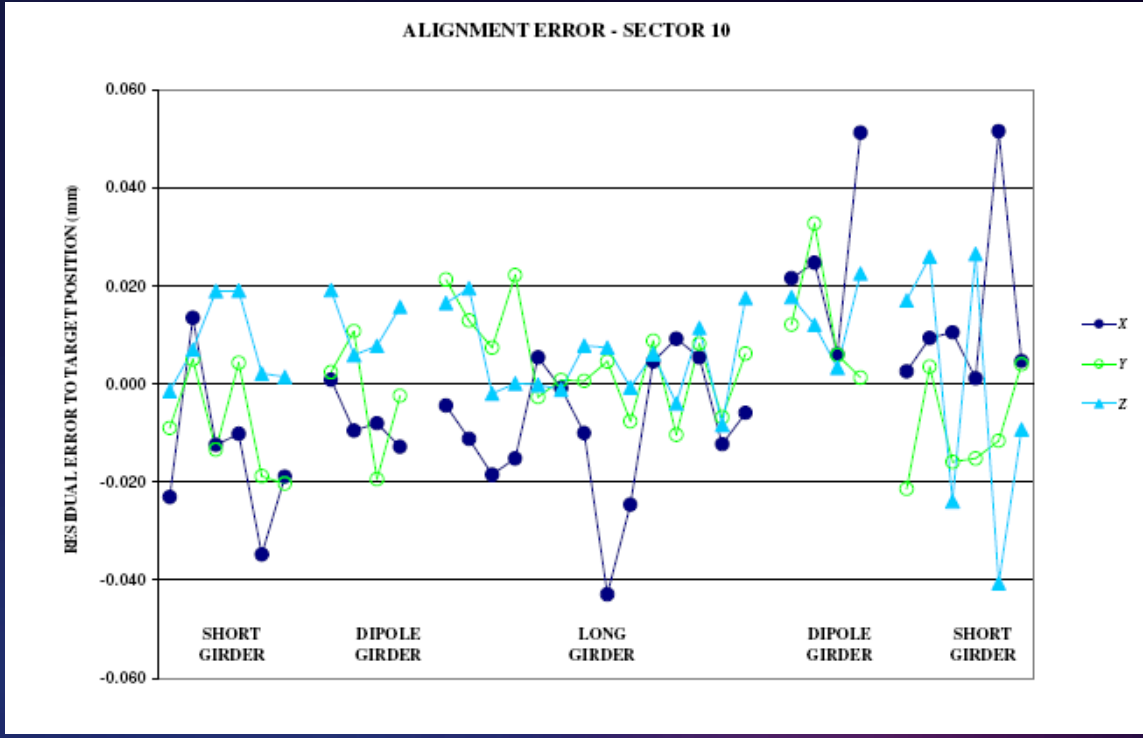
X-ray Diagnostic Beamline

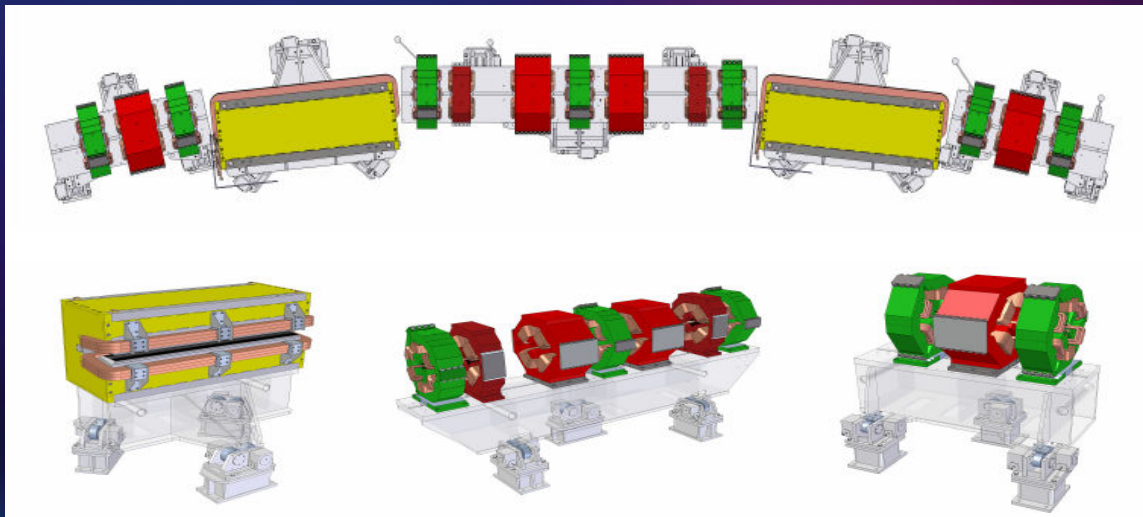


Optical Diagnostic Beamline

Alignment

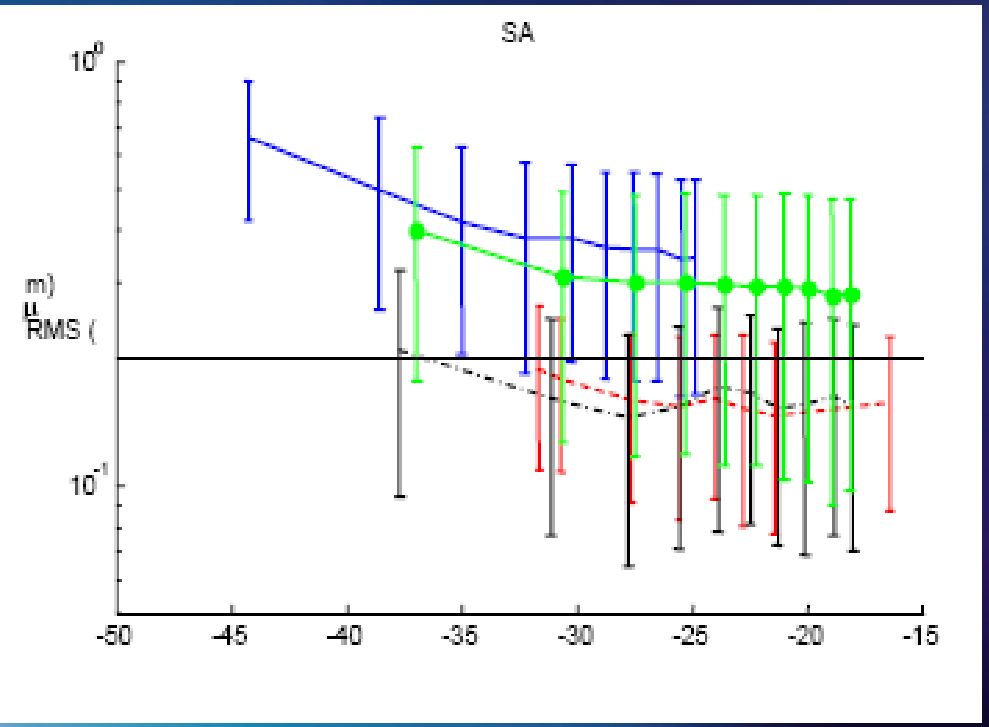
- Alignment error:
  26 μm Quadrupoles,
  18 μm Dipoles
- Intrinsic Fiducial and assembly error:
  16 μm (Quad)
  6 μm (Dipole)
- Full ring realignment conducted every year.
- Current ‘natural’ emittance coupling = 0.059%

