Development of the 50 TW laser for joint experiments with 1 MA z-pinches.

P P Wiewior, V V Ivanov, O. Chalyy
University of Nevada Reno, Physics Department, Reno, NV 89557
E-mail: pwiewior@unr.edu

Abstract. A 50 TW high-intensity laser (aka “Leopard” laser) was developed for experiments with the 1 MA z-pinch generator at the University of Nevada, Reno. The laser produces short pulses of 0.35 ps; energy is 15 J. Long pulses are 1 ns; energy is 30 J. The output beam diameter is 80 mm. The Leopard laser applies chirped pulse amplification technology. The laser is based on the 130 fs Ti:Sapphire oscillator, Öffner-type stretcher, Ti:Sapphire regenerative amplifier, mixed Nd:glass rod and disk amplifiers, and vacuum grating compressor. An adaptive optics system ameliorates focusing ability and augments the repetition rate. Two beam terminals are available for experiments: in the vacuum chamber of the z-pinch generator (aka “Zebra”), and a laser-only vacuum chamber (aka “Phoenix” chamber). The Leopard laser coupled to the Zebra z-pinch generator is a powerful diagnostic tool for dense z-pinch plasma. We outline the status, design, architecture and parameters of the Leopard laser, and its coupling to Zebra. We present the methods of laser-based z-pinch plasma diagnostics, which are under development at the University of Nevada, Reno.

1. Introduction
The Leopard laser was designed and built in the Nevada Terawatt Facility (NTF) at UNR to increase a capability of the 1 MA Zebra z-pinch generator. The coupling of the high-intensity Leopard laser and the high-current z-pinch opened many new research opportunities for high energy density physics, studied both theoretically and experimentally. Experiments historically performed on Zebra can benefit tremendously from new diagnostics driven by the intense laser (x-ray backlighting, Thompson scattering, proton radiography, x-ray plasma absorption spectroscopy, and others). In addition, the Leopard laser will be used for the study of the interaction of intense laser light with matter in exotic states and environments, such as strongly magnetized plasma, intense radiation sources, plasma jets, and other conditions in hot dense plasma. A more detailed understanding of these phenomena can assist in progress toward fast ignition fusion, as well as laser-driven plasma diagnostics. Last but certainly not least, this invaluable experimental tool will help fulfill the NTF’s primary mission to train students and young scientists in high energy density physics.
2. Description of the Leopard laser system

The Leopard laser is a hybrid Ti:Sapphire/Nd:glass laser system suitable to generate 15 J sub-picosecond pulses, with high spatial and temporal beam quality. The laser is composed of several major subsystems: a femtosecond front-end (oscillator, stretcher, and regenerative amplifier), flashlamp-pumped rod and disk amplifiers, a grating compressor, beam transport lines, diagnostics, and control system. Strong capability for joint experiments with Zebra motivated the design of the Leopard laser. The laser is optimized for high energy and intensity delivered on a target, including a high repetition rate front-end for convenient alignment throughout the entire system, ample bandwidth for sub-picosecond pulse length, minimal B-integral, and commercially available diffraction gratings. All together, these features produce long-lasting laser parameters, with easy and affordable maintenance.

2.1. Front-end

The Leopard front-end uses a femtosecond oscillator (Tsunami, SpectraPhysics) pumped by a 9.2 W cw frequency-doubled DPSS Nd:YVO₃ laser (Millenia Pro X, SpectraPhysics). The ultra short pulses from the oscillator are stretched in time from their original duration of 130 fs to almost 1.3 ns in the Öffner-type home-build stretcher. After the pulse picker, the stretched pulses are seeded to a Ti:Sapphire regenerative amplifier (custom made, Coherent) where they are amplified to 1 mJ. The regenerative amplifier repetition rate is 500 Hz. To improve contrast ratio, a fast Pockels cell (UPC, Leysop Ltd.) with 250 ps rise time is located after the regen. The Pockels cell also reduces the repetition rate to 100 Hz. The pulse selected for further amplification passes the serrated aperture where its spatial profile changes to “top hat” geometry; this enables better energy extraction from Nd:glass rod and disk amplifiers. The serrated aperture concludes the front-end of the Leopard laser.

