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DEVELOPMENT OF A LINEAR FAST SHUTTER FOR BM05 AT ESRF AND BEATS AT SESAME

C. Muñoz Pequeño [†], J. M. Clement, P. Thevenau, P. Van Vaerenbergh
European Synchrotron Radiation Facility, 38043 Grenoble, France

Abstract

A new linear fast shutter for X-ray topography and tomography is currently under development. This first prototype will be assembled and tested on the BM05 beamline at the ESRF, and another unit will be installed in the future BEATS beamline at SESAME. The new shutter aims to overcome the stability, control and thermal issues reported with previous versions. This versatile design can be used with monochromatic and white-beam, reaching minimum exposure times of 50 ms for a beam size of H 80 mm × V 20 mm.

Powered by two linear brushless DC motors, the exposure sequence is achieved through the synchronization of two tantalum blades. This concept has been tested in a dedicated bench to characterize the sequence produced by the linear motors, and exposure times of 50 ms with a maximum error of 1.5 ms have been measured. This article describes the main features of the shutter prototype design and its associated motion control system. The main results of the measurements with the test bench are discussed as well.

INTRODUCTION

Fast shutters are widely used in synchrotron beamlines for applications in X-ray topography and tomography. Topography typically requires exposure times ranging from milliseconds to hundreds of seconds. Due to its low signal-to-noise ratio, it is essential to shield the CCD detector during readout to avoid added noise [1]. In addition, shutters are of special relevance when performing white beam tomography in delicate samples that are easily degraded when exposed to high photon flux. The use of a shutter allows for sample repositioning and prevents sample irradiation when data is not being recorded. This highlights the importance of the control in the exposure time and its uniformity to guarantee an adequate image quality.

In the context of the refurbishment of the BM05 instrumentation beamline at the ESRF, an old shutter was installed in the tunnel located before the experimental hutch EH2. In this model, the exposure sequence was achieved through the synchronization of two stainless steel blades powered by electromagnets. However, in addition to the tremendous vibrations and the limited duration of the exposure cycle due to the electromagnets overheating, their control system was obsolete. The main motivation of this project was to develop a new shutter that can overcome these issues with up-to-date controls to replace the prototype installed at BM05. Another prototype is being developed for installation in the experimental hutch of the BEATS tomography beamline currently under construction at SESAME [2].

[†] munozpeq@esrf.fr

DESIGN

The main advantage of the proposed concept is its suitability for larger beams thanks to the use of linear brush-less DC motors featuring high dynamics and precision. Other technologies often employed in the synchrotron community, such as rotary and piezoelectric shutters [3], can achieve very small exposure times as well, but over much smaller beam apertures.

Table 1: Fast Shutter Specifications

Parameter	Value
Beam size [mm × mm]	80 × 20
Exposure time [ms]	< 100
Repetition rate [Hz]	> 1
Maximum beam power [W]	380
Blade material	Tantalum
Blade thickness [mm]	4

The motors have been selected to fulfil the specifications listed in Table 1. The objective is to achieve a reproducible and uniform exposure time over the beam window. The exposure cycle is achieved through the synchronization of two blades so that the exposure time depends on the delay between their opening and closing trajectories. Therefore, it is crucial that the trajectories of the blades are identical, i.e. to ensure the delay between the opening and closing of the blades, Δt_1 and Δt_2, is the same for all the points of the window (see Fig. 1).

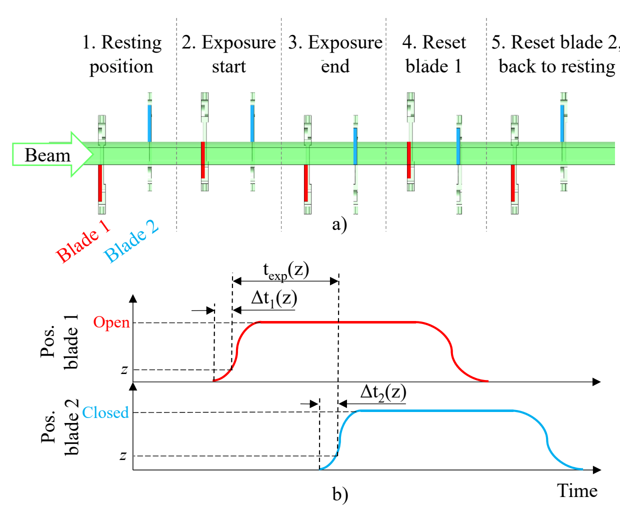

Figure 1: Exposure sequence, a) schematic of the phases of the exposure cycle b) diagram of the blades trajectories.

