Operating effects of mass reduction on a fast switching mirror and characterization of Ionization Profile Monitor parameters

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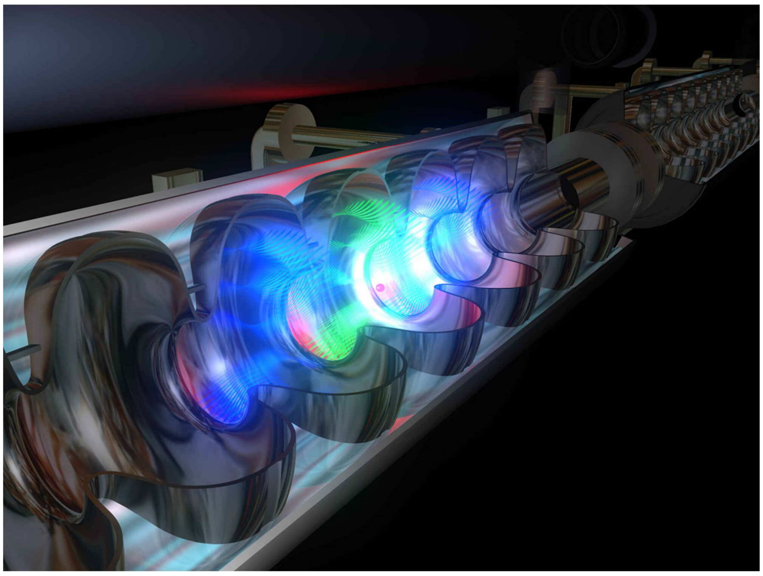

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Abstract
Logistical and metrological devices are crucial for the operation of modern accelerators and lasers. In the Free Electron Laser at Hamburg both are implemented, a beam-splitter is implemented in the form of a fast switching mirror and an Ionization Profile Monitor is used as a non-destructive, non-disruptive diagnostic device.

In this paper the performance improvements attempted with mass reduction of the mirror, and the recorded characterisation of the IPM parameters are outlined

1. Introduction

FLASH (Free-Electron laser at Hamburg) is a 315m linear accelerator that utilizes superconducting Niobium accelerating cavities to provide soft X-ray laser pulses. These laser pulses are in the order of femtoseconds, with a wavelength of between 4.5nm to 47nm, at a repetition frequency of up to 10Hz [1]. These unique pulses provide unparalleled experimental opportunities to investigate the atomic structure and the properties of materials, nanoparticles, viruses, and cells.

The beam can have a unfocussed width of 3mm to 5mm upon entrance to the experimental hall, the width of this beam has a dependence on the beam parameter settings; wavelength, train length, power, and repetition frequency. The beam can be focussed down to 20um with suitable optics, providing high photon density. Due to the high power, small pulsewidth, spotsize, and other unique properties, the laser pulses produced by FLASH are in high demand by users; the facility is perpetually overbooked.

Silicon mirrors, housed in large, evacuated steel chambers, are used to deflect the beam down different beam lines to the various experimental stations. Unfortunately, due to the nature of the light, the beam cannot be split to supply multiple experimental stations simultaneously; this monopolizes the beam to single operator for days, or even weeks. A possible solution to this issue was a new kind of switching mirror, providing automatic photon distribution between two beam lines.

A fast switching mirror unit was developed for such tasks and, depending on the time structure of the beam trains and on the demands of the user, the mirror could be moved freely back and forth up to a frequency of 2.5Hz. The prototype was installed in the FLASH experimental hall (*Fig. 1*) and is seen supported by an adjustment table and the developed vacuum vessel. Perpendicular to the beam, a high precision, fast moving linear motor was mounted. The motion of the mirror system was started with a machine trigger synchronized with the trains.

