Development of a few TW Ti:Sa laser system at 100 Hz for proton acceleration

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Abstract We report the development of a table-top high peak power Titanium:sapphire (Ti:Sa) laser that generates 100 mJ, 45 fs pulses at a repetition rate of 100 Hz and 10 W of average power. Every stage is pumped by Nd-based solid state lasers and fully powered by diodes. Thermal effects in the Ti:Sa amplifiers are compensated passively with optics. This system is intended to be used for proton acceleration experiments at high repetition rates.

1 Introduction

The field of high intensity physics has grown steeply in the last few years. Fields such as particle generation and acceleration show promising perspectives for the practical use of lasers: coherent x-ray generation [1], electron acceleration [2] and proton acceleration [3]. Although the accelerating gradient is many orders of magnitude higher than that of conventional accelerators [4], the state-of-the-art laser based accelerators do not provide enough current to be able to replace conventional radiofrequency technology. Most of the experiments have been single shot and those which are multi-shot are done with low average power lasers due to the lack of both high repetition rate targetry and high power lasers. This issue prompts the development of higher average power and high intensity lasers.

The introduction of the chirped pulse amplification (CPA) technique [5] fueled the development of high power, table top ultrafast laser systems, such as Titanium:Sapphire

(Ti:Sa) lasers, characterized by their broad bandwidth, able to hold pulses down to a few femtoseconds. However, its absorption band is located in a region of the visible spectrum where there are very few available high energy laser sources. These are generally frequency doubled flash-lamp pumped Nd-based lasers; these types of laser can typically achieve several joules of energy in tens of nanoseconds but their repetition rate is limited to 10 Hz. That is why the development of high power diode lasers able to pump Nd-doped crystals can improve the repetition rate of these lasers and therefore that of the Ti:Sa laser. Yet, the power output of the laser diodes is low compared to the output of a flash-lamp.

In this work, we present a compact Ti:Sa laser with a peak power exceeding the TW level, 100 Hz repetition rate and pumped by diode powered solid state lasers. The whole setup including all pump lasers fits into two optical tables, or an area of 7.35 m^2; it is based on CPA amplification and is composed of an oscillator, stretcher, a regenerative amplifier followed by two multipass amplifiers and a compressor as in Fig. 1. This system is specially tuned for particle acceleration so it includes a separate vacuum chamber where the compressor is located and another chamber where the experimental interaction of the laser with the target is performed.

2 Laser system description

The schematic of the ultrashort laser is presented in Fig. 1. The femtosecond laser pulses are generated in a Kerr-

