DEVELOPMENTS AND APPLICATIONS OF LASER FLUORESCENCE SPECTROSCOPY FOR STUDIES OF PARTICLE BAHAVIOURS IN FUSION PLASMAS

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I. INTRODUCTION

In order to expand the understanding of temporal and spatial behaviours of hydrogen (and its isotopes) and impurity atoms in fusion plasmas, a systematic efforts has been made of the developments of the laser fluorescence spectroscopy, from appropriate laser developments, to benchmark experiments to check the plausibilities in plasma measurements. Also, some has already been applied in high temperature plasmas, yielding an otherwise inaccessible plasma structure.

II. TUNABLE LASERS

Among various schemes, we adopted radiation sources, tunable to transitions of atoms to be detected, obtained based on tunable dye lasers, pumped either by flashlamps or by excimer lasers, as shown in Fig. 1. Among these, as shown in Fig. 2, density-measurements using techniques (a) and (b) are more or less established, in the sense that radiation sources enough to saturate transitions exist, and optical components and elements are readily available for the laser input/ fluorescence output optics and detection systems. A hundred Hz repetition system is now routinely used for the plasma-surface interaction studies on TEXTOR. However, for density-measurements of atoms whose transitions from the ground levels exist in vuv, like hydrogen and light impurities, reliable tunable radiation sources are still to be developed. For the purpose, the scheme (c) is being developed, and some are already tested for fluorescence measurements, yielding satisfactory performance. Also, lasers to be used for measurements of velocity-distribution function, using fast-frequency-scan of spectrally narrowed radiations, have been developed.

II-1. Developments of tunable vuv sources [1,2)]

The importance of the developments in tunable vuv laser sources is based on the fact that the resonance-wavelengths of such light-elements as hydrogen, carbon and oxygen are all in this wavelength region. In addition, many ionized elements also have their resonance-wavelengths in this region. Therefore, a systematic approach is necessary for developments of the tunable sources. Among various possible schemes for the generation of tunable vuv sources, we adopted frequency conversion of tunable dye laser light by the third harmonic generation or two-photon-resonance four-wave-sum-mixing in gaseous media, because of the flexibility in tuning to resonance-wavelengths of any element by properly selecting the nonlinear gaseous media.

In order first to exploit the laser source tunable to Lyman alpha (121.6 nm), the third harmonic generation in klypton gas was tested and yielded an expected scaling as shown in Figs. 3 (a) and (b). The maximum output was about 30 W (energy 70 nJ in 2.3 ns) in the Kr/Ar mixture at a pressure of 2 atm, and was limited by the breakdown in the gas. This power is enough for hydrogen detection near the wall of magnetically confining machines. Fluorescence signals were detected from the atomic hydrogen, the density of which could be varied by changing the distance between the position of a pair of electrodes of a dc discharge in hydrogen and the observation point. The results are shown in Fig. 4, where fluorescence has a clear peak due to the absorption of the incoming Lyman alpha beam and the fluorescence signal. A method for the absolute calibration of the system is now being developed.

Laser sources tunable to other light elements, like carbon and oxygen, are going to be obtained by the two-photon-resonance four-wave-sum mixing in metal vapours, as shown in Fig. 5. The heat-pipe-oven, working in magnesium vapour, has yielded satisfactory performance, and the experiments using two tunable laser lights will soon start.

II-2. Fast-frequency-scan dye lasers[3,4]

The velocity-distribution function of metal atoms and light elements, the latter using the transitions between excited states (like Balmer series for the case of hydrogen), whose wavelengths are below the fundamentals of cw dye lasers, was measured shot-by-shot by varying the spectrally narrowed pulse laser source. However, a more reliable method has been sought for due to the irreproducibility of the impurity-release on the one hand and the slow repetition of the plasma discharge in big machines on the other. A fast-frequency-scan dye laser, as shown in Fig. 6, has been constructed, where the duration of the laser emission was elongated to about 5 μs during which period the spacing of the thickest intra-cavity etalon was piezo-electrically (PZT) driven across the Doppler profile of the atoms to be measured. As a check of the validity of the technique, the velocity-distribution function of sodium-vapour was measured using the fundamentals of the dye-laser as shown in Fig. 7. As the results were satisfactory, the laser output was increased so as to obtain enough output at the second harmonic to be tuned at the ultraviolet wavelengths. The system was applied to measurements of the velocity-distribution function of iron atoms sputtered by iron-beam bombardments (3 kV, 60 μA), and the result is shown in Fig. 8. As the ion beam was directed near normal to the polycrystalline iron target and the fluorescence was also measured near normal to the target, the theoretical Doppler profile of modified Thomson formula was used for comparison. The result is satisfactory, which ensures that useful information can be obtained by applications in high temperature plasmas. The laser is presently being upgraded to allow high-repetition (> 10 Hz) in order to follow the temporal behaviour of the velocity-distribution function as well as the densities of atoms in high temperature plasmas.

