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https://doi.org/10.5109/7173501

出版情報：Reports of Research Institute for Applied Mechanics. 22 (70), pp.177-183, 1975. 九州大学応用力学研究所
バージョン：
権利関係：

Reports of Research Institute for Applied Mechanics
Vol. XXII, No. 70, 1975

INFRARED LASER SCATTERING SYSTEM FOR PLASMA DIAGNOSTICS

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The possibility of observing the collective scattering of infrared laser light from plasmas is discussed in terms of the laser power requirement, the necessary optical system and the detector performance, and is shown to be feasible with the present day techniques to get the ion temperature by means of a CO_2 laser on θ pinch plasmas. Based on this estimate, the construction of the TEA CO_2 laser and the preparations of the optical components have been started and some preliminary results of these are described.

1. Introduction

It has by now been well known [1),2)] that the measurements of the laser light scattering from plasmas can give various informations of the plasmas, such as the electron density and temperature [1),2)] (or in principle the electron distribution function), the electron drift velocity, the intensity of a magnetic field [3)], and the concentration of neutral atoms [4)] from the incoherent scattering from plasmas, and (in case of the presence of only the thermal fluctuation) the ion temperature [1),2),5)], electron drift velocity [1),2)], the concentration of impurity ions [6)] or (in case of the presence of the turbulent fluctuation) the turbulence spectra [7)] from the collective scattering, with good space and time resolutions without disturbing the plasmas.

As the scatterers of the laser light are electrons, it is relatively easy to get informations about them, and it is already the established technique to observe the incoherent scattering of ruby laser light [8)] from plasmas to get electron temperatures and densities. The ion informations which are essential for the thermonuclear fusion researches, however, must be deduced from the collective motion of electrons which follows and represents ion motions. In order to observe the collective scattering of a laser light from plasmas, the scattering wave-number $k \equiv |\vec{k}|$ has to be less than the Debye wave-number $k_D \sim 1/\lambda_D$ (where λ_D is the electron Debye length), which is difficult to be realized for high temperature and low density plasmas, such as commonly encountered in the thermonuclear fusion researches, by using the ruby laser light as shown in Fig. 1. In this figure, below and right hand side of each line satisfies the collective condition α $(\equiv(1/k\lambda_D))\gtrsim 1$ for four typical giant pulse lasers, namely ruby (wavelength 6943 Å), CO_2 (10.6 μm), HCN

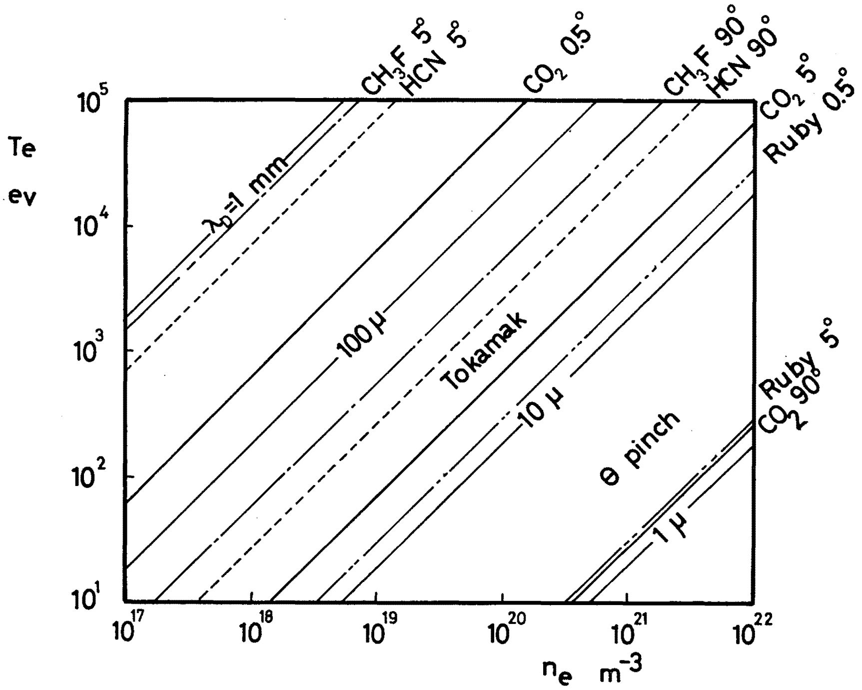

Fig. 1. Angles to give $\alpha (\equiv (1/k\lambda_D))=1$. Below and to the right of each line corresponds to the region where collective scattering from a plasma is observed.

