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Laser sources for polarized electron beams in cw and pulsed accelerators

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Abstract

We report the characterization of a high power, high repetition rate, mode-locked laser system to be used in continuous wave and pulsed electron accelerators for the generation of polarized electron beams. The system comprises of an external cavity diode laser and a harmonically mode-locked Ti:Sapphire oscillator and it can provide up to 3.4 W average power, with a corresponding pulse energy exceeding 1 nJ at 2856 MHz repetition rate. The system is tunable between 770–785 and 815–835 nm with two sets of diodes for the external cavity diode laser. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Laser sources; Polarized electrons

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1. Introduction

Spin-polarized electrons beams have offered a new tool for the detailed study of structures in diverse research fields such as atomic, particle and semiconductor physics. Electron accelerator facilities that undertake such studies are the MIT-Bates Linear Accelerator Center, Boston, USA, the Jefferson Laboratory (CEBAF), Newport News, Virginia, USA, the Johannes Gutenberg Universitat Mainz Microtron (MAMI), Mainz, Germany, the National Institute for Nuclear and High Energy Physics (NIKHEF), Amsterdam, The Netherlands and the Institute of Accelerating Systems and Applications (IASA), Athens, Greece. A reliable, stably running source of polarized electrons is of paramount importance for the success of these investigations in such accelerating systems.

The sources of polarized electrons that are used in these accelerating systems are usually based on optically pumped emission of electrons from GaAs-type semiconductor photocathodes. These polarized electron sources rely on a combination of two fundamental technologies: laser optical pumping and a semiconductor surface with negative electron affinity [1–4]. This method therefore requires the development of good-quality photocathodes and the existence of suitable laser systems in the wavelength range between 760 and 860 nm. Recent work has demonstrated that electrons with spin polarization around 75%, can be extracted from

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a single-strained-layer GaAs photocathodes with quantum efficiency exceeding 0.4% for illumination at 830 nm [5]. Similarly spin polarization approaching 68% has been demonstrated from AlGaAs-GaAs superlattice with quantum efficiency larger than 0.02% for illumination at 780 nm [6].

The choice of the type of photocathode as well as the operational requirements from the electron accelerator, set the requirements that the laser sources must meet. These requirements regard the following parameters and can be summarized as: (1) pulse repetition rate, (2) optical power and (3) wavelength tuning range. (1) Even though the electron beam may be generated by a cw operating laser source, during its subsequent acceleration by the RF electrical field in the machine, only a very small fraction of the cw electrons can be accelerated. Instead the majority (typically 60–85%) of the produced electrons is lost on the RF chopper, resulting in very small capture efficiency of the electrons in the machine. Apart from the waste of expensively produced electrons, for given electron beam current, the photocathode must be illuminated with a higher than necessary average optical power. This in turn results in a reduction of the lifetime of the photocathode. Clearly there is a significant advantage in using a pulsed laser source, generating picosecond pulses, at the frequency of the RF accelerating field. Typical values for the frequency of the RF accelerating field in the currently operating machines is between 500 and 3000 MHz. (2) An approximate estimate for the necessary average power required from the laser source, may be deduced from the photocurrent obtainable from photocathodes, which is λ(nm)/124 μA/mW/%QE. For laser illumination at 800 nm and for a continuous wave electron accelerator which requires 10 μA average accelerated current, which has a 10% transmission efficiency of the optical beam from the laser source to the target and a 20% capture efficiency and uses a 0.1% QE photocathode, a continuous wave laser source must provide 800 mW optical power while a RF pulsed laser must provide 160 mW average power. (3) The operating wavelength of the source is determined by the target photocathode and for the best performing photocathodes this is in the range 760–860 nm. As the photocathodes have a narrow operating wavelength range for large QE and spin polarization, it is desirable for the source to be tunable and to have as broad a tuning range as possible to cover a large variety of photocathodes.