III. APPLICATIONS FOR STUDIES IN PARTICLE BEHAVIOURS

The techniques (a) and (b) in Fig. 1 are now being applied for studies of particle behaviours in various plasmas, such as in linear machines, like RFC-XX-M at Nagoya and Gamma-10 at Tsukuba, and in Tokamaks, like JIPP T-IIU at Nagoya and TRIAM-1 at Kyushu. They are also being applied for in-situ studies of basic sputtering processes by ion-beam bombardments. Some of the results are described below.

III-1. Behaviours of hydrogen atoms in RFC-XX-M[5)]

Neutral hydrogen behaviours in the central cell of the RFC-XX-M machine at IPP Nagoya, which is a radio-frequency heated and plugged linear confinement machine with a central mirror-field with two anchor-cusps, has been studied using the laser fluorescence at the Balmer alpha. The optical system was calibrated using the Rayleigh-scattering of nitrogen gas, and the saturation of the fluorescence against the laser power was checked, assuring absolute measurements of n_2, the population density of hydrogen-atoms at the principalquantum number n=2. The Koopman-Gohil model was employed to interpret n_2 into the ground-state density n_1. Fig. 9 shows the results, where a marked decrease of the neutral hydrogen at the centre of the plasma was for the first time confirmed in the linear machines.

III-2. Basic sputtering studies

The capabilities of measuring densities and velocity-distribution functions of specified species, in situ, by the laser fluorescence spectroscopy, are being fully exploited by applications in basic sputtering process studies caused by ion-beam bombardments. In order to study the anisotropic collision-cascade regions, the energy and/or the incidence angle of the ion-beam was varied to cover the transition between the anisotropic to isotropic regions. A result of the angular distribution of sputtered particles at four different ion-beam energies at a normal incidence is shown in Fig. 10, which showed a marked departure from the cosine distribution at high energy. The velocity-distribution function and sublevel distribution in sputtered iron-atoms in the anisotropic as well as isotropic regions are currently being probed by the laser fluorescence technique being developed.

IV. CONCLUSION

Laser fluorescence spectroscopy is at varied stages of developments, ranging from laser developments for particular measurements to routine applications in various studies of particle behaviours. By pushing forwards in every front, it will yield useful informations for plasma studies. In addition, combined with particle beams, it has a tremendous potential for clarifications of plasma behaviours, such as plasma-edge studies in H-mode, or current-density measurements in Tokamaks, only to mention a few.

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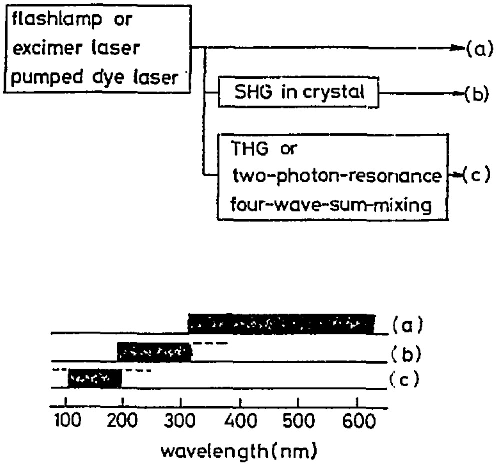

Fig. 1 Development of wide-range tunable sources based on dye lasers, pumped either by flashlamps or excimer-lasers.