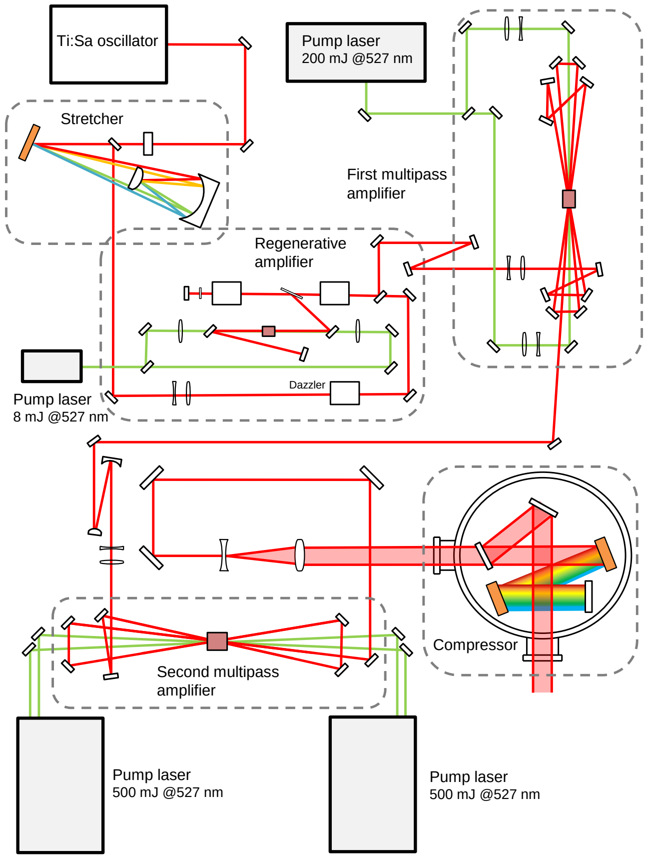

Fig. 1 Scheme of the CPA Ti:Sa laser developed in the thesis. A pulse oscillator sends a beam of a few femtoseconds that is stretched in time in a pulse stretcher. Then it enters a chain of amplification that starts with a regenerative amplifier that is followed by a first multipass amplifier and ends with a second multipass amplifier. The CPA chain ends with a compressor installed in a vacuum chamber.

lens mode locked Ti:Sa oscillator (Venteon). The 12 fs, 5 nJ seed pulses are stretched to 100 ps in an on-axis ffner stretcher [6]. The stretcher consists of two metallic spherical mirrors, one convex with 250 mm radius of curvature and a 500 mm concave mirror; the diffraction grating (Horiba Jobin-Yvon) has 1200 grooves/mm and is placed 15 cm from the common center of curvature of the two mirrors. A pulse shaping device (Dazzler from Fastlite [7]) is placed after the stretcher to control actively the spectral phase of the laser, specially third order dispersion.

Once stretched, the pulses enter a regenerative amplifier pumped by 7 mJ, 100 ns pulses from the output of a Nd:YLF laser working at 100 Hz. The configuration of this amplifier is a z-folded cavity, the plane-parallel Ti:Sa crystal measures $4\times6\times15$ mm and is anti-reflection coated. However, two fused silica Brewster windows, one on each side were added in order to minimize depolarization on each trip. Two Pockels cells are included in the regenerative amplifier. One acts as a pulse picker, decreasing the repetition rate to 100 Hz and the other acts as a quarter waveplate trapping and releasing the pulse once it is amplified.

Before the next amplifier a Faraday isolator is included in order to prevent feedback to the regenerative from the power amplifiers. The first multipass amplifier is pumped by 200 mJ at 100 Hz from a Nd:YLF laser. The Ti:Sa crystal is plane-parallel, cylindrical 6 mm in diameter, 15 mm length, absorbs 92% of pump light and is placed on a water-cooled mount. This amplifier is constructed in a multipass bow tie configuration where the seed beam undergoes up to four passes through the gain medium. The laser exits the amplifier with a good quality beam which retains its gaussian shape.

The output of the first multipass amplifier is magnified to a 8 mm diameter beam in order to be injected into the second multipass stage. This amplifier incorporates a $15\times16\times20$ mm crystal that is pumped by a total 1000 mJ of 527 nm radiation divided in four beams (two on each side). The seed beam experiences three passes through the gain medium in this amplifier

The pulse is finally compressed in a Treacy-type compressor made up of two diffraction gratings of identical characteristics to the one in the stretcher and enclosed in vacuum chamber.

3 Pump lasers

The scarcity of high repetition rate lasers suitable for pumping a Ti:Sa laser compelled us develop our own pump lasers using a Nd-doped active medium powered by laser diodes. In collaboration with Monocrom S.L (Barcelona, Spain) we designed and constructed a pumping head comprised by a solid state cylindrical laser rod surrounded by cooling water and six stacks each containing six laser diodes of 150 W maximum optical output [8].

In order to create a laser capable of generating high energy per pulse and repetition rate, these pumping heads were used as the building blocks of a MOPA laser. The scheme of the laser is shown in figure 2. It consists of an oscillator with a single pumping head and two pairs of amplifiers for a total of five. In order to improve the overall efficiency of the laser, a new scheme was developed where after the first two amplifiers a second harmonic generation stage is incorporated, but instead of dumping the unconverted infrared component, it is boosted in energy by a similar pair of amplifiers followed by another SHG crystal. This scheme improves the overall efficiency of the laser and lowers its cost and complexity.

