LASER SYSTEM FOR THE TTF PHOTOINJECTOR AT FERMILAB

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Abstract

We have developed a solid-state laser system to meet the requirements of the TESLA Test Facility (TTF) photoinjector, currently under development at Fermilab. The laser produces a 1 MHz train of up to 800 equal-amplitude pulses with up to 1 mJ per pulse (0.8 J per macropulse) at $\lambda = 1054$ nm. The laser pulse train is produced by a phase-stabilized, mode-locked, Nd:YLF oscillator and a fast selection Pockels cell. The pulses are amplified in an Nd:glass amplifier chain consisting of a multipass rod amplifier and a 5-pass zig-zag slab amplifier. The laser system employs chirped pulse amplification (CPA) to produce 10 ps pulses. After fourth harmonic generation of the laser to $\lambda = 263$ nm, 10 nC electron bunches can be extracted from a Cs_2Te photocathode in the RF gun.

1 TTF PHOTONINJECTOR DEVELOPMENT

A collaboration has been formed between FNAL, DESY, UCLA, INFN Milano, and the University of Rochester to develop a state-of-the-art photoinjector with a novel bunch structure for the Tesla Test Facility (TTF). The injector will consist of an RF gun[1] (UCLA, FNAL) with a high-quantum efficiency photocathode[2] (INFN Milano) driven by an advanced laser system[3] (Rochester), and a superconducting linear accelerator cavity (DESY).

The FNAL/TTF RF photoinjector is designed to match the requirements of the TTF accelerator[4], namely high bunch charge (8 nC), low emittance ($<$ 20 mm-mr) and high duty cycle (1%). The TTF pulse train consists of 800 bunches of 8 nC, spaced 1 μs apart, with a 10 Hz rep rate. The beam optics are optimized for an overall injector consisting of the electron gun followed by one linac capture section and a dipole chicane for magnetic bunch compression[1].

2 LASER PERFORMANCE REQUIREMENTS

The production of high charge, high brightness electron beams place increasingly challenging demands on the drive lasers used with RF photoinjectors[5]. The design of a laser suited to the requirements of the TTF photoinjector is largely determined by the unique temporal beam structure and high laser pulse energy required to produced high-charge electron bunches.

The macropulse structure of the laser pulse train must produce the required 800 bunch electron pulse train. The width of each laser pulse must be small compared with the RF period, but not so small that longitudinal space charge effects become unmanageable in the electron bunch; the nominal design pulse length is 10 ps. The laser must be phase locked to the accelerator RF with minimum ($<$ 1 ps) timing jitter.

Each laser pulse must have enough energy to emit the required bunch charge (10 nC) from the photocathode. UV photons are required for high quantum efficiency, so harmonic generation is used. Assuming a 1% efficient photocathode, 5 μJ/pulse is required to produce 10 nC/bunch. At least 10 times this much energy per pulse must be available at the fundamental (infrared) laser wavelength.

The need for constant beam loading in the superconducting capture cavity requires high bunch charge stability. Each laser pulse in the pulse train must have the same energy as the others; our goal for the pulse train “flatness” is $\leq$5% deviation from the average energy in a 100 μs time scale. Similarly the energy per laser pulse should not vary significantly from shot to shot; this presents a considerable challenge for a pulsed laser system.

3 LASER SYSTEM

3.1 Overview

A block diagram of the laser system is shown in Figure 1. A mode-locked Nd:YLF oscillator produces a low energy, continuous pulse train at 81.25 MHz. Pulses from the oscillator are stretched and chirped in a 2 km fiber. After the fiber, a train of 800 pulses is selected at 1 MHz from the oscillator pulse train by a high speed, low voltage, lithium tantalate (LTA) Pockels cell (Conoptics Inc., model 360-80 modulator). The narrow (18 ns) gate of the Pockels cell provides $\geq$ 50:1 discrimination of adjacent pulses.

Each of the 800 pulses are injected into a multipass amplifier which contains a flashlamp-pumped, $1/4 \times 6$ inch Nd:glass rod amplifier and a fast KD*P Q-switching Pockels cell (Conoptics Inc., model 350-105). Each pulse is trapped in the cavity by the Pockels cell and makes 20 passes through the cavity, amplifying up to 2 μJ before it is ejected by the Pockels cell. A Faraday isolator separates the input and output pulses. Another flashlamp pumped, Nd:glass rod amplifier is used in a two-pass configuration to provide an additional gain of 5. The high energy amplification in the system is provided by a flashlamp-pumped, zig-zag, slab amplifier. The pulse train makes five passes in the slab to achieve a gain of up to 1000. The energy in each pulse after the slab amplifier is expected to be 1 mJ, which corresponds to 800 mJ in the macro pulse and 0.8 W average power at a 1 Hz repetition rate.

