LA-UR-78-2360

MASTER

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TITLE: NEW TECHNIQUES FOR PLASMA DENSITY PROFILING

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SUBMITTED TO: International School of Plasma Physics -
"Course on Diagnostics for Fusion Experiments",
Varenna, Italy, September 4-15, 1978

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CONTRACT W-7405-ENG. 36

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NEW TECHNIQUES FOR PLASMA DENSITY PROFILING

by

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ABSTRACT

Two new techniques for the measurement of plasma density profiles are presented. The two approaches are aimed at simultaneously overcoming uncertainties due to both the Abel inversion, and plasma irreproducibility. Plasmas with densities $\gtrsim 10^{14} \text{ cm}^{-3}$ ($N \times L \gtrsim 10^{15} \text{ cm}^{-2}$) are considered.

The first technique combines standard heterodyne interferometry with rapid spatial scanning. The Abel inversion problem is addressed by the very high spatial resolution obtainable (e.g., ~ 100 spots/ μs of scan time at $\lambda = 3.4 \mu\text{m}$) while the plasma irreproducibility is overcome by multiple framing in a single discharge (interframe time as short as $10 \mu\text{s}$). The technique requires only a single detector channel and is applicable over a wide range in parameters. The apparatus has been built and successfully bench tested.

The second technique, currently in the design stage, is based on Thomson scattering of a short laser pulse. With a wavepacket small compared to the plasma, the nondispersed scattered light pulse shape is essentially the plasma profile. Additionally, the short light pulse allows time of flight discrimination against instrumental scatter. With very modest pulse energy, the scattered power greatly exceeds the plasma radiation and signal statistics determine the detection quality.

1. INTRODUCTION

Plasma density profile determination is one of the central problems in controlled fusion plasma diagnostics. Ideally, knowledge of the density at all points in both space and time during the discharge is desired. Although great progress has been made in pursuing one or the other of these goals on various plasmas, progress in combining them has been difficult; factors such as profile asymmetry and plasma irreproducibility often lead to considerable error bars. This is especially true where only side-on access is possible and inversion methods are used, as is the case for many CTR devices.

At Los Alamos we are developing several advanced diagnostic techniques for providing a more complete characterization of the plasma density. Non-contacting techniques are of course preferred for fusion plasmas, and the optical techniques described here are based on two of the most useful of these, viz. laser interferometry and laser light scattering.

The first technique combines heterodyne interferometry with fast spatial scanning of the plasma and was developed specifically with the requirements of Abel inversion in mind. As has been pointed out previously, [1] the problem of Abel inversion is quite serious. Several analyses [2,3] have shown that even for 20-30 data points on the phase profile, measurement errors on axis can be multiplied by factors of from 3 to 20, depending on the technique used. The scanning interferometer concept was developed specifically to achieve a spatial resolution (number of independent data points) far in excess of what is possible by other means at mid infrared wavelengths. The important parameter is actually the scan rate (number of revolution spots/ μ s). As will be seen later, scan rates of ~ 100 spots/ μ s have been achieved, which is more than adequate for a very large variety of CTR plasmas. The data may be used directly in an inversion, or when the errors are random, averaging may be used before inversion to reduce the error. Multiple frames during a single discharge are also possible. In the technique used here the frame interval can be as short as ~ 10 μ s. To enhance both accuracy and reliability only a single detector channel is used. This also lends itself well to automated data acquisition.

To address those cases where profile inversion is not practical, a second technique is being pursued. It involves Thomson scattering of a laser pulse whose spatial extent is much smaller than the path length through the plasma. With fast receiver circuitry, the plasma profile is contained in the output pulse shape. The entire (non-dispersed) scattered spectrum is used. The scattering cross section is assumed to be due only to Thomson scattering. A check on this can be provided by a single stationary interferometer beam along the laser line of sight.

