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NARROW-BAND, NEAR-UV, HIGH-REPETITION-RATE LASER-INDUCED FLUORESCENCE

SYSTEM FOR USE AS AN EDGE DIAGNOSTIC IN FUSION MACHINES

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ABSTRACT

A laser system for impurity diagnostics in the edge region of fusion devices is described, representing a substantial advance in repetition rate and capacity for velocity distribution measurements. A single mode cw dye laser with scan capability of 30 GHz in 100 msec is amplified by 3 fast flow dye cells, pumped by a high repetition rate excimer laser (60 mJ/pulse at 130 Hz at 308 nm). Average power during the 8 ns pulses of about 0.8 MW for amplified narrowband output at 604 nm, and 80 kW after frequency doubling in KD*P was achieved, with spectral bandwidth in the tenths of GHz regime. The usefulness of such high resolution is demonstrated by a model calculation for Fe velocity spectra involving the presence of thermal and sputtered flux, and spatial averaging. Laboratory velocity spectra are presented for Fe atoms, sputtered in the a^5D_4 ground state. These were obtained by excitation to the y^5D_4 state at 302.065 nm and monitoring fluorescence to a^5F_5 at 382.043 nm. From this data, velocity spectra seem achievable in a single Tokamak shot at densities of 10^{18} cm^{-3} . Rapid conversion of the system to a 50 GHz FWHM broadband operating mode, useful for absolute density measurements, was demonstrated.

Since the fluorescence signal is essentially proportional to atomic density in most LFS experiments designed for fusion devices, measurement of the velocity distribution is necessary if atomic flux is to be determined. In the plasma center, the velocity distribution of H atoms is of intrinsic interest as a measure of plasma temperature. In the edge region, however, it is desirable to obtain the velocity data sufficiently close to the surface of interest that perturbation of the departing atoms by electron collisions is small. The time scale involved is typically a few microseconds.

The resolution requirements for LFS velocity measurements for edge region metallic species are severe, as seen from the Doppler equation

$$\delta\nu = \nu/\lambda \quad (1)$$

giving the shift in frequency, corresponding to motion with velocity projection v along the laser propagation direction, for a transition at wavelength λ . For a thermal distribution of Fe atoms at 2000 K, the velocity width (FWHM) of 1300 m/s corresponds to a frequency shift $\delta\nu = 4 \text{ GHz}$, or a wavelength span of 0.001 nm, at the strong 302 nm transition $a^5D_4 \rightarrow y^5D_4$. Only narrowband laser excitation is practical for velocity scans of high Z atoms. By contrast, for thermal D atoms at 1 keV, a width $\delta\nu = 800 \text{ GHz}$, or wavelength range of $\sim 1 \text{ nm}$ easily permits the determination of Doppler shifts in detection.⁵ A detailed examination of spatial averaging effects in the following section shows high resolution is required to differentiate thermal from sputtered contributions to the velocity spectrum of high Z impurity atoms.

I. INTRODUCTION

Laser fluorescence spectroscopy (LFS) provides a powerful remote diagnostic for obtaining the concentrations and fluxes of atomic species in plasma devices. Advantageous features of spatial localization, selectivity as to species, and sensitivity, as well as freedom from dependence on local plasma conditions for excitation rates have been noted. Further technical aspects have been considered in several reviews.¹⁻⁵

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II. DOPPLER-SHIFTED LFS DIAGNOSTICS

A. Velocity resolution requirements

When there is the possibility of detecting LFS signal from atoms produced by both the mechanisms of sputtering and thermal evaporation, Doppler scanned velocity spectra can provide a direct means for measuring the contributions to the total impurity flux from each source. However, when substantial spatial averaging is involved, as will commonly be the case when probing the wall region of fusion devices, the most probable velocity is shifted toward zero, for both the slow (thermal) and fast (sputtered) components. As a result, high resolution in velocity and good signal/noise ratio are required for assessing the relative contributions to the observed composite spectrum. A model calculation is presented in Figs. 1 and 2 for the case of Fe impurity atoms either evaporated at a characteristic temperature of 2000 K or sputtered with a distribution given by the Sigmund-Thompson model¹⁶⁻¹⁸ for a fully developed collision cascade. In practice, a substantial contribution to the sputtered flux may come from light atom/ion bombardment of the wall region. In that case, the velocity distribution for the sputtered component will peak at values lower than the prediction of the Sigmund-Thompson model, as has been seen in laboratory experiments.^{9,10} The result will be greater overlapping of slow and fast components in velocity, but a reduction in the tendency of the signal from slow atoms to overwhelm that from the fast ones, as shown in the following.