(337 μm) and CH_3F (496 μm) lasers. It is now apparent that systems of the infrared laser scattering are necessary, as it is difficult to avoid too much stray light and poor spatial resolution for a too small scattering angle, to realize the collective condition in Tokamak and θ pinch plasmas which are believed to be the most promising among the thermonuclear fusion oriented approaches.

Among the giant pulse infrared lasers, the TEA CO_2 laser [9] is the most powerful. Therefore, the required power estimate has been made for it and it gives the result that even with the present day technique it is possible to observe the thermal fluctuation of θ pinch plasmas with sufficient spectral resolutions to get ion temperatures. Based on this estimate, the construction of a TEA CO_2 laser and the preparations of the optical components have been started and some preliminary results are now being obtained.

It is the purpose of this paper to describe these estimates, the required component performances, and the experimental results. Finally, some comments are made on the possibility of using the submillimetre lasers (HCN and CH_3F) for the Tokamak diagnostics.

2. CO_2 Laser scattering on θ pinch plasmas

Until recently, the ruby laser oscillating at 6943 Å had been the only giant pulse laser to have been used for the scattering experiments of plasmas, as crystal lasers oscillate at the visible or near infrared (e.g., a Nd-glass laser at 1.06 μm) region and much gain cannot be expected by the use of other lasers than ruby (c.f., Fig. 1). By the inventions of molecular lasers, a wide dimension has been opened for the collective scattering experiments on the high temperature and low density plasmas.

Among the molecular lasers, CO_2 laser is the most powerful and already an order of a few gigawatts has been obtained since the successful pumping of the gas by the TEA (Transversely Excited Atmospheric) discharges [9]. It is, therefore, natural to look at the possibility of using it for the laser scattering diagnostics of plasmas and some estimates [10] have already been published.

It is the purpose of this section to estimate the laser power requirement for the experiment with the combination of the recently advanced infrared semiconductor detectors without using the heterodyning and homodyning detections which is to a large extent still to be developed [11].

2.1. Laser power requirements

In the following estimates, we take the lower limits of the parameters of the θ pinch plasmas, above which density the collective conditions are easier to be realized, as $n_e=5\times10^{20}\ m^{-3}$ and $T_e=300\ ev$. Some typical values of the scattering angle θ are given in Table 1. In order to observe an ion feature of the collective scattering, we need $\alpha\gtrsim1.5$ [1),2)]. For the clear observation of the ion feature, we take $\alpha=2.5$. For this α and the above values of T_e and n_e, the half-width of the ion term is about 15 Å and therefore a spectral resolution of 1.0 Å is required to get enough informations of the ion motion (T_i, the impurity concentration, and the electron drift velocity). The Fabry-Perot interferometer is the most adequate for this fine resolution.

Table 1 Scattering angle for a CO_2 laser (10.6 μm). $n_e=5\times10^{20}m^{-3}$.

	T_e(ev)	200	300	500
λ_D (cm)		4.68×10^{-4}	5.73×10^{-4}	7.4×10^{-4}
θ degee	for $\alpha=1$	20.8	16.9	13.1
	2.5	8.3	6.7	5.2
	5	4.2	3.4	2.6

Based on these estimates of the scattering angle and the resolution system, the expected arrangement of the CO_2 laser scattering equipments on θ pinch plasma is shown in Fig. 2.

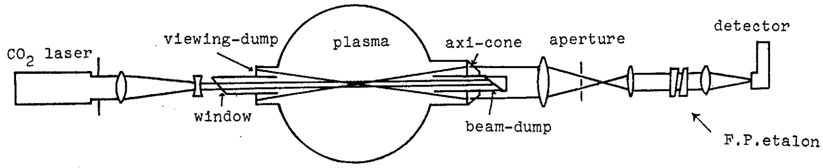

Fig. 2 Schematic arrangement of the equipments for the expected CO_2 laser scattering experiment.