High power, commercially available laser systems covering this wavelength range (760 nm – 860 nm) are either cw or mode-locked systems at low repetition rates (76 or 100 MHz) making them a poor match for application to accelerators. A mode-locked laser system operating at 76 MHz has been used in the past at MAMI [7] to prove the concept of use of pulsed lasers, but as it was forced to operate at a low subharmonic of the accelerating RF field, the average beam current was very low.

To address the issue of pulse repetition rate and power from the laser source, a number of research groups have recently developed custom, pulsed laser systems to be used in cw accelerators. These systems have been based on (a) gain-switched semiconductor diodes followed by power amplifiers [8], (b) passive mode-locking of a Ti:Sapphire oscillator [9] and (c) active mode-locking of a compound external cavity diode laser oscillator [10]. These systems have been successfully tested and used in cw accelerators, but as a result of their relatively low average power (up to 500 mW) and pulse energy (less than 150 pJ) they are unsuitable for pulsed electron accelerators. Recently, the output power obtained from the systems described in Refs. [8,10] has been raised with the use of coupled Ti:sapphire laser oscillators to reach 700 mW [11] and 3.4 W, [12] respectively.

In this paper we describe the characterization of a high power, short pulse, high repetition rate, laser system, which has been designed for use in the MIT-Bates Linear Accelerator Center [13]. The system comprises of an actively mode-locked external cavity semiconductor diode laser (ECL) [10] seeding a synchronously mode-locked Ti:Sapphire laser oscillator. The system can provide between 70 and 110 ps pulses at 2856 MHz repetition rate, with up to 3.4 W average power. The extracted energy within the 110 ps capture window exceeds 1 nJ and represents nearly a factor of 5 improvement in the pulse energy provided from any custom laser system developed for electron accelerators at this repetition rate. The system has been demonstrated to be capable of tuning between 770 – 785 and 815 – 835 nm with two sets of semiconductor diodes.

2. Experimental setup

The schematic diagram of the laser system is shown in Fig. 1 and comprises of an ECL oscillator and a synchronously, seeded, mode-locked Ti:Sapphire oscillator. The ECL system has been described in detail elsewhere [10] and here only a brief description is provided. It consists of an actively and harmonically mode-locked, external cavity semiconductor diode laser that uses an anti-reflection coated narrow stripe and a tapered gain, GaAlAs elements, to produce, high power picosecond pulses at repetition rates anywhere between 300 and 3000 MHz. Wavelength tuning of the ECL oscillator can be obtained within the gain bandwidth of the diode pair, by rotation of the grating which acts as wavelength selector. The MIT-Bates RF accelerator frequency is 2856 MHz and corresponds to a laser cavity length of 5.25 cm, which is too short to construct. Therefore, it was opted for the laser to be harmonically modelocked at the 6th harmonic of the fundamental cavity frequency (476 MHz, length = 31.5 cm). The choice of this fundamental cavity frequency is fortuitous as its 5th harmonic corresponds to the IASA-Athens master oscillator frequency at 2380 MHz making the testing of the system very easy. In order to match the repetition rate of the mode-locked pulses precisely to the required RF frequency, the cavity length of the ECL was adjusted by linear translation of a 90° prism.

This ECL oscillator has been previously tested at MAMI, producing stable electron beams at 2.45 GHz, with a polarization purity of 72% and transmission efficiency of 52% at an accelerated beam current of 10.1 μA [14]. In this demonstration the accelerated electron beam showed excellent characteristics, with high amplitude stability and very low timing jitter.

The Ti:Sapphire oscillator is a commercial unit with a standard, folded, astigmatically compensated cavity and includes a Lyot filter. Use of the Lyot filter has been found necessary during operation so as ensure means for wavelength tunability and so as to limit the oscillating bandwidth of the Ti:Sapphire oscillator. The cavity has been modified to allow for cavity length adjustment by positioning the high-reflector mirror on a PZT driven mount. As the output coupler is also used to introduce the external pulses from the ECL and in order to allow for more efficient seeding, the output coupler of the Ti:Sapphire has been replaced with a 10% output coupling element. In the absence of any seeding the Ti:Sapphire oscillator provides around 3.5 W output at the wavelength range 770 – 830 nm, for 18 W of pump power. To ensure synchronization with the master RF frequency and the ECL pulse train, the Ti:Sapphire cavity length was adjusted approximately to 63 cm, corresponding to a fundamental frequency of 238 MHz or the 12th subharmonic of the RF frequency.

