Ø320 mm beam positioning mirror mount for the EPAC project with 1 µrad stability

Contact *andrew.stallwood @stfc.ac.uk*

A. Stallwood

Central Laser Facility
STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK

I. Cheshire

Central Laser Facility
STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK

R. Sarasola

Central Laser Facility
STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK

Abstract

For the new Extreme Phonics Application Centre (EPAC) at the Central Laser Facility (CLF), a beam positioning mirror mount was designed to propagate a laser beam measuring up to 320 mm in diameter with 1 µrad stability under vacuum.

The end design consisted of the novel approach to integrate the mechanics within a solid aluminium vacuum chamber. This improved the rigidity of the mirror mount and exceeded the stability specification by offering less than 500 nano-radians peak to peak.

Introduction

The CLF is currently building a new state of the art laser facility called EPAC at Harwell in Oxfordshire. This centre will be providing a 10 Hz petawatt laser to two experimental areas.

Within the laser system there is a requirement to propagate a laser beam up to 320 mm in diameter under vacuum. In order to do this, a new mirror mount is required to handle large size optics and maximise beam stability with regards to drift, vacuum shift, and jitter.

The stability specification for this mount is 1 µrad, 1 - 2 orders of magnitude better than the existing facility.

This article describes how the mount was designed and tested to meet these needs.

EPAC Beam propagation

Once a laser pulse has been compressed in time, the energy density (energy per cross section of the beam) increases. In EPAC, this increased energy density is beyond the operating capacity of the optics and coatings. To reduce the energy density, the beam diameter is increased, therefore increasing the area. While the energy density is now lower, it is still beyond the threshold of propagating through air. Therefore the beam needs to propagate within a vacuum.

This increased diameter beam then needs to travel from the compressor to the experimental areas, where it is focused down using a parabola to the interaction point.

Within the EPAC building, the compressor is located on the 2nd floor, with the experimental areas located on the ground floor. These experimental areas are effectively concrete bunkers with no line of sight entry, to protect the outside world from dangerous radiation. Therefore the laser beam needs to enter these areas via a chicane, resulting in the need for large mirrors for propagation. These chicanes are compact in size and restricted for space.

Within the EPAC project, the compressed beam diameter is initially going to be 220 mm, with the option to increase it in the future up to 320 mm.

With the potential for two beams in each experimental area (EA1 and EA2), this equates up to 30 mirrors required to propagate the beam from the compressor to the final interaction points. Beam propagation is done both vertically and horizontally, so the mirror mounts need the flexibility to be installed in different orientations.

Therefore a modular design was required to enable different beam optic sizes and mounting methods.

Compared with the existing laser facility, which has a beam stability of >10 µrad, an improvement of 1 - 2 orders of magnitude is required.

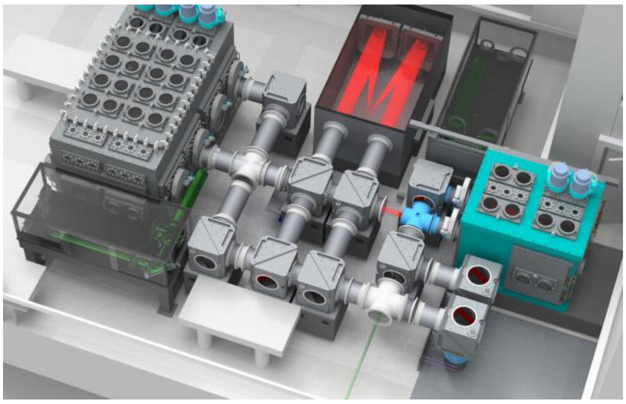

Figure 1: Multiple mirrors used in Experiment Area 2 (EA2) to propagate two beams from the compressor through various systems into the target chamber

Specification

Physical specification
Maximum external dimensions for the chamber (including any access): 900 mm x 900 mm x 900 mm

As the mount chambers are to be positioned on a 900 mm pitch, side access is not possible – adjacent chambers would need to be removed for access.

Largest Mirror Optic size: 500 mm x 360 mm x 75 mm, with a mass of over 35 kg.

Vacuum specification
Internal vacuum <1 x 10^{-6} mbar

Motion specification
Each mount is to have +/- 2° pitch and yaw adjustment.

Resolution of motion and measurement to be 100 nrad (10% of the required stability specification)

Motion to be about optic centre.

