# Performance of the Australian Synchrotron Storage Ring Alignment System.

J. McKinlay, B. Barg.

Australian Synchrotron, 800 Blackburn Road, Clayton, VIC 3168, Australia

## Abstract

The girders for the Australian Synchrotron Storage Ring are aligned by a cam and vee-block system that allows fine adjustment of each girder in all six degrees of freedom. The adjustment assembly also contains a constrained layer damping (CLD) plate to minimise the transmission of ground vibration to the magnets. An algorithm has been developed to calculate the required adjustment of each cam to achieve the desired movement. The performance of the adjustment system has been characterized and an efficient and accurate alignment strategy developed. Vibration measurements have also been taken to asses the effectiveness of the CLD plates in reducing magnet motion.

## 1. Introduction

The Australian Synchrotron (AS) is a 3 GeV, 200 mA light source currently under construction in Melbourne, Australia. At the time of writing the installation of the storage ring is complete and preparation for first turn is underway, including the final alignment of the storage ring magnets.

Each of the fourteen sectors contains fifteen magnets supported on five girders. The girders and their support and adjustment system were designed and manufactured locally under a single contract awarded to Metaltec Precision International, who sub-contracted the design work to Invetech, an engineering R&D company. The design of the adjustment system was based on that developed at the SLS[1] and was developed by Invetech in consultation with the engineering group at the AS.



Figure 1. Positions of quadrupoles (red), sextupoles (green) and dipoles (yellow) and their associated girders for a single sector of the Australian Synchrotron Storage Ring.

Extensive testing has been carried out on the adjustment system to characterise the performance of the system and develop an efficient and accurate alignment methodology in preparation for first turn.

## 2. Design Features

Each girder is supported by three adjuster units, the dipole girder version of which is shown in Fig 2. Each unit contains two large rollers mounted on an eccentric shaft. The rollers are slightly crowned and, between them, support one of three, vee-shaped blocks that are attached to the underside of the girder. The rollers can both slide and rotate on the shaft via a ceramic coated aluminium linear bearing which was chosen in preference to a ball-race type product due to the very high surface loads involved. Both the shaft and the bearing surface were coated with a molybdenum disulfide lubricant [2] to reduce stiction effects.



Figure 2. Cut-away view of dipole girder adjuster unit.

Rotation of the eccentric shaft is controlled by a 90:1 manual gearbox mounted on the side of the unit. Engraved dials on both the input and output (not shown) shafts allow the position of the shaft to be manually incremented in  $0.05^{\circ}$  steps.

In between the adjuster unit and the supporting pedestal is a packing plate and a constrained-layer damping (CLD) plate similar to those developed by the APS [3,4]. Locking bolts can be used to prevent movement of the adjuster unit during use and jacking bolts allow the entire unit to be raised so the packing plate or CLD plate can be replaced if required.

Two different size units were designed, a larger unit for the dipole girder (which has a net weight with magnet of 7960 kg) and a smaller unit for both the long girder (6150 kg) and short girder (2860 kg).

The adjuster units are arranged in a Y-format for the dipole and a T-format for the long and short girders. These arrangements are fully kinematic and allows precise control of the motion of the girders in all six degrees of freedom. Although the Y-format gives better motion control due to all six rollers participating in lengthways movements, the T-format gave some advantages in girder stiffness and use of floor space.



Figure 3. Configuration of pedestals and adjusters for dipole, long and short girders.

### 3. Prediction of motion

One of the perceived disadvantages of a adjustment system of this type is the difficulty in calculating the shaft positions required for a given movement of the girder. A complete analytical solution describing the motion of this system would be highly complex, but by taking advantage of the small range of motion of this system, a simplified motion model can be obtained with negligible loss of accuracy.

Rather than try to predict the position of the girder for every possible combination of gearbox settings, the analysis of the girder movement can be broken down into two parts; the transform between the current and the desired position of the girder, and the change in gearbox settings to achieve this movement.

To determine the required transform, the position of the girder relative to the alignment network is measured by an API laser tracker run by SpatialAnalyzer<sup>TM</sup> (SA), the graphical 3D metrology software package used for all alignment tasks at the AS. The measured position of the fiducial points can then be compared to the reference points set up in SA and the transform between the two sets of points calculated on a "best-fit" basis.

If this transform is applied to the vee blocks, then the amount the rollers have to move to re-establish contact with the faces of the vee blocks is the roller movement required to cause the desired movement of the girder. For a move in all six degrees of freedom, there will be a rotation of the vee blocks relative to the rollers. However, given the range of motion of the girders, this rotation is extremely small and the change in position of the vee block due to the change in contact position on the crowned surface of the rollers is even smaller. The simplifying assumption can therefore be made that the vee block remains orthogonal to the rollers at all times. In addition, motion of the vee block parallel to the shafts is caused by sliding of the rollers and does not effect the relative position of the vee block to the rollers. This reduces the movement of interest to a 2D problem in a plane perpendicular to the axis of the rollers as shown in Fig 4.



Figure 4. Decomposition of displacement vector into roller offsets.