In the model, the LFS apparatus is assumed to be an ideal detector of atomic density in the range of laboratory velocities v to $v + dv$ probed. The situation for detection of flux from an infinitesimal area element into a differential solid angle $d\Omega$ in a direction at angle θ to the surface normal will be described first. The distributions, G , of atomic density are:

$$G_t(v)dv d\Omega = (2/\pi v_m) w^2 \exp(-w^2) dw d\Omega \\ = g_t(w) dw d\Omega \quad (2)$$

$$G_s(v)dv d\Omega = [2n(n-1)/\pi v_b] \\ u^2/(1+u^2)^{n+1} du d\Omega \\ = g_s(u) du d\Omega \quad (3)$$

In Eqs. 2 and 3, the velocity v is conveniently expressed in terms of the reduced variables $w = v/v_m$ and $u = v/v_b$, for the cases of thermal and sputtered atoms,

respectively. The thermal case, identified by subscript "t" assumes a Maxwell-Boltzmann distribution with temperature T and peak velocity $v_m = (2KT/M)^{1/2}$ in customary notation. The sputtered distribution (subscript "s") is characterized by velocity v_b defined by $E_b = mv_b^2/2$, E_b being the one dimensional energy barrier to be traversed as the sputtered atom leaves the surface, usually taken to be the sublimation energy. The index n refers to an assumed sub-surface flux of atoms distributed in translational energy E as E^{-n} . Experiments and theory show $n=2$.

The corresponding flux from the surface area element is obtained by multiplying the density distribution functions by $v \cos \theta$:

$$F_t(v)dv d\Omega = (2/\pi) w^3 \exp(-w^2) \cos \theta dw d\Omega \\ = f_t(w) dw d\Omega \quad (4)$$

$$F_s(v)dv d\Omega = [2n(n-1)/\pi] u^3 (1+u^2)^{-n-1} \cos \theta du d\Omega \\ = f_s(u) du d\Omega \quad (5)$$

The normalization constants have been chosen, in both cases, to give unit flux into the forward hemisphere:

$$\int_0^\pi dy \iint_{(2\pi)} d\Omega f(y) = 1 \quad (6)$$

where y is the appropriate reduced velocity variable (u or w).

For comparison with the LFS Doppler experiments, density in unit laboratory velocity interval is needed:

$$G_t(v) = g_t(w) \frac{dw}{dv} = g_t(w)/v_m \quad (7)$$

$$G_s(v) = g_s(u) \frac{du}{dv} = g_s(u)/v_b \quad (8)$$

In the interesting case where impurity atoms from both mechanisms are present, the total flux Q is divided into a fraction x from thermal and $1-x$ from the sputtering mechanisms. The observed density $N(v)$ (in unit solid angle and velocity interval) is

$$N(v) = Q[x g_t(w)/v_m \\ + (1-x) g_s(u)/v_b] \quad (9)$$

Explicitly, for sputtering index $n=2$, and laser beam direction normal to the surface monitored ($\theta=0$):

$$N(v) = [x(2/vv_m^2)w^2 \exp(-w^2) + (1-x)(4/vv_b^2)u^2/(1+u^2)^3] \quad (10)$$

Equation (10) has been plotted for Fe in Fig. 1, with the parameter $E_b = 4.32$ eV (energy of sublimation at 0 K), and $T = 2000$ K, giving $v_b = 3861$ m/s and $v_m = 771.7$ m/s. Curves for $x = 0.0, 0.01, 0.05$ and 1.0 were normalized individually to a peak value of unity. It is clear that a small fraction of

now representing the perpendicular velocity component, the distributions for density become:

