HIGH AVERAGE POWER LASERS FOR THE PHOTON COLLIDER *

B. Stuart, J. Gronberg, LLNL, Livermore, CA 94550, USA
A. Seryi, SLAC, Menlo Park, CA 94025, USA

Abstract

The idea to convert an electron collider into a high energy photon collider has existed for several decades [1]. A key technological limitation to realizing this idea is the need to create a large amount of laser power to drive the Compton back-scattering. A concept to reduce the required laser power using a recirculating cavity [2, 3] has been proposed. We describe a concept for a laser architecture that could drive such a cavity.

INTRODUCTION

A laser system to drive a resonant stacking cavity for the Gamma-Gamma Collider should meet the following output requirements:

- Pulse energy of 30 mJ, pulse duration 1 ps (FWHM), wavelength of $\approx 1\mu m$
- Trains of ≈ 3000 pulses at 2-3 MHz (300-400 ns separation) with uniform energy
- Pulse trains at 5 Hz
- Near-diffraction-limited focusability
- Controllable polarization
- Spatial and temporal fidelity to drive the resonant cavity with minimal loss

The main challenge on the laser side will be reaching the required average power (≈kW) and short pulse duration while maintaining spatial and temporal pulse fidelity through the amplification process. Gain saturation, dispersion, nonlinear effects, optical inhomogeneities, and thermal effects must all be controlled in a way to allow coherent addition of successive pulses in the resonant cavity.

The initial concept for such a laser, shown in Figure 1, is based on conventional chirped-pulse amplification (CPA) [4]. After generation in a short-pulse (<ps) oscillator, the laser pulses are stretched to approximately 1 ns before amplification. Acoustic-optic and electro-optic modulators are used to produce the required pulse train format. Amplification is achieved in a series of single or multipass amplifiers, which must be configured to minimize nonlinear, gain, and thermal effects. After amplification, the pulses are temporally compressed back to the ps range, before injection into the stacking cavity.

* This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

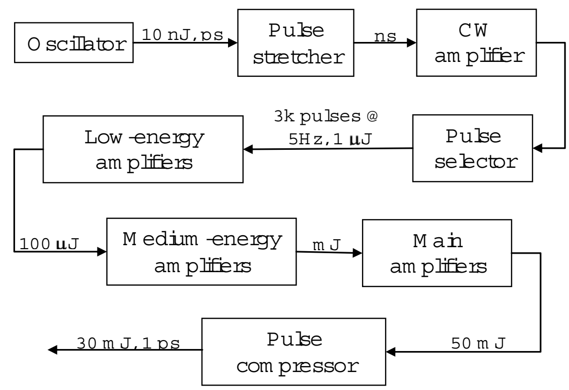

Figure 1: Block diagram of initial concept for the laser system.

Laser systems that can produce uniform energy across the ≈ms pulse train have been demonstrated up to the 100 μJ level [5, 6]. These systems were frequency converted and used to drive a photocathode, but not injected into a resonant ring cavity. This level of amplification is designated by the low-energy amplifiers in Figure 1. The medium-energy amplifiers will boost the energy to the few-mJ level. This is where nonlinear and thermal effects become increasingly important, and is a good level at which to demonstrate an initial system capability. Thermal, nonlinear, and gain saturation effects will be major issues in the main amplifiers. This is where the majority of the laser system design effort will occur.

DESCRIPTION OF SYSTEM COMPONENTS

Oscillator

The oscillator will create the short (<ps) pulses that will be amplified through the rest of the laser system. There are many types of short-pulse oscillators, ranging from fiber-based to high-average-power bulk systems. The choice of gain material will be driven by the main amplifiers, and the oscillator will need to produce pulses within this gain bandwidth. For coherent addition in the resonant cavity the oscillator must operate at some multiple of the cavity frequency, and the carrier envelope phase (CEP) of the oscillator pulses must be locked (constant). CEP-locked oscillators operating at 75-100 MHz and 800 nm are commercially available [7]. There are also extended-cavity oscillators that operate down to 2 MHz [8], but have not been CEP-locked. The best choice for stability is probably a

shorter cavity that operates at ≈100 MHz. The repetition rate can be locked to a multiple of the 2-3 MHz cavity frequency, and pulses selected at 2-3 MHz from the 100 MHz train by an acoustic-optic deflector. The pulse energy lost by choosing a higher repetition-rate oscillator can be made up by a CW-pumped fiber or bulk amplifier.