Following the slab amplifier, the beam is spatially filtered and then compressed in time using a pair of parallel diffraction gratings. The pulse length is adjustable from 3–

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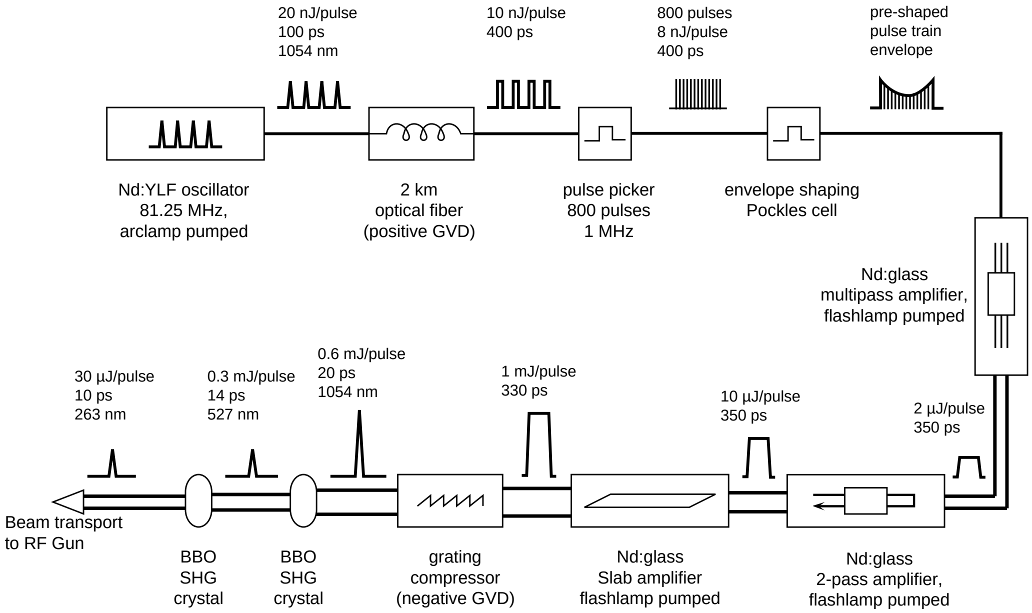

Figure 1: Block diagram of the FNAL/TTF photoinjector laser system.

30 ps. The pulses are frequency doubled and quadrupled in a pair of BBO crystals. The UV pulse train is expanded and transported 15 m in vacuum to a final set of imaging optics which relay the beam to the photocathode.

3.2 *Laser Performance*

3.2.1 Timing

The oscillator is mode-locked by an acoustooptic modulator which is phase-locked to the same master oscillator that produces the 1.3 GHz RF for the photoinjector. To reduce the timing fluctuations in the oscillator relative to the phase of the photoinjector RF, an electronic feedback loop is used to shift the phase of the mode-locker RF relative to the 81.25 MHz reference signal. We use a commercial phase-lock loop timing stabilizer (Lightwave Model 1000) designed specifically to stabilize the timing of mode-locked, solid-state lasers. A detailed description of the operation of the Lightwave stabilizer can be found in Ref. [6].

The oscillator timing jitter is measured by monitoring the laser output with a photodiode and a spectrum analyzer and measuring the relative powers of a high order (5–100) laser harmonic and its phase-noise sidebands; in the 81.25 MHz oscillator we measure a timing jitter of $\lesssim$2 ps RMS.

3.2.2 Amplification

The multipass and 2-pass amplifiers were built and tested at FNAL during 1996–97. A train of 200 pulses at 0.5 MHz from the multipass is shown in Figure 2. The the glass and the mounting/cooling frame for the slab amplifier have been fabricated and assembled, and the 20 kJ, 1 Hz power supply for the four slab flashlamps is nearly complete. We expect to commission and test the slab amplifier during the summer of 1997.

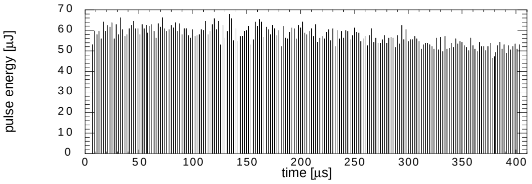

Figure 2: 200 pulses at 0.5 MHz spacing extracted from the multipass amplifier after 24 passes. The total pulse train energy is 11.5 mJ.

The primary challenge in the laser system is in producing uniform amplification for all pulses in the 800 μs pulse train. The gain of each amplifier can vary substantially during the macropulse depending on the pump rate and the rate at which stored energy is extracted by amplifier action and spontaneous emission. An analysis of the time-dependent gain of the amplifier chain during the macropulse is given in Ref. [3].

In order to provide a flat-top macropulse laser energy profile, each of the laser amplifiers is driven by a custom designed power supply which provides nearly constant current discharge to the flashlamps for $\geq$800 μs.

