A MECHANICAL SHUTTER TO SELECT SINGLE BUNCH TRAINS AT THE FLASH FACILITY AT DESY

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Abstract

A fast mechanical shutter to select single photon bunch trains of the free electron laser FLASH is described. FLASH is installed at the Deutsches Elektronen-Synchrotron DESY in Hamburg and is based on superconducting linear accelerator technology. The accelerator provides bunch-trains with a repetition rate between 5 and 10 Hz. This time interval of down to 100 ms makes it possible to use a mechanical shutter system to select single bunch-trains for sample excitation.

A programmable logic controller (PLC) is used to steer a servo system based on an electronically commutated (EC) low-voltage motor. To select a bunch-train, the motor is started at the time when one train passes the station. During the following 100 ms, the cylinder is turned by 180°, leading to a movement of the shutter by 48 mm to the fully open position, thus allowing the passage of the following bunch-train. During the next 100 ms the rotation is continued to the 360° position, thus blocking the next bunch-train by pushing the shutter back to the fully closed position.

INTRODUCTION

Since 2005 the first FEL user facility for soft X-ray coherent light experiments FLASH is in operation at DESY [1]. The facility consists of a superconducting accelerator in combination with a 30 m long undulator producing highly intense (~GW) and extremely short (~10 fs) photon pulses. The superconducting linear accelerator creates and accelerates bunch-trains with up to 7200 bunches within 800 µs (at 10 Hz).

The experimental hall of the user facility is located approximately 30 m behind the last dipole magnet which separates the electron and the photon beam. The photon beam transport system delivers the FEL radiation under ultra high vacuum conditions to the five different end stations, which can be used alternatively.

The photon pulses energies are generated with an average energy of 10 µJ. Solid state samples irradiated in normal incidence are easily destroyed when the photons are focused to a spot size of ~20 µm. To study such damage processes it is important for FEL users to control the irradiation process. The 5 to 10 Hz repetition rate of the bunch trains allows the use of a mechanical shutter to select single bunch trains for sample irradiation.

The fast mechanical shutter is installed in the shared part of the first three beamlines. Figure 1 shows the shutter installed in the beamline system.

The fast shutter consists of a glassy carbon [2] shutter blade with a thickness of 4 mm. The blade motion is generated by a special linear drive developed for fast wire scanners for FEL electron beam diagnostics [3, 4]. The shutter covers the beam aperture of 20 mm.

In this paper, we report on the technical layout of the fast shutter, and first experimental results of a time-resolved damage and ablation measurement are presented.

TECHNICAL LAYOUT

Mechanical Set Up

Figure 2 shows the mechanical design of the fast shutter. The central part is the glassy carbon blade connected to the linear drive unit. Glassy carbon is chosen because of its low density of 1.6 g/cm^3 combined with high mechanical stability, good reflectivity in the spectral

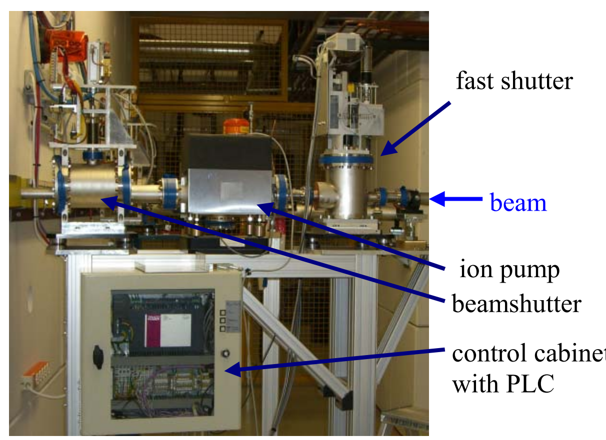

Figure 1: The fast shutter installed in the FLASH beam-line system .

range of the FEL and the thermal robustness of carbon. The fast shutter has to be operated under ultra high vacuum conditions. As linear vacuum feed through a welded bellow is used. An incremental length gauge for position detection is connected to the linear drive. The essential features of the fast shutter are the stroke of 48 mm combined with a maximum shutter speed of 1 m/s in the linear velocity range of 24 mm. The speed is needed to shorten the opening and closing times into the ms range. The movement of the shutter blade is based on a slot winding cylinder (see Fig. 2 + 3) transforming the rotation of the servo motor into a linear motion [3, 4].