Pulse stretcher

Before amplification, the laser pulses from the oscillator need to be stretched to approximately 1 ns to avoid nonlinear effects in the amplifiers and other transmissive optics. This level of stretching can be easily reached by many different designs of pulse stretchers. One important aspect of the stretcher is that it must be extremely stable against beam pointing jitter that will lead to phase noise and reduced efficiency in the resonant cavity.

CW-pumped amplifiers

As much amplification as practical should be produced in CW-pumped amplifiers, where each pulse will see the same temporal and spatial gain profile. This can be achieved up to the 10-Watt level (few uJ pulses at 2-3 MHz) in a combination of diode-pumped fiber and bulk amplifiers.

Pulse selector

After reaching a practical average power limit in the CW amplifiers, the duty cycle will need to be reduced before further amplification. An electro-optic modulator (Pockels cell) will be used to carve out the ≈3000 pulse trains at 5 Hz. Some pulse train shaping may be necessary at this point to achieve uniform output energies.

Amplification

The gain medium for the main amplifiers must support the required bandwidth, have a reasonable gain cross section, and produce minimal thermal distortion. The gain medium for the earlier amplifiers does not necessarily have to be the same, but it must have sufficient bandwidth and match the wavelength of the main amplifiers. Regenerative amplifiers with cavity lengths of 1-3 m are typically used to produce high gain (109) and excellent beam quality. With our requirement for ≈1 ms pulse trains, a regenerative amplifier is not practical and a series of single- or multi-pass amplifiers will be needed. In order to maintain beam quality and reduce pointing jitter, the pulses will be relay-imaged and spatially filtered between stages. An analysis will need to be made to determine the optimum spatial profile at each stage typically either Gaussian or flat-top.

Low-energy amplifiers

The low-energy amplifiers will increase the energy from the μJ level to the 100 μJ range. Similar systems exist today for driving photocathodes. The TTF system [6] produces uniform trains of 2400 micropulses at 3 MHz in the train (800 μs total length). The Nd:YLF gain medium results in a pulse duration of 11 ps FWHM and the pulses are not required to be phase-stabilized for injection into a resonant cavity. Micropulse energy of 140 μJ at 1047 nm is generated at 10 Hz. Timing of the flashlamp pulse is used to control the temporal gain profile and produce uniform-energy pulse trains. This system demonstrates feasibility of producing uniform gain at the 100-μJ level.

Medium-energy amplifiers

The medium-energy amplifiers will boost the energy to the mJ range. With average power in the 20-W range, thermal effects will become increasingly important. As the irradiance increases to the GW/cm2 range, nonlinear phase accumulation (B-integral) will also come into play. This is a good level for an initial demonstration of a scaled-down laser system coupled into a resonant cavity.

Main amplifiers

The biggest challenge in the laser system will be in the design and operation of the main amplifiers. The average power will be increased to 0.8-1 kW as the pulses are amplified to the 50-mJ level. This must be accomplished while minimizing nonlinear and thermal effects, and maintaining excellent beam quality. New laser materials, such as ceramics made from sesquioxides (Y2O3, Lu2O3) and oxyorthosilicates (LSO, YSO, LYSO), should be investigated to provide the required emission bandwidth along with high thermal conductivity. The Mercury Laser [9] at LLNL uses He gas cooling of Yb:S-FAP laser slabs in its main amplifiers to produce 65 J pulses at 10 Hz. This is on the same order average power required for the Gamma-Gamma Collider laser system, although both Mercury and HALNA [10] are designed for only five-times diffraction-limited beam quality. Spreading the energy into pulse trains will greatly reduce the optical damage risks and nonlinear effects compared single high-energy pulses. Of great concern will be the changing thermal profile during the pulse train amplification. This will lead to changes in refractive index and consequently phase variations spatially across the beams and temporally through the pulse train. The magnitudes of these variations that still permit coherent addition in the resonator cavity need to be understood.