The transform from SA is applied to the coordinates of the centre of each vee block. The difference between these points and the original points is a vector representing the relative displacement of the vee block. **d** is the component of that vector in the plane of rollers. This can be decomposed into two components, **a** and **b**, normal to the two faces of the vee block. These two vectors represent the required offsets of the rollers, which is a function of the eccentricity and current rotational position of the shaft. Assuming bottom dead centre of the shaft occurs at a setting of  $0^\circ$ , the new gearbox setting is given by

$$\sigma = \sin^{-1} \left( \sin(\theta - 90) + \frac{offset}{E} \right) + 90$$

where  $\theta$  is the current gearbox setting and E is the shaft eccentricity. Positive rotations are defined as those that result in the vee block moving away from the centre of the relevant shaft.

The accuracy of this approach was confirmed using a parametric CAD model of the system, as real girders and adjusters were not available at the time. Errors due to simplifying assumptions listed above were confirmed as negligible.



Figure 5. GUI for SpatialAnalyzer (left) and Excel (right) showing best fit transform menu and interface to adjuster position calculator.

This calculation was integrated into an Excel spreadsheet that also incorporated a database of current gearbox settings for the entire storage ring. Scripts in SA have allowed the measurement process to be largely automated and the required transform written out to a text file. This can then be read into the adjustment spreadsheet, along with the correct gearbox settings and the new settings computed.

## 4. Performance of adjuster system

Initial testing of the adjuster system showed a discrepancy of up to 80% between the predicted and actual movements. This was shown to be due to the shearing of the CLD material in the damping plates under reaction loads in the adjuster assemblies set up due to friction forces opposing sliding of the bearings. For the alignment required for installation, the adjuster assemblies were bolted down but this was not acceptable in the long term as the locking bolts prevented the CLD plates being effective dampers. Performing an alignment with the adjusters locked down and then undoing the bolts results in some movement of the girder due to redistribution of reaction loads set up during the adjustment process. Leaving the adjusters unlocked prevented accurate alignment due to the movement in the CLD plate. To allow high resolution adjustment and the CLD plates to be effective, a method of locking the adjusters down was required that could be reversed without affecting the aligned position of the girder. A number of methods were trialed, the most effective being the use of parallel wedges inserted close to the locking bolts as shown in Figure 6.



Figure 6. Wedges used to prevent shearing of CLD plates during adjustment process.

This provides a very stiff assembly during adjustment and can be undone with minimal impact on the position of the girder.

## 1.1. Hysteresis

Due to large friction loads from the high contact forces in the solid bearings, the adjustment system exhibits significant hysteresis when the direction of motion is reversed. A small component of this can be attributed to the gearbox. This is always loaded in the same direction due to the weight of the girder, but there is a difference between forcing the girder to move against its weight and the friction forces and allowing the girder to "fall" into position under its own weight. The use of a zero backlash gearbox may improve the performance in this regard.

The majority of the hysteresis appears due to the reaction loads set up in the adjuster assemblies. Upon reversal of the movement direction it takes some time before the system is fully loaded in the opposite direction, clearances are taken up and the motion becomes consistent. This is effected by the rigidity of the connection between the adjuster assembly and the supporting pedestal as shown in Fig 7, with  $0.9^{\circ}$  lost on reversal of movement even with the CLD material removed and a direct steel to steel connection between the assembly and the pedestal. This effect is less pronounced in the vertical due to the higher stiffness of the assembly in this direction.



#### HYSTERESIS IN DIPOLE GIRDER MOVEMENT (X DIRECTION)

Figure 7. Hysteresis of dipole horizontal movement in x direction (transverse to e-beam).

The presence of hysteresis reduces the ability to accurately predict the motion of the system. It is not a simple task to include any compensation into the predictive algorithm as the interaction between the adjusters' motion makes it difficult to predict where loads will be reversed for a given movement and what effect this will have.

As the movement of the girder is more reliable in the vertical direction, the first adjustment move is not made to the target location, but to a location 250  $\mu$ m above the target. This allows subsequent moves to be made with all gearboxes being adjusted in the same direction. A stepwise adjustment is followed to allow the reaction forces to stabilize and the movements to become reliable. Typically four steps are required; 250  $\mu$ m above the target, 100  $\mu$ m above, 30  $\mu$ m above and then a final move to the target. This generally gives good results, although stiction effects can occasionally cause a 'jump' in the motion during the final adjustment that requires further corrections to be made.

### 1.2. Resolution

It is not possible to exactly quantify the resolution as the system is adjusted manually. This results in a practicable limit of  $0.05^{\circ}$  increments, which gives a theoretical resolution of 6 µm. There is no encoder on the output shaft, so this motion is inferred from the input shaft setting. The 3D position of the girder is measured with a laser tracker, which has a resolution of about 5 µm for a multi-point measurement at this range. This has been found to be the limiting factor for the alignment of a single girder and it can therefore be inferred that the true resolution of the system is in the <5 µm range.



ALIGNMENT ERROR - SECTOR 10

Figure 8. Residual error for Sector 10 girders compared to target position.