Nd:YLF was chosen as the active medium, as it has some advantages with respect to Nd:YAG, including higher stored energy and less thermal lensing optical power. For a MOPA these properties mean more gain in the amplifiers and less restrictions due to thermal management. The wavelength of the laser was chosen as the 1053 nm line of Nd:YLF.

The oscillator of this laser is powered by one pumping head loaded with a 5 mm of diameter, 0.8% at. Nd:YLF rod. The resonator length was 55 cm and comprised a 3000 mm radius of curvature reflective mirror and a 25% reflective plane-parallel mirror as the output coupler. The TFP was tuned to transmission in Q-switch mode for the 1053 nm line. The laser diodes were powered by pump square pulses 150 μs long with a current of 100 A. The output energy was fixed at 67 mJ while the pulse duration was held at 19 ns.

After the oscillator, the first component to be installed was a Faraday isolator for protecting the oscillator from subsequent stages. Despite the low emission cross section of the 1053 nm line of Nd:YLF, the feedback from the amplifiers was so high that the issue of parasitic QCW lasing was still observed in this setup. The telescope located after the isolator collimated and increased the beam size to a diameter of 4.8 mm.

The collimated beam traverses the first pair of amplifiers. The two pumping heads were operating with 300 μs long pump pulses and 100 A. Up to 540 mJ per pulse was achieved for 67 mJ of input and single pass configuration, which results in total extracted energy of 473 mJ, 195 mJ from the first amplifier and 278 mJ from the second amplifier.

Due to the natural birefringence of Nd:YLF, thermal induced depolarization is almost non existent in the oscillator or any of the two pairs of amplifiers, measured as less than 4% at full power. A relevant condition for a low birefringence compensation is that the input polarization is perfectly aligned to the actual optical axis; for fine tuning of the polarization a half waveplate is situated before each and every amplification stage.

Thermal lensing is not an issue in these amplifiers. The factor dn/dT for the 1053 polarization of Nd:YLF was much weaker than Nd:YAG and negative, so a beam experiencing thermal lensing on Nd:YLF will expand instead of focusing. However, the different thermal behaviour of the axes introduces astigmatism in the beam.

A first SHG crystal was positioned after the first pair of amplifiers. The crystal was a type II KTP (Crystal Laser), which worked at 25 C. The crystal was clamped with a copper mount. At that temperature we used the same cooling circuit of water as the pumping heads. This simplified the electronic circuit but did not introduce any noticeable instability in the SHG conversion although the time required for *turn-on* stabilization increased.

