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NEAR-INFRARED LASER SYSTEM FOR DIELECTRIC LASER ACCELERATION EXPERIMENTS AT SINBAD

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Abstract

The technique of dielectric laser acceleration (DLA) utilizes the strong field gradients generated by intense laser light near the surfaces of microscopic photonic structures, possibly allowing compact accelerator devices. We report on the 2 µm laser system at the SINBAD facility at DESY, where first experiments of Dielectric Laser Acceleration (DLA) with relativistic electrons pre-accelerated by the ARES linear accelerator started in late 2020. We constructed a low-noise Holmium fiber oscillator producing pulses at a wavelength of 2050 nm, seeding a Ho:YLF regenerative amplifier. Pulses of 2 mJ and 2 ps duration from the amplifier are transported over a distance of about 30 m to the DLA interaction point. To ensure timing overlap between the electrons and the laser pulses, the laser system is synchronized to the accelerator RF.

INTRODUCTION

The method of Dielectric Laser Acceleration (DLA) [1] allows to generate high gradients of the electric field with intense laser radiation, which may be utilized to overcome limitations of conventional RF particle accelerators. Using this technique, compact, table-top size particle accelerator devices e.g. for medical purposes seem possible. Within the international ACHIP collaboration [2], acceleration of relativistic electrons utilizing the DLA method are investigated experimentally at the SINBAD accelerator R&D facility at DESY. We here report in the near infrared laser system used for these experiments.

EXPERIMENTAL SETUP

A schematic overview of the experimental setup for DLA experiments at SINBAD is shown in Fig. 1, incorporating the ARES electron linac and two laser systems. A commercial UV laser system, emitting 150 fs pulses at 257 nm is used to generate photoelectrons at the cathode of the ARES electron linac [3]. These electrons are accelerated by the ARES gun and by two additional accelerating structures, generating short electron bunches of about 150 MeV energy. The second laser system operating in the near infrared is intended to drive the DLA. It consists of a Holmium fiber oscillator and a Ho:YLF regenerative amplifier.

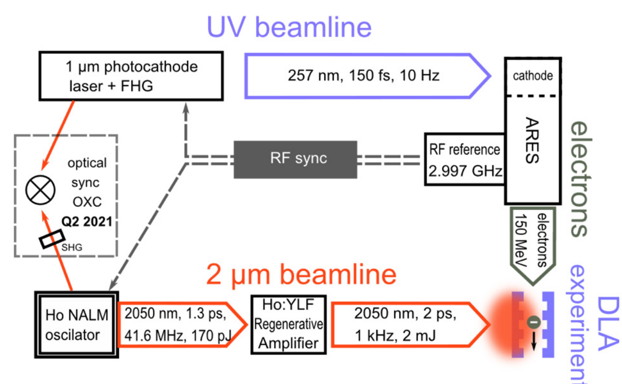

Figure 1: Overview of the setup for DLA experiment.

Holmium Fiber NALM Oscillator

For seeding the Ho:YLF regenerative amplifier, a synchronizable, long-term stable and low noise oscillator was required. Considering the different mode-locking schemes available, we decided to construct an Holmium fiber oscillator in-house which is based on the technique of a Nonlinear Amplifying Loop Mirror (NALM) [4]. NALM oscillators have been shown to offer a low noise performance, comparable to that of solid state lasers. They can be constructed using exclusively polarization-maintaining fibers, which greatly enhances their environmental stability [5]. As a NALM acts as artificial saturable absorber, the common problem of degradation of "real" saturable absorbers (e.g. made from semiconductor materials or carbon nanotubes) can be mitigated, thus allowing long-term stable operation. Our oscillator consists of a NALM loop containing a Holmium-doped gain fiber, which is connected by a fiber coupler to a linear arm. The latter comprises a short free space section, terminated by a piezo-mounted end mirror. Together with a slow stage for drift compensation, this end mirror can be used to lock the repetition rate to 41.6 MHz, which is a fraction of 1/72 of the ARES RF reference frequency. A tuneable bandpass filter in the free-space section allows control of the center wavelength between 2035 and 2075 nm. As a pump source

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for the oscillator, we are using a commercial Thulium pump laser.