Other specifications
Along with the beam stability, and the requirement to hold different size and shaped optics under vacuum, the mounts also need to be easy to service and access, mountable in any orientation, have quick change optics and various drive options.

Chamber Design

Working with the constraints given, and starting with the largest optic size, it was clear that providing a stable mount within the space required was going to be a challenge.

It quickly transpired that going for a conventional "welded box" chamber design, with an internal support structure, was not going to fit without compromising on the stiffness of the support structure. Therefore the approach was taken of combining the two together.

This approach is frequently dismissed due to the shift that can occur when pumping down the system from atmospheric to vacuum pressures. However, making the chamber part of the support structure also enabled the chamber to be much stronger, the weakest point in the chamber being a wall 55 mm thick x 80 mm tall. Most wall sections are well in excess of 100 mm.

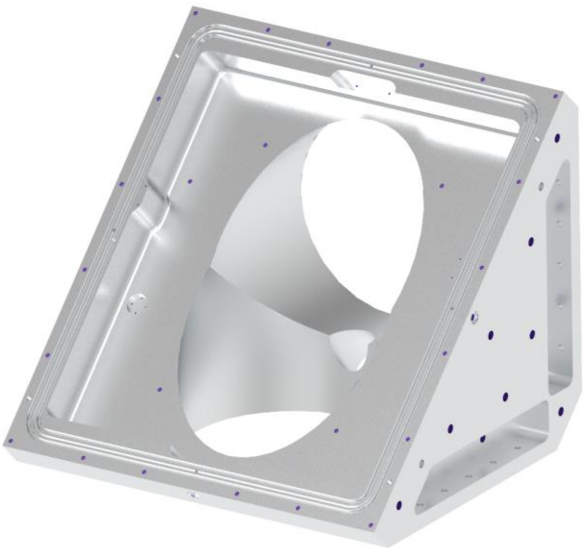

Figure 2: Solid chamber with integrated support structure

Machining from a solid aluminium billet also opened up more supply avenues. A welded construction would require the use of specialist vacuum chamber manufacturing companies, whereas a solid machined chamber could be supplied by any machining company with the capability of machining this size of component. Cleaning of the chamber could either be done in-house or by another sub-contractor. This reduced the cost of the chamber.

The material chosen for the chamber was a fine grain structured 5083 aluminium alloy, specifically engineered for vacuum use.

Internal access

How to access the internal optic without dismantling sections of the adjoining pipework also needed to be considered. Not only would this process be time consuming, there is always the potential for a leaks on re-assembly (which ultimately means more down time).

With a conventional box design, access would be through one face of a cube. However, this would mean reaching inside the chamber to access some components and space is tight.

Splitting the chamber at 45 degrees, in line with the optic reflecting surface, improves access considerably.

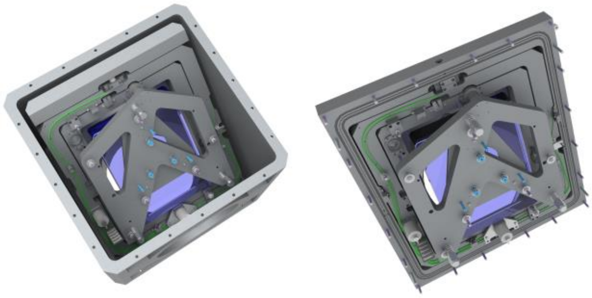

Figure 3: Access comparison between box design (left) and wedge design (right)

Chamber mounting, space and orientation

The mounting of the chamber was also an important consideration during the design. Multiple mounting holes on each side of the chamber allow for fixings to be added either from the top or the bottom of the chamber. Each installation position was considered, along with the supporting structure, which is either granite support blocks where possible, or welded steel frames where not. Further vibration damping layers are to be added between the support and concrete building structure.

Vacuum

The vacuum base pressure specification is 1 x 10^{-6} mbar. This can be easily achieved with an O ring seal and good vacuum practices. All internal voids were vented and only vacuum compatible materials and components were used. As the chamber is likely to be opened many times within its lifespan, an additional O seal was added along with the capability to differentially pump the void in-between. Differential pumping ports were added on each face to give flexibility when installed in different orientations.