As will be seen, this approach actually places the scattering measurement in a new regime. By using standard source energies ($\sim .5$ joule) but in very short pulses ($\sim .1$ ns), scattered light flux levels far in excess of plasma self-luminosity can be achieved. The measurement is thus limited only by signal statistics. Not only does this situation provide the most favorable signal to noise ratio, but it also permits significant flexibility in receiver design.

2. SCANNING HETERODYNE INTERFEROMETRY

In the visible region of the optical spectrum, there are many well developed techniques for obtaining high resolution spatial profiles of plasmas. These include holographic, [4] Mach-Zender and streak interferometry, [5] among others. However, their principal use is

where plasma area density gives substantial phase shift in the visible i.e. where $\int ndl \sim 10^{17} \text{ cm}^{-2}$. Obviously, many situations do not fall in this regime, and infrared wavelengths are used to increase the plasma phase shift. (6-10) Unfortunately, sensitive planar detectors do not exist in the infrared so that the above techniques do not readily carry over. As a result, in most infrared applications, detectors are used which give time resolved electrical signals, rather than spatial profiles. In the present application a time resolved technique (heterodyne interferometry) is combined with fast spatial scanning to give multiple frame, high resolution profiling capability.

In heterodyne interferometry, the plasma density variation is observed as a phase distortion of the beat (heterodyne) signal between two optical beams of different frequency. [11] The beat signal without plasma represents a known phase shift with time and is compared to a similar signal with the plasma present. The difference gives the plasma phase shift vs time. In the scanning mode, the temporal phase distortion corresponds to the beam sweeping across the plasma, and in this way the profile is obtained.

Using heterodyne interferometry as the basis of the measurement has many practical advantages, compared e.g. to amplitude techniques. Since the plasma effect is a modulation of the basic heterodyne frequency, the sign of the phase shift is readily found from the direction of the frequency change. This is valid as long as the plasma phase rate does not exceed the heterodyne frequency, i.e., $|d\phi_p/dt| > 2\pi f$, where f is the heterodyne frequency. In fact, this relation is the basis for selecting the frequency. A second advantage is the multi-fringe capability. As long as the rate does not exceed the above limitation, there is no ambiguity in total fringe shift. A further advantage is the basic accuracy of the frequency measurement, independent as it is of gain fluctuations, baseline drift, detector nonlinearities, etc. The accuracy is limited principally by the time allowed to measure the frequency. However, even counting individual cycles on the oscilloscope can yield better than 0.1 fringe resolution. Transient waveform digitizers have been used to give 0.01 fringe resolution.

There are many ways to generalize this technique to profile measurement, rather than just a single chord. Scanning is chosen as opposed to the multiple beam approach because of the practical advantages of a single detector channel, rather than a large number (e.g. 50) in interferometry. Even within the realm of scanning, many possibilities exist, depending on parameters such as scan time, phase shift, optical access, etc. In the present application (0-pinch side-on viewing) conditions are such that signal to noise considerations demand attention, and this has been the basis of selection of the technique used. In the optical heterodyning processes, maximum heterodyne signal is obtained when both scene and reference beams have the same profile, and when both beams fall entirely on the detector. The reference beam is therefore made to match the scene beam, and is scanned over a virtual object plane in the reference arm, in synchronism with the scene beam scanning over the real object. Both beams are then superposed on a beamsplitter and focused onto a detector in such a way that for all points in the scan they remain superposed, and entirely on the detector surface.

The scan parameters are determined by the dynamics and geometry of the plasma. In order to "freeze" the motion in a 0-pinch, sub-microsecond scan times (e.g. $1/4 \mu\text{s}$) are required. At the same time a spatial resolution of $\sim 2 \text{ mm}$ over a field of $\sim 5 \text{ cm}$ is needed. These two requirements together determine the required scan rate, which is about 100 spots/ μs . A high

speed turbine driven rotating mirror was found to be the only scanning device capable of this high a scan rate in the infrared.