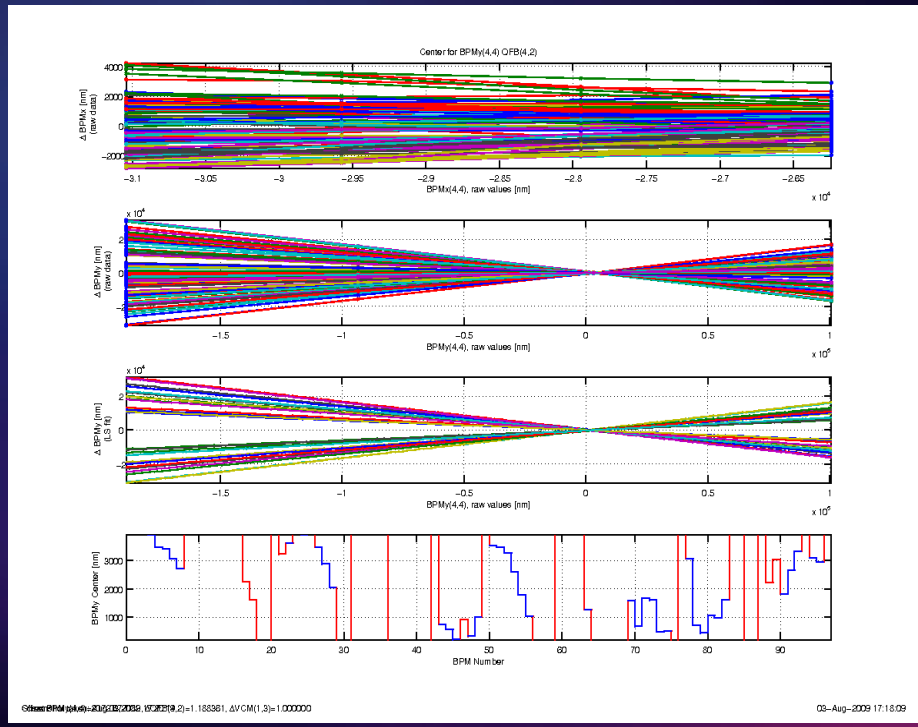




BPM resolution and Beam Based Alignment

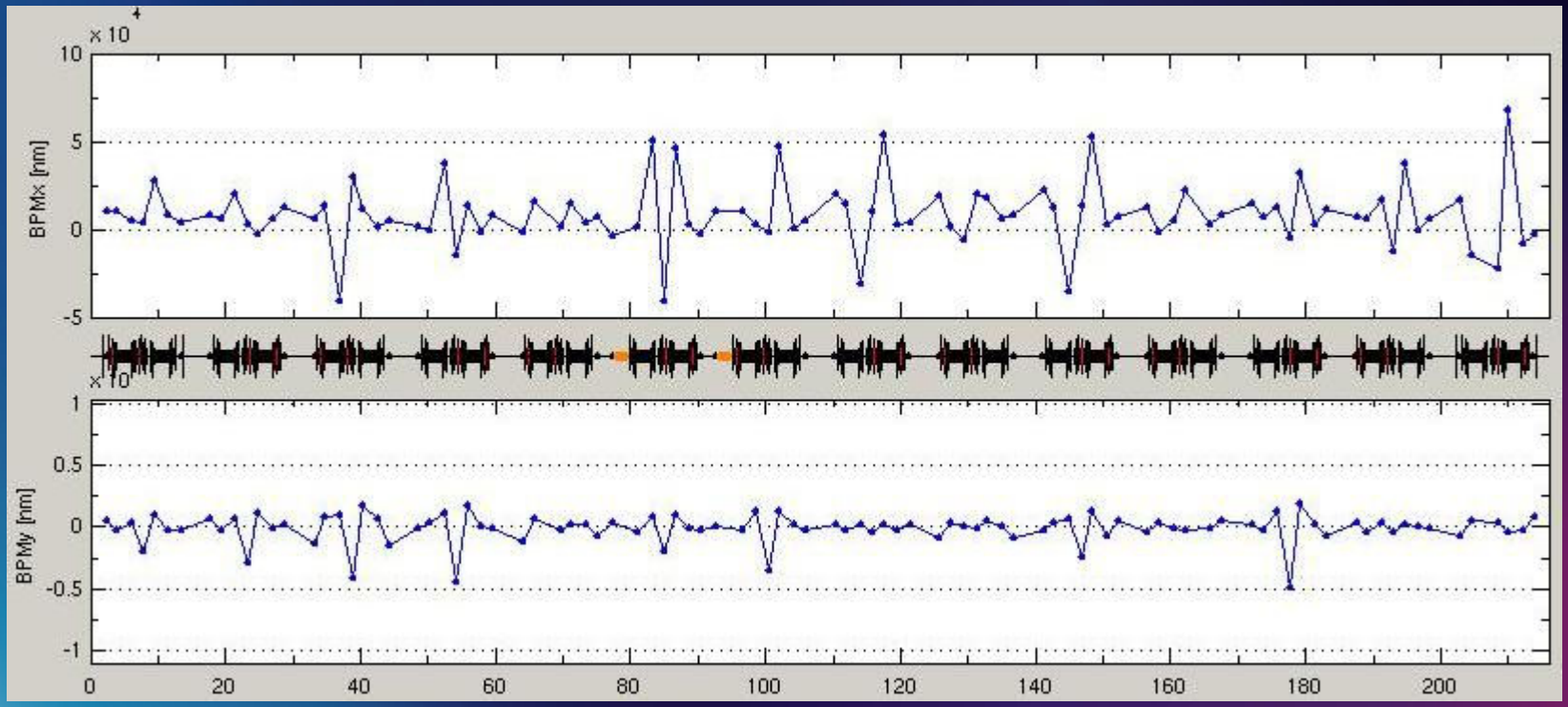
- Libera BPM electronics
- BPM resolution ~0.1 um (rms)
- Resolution of BBA is ~10 um.
- BPM mechanical alignment resolution <20 um