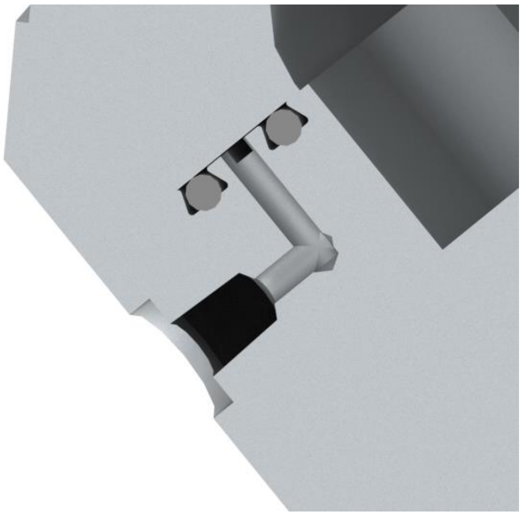

Figure 4: Cross-section through differentially pumped seal

Internal mechanism

The internal mechanism is a gimbal type design to provide rotations about the centre point of the optic. Two motion frames mounted inside each other supply the pitch and yaw motions. To minimise costs, both frames can be water cut from a single plate, with all the machining done from the front and rear.

These frames are mounted with flexures rather than conventional bearings. These offer zero friction, high rigidity with no play – improving the optic stability and allowing for fine motion control without stiction.

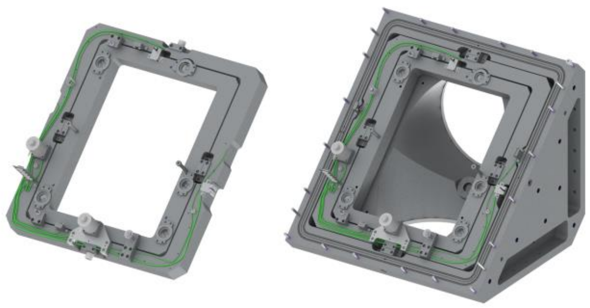

Figure 5: Internal frame (left), shown mounted in chamber (right)

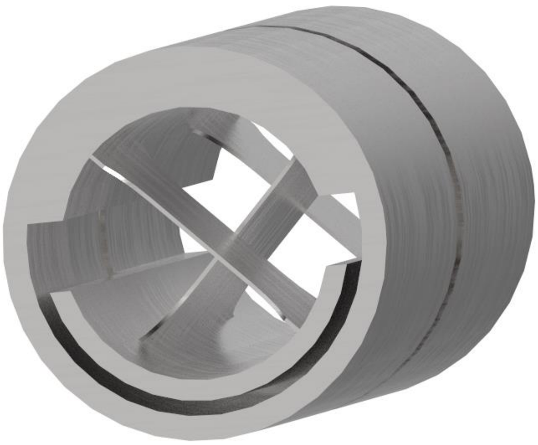

Figure 6: Flexure pivots used for bearings

Interchangeable optic holders

On top of the inner motion frame is a kinematic interface of three balls and three vees. This interface provides high rigidity and repeatability between the mount and the optic holder.

Strong magnets were installed to hold the optic holder against the kinematic interface. The intension was for this to speed up the optic change process and remove the need for loose fixings. Jacking screws incorporated into the optic holder would enable a controlled lowering and raising of the holder onto the kinematics. Although these magnets do aid the insertion of the optic holder, they do not generate the force (or peace of mind) to retain the optic holder permanently; therefore shoulder bolts and springs were also added as a precaution.

The optic holder provides a convenient and safe way to transport the optic. By characterising the kinematic interface, optic holders can be measured in an offline jig for position and angle. This data will enable an optic to be changed and setup without re-aligning the beam.

The different configurations of the optic holders included two optic sizes, for a 220 mm and a 320 mm beam, and horizontal or periscope mounting. The main difference between the orientations is an edge-supported optic for the horizontal bounce, and rear three-point mounting for periscopes to minimise optic sag under the force of gravity. The edge supported holders also enable full beam transmission for beam diagnostics.

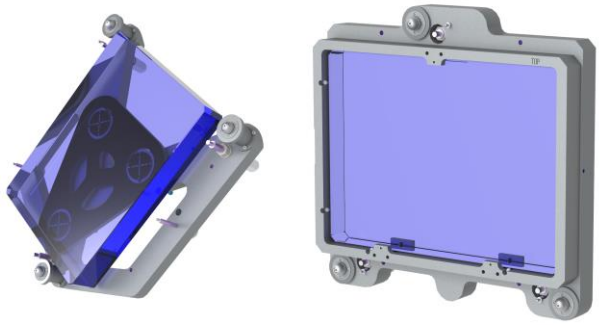

Figure 7: Large optic frame for periscopes (left) and transmission (right)

Actuators

While fine motion is required for most of the optics, some require just manual positioning and others could accept a coarser motion.