$$G_t(v)dv = (2/v_m) \exp(-w^2)dw \\ = g_t(w)dw \quad (11)$$

$$G_s(v)dv = [2(n-1)/v_b] (1+u^2)^{-n} du \\ = g_s(u)du \quad (12)$$

Now the corresponding flux distributions are obtained by multiplication by v , and again are normalized to unit flux:

$$\int_0^\infty F(v)dv = 1 \quad (13)$$

Equation (9) is calculated for the distributions defined by the one dimensional distributions Eqs. (11,12) and plotted, with unit peak normalization, in Fig. 2. The extensive spatial averaging has caused the peak in both types of distributions to shift to zero velocity. This represents an extreme case of the effects seen for modest spatial averaging in laboratory experiments.^{9,11} We note that Δv the velocity FWHM for the thermal distribution of Fig. 2 is given by $\Delta v = v_m \sqrt{\ln 2} = 642$ m/s corresponding to a frequency shift of 2.1 GHz by Eq. (1). It is evident that an intrinsic laser linewidth of somewhat less than 1 GHz is desirable if conclusions concerning impurity release

Fig. 1. Sputtered and thermal velocity distributions for a differential solid angle element.

thermal flux can shift the distribution function strongly, to peak near v_m . The effect is caused by the $v_m^{-2}(v^2)$ dependence of the thermal (sputtered) contributions to Eq. (10), since v_b is substantially larger than v_m . The explanation is that the sputtered atoms are spread out more in physical space and velocity space than those produced thermally. Equation (10) thus predicts a drastic decrease in signal as the fraction of the flux attributable to sputtering increases (not shown in the normalized curves of Fig. 1). Some possibility of resolving the individual contributions is provided by the fact that the peak velocities (v_m for thermal, $v_b/\sqrt{2}$ for sputtered density) are well separated.

In actual measurements, however, the surface area contributing to the signal can subtend a large solid angle at the LFS probed volume. To model this situation in a limiting case, the integral over 2π sr is performed by integration over all components of velocity parallel to the surface. With v

Fig. 2. Sputtered and thermal velocity distributions integrated over 2π sr. mechanisms are to be drawn from measured velocity distributions.

Curves appropriate to the "parallel" distribution (with the laser beam parallel and close to the monitored surface) are simply obtained by extending the distributions to negative velocities, symmetrically about $v = 0$. An arbitrary angle to the surface may also be used, and results are intermediate between the cases mentioned above.

It is also of interest that the density distributions may be integrated by elementary means, giving, for the relation between total density N and total flux Q :

$$N_t = \sqrt{\pi} Q/v_m \quad (14)$$

$$N_s = \pi Q/(2v_b) \quad (\text{for } n=2) \quad (15).$$

The integration over velocity space has reduced the inverse square dependence of density on characteristic velocity [Eq. (10)] to the expected inverse dependence for a given flux.

B. Experiments in Fusion Devices

Experiments on metallic impurities in fusion devices, studied by LFS techniques^{5,12-19} are summarized in Table I. A majority have used laser wavelengths in the 300 nm region conveniently produced by doubling light from Rhodamine dyes. Repetition rates have been essentially one laser shot per tokamak shot for the flashlamp pumped systems, and in the 10-20 Hz regime for Nd:Yag case. Only one experiment was reported with a broadband excimer-pumped laser, reaching the 100 Hz regime.

Experiments listed in the upper half of Table I used a bandwidth equivalent to about 10 km/s by Eq. (1), sufficient to excite all thermal and sputtered atoms simultaneously. The authors of Ref. 15 were able to deduce the presence of sputtered Ti atoms from moderate changes in the line profile, dominated by the exciting laser linewidth, when tokamak shots were compared with thermal flux. Other experiments with the flashlamp-pumped system have used a bandwidth of ~2 GHz, corresponding at $\lambda = 300$ nm to a velocity width of 0.6 km/s. Although a higher resolution may be useful (section II A, above) the main limitation for fusion diagnostics has been the single-shot sampling capability.