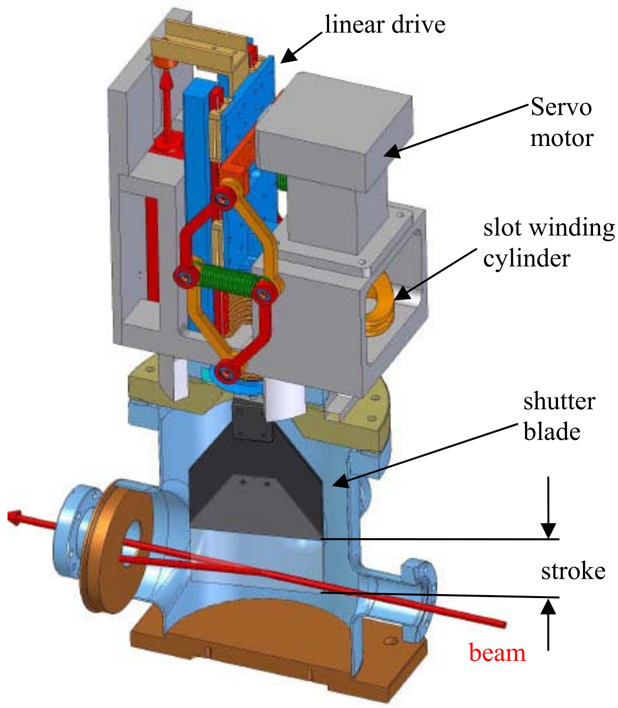

Figure 2: The mechanical layout of the fast shutter.

The cam of the slot winding cylinder uses the transfer function of a Bestehorn-sinuide (see Fig. 3):

$$S = s_0 \left[\omega t - (1/2\pi)\sin(2\pi\omega t)\right]$$
$$0 \leq \omega t \leq 1$$

where S is the stroke of the run up and down phase, s_0 the maximal stroke of 24 mm and ωt the normalized transmission angle. The region ωt = 0 until ωt = 1/2 represents the run up phase while ωt = 1/2 until ωt = 1 describes the run down phase. The speed and acceleration is given by

$$S' = s_0\, \omega \left[1 - \cos(2\pi\omega t)\right]$$

$$S'' = s_0\, \omega^2\, 2\pi \sin(2\pi\omega t)$$
$$0 \leq \omega t \leq 1$$

At a stroke of 0mm the shutter is totally closed. The start up range between 0 and 12 mm accelerates the shutter to the opening speed of 0,36m/sec. Between 12 and 36 mm the shutter blade releases the photon beam aperture of 20mm. In the range from 36 to 48 mm the shutter blade changes the moving direction. When the blade transfers this range the photon bunch train can pass the shutter. Figure 3 shows the stroke, speed and acceleration of the blade during one turn, assuming that the shaft is rotating with constant speed.

The motor is connected to the slot-winding cylinder with a gearing-ratio of 15:1. For 10Hz operation, rotation speeds of the shaft of 450rpm and accelerations of 6750rpm/s are needed.

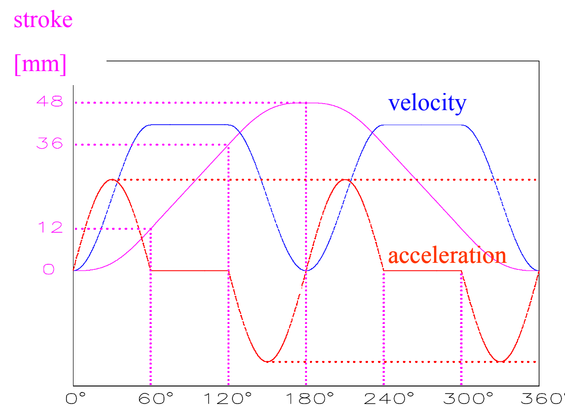

Figure 3: The transfer functions of the slot winding cylinder (Bestehorn sinuide).

Electronic Set Up

The electrical setup of the fast shutter is shown in Fig. 4. The central part is a PLC-controller with IO-Modules [5]. The controller acts on a servo system via a field-bus (CAN open [6]). The servo system consists of the servo controller/amplifier, the motor and two integrated feedback systems [7]. These components alone allow the