2.2. Amplifiers

The amplifier section includes Nd:glass rod and disk amplifiers, Faraday isolators, Pockels cells, and a spatial vacuum filter/image relay system. Rod amplifiers in the chain are: 6 mm diameter phosphate glass (double pass), 19 mm diameter silicate glass (double pass), second 19 mm phosphate glass (single pass), and 45 mm diameter phosphate glass (single pass). The disk amplifier is 94 mm phosphate/silicate mixed glass (single pass). The laser beam is spatially expanded, spatially filtered and relay imaged between sequential amplification stages. The Pockels cells and Faraday isolators improve contrast ratio and protect the amplifiers from damage due to back-reflections. The 6 mm amplifier is an old Quantel device refurbished at the NTF. The 19 mm and 45 mm amplifiers are units decommissioned from the petawatt laser system at Lawrence Livermore National Laboratory (LLNL), also refurbished at the NTF. The 94 mm disk amplifier is a refurbished unit from LLNL NOVA laser. The disk amplifier is cooled by the flow of nitrogen delivered from liquid nitrogen container; the rod amplifiers are water-cooled. The beam leaving the amplifier chain is spatially filtered and relay imaged to a vacuum pulse compressor.

2.3. Compressor and beam transport

The amplified pulse is compressed in a home-build vacuum compressor. The compressor operates in a double pass, dual diffraction gratings configuration. The gratings used are gold-coated compression gratings manufactured by Jobin-Yvon/Horiba. Each has 1740 grooves per millimeter, delivers 90% of absolute efficiency, with more than λ/8 surface figure at 1 μm. All crucial optical elements are mounted on remote-controlled rotational and/or translational stages, and the alignment process can be done under the vacuum. The overall compressor efficiency is approximately 60%.

The vacuum beam transport lines deliver the high-energy compressed beam using 15 cm diameter tubes, interconnected with turning boxes. The turning boxes contain large-diameter dielectric mirrors, on remote-controlled mounts. The beam is focused in either the laser-only Phoenix target chamber, where experiments with laser plasma are conducted, or in the Zebra target chamber, where the
Leopard-Zebra coupled experiments are conducted. The mirror in the first turning box after compressor can steer the laser beam to either terminal. An off-axis parabolic mirror focuses the laser beam on the target in the Phoenix target chamber. The Zebra target chamber is presently equipped only with a preliminary lens focusing system, although the final setup will also employ an off-axis parabolic mirror. The entire beam transport system is routinely maintained 10^5 Torr vacuum, and is separated from the target chambers by large diameter gate valves.

2.4. Diagnostics and adaptive optics system
The diagnostics and control system are necessary to optimize and monitor the essential parameters of the Leopard laser. Two separate diagnostics sub-systems have been developed: one measures parameters at selected locations in the laser chain, the other measures parameters of the output beam at full energy. Diagnostics inside the Leopard laser include oscillator characteristics (average power, spectrum, pulse duration, stability of the pulse train), regen characteristics (average power, pointing and direction, spectrum, pulse duration), and other selected locations in the beam where the energy, direction, and spatial profiles are monitored. In addition, several photodiodes monitoring the temporal position of amplifier fluorescence, with respect to the amplified pulse, are installed in the amplifier chain. A computer with LabView software records the signals from these photodiodes, as well as from cameras measuring the spatial beam profiles.