In the case of the cw laser experiments,¹⁹ the high duty cycle and scannable narrow bandwidth are advantageous but the limitation to visible wavelengths and the low output power represent problems. It is

desirable to be able to pump metallic atoms to upper states reached via near-UV wavelengths since radiative lifetimes in the 10 ns regime can be utilized, minimizing the effects of electron collisions. The need for high power can be understood from a brief discussion of saturation and power broadening.

For broadband light of spectral width $\Delta\nu$ [Hz] and intensity I [W/cm²] at wavelength λ connecting lower and upper levels of degeneracy g_1 and g_2 , a saturation parameter S can be defined² as

$$S = \frac{\lambda^3 I}{8\pi h c \Delta\nu} \frac{g_1 + g_2}{g_1} \quad (16).$$

For example, Fe at $\lambda = 302$ nm, $\Delta\nu = 50$ GHz and $g_1 = g_2$; requires 453 W/cm² to achieve $S=1$. In a 3-level system "pump-over" saturation²⁰ during a long pulse requires less intensity because of the increased time allowed. Transport processes in the laser-illuminated volume may come into consideration, however.

When a laser of bandwidth much less than the Doppler width is used a "hole" is burned in the population. Now the saturation parameter^{19,20}

$$S' = I/I_s \quad (17)$$

is used with $I_s = \pi h c / (3\lambda^3 \tau)$. Then the linewidth of the hole is given by

$$\gamma' = \gamma \sqrt{1+S'} \quad (18)$$

with the homogeneous linewidth $\gamma = 1/\tau$ + other contributions to the homogeneous linewidth (collisions, transit time). Again the example of Fe at 302 nm, $\tau = 6.4$ ns²¹ gives $\Delta\nu = 1/(2\pi\tau) = 25$ MHz, and $I_s = 122$ mW/cm². The saturation of a broad Doppler profile via monochromatic light requires high power because of the S' dependence in (18). Thus $S' = 10^6$ or $I = 122$ kW/cm² would be appropriate for the width of sputtered distributions. Hence, the use of broadband light is more efficient, when atoms of all velocities are to be accessed simultaneously.

It can be seen that the ideal system for edge region LFS should combine several characteristics. It is desirable to utilize short UV pulses and lifetimes in order to reduce the complications in analysis caused when electron collisions and atomic transport are significant. In general, atomic density is determined, at a fixed laser frequency and Doppler scans are needed to provide velocity data. High repetition rate is desirable in

Table 1. Metallic Impurity Diagnostic Experiments by Laser-Induced Fluorescence Spectroscopy on High Temperature Plasma Devices.

Atom	Wave-length pump/det. (nm)	Minimum Band- width ^a (GHz)	Repetition Rate (Hz)	Pulse Length (ns)	Average Pulse Power (W)	Laser System Type ^b	Plasma Device	Reference
Fe	302/382	60	10	5	1x10 ⁶	N	ISX-B	12,13
Ti	294/445							
Ti	294/445	52	17	5	6x10 ⁵	N	D-III	5
Ti	294/445	28	1	500	800	F	ASDEX	14
		24	100	15	4x10 ⁴	E		
Ti	294/445	24	1	500	800	F	ASDEX	15
Fe	302/382	2.0	1	500	700	F	ISX-B	16
Al	308/308	3.2	1	300	100	F	EBT-S	17
Mo	300/458	1.7	1	300	1.7x10 ³	F	W VII-A	18
Zr	614/594	0.043 ^a	cw	5000 ^d	0.3	C	APEX	19

^aRefers to value actually used in indicated experiments.

^bAll systems used dye lasers and all except C used second harmonic generation in crystals. Pump sources were N:Nd:Yag laser, F:flashlamp, E:Excimer laser. C was an argon-ion pumped ring dye laser.

^cIncluding transit time and power broadening effects.

^dAcousto-optically modulated.

order to monitor real time variation in plasma behavior or to scan velocities during quiescent periods. It is also useful to have both narrow- and broadband modes available as well as high power for saturation studies.