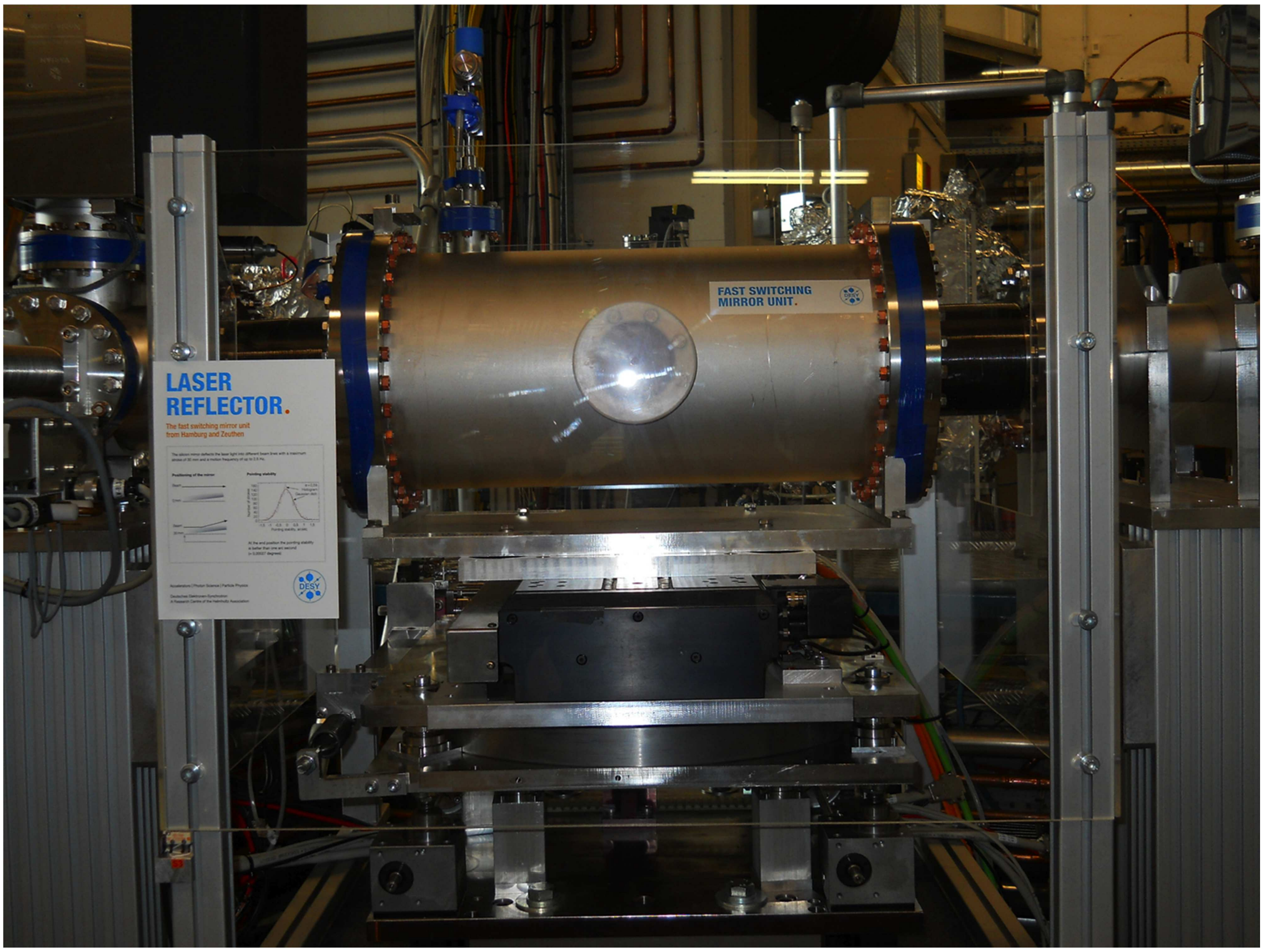

Figure. 1: Prototype fast switching mirror installed at FLASH in DESY Hamburg.

While the currently installed fast switching mirror can provide accurate and reliable results, it operates only up to a frequency of 2.5Hz. The maximum operational frequency of FLASH is 10Hz. In order to match this, the optimal operating frequency of the mirror would be 5Hz. It was anticipated that by reducing the mass of the chamber, a higher operating frequency could be obtained. To this end, the chamber was redesigned in Titanium instead of Steel, in order to reduce the mass from approximately 65kg to 42kg. The aim of this project was to determine the maximum obtainable operating frequency with increased speed, while maintaining matching precision, i.e. the error of the mirror has to be only few μm in position and about 1arcsec in angle.

2. Theoretical considerations

2.1. Positioning of the mirror

In order to facilitate the splitting of the beam, a fast moving mirror is implemented in order to deflect alternating bunch trains as desired.

The mirror must be synchronized with the generation of the pulses, as seen in the time scheme (*Fig. 2*), and contains dynamic motion periods and rest periods. For simplification, two assumptions on the mirror positioning (*Fig. 3*) were made: it was assumed that while in the extended position the mirror must be simply be absent from the beam path, and conversely, in the rest position it was assumed that the train duration was almost-instantaneous, or certainly in the sub-microsecond range, and that by extension, precision and reliability need only be maintained for a few microseconds.