	RESONANCE-WAVELENGTH λ	LASER DEVELOPMENTS		BENCHMARK EXPERIMENTS	PLASMA MEASUREMENTS	ELEMENTS
DENSITY	λ > 200 nm	Dye laser pumped by flashlamps or excimer lasers		Knudsen cell (Fe, Al) DC-discharge in $H_2(H_\alpha)$	RFC-XX-M (H_α) Tokamaks (Fe, Ti, ···)	Fe, Mo, Ti, Cr, Al, ··· H $(H_\alpha$, ···
DENSITY	λ < 200 nm	Frequency-conversion of dye lasers by THG or two-photon-resonance four-wave-sum-mixing		Beam transmission Tuning Fluorescence detection (L_α)		H (H_α), C, O, ···
VELOCITY DISTRIBUTION FUNCTION	λ > 200 nm	Single pulse	Fast-frequency-scan dye laser	Na (Fundamentals) Fe (SHG) Fluorescence	Tokamaks (Fe, Ti, ···)	Fe, Mo, Ti, Cr, Al, ··· H $(H_\alpha$, ···
VELOCITY DISTRIBUTION FUNCTION	λ > 200 nm	Repetition > 10 Hz	Stability Wavelength monitor			

Fig. 2 Developments of techniques for measurements of density and velocity-distribution function at visible, uv and vuv wavelength-regions.

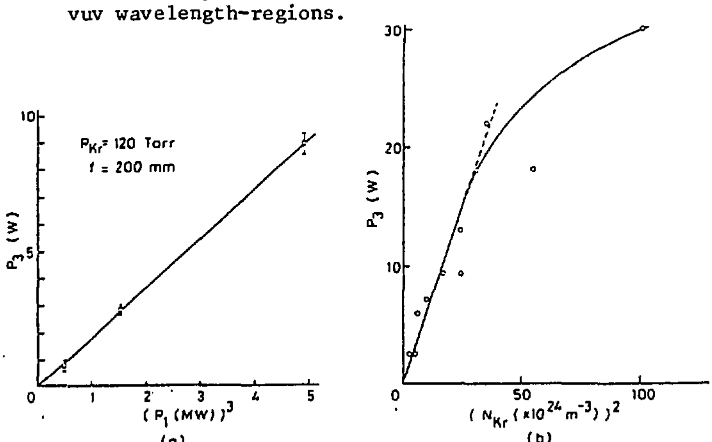

Fig. 3 Output-power of the vuv source tunable to L_α. (a) is the dependence on input-power and (b) is that on Kr density. Straight lines indicate theoretical scalings.

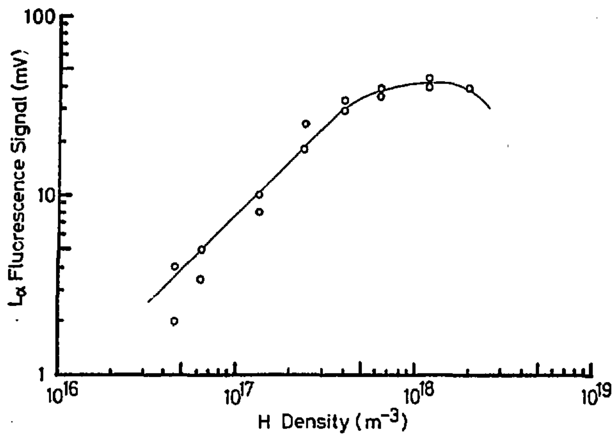

Fig. 4 Fluorescence signals at L_α against the hydrogen-atom density in the observation volume. The hydrogen-atom density was obtained by the absorption of the L_α radiation in the gas.

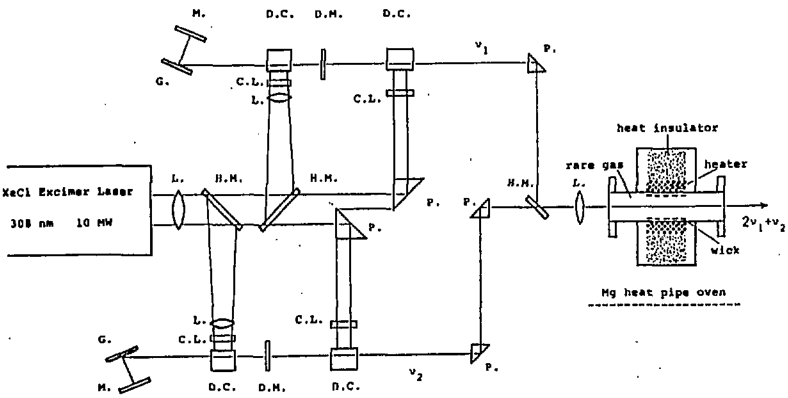

Fig. 5 Setup of the two-photon-resonance four-wave-sum-mixing in metal vapour.