The Holmium NALM oscillator emits 1.3 ps, 170 pJ pulses at a wavelength of 2050 nm. The optical spectrum and an autocorrelation trace are shown in Figs. 2 a) and b).

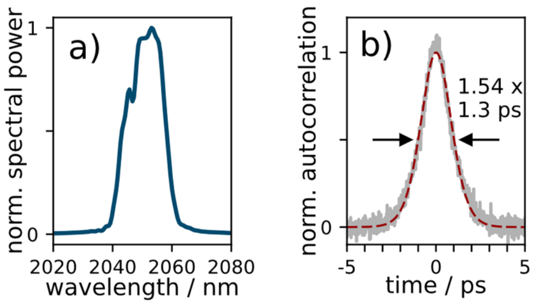

Figure 2: Output characteristics of the Holmium NALM oscillator. a) optical spectrum. b) intensity autocorrelation.

Ho:YLF Regenerative Amplifier

In a second stage of the 2 µm beamline, a Ho:YLF solid state amplifier system [6, 7] is used. It consists of a Regenerative cavity containing a Ho:YLF crystal and a subsequent single-stage Ho:YLF amplifier. To prevent the effect of gain-narrowing, the cavity gain shape is controlled by an etalon, allowing shorter output pulses. With this configuration, the amplifier system can generate 2 mJ, 2.2 ps output pulses at a repetition rate of 1 kHz.

Beam Transport

For the DLA experiments, the 2 µm laser pulses have to be transported over about 30 m from the laser laboratory to the experimental area downstream the ARES accelerator. For this, we implemented a *4-f* relay imaging system, which minimizes the beam pointing instabilities. The beam is transported inside an evacuated vacuum tube to prevent disturbances e.g. by turbulent air flow. At the exit of the tube, the beam is adapted in size by a telescope and guided towards the interaction point. An active beam stabilization system, using a set of cameras and computer actuated mirrors is used direct the beam on the DLA.

Synchronization

To ensure the proper synchronization and timing for the experiments, both the photocathode laser and the 2 µm laser system have to be tightly locked to the ARES RF reference at 2.997 GHz. We here are utilizing an RF-to-optical synchronization scheme for each laser. In this scheme, a fraction of the respective laser output is sent to a photodetector, generating an RF spectrum with spectral lines at integer multiples of the oscillators repetition rate. For the Holmium oscillator, the 73rd harmonic (3.04 GHz) is bandpass-filtered and subsequently mixed with the ARES reference signal. The resulting intermediate frequency signal is digitized and processed in an all-digital loop filter, similar to the one described in [8]. A feedback signal is generated, acting on the oscillator end mirror and thus changing the repetition rate. With this configuration, we could successfully synchronize 2 µm laser system to the accelerator. Integrating the phase noise in the frequency interval [10 Hz, 100 kHz] yields a residual timing jitter of about 45 fs. Figure 3 shows example long-term data for the Holmium oscillator locking performance. A typical timing jitter of 45 fs with a standard deviation of 1.3 fs could is maintained for a period of over 6 days. The plot also shows the excellent stability of the oscillators output power.

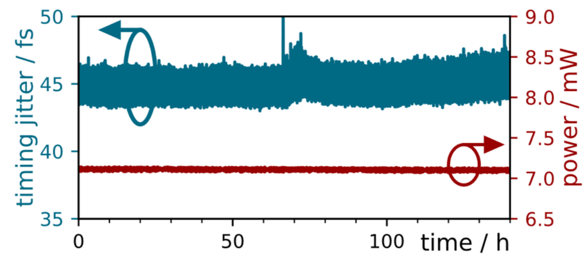

Figure 3: Long-term output stability of the Holmium NALM oscillator: residual timing jitter and output power.