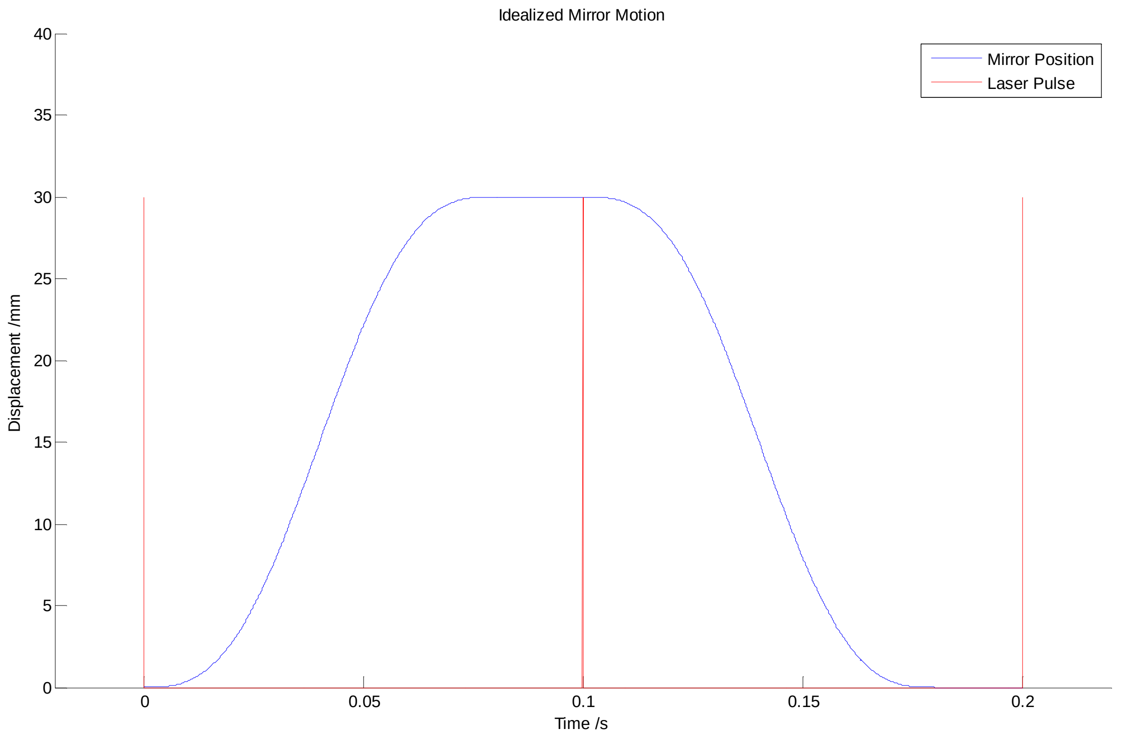

Figure. 2: General time scheme of the motion of the mirror.

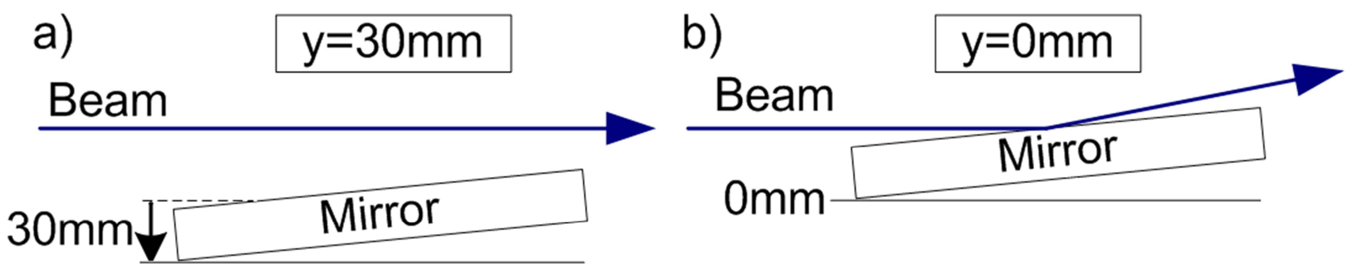

Figure. 3: Beam motion in (a) extended position (y=30mm) and (b) rest position (y=0mm).

2.2. Positioning and angular error

As was determined in the previous paper [2], the resulting positioning error must be small in relation to the diameter of the deflected beam. A positional error of between ±10μm was deemed an acceptable error tolerance, as the smallest the beam may be is 3mm. Similarly, as previously shown the horizontal angular tolerance is the only significant angular factor and required to be less than 1 arcsecond.

3.1. Main control block

A simplified block diagram of the mirror control is shown in (*Fig. 4*). It shows a vacuum vessel, a linear drive and a control system with a reference curve generator. A position encoder is used to measure the absolute position of the vacuum vessel, and this value is used as a feedback signal in the control system. The inputs of the mirror control are the system trigger, the frequency of motion *f* and the total stroke y_{max} which is constant (i.e. y_{max}=30 mm) in our system setup.

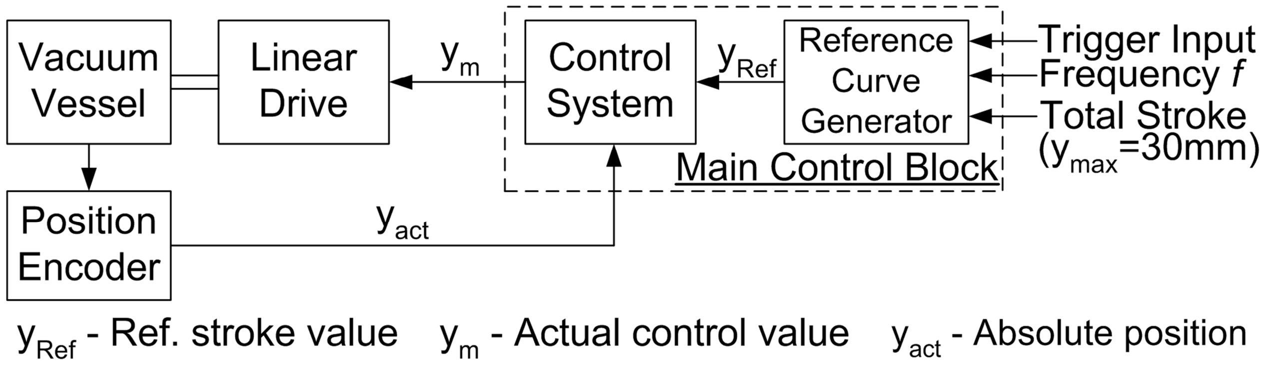

Figure. 4: Simplified block diagram of mirror control.

The vacuum vessel is driven by a linear motor [3] with a step precision of 0.1μm and a positioning accuracy of ±1μm. A drive-integrated motion and logic device [4] is applied to function as the main controller since it combines drive functions, motion control and processing logic in one device.

3.2 Driving the system

Due to the forces acting upon the system as a result of the pressure differential between atmospheric and the internal vacuum of the chamber and umbilicus, and a range of other variables, the acting forces on the system are unpredictable. As such the theoretical motions could only be loosely modelled in Matlab [5] to provide approximate figures for the velocity, acceleration and jerk of the system (*Fig. 5*).