Output beam diagnostics necessarily use indirect measurement techniques. A low-energy sample beam is picked off inside the vacuum compressor, and delivered to an adjacent Faraday cage. The sample beam diameter is approximately 80 mm, with maximum energy of 150 mJ. The beam diameter is reduced using a down-collimating telescope; beam intensity is also reduced. We produce four different measurements: an energy measurement (using calibrated energy meter), laser pulse duration time (using FROG Grenouille in single shot mode), focal spot size (using the long distance microscope equipped with 16-bits CCD camera), and a beam wavefront quality (using a Shack-Hartmann sensor). The Shack-Hartmann sensor is a part of an adaptive optics system implemented on the Leopard laser. The system is manufactured by Imagine Optic (France), and is tailored to the particular requirements of the laser. The system was installed and commissioned by Imagine Optic together with NTF personnel. In addition to the Shack-Hartmann sensor, the system consists of a deformable mirror, control electronics, and software with a correction algorithm. The adaptive optics system allows significant correction of the laser beam wavefront aberrations, and leads to greatly improved intensity and focus on target. The corrected wavefront exhibits approximately 50 nm rms variation. The Strehl ratio of the focal spot is approximately 0.8. The measured focal diameter is about eight times smaller than without the adaptive compensation, and intensity in the focus is increased by a factor of 60. The measured fwhm of the focal spot produced by an f/10 lens is approximately 20 microns. Besides the dramatic improvement of the wavefront quality, and the resulting increase in intensity on target, the repetition rate is also greatly improved. Before adaptive optics, cooling time (mainly the disk amplifier) was two hours minimum. We were usually limited to four shots per day. With adaptive optics, the laser can be fired four to five times per hour (10-15 minutes is required for flashlamp cooling). The repetition rate in not longer given by disk amplifier cooling, but by changes to the experimental setup.

3. Development of Leopard-based plasma diagnostics methods.
The Leopard laser is a powerful tool for high energy density physic studies, using the Phoenix target chamber, and through joint experiments with the Zebra. Leopard delivers sub-picosecond or nanosecond pulses to the Zebra vacuum chamber through the vacuum beam path. Zebra is triggered from the clock of the Leopard laser, does not have laser triggering, and the timing setup of laser and pulsed power generator has jitter of ±20 ns. This timing allows an investigation of main stages in wire array implosion.
The Leopard laser is used for astrophysical experiments with a 1 MA z-pinch generator as a source of the 1 MG magnetic field [1]. Several Leopard-based diagnostics are under development for dense z-pinch plasmas. First, the Leopard laser can be used as a backlighter for z-pinch plasma. Experimental methods for the laser backlighting of the z-pinch were developed and are presented, for example in [2, 3]. Second, the absorption spectroscopy has been developed for z-pinches at the NTF. Investigation of the electron temperature $T_e$ and density $n_e$ profiles in the z-pinch plasma and their dynamics is crucial for understanding of the physical mechanisms of plasma heating and x-ray generation. The x-ray spectroscopy is the main method to derive the plasma electron temperature and density in z-pinch at the radiative stage. The absorption spectroscopy can derive the electron temperature and density of the wire-array plasma at the non-radiative ablation and implosion stages. The absorption spectroscopy was applied to laser plasma [4], but still was not used for z-pinches. The Leopard laser provides a broadband x-ray backlighting with Sm and Ge targets. The target will be installed in the Zebra chamber for probing z-pinches at the ablation stage. The x-ray emission of the main z-pinch will be blocked to protect a time-integrated spectrometer.

Next, we suggest investigation of parametric conversion of laser radiation with intensity $10^{14}$, $10^{15}$ W/cm$^2$ to $3/2\omega$ and $1/2\omega$ harmonics in z-pinch plasma. Parametric conversion resulting from a two-plasmon decay can be used to derive a temperature of plasma with the electron density near the 25% of critical density, because a spectral separation of “blue” and “red” satellites in harmonics depends on the electron temperature. For radiation of wavelength $\sim 1 \mu m$ the 25% of critical density is $2.5 \times 10^{20}$ cm$^3$. This density was measured in z-pinches on the Zebra generator with the x-ray spectroscopy. Parametric conversion is a non-spectroscopic method for estimation of the electron temperature and plasma density in z-pinch plasma.

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