THE LASER SYSTEM FOR THE ERL ELECTRON SOURCE AT CORNELL UNIVERSITY *

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Abstract

A master oscillator-power amplifier (MOPA) laser system has been developed to meet the requirements of the Cornell ERL high brightness electron photoinjector. The system is comprised of a Yb-fiber laser oscillator, a single-mode fiber pre-amplifier and a double-clad, large mode area fiber amplifier. The system provides 5 watts average infrared power in a train of 3-ps pulses at 50 MHz. These pulses are efficiently frequency-doubled to produce 2-ps pulses at 520 nm with more than 40 nJ energy per pulse. We demonstrate an efficient longitudinal pulse shaping technique that allows us to achieve 20- to 40-ps-long, nearly flat-top pulses with sharp rise and fall times. We characterize the noise properties of the fiber oscillator and discuss the route to upgrade the system to achieve 130-watt average infrared power and a repetition rate of 1.3 GHz.

INTRODUCTION

Cornell University is developing a high brightness, high average current electron source for the injector of an Energy Recovery Linac (ERL) based synchrotron radiation source. The source is a very high voltage DC electron gun with a negative electron affinity photoemission cathode [1]. The production of high charge, low emittance electron beam imposes challenging requirements on the laser illuminating the photoinjector. The necessary lasers are state-of-the-art, operating at GHz repetition rates, with high pulse energies, temporally and spatially shaped pulses, and well synchronized to an external master clock [1].

The Cornell photoinjector is designed to deliver a 100 mA average current at repetition rate of 1.3 GHz. The drive laser has to match at this repetition rate and to provide 15-nJ-pulses at a central wavelength of ~500 nm with a duration of 20 to 40 ps. To handle nonlinear space charge effects, the pulses must to be shaped to flat-tops in both space and time [2]. As an intermediate step, to meet the initial needs for injector development, we built a laser system that operates at the 26th sub-harmonic of 1.3 GHz with pulses meeting all the requirements of the final system. The system is a MOPA type with a fiber oscillator and two fiber based amplification stages. The fundamental pulse width is ~ 2.5 ps FWHM and nearly Gaussian. This pulse is split and differentially delayed in a series of birefringent crystals of differing thicknesses to produce a nearly flat top temporal profile with fast rise and fall times. The final pulse width is measured by cross-correlation. The pulses are transversely shaped by a commercial aspheric lens system. All laser parameters essential to the performance of the electron source the have been demonstrated, and a full power system operating at the 50 MHz repetition rate is installed for electron beam measurements.

LASER SYSTEM DESCRIPTION

The system schematic is shown in Fig. 1. The seed is a Yb-doped fiber laser built in a ring cavity. The net dispersion is large and anomalous and the laser operates in the soliton regime. The output of the oscillator is first amplified in a single-mode Yb-fiber pre-amplifier. The second amplification stage is a double-clad, large mode area Yb-doped fiber. This fiber (Liekki Yb1200-30/250DC-PM) is polarization maintaining with a core diameter of 30 micron and a fiber length of 3.5 meters. The amplifier is pumped by a fiber-coupled semiconductor laser diode stack (LIMO) operating at 976 nm that can deliver 25 watts maximum power. We pump the amplifier with up to 18 watts which should allow us to run the laser system stably for a long time.

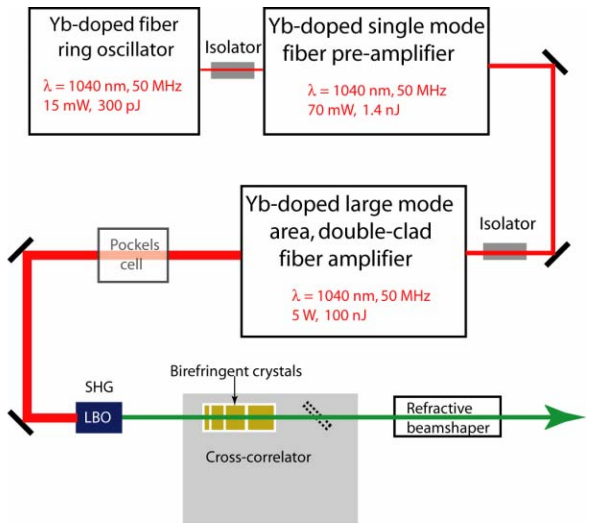

Figure 1. Schematic of the laser system.

A BBO Pockels cell with essentially no acousto-optical ringing is used to reduce the electron beam duty factor for beam measurements without changing the parameters of the individual pulses reaching the photocathode. The

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amplified beam is frequency doubled in a non-critically phase matched (NCPM) 15-mm-long LBO crystal. A sequence of n birefringent crystals (YVO$_4$) is used for longitudinal pulse shaping by stacking 2^n short pulses, resulting in nearly flat-top longer pulses with fast rise and fall times. Transverse shaping is achieved with a commercial refractive beam shaper (Newport Corp.) based on aspherical lenses, and a demagnified flat-top is imaged onto the photocathode.