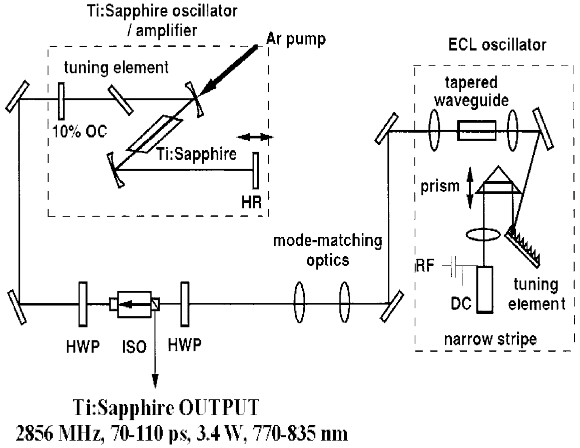

Fig. 1. Schematic of ECL/Ti:Sapphire laser system.

In order to couple the ECL beam into the Ti:Sapphire oscillator, a four mirror arrangement is used. As the beam profiles from the two oscillators differ in size and divergence, the mode-locked pulse train from the ECL is down collimated using an adjustable 5:1 beam expander. The mode-locked output of the Ti:Sapphire oscillator is stopped from entering the ECL oscillator using a broadband (700–900 nm), high isolation (> 40 dB) Faraday rotator which also acts to couple-out the mode-locked pulse train from the system. Half-wave plates are used for optimization of the polarization of the two beams for best performance.

3. Results and discussion

As it was the purpose of this work to investigate the performance of the system around 780 and 825 nm in order to match with the GaAs and superlattice $In_xGa_{1-x}As$ photocathodes, two different sets of diodes were used in the ECL cavity. The first diode set was antireflection coated ($R \leq 2\times10^{-4}$) and the narrow stripe diode had maximum gain at 827 nm, while the tapered waveguide amplifier had maximum gain at 830 nm. The second diode set was also antireflection coated ($R \leq 4\times10^{-4}$) and the narrow stripe diode had maximum gain at 774 nm, with the tapered waveguide having a peak gain at 790 nm.

For mode-locked operation of the ECL, the narrow stripe diode is biased with about 40 mA DC current and is driven with approximately 600 mW of RF power provided by an RF signal generator and amplifier. The tapered waveguide amplifier element was driven with approximately 1.5 A of DC current. Under these conditions and provided that the fundamental frequency of the ECL oscillator was adjusted to a subharmonic of the RF signal, the ECL output broke into mode-locked pulse train operation.

Fig. 2a shows the 2856 MHz mode-locked pulse train from the ECL for the 825 nm diode set at 825 nm, monitored on a Hamamatsu OOS-1 optical oscilloscope. The ECL provided 70 ps pulses with peak to background ratio of 30:1, an average mode-locked power of 250 mW and 80 pJ pulse energy within the 110 ps capture window. Fig. 2b shows the output pulse train obtained from the ECL/Ti:Sapphire system with 250 mW of seed power from the ECL. The pulses are broadened to 75 ps and the peak to background ratio is now 25:1. The average mode-locked power form the system is 3.4 W corresponding to a factor of 14 increase in average power form the ECL. The peak pulse energy that was measured within a 110 ps window for the MIT-Bates machine, was 1 nJ and corresponds to a factor of 13 increase from the direct ECL output. Fig. 3a and b show the corresponding pulse trains at 2856 MHz, at 781 nm from the ECL and ECL/Ti:Sapphire system. The ECL provided 95 ps pulses with peak to background ratio of 12:1, average mode-locked power of 140 mW and 40 pJ pulse energy within 110 ps around the pulse. The ECL/Ti:Sapphire system provided 106 ps pulses with a peak to background ratio of 9:1. The average mode-locked power of the ECL/Ti:Sapphire system was 3.4 W, representing a factor of 24 increase from the ECL oscillator. Within the 110 ps capture window the system provided a maximum 0.95 nJ energy corresponding to a factor of 23 increase from the direct ECL output. The figures for the extracted pulse energy