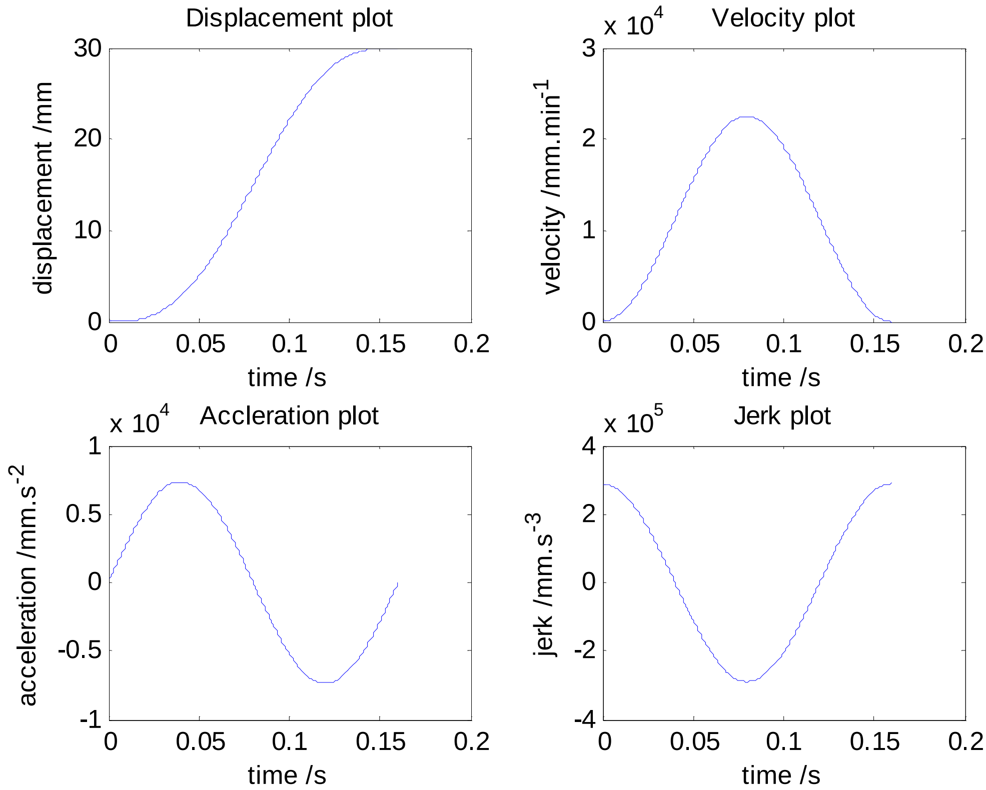

Figure. 5: Theoretically calculated kinematic approximations.

These values were then applied as the basis for achieving the desired frequency of operation. Additionally, the relaxed system tends to a stable state with minimum volume, thanks to the same restorative, atmospheric force that introduces the theoretical unpredictability. While this force resists systematic changes, reducing acceleration, it assists restorative changes. This was exploited as an additional accelerant for the return stroke to provide additional settling time.

In order to obtain the required accuracy, the controller settings then had to be experimentally derived through manual tuning of the system.

This was achieved using the inbuilt Oscilloscope of the controller software. This was then used to monitor the shape and magnitude of the kinematics, the error between the command position and feedback position in response to varying controller tunings.

4. Results

The previous prototype installed in Hamburg achieved a maximum driving frequency of 2.5Hz, and an accurate operating frequency of 1Hz. Instead, with the reduced mass, all attempts were made to bring the accuracy and precision of the 2.5Hz driving frequency within tolerance ranges.

One of the first successes of the reduced mass was to permit a maximum driving frequency of 3.125Hz with the increase in acceleration (*Fig. 6*).

