Ion Acceleration Experiment with the High Intensity, High Contrast J-KAREN-P Laser System

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We report on the status of ion acceleration carried out with the J-KAREN-P laser facility at National Institute for Quantum and Radiological Science and Technology (QST) during the commissioning periods of the system. The system can provide PW peak power at 0.1 Hz on target and can deliver short pulses with an energy of 30 J and pulse duration of 30 fs after compression with a contrast level of better than 10^12. The current experiment was performed with the laser intensity of up to ~5 × 10^17 W/cm^2 with and energy of ~9 J on target. The interaction with a 5-μm stainless steel tape target provides electrons with a typical temperature of more than 10 MeV and energetic proton beams with typical maximum energies of > 40 MeV with good reproducibility. The protons are accelerated in the Target Normal Sheath Acceleration regime, which is suitable for many applications suitable for many applications including an injector for medical use, which is one of our objectives.

Key Words: Laser-plasma interaction, Ion acceleration

1. Introduction

Over the last decade many petawatt (PW) class laser systems have been constructed all over the world for pursuing high intensity physics. However, in reality still only a limited number of facilities can achieve really high intensity laser interaction on target. This is because there are still many technical challenges to overcome to achieve high intensity laser pulse onto target as stated below.

PW-class laser systems are based on the Chirped Pulse Amplification technique. A seed pulse with a ~femtosecond pulse duration is first stretched to nano-second duration, up-collimated for amplification and finally compressed both in the time and space domains. In order to deliver the high intensity laser pulses onto the target for exploring high intensity physics, the typical beam size is expanded to more than 20 cm in diameter to deliver enough laser energy while not damaging the laser beam transport optics. However, the fabrication of large aperture and high quality amplifier crystals, beamline mirrors, and compressor gratings is technically challenging and therefore limits the wavefront quality of the laser pulses. The careful treatment of the wavefront of such large diameter laser pulses is one of the critical issues.

Another difficulty for very high intensity laser systems is to deliver a sufficiently high laser contrast level onto the target, where the contrast is defined as the intensity ratio between the main pulse and pre-pulse. The pre-pulses or the pedestal which precede the main peak pulse interact with the target and modify or destroy the target before the main pulse arrival.

The J-KAREN-P laser system at Kansai Photon Science Institute in QST has been continuously upgraded since 2013, with the goal to achieve ~1 PW, 30 fs 10^17 W/cm^2, with a contrast level of better than 10^12. In this paper we report on the J-KAREN-P upgrade status and describe our latest achievements during the commissioning experiment on ion acceleration.

2. J-KAREN and J-KAREN-P Laser

The previous J-KAREN laser was a Ti:sapphire laser system based on chirped pulse amplification (CPA) with a high-contrast ratio of 10^12. The good contrast was achieved by the combination of the techniques of a double CPA system, saturable absorbers, and an optical parametric chirped pulse amplifier (OPCPA) instead of a standard regenerative amplifier. The system was operated at 10 Hz up to the power amplifier stage (~2 J) and the final booster amplifier (~30 J) was operated at single shot.

In the J-KAREN-P system we have made an upgrade based on the following concepts: 1) Replacement of the small-diameter optics of the previous system limiting the laser energy delivered on target, including mirrors, diffraction gratings, and interaction chambers. 2) Replacement of old pump laser for the final amplifier with new pump lasers. 3) The final amplifier is divided into two stages. The amplifier is pumped by six Nd:Glass lasers to increase the maximum laser energy extracted from the amplification stage. Table 1 shows the parameters of the previous J-KAREN, J-KAREN-P upgrade target and at the time of commissioning in March 2017.

To achieve high laser focussability on target, newly installed large flat mirrors and diffraction gratings were characterized using an interferometer (ZYGO GPI) before and after mounting them on optomechanical mounts. To avoid angular chirp effects, the diffraction gratings in the pulse compressor should be aligned with the accuracy of ~10 μrad. We have aligned the gratings in air with parallelism within ~100 μrad and fine-tuned the final grating in vacuum with the accuracy of
~10 μrad to have negligible angular chirp. A deformable mirror and a wavefront sensor are used to correct the distorted wavefront. In March 2016 when we performed the first full system commissioning campaign, the Strehl ratio was ~0.1 on target. We therefore improved the system as follows. 1) We improved the imperfect algorithm of the closed-loop in the deformable mirror and the wavefront sensor, 2) improved the imperfect beam expander mirrors which had caused higher order spherical aberration, and 3) replaced several lens beam expanders which had caused chromatic aberration to the reflective type optics.

After the March 2016 campaign, the improvements mentioned above resulted in a Strehl ratio of ~0.5 for the next full system commissioning campaign which was carried out from Dec. 2016 to March 2017.2, 3)

The contrast level in March 2016 was $10^{10}$ at 500 ps before the main pulse. By carefully adjusting the pump power timing and energy for each amplification stage we achieved a drastically improved contrast level in March 2017 of $10^{12}$ at 500 ps before the main pulse peak. Table 1 shows the laser parameters at the time of the ion acceleration experiment carried out during the system commissioning Dec. 2016 to March 2017.