Orbit correction

RMS orbit deviation typically: <20 μm Horizontal, <10 Vertical



LOCO

- 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**

LOCO - Inputs

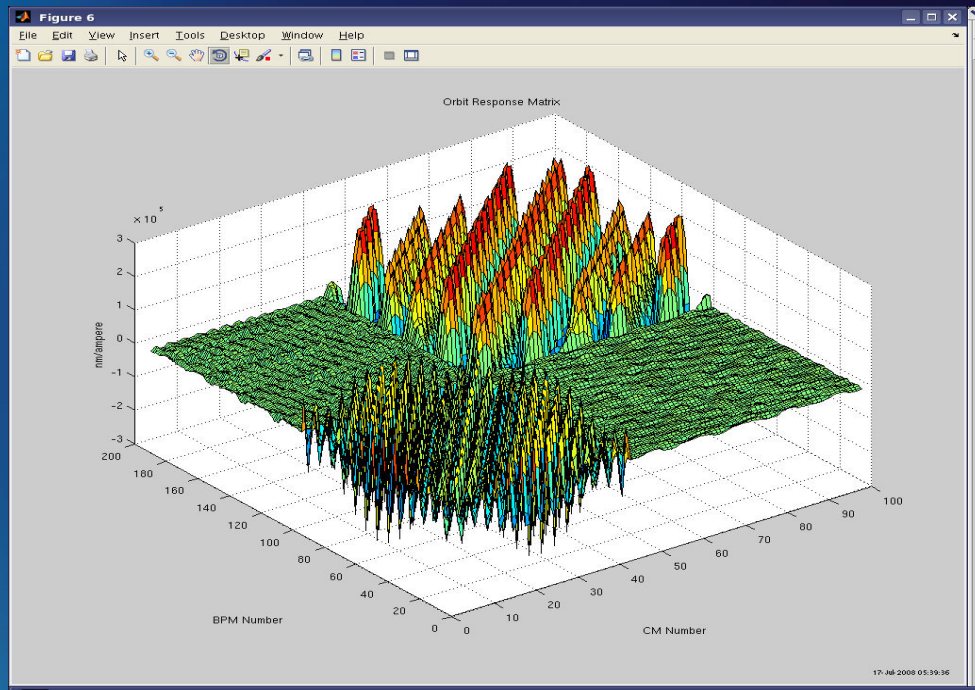


Figure 6
File Edit View Insert Tools Desktop Window Help
Orbit Response Matrix
nm/ampere
BPM Number
CM Number

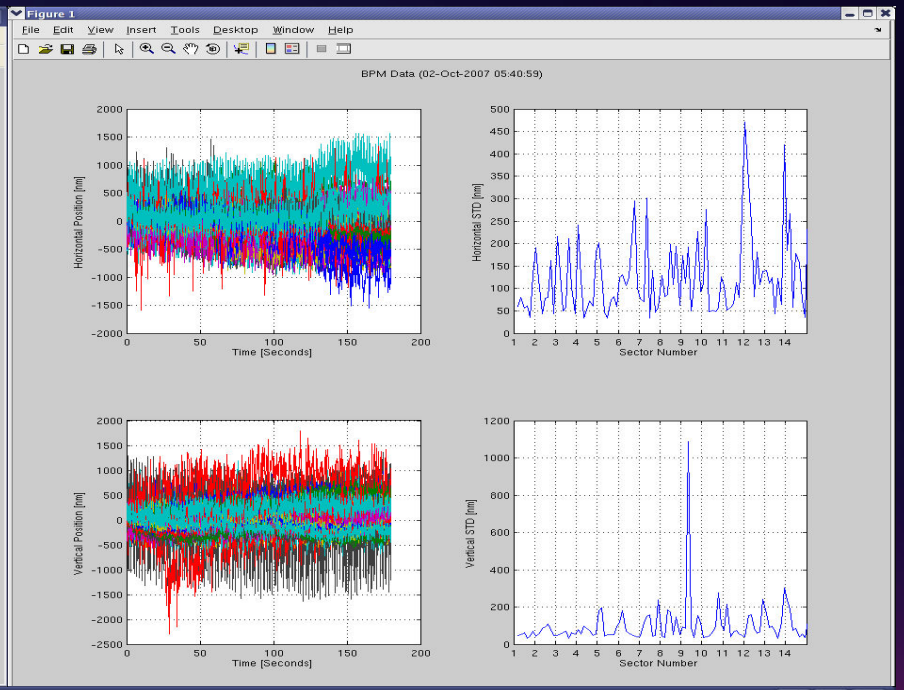


Figure 1
File Edit View Insert Tools Desktop Window Help
BPM Data (02-Oct-2007 05:40:59)
Horizontal Position [nm]
Time [Seconds]
Horizontal STD [nm]
Sector Number
Vertical Position [nm]
Time [Seconds]
Vertical STD [nm]
Sector Number