The scan time also puts a lower bound on the heterodyne frequency, since one desires at least one data point per resolution element. Measuring individual fringe displacement permits maximum possible bandwidth (as opposed to analog phase detection) and if only the peaks or the valleys are used, then the heterodyne frequency needs to be at least 100 fringes/ μ s, or 100 MHz. Another firmer but less stringent requirement is that the heterodyne fringe rate be greater than the maximum plasma fringe rate, to avoid directional ambiguity. Scanning a plasma profile of ~ 2 fringes/cm at the above rate dictates a minimum rate of 40 MHz. 100 MHz was therefore chosen to satisfy both requirements. This seemed to be most directly obtainable using Bragg diffraction in an acousto-optic cell.

Operation of an acousto-optic cell, and its use in a general two beam set-up are shown in Figs. 1 and 2. A traveling acoustic wave is generated in a crystal by a piezo-electric transducer on the surface. The index periodicity due to the wave generally will diffract a beam into many orders, each with a frequency shift at a harmonic of the acoustic frequency. This is the Raman-Nath regime. However, when the input beam is aligned so that the specular reflection from the acoustic wavefronts is along the first order, then all the diffracted light appears in this order. This is the Bragg regime, and is the mode most useful for present applications. Typical crystals in commercially available cells are lead molybdate and germanium, useful from the visible to $\sim 15 \mu$ m. Diffraction efficiencies of 70% are readily obtained, although generally only $\sim 50\%$ is needed.

In a simple two beam setup, shown in Fig. 2, the zero order is used in one arm and the first order in the other arm of an interferometer. The two beams are recombined on a photodetector, which produces the beat frequency containing also the relevant phase information (usually the reference arm has $\phi(t) = 0$).

Combining these ideas with spatial scanning led to the concept shown in Fig. 3. A CW laser beam at 3.39μ m from a helium-neon laser system (~ 8 mw) is focused inside a lead-molybdate acousto-optic cell. When aligned for Bragg diffraction, all the diffracted light appears in the first order, which is frequency shifted an amount equal to the acoustic frequency, in this case 100 MHz. The cell is a commercially available unit, [12] requiring about 40 watts of rf to produce 50% diffraction efficiency at this wavelength. To avoid destroying the cell it is pulsed at 5% duty cycle, the pulse being triggered from an optical detector shortly before the scan. As shown in Fig. 3, the two output beams are then collimated and impinge on the turbine mirror surface. The zero order beam is used as the scene beam, while the first order is reference. Scanning the two beams this way, in identical fashion, effects an enormous reduction in spurious differential phase shifts that might otherwise occur.

The recollimating optics at the output of the cell consist of two cylindrical lenses, with orthogonal axes of curvature. The reason is that the collimation requirements differ in the two directions. Parallel to the rotor axes, the two beams must fit side by side, but with a usable separation on the rotor (which has a 2.4 cm mirror length). This lens is thus determined by the Bragg diffraction angle (~ 0.1 rad) and the beam separation (~ 1.5 cm). In the other direction, the desire is to provide maximum possible spatial resolution in the object plane, which means minimum far field divergence, which in turn means illuminating

almost the entire rotor mirror (perpendicular to the axis). The beams are thus expanded to ~ 6 mm, which requires ~ 7 times the focal length of the first lens.

The turbine mirror is a Beckman-Whitely model 200-04. It has a beryllium rotor and a maximum rated speed of 10 kHz. Based on previous work [13] beryllium was found to be essential to prevent mirror distortion at high speed from compromising the spatial resolution. Facet size is 12 mm by 24 mm.