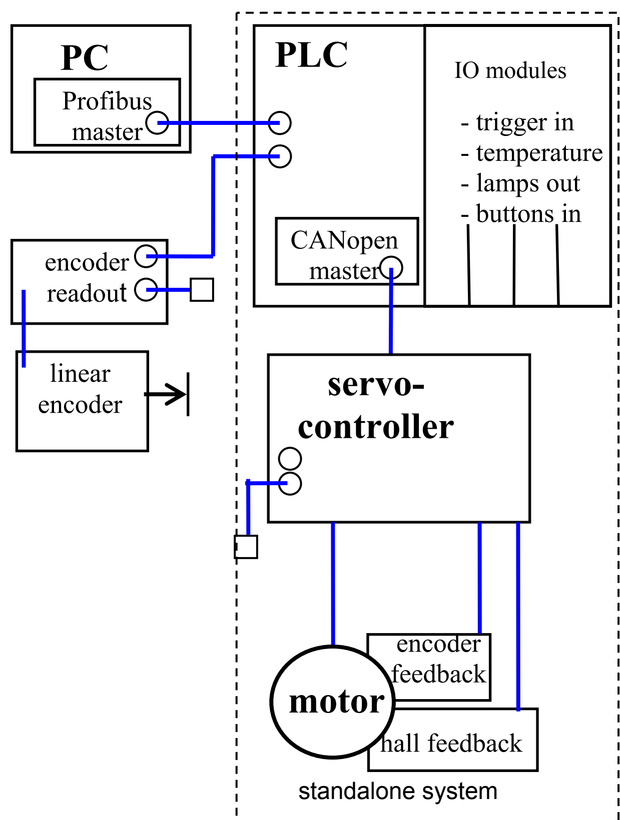

Figure 4: Layout of the electronic set-up.

operation of the fast shutter. In addition a PC, housing a Profibus-master card, was connected to the PLC. With the PC the parameterization and programming can be performed. Furthermore a Profibus-interface to read out the linear gauge is connected to the Profibus line. The linear gauge can only be accessed by the PC and be used for an independent feedback of the shutter position for diagnostics. All major components are described in the following.

All electronics parts are standard components from the general automation market. They are contained in a standard compartment, as shown in Fig. 1. Most space is occupied by the power supplies and the terminals to route the various electrical signals.

The PLC controller is programmed and parameterised from an external PC, but operating in a standalone mode afterwards. The cycle time for the SPS program was chosen to run at 3ms, which means that the whole program is running within 3ms under any condition while sampling inputs and setting outputs. The controller acts as a client on the Profibus and reactions to Profibus commands can be programmed. This allows the control from a master PLC in our case running on the PC. The connection to the beamline interlock system can be routed via this bus.

For the CANopen subsystem, the controller acts as a master. The CANopen subsystem is running with the cycle time of the PLC, allowing a fast reaction on events. Inputs and outputs are provided by appropriate IO-modules. Most important inputs are the user commands, generated by output cards of the FLASH experimental control system, by button states and the bunch signal. The bunch signal, derived from the FLASH-timing, announces the arrival of a photon bunch. This signal is stretched to 10 ms to be detected by the PLC.

The servo system uses an electronic commutated motor. While the controller/amplifier is connected to 48V DC, the motor is provided with two sinusoidal voltages to its static coils. The rotating permanent magnet follows the generated current. In contrast to a stepper-motor, the rotor position is measured by hall-elements to determine the absolute position of the magnet. To reach the ultimate precision for the velocity and position-control loops, an additional incremental encoder is attached to the motor shaft.

The controller firmware enables the user to work with the three nested servo-loops (current, velocity and position) in an easy way. Parameters are determined by an automatic tool and are stored together with further application specific data on the internal flash memory. Due to the CANopen standard, devices of various vendors can be mixed and exchanged, securing investments over the coming years.

In contrast to stepper-motors, the servo system can use a much larger speed-torque parameter space due to the active regulation.

Operational Principle

The shutter can be opened and closed by electrical signals, i.e. generated by buttons. The user commands are routed by the FLASH-control system via output-cards to 5V inputs of the PLC. Status information is transferred from the PLC via 5V terminals and input-cards to the user.

The states of the shutter are: ‘open’, ‘close’, ‘single shot’, ‘synchronized shot’ and ‘home’.

The home-mode is needed to orient the controller after power up. The shutter is driven to the open position until a precision switch mounted close to the open position is triggered.

All other movements are always executed synchronously to the bunch-trains.

After an open or close signal, the next following bunch-train-clock is waited for. When the PLC detects a rising edge on the bunch-signal, the motor is commanded to perform a 180ºrotation of the cylinder. This is thus changing the state of the shutter from closed to open or vice-versa.

After the detection of a single-shot signal, the procedure is executed in the same way but initiating a 360º turn of the cylinder. The timing of the later procedure is depicted in Fig. 5.

