Injection and Confinement of a Laser Pulse in an Optical Cavity for Multi-Pass Thomson Scattering Diagnostics in the TST-2 Spherical Tokamak Device

Hiro TOGASHI, Akira EJIRI, Makoto HASEGAWA[1)], Junichi HIRATSUKA, Yoshihiko NAGASHIMA[1)], Keishun NAKAMURA, Kazumichi NARIHARA[2)], Yuichi TAKASE, Hiroshi TOJO[3)], Naoto TSUJII, Ichihiro YAMADA[2)], Takashi YAMAGUCHI and the TST-2 Team

The University of Tokyo, Kashiwa 277-8561, Japan
[1)]*Kyushu University, Kasuga 816-8580, Japan*
[2)]*National Institute for Fusion Science, Toki 509-5292, Japan*
[3)]*Japan Atomic Energy Agency, Naka 311-0193, Japan*

(Received 8 December 2013 / Accepted 13 December 2013)

A multi-pass Thomson scattering (TS) system based on confining laser pulses in an optical cavity was constructed for measuring very low-density plasma in the TST-2 spherical tokamak device. This paper describes the setup of the optical system, injection of the laser pulse into the cavity, and properties of the confined laser pulse. A combination of Pockels cell plus polarizer, which serves as an optical shutter, allows us to inject and then confine intense laser pulses in the cavity. A photodiode signal monitoring the very weak light leaking from the cavity mirrors demonstrated that the laser pulse makes many round trips, with a round-trip efficiency of approximately 0.73. The effective number of round trips (i.e., the signal enhancement factor) is approximately 3.7. For an injection efficiency of approximately 0.69, a cavity-confined laser pulse, applied to Thomson scattering, will yield a scattered signal that is five times larger than that from a single-pass laser pulse.

Keywords: Thomson scattering, multi-pass, TST-2, diagnostics, spherical tokamak device

DOI: 10.1585/pfr.9.1202005

In fusion plasma experiments, electron temperature T_e and density n_e profiles are indispensable data for analyzing the experiments. Most reliable T_e and n_e data are obtained by Thomson scattering (TS). Usually, the laser energy per pulse is a few joules, which is enough to yield high quality data for contemporary fusion plasma experiments, where $n_e > 10^{19}\,\mathrm{m}^{-3}$. However, there are very low n_e plasmas ($n_e \ll 10^{19}\,\mathrm{m}^{-3}$) such as plasmas started-up and sustained by RF in the TST-2 that give us interesting subjects to study, but for which the laser energy is not enough to yield high-quality data. Adopting a 10-J laser is not realistic. One conceivable way to alleviate this difficulty is to reuse (recycle) the dumped laser energy. This concept, though slightly different, was first realized as a multi-pass intra-cavity TS system on TEXTOR [1]. It was demonstrated that more than 40 laser pulses at 5 kHz repletion frequency generated 900 J of total probing energy. It seemed easy to adopt a similar multi-pass optical system for TST-2, but a few drawbacks were encountered; e.g., at each pass, the laser beam path is slightly different, and the number of passes is limited by the drift of the laser beam spot on the mirror surface; therefore, the spot eventually reaches the entrance hole. A more elegant scheme is to inject and confine the laser pulse in a cavity by using an optical shutter composed of a Pockels cell plus a polarizer. If the attenuation in the cavity is negligibly small, then this approach is free from the drawbacks mentioned above. A similar concept has been tested on GAMMA-10 [2], but confinement of the laser pulse over a round trip was not confirmed and no quantitative description of the performance was given. To examine if this scheme is really effective for very low n_e measurements in TST-2, we set up an optical system and made comprehensive measurements on the behavior of the laser pulse during injection and confinement.

Figure 1 schematically illustrates the optical setup. All optical components except concave mirror #2 were placed on an optical table of 900×1200 mm. The concave mirror #2 was mounted on a post. A laser beam with pulse width 10 ns, energy 1.6 J, repletion rate 10 Hz, beam diameter $\sim$ 10 mm, divergence $\leq$ 0.6 mrad, and $M^2 \sim 9$ was delivered from a Nd:YAG laser (YG981E, Quantel). In this experiment, we used laser energies of 2–200 mJ. Laser pulses were confined in a cavity formed by a pair of spherical mirrors #1 and #2 with focal lengths of $f_1 = 2500$ mm and $f_2 = 2000$ mm, respectively. The distance between the mirrors was $L \sim 8950$ mm. The combination (f_1, f_2, L) was chosen and adjusted so that (1) the periodic sequence of laser beam propagation was stable, (2) the laser beam

author's e-mail: togashi@fusion.k.u-tokyo.ac.jp

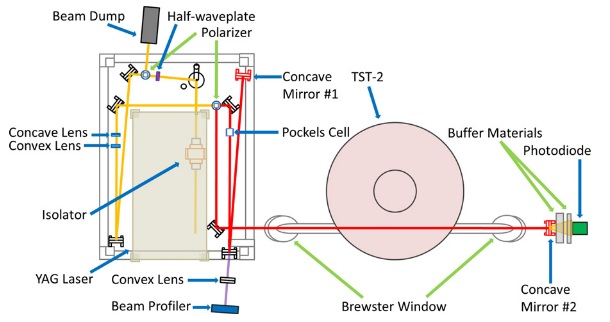

Fig. 1 Schematic of the optical system for multi-pass Thomson scattering (TS) and the measurement setup in TST-2. A laser pulse can be confined between concave mirror #1 and concave mirror #2 (red lines).