The alignment accuracy of a girder to its target position, including repeatability of fiducial measurement and measurement error, over an entire sector is typically 22  $\mu$ m in the horizontal plane and 12  $\mu$ m in the vertical plane (1 $\sigma$ ). This gives a good indication of the performance of the girder adjusters and the alignment process as a whole and compares well with the accuracy of the fiducials on the magnets, which are typically 25  $\mu$ m (1 $\sigma$ ), depending on magnet type.

### 5. Performance of the CLD system.

The CLD plates incorporated into the adjuster design are based on the developments in this area by the APS [3,4]. It consists of a sandwich of three stainless steel sheets with layers of a viscoelastic damping polymer [5] in between.

The performance of this design is currently under evaluation to determine the likely impact of leaving the adjusters bolted down during the early part of the storage ring commissioning and to see if the performance of the CLD plates can be improved by optimising the size of the plate.

The assessment criteria for CLD plates was taken as the reduction in RMS motion of the magnets compared to the floor. Using RMS motion gives a single number that directly relates to the electron beam stability via the optics amplification factors. Given a stability criteria of 10% of the beam size [6], this corresponds to magnet vibrations levels of the order of 2  $\mu$ m horizontally and 0.1  $\mu$ m vertically.

Due to the largely flat acceleration spectrum at the AS site, the RMS displacement value is dominated by the contribution of the low frequency end of the spectrum.



Figure 9. Power spectral density curves for dipole girder and technical floor. (Note: vibration measurements to date have mostly been taken outside of normal operational hours due to construction work. In addition, not all plant has been fully commissioned, so vibration levels may not be indicative of those that will be present under normal operation.)

The RMS value is determined from the square root of the integral of the power spectral density (PSD) curve. A sensible low frequency cut off value for the PSD integral needs to be chosen, otherwise the effectiveness of the CLD plates may be severely under or over-estimated. To do this, vibration measurements were taken with sensors on the two short girders at either end of the sector. The point at which the coherence start to degrade ( $\sim 0.95$ ) is taken as the PSD integral cut off. Below this frequency the entire sector is following the motion of the floor and essentially behaving as a single body. Under these conditions the presence of the CLD plates has no impact on the relative motion of the magnets within a single sector. These measurements were taken in x, y and z directions and the summarised results are shown in Table 1.

PSD integral range								
Х	6.5 – 100 Hz							
Y	5.5 – 100 Hz							
Ζ	7.5 – 100 Hz							

Table 1. PSD integral range used to determine RMS displacement values.

At the time of writing, vibration measurements [7] have only been carried out for the dipole girder in x an y, and the long girder in x. The results are summarized in table 2. All measurements were carried out with the storage ring cooling water system off.

#### PSD of DIPOLE GIRDER in X-DIRECTION

	Damping	RMS motion floor	RMS motion magnet	ratio	1 <sup>st</sup> nat. freq.
Dipole girder - Y	YES	6.7 nm	7.1 nm	1.06	55 Hz
	NO	7.6 nm	8.0 nm	1.05	55.3 Hz
Dipole girder - X	YES	2.8 nm	5.5 nm	2.0	20 Hz
	NO	2.8 nm	8.3 nm	3.0	21.8 Hz
Long girder - X	YES	4.9 nm	12.4 nm	2.53	17.3 Hz
	NO	6.3 nm	21.4 nm	3.39	19.3 Hz

Table 2. Effect of damping on girder displacement values.

It can be seen that the CLD plates have no effect on the vertical motion and reduce the horizontal motion by approx. 30%. Given that the floor motion at the AS site is approx twice as large vertically as it is horizontally, and that the beam stability requirement vertically is 20 times more stringent than horizontally, a reduction of 30% in the horizontal motion of the magnets is likely to have only marginal impact on the overall stability of the electron beam and should not unduly affect the commissioning of the storage ring.

Recent tests of the long girder indicate the magnet motion is likely to increase by >30% horizontally when the cooling water system is fully operational. The CLD plates have no impact on vibration caused by water flow through the magnet windings and hence their impact on the overall motion of the magnets is further reduced.

## 6. Conclusion

A high load capacity, high precision girder adjustment system has been successfully implemented for the AS storage ring. Alignment test results show that girder to girder positions within a single sector can be controlled to a standard deviation of 22  $\mu$ m horizontally and 12  $\mu$ m vertically, which is comparable to, or exceeds, the manufacturing and assembly tolerances on the individual girders and magnets. The achievable accuracy of the alignment for first turn is currently limited by the uncertainty in the alignment network and the uncertainty of the true location of the magnetic field centres relative to the magnet fiducials. By using beam-based alignment after the storage ring has been commissioned, these limiting factors will be removed and the resolution of the adjustment system can be fully exploited to achieve optimal storage ring performance.

The relatively minor reduction in RMS displacement of the magnets through the use of a CLD system is due to the high stiffness and high natural frequencies of the girders, combined with very low ambient vibration levels in the technical floor. The performance of the CLD plates may be improved by optimizing the stiffness of the plate in relation to the stiffness and mass of the girder assembly.

## 7. Acknowledgements

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### 8. References

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