A FAST SWITCHING MIRROR UNIT AT FLASH

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Abstract

At the Free Electron Laser Hamburg the laser beam is diverted towards 5 different test sites by massive silicon mirrors, which are mounted into vacuum vessels. One of these vessels can be operated in permanent switching mode. The target switching frequency is 5 Hz. The initial design of this particular vessel with a steel body permitted a switching at 2,5 Hz at the demanded precision. By substituting the steel body with one made of titanium and with further mass reduction, the frequency could be increased up to 5 Hz. Initial measurements revealed that the demanded accuracy could roughly be met, but strong vibrations necessitate further optimization of the test site. By moving the mirror inside the vacuum by piezo motors, the translator inertia can be reduced significantly, but the heat generation of these motors proved problematic. Measurements revealed that under vacuum conditions parts of the motors reach temperatures up to 105°C, so the development of suitable cooling provisions is mandatory.

INTRODUCTION

The Free Electron Laser Hamburg (FLASH) is a linear accelerator producing brilliant laser light from four to sixty nanometre wavelengths, providing unique experimental opportunities to investigate the atomic structure and the properties of materials, nanoparticles, viruses and cells. In the experimental hall, the laser beam can be directed towards five different test sites by massive silicon mirrors which are mounted into vacuum vessels. The movement of the vessels is carried out perpendicular to the beam by linear drives; the mirror itself is mounted into a vessel with an angle of three degrees to the incoming beam. With the vessel moved out of the beam the laser goes through it into the beam line straight ahead without being deflected, with the vessel moved into the beam it is deflected into the diverging beam line.

One of these vessels can be operated in permanent switching mode, allowing a simultaneous use of the laser beam at two different test facilities. Since the laser beam at FLASH is pulsed with a frequency of 10 Hz, the motion has to be synchronized to the beam pulses (trains). The ideal switching frequency would be 5 Hz, with one train passing through and one being deflected respectively. The motion is processed according to a reference curve (see figure 1) which guarantees minimal stress for the mirror. Nonetheless, when the rest state begins, the mirror always shows a certain horizontal angle distortion and a position misalignment. The limit of the angle distortion is 1 arc second, while the position misalignment must not exceed few micrometres. The limits for these errors must be maintained repeatedly, which in practice limits the switching frequency.

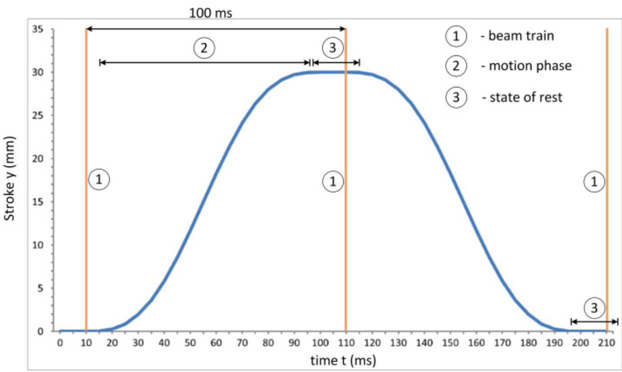

Figure 1: Ideal motion scheme of the mirror at 5 Hz.

INITIAL DESIGN

Motion Concept

As can be seen in figure 2, the vacuum vessel consists of a round tube with DN 250 flanges on each side. The mirror is mounted in the middle of the vessel onto a fastening plate, which is attached to the chamber flanges. In case of heat input into the mirror by the FEL beam, a cooling plate on top is supposed to ensure a fast heat transport from the mirror towards the cooling pipe and out of the vessel. The vertical fastening of the cooling plate and the mirror is assured by screws. Additionally, on the back side of the mirror, there are two taper keys pushing the mirror towards elevations in the fastening plate.

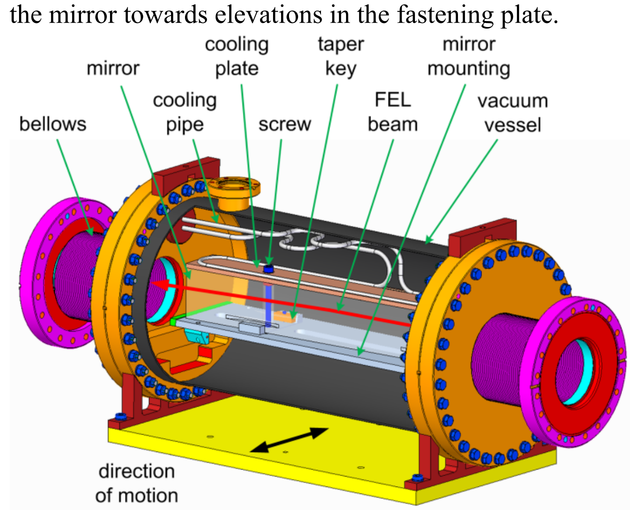

Figure 2: Initial vessel design (3D-CAD-model). [1]

The overall mass of the original steel assembly is more than 60 kg, which limits the maximum switching frequency to 2,5 Hz. Measurements revealed that the horizontal angular distortion as well as the positional misalignment met the requirements (see figures 3 and 4) [2].