III. EXPERIMENTAL

A. Laser System

The laser system described here was designed to meet the objectives for LFS fusion diagnostics discussed above. In essence, it consists of a narrowband oscillator, operating at visible wavelengths followed by a sequence of amplifiers which provide sufficient power for efficient frequency doubling into the near UV region. The design of such systems has benefitted from considerable recent development in various laboratories.²²⁻²⁹ An early

version²² employed a pulsed oscillator of moderate bandwidth followed by a pulsed amplifier system, all pumped by a 1 MW nitrogen laser. Use of a high finesse Fabry-Perot cavity to filter the oscillator stage, for bandwidth narrowing produced considerable amplitude jitter in the output (resulting from frequency jitter in the oscillator). Thus there was interest in the properties of saturated amplifier stages for reduction of output amplitude variation.²³ Subsequently, standing-wave cw dye lasers have been used as the oscillator stage in these systems,²⁴⁻²⁹ providing single-mode narrowband (~10 MHz bandwidth) output and good amplitude stability but low power (~10 mW, cw).

In the present system shown schematically in Fig. 3, a cw scanning ring dye laser³⁰ has been used, providing several advantages. Output power is increased to the level of a few hundred milliwatts for single-

Fig. 3. The principal components of the laser system.

mode, narrowband output ($\Delta\nu = 20$ MHz, p-p). The extra power enables a good contrast ratio [of amplified narrowband to amplified spontaneous emission, (ASE)] to be maintained in the first amplifier stage, as will be discussed further below. Also, since in a ring laser the mirrors are not orthogonal to the output beam, problems of auxiliary cavities formed with the subsequent amplifier cells are avoided. Perturbation of the ring laser by the amplifier output has not been observed, so optical isolators^{24,25} were not necessary at an operating wavelength of 600 nm. The scan range of the ring dye laser is 30 GHz, corresponding to a Doppler velocity of 18 km/s (94 eV Fe atoms). Scans are electro-mechanically controlled by intra cavity elements with a maximum rate of 30 GHz/100 ms. Broadband operation can be accomplished by removing the thick etalon and optical diode from the laser cavity thus allowing power to be shared among many

longitudinal modes, 240 MHz apart, with about a 50 GHz envelope.

The pulsed amplifier cells were transversely pumped by a commercial excimer laser [Lumonics, 861-T], operating on XeCl at 308 nm. Operation for maximum average power (130 Hz) gave 60 mJ/8 ns pulse at 130 Hz. Operation at higher rates is also possible with reduced average power. In cases where the maximum energy/pulse is not required the high repetition rate is attractive (a recent version of this excimer reaching 8 mJ/pulse at 500 Hz).

As indicated in Fig. 3, portions of the excimer laser beam were intercepted by pickoff mirrors and directed into flowing dye cells. This technique allows flexibility for optimizing the fraction of the total pump power into each cell (eventually set at 5, 30, and 65% to the first, second and third cells respectively). An acousto-optic modulator deflected the cw laser beam into the amplifier cell system for 1 μ s coincident with each excimer shot. The first order diffracted spot containing ~70% of the ring output power was directed through the amplifier cells. The undeflected cw beam is sent to 3 and 300 GHz FSR spectrum analyzers. Beam waists of about .25, .5, and .8 mm were produced in cells 1-3 respectively by appropriate lenses, placed as shown in Fig. 3. The figure is accurately scaled with respect to component spacings, the optical table length being 3 m.

For operation at 604 nm, the dyes employed were: Rhodamine 6G in the ring laser, and Rhodamine B in the amplifier cells 1-3. The concentrations, 4.6×10^{-4} M in cell 1, 3.8×10^{-4} M (methanol solvent) in cells 2 and 3 were individually optimized in sequence, in separate circulation systems. The amplified laser signal was monitored with fast photodiodes and beamsplitters following cells 1 and 3. The typical gains monitored in the center of the laser mode were 10^4 , 200 and 10 in cells 1-3, somewhat larger than the actual power gain integrated over the beam area. To a considerable extent, the contrast ratio (CR) of narrowband to broadband power is determined in the first amplifier cell. The gain ($\alpha \text{ cm}^{-1}$) of the homogeneously broadened dye is related to the parameters α_0 : small signal gain, I : laser intensity, I_s : the saturation intensity by²²

