The Application of a Multipass System for Thomson Scattering Diagnostics in Magnetically Confined Plasmas

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Multipass systems are helpfull on Thomson scattering measurements for determination of electron temperatures and densities in plasmas, increasing the intensity of the scattered spectrum. A low cost, simple and effective multipass construction originally developed for aplications in tokamak plasmas was built and tested for the first time in a theta–pinch device, the compact torus TC–1. A detailed analysis about the gain on the scattered signal provided by the multipass system is discussed. The use of multipass for Thomson scattering experiments in theta–pinch devices or in more dense plasmas as well as in plasmas with higher Z_{eff} can be recommended for reduction of the relation between laser and bremsstrahlung signals. The successfull results obtained are shown. Multipass and single pass measurements are compared. The application of this system on the recently installed tokamak NOVA–UNICAMP is also discussed.

I. Introduction

Thomson scattering has become the most important diagnostic technique for electron density n_e and temperature T_e determination in fusion research plasmas. High spatial and temporal resolution can be achieved using this technique. The difficulties in operating this diagnostic lie mainly on the low ratio between scattered and incident laser power. The total power P_s integrated over the scattered spectrum can be written, for a Maxwellian electron distribution, as:[1]

$$dP_s = P_i \frac{d\sigma_T}{d\Omega} n_e L_s \, d\Omega , \qquad (1)$$

where P_i is the incident laser power, L_s is the length of the scattered volume and Ω is the observation solid angle. $d\sigma_T/d\Omega$, the differential Thomson cross section, is related to the direction of the incident light (vector unit $\mathbf{n}$) and its polarization (vector unit $\mathbf{E_i}$): $d\sigma_T/d\Omega = r_0^2 \mid \mathbf{n}\times\mathbf{n}\times\mathbf{E_i} \mid^2$, where r_0 is the classical electron radius.

For 90^o scattering, with $\mathbf{n}\times\mathbf{n}\times\mathbf{E_i} = 1$ and a typical value of $L_s = 0.01$ m and for an observation solid angle $\Omega_M = 0.01$ Sr, one can obtain a total power ratio P_s/P_i for most theta–pinch ($n_e = 10^{21}$ m^{-3}) and tokamak plasmas ($n_e = 10^{19}$ m^{-3}) of about 10^{-12} and 10^{-14}, respectively. The problem of intensity on the measurement of the scattered spectrum becomes more critical due to the limited observation solid angle and losses on the chamber windows, collection optics, spectrometer and detector sensitivity. This problem becomes especially critical in low density plasmas, as in tokamaks, leading doubts about the reliability of the method due to increased errors. This reason forces the use of pulsed high power lasers for light injection. The most common laser used for this purpose is the ruby laser ($\lambda_i = 694.3$ nm). Its light is especially convenient because photomultipliers sensible in the visible region can be used as detectors.

The intensity of the scattered light on the other side, can be increased by using of a multipass system, instead of more powerfull and expensive lasers. The laser light is forced, in this method, to pass many times through the scattering region of the plasma, increasing the effective laser energy ω_i inside the scattering volume and reducing errors originated by the poor relation between Thomson scattering signal and the signal originated from bremsstrahlung and stray light emission.

The multipass system used here is especially usefull due to its low cost, simple and effective construction, and utilizes only two spherical mirrors as reflecting surfaces, in contrast to more complicate alternatives for example using many mirrors or using active elements to deviate the laser beam. [2,3,4] Although the set up decribed here has been already developed and tested in tokamak plasmas, [5] some questions about the light intensity gain due to the multipass alone remained unclear. In that experiment the laser light came back to the ruby laser, which uses a phototropic filter in its cavity, inducing multiple lasing. So, the observed scattered signal was influenced by the multipass system and laser itself. This signal appeared as a time–elongated pulse of 500 ns duration, in contrast to the 70 ns single pulse, as a result of the rather large distance Δ between mirrors ($\approx$ 7 ns delay time for one pass) and multilasing (100 – 200 ns pulse interval). For quasi–stationary tokamak plasmas, the use of elongated probing pulses is justified. However, this is not the case for rapidly changing plasmas of theta–pinch, with the density rise time of 3 μs and a total lifetime of less than 10 μs.