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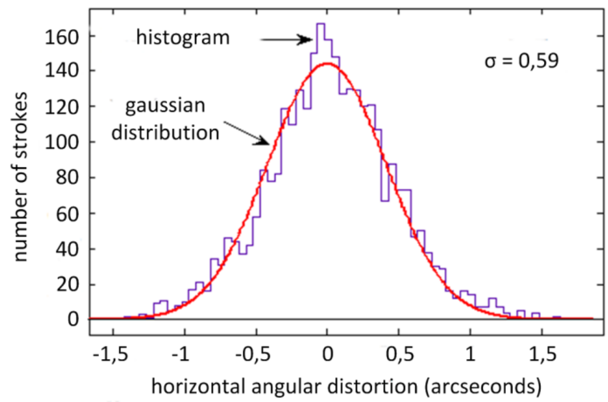

Figure 3: Horizontal angular distortion (f = 1 Hz).

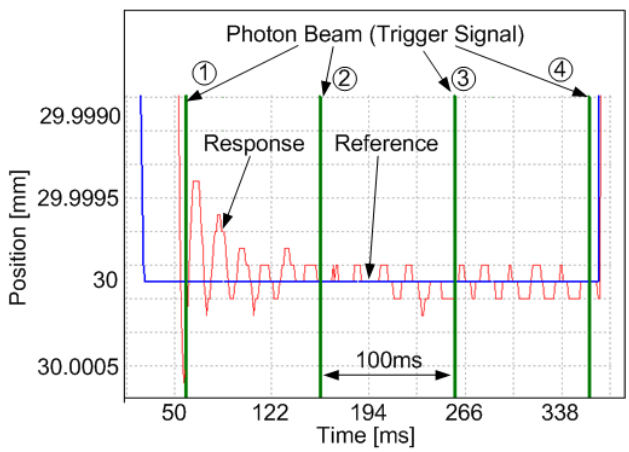

Figure 4: Positional misalignment (f = 1 Hz).

Implemented and Proposed Improvements

In order to increase the possible switching frequency, the translatory inertia had to be reduced significantly. This goal could be achieved by substituting the construction material of the vacuum vessel. A suitable material was found in titanium, a metal which is applicable for the use under vacuum conditions, whose mass is only half the one of steel and which offers a sufficient stiffness. Nonetheless, first tests with a vessel made of pure titanium (titanium grade 2) were not successful. After being mounted 3 times, the sealing edge of the flanges became unsuitable, showing deep striations and mechanical flattening. As a result, for the second test, the vessel was made of a titanium alloy (titanium grade 5 or TiAl6V4) which turned out satisfactory. The sealing edge endured a 20-fold reutilization without showing any damage.

By using titanium as vessel material, the mass of the assembly could be reduced to about 42 kg. Further mass reduction (ca. 5 kg) could be achieved by redesigning the aluminium adapter plate between the motor and the vessel. These provisions made it possible to enhance the maximum switching frequency to the desired 5 Hz. For the accuracy measurements, however, a roller-switch had to be installed in the travel path of the chamber, and the activation of which was correlated against the trigger impulse of the driving PLC. The switch was then used to synchronize the timing of the motion of the chamber with the measurements of a Newport Conex autocollimator. The chamber was then driven at 5Hz and the angular deflection measured at 200 ms intervals synchronized with the roller-switch. 46 measurements were taken, seemingly showing a distribution within the required 1 arcsecond deflection requirement (see figure 5).

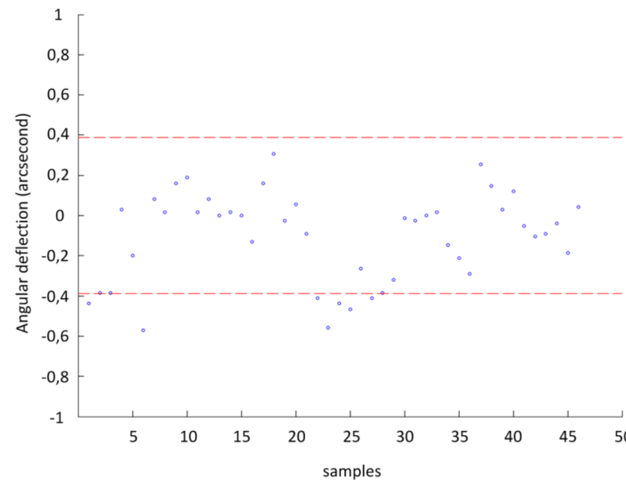

Figure 5: Angular deflection at 5 Hz.