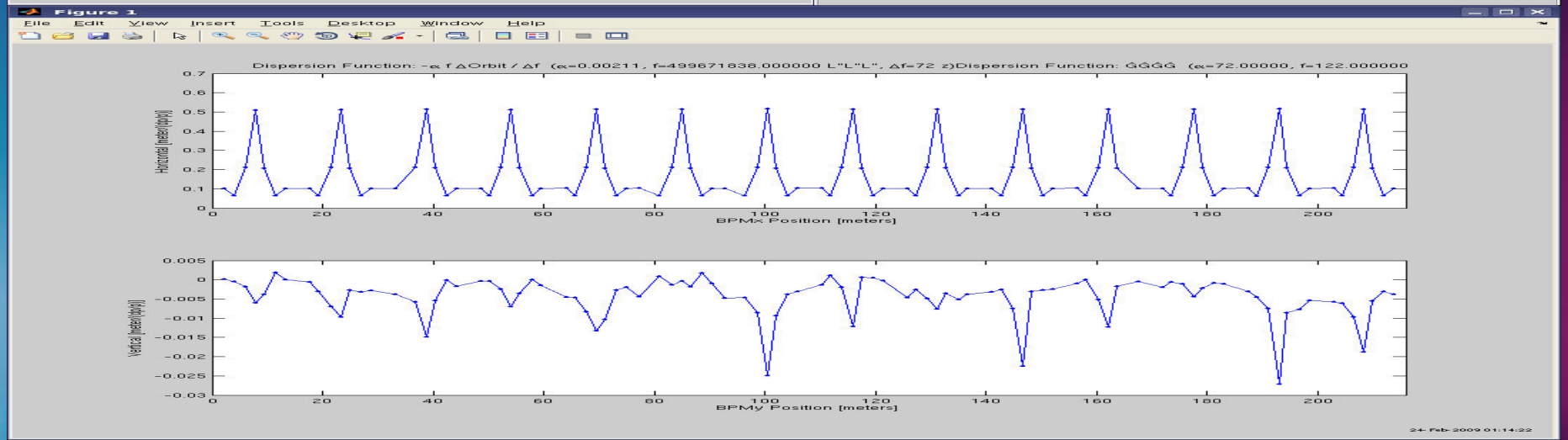
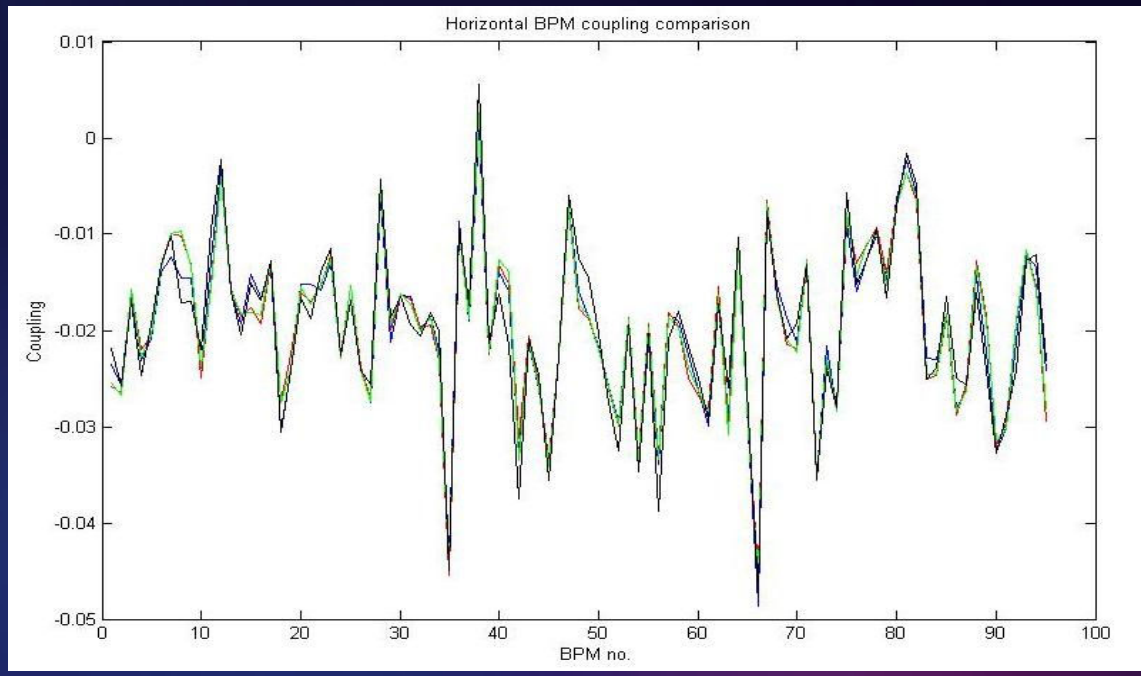
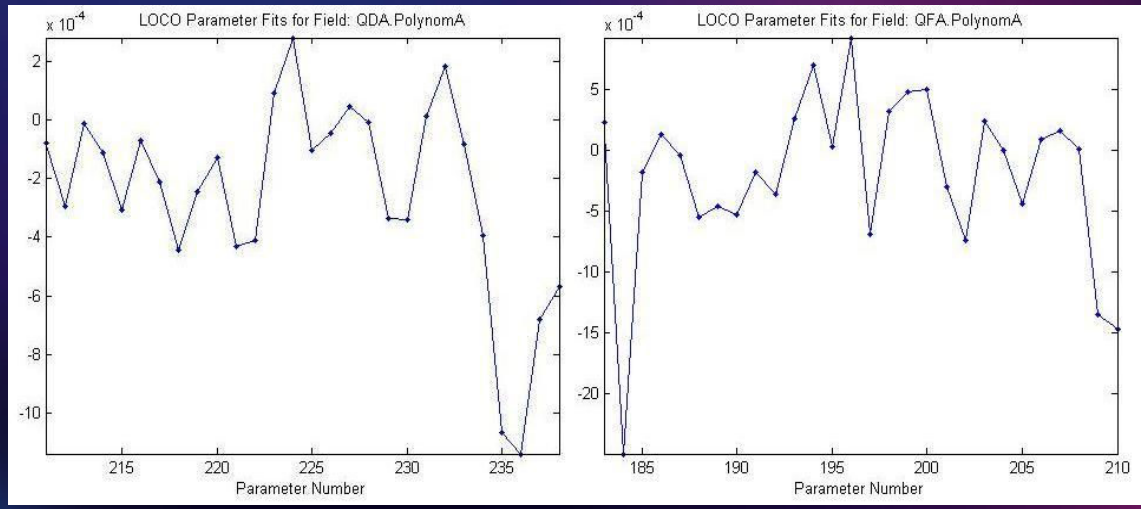


Figure 1
File Edit View Insert Tools Desktop Window Help
Dispersion Function: -α f ΔOrbit / Δf (α=0.00211, f=499671838.000000 L"L"L"; Δf=72 z)Dispersion Function: ĜĜĜĜ (α=72.00000, f=122.000000
Horizontal [meter/(rad/s)]
BPMx Position [meters]
Vertical [meter/(rad/s)]
BPMy Position [meters]

LOCO - Outputs

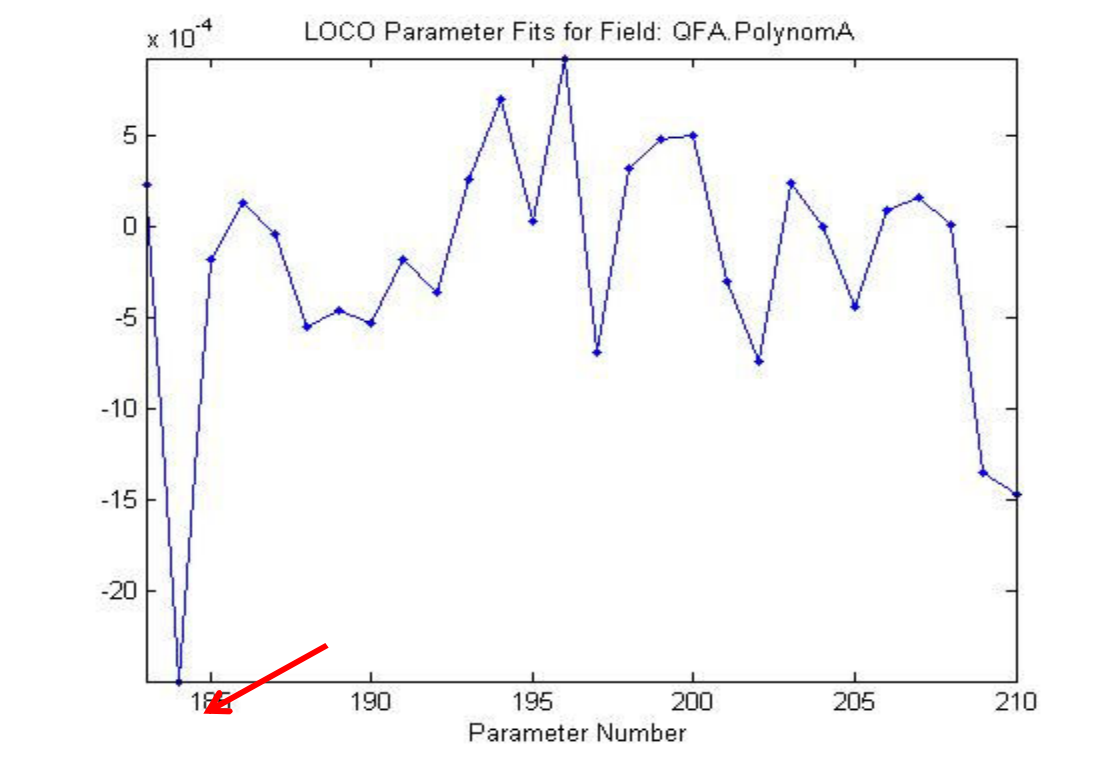
- BPM Gains
- BPM couplings
- Skew components
- Quad Strengths
- Corrector gains/tilts
- Full Calibrated model

