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GENERATION AND DELIVERY OF AN ULTRAVIOLET LASER BEAM FOR THE RF-PHOTOINJECTOR OF THE AWAKE ELECTRON BEAM

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Abstract

In the AWAKE experiment, the electron beam is used to probe the proton-driven wakefield acceleration in plasma. Electron bunches are produced using an rf-gun equipped with a Cs_2Te photocathode illuminated by an ultraviolet (UV) laser pulse. To generate the UV laser beam a fraction of the infrared (IR) laser beam used for production of rubidium plasma is extracted from the laser system, time-compressed to a picosecond scale and frequency tripled using nonlinear crystals. The optical line for transporting the laser beam over the 24 m distance was built using rigid supports for mirrors and air-evacuated tube to minimize beam-pointing instabilities. Construction of the UV beam optical system enables appropriate beam shaping and control of its size and position on the cathode, as well as time delay with respect to the IR pulse seeding the plasma wakefield.

INTRODUCTION

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) aims at studying plasma wakefield generation and electron acceleration driven by proton bunches [1, 2]. In the AWAKE experiment a 400 GeV proton beam is extracted from the CERN Super Proton Synchrotron, SPS, and utilized as a drive beam for wakefields in plasma to accelerate electrons from 19 MeV energy up to 2 GeV [3]. A plasma is generated in a 10 m long rubidium vapour source via the over-the-barrier ionization by high intensity laser field. The short laser pulse propagating co-axially with the proton beam seeds a self-modulation process within the proton bunch on the front of plasma creation. Thus, the long SPS proton bunch (σ_z=12 cm) is transformed into a train of micro-bunches driving the periodic wakefield [4, 5].

An electron beam for AWAKE is supplied by the electron beam accelerator consisting of an rf-gun and a booster structure [6, 7]. The electron bunch in the rf-gun is produced using a photoemission driven by an UV beam generated from the same laser source. In this paper, we present the design of the UV beam line and results of its commissioning regarding IR/UV conversion, beam pointing stability, and means of beam control and monitoring. Measurements of electron beam emittance and extracted bunch charge in relation to the UV beam parameters enabled achieving optimal performance of the electron beam during AWAKE runs.

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GENERATION OF THE UV BEAM

The AWAKE laser installation is located in the underground TSG40 tunnel which was refurbished and equipped according to requirements for clean laser room [8]. The laser system CENTAURUS supplied by Amplitude Technology comprises a mode-locked fibre laser oscillator, pulse stretcher, a series or Ti:Sapphire amplifiers associated with Nd:YAG pumping lasers and two pulse compressors as shown on Fig. 1. The output of the main amplifier consists of two IR laser beams with central wavelength of 780 nm. The main (primary) beam is injected into vacuum system where pulses with energy up to 660 mJ are compressed to 120 fs and transported further (450 mJ maximum) to the rubidium vapour source for producing the plasma. The secondary IR beam with 2 mJ pulses at the repetition rate of 10 Hz is perfectly synchronized with pulses of the main laser beam since it originates from the same oscillator.

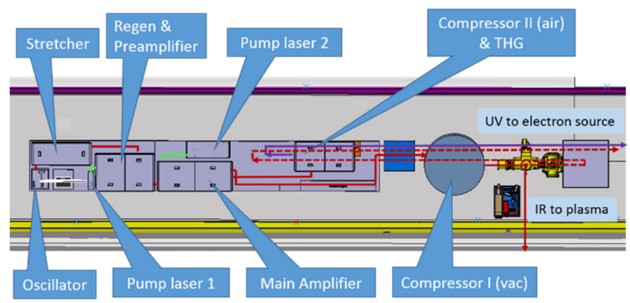

Figure 1: Layout of the AWAKE laser installation.

The secondary beam was used to produce pulsed UV light required to generate electron bunches in the AWAKE experiment. It was produced by third harmonic generation (THG) of the compressed IR pulse using the THG Extended Femtokit FKE-800-100-10M from EKSMA Optics.

It was possible to control the UV pulse duration by changing the distance between diffraction gratings (1500 lines/mm) in the secondary beam pulse compressor. The plot on Fig. 2 shows the FWHM duration of the IR and UV pulses measured using the streak camera Hamamatsu C10910-05 equipped with S-20ER photocathode and UV compatible optics. The second grating was linearly translated and for each grating position 500 pulses of IR and UV light were recorded. Two approaches were applied for the analysis of the images: i) all 2D-profiles were aligned on their centres and summed up, the widths of resulting profiles are displayed by symbols marked “IR, sum” and “UV, sum”; ii) a value of pulse duration was extracted from each measured profile and averaged afterwards. These points are

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marked as “IR, av” and “UV, av”. The negligible difference between results obtained using these two methods proves the correctness of analysis. Following these measurements, the compressor grating was set to a position corresponding to UV pulse duration of 5.2 ps which was used during the AWAKE physics runs in 2018.

