LASER PULSE TRAIN MANAGEMENT WITH AN ACOUSTO-OPTIC MODULATOR

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Abstract

Photo injector laser systems for linac based Free Electron Lasers (FELs) sometimes have the capability of generating pulse trains with an adjustable length. For example, the currently installed laser at the Photo Injector Test Facility at DESY, Zeuthen Site (PITZ) can generate pulse trains containing up to 800 pulses. Repetition frequencies are 10 Hz for the pulse trains and 1 MHz for the pulses within a train, respectively [1].

Mostly due to thermal effects caused by absorption in amplifier and frequency doubling crystals, pulse properties are changing slightly within a pulse train and also shot-to-shot, depending on the pulse train length. To increase stability and repeatability it is desirable to run the laser under constant conditions. To achieve this while still being able to freely choose pulse patterns a pulse picker can be installed at the laser output to sort out unwanted pulses. A promising candidate for this functionality is an acousto-optic modulator which currently is being tested at PITZ. First experimental results will be presented and discussed towards the possibility of including this device into an FEL photo injector.

INTRODUCTION

A central issue for running high quality experiments with a FEL is the stability of its output, requiring every subsystem including the photocathode laser to meet set specifications. In the case of an FEL with a multi-bunch structure, e.g. FLASH and the European XFEL, where each output event is a pulse train of varying length, the stability criterion has to be met not only shot-to-shot but also within each laser pulse train.

One critical part of the photocathode laser system is the frequency quadrupling where the laser output wavelength is converted from the near infrared (1030 nm) via green (515 nm) into the ultraviolet (UV at 258 nm). This is done in two steps with nonlinear crystals, each doubling the laser wavelength. The second conversion step from green into UV is done with a beta barium borate (BBO) crystal which absorbs a tiny fraction of the converted UV light. The resulting temperature variation in the crystal leads to small but measurable variations of e.g. charge and delay of pulses within a pulse train [2]. Absorption of light in the other conversion crystal and amplifier crystals of the laser adds to this effect.

A possible solution to this problem is to let the laser run constantly to stabilize the temperature of the crystals and define the pulse trains by picking the appropriate pulses behind the laser. Such a pulse picker may be realized using a UV Pockels cell or an acousto-optic modulator (AOM). This improves the situation because of the difference in the physical processes: the wavelength conversion in the BBO crystal is a nonlinear process requiring high light intensity. Small variations in operating conditions have big effects on arrival time and conversion efficiency. The AOM on the other hand is based on the linear acousto-optic effect, making it possible to operate the pulse picker at low intensity, which should, together with the low UV absorption of the AOM material (quartz), reduce the influence of heating enormously.

In order to prove the anticipated advantages experimentally such an AOM is currently being tested at the Photo Injector Test Facility at DESY, Zeuthen Site (PITZ) and in the following we will first explain the function of this device and then present initial experimental results.

THE ACOUSTO-OPTIC MODULATOR

The function of an AOM is based on the acousto-optic effect which is an interaction of light with a sound wave [3]. An AOM is a device which utilizes this effect to deflect a light beam as illustrated in Fig. 1.

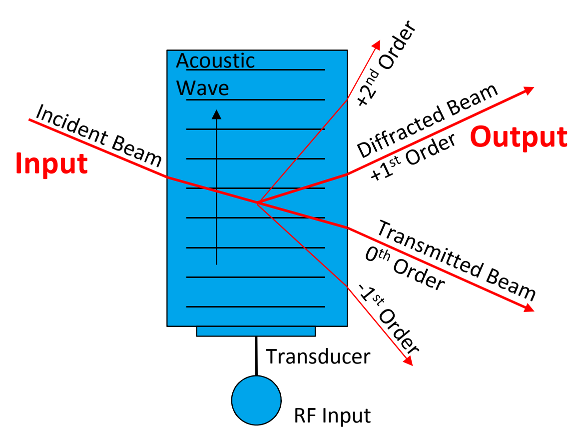

Figure 1: Function of an AOM.

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An RF wave with a frequency typically between 10 MHz and 1 GHz is coupled into the device via a transducer which converts the RF signal into an ultrasonic acoustic wave running through the AOM. This density wave modulates the refractive index of the AOM crystal and thereby produces a running optical grating. When an optical beam is coupled into the AOM with the Bragg angle it can be diffracted at this grating very efficiently into the 1st order. The 1st order is used as the AOM output because a very high contrast ratio (ratio of light transmitted in the on-state divided by light transmitted in the off-state) can be achieved compared to the 0th order: the 0th order has the highest transmittance (nearly 100% when the RF wave is off) but this cannot drop below about 10% for practical devices, giving a contrast ratio of about 10:1. The 1st order, on the other hand, receives no light when the RF wave is completely off, by far offsetting the disadvantage that less than 100% light is diffracted into this order in the on-state. Therefore the contrast ratio for the 1st order is only restricted by the on/off-ratio of the RF generator which can be very high. By modulating the RF amplitude synchronized with pulse arrival times, laser pulses can be transmitted with a given pattern.