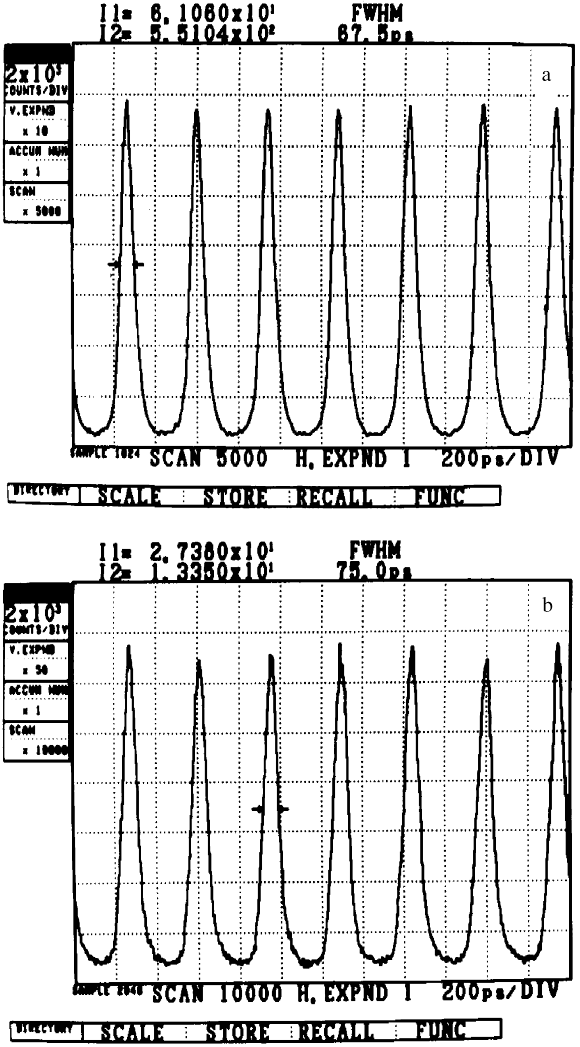

Fig. 2. Pulse trains at 2856 MHz from (a) ECL and (b) ECL/Ti:Sapphire laser systems using the 825 nm diode set.