The use of a multipass system in theta–pinch plasmas is reported here for the first time. In this work we show results of single pass and multipass measurements on the compact torus TC–1 UNICAMP. [6] The light gain as a function of the number of passes was obtained. As a result, an amplified scattered signal only slightly exceeding the width of the single pulse (40 ns) was obtained. Here, we used the Δ = 0.5 m to keep small the delay time.

II. Experiment

The TC–1 device is a field-reversed theta-pinch with a coil length of 65 cm and 14 cm in diameter. It works with an energy of 9 kJ, and produces a maximum magnetic field of 0.36 T that is reached after a rise time of 5 μs. Hydrogen at about 1 mTorr fill pressure has been used to produce plasmas of field–reversed configuration – FRC.

The Thomson scattering system uses a ruby laser in Q-switched mode, with an energy pulse of 3 J in 40 ns, and beam divergence of about 2 mrad. The laser beam follows the optic shown in Fig. 1(a). After side–on injection, through Brewster windows, the laser light is collected in a beam dump especially constructed to reduce stray light. A helium–neon laser was used for alignment purposes. The light collection occurs through a special optic system. A spectrometer (Spex 0.75m, 11 Å/mm) with a photomultiplier (RCA 31034 or 7265) has been used to measure the scattered light. The laser power was monitored by a photodiode. Intensity calibration was carried out by Rayleigh scattering on nitrogen neutral gas.

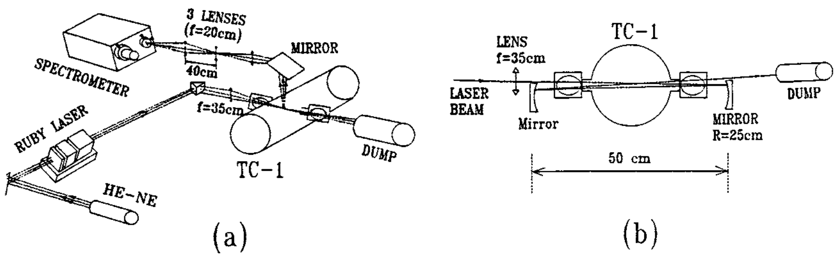

Figure 1: a) Thomson scattering system on TC–1. b) Details of the multipass system.

Details of the multipass system can be seen in Fig. 1(b). Two almost concentric concave mirrors, with diameter D = 6 cm, force the reflection of the beam several times into the plasma. The maximum number of passes can be expressed approximately as: $M_p = 4(D - a)/a$, where a is the distance between laser beam axis and mirror edge at the entrance.[5] The number of passes can be changed by adjusting the position of the mirrors and the incident angle of the beam. A numerical code especially developed for simulation and optimization of the multipass system was used for the TC–1 setup. The maximum number of 6 passes for this experiment was actually limited by the diameter of the access windows of the TC–1, reducing effectively D.

Figures 2(a) and 2(b) show Thomson scattering signals for different number of passes, measured at 688.0 nm with the same plasma conditions. An example of measurements with single pass and with 3 passes is shown in Fig. 2(a).