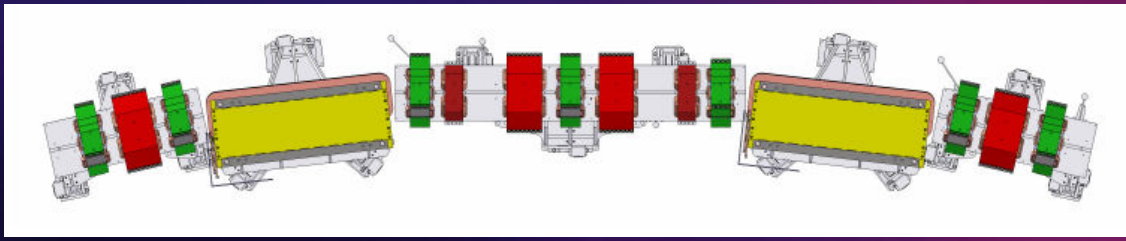




Realitiy Check – girder rolls

- Fitted skew components show a consistent spike in Sector 1, girder 3.
- Alignment metrology data does not show a significant roll
- Manual measurements using a spirit level confirm the girder does has a large roll

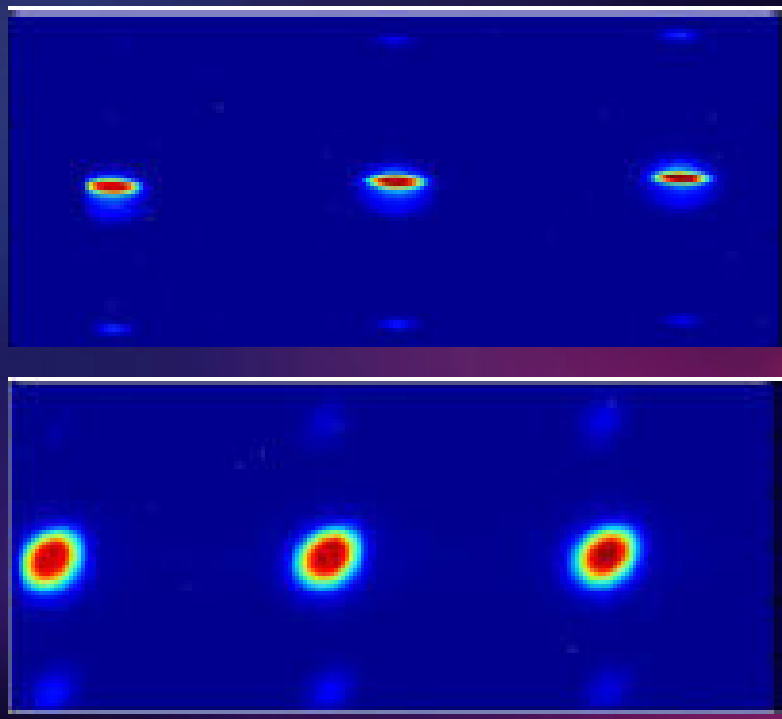




Emittance Coupling minimisation

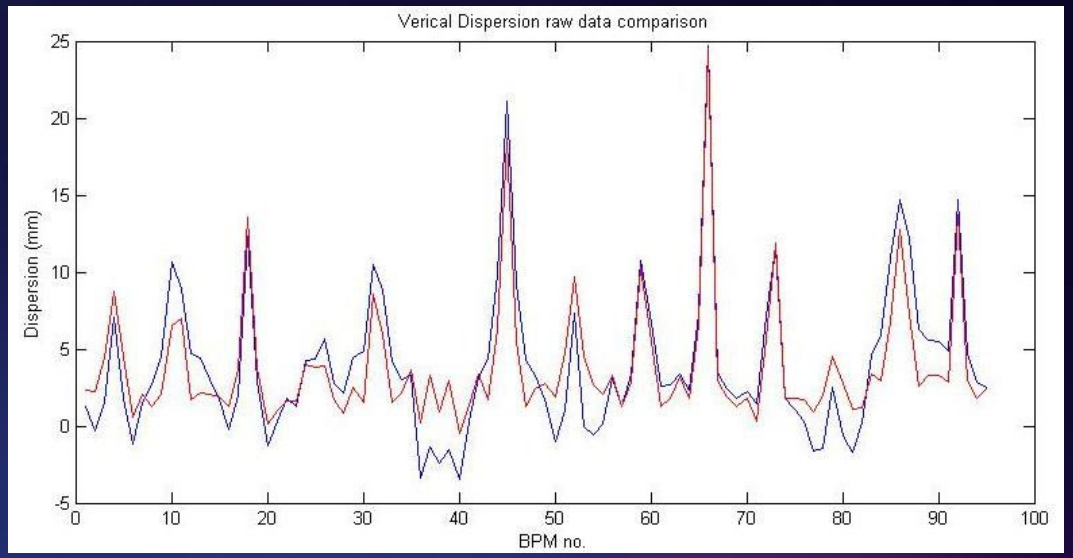
- Emittance coupling calculated from LOCO Calibrated model (using beam envelope calculation from particle tracking).
- Minimisation algorithm used to adjust skew quads to desired emittance coupling.
- Emittance coupling can be adjusted to arbitrary amounts