To accommodate these features, three different actuator types can be installed: piezo, stepper and manual.

As the optics are quite large, the actuation point for each axis could be placed ~300 mm away from the rotation axis, offering good leverage and fine control. Acting perpendicular to the surface, 30 nm of actuator motion equalled 0.1 µrad of motion.

The piezo actuators (PiezoMotors LTC300) offer the best control and are intended to be used in closed loop with the optical encoders. These actuators have nanometre resolution and suffer from no backlash. When powered off they retain full pushing force, which is advantageous as it minimises heat dissipation within the vacuum chamber. In theory, these actuators, coupled with the fine resolution encoders, would offer ~ 5 nrad angular control; however, in reality, this is extremely hard to confirm, due to the baseline vibration emitted in the test areas.

The stepper actuators (Standa 8MAV-16) have a minimum incremental motion of 50 nm (~0.17 µrad of optic motion). These would not be used in closed loop, as they tend to suffer from backlash and overheat heat in vacuum when powered on. They will be used for initial setup and to correct for long term drift caused by ground movement, building motion, and seasonal variations.

The manual actuators are threaded adjusters with 254 threads per inch (0.1 mm pitch). Assuming an adjustment of 5° can be made to these, it equates to ~4.6 µrad of motion. There are two downsides to using the manual adjustment: 1) they can only be adjusted in air, so they suffer from shift in the system when it is pumped down; and 2) movement can occur when tightening the locking nut.

All motions are then measured by Renishaw optic encoders that have a measuring resolution of 1 nm.

In addition to the actuators and encoders, each motion was fitted with hardstops, limit switches and adjustable spring pre-load.

Motion control

Control of the piezo motor feedback loop was done using an ACS SPiiPlus controller. This was connected to an ACS UDlhp motor drive interface, which has a 16 bit DAC that outputs a +/-10V signal to the PiezoMotors PMD301 controller. The encoder signal plugs into UDlhp drive interface.

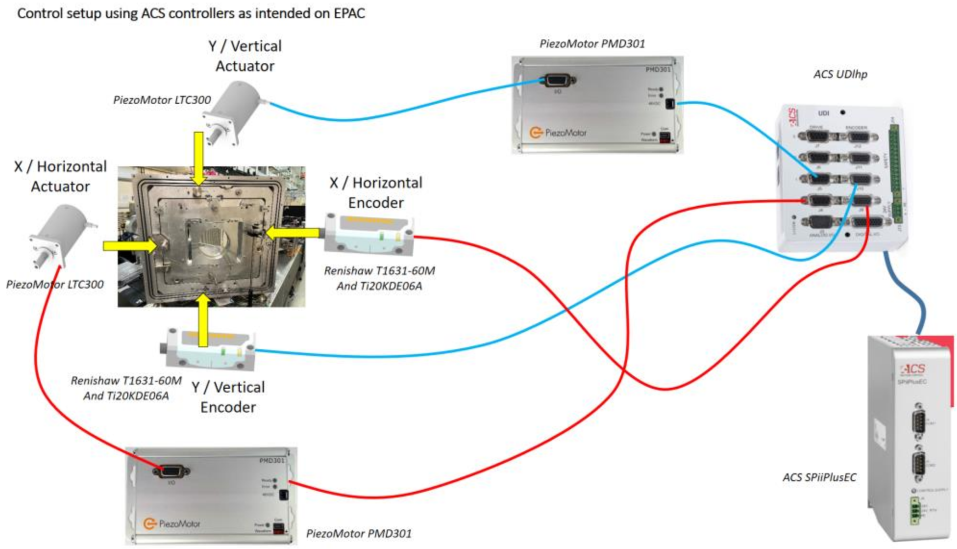

Figure 8: Control setup

Figure 9: Optical setup test, the positioning mirror is on the left hand side

End design specification

External sizes: 800 mm x 700 mm x 700 mm

Largest optic size: 500 mm x 360 mm x 75 mm

Orientation: Horizontal or vertical

Pitch: +/- 2°

Yaw: +/- 2°

Actuation: Piezo, Stepper or Manual

Actuator Resolution:

Piezo 0.1 µrad

Stepper 0.2 µrad

Manual 5 µrad

Stability: <0.5 µrad

Vacuum base pressure: <1 x 10^{-6} mbar

Vacuum seal: Twin O ring differentially pumped

Connecting ports: ISO400

Other features: Camera ports for observing the front and rear of the optics

Testing

Testing of the mount has proved to be difficult. Initially the mount was tested with an laser optical setup which is used for beam positioning. However, this system was prone to more noise and less accuracy than the tests required. The testing equipment was less stable than the mount.