The most important problem is to estimate the laser power above which we get sufficient signal from the ion term. Among various infrared detectors [12),13)], we choose CdHgTe photoconductive detector working at the liquid nitrogen temperature which is earier to handle than say Cu-Ge detector working at the liquid helium temperature. From a catalogue of a maker, the values shown in Table 2 seem to be attainable at the wavelength of 10.6 μm. From these values, the minimum detectable power is estimated to be 2.7×10^{-8} *watts*, in which we used the detection bandwidth of 8 *MHz* as the pulse width of the CO_2 laser is about 100 *ns*.

Table 2 Specifications of a CdHgTe detector.

Specific detectivity	$D^*\geq 2\times10^8 m\cdot Hz/w$
Sensitive area	$2\,mm\times 2\,mm$
Responsivity	$1000\,V/W$
Rise time	$\sim 1\,ns$

The scattered light falling on the detector is given by [1),2)]

$$I=I_0\sigma_T n_e\frac{\delta\Omega}{4\pi}d\lambda S(\Delta\lambda)V_sT \qquad (1)$$

where I_0 is the incident laser light intensity, σ_T the total Thomson cross section, $\delta\Omega$ the solid angle of observation, $d\lambda$ the resolutional bandwidth, $S(\Delta\lambda)$ the wavelength spectrum of the scattered light, V_s the scattering volume, and T the total transmission of light. The detailed shape of the spectrum $S(\Delta\lambda)$ is given in a reference [1)], but for the present purpose, the value at the spectrum centre is enough to be considered which is given by

$$\underset{\alpha=2\cdot5}{S(0)}=9.5\times\frac{c}{2\sqrt{\pi}}\left(\frac{1}{\lambda v_e\sin(\theta/2)}\right) \qquad (2)$$

where $v_e=\sqrt{2\kappa T_e/m_e}$.

In order to obtain the signal to noise ratio S/N greater than 1, the scattered power calculated from Eq. (1) must be larger than the minimum detectable power of the detector of 2.7×10^{-8} *watts*. Taking $n_e=5\times10^{20}\ m^{-3}$, $T_e=300\ ev$, $\delta\Omega/4\pi=4.3\times10^{-3}$, $d\lambda=1.0$ Å, $V_s=50\ mm^3$, $T=0.75$ and $\theta=7°$ for hydrogen plasmas, we get I_0 to be greater than 0.45 MW/mm^2. If the laser beam is focussed to $3mm\ \phi$ at the focal point, the required minimum laser output is 3.2 *MW*. Therefore, the required CO_2 laser power to get $S/N=10$ is 32.0 *MW* which is supposed to be easily obtainable with the present technique [14].

Other factors, such as the ratios of the plasma radiation and the black-body radiation from the discharge chamber wall to the scattered light, have been considered and found to require much less power than 32.0 *MW* for the scattering signal to be bigger.

2.2. The system construction

Based on the above estimates, the whole CO_2 laser scattering system has now been designed and a part of it performance-tested. In this section, we will present the construction and some early results of CO_2 laser only to show that the required power is actually available with a hand-made CO_2 laser.

The CO_2 laser is of the Lamberton and Pearson type [14] with double Rogowski electrodes. The electric circuit is shown in Fig. 3 and the details of the electrodes arrangement in Fig. 4. The main dimensions and parameters of the laser are; the discharge length 0.6 *m*, the discharge height 26 *mm*, the discharge volume 0.45 *l*, the cavity length 1.8 *m*, the mirror radius of curvature 5 *m*, and the reflectivity of the plane output window 80 %.

The uniformity of the discharge has now been achieved by a proper mixing of CO_2, N_2 and He gases and by the optimization of the charging voltage as shown in Fig. 5. Output energy of more than 2 *J* (~20 *MW* in case of 100 *ns* pulse width) has been obtained. The parameter studies are now being made to get the maximum power.

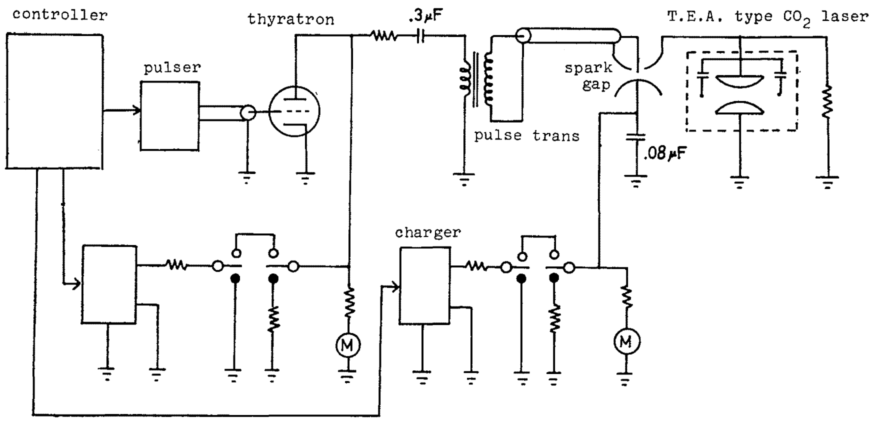

Fig. 3 Electrical circuit for the TEA CO_2 laser.