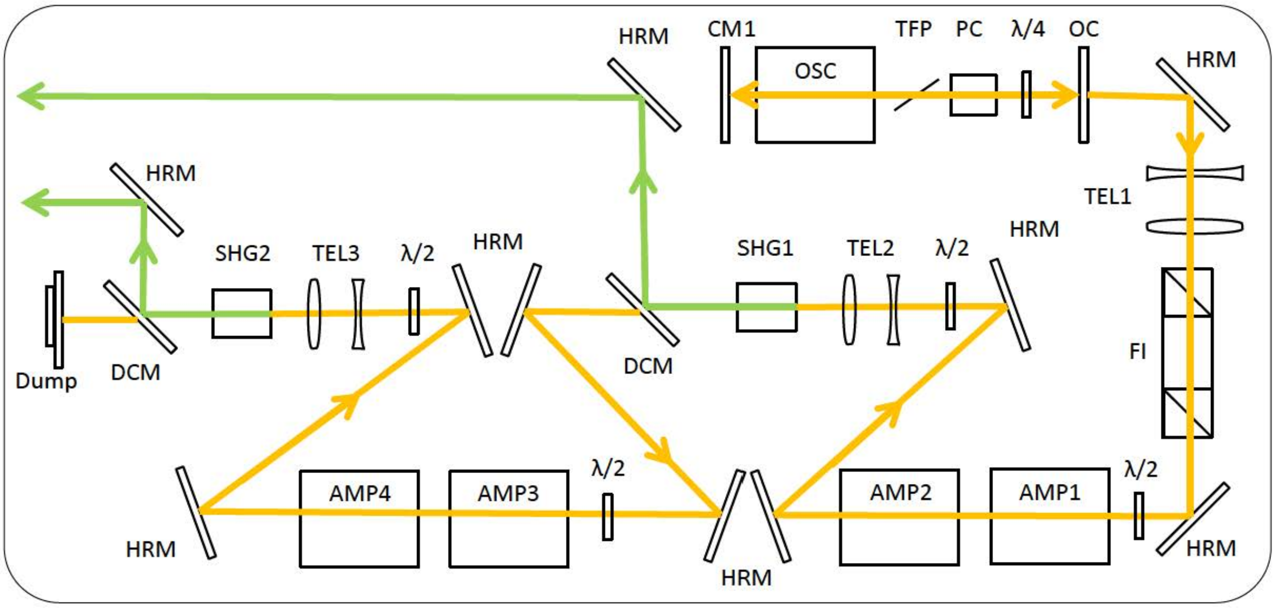

Fig. 2 Scheme of a MOPA Nd:YLF laser with 5 pumping heads (OSC, AMP1-4). CM1 and OC are the two mirrors that comprise the oscillator, along with a pumping heads, a thin film polarizer (TFP), a Pockels cell (PC) and a quarter waveplate $\lambda/4$. The setup includes a Faraday Isolator (FI) and three telescopes (TEL1-3). (SHG1&2) represent non-linear crystals for second harmonic conversion. There are two dichroic mirrors (DCM1&2) and a beam dump. HRM are high reflectivity mirrors.

Once the laser is converted to green, in order to improve the efficiency of the laser, the unconverted infrared laser is further amplified in another chain of two amplifiers. A telescope is placed to collimate the beam which then enters the second pair of pumping heads and its energy is boosted to 465 mJ, a level similar to the output of the first pair of amplifiers.

A final KTP crystal, on an identical mount as the first, converts the amplified infrared radiation. A dichroic mirror sends the second harmonic towards the crystal to pump while the unconverted energy is stopped with a beam dump. While the maximum efficiency was about 55% individually on each crystal, this method of post-amplification and post-conversion of the beam allows for a total overall efficiency of the laser of almost 70%. The overal efficiency can be defined as the ratio of the total second harmonic radiation energy and the total output energy.

The output energy of this laser was limited due to the size of the Nd:YLF rods. The duration of the pump pulses was limited to 300 μs, although more energy can be stored in the active medium if the pump pulses are lengthened to 500 μs. The Frantz-Nodvik simulations predict that an energy per pulse and beam of 500 mJ at 527 nm can be obtained with an efficiency of 58% in the KTP.

4 Management of the thermal load

The management of the thermal lensing effect is of capital importance in the development of a high average power laser, since it can lead to deformations of the spatial properties of the beam and optical damage in any element of the amplifiers.

Thermal lensing begins to be problematic at the first multipass stage, since the active medium is pumped by a maximum of 20 W of optical power, of which about 8 W are converted to heat. The focal length of this crystal was found to be 5 m when pumped with a fluence of 2 J/cm^2 using 100 mJ pump pulses or 2 m when using 200 mJ pulses. This effect, if unchecked, can lead to poor beam quality and damage in any of the optics or the active medium, as the beam makes up to four passes through this crystal. In order to compensate the action of thermal lensing in this amplifier and improve the extraction efficiency, we implemented a telescope situated prior to the first pass. The beam coming from the regenerative amplifier passes through a telescope where the distance between the positive and negative lens is chosen so that the beam exits with a size of 1.5 mm in diameter. This telescope does not collimate the beam but introduces divergence so that the beam increases in size through amplification, compensating the convergence and alleviating thermal lensing. However, the magnitude of the thermal lensing effect is so strong in the case of 200 mJ pump energy that at least a convex curved mirror has to be placed in the second pass to help the beam retain some divergence and grow for the last pass through the amplifier. In the three pass configuration, the laser leaves the amplifier with a beam diameter of 2.5 mm, while in the four pass configuration, the laser leaves with a slightly smaller diameter of 2.4 mm and converging in the case of 100 mJ pump energy and 3.4 mm in the case of 200 mJ pump energy.