The AOM used for the experiments at PITZ is the 35110-2-244-BR (Gooch & Housego) model which works at optical wavelengths from 244 nm to 260 nm. The crystal material is quartz which has a very low optical absorption in the UV and the RF centre frequency is 110 MHz. The minimal transmission rise time is less than 100 ns making it possible to separate pulses within 1 MHz (FLASH) and 4.5 MHz (European XFEL) pulse trains.

EXPERIMENTAL RESULTS

The goal of the initial testing was to verify the AOM functionality together with the PITZ photocathode laser and check for detrimental effects on laser and overall linac performance. In this chapter the most pertinent results of these tests are summarized.

Basic Functionality / Extinction Ratio

For the first test a fast photodiode was connected to the output of the AOM to record specific pulse selection patterns as shown in Fig. 2.

The upper trace of this scope output shows the laser pulse trigger demarking positions of laser pulses, a pulse train of eight pulses with a repetition frequency of 1 MHz in this case. The middle trace represents the envelope of the AOM RF input with the AOM transmitting laser pulses when the envelope is at high level, which is the case for the second through the fifth pulse slots. The lower trace shows the photo diode signal at the AOM output. Here it can be seen clearly that indeed, following the AOM envelope, only pulses 2 to 5 are transmitted while the others are suppressed. Pulse to pulse switching at 1 MHz was demonstrated with a contrast ratio of at least 500:1 with the measurement of the latter restricted by the photo diode noise level.

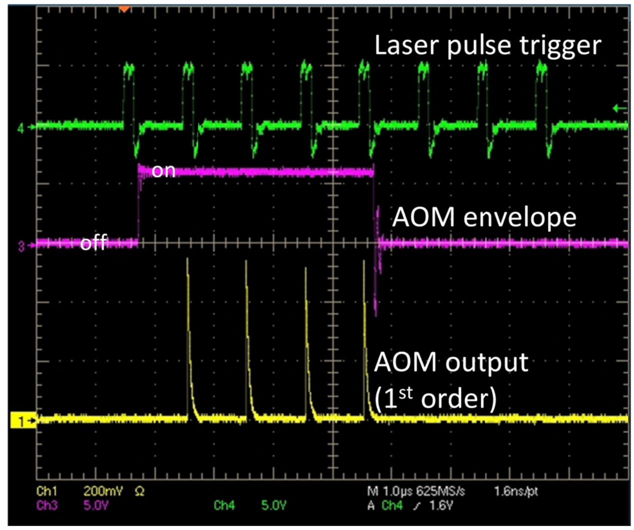

Figure 2: Pulse selection with AOM. Upper trace: laser pulse trigger at 1 MHz repetition frequency. Middle trace: AOM control envelope. Lower trace: AOM output.

The diffraction efficiency was measured with an energy meter (Ophir Nova II with thermal sensor head) to 79%, meaning that with the RF signal switched on about 80% of the laser pulse energy is diverted from the 0th order (light passing straight through the AOM and being dumped in a beam stopper) into the 1st order, which is the AOM output.

Transverse and Temporal Profile

After checking the basic functionality of the AOM we started to look for possible changes of the laser output caused by the diffraction process in the AOM. The transverse laser profile was recorded at a virtual cathode position which is equivalent to the position of the PITZ linac photocathode.

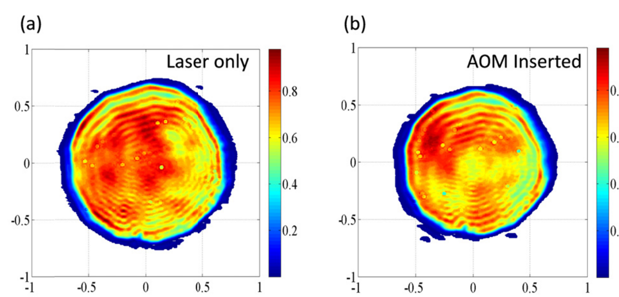

Figure 3: Transverse laser profile at virtual cathode with the laser used only (a) and with the AOM inserted (b).