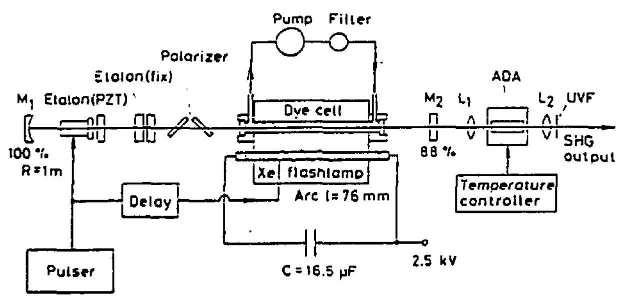

Fig. 6 Setup of the fast-frequency-scan dye laser.

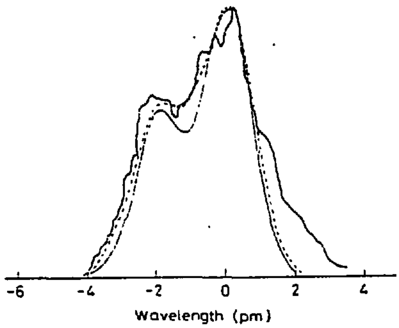

Fig. 7 Measurements of the Doppler profile of sodium-vapour at 100°C. A PZT-scanned etalon with 4mm spacing and two fixed etalons of 10 μm and 100 μm were used. Heavy full line: experiment, thin full line: Doppler profile, and dashed line: convolution of the Doppler profile with laser width of 0.75 pm. The fine structure of the Na D_2 line is clearly seen.

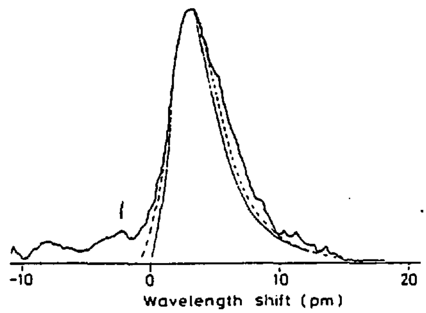

Fig. 8 Doppler profile obtained using the second harmonic of the fast-frequency-scan dye laser (heavy solid line), shown together with the modified Thompson formula (thin full line) and the convolution of the thin full line with the laser line width of 1.5 pm (dashed line). The arrow indicates fluorescence by laser light back-scattered from the target surface.

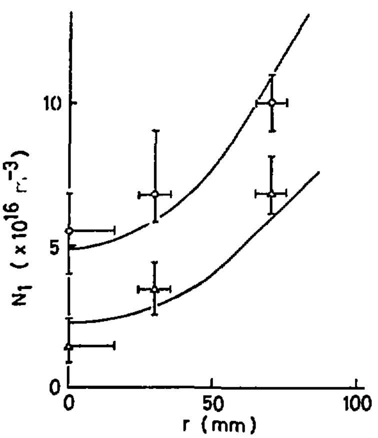

Fig. 9 Radial distribution of neutral hydrogen-atom density in the central cell of the RFC-XX-M machine. The circles are for the case without RF plugging at the line cusps, and the triangles are with it. The vertical error bars indicate range of scatter of several different measurement, and horizontal ones for spatial resolutions. The full lines are calculated values for the plasma conditions.

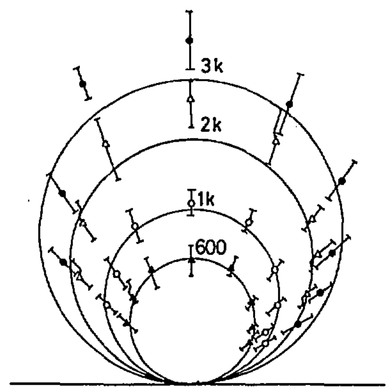

Fig. 10 Angular distribution of sputtered iron-atoms by an Ar-ion bombardment at four different energies. The solid circles are for 3 kV, open triangles for 2 kV, open circles for 1 kV and solid triangles for 600 V. Four circles are cosine distributions for each case. Error bars indicate range of scatter of several different measurements.