$$\alpha = \alpha_0 / (1 + I/I_s) \quad (19).$$

Here, I_s is a complicated function of the parameters in the rate equations for the dye medium,^{31,32} but increases approximately linearly with high pump power. The local efficiency η for conversion of pump photons

to laser output is given by²² $\eta = (1 + I_s/I)^{-1}$ so that it is very desirable to have high laser intensity, I , in the final amplifier stage. However, amplified spontaneous emission becomes comparable to I_s , i.e. of the order of the maximum output laser signal when the gain per stage reaches $(L/R)^2$, the length L to active radius R ratio, squared (about 5×10^4 in our first cell). The use of several stages minimizes this problem and avoids the use of high pump power (and high I_s) until the laser intensity is sufficient for reasonable efficiency.

Because of gain narrowing³³ at high intensity, operation near the gain maximum has been recognized as important for some time.²² For a fixed output wavelength, this can be accomplished by dye mixing.³⁴ Addition of sulforhodamine B to cell 1, at 1.8×10^{-5} M, enabled CR of 100 to 200 to be obtained in routine operation as measured by blocking the ring laser input, typically 200 mW, to the cell. Conversion of the excimer photons to narrowband output from cell 3 at 604 nm was achieved with the optimum energy efficiency^{35,36} of ~10%. Typical visible output was a few millijoules in a pulse of ~9 ns duration. The output beam was focused to a ~5 mm waist for second harmonic generation by type I, angle tuned phasematching in a 95% deuterated KD*P crystal. Efficiencies of >20% and pulse energies of 0.6 mJ of narrowband UV have been obtained. Since the broadband background light is less efficiently doubled, substantial improvement in CR is obtained. One measurement showed CR=400 at 302 nm, for a relatively low CR=40 at cell 1. The UV beam shows the customary elliptical cross section for focused frequency doubling,³⁷ with near diffraction limited divergence, and is strongly polarized in the horizontal plane.

With a nominal lifetime³⁸ of ~10 Kh, the Rhodamine B in the flowing dye cells exhibits useful life of ~10⁶ shots of the excimer laser, at which point both gas and dye are usually replaced. Tests at rates of up to ~80 Hz showed no degradation of average pulse energy and slight increase in individual pulse fluctuations.

The Fourier transform limit for the nominal 8 ns pulse is ~100 MHz from the amplifier chain (200 MHz, frequency doubled). We have not yet experimentally verified achievement of this limit in the UV, although optogalvanic spectroscopy on the Fe hollow cathode lamp implies a bandwidth substantially below 1 GHz. [An upper limit is provided by one test, at poor contrast ratio, with a visible etalon showing $\Delta\nu < 0.3$ GHz. This should be improved in the

SHG process. Further UV tests are planned via gas phase spectroscopy.] Additional reduction of ASE can be achieved by the use of dispersive devices^{22,24-26} between stages. The intrinsic velocity width of the distributions being probed, as well as residual Zeeman splitting probably diminish the benefit of further bandwidth reduction.

The wavelength range of this system is 500 to 890 nm prior to frequency doubling, except for a small region 770-810 nm currently inaccessible to the ring laser using an argon ion pump. A krypton ion pump laser allows the ring to reach the missing region, but this is unnecessary for almost all metallic impurity studies.

B. Fe velocity distributions - laboratory experiments

The velocity distribution for Fe atoms, sputtered by 3 keV argon ions was measured in the ultra high vacuum chamber shown in Fig. 4. Base pressure was $\sim 3 \times 10^{-10}$ Torr after mild 200°C baking. Key modifications from this previously described^{39,40} arrangement are as follows. A thin mask (molybdenum) with a 3.9 mm aperture, of

Fig. 4. UHV chamber for velocity distribution measurements on sputtered Fe.

comparable size to the ion beam spot, was used to define the sputtered area. Also, an intermediate image, formed in the light collection system, enabled the region within 5 mm of the target to be masked from the detector field of view, thus drastically reducing distortion of the velocity spectrum from spatial averaging effects, and eliminating any problems associated with photons produced near the target surface. The viewing system is aligned on a position 10 mm from the target surface with the use of a pin mounted on a translation feedthrough.