A second test setup with two MicroEpsilon confocal sensors (IFC2403-1.5) that have a maximum resolution of 16 nm. These were mounted to the same optical table that the mount was sitting on.

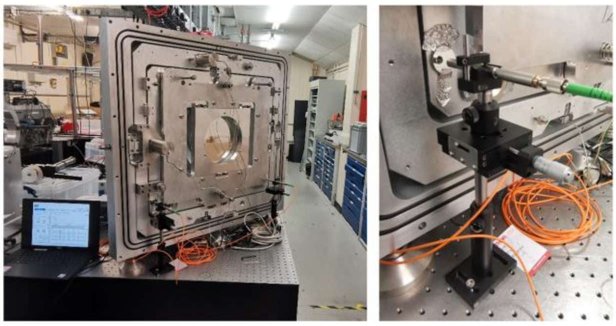

Figure 10: Confocal sensor test setup

Testing was carried out in the TA1 laboratory, which is located close to a roadway and a source of large vibrations; there are also various pieces of equipment within the laboratory, including pumps and the air conditioning unit, which add to signal noise. The laboratory is also in constant use with people coming in and out through the sprung closed doors.

Temperature is coarsely monitored and controlled, but the set points for control offer quite a variance in temperature – cycling from 20.6°C to 21.6°C and back again every 54 minutes.

Using the confocal test configuration, the system was fine-tuned by adjusting the motion control parameters. This fine-tuning improved the accuracy and precision, as seen in Figures 11 and 12.

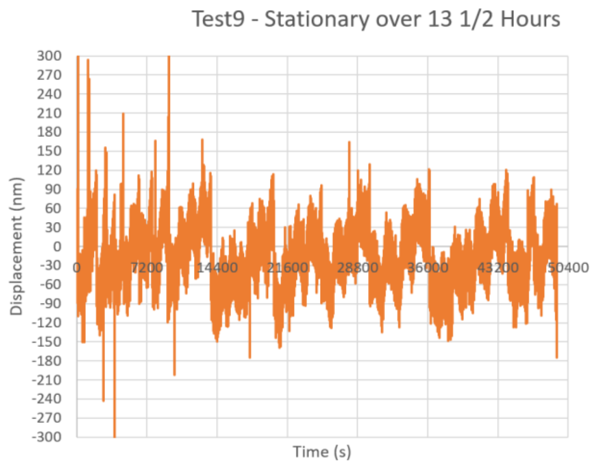

Figure 11: A 13.5 hour test showing stability before the motion control was tuned (30 nm = 0.1 µrad)

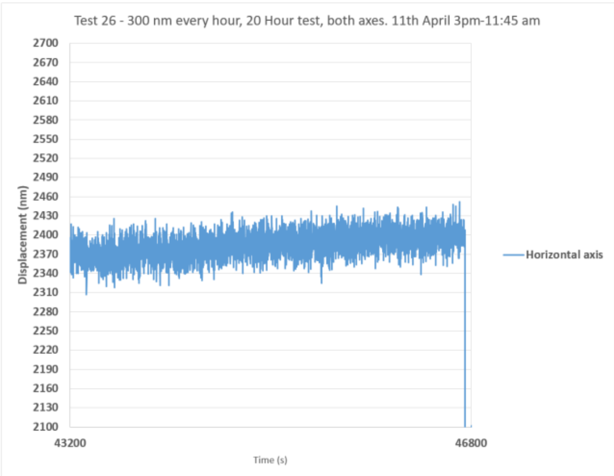

Figure 12: Test 26 - results after tuning

Test Results

Repeated tests with the confocal sensors indicated that the encoder data proved to be representative of the actual movement of the optic.

The final long stability test (Figure 13) showed closed loop control of the piezos gave a mean positioning accuracy of 22 nm (0.07 µrad) and a standard deviation of 30 nm (0.1 µrad).

These figures are based on the whole duration of the test. If the high vibration times are removed from the figures, then a mean positioning accuracy of 13 nm (0.04 µrad) and a standard deviation of 15 nm (0.05 µrad) can be achieved.