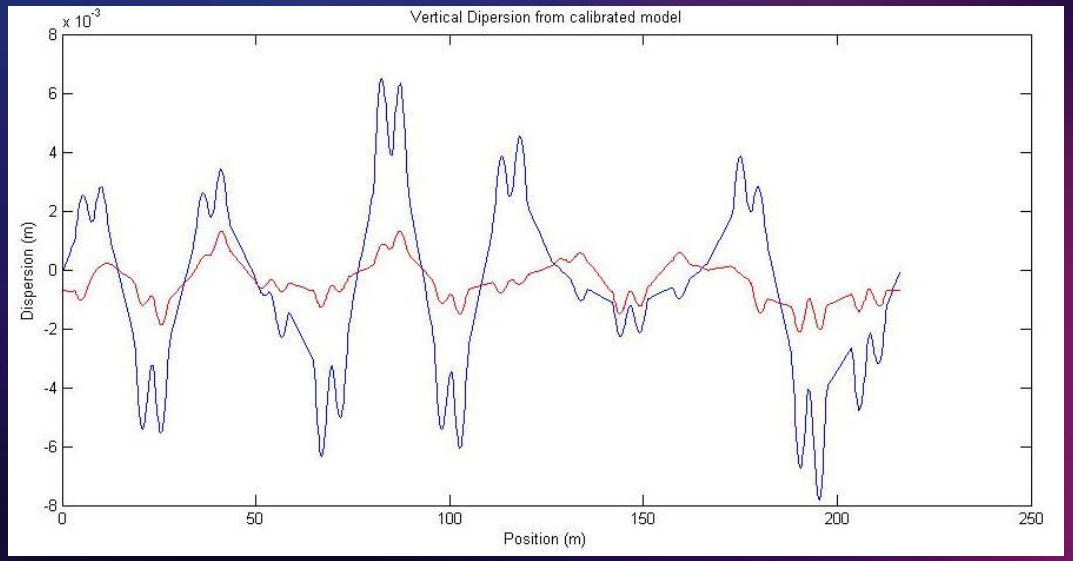
Set Coupling	LOCO Measured Coupling	Calculated ε_y (pm)
0.0%	0.009%	0.9
0.1%	0.12%	12.2
0.2%	0.23%	23.5
0.3%	0.33%	33.7
0.4%	0.43%	43.9
0.5%	0.54%	55.1
0.6%	0.64%	65.3
0.7%	0.74%	75.5
0.8%	0.84%	85.7
0.9%	0.92%	93.8
1.0%	1.04%	106.1



Reality Check – Dispersion Minimisation

- Same method used to minimise vertical dispersion only
- Clear reduction found in dispersion, but linear coupling increases.
- $\varepsilon_y/\varepsilon_x$ ~ 0.9%
- Vertical dispersion reduced from 3.4mm to 0.9mm (rms)

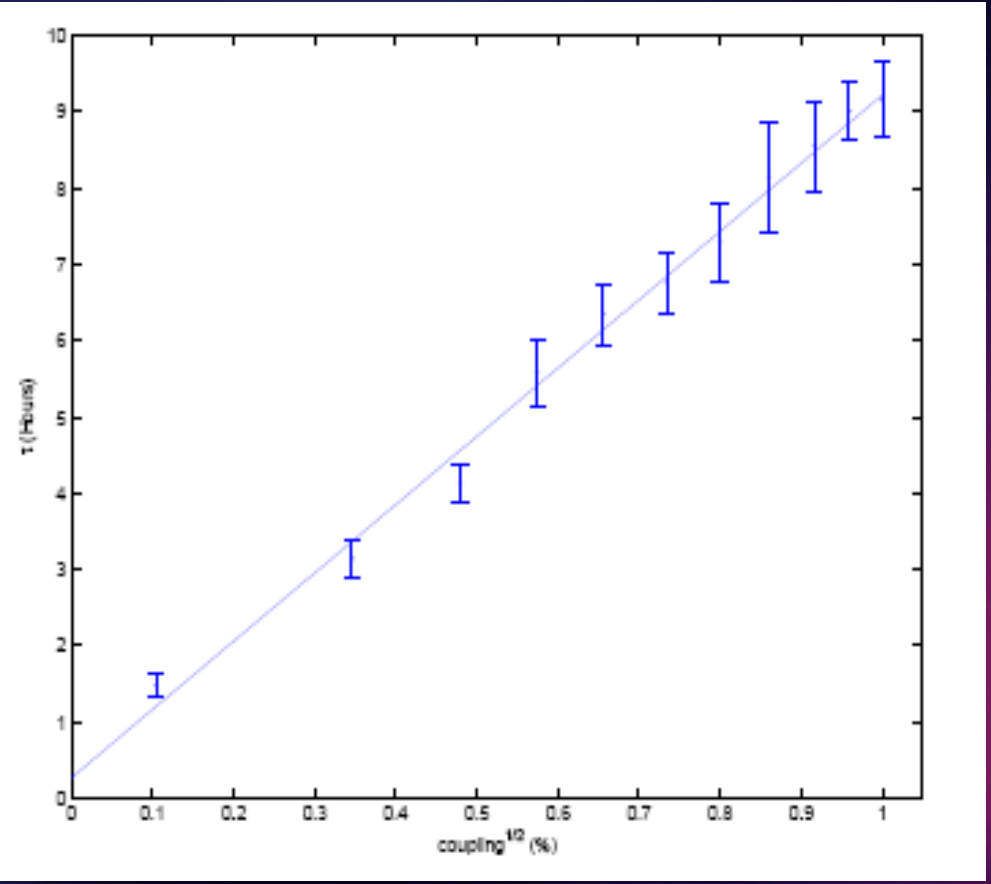




Tousheck Lifetime

- Tousheck lifetime depends on bunch volume and hence ε_y
- Lifetime measured in 8 mA single bunch – Tousheck dominated
- Should show dependence on coupling$^{1/2}$

LOCO Measured Coupling	Measured lifetime (h)
0.009%	1.49 ± 0.06
0.12%	3.15 ± 0.25
0.23%	4.13 ± 0.25
0.33%	5.58 ± 0.44
0.43%	6.35 ± 0.40
0.54%	6.76 ± 0.42
0.64%	7.29 ± 0.49
0.74%	8.14 ± 0.74
0.84%	8.55 ± 0.60
0.92%	9.01 ± 0.39
1.04%	9.16 ± 0.50