As the autocollimator was not completely insulated from the significant vibrations resulting from the movement of the chamber, nor protected against errors resulting from air currents, and the low sample count, one can only give a tentative conclusion that the angular accuracy of the chamber may be acceptably within the 1 arcsecond tolerance requirement. Further tests are needed, and a greater sample population to give a proper statistical estimate of the accuracy of the chamber.

MIRROR MOTION WITH PIEZO MOTORS UNDER UHV-CONDITIONS

The mirror motion executed from outside the vacuum always requires components to compensate the motion, i.e. bellows. These bellows have a limited lifetime; the ones used guarantee 10 million cycles. Under a constant switching frequency of 5 Hz this would necessitate their replacement approximately every 23 days. With the operation of the drive components inside the vacuum vessel the bellows remain stationary. Furthermore the masses can be reduced significantly, the assembly becomes more compact. At the time of conception the availability of motors suitable for UHV conditions was in question, so the motion concept shown in figure 6 was developed. The mirror is moved by four piezo motors. These motors are attached to a stationary base plate which is mounted into the vessel. Linear bearings assure the motion perpendicular to the laser beam and two encoders continuously measure the position and a possible tilt of the mirror. The mass of the moved parts is approximately 10 kg.

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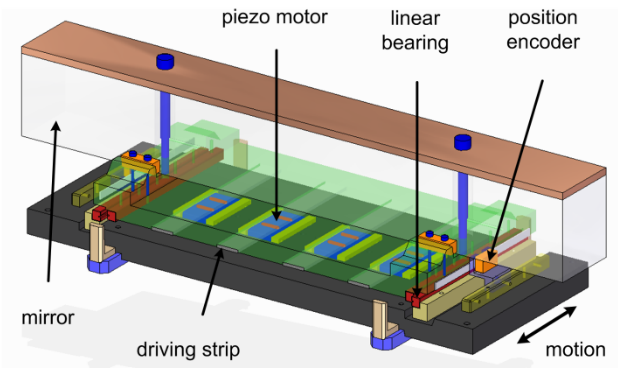

Figure 6: Motor test site with 4 piezo motors. [1]

The installed motors are the most powerful ones of the piezo motors series from the supplier Nanomotion (see figure 7). The Nanomotion HR8 motor has 8 finger tips. Through combining 2 oscillations with similar frequencies, these fingers generate elliptical movements. As the tips are pushed against ceramic driving strips, the slide performs a translational movement along the strips. Due to the small oscillation amplitudes the precision of the motor is below 100 nm.

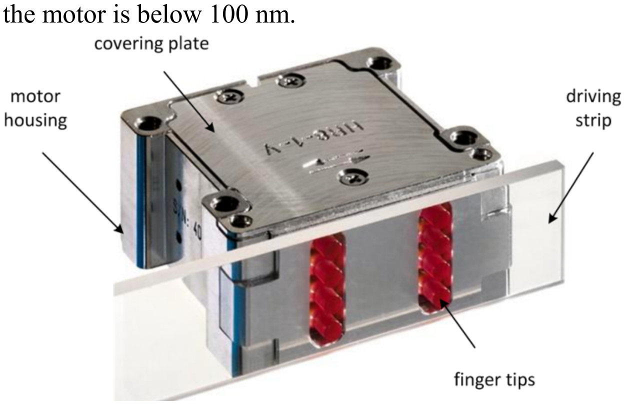

Figure 7: Piezo motor Nanomotion HR8. [3]

The maximum velocity the motor is able to achieve depends on the mass of the sliding carriage. Figure 8 shows a force vs. velocity diagram given by the supplier. In the test setup shown in figure 6 each motor has to move about 25 N, so the motion has to be executed in accordance to line h. Since adequate motor cooling has to be ensured (a total of 2 Watts has to be transported from each motor), under vacuum conditions the supplier permits a motion phase of only 40s, followed by a 400s cool-down phase. Furthermore the speed is limited to about 50 mm/s, which is far too slow for a mirror motion at the desired frequencies.