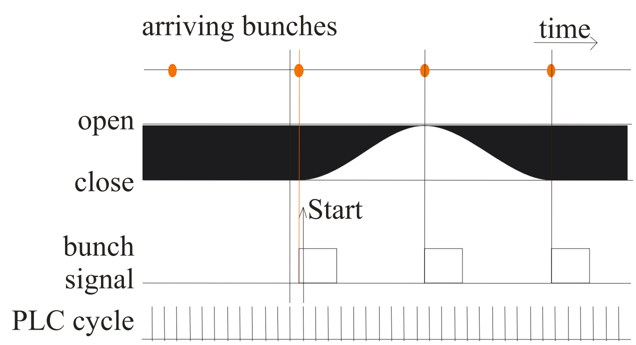

Figure 5: Timing scheme of the synchronous movements.

The synchronised move allows to trigger a single shot on an external 5V or TTL signal, generated by users instrumentation.

Since the bunch-train-frequency of FLASH can be adjusted by the operation-crew, a part of the PLC-software evaluates the frequency of detected bunch signals and automatically adjusts the appropriate velocity and acceleration values.

FIRST EXPERIMENTS

One of the first experiments that used the fast mechanical shutter at FLASH was a time-resolved damage and ablation measurement [8]. The aim of this experiment was to study the interaction of ultra short FEL pulses in the VUV wavelength range with solid state surfaces at moderate irradiation intensities (I=10^{11}-10^{14}

W/cm²). The irradiation with ultra short VUV pulses permits a high degree of electronic excitation but essentially without any non-linearity. In addition, the increased absorption depth for some materials helps to minimize the influence of transport effects, e.g., carrier diffusion and heat conduction. Therefore, ultra short VUV pulses allow the preparation of rather well defined excitation conditions in relatively large sample volumes as compared to femto second optical pulses. To directly study the dynamics of ultra fast VUV-induced phase transitions and ablation, time-resolved measurements of the optical reflectivity have been performed in a VUV pump - optical probe configuration. The VUV pulse (λ=32 nm) is used for sample excitation and a delayed visible probe pulse (λ=532 nm) serves as illumination in an optical microscope. This allows to follow the reflectivity evolution of the VUV irradiated surfaces with both temporal and spatial resolution.

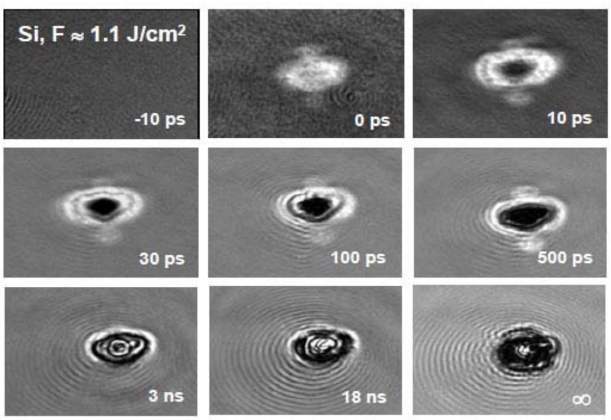

Figure 6: Surface of Si-wafer after irradiation with a <50 fs FLASH pulse (λ=32 nm) with a fluence of 1 J/cm². Frame size is 120 x 80 µm².

During the measurement FLASH was running in a single bunch operating mode having only one bunch in the bunch train. The mechanical shutter allowed the irradiation of the samples with exactly one ultra short VUV pulse of known intensity which was measured with a gas monitor detector system [9]. After irradiation the sample is moved to a new non-irradiated position and the reflectivity of the optical pulse is then measured at a different time delay. Figure 6 shows a sequence of time-resolved snapshots obtained on a bulk silicon sample for an excitation fluence of ~ 1 J/cm².

At early time (10 ps) a pronounced increase of the reflectivity is observed which can be attributed to a solid-liquid phase transition of the material. Although the temporal resolution was limited by the probe pulse duration to about 10 ps, this transition is most likely of electronic nature and occurs on sub-ps time-scales. Already after 10 ps the decrease of the reflectivity in the centre of the spot, where the fluence is highest, marks the onset of ablation. However, even after 18 ns ablation has not come to an end and the irradiated surface has not reached its final state.

The main goal of this measurement at FLASH was to establish the experimental technique and to obtain a first overview of the dynamics of the induced processes. Further measurements with enhanced temporal (<100 fs) and spatial resolution will follow which would provide a more detailed picture of these processes. Compared with femto second optical excitation distinct differences in the material response have been observed that are attributed to the larger absorption depths of the VUV radiation and the absence of non-linearity.

CONCLUSIONS

On the basis of existing wire scanner technology a fast shutter has been implemented in the FLASH beamline system. This allows users to choose single bunch trains with a repetition frequency of up to 10 Hz. First experimental results show the benefit of the fast shutter.

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