### Table 1 The parameters of the J-KAREN-P system.

| parameters          | Before 2013 | Target parameters | 2017 March |
|---------------------|-------------|------------------|------------|
| Peak power (TW)     | 200         | 1000             | 250        |
| Rep-rate (Hz)       | 1/30        | 0.1              | 0.1        |
| Beam diameter (cm)  | 15          | 25               | 25         |
| Laser energy (J)    | 8           | 30               | 9          |
| Pulse duration (fs) | 30          | 30               | 35         |
| Peak irradiance (W cm$^{-2}$) | $10^{11}$ | $10^{12}$       | $5 \times 10^{12}$ |
| Contrast ratio      | $10^{12}$   | $10^{12}$        | $10^{12}$  |

3. Ion acceleration experiment

Laser acceleration of charged particles is one of the important applications of the J-KAREN-P laser.4, 5) By using a relatively thick 5-μm stainless steel tape target, which enabled us to deliver a fresh target surface to the laser focal spot up to 10 Hz, we carried out laser ion acceleration, mainly based on the target normal sheath acceleration (TNSA) regime. In this regime, energetic ions are accelerated along the normal to the target surface, while energetic electrons are mainly accelerated along the laser direction.6) In order to avoid serious damage from the back reflection of light from the target towards the laser system we choose an incidence angle of 45° with respect to the target normal.

The monitor system adjacent to the interaction chamber enables monitoring the laser parameters for each shot. The parameters monitored are the far-field image, providing information on the pointing and focussability, the near-field image showing the position of the beam and beam pattern, and the spectrum showing shot-to-shot fluctuation of the pulse duration, energy, and pre-pulses in the sub-ps range.

Tape targets of several μm thicknesses are used (Fig. 1 and 2). The alignment of the target is carried out by a target alignment system with a precision of ±2 μm in depth of focus which is well within the Rayleigh-length of our beam, ~4 μm. The beam pattern of the reflected and transmitted laser beam after the interaction with the target are monitored in both the fundamental and second harmonic frequencies. This provides information on whether the shot is performed at best or away from focus. The spectra of the reflected and transmitted light are monitored by spectrometers covering the spectral range from the fundamental to the 4th harmonic frequency.

A portion of the beam is delivered to optical probe lines with a pick-off mirror. Even though our J-KAREN-P laser system can deliver a high contrast laser beam, shot-to-shot fluctuations of the short duration pre-pulse components and/or pedestal (rising edge) component of the main pulse peak may cause pre-plasma generation before the main pulse irradiation. The pre-plasma causes shock penetration through the target and deformation of the sharp density gradient on the rear side of the target. This results in inefficient sheath field formation on the rear side of the target causing a decrease of the energies and nonuniformity of the spatial profile of the accelerated ion beam. This is the critical issue for ion acceleration. The probe beam (shadowgraphy and interferometry) monitor the target condition at several timings up to the ~100 ps range before and after the main pulse interaction from both the transverse and reflected direction on the rear surface of the target.

The electron energy spectra are measured by a magnetic field electron spectrometer (ESM) consisting of 0.4 T 25 cm-long magnets with a DRZ-high scintillator (Gd2O2S:Tb) imaged onto a 12 bit CCD camera along the direction of the incident laser beam. The spatial profile of the electron beam is monitored by a DRZ-high scintillator combined with energy
filters imaged by a 12-bit CCD camera, which is placed in front of the ESM along the laser direction.

The protons and ions are measured by a time-of-flight ion spectrometer (TOF) consisting of a vacuum tube and a plastic scintillator which is coupled with a photomultiplier and an oscilloscope. A footprint of the ion beam is measured by an online scintillator-based proton footprint monitor and insertable stack of radiochromic films (RCF) with optimized filter sets for each shot. A Thomson parabola spectrometer consisting of a strong electric field and magnetic field combined with detectors such as Imaging Plates measures the ion spectra for each charge state.

The laser energy was limited to a moderate energy < 10 J on target. The pulse duration was ~ 40 fs (FWHM), the contrast ratio was improved to $3 \times 10^{12}$ at ~500 ps, the focal spot was also improved to $1.32 \pm 0.03 \mu m \times 1.37 \pm 0.03 \mu m$ at full width at half maximum (FWHM). The typical peak irradiance on target was $< 5 \times 10^{19}$ W/cm$^2$.

By using a 5-μm Stainless Steel tape target, a proton beam with a maximum energy exceeding more than 40 MeV with a smooth spatial distribution was produced with good reproducibility, attractive for many applications. When using thinner targets, protons with energies in excess of > 50 MeV are obtained.\footnote{H. Kiriyama, T. Shimomura, H. Sasao, Y. Nakai, M. Tanoue, S. Kondo, S. Kanazawa, A. S. Pirozhkov, M. Mori, Y. Fukuda, et al.: Opt. Lett. 37 (2012) 3363.}

4. Summary

The ion acceleration experiment carried out in the course of the commissioning of the upgraded J-KAREN-P laser facility at Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology was discussed. A proton beam with energy in excess of 40 MeV with a smooth spatial distribution is reproducibly generated by using a stainless steel 5-μm tape target, which in principle enables us to deliver a fresh surface to the laser focus position with a 10 Hz repetition rate. By using a thinner foil targets, proton beams with energies > 50 MeV are generated. We are currently enhancing the laser system to improve the contrast and enhance the laser energy to further improve the energy and flux of protons and ions for applications.

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