		Mean		Difference		Deviation	
Vibration	Position	H	V	H	V	H	V
High	0	16	29	16	29	68	60
	300	326	340	26	40	45	35
	600	642	637	42	37	24	27
	900	921	933	21	33	34	23
Low	1200	1240	1226	40	26	20	25
	1500	1540	1526	40	26	18	24
	1800	1840	1823	40	23	18	25
	2100	2142	2119	42	19	20	28
	2400	2439	2416	39	16	18	28
	2700	2738	2730	38	30	19	25
	3000	3041	3024	41	24	18	24
	2700	2691	2699	-9	-1	18	26
	2400	2384	2391	-16	-9	20	27
	2100	2095	2101	-5	1	27	29
	1800	1802	1809	2	9	27	31
	1500	1519	1518	19	18	30	29
High	1200	1233	1230	33	30	31	28
	900	928	931	28	31	52	41
	600	622	624	22	24	35	33
	300	333	330	33	30	30	30
	0	-20	6	-20	6	36	41
			Mean	22	21	29	30
			Mean	13	9	12	15

Figure 14: Test 26, mean position and standard deviation

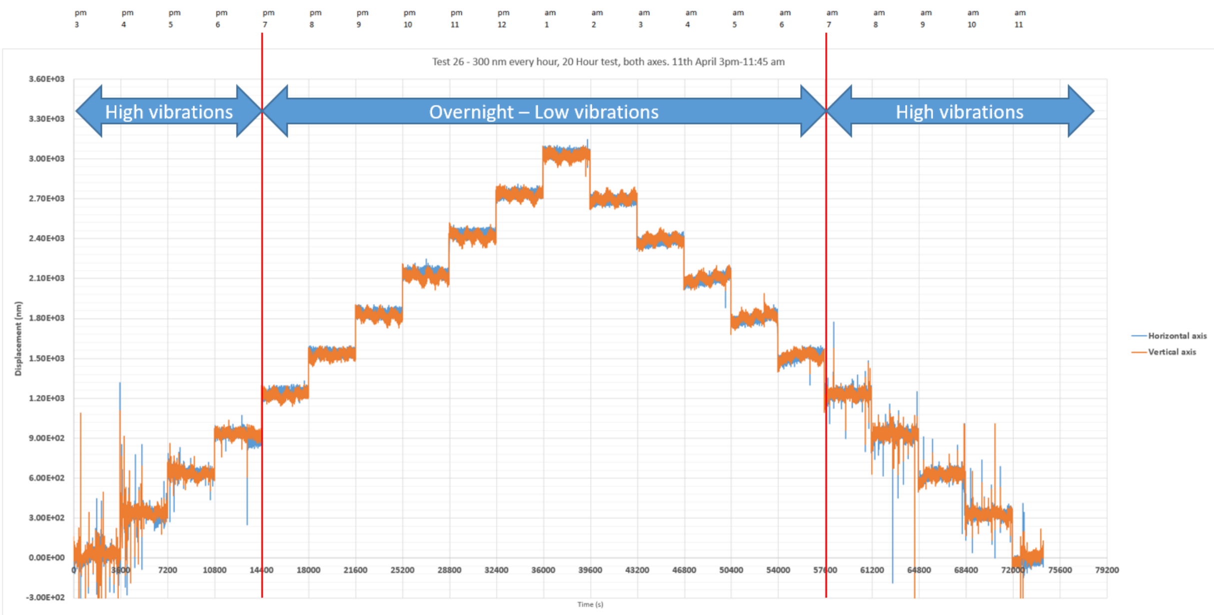

Figure 13: Test 26, 20 Hour test, 1 µrad every hour

Testing is still ongoing, to see if the motion control can be improved and to evaluate the performance of stepper motor actuators for situations where the beam stability is not so important.

Investigations were carried out after a particularly violent set of vibrations occurred (resulting in a 10 µrad shift in results). It was discovered that a roller had just been unloaded from a lorry just outside the lab – just exiting the picture on the left hand side of Figure 15.

Figure 15: A source of vibration - left

Conclusions

In conclusion, the integrated vacuum chamber optical mount worked.

Fine tuning of the motion control system improved the performance of the optic mount.

The 1 µrad specification was exceeded, with peak to peak positioning stability well within ±100 nm (±0.3 µrad), positioning accuracy <0.1 µrad, and standard deviation <0.1 µrad.