SYSTEM CHARACTERIZATION

The oscillator operates in the soliton regime and provides nearly transform limited 2.5-ps FWHM pulses. The interferometric and intensity autocorrelation traces (solid line), and pulse spectrum are shown in Fig. 2a and Fig. 2b, respectively. The time-bandwidth product is 0.4 confirming the high pulse quality. The oscillator pulses are directed into a single-mode Yb-fiber preamplifier to boost the pulse energy to 1.4 nJ. The pre-amp utilizes the divided-pulse amplification [3] technique to achieve nearly distortion-free amplification. The pre-amplified pulse autocorrelation and spectrum are essentially the same as those of the oscillator pulses. The phase noise of the oscillator was measured following the approach described by von der Linde [4] and the total rms jitter between 100 Hz and 10 MHz was determined to be around 4 ps (Fig. 3). Most of the jitter is at low frequencies, making it possible to be greatly reduced by a phase locked loop. Synchronization work is underway and results will be presented in the near future. We measured the jitter of the laser encloses in a plastic box to reduce the air current and temperature vairation with a fast digital oscilloscope to be ~1.5 ps. The oscilloscope (Agilent 86100A, 40 Gbits/s) has an optical and electrical plug-in module (Agilent 86109A, 30 GHz optical bandwidth) to measure the timing jitter.

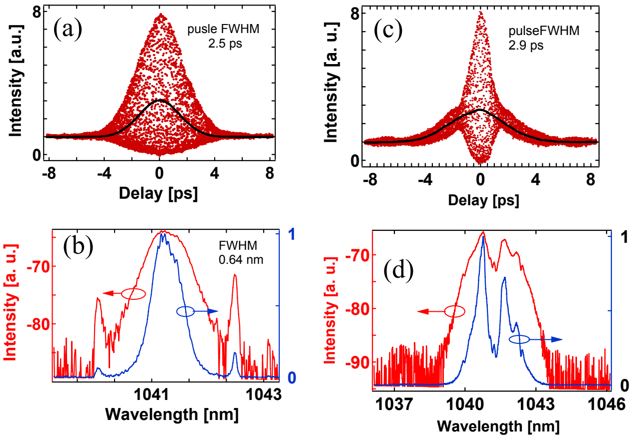

Figure 2. (a) Interferometric (red dots) and intensity (solid black line) autocorrelation of the oscillator pulse. (b) Oscillator spectrum in linear scale (blue line) and logarithmic scale (red line). (c) Interferometric (red dots) and intensity (solid black line) autocorrelation of amplified pulse with energy of 100 nJ. (d) Amplified spectrum in linear scale (blue line) and logarithmic scale (red line)

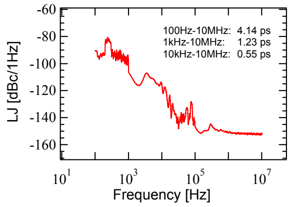

Figure 3. The noise measurement of the un-synchronized laser.

The amplifier is based on polarization maintaining (PM), double clad (DC), large-mode area (LMA) Yb-doped fiber. The amplifier slope efficiency is shown in Fig. 4a. The pump coupling was determined to be 80% from measurements done with short pieces of doped fibers. The fiber was coiled in two planes to achieve a nearly diffraction limited output beam [5], confirmed by measurement of the propagation factor M^2 (Fig. 4b). The spectral contrast ratio between the signal and the ASE is more than 25 dB (Fig. 4c). In Fig. 4d we show the integral of the spectrum from Fig. 4c. From this, we can conclude that the amplified spontaneous emission (ASE) contributes about 5% of the total power. The amplified pulse duration is 3 ps FWHM (Fig. 2c). The spectrum at a pulse energy of 100 nJ is shown in Fig. 2d and indicates that the total nonlinear phase shift is about 1.5π. The autocorrelation trace and the spectrum show that the pulses experience moderate distortion at energy levels of 100 nJ. The good quality of the amplified pulses is confirmed by very efficient second harmonic generation.

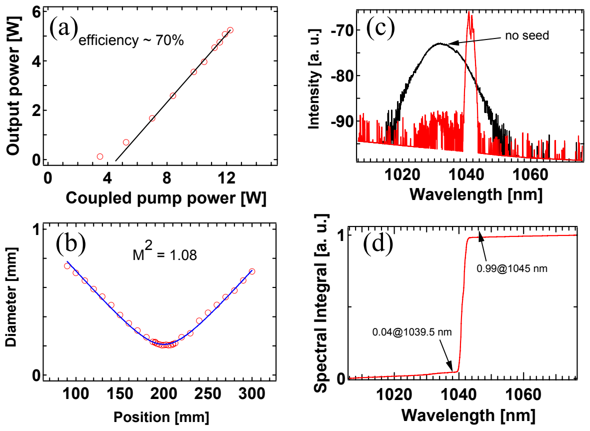

Figure 4. (a) Amplifier efficiency. (b) M^2 measurements results. (c) Long span amplified spectrum. The black line is the ASE spectrum with the seed blocked. (d) Integral of the spectrum depicted in (c).