The measured intensity in Fig. 3 is colour coded as indicated on the right hand side bar and it can be seen that the shape is unaffected by the AOM (the small difference in size is caused by different laser beam line settings) while the intensity distribution on the flat top is within normal fluctuations. Therefore the AOM is not influencing the ability to generate a transverse flat top light distribution on the photocathode.

We also checked the temporal pulse profile with the optical sampling system of the laser with results depicted in Fig. 4.

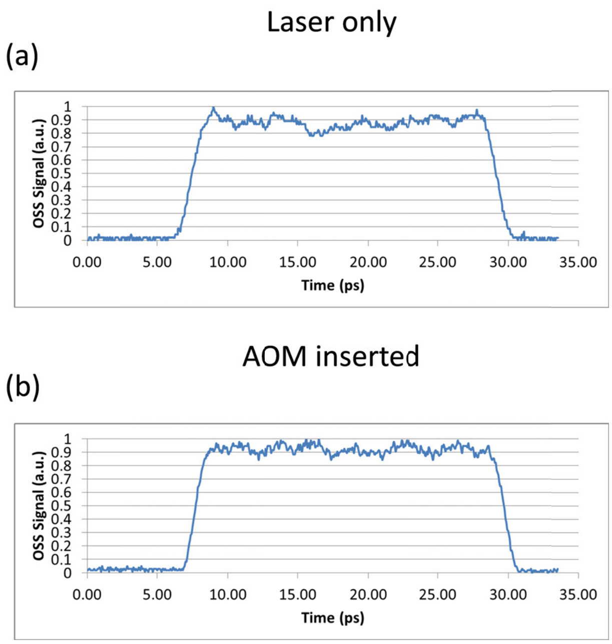

Figure 4: Temporal laser profile with the laser used only (a) and with the AOM inserted (b).

As in the case for the transverse profile, the temporal pulse profile is unaffected by the AOM as can be seen in Fig. 4. The rise- and fall times which could be influenced by dispersion in the quartz crystal are very similar in both measurements while the total pulse length and flat top fluctuations are within normal boundaries.

Laser Pointing Stability

The most important check of possible influence on the laser quality is the measurement of pointing stability of the laser beam. Jitter of the laser beam translates directly to electron beam jitter and has to be kept as low as possible to minimize e.g. emittance. The pointing stability was measured by recording the laser beam position with a CCD camera with results shown in Fig. 5.

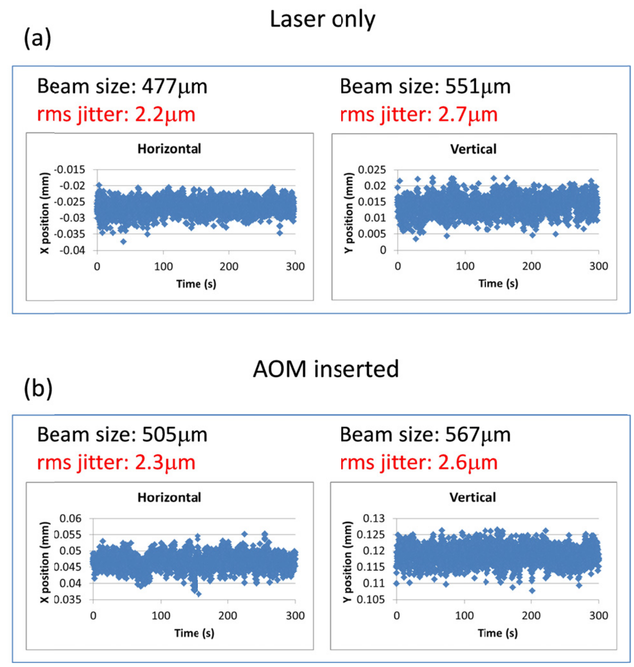

Figure 5: Laser pointing stability with the laser used only (a) and with the AOM inserted (b).

The pointing stability of the laser is not deteriorated by the AOM, possible influences of fluctuations of the diffraction grating position shot-to-shot and movement of the grating during the pulse are small.

Electron Bunch Charge

After having confirmed that the laser output is not influenced by the AOM we conducted charge measurements of the electron bunches in the PITZ linac as shown in Fig. 6.