The electron bunch length was measured using the same streak camera. The OTR light produced by electron bunches on a SiAg screen installed 2.6 m upstream the plasma source was optically transported to the streak camera location. The group velocity dispersion caused by the broad spectral response of the OTR was partially reduced by applying a 50 nm band pass filter at 525 nm central wavelength. This produced a time profile with average FWHM duration of 10 ps. The reasons for the almost two-fold difference of the electron bunch and laser pulse lengths are to be investigated.

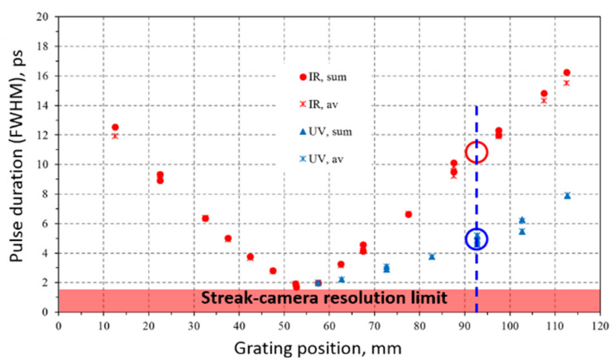

Figure 2: Duration of IR and UV pulses in the secondary laser beam as a function of the second diffraction grating position in pulse compressor II.

UV LASER BEAM TRANSPORT TO THE ELECTRON SOURCE

The photoinjector of the AWAKE electron source was installed inside a shielded bunker located at the same level as the laser room. The UV beam transfer system was designed to ensure a maximal stability of the beam and according to laser safety requirements. The main path was arranged inside a straight vacuum pipe of 14.2 m length. This pipe was fixed at 2.1 m height above the floor and pumped using a dry scroll pump IDP-15 of Agilent Technologies. Thus, possible UV beam perturbations due to differences in air pressure and temperature between the two zones were avoided. On both sides of the pipe two dielectric high-reflectivity UV mirrors were mounted on optical breadboards inside specially designed boxes. Vibrations of the mirror mounts were minimized by fixing the breadboards on rigid pillars installed on the optical table (in the laser room) and on the floor (in the electron source bunker).

It is worth noting that the same pipe and mirror-supporting breadboards were used for transporting a reference IR laser pulse from the laser room to the streak camera used to study self-modulations of the proton bunch in plasma [5]. The signal produced by the reference beam enabled a demonstration of the wakefield phase stability with respect to the ionizing laser pulse (to be published).

A simplified optical scheme of the UV laser beam transport is depicted on Fig. 3. At the exit of THG setup the beam was expanded using two positive lenses with the focal lengths of 100 mm and 250 mm respectively. The distance between these lenses was adjusted for producing a diffraction limited focus at the aperture installed on the optical table near the electron gun. The aperture was imaged to the photocathode plane using a combination of reducing telescope (M=1:2) and a single lens with the focal length of 1000 mm. Application of this scheme was essential for minimizing the pointing instability of the UV beam on the photocathode.

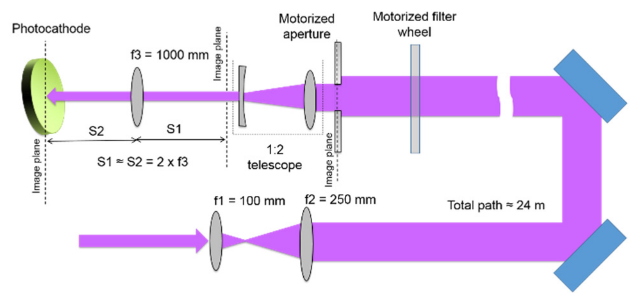

Figure 3: Simplified optical scheme of UV beam delivery to the photocathode of the AWAKE electron source.

UV BEAM CONTROL AND MONITORING

The so-called “virtual cathode” setup was assembled on a small optical table installed near the electron gun. As shown on Fig. 4, the virtual image of the beam arriving at the photocathode is created at the CMOS digital camera (Basler acA2500-20gm).

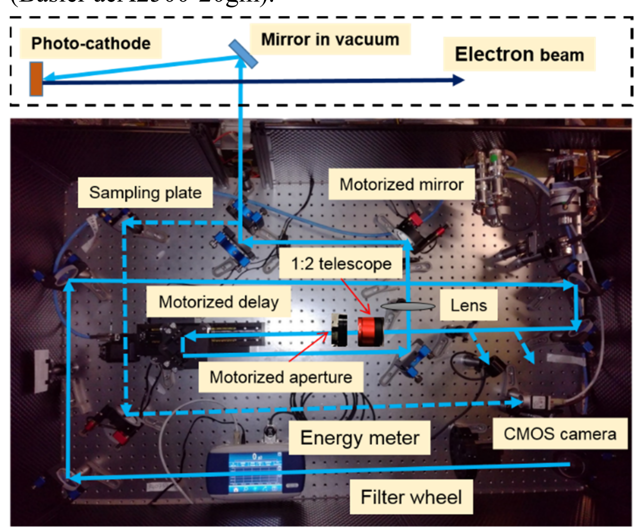

Figure 4: Virtual cathode setup. The light-blue lines show the UV beam path starting from the 1st mirror in the right bottom corner up to the photocathode. The reference beam path from a sampling plate to the CMOS camera is shown by the dashed blight-blue lines. Elements inside the vacuum system (in the dashed rectangular) are shown schematically.