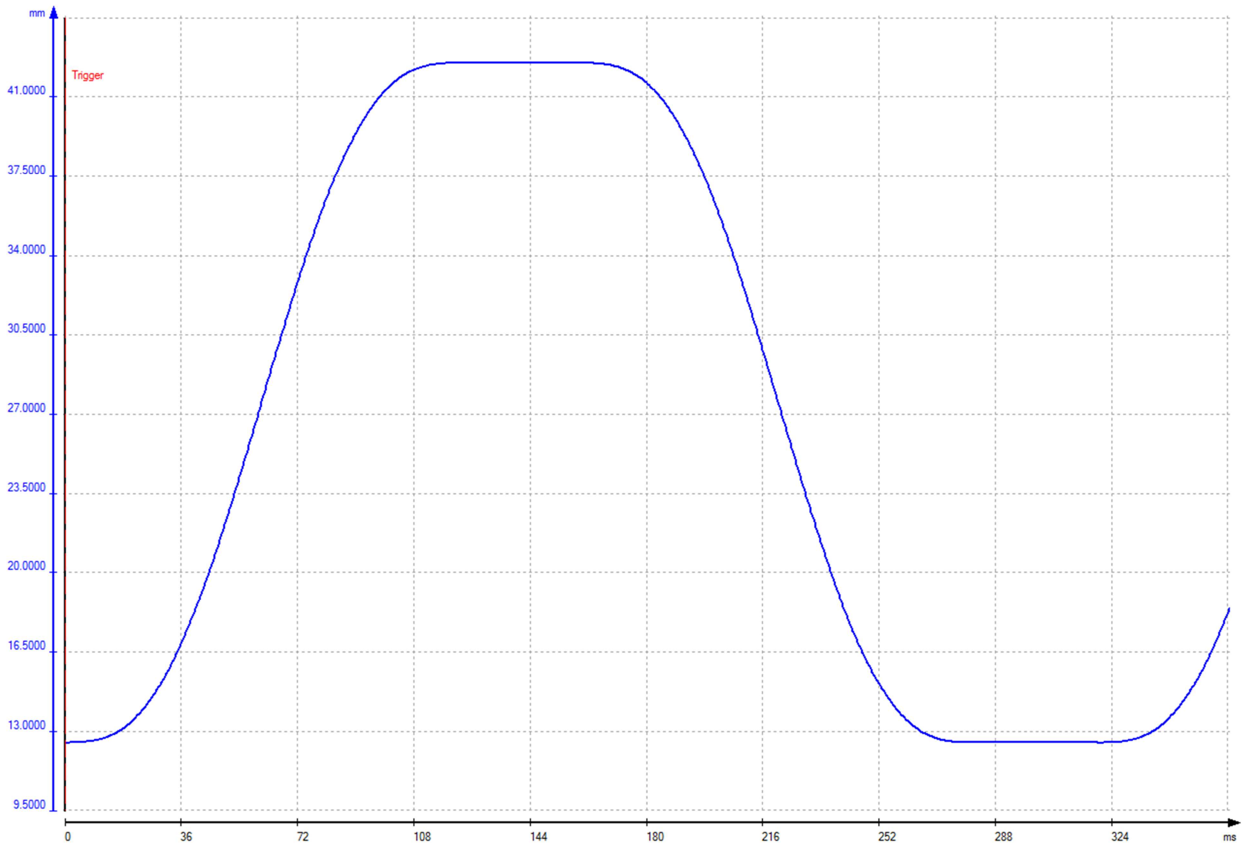

Figure. 6: 3.125Hz motion trace of the Titanium-housed fast switching mirror.

Further experimental work and careful tuning brought the motion of the chamber at 2.5Hz within acceptable positioning tolerances. To balance forces and speed with settling time, a 160ms stroke period was mated with a 40ms settling window to provide a 200ms half-period. A smooth motion was obtained on the return stroke with a 1.2µm variance over the tailing 10ms motion (*Fig. 7*).

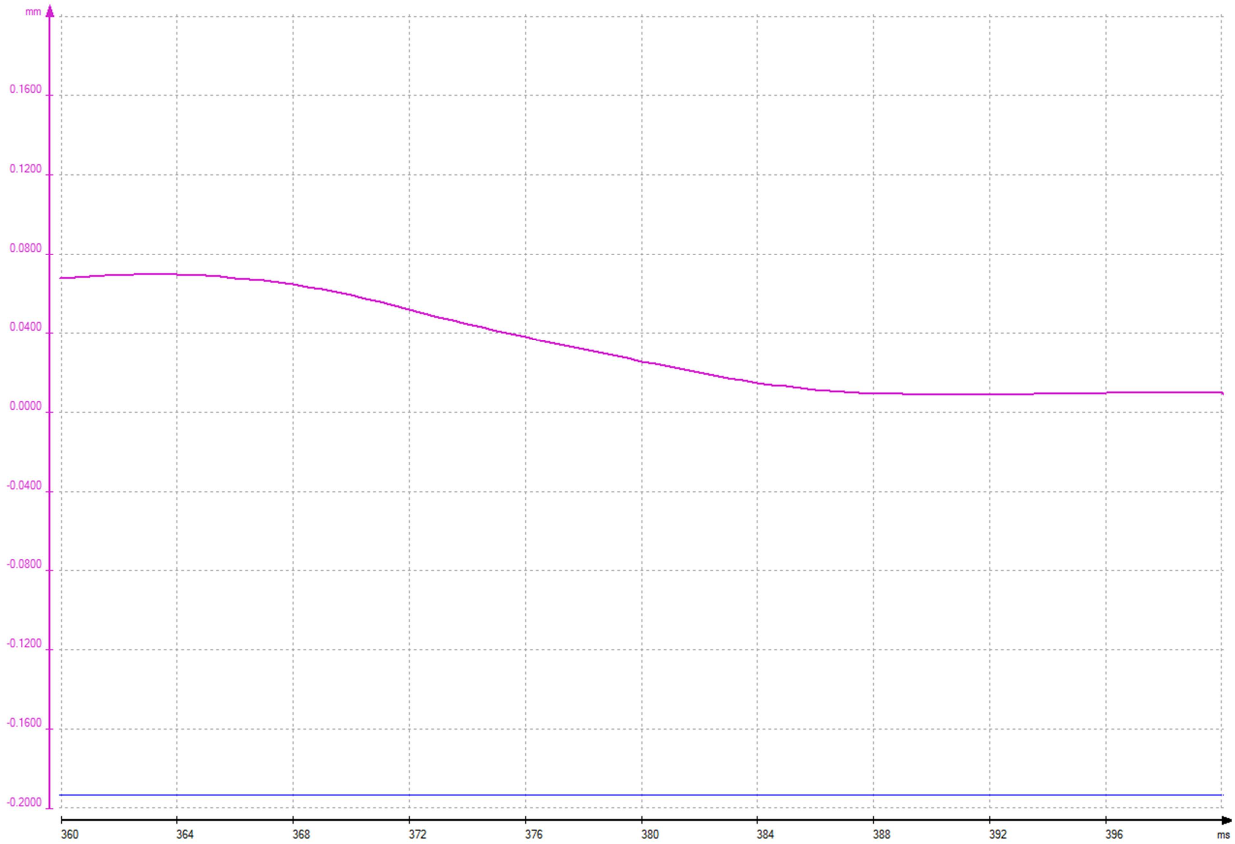

Figure. 7: 40ms settling window for 2.5Hz operation with 1.2um variance over a 10ms tail.