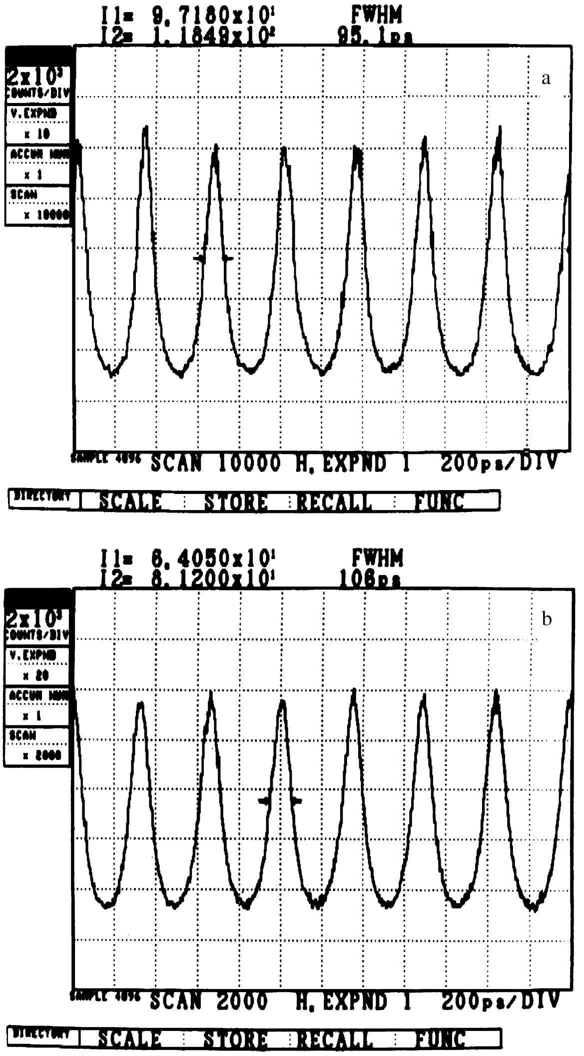

Fig. 3. Pulse trains at 2856 MHz from (a) ECL and (b) ECL/Ti:Sapphire laser systems using the 780 nm diode set.

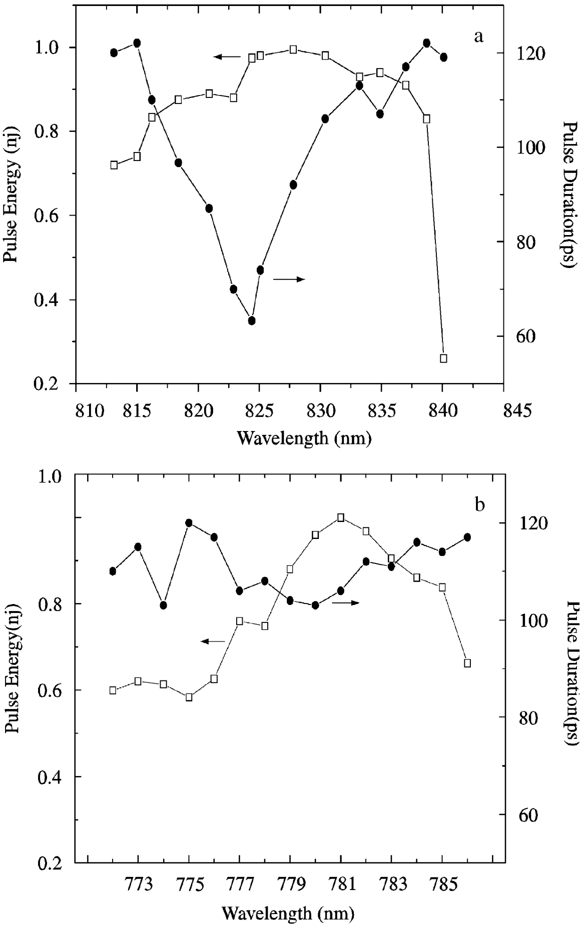

Fig. 4. Pulse duration and pulse energy in 110 ps capture window tuning curves for ECL/Ti:Sapphire laser system with (a) 825 nm diode set and (b) 780 nm diode set.

from the ECL/Ti:Sapphire system were obtained with 18 W of pump power and it is expected that they may be further improved for higher pump levels. These figures must be compared to the 0.8 nJ equivalent pulse energy that is now provided at the MIT-Bates polarized source, by an 4 W Ti:Sapphire system, pumped with a 29 W Argon ion laser.

Fig. 4a shows the tuning curves for pulse width and pulse energy within the 110 ps capture window, for the ECL/Ti:Sapphire system with the 825 nm diode set. These tuning curves were obtained only with the rotation of the grating element in the ECL oscillator and adjustment of the Ti:Sapphire Lyot filter and no further parameter optimization. Mode-locked operation of the system was obtained between 812 and 840 nm and the average power was approximately constant at 3.4 W throughout this tuning range. The shortest pulses were 70 ps and were obtained at 825 nm, close to the peak gain of the ECL diode set. Moving away from the peak gain of the ECL diode set, resulted in a gradual pulse broadening and a subsequent reduction of the pulse energy in the 110 ps window of interest. The ECL/Ti:Sapphire system provided more that

0.8 nJ of pulse energy for a tuning range between 815 and 837 nm.