Laser Noise Analysis and Future Improvements

We carefully investigated both the relative intensity noise (RIN) as well as the phase noise of the oscillator. Two commercial pump lasers (called A and B) were test and their RIN properties recorded. We found that the RIN characteristics of the pump lasers are inherited to the respective oscillator RIN, especially for frequencies below 10 kHz. This is clearly visible in the traces are shown Fig. 4 a). Furthermore, these RIN features also are transferred to the oscillator phase noise (shown in Fig. 4 b)), limiting the frequency locking bandwidth. Albeit the two pump lasers showing quite different noise characteristics, the residual timing jitters (Fig. 4 c)) are comparable.

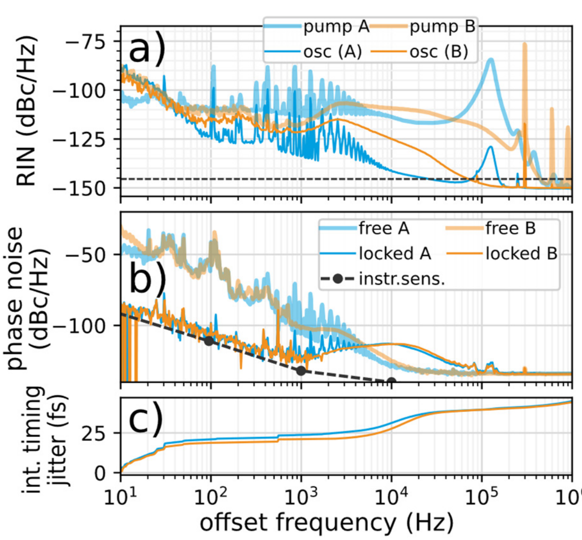

Figure 4: Intensity noise and phase noise properties of the Holmium oscillator. a) Relative intensity noise, comparing two commercial pumps (A and B) with the respective oscillator traces. b) Phase noise of the oscillator for the free running and locked case, shown for both pumps. c) integrated timing jitter for the locked cases in shown in b).

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We plan to address the pump laser noise by constructing a low-noise pump laser in-house. By the using a frequency stabilized seed diode and low noise optical amplifiers, we are confident we can achieve a lower noise level compared to the commercial systems, which will improve the locking performance of the 2 µm laser system.

Another measure to reduce the timing jitter between the electrons from the accelerator and the 2 µm pulses is to add an additional synchronization scheme which overcomes the limitations of the RF-locking. We are started implementing an optical synchronization between the photocathode and the 2 µm laser systems, based on a balanced optical cross correlator (BOC) [9]. For this, a Periodically Poled Lithium Niobate (PPLN) crystal will be used to generate the second harmonic of some fraction of the 2 µm radiation. These pulses will then be amplified and can be correlated with the 1 µm fundamental of the UV laser in an β-Barium Borate (BBO) crystal. The correlation signal is detected and, as before, processed in a digital loop filter, feeding back on the Holmium oscillator. The expected improvement is due to the fact that this synchronization scheme is much more sensitive to frequency deviations than the RF-to-optical locking.

CONCLUSION

We reported on the near infrared laser system which was implemented for DLA experiments at the SINBAD facility at DESY. It consists of a Holmium fiber oscillator, an regenerative Ho:YLF amplifier and a beam transport system. We demonstrated the generation of 2 mJ, 2.2 ps pulses at 2050 nm, the beam delivery, and the synchronization to the reference RF of the ARES electron accelerator. A careful analysis of the noise revealed that relative intensity noise and timing jitter of our oscillator delicately depend on the pump laser noise. To address this issue, a low noise pump laser is being constructed in-house as a replacement for the commercial Tm pump used currently. Further improvement can be expected from a direct optical synchronization of the 2 µm laser system to the ARES photocathode laser by the means of a balanced optical cross correlator. The next DLA experiments at SINBAD are planned for Q3 of 2021.

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