The major issue in the development of the second multipass amplifier proved to be thermal lensing. The total power pumped into the Ti:Sa can reach 100 W and about 31 % of this quantity is converted to heat that must be dissipated from the crystal. The focal length of the crystal was measured using the same method as for the first multipass, resulting in 2 m at a cooling temperature of -20 C and 1.2 m at 15 C. Although cooling the crystal to -20 C helped in decreasing the power of thermal lensing, the anti-reflection coated windows of the vacuum chamber could not resist the intensity of the Ti:Sa beam and were slightly damaged, which affected negatively the performance and quality of the laser beam. This event forced us to work with a cooling temperature of 15 C for the rest of the experiment. In order to mitigate the action of the thermal lensing, several approaches were used. First was that the input seed beam from the first multipass amplifier was enlarged to 5 mm of diameter using a telescope made of two curved mirrors. Then, a telescope of low magnification introduced divergence in the beam by changing the distance between the lenses following the calculations in [9]. Additionally, a convex mirror of radius of curvature -2000 mm had to be inserted before the last pass, in order to increase the divergence of the laser and to prevent the beam from leaving the amplifier converging.

5 Laser performance

The 5 nJ, large bandwidth pulses generated by the oscillator and stretched to 100 ps are boosted in the three amplification stages described in section 1. The first stage, a regenerative amplifier, outputs 1.5 mJ per pulse when pumped with 7 mJ from a Nd:YLF laser. The spatial profile of the beam after this amplifier is gaussian, measuring 1.5 mm in diameter. However, the thin-film polarizer used to couple/un-couple the pulses out of the resonator generates pulse replicas separated in time by a rountrip, due to the reflectivity of the thin film polarizer. These pulse replicas turn into pre-pulses that decrease severely the contrast of the laser. In order to compensate for this effect a saturable absorber is placed before the next amplification stage.

The next amplification stage is a multipass amplifier. It produces 40 mJ pulses when pumped with 200 mJ from a doubled Nd:YLF laser and four passes through the active medium. The output beam retains its gaussian shape through amplification. Another saturable is placed at the exit of this amplifier in order to mitigate further the intensity of the pre-pulses introduced in the regenerative amplifier; the energy of the laser drops to 25 mJ.

The last amplification stage is a multipass amplifier pumped by 1000 mJ divided in four beams from two identical Nd:YLF lasers. In three passes the energy reaches 315 mJ, an amplification efficiency close to 30%. The beam loses its gaussian shape and becomes more multimode, resembling the multimode profile of the pump beams. The bandwidth of the laser also suffers modification through the amplification stages due to gain narrowing and gain shifting. After the second multipass amplifier the spectral bandwidth of the laser has been reduced to 19 nm.

6 Compression and focalization

The output beam from the second multipass amplifier is increased to 50 mm of diameter as it goes through a collimating telescope and is injected into the compressor chamber. The compressor features a Treacy design [10] with a configuration of two diffraction gratings and a roof mirror. Both gratings are identical to the one in the stretcher (1200 grooves/mm). The efficiency of each grating is higher than 90% and the efficiency of the compressor is 63.5%. The angle of the gratings was optimized for compensating third order dispersion. The energy of the compressed pulse was measured to be 98 mJ.