One issue encountered during the late development stage was the measuring frequency of the auto-collimator used to measure the angular deflection of the mirror. The collimator has a polling time of 40ms, which for an operating frequency of 1Hz is not an issue. In a half-period of 500ms, a 40ms measurement window is not a problem, but with a 200ms half-period the window is too large over a smaller few-ms photonic window, and introduces huge uncertainties in the measurement. Consequently, the collimator could not be used to measure the angular deflection of the mirror.

A proposed solution to this problem would be the synchronization of a visible laser pulse and a camera with the mirror trigger, and measuring any resultant displacement due to angular error with the camera on a distant screen (*Fig. 8*). Unfortunately, the available camera and optics had a resolution limit of 50µm, for a displacement error of this magnitude to appear, the screen would have to be 10m from the mirror. Such a distance through air might introduce optical distortion uncertainties.

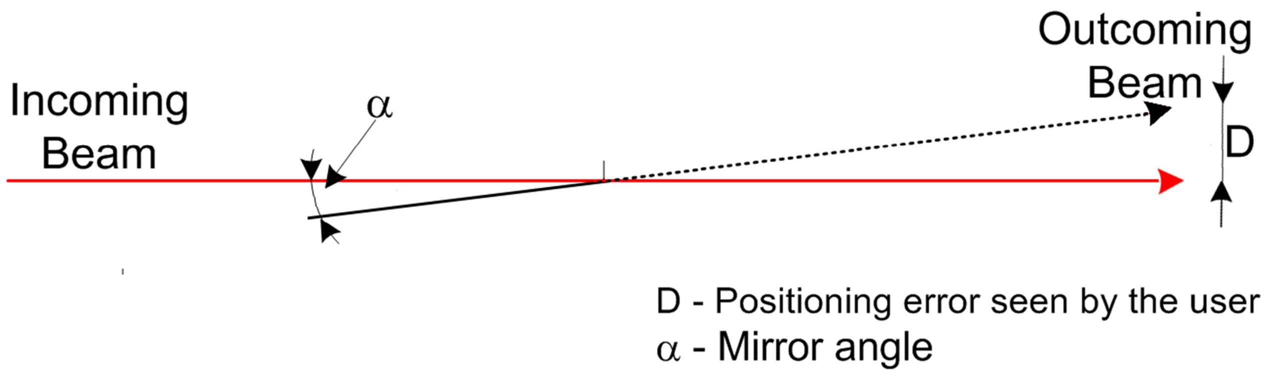

Figure. 8: Displacement due to angular deflection.

5. Conclusion

The mass reduction of the chamber facilitates the improvement in operational frequency never before achievable with the previous setup. The device can perform within the same positional error specifications but at a much higher frequency. Unfortunately due to equipment and time constraints, the angular error could not be investigated, but alternative investigative paths are proposed.

6. Introduction

Due to the high demands of FLASH users, every pulse is valuable and the stability and reliability of the beam is crucial. As such, while the traditional beam diagnostic tools such screens, wire-scanners, beam profiles, et al have their place as maintenance tools, the invasive and disruptive nature of these tools makes them undesirable during operational hours.

To remedy this, an Ionization Profile Monitor (IPM), based on the original prototype developed in DESY-Zeuthen, was implemented in the photon diagnostic section in FLASH. These devices work on the detection of secondary particles, as ions are generated by the interaction of the beam with the residual gas in the evacuated beamline. These particles are then accelerated perpendicularly to the beam by an independent, uniform electric field and towards a detector, a Multi-Channel Plate.

As the characteristics of the various parameters of the devices were never examined, what is presented here is the experimental investigation of the original prototype.

7. IPM Configuration

7.1 Working principle

The working principle of the original IPM prototype compares to that of the IPMs installed at FLASH, which have been previously discussed. [2] Consequently, only a brief overview and significant differences will be presented here.

The device consists of a cylindrical chamber built about the evacuated beamline, with a 25mm diameter MCP as a detector on one face, and the repeller plate on the other. The uniformity of the electric field produced by the repeller plate is reinforced by three further plate electrodes (*Fig. 9*). Despite the difference in construction design, the uniformity of the field compares to that of the "box" design of the FLASH IPMs.

