# A HIGH POWER AND HIGH REPETITION RATE MODELOCKED TI-SAPPHIRE LASER FOR PHOTOINJECTORS

Matt Poelker† and John Hansknecht, JLAB, Newport News, VA, 23606, USA

*Abstract*

A high power cw modelocked Ti-sapphire laser has been constructed to drive the Jefferson Lab polarized photoinjector and provide > 500 mW average power with 50 ps pulsewidths at 499 MHz or 1497 MHz pulse repetition rates. This laser allows efficient, high current synchronous photoinjection for extended periods of time before intrusive steps must be taken to restore the quantum efficiency of the strained layer GaAs photocathode. The use of this laser has greatly enhanced the maximum high polarization beam current capability and operating lifetime of the Jefferson Lab photoinjector compared with previous performance using diode laser systems. A novel modelocking technique provides a simple means to phase-lock the optical pulse train of the laser to the accelerator and allows for operation at higher pulse repetition rates to ~ 3 GHz without modification of the laser cavity. The laser design and characteristics are described below.

## 1 SYNCHRONOUS PHOTOINJECTION

Picosecond pulse lasers with repetition rates synchronized to the accelerator cavity rf frequency are used to drive the polarized photoinjector at Jefferson Lab. With such lasers, electrons are extracted from the photocathode only during the portion of the rf cycle when they can be accelerated in the machine. Few electrons are dumped at the injector chopper as would be the case for dc laser illumination. This efficient use of the extracted electron beam helps to preserve the operating lifetime of the photocathode. Synchronous photoinjection also provides a means to generate high bunch charge without the need for subharmonic bunching and chopper cavities, as demonstrated at the photoinjector at the Jefferson Lab Free Electron Laser.

The largest obstacle to synchronous photoinjection has been the lack of commercially available high power picosecond-pulse laser sources with GHz repetition rates. Diode laser systems [1] are extremely reliable and provide high repetition rates but average output power from these systems is low, typically < 100 mW. Low output power combined with inherently low quantum efficiency from strained layer GaAs photocathodes limits the maximum beam current with high polarization to approximately 70 μA. Moreover, a key component of these systems (diode optical amplifier, SDL Inc. Model 8630-E) is no longer manufactured and an alternate vendor has not been identified.

†poelker@jlab.org

## 2 JLAB MODELOCKING TECHNIQUE

At Jefferson Lab, we have built an actively modelocked Ti-sapphire laser that emits 50 ps pulses and provides > 500 mW output power with ~ 30 nm wavelength tunability centered at 850 nm. Modelocked operation is obtained by introducing light from an injection-locked gain-switched diode laser into the Ti-sapphire laser cavity. The diode laser light introduces gain-modulation within the Ti-sapphire laser cavity, which initiates and maintains modelocked operation when the repetition rate of the gain-switched diode laser is set to the axial mode spacing of the Ti-sapphire laser. Moreover, the pulse repetition rate of the Ti-sapphire laser can be varied by setting the repetition rate of the gain-switched diode laser to multiples of the axial mode spacing, without changing the Ti-sapphire laser cavity length. Repetition rates from 250 MHz to 3 GHz have been obtained (in 250 MHz intervals) from one laser having a constant cavity length of ~ 60 cm. The Ti-sapphire laser optical pulse train follows that of the gain-switched diode laser which is easily be locked to the accelerator.

### *2.1 Description of the Laser*

A schematic of the laser is shown in Figure 1. The Ti-sapphire crystal (20 mm x 6 mm dia., 0.03% dopant) is mounted in a water-cooled, temperature-controlled copper block, midway between two curved mirrors (radius of curvature, 10 cm). The double-fold geometry provides correction for astigmatism introduced by the Brewster cut Ti-sapphire crystal faces [2]. The ~ 60 cm long cavity length is very manageable; it provides a compact design but still allows the use of relatively inexpensive commercial optic mounts. A prism located near the flat high reflector mirror provides wavelength selection.