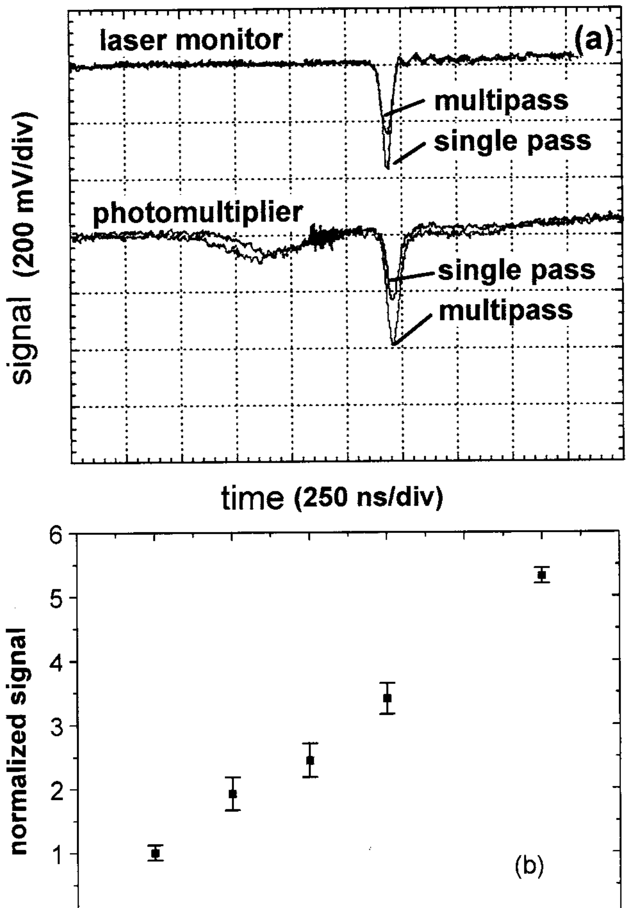

Figure 2: a) Comparision between single pass and multipass Thomson scattering. The upper signal is the laser monitor and the lower signal is the plasma continuum and Thomson signal ($\lambda = 688.0$ nm). b) Normalized signal as function of the number of passes.

For 3 passes, a normalized signal (scattered light/laser monitor) of a factor 2.5 times higher than for single pass is observed. Figure 2(b) shows the intensity of the signals for different number of passes. These intensities are again normalized to the averaged value of the signal obtained for single pass, in order to show more clearly the amplification due to multiple passes. The error bars correspond to the standard deviation after a sequence of 4–6 shots. At this wavelength, the stray light signal could be completly neglected. The estimates of the total number of signal photoelectrons N_{pe} generated by the scattered light give the values of about 2×10^4 for single pass and 5×10^4 for 3 passes. Therefore, the accuracy of measurements was determinated not by the statistics of photoelectrons, but mainly by the relatively low reproducibility of the theta–pinch discharge, as well as by plasma bremsstrahlung, which is substantial for dense theta–pinch plasmas.

The ratio between N_{pe} and N_b, the total number of photoelectrons produced by bremsstrahlung along the same spectral region as for Thomson scattering, for incoherent scattering with $\mathbf{n} \times \mathbf{n} \times \mathbf{E_i} = 1$, as in this experiment, can be approximated by:[1]

$$\frac{N_{pe}}{N_b} \approx 6\times10^{17} \frac{\omega_i(\mathrm{J})}{\tau_i(\mathrm{s})Z_{eff}} \frac{\lambda_i(\mathrm{m})}{n_e(\mathrm{m}^{-3})\, sin\frac{\theta}{2}} \frac{L_s(\mathrm{m})}{V_p(\mathrm{m}^3)}, \quad (2)$$

where ω_i is the imput laser energy, τ_i is the pulse duration, θ is the scattering angle and V_p is the plasma volume from which the continuum light is collected. $Z_{\text{eff}} = \sum_{i,Z} Z^2 n_Z^i / n_e$ is the effective charge, where n_Z^i is the ion density of the atomic species i with charge Z.

For the plasma conditions of this experiment, with $n_e \approx 6 \times 10^{21}$ m^{-3} and $V_p \approx 2$ cm^3, and for typical values of $Z_{\text{eff}} = 2 - 4$ one obtains $N_{pe}/N_b \approx 20 - 10$. Large continuum signal due to bremsstrahlung emission can appear ovelapped to the Thomson signal, especially when the effective charge increases due to impurities or by using gases other than hydrogen. The use of a multipass system becomes in this case relevant, increasing the effective laser energy inside the scattering volume and reducing errors originated by the poor relation between N_{pe} and photoelectrons produced by bremsstrahlung and stray light emission.