Fig. 4b shows the tuning curves from the ECL/Ti:Sapphire system for the 780 nm diode set. Mode-locked operation was obtained between 772 and 786 nm while the average mode-locked power was approximately 3.4 throughout this range. The peak gain wavelength for the narrow stripe diode was at 774 nm and was considerably different from the peak wavelength of the tapered waveguide diode which was at 790 nm. As a result of this difference the pulsewidth curve is considerably flatter than for the 825 nm diode set, at the expense however of longer duration minimum pulse. The system performed best close to 780 nm, providing about 100 ps pulses and approximately 1 nJ energy/pulse in the 110 ps window.

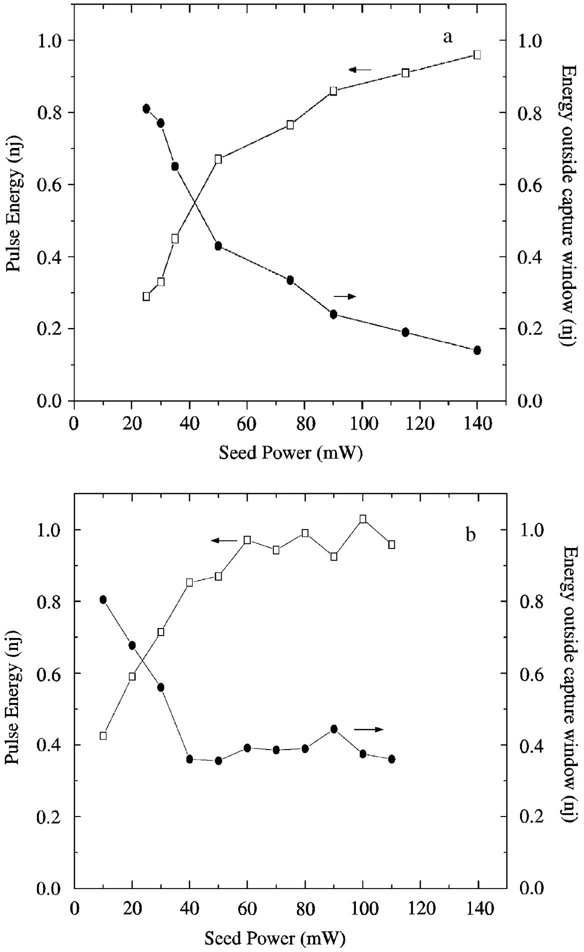

Fig. 5. Pulse energy within and without 110 ps capture window for (a) 825 nm diode set and (b) 780 nm diode set.

The degree to which the performance of the ECL/Ti : Sapphire system depends on the seeding signal was examined, by adjusting the half waveplate at the input of the isolator. Fig. 5a and b show the extracted energy within the 110 ps window and the energy that remains without for the 825 and 770 nm systems, respectively. This figure shows that less than 50% of the energy is extracted within the 110 ps window for input seed powers below 40 and 30 mW for the 770 and 825 nm systems, respectively. The key to obtaining high pulse energies from the system is to ensure a high level of seed power from the ECL to the Ti:Sapphire.

We have also measured the amplitude stability of the ECL/Ti:Sapphire using a fast photodiode and a 1 GHz analogue oscilloscope. The amplitude stability directly from the ECL oscillator was found to be better than 1% and from the ECL/Ti:Sapphire system was about 5% for 18 W pump power for either ECL diode sets. The reduction of the amplitude stability from the ECL/Ti:Sapphire system was found to be primarily due to the high pump power in the Ti:Sapphire oscillator and was not due to the seeding process. The introduction of a mechanical chopper in the pump beam readily improved the amplitude stability of the system to better than 3%.

4. Conclusion

In summary we have characterized a laser system designed to be used in polarized electron guns of electron accelerators. The laser system provides mode-locked pulse trains with duration as short as 70 ps at 2856 MHz repetition period, with up to 3.4 W average power corresponding to 1 nJ pulse energy. The laser system has been operated between 770–785 and 815-835 nm with the use of two sets of GaAlAs laser diodes in the ECL system. The ECL/Ti:Sapphire laser system has achieved nearly one order of magnitude increase in pulse energy compared to the other custom laser systems demonstrated so far for electron accelerators and is thus suitable for the use in high peak current pulsed machines.

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