The technique used to scan the plasma and collect the beams is illustrated conceptually in Fig. 4 and a complete optical schematic is shown in Fig. 5. To maintain a high level of contrast in the heterodyne signal, both beams traverse nearly identical optics (except for the plasma itself and its access windows). The angular scan due to the rotating mirror is converted to a linear scan by placing the rotor at one focal plane of a 2 m scan lens. The two beams then scan side by side and are thus easily separated and deflected into the scene and reference arms. Beyond the scan lens the beams converge to the far field spot at the back focal plane. At this point the return mirrors are placed, making the system double pass. The plasma is placed as close as possible to the return mirror to achieve maximum resolution. The scene and reference arms are made approximately the same length to keep the contrast high. The end mirror of each arm is tilted out of the scan plane slightly so that the return beams are superposed on the beamsplitter. A collecting lens then focuses the entire scan field onto the detector. This is equivalent, together with the scan lens, to imaging the rotor onto the detector, which ensures a stationary spot on the detector during the entire scan. This was done to reduce the required detector area, since fast, sensitive infrared detectors only come in small sizes. The focusing is done by an $f/3.3$ CaF_2 doublet lens onto a mercury doped germanium photoconductive detector. Active area is 1 mm diam., with a nominal frequency response beyond 400 MHz. [14] The dominant source of noise in the system is the preamplifier following the detector. The detector is run at a high bias voltage (450 V) to improve the signal, without materially affecting the noise level.

The resolution (number of spots across the field) is simply θ_S/θ_B where θ_S is the angle scanned in the allowed time and θ_B is the far field beam divergence of the beam leaving the rotating mirror. Since $\theta_B \propto \lambda$ (diffraction limited), increasing wavelength tends to reduce the resolution. Fortunately, however, those plasmas where longer wavelengths are needed are usually slower, and can therefore tolerate larger scan angles to compensate.

Using this technique, a new profile scan is made at each reappearance of the mirror surface. While the test results reported here were done with a single facet rotor with a top speed of 10 kHz, a 12 sided rotor with the same speed has been built.

Spatial resolution (spots across the field) and scan rate (spots/ μ s) are most easily determined by observing the scene beam alone during the scan, with different resolution test grills in place of the phase object. The results of such a test are shown in Fig. 6 for two different rotor speeds. Figure 6(a) is the bare scan, with no test grill. The amplitude modulation is due to mild resonances in the sapphire detector window caused by the beam sweeping in angle as well as position across the window. Their effect on the heterodyning is negligible.

In Figs. 6(b)-(d) test grills of 10, 5, and 2.2-mm/LP are used, corresponding to 11, 21, and 50 spots across the field. The resolution is ~ 30 spots at low speed and ~ 25 spots at high speed. The scan rate corresponding to this is ~ 100 spots/ μ s.

A When scene and reference beams are permitted to interfere with each other, the heterodyne signal is produced. This is shown in Fig. 7 for low speed scanning. Figure 7(a) shows the bare scan and demonstrates that it is possible to obtain virtually 100% contrast in the interference pattern.

Figures 7(b)-(d) show spatial resolution tests in the presence of heterodyning, demonstrating results in full agreement with the resolution tests of Fig. 6. This also indicates the absence of any observable degradation in beam quality due to the acoustic wave in the Bragg cell.

Heterodyning while scanning at maximum speed is shown in Fig. 8. The slow time base (50 ns/div) shows the overall envelope while the faster time base shows the detailed fringe structure. For comparison, in each photo the acoustic signal (rf signal to the Bragg cell) is shown in the upper trace at the same sweep speed. In Fig. 8(a) and (b) the interferometer is adjusted for near parallelism between scene and reference beam wavefronts. This condition can be determined by the approximate match of the heterodyne frequency and the acoustic frequency. As can be seen, the match is only approximate: the heterodyne frequency actually varies during the scan due to small phase differences in the scene and reference beam optics. For this reason a double exposure technique is used in analyzing the data: a scan made in the presence of the object (data scan) is measured against a scan made without the object (reference scan). Each scan gives a plot of phase vs position, and the difference between the two curves is the phase profile of the object. This is then the analog of holographic interferometry, where the instrumental phase variation is automatically calibrated out the data.