Pulse compressor

After amplification, the laser pulses must be temporally compressed from 1 ns back down to 1 ps. This can be accomplished in a conventional pulse compressor incorporating multilayer dielectric diffraction gratings. These gratings exhibit high efficiency ($> 98\%$) and high damage threshold ($> 3J/cm^2$ @ 1 ps) at 1 μm wavelength [11], and have been shown to handle average power densities of 2 kW/cm2 [12] without thermal distortion.

FURTHER DESIGN STUDIES

Numerous questions need to be answered in designing the Gamma-Gamma Collider laser system. A comprehensive model should be developed to investigate how the nonlinear, thermal, pointing, and gain effects affect the ability to coherently add the pulses in the resonant cavity. Control points and feedback loops need to be identified and designed. A full 4D spatial/temporal model is desired, but much insight can be gained from a simple 2D calculation. Some of the questions include:

1) How does a changing thermal distribution affect the coherent addition of pulses? Is there a maximum allowable rate of change in temperature? 2) How does nonlinear phase accumulation across the beam affect the resonant cavity? Is B-integral a concern in changing the pulse temporal shape? 3) How does gain saturation affect coherent addition? Must all pulses see the same gain? 4) Should the injected pulses have a Gaussian or top-hat spatial profile? 5) What gain material is optimal? 6) What type of laser oscillator should be used? 7) Where are the control points to maintain resonance?

CONCLUSIONS

The basic technology to create a laser pulse train of the correct energy and timing to drive a recirculating cavity for the Gamma-gamma collider exists. Further work is needed to quantify the tolerances required for the laser system so that it can successfully drive the recirculating cavity. Work toward this goal is currently on-going.

REFERENCES

[1] I. Ginzburg, G. Kotkin, V.Serbo and V. Telnov, *Pizma ZhETF* **34** (1981) 514; *JETP Lett.* **34** (1982) 491 (Preprint INF 81-50, Novosibirsk (1981) in English).

[2] I. Will, T. Quast, H. Redlin and W. Sander, "A Laser System For The TESLA Photon Collider Based On An External Ring Resonator", *Nucl. Instrum. Meth.* A **472** (2001) 79.

[3] G. Klemz, K. Monig, I. Will, "Design study of an optical cavity for a future photon-collider at ILC", *Nucl. Instrum. Meth.* A **564** (2006) 212.

[4] D. Strickland and G. Mourou, "Compression of Amplified Chirped Optical Pulses", *Opt. Comm.* **55**, 447-449 (1985).

[5] A.R. Fry, M.J. Fitch, A.C. Melissinos, B.D. Taylor, "Laser system for a high duty cycle photoinjector", *Nucl. Inst. and Meth.* A **430**, 180-188 (1999).

[6] I. Will, G. Koss, I. Templin, "The upgraded photocathode laser of the TESLA Test Facility", *Nucl. Inst. and Meth.* A **541**, 467-477 (2005).

[7] Femtolasers Femtosource Rainbow, `http://www.femtolasers.com`; KMLabs Griffin, `http://www.kmlabs.com`.

[8] S. Naumov, A. Fernandez. R. Graf, P. Dombi, F. Krausz, A. Apolonski, "Approaching the microjoule frontier with femtosecond oscillators" *New J. Phys.* **7**, 216 (2005).

[9] A. Bayramian, *et al.*, "The Mercury Project: A high average power, gas-cooled laser for inertial fusion energy development", *Fusion Sci. and Tech.* **52**, 383-387 (2007).

[10] T. Kawashima, *et al.*, "The HALNA project: Diode-pumped solid state laser for inertial fusion energy", *J. Phys. IV France*, **133**. 615-620 (2006).

[11] M.D. Perry, *et al.*, "High-efficiency multilayer dielectric diffraction gratings", *Opt. Lett* **20**, 940-942 (1995); I. Jovanovic, *et al.*, "Precision damage tests of multilayer dielectric gratings for high-energy petawatt lasers", *Proc. SPIE* **5647**, 34-42 (2005).

[12] K.-X. Sun, *et al.*, "Characterization of highly efficient lasrge dielectric gratings", presented at LSC LIGO-VIRGO Meeting, Caltech (2009).