The experimental scattering profile was obtained after intensity measurements along the spectra. The electron density n_e and temperature T_e were determined after fitting of the theoretical curve, assuming maxwellian electron velocity distribution, [1] to the experimental points. Figure 3 shows the results obtained on TC-1 for single pass and multipass measurements. The experimental measurements are represented by points. Each point corresponds to the mean value of a series of about five discharges. The

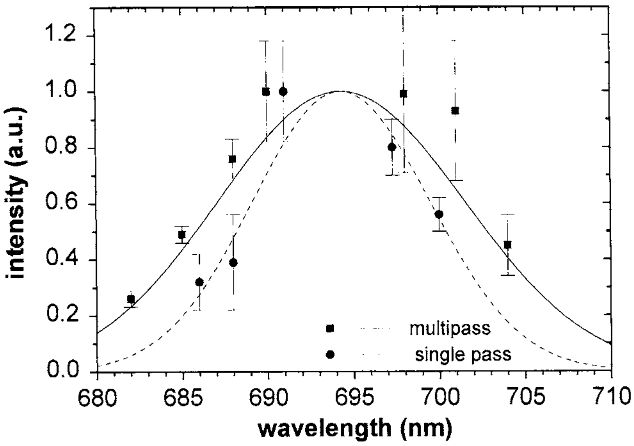

Figure 3: Thomson scattering profiles. Experimental results are represented by points and best theoretical fitting by curves. The measurements were performed for different times t after beginning of the discharge. For single pass ($t = 3\,\mu$s): $n_e = (1.3 \pm 0.2) \times 10^{22}$ m^{-3}, $T_e = (15 \pm 4)$ eV; for multipass ($t = 5\,\mu$s): $n_e = (5.7 \pm 0.5) \times 10^{21}$ m^{-3}, $T_e = (26 \pm 4)$ eV.

best theoretical curves which fit the experimental profiles are shown in lines. The single pass and multipass measurements show different results, because the measurements were performed under two different plasma conditions, i. e., at different time delays after the start of the TC-1 main discharge.

For the tokamak NOVA-UNICAMP[7], recently installed in our laboratory, the expected Thomson signal is about a factor of two orders of magnitude lower than for the TC-1 plasma. So, the total number of signal photoelectrons is expected to be about 200 for measurements with single pass. In this case, the use of a multipass system is very important in order to maintain the reliability of the method. Figure 4(a) shows a simulation for this multipass geometry with 24 passes. Thus, with the approximately 20-fold increase of probing energy, the expected total number of signal photoelectrons can be increased up to 4×10^3 with the same optical detection system. With the high discharge reproducibility of the tokamak NOVA-UNICAMP and low intensities of plasma bremsstrahlung, this number of photoelectrons can provide the accuracy, determined in this case by the statistics of photoelectrons, for electron density and temperature measurements of about 5 % and 10 %, respectively. Figure 4(b) shows the cross section of the laser beam in the central part of the system, i.e., in the scattering region. One observes that, even for a large number of passes, a good spatial resolution can be obtained.