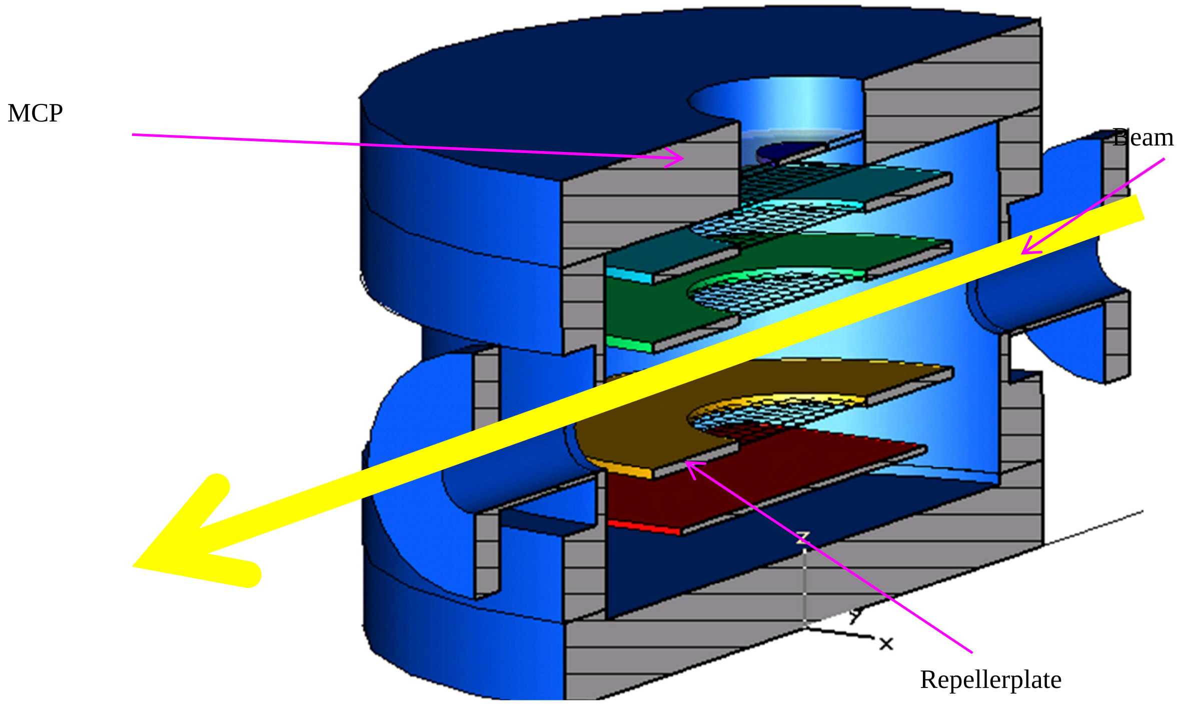

Figure.9: Schematic overview of the IPM.

In the laboratory, an electron beam was used to continuously generate the ions, with a beamline pressure of 10^{-6}mbar.

7.2 Micro-Channel Plate

The MCP used here is identical, and operates in the exact same way. The images produced by the plate were instead captured using a Basler A1390-17fc firewire camera with a Cosmicar/Pentax lens of 0.12m focal length. This provided a 250000pix^2 image with a 50µm.pix^{-1} resolution.

8. Characterization

8.1 Electric field uniformity

One of the prerequisites of the original IPM design was for the electric field to be as uniform as possible throughout the chamber, as any variance in the field would cause non-linearity in the resultant image. To test this, the IPM was set up (*Tab. 1*) and activated as per usual at a pressure of $2e^{-6}$mbar.

IPM settings

Parameter	Voltage /V	Voltage ramp up /V.s^{-1}	Voltage ramp down /V.s-1	Current limit /µA
Repeller plate				
Gegen	1496	50	100	100
Netz1	1193	50	100	100
Netz2	552	50	100	100
Netz3	212	50	100	100
MCP				
MCP in	-141	50	100	50
MCP out	1392	50	100	15
Screen	5984	50	100	10
e--gun				
Accelerating voltage	4500			
Filament current				40

Table.1: IPM settings for electrical field investigation.

The IPM was then displaced vertically, perpendicular to the beam, in steps of 1mm using a stepper motor and a positional encoder of 100nm accuracy. The 12mm range of displacement was limited by the edges of the field, in which electrical flashovers in the MCP began to occur. Images were recorded at each position; these were then imported into Matlab, averaged, and the profile center found. This was then plotted against the vertical displacement (*Fig. 10*).

For a perfectly homogenous electrical field, one would expect a linear correlation of physical displacement with image displacement. Any discrepancies in this would be an indication of field irregularities.