In the experiments, the laser intracavity elements are scanned in response to a staircase ramp generated by a computer controlled CAMAC module. Typically, one or more shots of the laser system is fired at each laser frequency, across the scan range (usually 30 GHz for sputtering experiments). Fluorescence signal is detected by a cooled 9659QB ENI phototube, with a band pass interference filter (40% trans., 10 nm bandwidth at 383 nm) plus UV cutoff filters to attenuate scattered laser photons and filament light. A level diagram of the transitions involved in measurements on ground state Fe atoms is given in Fig. 5.

Fig. 5. Spectroscopic data for LFS velocity distribution measurements on ground state iron.

A few percent of the laser light near 302.07 nm is sent to an iron hollow cathode lamp and the photogalvanic signal is digitized along with the fluorescence signal on each laser shot. The strong photogalvanic peak serves as zero-frequency-shift marker, allowing the precise alignment of successive 30 GHz sweeps for averaging. The 3 GHz interferometer is used as a fixed etalon, generating calibrating frequency markers as the laser scans. A signal proportional to the integrated UV energy, which can be made essentially invariant across the 30 GHz scan, is also recorded for each shot. Absolute power measurements are checked at a position equivalent to that of the sputtering region (~2 m from the doubling crystal). There the central portion of the beam (~10% of the total energy) passes through a 1.2 mm diameter hole. An external beamsplitter and position-monitor diode verifies spatial stability during the frequency scan. An example of the data produced is given in Fig. 6.

Fig. 6. Velocity spectrum of sputtered iron by narrowband LFS.

The experiment was performed with a static argon gas pressure in the chamber of $\sim 6 \times 10^{-5}$ Torr, producing a current of 18 μ A at the target. From sputtering yield data for iron¹ and the known geometry a density of $\sim 1 \times 10^8$ cm⁻³ for Fe, distributed over all states, is calculated at the center of the detection region. The laser was attenuated to 1.8 kW/cm² where power broadening of the

measured distribution was not significant. As the intensity I in the chamber is increased, signal is observed to grow as $\sqrt{I}$ as expected for narrowband excitation. A weaker velocity peak appears to the negative side of the velocity spectrum at high intensity, attributed to fluorescence induced by laser photons returning through the viewing region after scattering in the ion gun. A small signal of this type is still present in Fig. 6. A total of 100 laser shots per point were averaged in Fig. 6, which was obtained at an excimer laser repetition rate of 40 Hz. The data system is temporarily limited to a repetition rate of 80 Hz where a small increase in pulse energy fluctuations is seen.

The solid line through the points is the density distribution Eq. (3), constrained to $n=2$ and the thermochemical⁴² value of 4.315 eV for the iron sublimation energy. No allowance for spatial averaging has been made. Model calculations indicate a peak shift of $< 2\%$ for the actual geometry.

IV. IMPLICATIONS FOR FUSION IMPURITY DIAGNOSTICS

It is apparent from laboratory experiments that the bandwidth requirements for high resolution velocity distribution studies are met by pulsed amplifier laser systems of the type reported here. Existing flowing-dye cell technology seems adequate for operation in the 100 laser shots per second regime. Operation at 500 Hz is, as yet, untested although excimer laser systems exist for doing this. (Similar dye amplifiers have been demonstrated at much higher rates ($\sim 10^4$ Hz) but lower pulse energies with copper vapor pump lasers.³²) High power is available for use in both broadband and narrowband operation. The de-coupling of oscillator and amplifier stages is very convenient for overall stability, since both excimer pulse energy and amplifier dye conversion efficiency degrade with operation.

Narrowband operation in a magnetic field requires a favorable spectroscopic situation, as is well known, since the velocity spectra may be broadened by Zeeman splitting of the pump lines at $(14 \text{ GHz/Tesla})(g_M - g_L)$ for Lande g factor and magnetic quantum number M in upper and lower states. The rather favorable case for Fe is shown in Fig. 7, where all the $\Delta M=0$ (π) lines can be simultaneously excited by the narrowband laser by selection of its polarization along the magnetic field,¹⁹ and no interfering lines are present within 100 GHz. The situation for non-resonant fluorescence is shown in the lower portion of Fig. 7, where a bandwidth of 250 GHz is spanned by all contributing Zeeman lines.