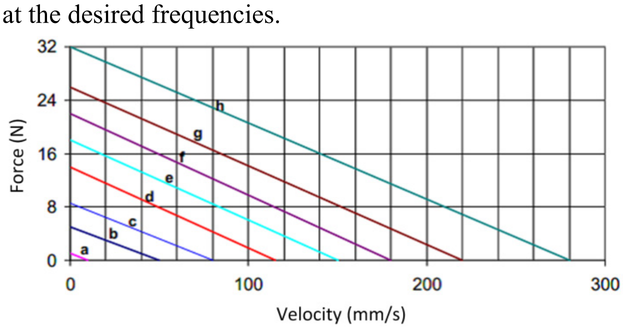

Figure 8: Force vs. velocity diagram of HR8 motor. [3]

Temperature Tests

To achieve a high switching frequency, it was necessary to make the motors operate out of the specifications given by the supplier, risking motor failures or even breakdowns due to overheating. Consequently, studies investigating the temperature development of these piezo motors under air as well as under vacuum conditions (10^{-4} mbar) were performed.

Although the maximum motor temperature under continuous motion is not given by the supplier, the bake out temperature is specified to be 140°C and is therefore considered the maximum temperature. At the beginning of the investigation, the “hot spots” of the motor under continuous motion on air were identified with the help of a thermal camera (see figure 9). For further investigation, a total of 6 thermal sensors (PT 100) were placed in these spots (figure 9). For the initial measurements the covering plate was left unattached. Motion was carried out with a maximum speed of 100 mm/s over a period of 15 minutes, while the stroke was defined 30 mm.

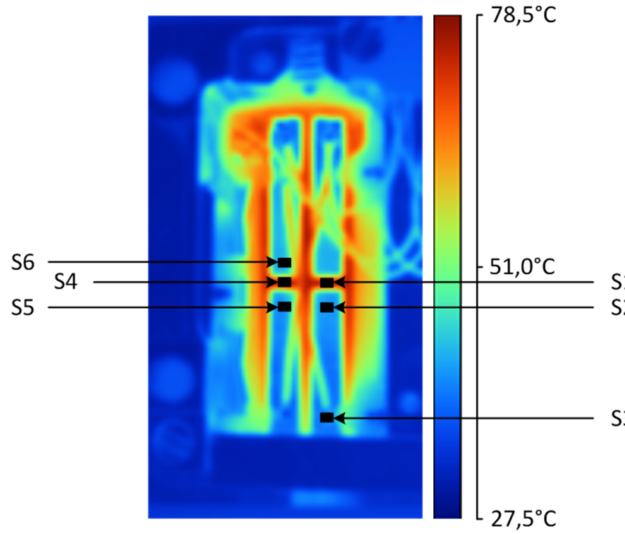

Figure 9: Thermal image of one of the piezo motors with PT100 sensor positions. [4]

The growth of the sensor temperatures in air can be seen in figure 10. The plot shows a tendency of each sensor to reach a stable temperature plateau after a short period of time. The sensor at the hottest spot reaches approximately 65°C, a value which is less than half of the defined maximum, so continuous motion can be assured.

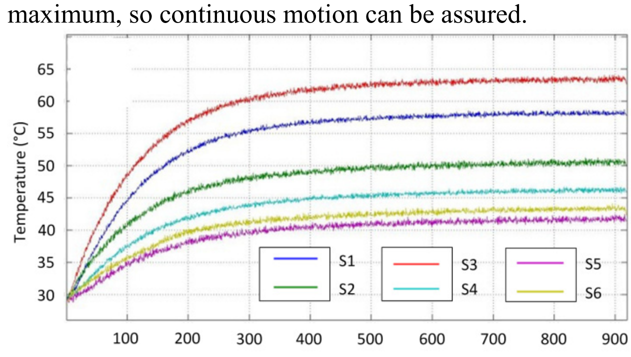

Figure 10: Sensor temperatures over time on air.

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When measuring the sensor temperatures with the motors running under vacuum conditions (10^{-4} mbar), a 25% increase in temperature of the surface sensors can be noticed (see figure 11). The maximum temperature is measured by sensor 3 with 85°C. The lateral sensors were affected even more by vacuum conditions and their temperature raised by 30% due to the lack of convection. The plot also shows that after 15 minutes the temperatures of all sensors are still rising, a stable plateau is not yet reached. This fact suggests performing additional measurements with continuous motion longer than 15 minutes.