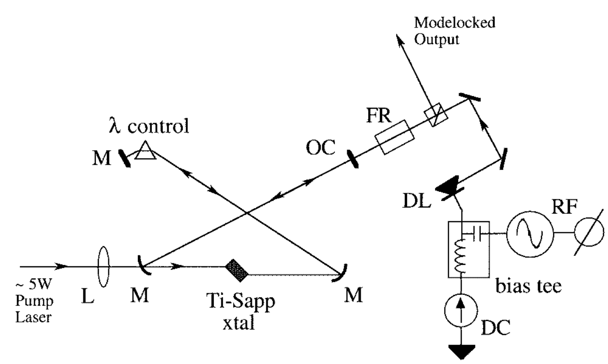


Figure 1. Schematic of the modelocked Ti-sapphire laser. L, lens; M, laser mirror; OC, output coupler; FR, Faraday crystal and halfwave plate; DL, gain-switched diode laser.

 

Light exits the laser cavity through a 5% transmissive flat output coupler and passes through a Faraday rotator crystal and permanent halfwave plate which rotates the laser polarization 90 degrees. The output beam is reflected at a right angle from a polarizing beamsplitter cube. Output power is very nearly the same in dc or modelocked operation; ~ 600 mW output power is obtained with 5 W of pump power from a solid state green laser at 532 nm (Verdi-10, Coherent Inc.).

The Faraday crystal/halfwave plate and polarizing cube provide an efficient means to introduce light from the gain-switched diode laser into the Ti-sapphire laser cavity. Light travelling in one direction (Ti-sapphire laser light moving left to right in Figure 1), experiences a 90 degree polarization rotation and is reflected at a right angle from the polarizing cube. Light travelling in the other direction (diode laser light moving right to left in Figure 1) experiences no net polarization rotation and is introduced into the Ti-sapphire laser cavity through the output coupler. In practice, a small amount of light from the Ti-sapphire laser passes through the polarizing cube and is directed into the diode laser. This is a necessary condition that serves to injection lock the diode laser (i.e., the diode laser wavelength is the same as the Ti-sapphire laser wavelength). Under this condition, there is interference between the Ti-sapphire and diode laser light providing rapid gain modulation within the Ti-sapphire laser cavity at the axial mode spacing (or multiple thereof). Very little diode laser light is required to initiate and maintain modelocked operation; less than 1 mW as measured at the face of the diode laser.

Pulsed output from the diode laser is obtained using the technique known as gain-switching [3]. The diode laser is biased near threshold and then ~ 1W of rf power is applied to the laser using a bias-tee network. The pulse repetition rate can be varied over a wide range frequencies by merely changing the frequency of the applied rf and the amount of dc bias current (higher frequencies require higher dc bias currents). The technique is purely electrical in nature; there are no cavity length concerns. It is a trivial matter to operate diode lasers at repetition rates from ~ 100 MHz to 3 GHz. When properly biased, optical pulsewidth is very nearly constant (~50 ps) over this range of repetition rates. Typical output power from the gain-switched diode laser is 5 to 10 mW, considerably more power than necessary to force modelocked operation of the Ti-sapphire laser. Standard commercial rf phase shifters are used to control the optical pulse train of the diode laser; this in turn provides control of the Ti-sapphire laser pulse train since the two pulse trains are locked together.

The Ti-sapphire laser rests within a nitrogen-purged plexiglass box (Fig. 2). The maximum available output power drops from 500 mW to 300 mW during a three week period. Power is restored when the laser mirrors and Ti-sapphire laser crystal faces are cleaned.

All of the laser systems used for production electron beam delivery at Jefferson Lab are remotely controlled and located within a light-tight aluminum enclosure placed next to the injector beamline. A number of remote

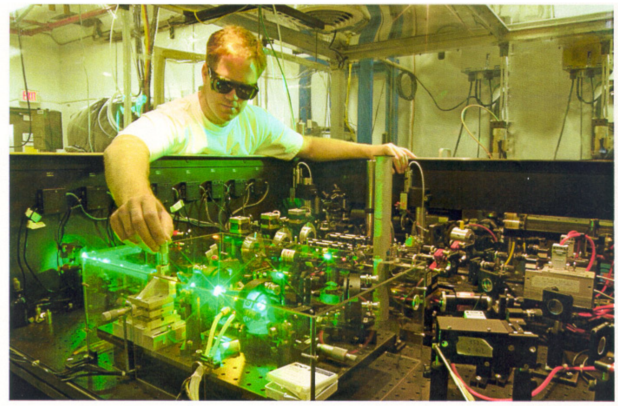

Figure 2. Author making a Ti-sapphire laser adjustment. The Ti-sapphire and diode lasers at Jefferson Lab are remotely controlled and operate for weeks unattended within the injector tunnel.

adjustments can be made to optimize laser performance when necessary; Picomotors (New Focus Inc.) are used to align laser mirrors, adjust laser cavity length and to move the laser spot at the photocathode by small amounts. A plastic “hut” surrounds the laser enclosure and straddles the electron beamline vacuum chamber to provide a temperature controlled environment stable to within 0.2 $^{o}$C.