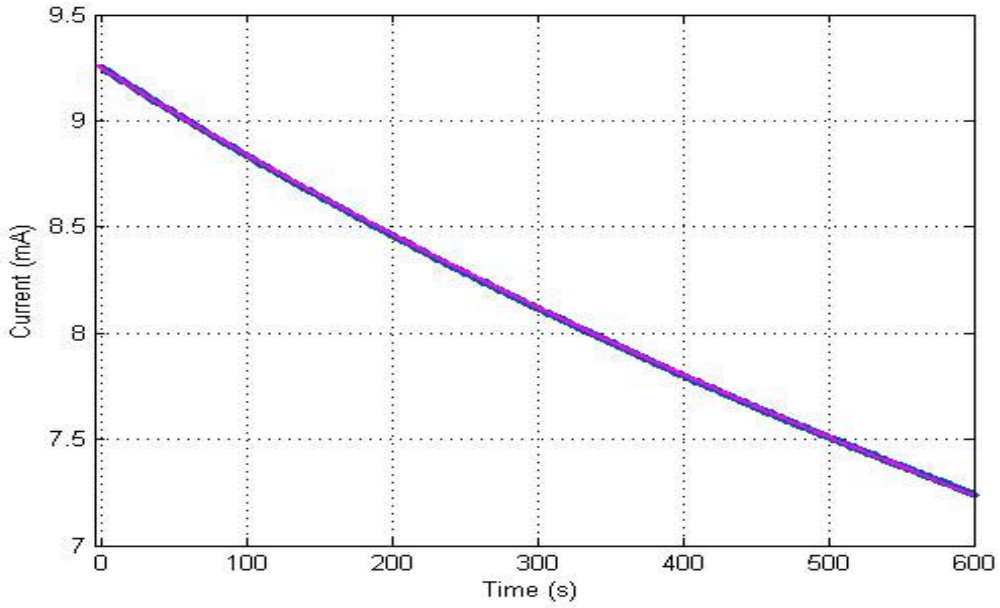


Tousheck Lifetime vs RF

- By taking single bunch lifetime over extended period the Tousheck component of the lifetime can be extracted.

$$\frac{1}{\tau} = \frac{N r_e^2 c}{8 \pi \sigma_z \gamma^2} \left\langle \frac{D(\varepsilon)}{\delta_{\max}^3 \sigma_x \sigma_y} \right\rangle, \varepsilon = \left(\frac{\delta_{\max} \beta_x}{\gamma \sigma_x} \right),$$

$$D(\varepsilon) = \sqrt{\varepsilon} \left(-\frac{3}{2} e^{-\varepsilon} + \frac{\varepsilon}{2} \int_\varepsilon^\infty \frac{e^{-u} \ln(u)}{u} du + \frac{1}{2} (3\varepsilon - \varepsilon \ln(\varepsilon) + 2) \int_\varepsilon^\infty \frac{e^{-u}}{u} du \right)$$



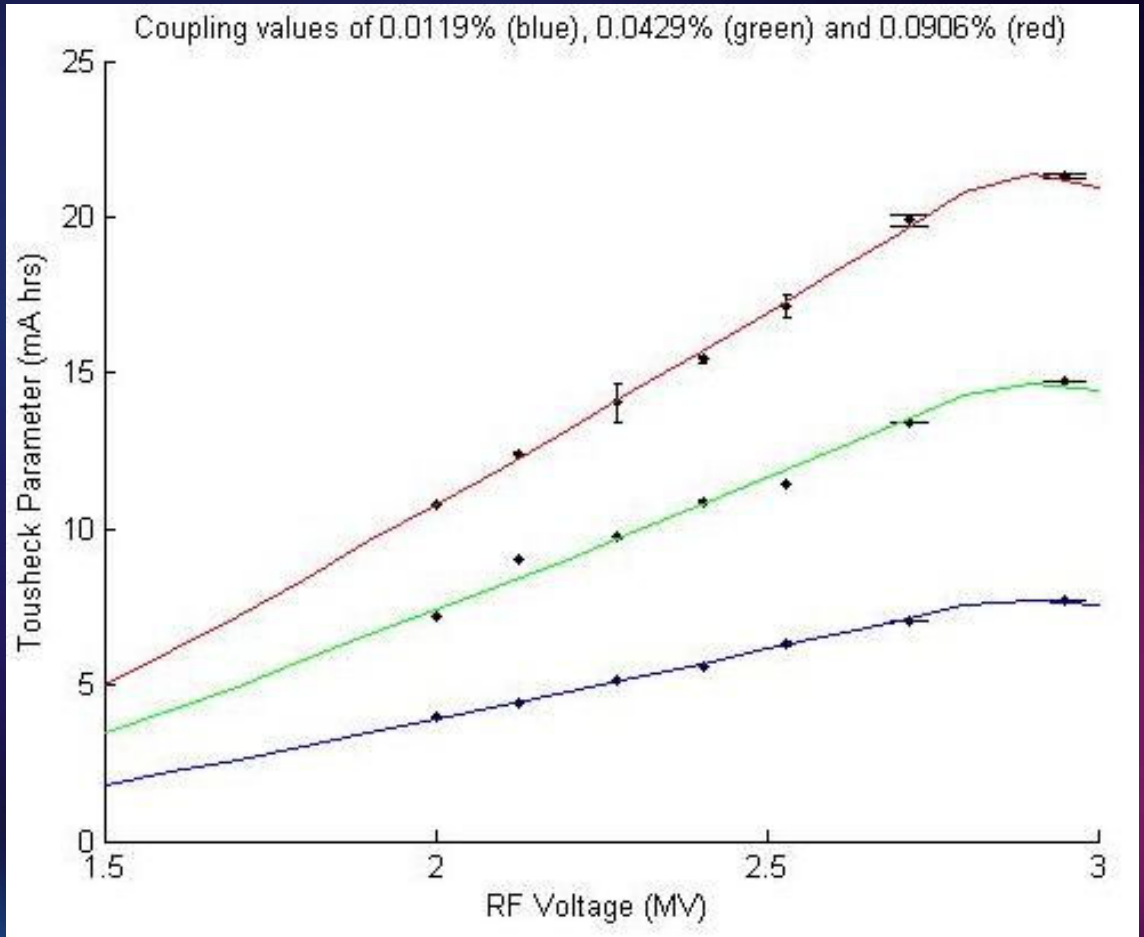
$$\frac{di}{dt} = -\frac{i}{a} - \frac{i^2}{b}$$

$$i(t) = \frac{i_0 b e^{-\frac{1}{a}}}{b + i_0 a (1 - e^{-\frac{1}{a}})}$$

Tousheck Lifetime vs RF

- Tousheck component will also change with RF voltage.

- Measurements taken at 3 settings – Minimum, natural and 0.1% emittance coupling.
- 2.1% energy acceptance (measured)
- Curve fit by varying $\varepsilon_y/\varepsilon_x$, other values fixed.
- Blue curve fit corresponds to ε_y = 1.24 pm



Tune Crossing

- Separation of Horizontal and Vertical tunes when brought to difference resonance will indicate the level of linear coupling.