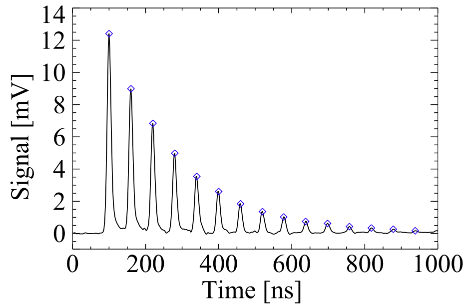

Fig. 2 Signal at the photodiode detector. Blue diamonds mark observed peaks for each round trip.

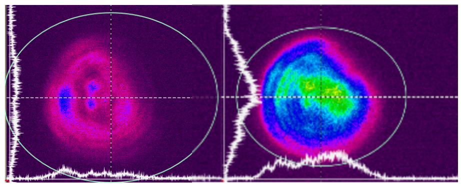

Fig. 3 Beam profile for only the first pass (left) compared with that for all multiple-passes (right).

diameter was less than 6 mm in the region where plasma is present and measured by TS, and (3) optical elements were not damaged by the small beam spot with high energy density. The Pockels cell (ϕ15, EM515M-D-AR1064, Leysop) combined with the polarizer (20×20 mm, PBSHP-20-1064, Sigma Koki) function as an optical shutter according to a well known principle, allowing laser pulse injection and confinement.

A pair of concave and convex lenses was used for adjusting the beam divergence at the entrance. Two diagnostics were used in this experiment. One was a photodiode set behind mirror #2, which monitors the area of integrated light leaking from the mirror, and other was a beam profiler that viewed the weak light transmitted through a mirror.

The injection efficiency was optimized by controlling beam divergence, discharge timing, and duration of the high voltage applied to the Pockels cell. A power meter set in front of mirror #2 showed that the injection energy of approximately 0.69 times lower than the initial laser energy was injected into the cavity; in comparison, the efficiency of the previous single-pass Thomson scattering system was approximately 0.93.

Figure 2 shows an example of the photodiode signal when all control parameters were finely tuned. The figure shows a train of laser pulses incident on mirror #2. The width of each pulse is approximately 13 ns, which is almost the same as the laser pulse width of 10 ns. The interval between two successive pulses is 60 ns, which corresponds to the round trip time in the cavity, $2 \times 9\,\mathrm{m/c} = 60\,\mathrm{ns}$, where c is the speed of light. Thus, it can be confidently said that a laser pulse was really confined in the cavity. The pulse height decreases at a geometric rate of $\eta = 0.73$, which is the ability of the laser pulse to survive a round trip, i.e., the round-trip efficiency. A laser pulse going around the cavity experiences attenuation at each optical component. The five mirrors have a reflectivity $r_{\mathrm{m}} \sim 0.99$, the transmissivity of the two Brewster windows is $t_{\mathrm{B}} \sim 0.98$, the transmissivity of the Pockels cell is $t_{\mathrm{P}} \sim 0.95$, and the reflectivity of the polarizer is $r_{\mathrm{pl}} \sim 0.99$. By multiplying all these factors, we obtain the round-trip efficiency $\eta = r_{\mathrm{m}}^8 \times t_{\mathrm{B}}^4 \times t_{\mathrm{P}}^2 \times r_{\mathrm{pl}}^2 \sim 0.78$, which is in rough agreement with the observed η of 0.73. Note that η is very sensitive to the setting angle of the Pockels cell; a precise setting within ±0.2° was necessary for realizing $\eta \sim 0.73$. Summing these decaying signals gives the effective number of round trips, $1/(1-\eta) \sim 3.7$, and the effective number of passes is approximately $2 \times 3.7 = 7.4$. If we use 1.6 J for the laser energy, with an injection efficiency of ~ 0.69, the effective probing energy will be approximately $1.6 \times 0.69 \times 7.4 \sim 8.2$ J, which is larger than that of a single-pass pulse by more than a factor of five.

Figure 3 compares the beam profile of an unconfined beam and the time integrated profile of a confined beam. Here, the profile of the confined beam is a superposition of many snapshots of the laser pulse in the cavity. An area integration of each profile is proportional to the total energy received by the beam profiler; the results for both profiles give a total energy ratio of 1:3.5 ±0.3, which is consistent with the photodiode data.

In conclusion, we have demonstrated that a laser pulse can be injected and confined with a round-trip efficiency of approximately 0.73 in a cavity of the multi-pass TS system installed on TST-2. This will give TS signals five times larger than that from the single-pass TS. In near future, this system will be used for TST-2 plasma experiments. For estimating efficiency, we found that reducing the number of optical components in the cavity and improving the efficiency of the Pockels cell is important.

This work was supported by Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research Nos. 24656556 and 21226021 and by the National Institute for Fusion Science (NIFS) Collaborative Research Program No. NIFS12KUTR078.

[1] M. Yu. Kantor *et al.*, Plasma Phys. Control. Fusion **51**, 055002 (2009).
[2] R. Yasuhara *et al.*, Rev. Sci. Instrum. **83**, 10E326 (2012).