The accuracy with which the phase comparison can be made is one of the important system parameters. One way to determine it is to tilt the scene beam return mirror (in the scan plane) by a known amount. This imparts a strictly linear phase profile, which the data analysis should reproduce. The resulting scans are shown in Fig. 8(c)-(f), which correspond to mirror tilts of about 1/4 mrad in each direction. The data analysis is done with the fast sweep data using Fig. 8(b) as the reference scan. The trough locations in the fringe pattern are digitized on a Summagraphics digitizer. Using a spline fit to the reference scan, the difference between it and the data scans (Fig. 8(d) and (f)) are computed and the results plotted in Fig. 9. The worst case deviation from the linear profile is 0.1 fringe. It should be noted that the reading precision is ~ 500 spots across the scope face, corresponding to 0.04 fringe, and therefore is a major contribution to the 0.1 fringe error. The system itself is therefore somewhat better than 0.1 fringe.

Testing the phase accuracy as described above demonstrates some tolerance of schlieren effects. The practical limit (severe contrast loss) to beam bending, regardless of the source, is $\sim \pm 1/2$ mrad. In this context the window requirement is that the deflection remain small compared to the limits discussed above, which implies less than $\sim 1/10$ mrad of differential bending (i.e. variation in deflection) across the field, for both windows. This requirement is generally easy to meet, even for windows under a pressure differential.

The turbine mirror used in the present system has only one reflecting facet, which limits the frame interval to 100 μ s or greater. A sequence of four successive frames may be obtained on a single scope photo by suitable triggering. An example is shown in Fig. 10, which contains data taken on a CO₂ gas jet in air. In Fig. 10(a), the jet density gradient is large enough to make the data ambiguous. In Fig. 10(b) the pressure is lower and the

data is readily analyzable. The resulting profiles, using the data and references traces of Fig. 10(b), are shown in Fig. 11. The differences between the profiles, while due in part to the measurement accuracy, may also be caused by real effects, such as turbulent flow variations in the 100 μ s frame intervals.

Recently, a turbine mirror with 12 facets has been built, with the same top speed, providing a frame interval of 8.5 μ s. An alternative technique for achieving closer frames might be to use several beams at different angles of incidence on the rotor.

The application of the technique described here is probably close to the limits of its usefulness because of the short scan time allowed. For slower plasmas, with longer allowed scan times and frame intervals, the rotation speed, heterodyne frequency and bandwidth can all be reduced, resulting in great simplification. At the same time exceptional spatial resolution can be attained by using larger scan angles and faster scan lenses. Choice of wavelength is another important parameter. Where 10 μ m light is permitted by the window access, then the much higher power CO₂ lasers ($\sim$ watts) may be used, thereby greatly increasing signal to noise ratio.

As an example, in a large Tokamak plasma where perhaps a 5 μ s scan time may be adequate, a resolution of over 150 spots is possible at 10 μ m wavelength. At the same time, the lower bandwidth and higher power should readily permit a phase accuracy of .01-.02 fringe, which is adequate for peak area densities $\gtrsim 2 \times 10^{15}$ cm⁻².

With larger formats it is probably best to use expansion optics at the object, rather than scan the large format at all points in the optical train. For modest dimensions refractive optics are suitable while for the largest formats off axis reflective optics would be more appropriate.

3. Short Pulse Scattering

The short pulse scattering concept involves 90° viewing of the light scattered from the plasma along the entire beam path through the plasma. As with any scattering experiment, a prerequisite for success is a satisfactory signal to noise ratio in the receiver. In this regard there are several differences from a conventional scattering experiment. On the positive side: (1) the entire scattered spectrum is integrated and (2) at any instant of time the entire wave packet is seen by the receiver rather than just a small slice. On the negative side: (1) background light is integrated from along the entire length of beam path and (2) the band width is large. The net result is a significant advantage in signal to noise ratio, for a given laser energy. This arises from the massive dominance of instantaneous scattered light over plasma light, due to the high laser power level.