An additional correction to the flatness of the macropulse envelope is made by pre-shaping the profile of the injected micropulses by means of an amplitude modulating Pockels cell. Preliminary results using a static correction pulse train shape have significantly improved the flatness of a train of 600 pulses (Figure 3). Preshaping the input pulse changes the gain loading of the amplifiers, so the input shape must be iteratively corrected to produce a flat output. We are currently working on an adaptive feedback system to monitor the the pulse train shape over several shots and produce a best-average-correction shape.

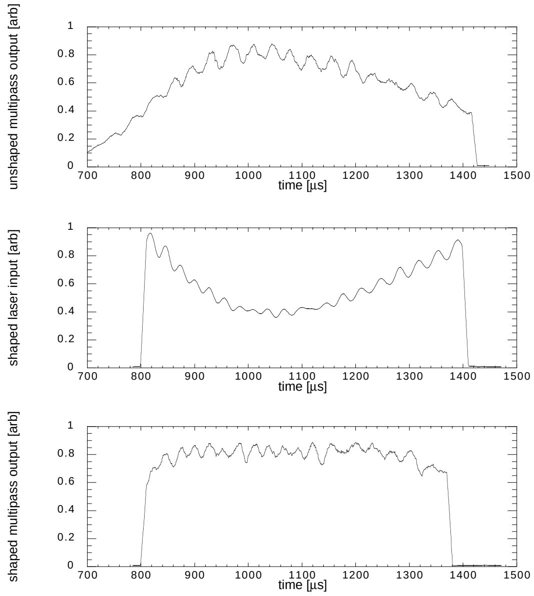

Figure 3: Amplified pulse train envelope with no preshaping (top), shaped input pulse train envelope (middle), and the resulting, amplified pulse train envelope (bottom).

Because the amplifiers are not run to saturation, the amplitude of the output is sensitive to small changes in the gain on a shot-to-shot basis. Consequently it is preferable to run with high gain and fewer passes in the multipass amplifier to reduce amplitude fluctuations. The peak flashlamp power required to achieve the necessary gain in the multipass amplifier limits the rep rate to $\leq$1 Hz.

Currently, the standard deviation of shot-to-shot pulse train energy is $>$40% of the average. We are working to improve the shot-to-shot variation by improving the optical alignment, designing resonator cavities for the oscillator and the multipass amplifier with increased mechanical stability, and adding feedback systems to the flashlamp power supplies.

3.2.3 Pulse Compression

Short, high energy pulses are produced using the technique of chirped pulse amplification (CPA)[7]. In CPA, pulses from the oscillator are stretched in time and swept in frequency ("chirped") by propagation through an optical fiber. The long, chirped pulse is amplified at low peak intensity through the amplifier train. After amplification the chirp is reversed by the the negative group veleocity dispersion of a pair of parallel diffraction gratings to produce a 3–30 ps pulse.

Each stage of frequency doubling reduces the FWHM of a gaussian pulse by a factor of $\sqrt{2}$, so the IR pulse should be $\sim$20 ps to produce a 10 ps UV pulse. The Nd:glass amplifiers in the laser system have a broad enough gain bandwidth to produce sub-picosecond pulses, so it is relatively easy to produce the 10 ps pulses required for the photoinjector.

The grating compressor is set for a particular frequency chirp, and variations in the pulse width or the bandwidth of the laser pulses will affect the compressed pulse width. We do not yet have an instrument to measure the pulse width on a single shot basis (such as a streak camera or single-shot autocorrelator), but the width can be measured over several shots with a scanning autocorrelator. On a shot-by-shot basis we infer the amplified width by compressing the oscillator output in a second pair of compression gratings and measuring the compressed pulse width in a rotating-mirror autocorrelator.

3.2.4 Harmonic Generation

The pulse train undergoes second harmonic generation (SHG) in a $5\times5\times10$ mm BBO crystal and 4th harmonic generation (4HG) to the UV in a second $5\times5\times10$ mm BBO crystal. The conversion efficiency is a non-linear function of the intensity of the laser. With 200 μJ/ IR pulses we have measured SHG efficiency as high as 50% and 4HG efficiency as high as 10%. With the higher pulse energy available with the slab amplifier, we expect even higher overall conversion efficiency.

4 CONCLUSIONS

The laser system is currently capable of producing up to 800 1 MHz-spaced pulses amplified to 10 μJ/pulse with limited pulse-train flatness. The CPA technique enables us to produce IR pulses from 3–30 ps. Even at 20% of the design energy, the 4HG efficiency is 10%. With the addition of the slab amplifier and the preshaping system, we will be able to produce a considerably flattened pulse train with 1 mJ/pulse. Commissioning of these systems is expected in the summer of 1997.

DC illumination tests of the Cs$_2$Te photocathode show that the quantum efficiency is $>$10%[2]. Even if the QE degrades by a factor of 10 when exposed to the RF of the photoinjector, the laser system will still be able to deliver enough UV energy per pulse to extract 10 nC/bunch. First tests of the photocathode in the photoinjector will begin in spring 1997 using the laser to produce a reduced (200 pulse) pulse train.

5 REFERENCES

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