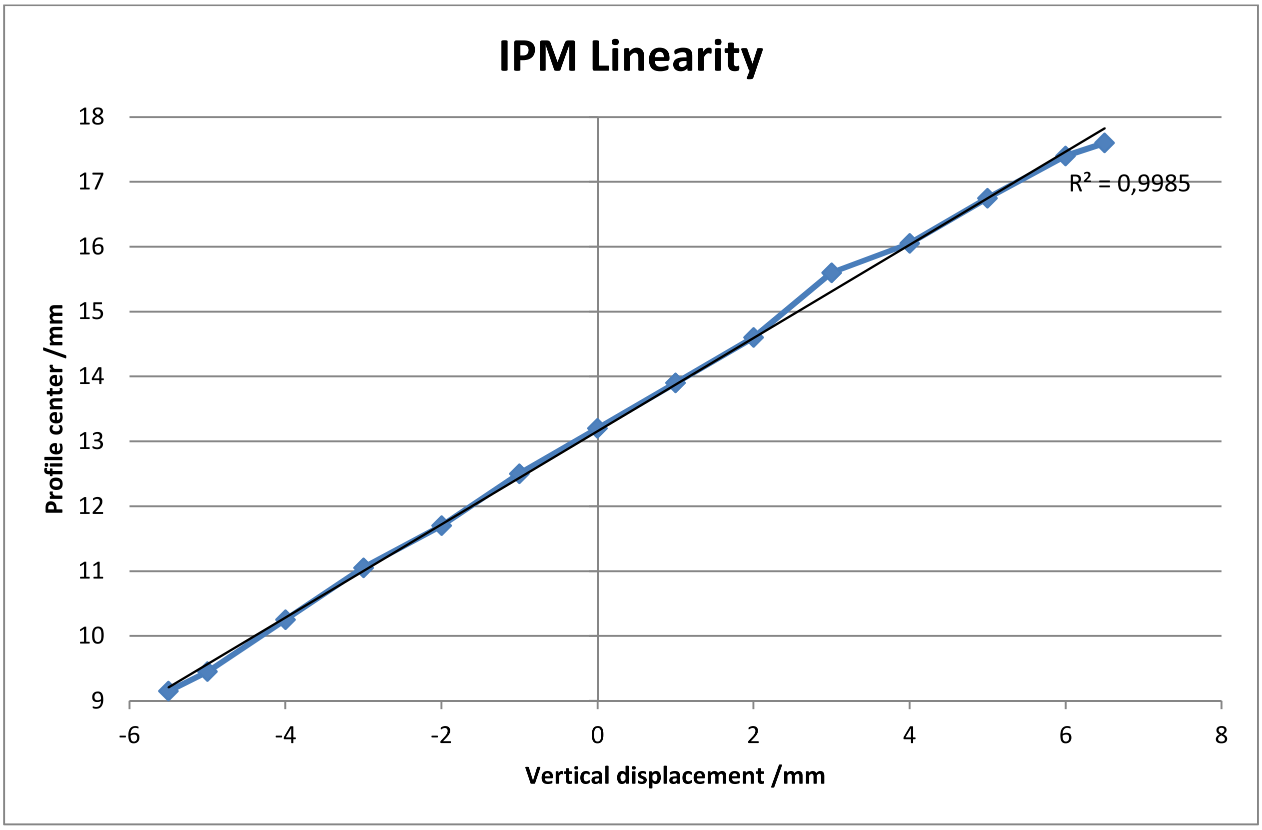

Figure.10: Relationship of displacement with profile center.

As can be seen, the linear relationship manifests itself, while the curving tails of the graph indicate the expected non-uniformity of the field at the very edges.

8.2 Electric field strength

Another avenue of investigation was into the effect of the strength of the electric field on the profile. One would expect that with greater electric field more particles would be captured with greater velocity, and that the image would become brighter, but noisier.

The repeller plate voltage was increased in steps of 500V, while the electron gun was maintained with an accelerating voltage of 4.5kV and a filament current of 40µA, all measurements were taken at a pressure of 10^{-7}mbar.

Gegenplatte settings

Parameter	Voltage /V	Voltage /V	Voltage /V	Voltage /V
Repeller plate				
Gegen	500	1000	1500	2000
Netz1	399	798	1196	1595
Netz2	185	369	554	738
Netz3	71	143	214	286
MCP				
MCP in	-48	-95	-143	-195
MCP out	1300	1300	1300	1300
Screen	6000	6000	6000	6000
Magnetic correcting coils				
Upcoil	2,4	4	5,18	6,8
Downcoil	2,4	4	5,7	6,8

Table. 2: Repeller plate voltages with MCP and magnetic corrections.

Unfortunately, this vacuum was too good, and left too little residual gas in the chamber to be ionized and accelerated for repeller plate voltages below 1.5kV, as such only images for greater voltages were recorded. A corresponding increase in brightness was observed for increasing voltage, but no definitive correlations could be made with so few measurements (*Fig. 11*).

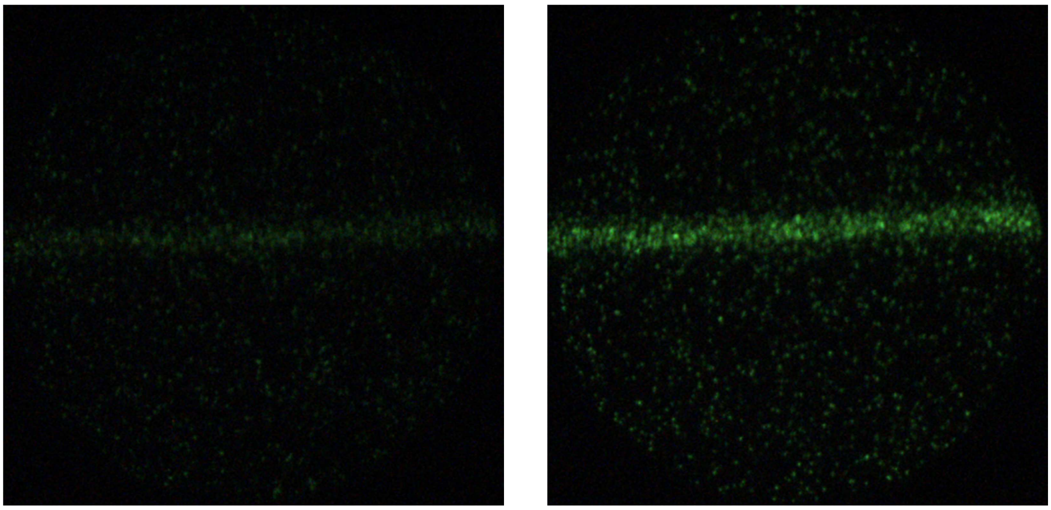

Figure. 11: Comparative images of 1.5kV and 2kV repeller plate settings.

9. Conclusion

The tests performed revealed expected characteristics. The electric field was found to be quite uniform, and image bright was found to increase with increasing field strength. However, improvements on both measurements could be made.

For the field uniformity, smaller steps of 0.5mm could be taken, with higher resolution optics preferably providing a resolution of 10µm.pix^{-1} to match the 10 µm resolution of the MCP. For field strength measurements, a stable pressure of 10^{-6}mbar or an electron gun capable of higher filament currents would provide greater signals from lower repeller plate voltages.

One further test that could be performed is effect of various residual gases over differing pressures, N_2, Xe, Ne, etc. on the beam profile and brightness.

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