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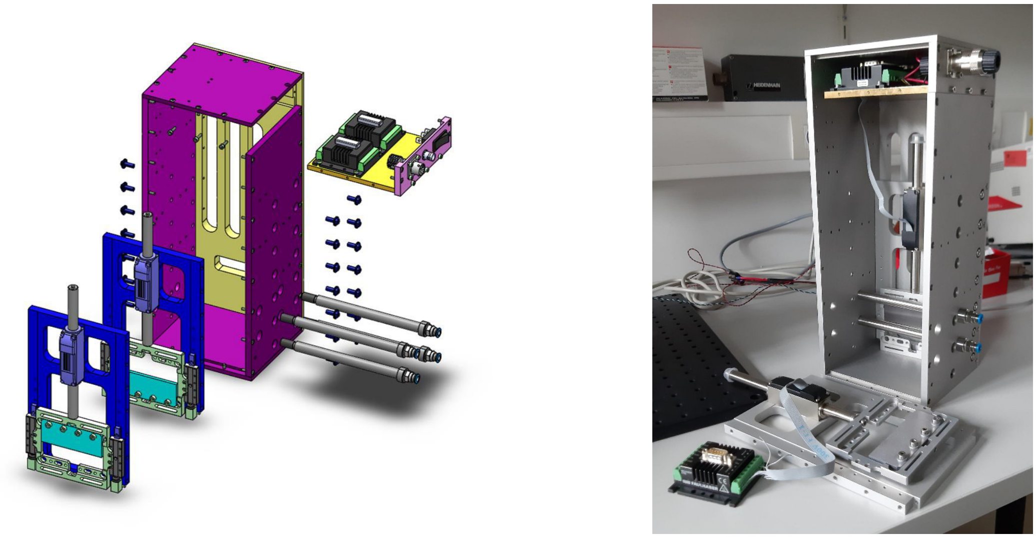

Figure 2: 3D model and picture of the prototype in construction.

The proposed sequence is schematized in Figure 1. When the exposure starts, the first blade is opened, allowing for beam exposure. Once the desired exposure time is reached, the second blade is closed, stopping the beam irradiation. Then, the first blade and the second blade are reset to their original position one after the other.

Linear Motors and Control

The chosen solution for the blades motion are brushless DC linear motors from Faulhaber. The main parameters of the employed model LM2070-80-11 are listed on Table 2. They feature high compactness, easy installation, and a good dynamic performance that allows for the rapid timing required for short exposures. These motors consist of a 3-phase coil housed in a non-magnetic steel stator. The high-power magnets drive a magnetic multi-pole rod, and Hall-sensors are integrated in the stator housing for positioning control.

Table 2: Linear Motor Specifications

Parameter	**Value**
Stroke [mm]	80
Continuous force [N]	9.2
Peak force [N]	27
Continuous current [A]	0.79
Peak current [A]	2.4
Accuracy [µm]	300
Repeatability [µm]	80
Temperature range [°C]	-20 – 150

Each motor is actuated by a controller MCLM3006 S with interface RS232, which is programmed independently to follow a sequence that can be triggered by a TTL signal. The two positions of the blade are pre-programmed, and to switch between them, a basic triangular profile of velocity is implemented, i.e. the blade is accelerated up to the mid-point of the movement with the maximum acceleration, then it brakes with the maximum deceleration.

The sequence is programmed as it follows:

- Power ON: the blades go to their resting position.
- Control signal transition from 0 to 1: the first blade moves to the open position.
- Control signal transition from 1 to 0: the second blade moves to the closed position. The first blade waits for a delay and returns to its original position. After another delay, the second blade returns to its original position.

Mechanics

Figure 2 shows the general overview of the shutter. The blades are installed in two identical aluminium frames optimized to avoid stress concentrators while keeping a light mass. The assembly blade-motor is attached to a support with two ball bearing guideways Schneeberger of the MSQ line. These can work at velocities and accelerations up to 3 m/s and 300 m/s^2, while withstanding temperatures up to 150 °C.

These supports are assembled onto a protective cage of dimensions $15 \times 15 \times 40$ cm , which has been carefully designed to respect the distances between the motors and the rest of the elements to avoid magnetic forces that would compromise their performance. The controllers are assembled onto a 5 mm thick lead plate to shield the electronics from radiation. Each blade is cooled by two buffers that ensure continuous nitrogen flow at the two blade positions.