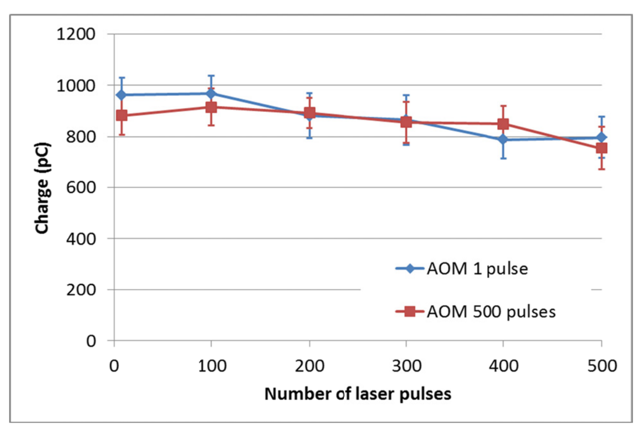

Figure 6: Measured charge of the leading electron bunch as a function of the number of laser pulses per pulse train. Error bars show statistical error.

The bunch charge was measured with an integrated current transformer; given is the charge of the leading bunch of the train. This measurement was conducted with a varying number of laser pulses for two AOM settings to investigate the effect of the laser load on the BBO conversion crystal compared with the corresponding load on the AOM quartz material. While the number of pulses actually generated by the laser was varied from 1 to 500 per pulse train, the AOM was operated in two modes. In the first it was set to transmit only the leading pulse to the linac (blue curve, diamonds), while in the other mode all pulses were transmitted by setting the gate length to 500 pulses (red curve, squares). Both measurement series give similar results within the statistical measurement errors showing that the status of the AOM does not influence the electron bunch charge. This measurement illustrates also how the AOM could improve the quality of future experiments: when measuring emittance with the slit scan method it is necessary to adjust the number of electron bunches per train during the experiment [4]. The dependence of the charge on the number of pulses in the train which can be seen clearly in Fig. 6 will certainly influence the final result. This can be prevented by putting the number of pulses emitted by the laser to the maximum number needed and control the number of electron bunches with the AOM.

This was investigated further by measuring the emittance directly as detailed next.

Emittance

The emittance (for test purposes only the x plane was considered here and the measurement setup was not completely optimized leading to elevated results) was measured using the slit scan method [5]. While keeping the number of electron bunches constant at 5 with the AOM, the number of laser pulses was varied from 5 to 200 as shown in Fig. 7.

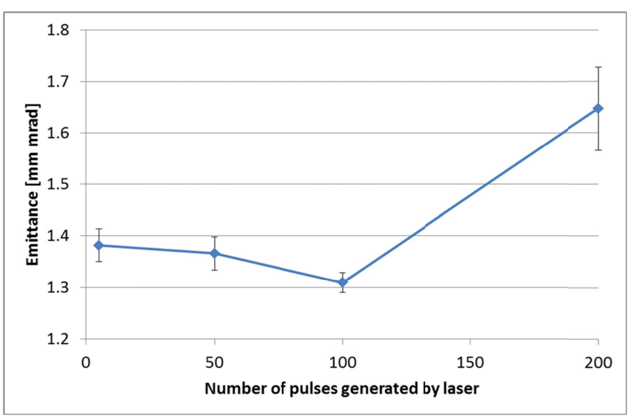

Figure 7: X-Emittance measured vs. number of laser pulses. Error bars show statistical error.

While the error bars only represent the statistical measurement error, the systematic error is small in this case since the measurements were done within a few minutes [4]. As can be seen clearly, the measured emittance is dependent on the number of laser pulses originally generated by the system. So, as it was expected after the charge measurements the accuracy of emittance measurements should be increased when using an AOM to choose the number of electron bunches used for a measurement.

SUMMARY

The acousto-optic modulator (AOM) is a device which could help to increase the stability of FEL operation. The basic operation is that of a pulse picker, set between the photocathode laser and the photocathode. While the laser is running in a constant, stable mode, arbitrary pulse patterns can be defined with the AOM by utilizing the acousto-optic effect.

One specific device was tested at PITZ regarding its suitability towards possible operation at the FLASH and European XFEL free electron lasers. Test results are summarized in the following:

- The AOM is capable to select individual pulses out of a train and suppress neighbouring pulses in a 1 MHz pulse train with a contrast ratio of at least 500:1. The diffraction efficiency for selected pulses is about 80%.
- Transverse and temporal pulse profiles are not measurably influenced by the AOM.
- Laser pointing stability is not deteriorated as well.
- The electron bunch charge is independent of the AOM gate length.

In a preliminary test regarding emittance measurements it was demonstrated that an AOM could help to increase measurement accuracy by stabilizing machine conditions during experiments. With the AOM it was possible to observe that the measured emittance is sensitive to the number of generated laser pulses.

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