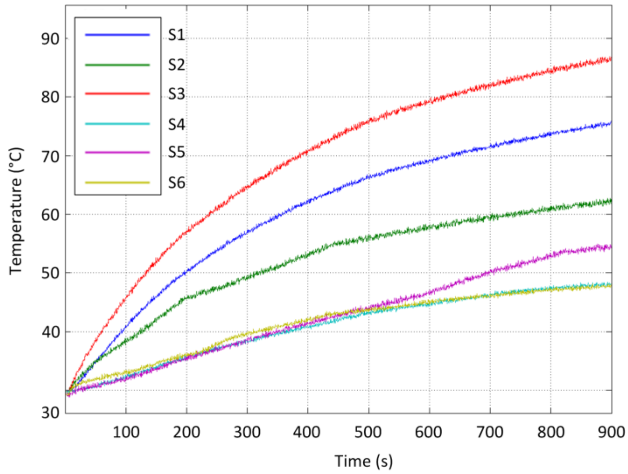

Figure 11: Sensor temperatures under vacuum conditions.

In the final measurements the impact of the covering plate on the sensor temperatures was studied. The period of measurement in this case was 50 minutes, in the interest of studying the cooling curve as well. It can be deduced from the figure 12 that heat reflection due to the mounted covering plate seems to play a major role. This can be seen in the increase of more than 20°C in the temperature of the hottest sensor, which now reaches 105°C. Nonetheless, continuous motion was still possible. The irregularities in the S1 sensor were caused by a bad contact with the motor's surface induced by the vibrations during the movement. Concerning the cooling, it can be described as a quite pronounced exponential.

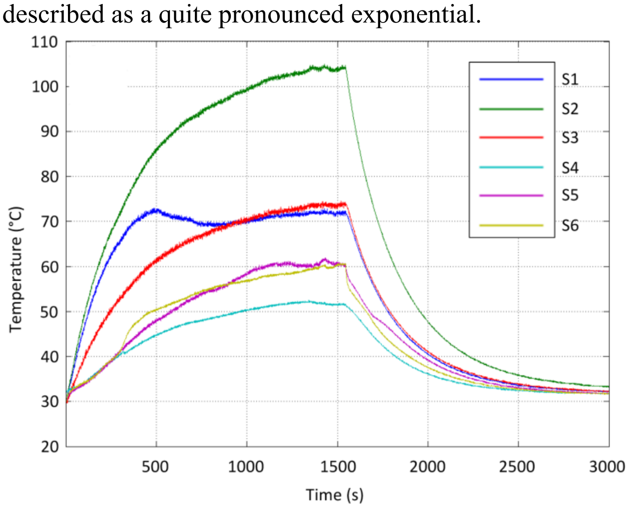

Figure 12: Sensor temperatures under vacuum conditions with mounted covering plate.

SUMMARY AND OUTLOOK

By using the present linear drive a motion from outside the vacuum vessel at a switching frequency of 5 Hz can be assured at the demanded precision. Problems occur as due to the high frequency strong vibrations affect the accuracy. Furthermore, vacuum bellows are inevitable, which therefore necessitate a frequent replacement due to their limited lifetime. By executing the motion of the mirror exclusively inside the vacuum vessel by piezo motors, masses can be reduced significantly and the frequent replacement of the bellows can be avoided. As the cooling of these piezo motors poses the biggest problem, temperature measurements were performed both in air and under vacuum conditions. It could be shown that during the measurements the motors reached temperatures up to 105°C. This issue is currently being addressed, and a possible solution has been determined, as can be seen in figure 13. It is planned to develop a new temperature test setup, which will feature a new piezo motor housing as well as provisions for water cooling.

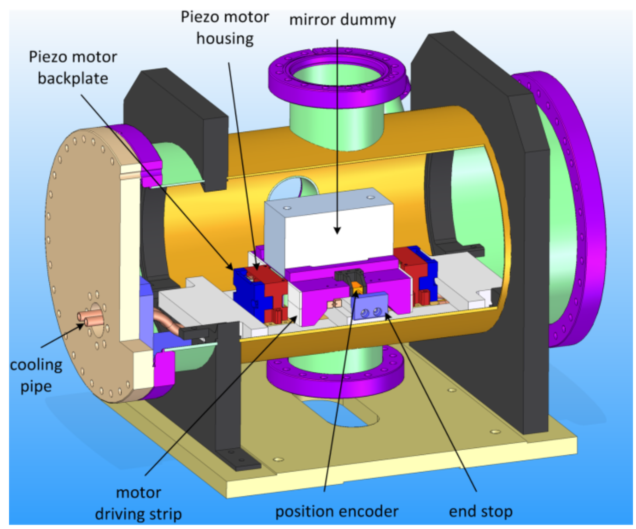

Figure 13: Proposed temperature test setup. [1]

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