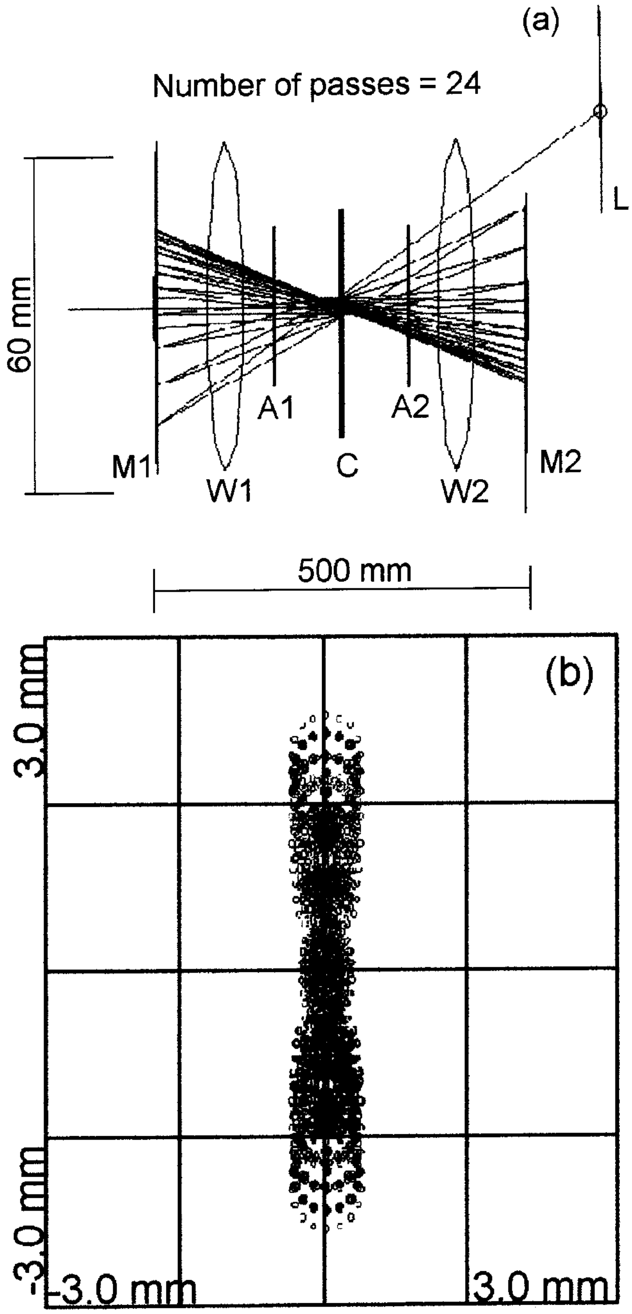

Figure 4: a) Multipass system for the tokamak NOVA. L is the focusing lens, M_1 and M_2 are the reflecting mirrors, W_1 and W_2 the entrance windows, A_1 and A_2 the aperture limitation of the chamber and C is the center plane of the scattering region. b) Cross section of the laser beam in the center plane C.

The technique of multipass for increasing of the Thomson scattering signal in plasmas is easily applicable for symmetrical velocity distributions, or in cases when the Doppler shift due to a drift velocity V_D of the entire distribution function can be neglected. This is the case in this and in most experiments with magnetically confined plasmas, when V_D is much less than the electron thermal velocity. In this experiment, $V_D \leq 1 \times 10^5$ m/s, as measured from fast photographs and from the time evolution of the separatrix radius, derived after measurements of plasma diamagnetismus by means of a set of excluded–flux loops. Altough this technique can be applied in other cases, care must be taken concerning the net drift direction of the electrons and the scattering geometry in order to provide adequate geometry measurements.

III. Conclusions

A simple, effective and low cost multipass system originally constructed for Thomson scattering experiments in tokamak plasmas was built and tested on the theta–pinch device TC–1 UNICAMP. The pulse duration of the amplified light was approximately the same as that of the imput laser beam of about 40 ns, differing from the original application[5] where wide pulses (500 ns) produced by many–fold lasing were used. Small pulse durations are essential for studies in fast discharge plasmas, as in this experiment. Discharges in hydrogen show an increase in the scattered intensity by a factor of 5 for 6 passes. The maximum number of 6 passes for this experiment was limited by the diameter of the access windows of the TC–1, reducing effectively D. The results for density and temperature measurements were obtained after fitting of the theoretical curve to the experimental profile making use of a numerical code for minimization of the error function.

The accuracy of the measurements was determined not by the statistics of photoelectrons, but mainly by the low reproducibility of the theta–pinch discharge, as well as by plasma bremsstrahlung, which is substantial for dense plasmas of theta–pinches. The use of multipass for Thomson scattering experiments in theta–pinch devices or in more dense plasmas as well as in plasmas with higher Z_{eff} can be recommended for reduction of the relation between laser and bremsstrahlung signals.

A computer simulation shows for the tokamak NOVA–UNICAMP the possibility to increase number of passes up to 24. This number can be adjusted by changing the incidence angle of the laser beam and the geometrical positions of the concave mirrors.

Acknowledgments

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