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Steering of the UV beam on the photocathode is performed using a motorized mirror mount. A motorized filter wheel equipped with a set of neutral density filters is used for varying the energy of UV laser pulses, while the laser energy meter (MAESTRO of Gentec-EO) provides reading of the pulse energy. The length of the UV optical path was adjusted to match arriving of electron bunches to the plasma source with ionizing laser pulses. Fine tuning of the delay time within 1 ns range is performed by means of two mirrors installed on a remotely controlled motorized stage.

The motorized aperture enables remote control of the laser beam spot size on the cathode. Examples of laser beam images recorded with the virtual cathode camera are presented in Fig. 5. In combination with control of the pulse energy delivered to the cathode, it was possible to perform measurements of electron bunch charge and emittance versus the laser beam size and pulse energy. The results of this study will be published elsewhere.

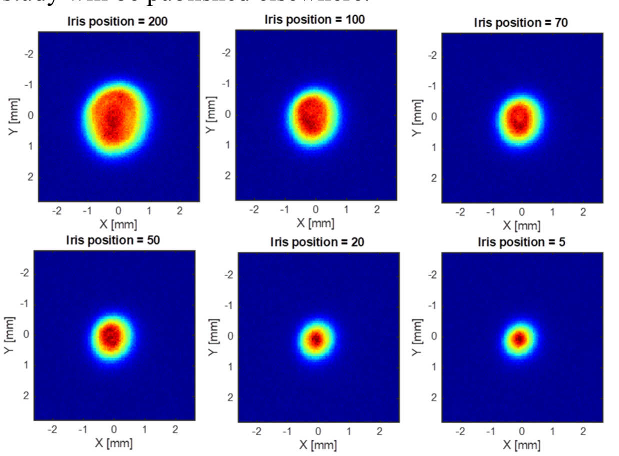

Figure 5: Images of the UV laser beam registered with the virtual cathode camera at different settings of the motorized aperture.

CONCLUSION

The performance of the constructed UV beam line is summarized in Table 1. The requirements for the phase 1 of the AWAKE experiment are completely fulfilled.

An important prerequisite of this achievement was the capability to operate the rf-gun with highly-efficient Cs_2Te photocathodes produced in the CERN photoemission laboratory [9]. In particular, the photocathode used in AWAKE showed the quantum efficiency QE ~ 20% measured in the dc-gun just after the fabrication process. This cathode supplied electron beams since the commissioning in November 2017 till the end of physics runs in December 2018. After replacement by a new cathode it was analysed again in the dc-gun. The measured QE-maps of the fresh and used photocathode are presented in Fig. 6. The dip in central area demonstrates a local reduction of the photocathode performance due to the long operation time. However, the residual QE ~ 2% allowed generation of decent electron beam till the last days of AWAKE physics run.

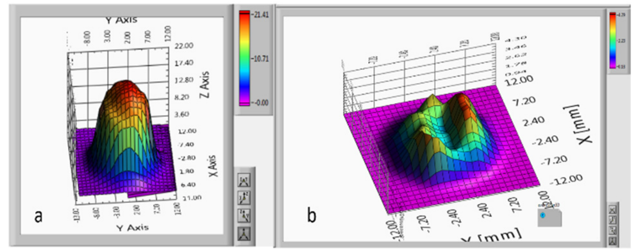

Figure 6: 2D-distribution of photocathode quantum efficiency measured in the dc-gun just after the photocathode production (a) and after a year-long operation in AWAKE experiment (b).

Table 1: Parameters of the AWAKE UV Beam in Relation to the Photocathode Performance

Parameter	Project value	Typical value
Electron bunch charge	200 nC	700 nC
Bunch length (σ)	4 ps	4.2 ps
Photocathode QE	3 %	4 %
Laser wavelength	260 nm	260 nm
UV pulse energy at the entrance to rf-gun	40 nJ	100 nJ
Beam shaping factor	0.05	0.1
UV transport efficiency	40 %	40 %
THG efficiency	0.1 %	0.25 %
UV pulse duration (FWHM)	10 ps	5.2 ps
IR pulse duration (FWHM)	12 ps	11.2 ps
Transmission of the pulse compressor	80 %	84 %
IR pulse energy before compression	2 mJ	1 mJ

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