Thermo-mechanical Analysis

A thermo-mechanical FEA analysis has been implemented with Ansys to determine if nitrogen cooling is enough to guarantee the safe operation of the shutter. The convection coefficient has been estimated at 300 W/m^2°C through empirical correlations [4] with an inlet pressure of 1.4 bar.

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The results are shown in Fig. 3, which depicts a maximum temperature of 218 °C and a maximum stress of 173 MPa in the aluminium frames, well below its maximum working temperature and elastic limit.

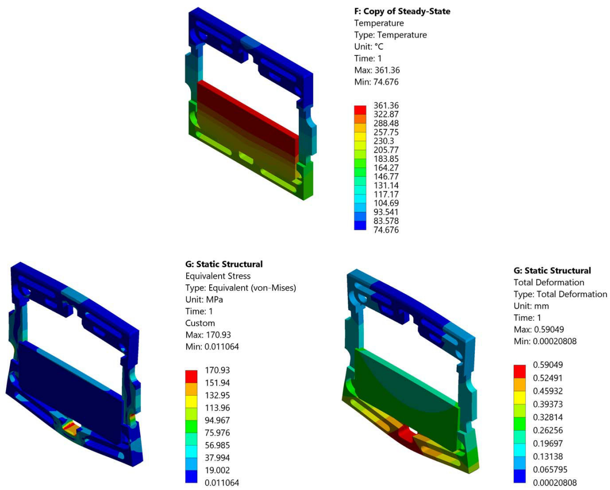

Figure 3: FEA analysis results of the shutter blade and frame.

TEST MEASUREMENTS AND RESULTS

The synchronization of the motors has been tested in a dedicated bench to recreate their working conditions and characterize the blades trajectories. The goal of this setup was to reconstruct these trajectories by measuring the delay the blades take to reach different positions of the window.

To do so, a movable frame containing a laser and a photodiode is fixed at different heights to perform the measurements (see Fig. 4). The photodiode detects the laser beam passing through the shutter, and its output is connected to an oscilloscope to analyse the resulting signal.

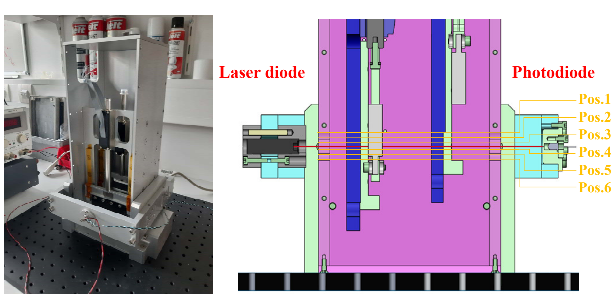

Figure 4: Picture and 3D model of the test bench setup.

When the laser-photodiode is fixed at a position , the time elapsed between the opening order for the first blade and the detection of light by the photodiode is the time taken by the first blade to reach position , $\Delta t_1()$. Analogously, the time elapsed between the closing order for the second blade until light is no longer detected corresponds to the time taken by the second blade to reach position , $\Delta t_2()$.

40 cycles have been measured at 6 different heights with an exposure time of 100 ms, as shown in Figure 4. The average trajectories reconstructed through these measurements are shown in Fig. 5, revealing that the maximum deviation in the exposure and reaction times is 1.5 ms. The reaction time ranges between 6 -7 ms, while the rising times for rearming are between 62-70 ms. Time between exposures down to 300 ms can been used, but the system becomes unstable if values lower than this threshold are used.

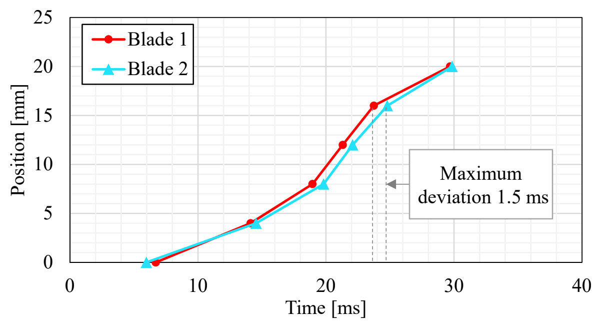

Figure 5: Measured blade trajectories.

CONCLUSION

A versatile design for a linear fast shutter based on linear brushless DC motors has been presented. The feasibility of this concept has been proved through a series of tests, which show that short exposures of 50 ms can be reached with a maximum error of 1.5 ms and time between expositions down to 300 ms. The prototypes for BM05 and BEATS are almost ready for commissioning, and in later stages, the thermal and fatigue behaviour of the system under white beam will be analysed. This design can be adapted to other shutters with different strokes and blade materials if the timing of the motors is optimized.

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