## 3 RESULTS AND DISCUSSION

The Ti-sapphire laser has been in near-continuous use for nine months. With ample laser power headroom, it is possible to deliver high beam current (> 100 µA) and high beam polarization (> 80%) for many days before steps are required to restore the photocathode quantum efficiency. This laser helped ensure the recent successful completion of two noteworthy nuclear physics experiments to measure proton and neutron form factors (E99-007 and E93-038). It would have been impossible to complete these experiments in the allotted time using the Jefferson Lab diode laser systems.

A number of features were incorporated into the laser design in an attempt to ensure reliable laser operation. These include the use of an all-solid-state pump laser, the use of stable remotely-controlled mirror mounts and the construction of the laser “hut” to provide a clean, temperature-controlled environment for the lasers and related optics. Under typical operation, remote cavity length adjustments of approximately one micron are required ~ once per day. Laser mirror alignment is required less frequently. The laser mirrors and crystal faces must be cleaned every three weeks during scheduled maintenance periods.

Aside from added complexity, the Ti-sapphire laser suffers a significant disadvantage compared with the diode laser systems used previously. The Ti-sapphire laser produces an electron beam with more amplitude noise than beam produced by diode laser systems. Understanding the origin of this noise and eliminating it has been problematic. The spectrum of the beam noise is “white”, extending to many kilohertz. The typical beam noise values are ~ 3% rms measured over a few minutes time scale and ~ 1% at 30 Hz. These values are approximately four times greater than those when diode lasers are used to extract beam. Beam noise effects the nuclear physics program at Jefferson Lab in a number of ways. Excessive beam noise at 30 Hz (i.e., the beam helicity flip rate) increases the amount of time nuclear physics Users must take data in order to obtain the statistically accurate measurements. Beam noise at 60 Hz confounds software programs designed to keep beam position constant in the machine. Beam noise at kHz frequencies is misconstrued as beam loss by machine protection systems; these systems react by turning off the beam (i.e., closing a laser shutter).

Over the past nine months of production operation, a number of observations have been made that relate to beam noise and the Ti-sapphire drive laser; 1) it is important to eliminate optical reflections into the Ti-sapphire laser cavity from the surfaces of transport optics downstream of the laser, 2) it is important to force the Ti-sapphire laser to operate at a well defined, constant wavelength, and 3) the lowest beam noise values are obtained when the Ti-sapphire laser cavity is adjusted to yield the best optical pulses.

## 4 CONCLUSIONS AND FUTURE WORK

The laser in its present form has already been used to perform demanding nuclear physics experiments that would have taken considerably longer using diode laser systems. However, it is clear that future experiments will benefit greatly if the laser can be made to produce beam with reduced amplitude noise. For this reason, an automatic cavity lock circuit is under construction using the electrical signal from an ac-coupled fast photodiode looking at the optical pulses from the laser and a piezo-driven mirror mount. In addition, a unidirectional travelling wave geometry is being tested with the hopes that it will provide a more reliable means to injection lock the diode laser and provide more uniform gain extraction within the Ti-sapphire laser crystal.

Finally, it is worth noting that 2 W output power at 780 nm was obtained using a laboratory version of the production Ti-sapphire laser system. This laser, together with a bulk GaAs photocathode (typical quantum efficiency at 780 nm > 10%), represents a necessary ingredient for delivering beam current in excess of 100 mA from GaAs based photoemission guns of the sort used at Jefferson Lab.

## 5 REFERENCES

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[2] H. Kogelnik, E. Ippen, A. Dienes, C. Shank, “Astigmatically Compensated Cavities for CW Dye Lasers,” IEEE J. Quantum Electron, QE-8 (1972) 373.

[3] See for example, P.T. Ho, in Picosecond Optoelectronic Devices, C.H. Lee (Ed.), Academic Press, New York, 1984.