- Table shows tunes at minimal sparation for different coupling settings and the corresponding coupling

Setting	Vx	Vy	Coupling
Min (0.01%)	.2506	.2505	<0.0045%
Natural (0.06%)	.2498	.2508	0.018%
0.1%	.2484	.2512	0.063%
0.2%	.2483	.2512	0.142%
0.3%	.2487	.2514	0.124%
0.4%	.2480	.2515	0.204%
1.0%	.2469	.2527	0.528%

Conclusions

- Naturally low coupling achieved by good mechanical and beam based alignment.
- LOCO is an effective tool for lattice measurements and manipulations
- Large number of skew quads allows for good control of coupling
- Tousheck Lifetime Analysis indicate ε_y ~ 1-2 pm
- Direct measurements (interferometer) would be nice.

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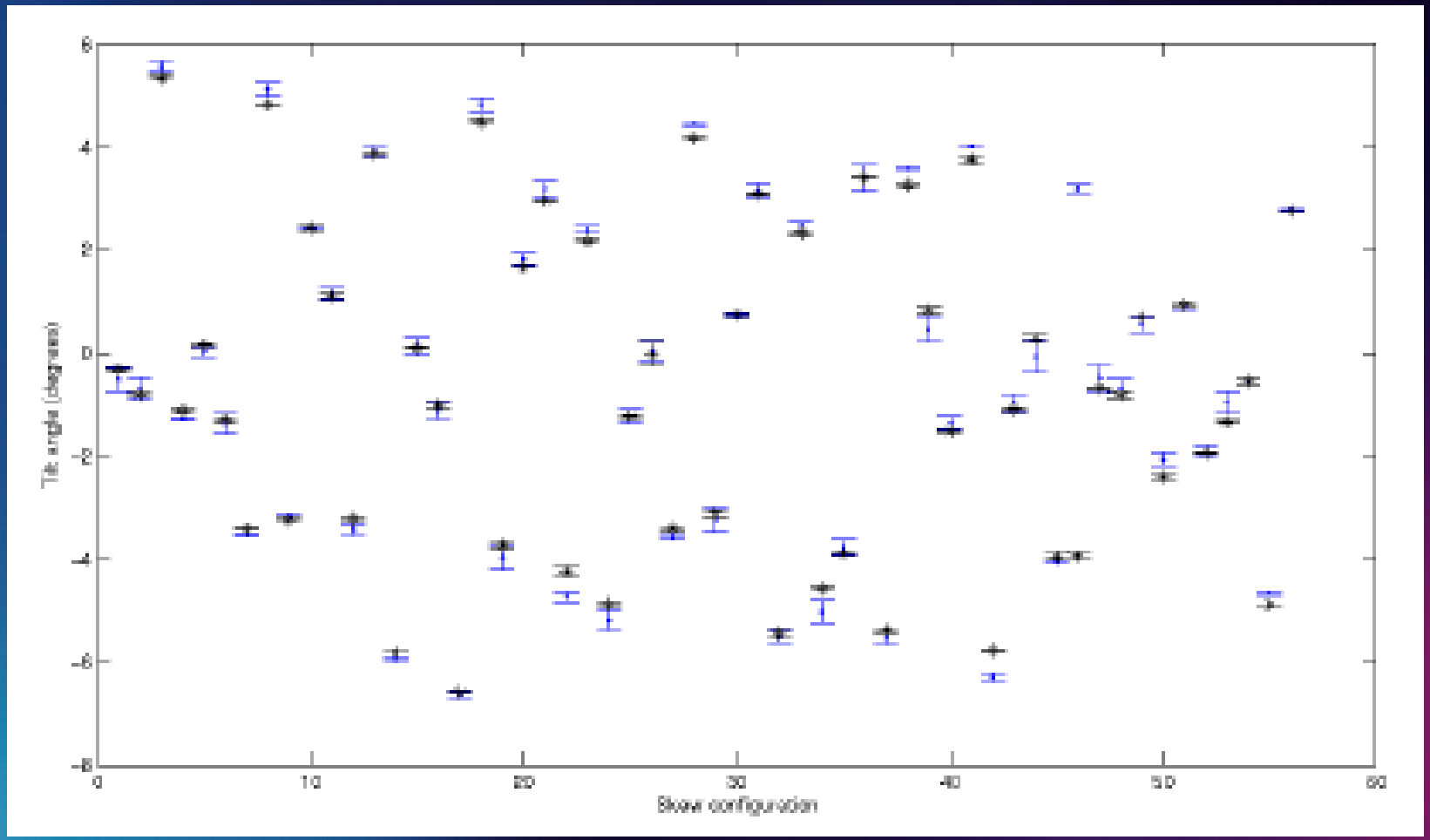
Additional Slides

Beam tilt analysis.

Comparison of model predictions (black) vs measurements (blue) of beam tilt angle at X-ray diagnostic beamline



Optical interferometer

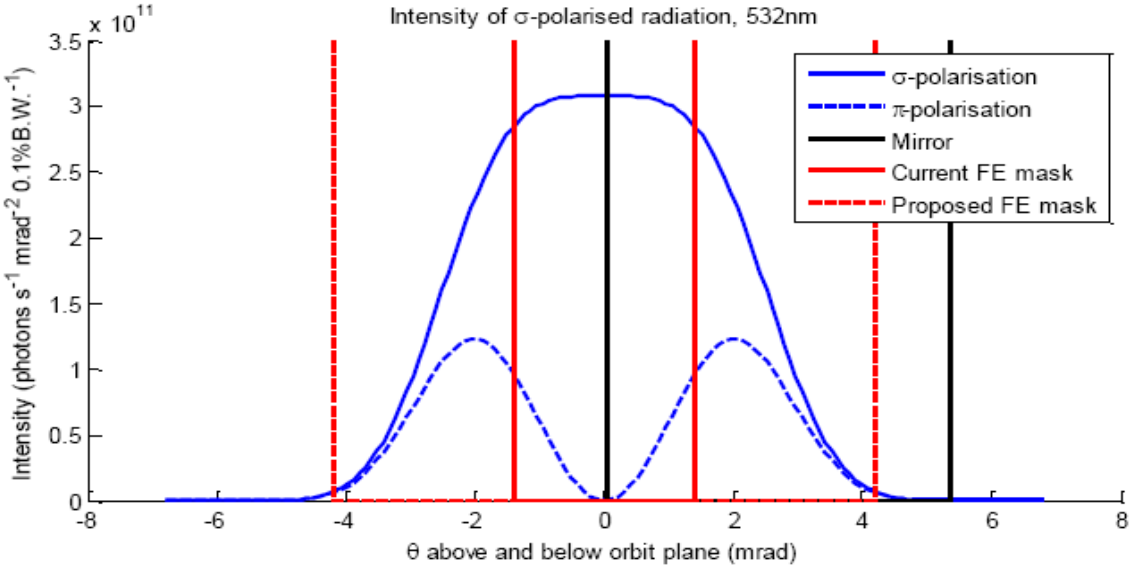


Figure 4-6: ODB apertures and angular SR profile for λ = 532 nm, using (4).