ABSORPTION

$$\text{STATE: } \sigma^3 D_4 \rightarrow \gamma^3 D_4^0$$

$$g_J: 1.496 \quad 1.496$$

$$\lambda_{\text{pump}} = 302.065 \text{ nm}$$

$$\delta\nu \leq 0.5 \text{ GHz}$$

$$B_0 = 5 \text{ T}$$

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$$\text{STATE: } \gamma^3 D_4^0 \rightarrow \sigma^3 F_3$$

$$g_J: 1.496 \quad 1.404$$

$$\lambda_{\text{det}} = 382.043 \text{ nm}$$

Fig. 7. Fe Zeeman Spectrum.

A good detector system can be composed from a closely spaced Fabry Perot etalon matched to the emission line, in tandem with a conventional bandpass interference filter. Signal would be carried on 1 mm diameter UV fiber optics with f/1.1 collimator optics at the interferometer and, eg. f/11 optics and a 1 cm diameter collection region in the fusion machine. A signal of 5 photoelectrons per laser pulse can be expected according to

$$dS = n_0 (X_a X_v) (e_p e_i e_f) (dq/4\pi) dA dz \quad (20)$$

for a density of n_0 atoms/cm³ in all states, fractions X_a and X_v in the initial atomic state and velocity range probed, effective branching ratio X_b to the final state monitored, photo cathode, interference filter and Fabry-Perot efficiencies e_p , e_i , and e_f , respectively, and solid angle $d\Omega$, viewing area dA and depth dz in the probed region. We use numbers for the present Fe experiment $X_a = 0.6$, $X_b = 0.6$, and assume $X_v = 0.1$, $e_p = 0.2$, $e_i = 0.4$, $e_f = 0.5$, $d\Omega/4\pi = 5.2 \times 10^{-4}$ (f/1.1), $dA = 0.8 \text{ cm}^2$ and $dz = 1 \text{ cm}$, giving $d\Omega = 6 \times 10^{-7}$ n_0 photoelectrons/pulse. Thus impurity densities of $10^8/\text{cm}^3$ should allow analysis at one laser shot per velocity sampled with $\sim 13\%$ statistical fluctuation.

For comparison, the laboratory experiments also operate with $n_0 = 10^9$. The geometric factor alone $(\partial\Omega/4\pi)dAdz$ is 2.4×10^{-4} for the lab system and 4.2×10^{-4} (sr cm^3) for the proposed tokamak diagnostic. Since the latter includes $\epsilon_F = .5$, not needed in the lab configuration, the two systems are closely comparable. Figure 8 is an example of a lab experiment at one laser shot per data point. Higher laser beam intensity

photons/(cm^2 sr s) is obtained for the arrival rate using the previously assigned values of the other quantities in Eq. (21). For $n_0 = 10^9$, previously assumed, the estimated photon arrival rate for LFS signal is two orders of magnitude above continuum background estimates, in a 300 GHz bandwidth, and comparable to weak line emission from the plasma. Successful velocity distribution measurements may thus depend on good viewing geometry, to avoid collecting radiation from the line of interest excited by electron collisions in other regions of the plasma.

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Fig. 8. Fe ground state velocity spectrum at 1 laser shot per point (40 Hz rate).

(77 kW/cm^2) was used to enhance the signal). At this level, some power broadening is distinguishable in intensity variation studies, but the fit with constrained $n=2$ and $E_0 =$ sublimation energy (Fe) is still good.

For comparison with background light levels in a tokamak it is useful to express the signal in photons/(cm^2 sr s) at the detector as

$$(dR/d\Omega d\Omega dt) = n_0 (X_A X_B X_C)$$

$$dz/(4\pi \Delta t) \quad (21)$$

where it is appropriate to use the gate duration Δt of the data system. With $\Delta t = 30$ ns, a value of $10^5 n_0$

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