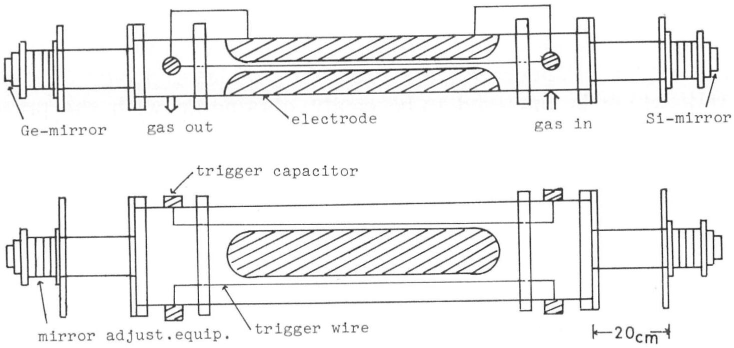

Fig. 4 Electrodes arrangement of the TEA CO_2 laser.

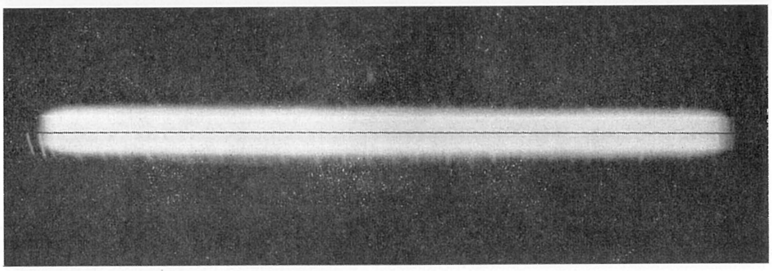

Fig. 5 CO_2 laser pumping by TEA discharge showing a uniform current distribution.

3. Discussion

There have recently been several reports [15),16)] in which the turbulence spectra at the collionless shock front were measured by a collective scattering of a CO_2 laser light. In order to observe the density fluctuation of the thermal level by the collective scattering (a turbulent fluctuation 100 times thermal is commoplace [7)]), more powerful lasers and carefully designed detectors are required. In this paper, by the recent advances of the CO_2 laser and semiconductor detectors, a CO_2 laser scattering system has been shown to be feasible in observing the ion feature (from which ion temperature, the electron drift velocity, and the impurity concentration can be deduced) of the collective scattering of θ pinch plasmas with the present day techniques.

Based on these estimates, preparations of the equipments of the system have been started and very preliminary data have been obtained. More detailed results of the performance of each component will be reported in the near future.

In order to observe the ion feature of the collective scattering from the Tokamak plasmas, far infrared lasers are required (c.f., Fig. 1). In this wavelength region, there is a CH_3F laser oscillating at the wavelength of

496 μm which has recently lased up to the power of 30 kW[17], besides the well-known HCN laser (337 μm), the maximum available power of which has been limited to 1 kW for the last few years. The CH_3F laser is pumped by a CO_2 laser and by the simple extension of the present technique the lasing at the power level of MW is expected possible, and its application to the Tokamak diagnostics has been discussed[18]. In order to pump the CH_3F laser to get the output of a few MW which is supposed to be necessary for the measurement, the CO_2 laser output of more than a few GW is required. The possibility of doing this experiment will be looked at more closely as an extension of the present CO_2 laser scattering experiments on θ pinch plasmas.

A part of this work has been supported by the Grant-in-Aid for the Scientific Researches from the Ministry of Education. The authors wish to thank Professor M. Yokoyama, Drs. C. Yamabe and M. Matoba for their helpful discussions and advices of the operations of a CO_2 laser, and Professor K. Kitajima for his continuous encouragement.

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(Received November 30, 1974)