We used a non-critically phase matched (NCPM) 15-mm-long LBO crystal for second harmonic generation and the SHG power as a function of the input infrared power is plotted in Fig. 5a. We see the initial quadratic trend and the deviation from this due to the depletion of the pump power and the broadening of the spectrum of the fundamental pulse.

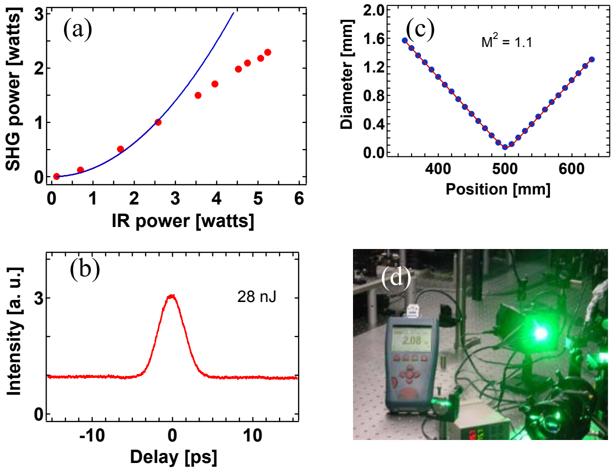

Figure 5. (a) The efficiency of the SHG process. (b) Intensity autocorrelation of a green pulse with pulse energy of 28 nJ. (c) M^2 measurement results for the green beam. (d) SHG generation.

Fig. 5b shows the autocorrelation trace of the green pulse with energy of 28 nJ. As expected, the pulse is about 1.4 times shorter than the fundamental pulse. Since it is important for spatial beam shaping, we measured the propagation factor of the green beam, with the results shown in Fig. 5c indicating a diffraction-limited beam.

LONGITUDINAL PULSE SHAPING

Our approach to longitudinal pulse shaping is based on the stacking of pulses in a sequence of birefringent crystals as demonstrated in [6]. Here we extend the technique to produce nearly flat top pulses with fast rise and fall times [7]. Using a set of YVO_4 crystals with lengths and orientations chosen to achieve the desired shape and duration by stacking 2 ps input pulses. The rise/fall time of the fundamental pulse determines the rise/fall time of the stacked pulse and the duration is determined by the number of the crystals used and their length. The technique is very easy to implement and is nearly 100 % efficient with surface reflections being the only loss.

In Fig. 6a and Fig. 6b, we show the experimental and theoretical results for stacking of 8 pulses (3 crystals) to produce a pulse with duration of around 30 ps. The crystal lengths from the vendor used for this demonstration were not exactly correct, leading to a slight discrepancy.

In principle, the oscillations on the top of the pulse can be smoothed out by reducing the spacing between the stacked pulses with more, thinner, crystals. In fact, the stacked-pulse spacing can be continuously varied if two birefringent crystals are wedge-shaped, placed together and moved with respect to each other

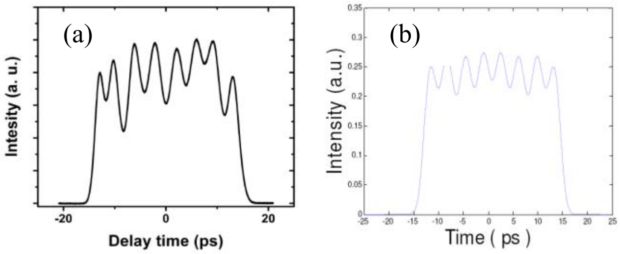

Figure 6. (a) Experimental cross-correlation trace of a stacked pulse achieved with a set of 3 crystals. (b) Calculated cross-correlation trace for the experimental data shown in (a).

TOWARD THE 1.3 GHz SYSTEM

The laser system described here has all the optical parameters required for the final system except the repetition rate and average power. Increasing the repetition rate a factor of 26 to reach 1.3 GHz will result in the 26-fold increase of the average power. To keep the gain of each stage below 20 dB, where ASE remains low , we will need to include one more stage into the amplification chain. The more challenging problem is to build the 1.3 GHz oscillator. We investigated the possibility of passively harmonically mode locking of a Yb-fiber ring soliton laser [8]. The results were good in terms of pulse quality and energy consideration but the timing jitter was unacceptably large. We investigate now the possibility of using an actively harmonic mode locked oscillator. Our initial results are encouraging and will be presented soon.

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