The pulse duration was measured with a Wizzler (Fastlite), which uses the third-order technique of self-referenced spectral interferometry [11]. A feedback loop

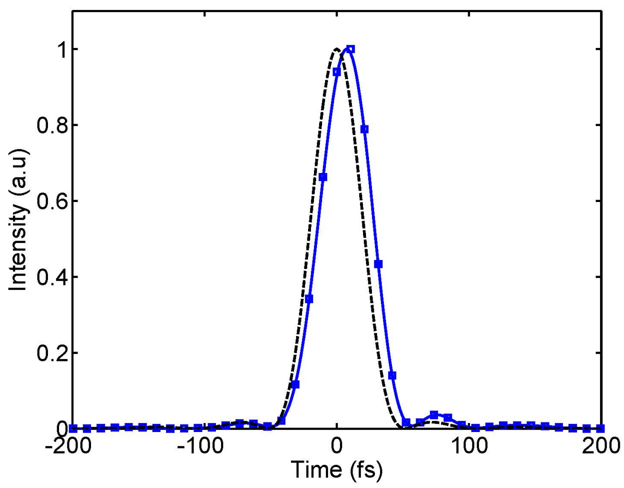

Fig. 3 Pulso

can be set up between this device and the spectral shaper located before the regenerative amplifier in order to optimize the dispersion, especially third order, which was found to be the term which contributed the most to aberrations in the spectral phase. The pulse duration was determined to be 45 fs and the spectral bandwidth retrieved is 19 nm FWHM, close to the 42 fs of the transform limited pulse as seen in Fig. 3.

After the compressor, the laser beam enters the interaction chamber, where the laser is focused and the experiments are performed. The beam is focused through an off-axis parabola with a focal length of 100 mm and angle of 60°. The percentage of the total energy in the focus area is 80% as seen in Fig. 4. The spot size is 5×9 μm FWHM, meaning that the intensity on focus exceeds 10^{18} W/cm^2. The lack of symmetry in the focal spot responds to the use of spherical mirrors for the compensation of the thermal lens.

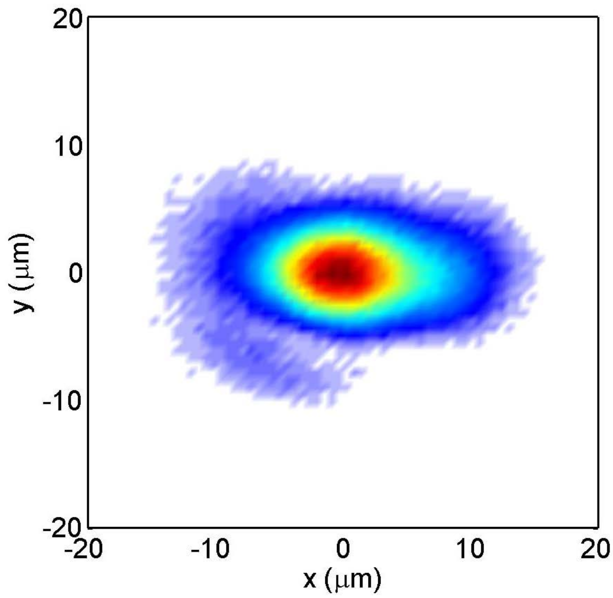

Fig. 4 Foco tisa

7 Conclusion

In conclusion, we have developed a reliable 2.4 TW peak power 100 Hz CPA Ti:Sa laser. The management of the high thermal load in the active crystals of the three amplification stages without cryogenic cooling was possible thanks to the implementation of a passive optics means of alleviating thermal effects. The laser could reach very high intensities when focused with an off-axis parabola without the need for adaptative optics. The pumping energy is provided by diode-pumped solid state lasers especially designed and built for this purpose. Nd:YLF has proven to be advantageous over Nd:YAG at this repetition rate. This laser is intended to be used in plasma physics experiments where flux and current are the most important parameters. The contrast of the laser, another parameter quite important for this interaction, could not be measured in a wide dynamic range, but was measured to be better than 10^5. Note that for this level of contrast, the intensity of the pedestal is still not high enough to produce plasma in the target.

As for improvements, it is estimated that the pulse duration can be reduced to 30 fs after inserting an etalon filter in the regenerative amplifier, where the gain narrowing effect is the strongest of all the amplification chain. The energy of the laser is expected to be increased using more powerful pump lasers. Also, it is planned to add saturable absorbers to the amplifier chain in order to improve the contrast.

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