As a concrete example we use the set of parameters shown in Table I. The density level corresponds to a plasma somewhere between a high density Tokamak and a Reversed-Field Z Pinch.

a. Beam Handling

Fitting about 10 wavepackets across the plasma implies a laser pulse width of 100 ps. Anticipating energy levels in the joule range then leads to power levels of $\sim 10^{10}$ W, which are sufficiently great that care must be taken to avoid optical damage. However, considerations of damage levels and depth of focus impose conflicting requirements on the beam diameter at the entrance and exit windows. The conflict may be avoided by using high

TABLE I. SPS Measurement Parameters		
1. Plasma	n(central density)	$5 \times 10^{14} \text{ cm}^{-3}$
	a(radius)	15 cm
	T_e (electron temperature)	1 KeV
2. Laser	E_L (energy)	.5 J
	T_L (pulse width)	100 ps
	λ_L (wavelength)	.53 μm
	E_{DL} (energy density on windows)	.5 J/cm ²
	FL (entrance/exit focal length)	1.5 m
	D_C (focused spot size)	1 mm
	D_e (spot size at plasma edge)	2 mm
3. Scattering	$\Delta\lambda$ (optical bandwidth, FWHM)	2000 Å
	α (scattering parameter)	$\sim .01$
4. Receiver	T_r (risetime)	130 ps
	B (electrical bandwidth)	3 GHz
	S (photocathode sensitivity)	.1 A/W
		(QE $\sim$ 23%)
	G (detector gain)	4×10^3
	Ω (solid angle)	5×10^{-3} str.
	V_e (plasma emission volume)	140 cm ³
5. Detection	η (optical efficiency)	15%
	I_S (signal photo current)	40 μA
	I_B (10 x bremsstrahlung photo current)	2 μA
	I_S/I_n (Signal to noise ratio)	200

quality optics and housing them in a clean environment, as shown in Fig. 12. There have been numerous studies [15-18] of laser damage levels and mechanisms, which show that when high quality (especially regarding inclusions and defects) and dust free optics are used, damage thresholds of over 1 J/cm^2 are readily obtained for both surface and bulk breakdown with pulses in the 10-100 ps range. The configuration shown in Fig. 12 permits half this level to exist on the windows, while permitting much lower energy densities for open air beam transport.

Taking care with the entrance optics in this manner should also reduce the amount of stray laser light, compared to more casual handling, and may even make internal baffling unnecessary. A significant advantage of the short pulse technique is the time discrimination against stray laser light. The beam dump is fundamentally the largest source of stray light, but its return is discriminated against by transit time considerations; it does not arrive at the receiver until the plasma scattering is over. Similar reasoning applies to stray light caused by wandering of the beam due to plasma density gradients.

b. Detection

In the simplest detection scheme, a single lens system images the entire beam path onto a single photodetector, as shown in Fig. 12. In this application we consider a crossed-field photomultiplier, such as the Varian model VPM-148S. As can be seen from the parameters in Table I, the tube is characterized by a very high quantum efficiency and short risetime. The gain is modest, but more than adequate because of the high signal flux rates. The major disadvantage of the tube is its rather restrictive format (5 mm diam.). With simple imaging of the plasma down to this level, solid angles of only $\sim 10^{-4}$ str would result. A vast increase can be obtained by first transforming the 5 mm disc to a long strip of $\sim .5 \times 50 \text{ mm}$ using either a fibre bundle or cylindrical optics. Then even with $f/2$ focusing, a solid angle of $\sim 5 \times 10^{-3}$ str results. The effective radiating volume is roughly a disc of plasma with the minor cross section area and thickness equal to the beam diameter. Assuming a laser beam divergence of 5 times diffraction limited, then the entrance optics (1 cm active aperture, 1.5 m FL) produce a beam diameter $\leq 2 \text{ mm}$ at all points on the plasma.

Using these parameters, as well as the others listed in Table I, the bremsstrahlung photocurrent may be calculated from (with T_e in $^\circ\text{K}$) [19]:

$$I_B = \int_{\Delta\lambda} 2.39 \times 10^{-47} \frac{n^2}{T_e^{1/2}} \left[26.41 + \ln \frac{T_e}{\omega} \right] v_e \Omega \frac{2\pi C}{\lambda^2} \eta S d\lambda \quad (1)$$

This results in a value of $\sim .2 \mu\text{A}$. Allowing for a factor of 10 more plasma light, which is not uncommon in fusion plasmas, gives $2 \mu\text{A}$ of background photocurrent. The signal current, calculated simply from:

$$I_S = \frac{3\sigma_T}{8\pi} E_L \Omega n C \eta S \quad (2)$$

is $40 \mu\text{A}$. The peak signal level is thus some 20 times greater than the estimated background. The noise level may be found from shot noise considerations; $I_n = (2eIB)^{1/2}$ where $I = I_S + I_B$. This gives $I_n \sim .2 \mu\text{A}$, which yields a total signal to noise ratio,

I_S/I_n , of ~ 200 (signal noise limited). While this is a comfortable regime to be in the treatment ignores possible nonthermal fluctuations in plasma light. These contribute directly to I_n and can potentially degrade I_S/I_n . Their presence can only be determined by experiment.

A minor complicating factor in the measurement is the transit time dispersion in the optical system, which indicates that a calibration of the receiver time base is in order. It should actually be possible to compensate for this effect in the fibre optic image transformer between the lens and PMT.

Acquisition of the detected signal can be accomplished in several ways. The most straightforward, but by far the most costly, is with a high speed oscilloscope. Scopes are available with bandwidths of 5 GHz and deflection factors of ~ 200 mV/cm, but are very expensive. Two more reasonable approaches are shown in Fig. 13. Both schemes rely on sampling techniques. In Fig. 13a the tube output is fed to a low loss transmission line through a normally open switch. The line is terminated in a very low impedance, which is in parallel with the input of a single channel sampler (e.g., a sampling oscilloscope). When the pulse is acquired on the line the switch is closed (switch response time in the nano-second range is adequate). The pulse then rattles back and forth on the line between the low impedance and the shorting switch, but on each pass feeding a fraction through to the sampler. In effect this makes the pulse repetitive, and eight transits are required to equal the resolution permitted by the PM tube risetime. The load impedance is chosen small enough so that the droop at the last pulse is not excessive (say $\sim 50\%$) but large enough for sufficient voltage feed through. A normalized load of 2% is adequate. The drop-off in signal is of course included in the overall calibration, which will be via the usual Rayleigh scattering. It appears that optical breakdown will not be a problem at the required neutral gas densities.

The setup shown in Fig. 13b uses many samplers along the pulse. They are fed by a distributor which allows power division without waveform distortion. The samplers feed storage capacitors which are read by analog to digital converters. This technique is suitable for multiple pulse (mode-locked train) operation. By simply gating the samplers for as many of the pulses as desired, the profiles are automatically integrated. At the end of the sequence the results are read out to the computer. Complete units have been built from 10 to 20 samples, and with jitter in the 10 ps range. For the present application only about eight samples are needed. This approach has the advantage of allowing much higher signal levels than the scheme in Fig. 13a, but probably with a lower bandwidth.

c. Pulse Generation

The generation of laser pulses in the 10-100 ps range is most readily accomplished by passive mode-locking of a solid state laser. Since the first demonstrations of dye cell modelocking [20,21], the production of such pulses has become almost routine. The development has been particularly strong for the Nd:glass laser, since this material is capable of the highest energies and power densities of all the solid state lasers.

The system considered here uses frequency doubling to convert the 1.06 μm laser wavelength to 0.53 μm . At this wavelength photocathode sensitivity is much improved compared to either 1.06 μm or .69 μm . Two of the most useful non-linear materials for these wavelengths and power densities are KDP and CDA. The former has yielded conversion efficiencies of up

to 80% [22,23], while the latter has produced 57% [24]. Conversion losses are thus quite acceptable, considering the gain in detector quantum efficiency. These materials have been operated at equivalent power levels of $4\text{GW}/\text{cm}^2$ in short pulses. [25] From long pulse damage threshold measurements also, the short pulse thresholds may be expected to be of this order. For example, assuming power threshold scaling of $1/T^{1/2}$, [18] then the $400\text{MW}/\text{cm}^2$ threshold measured for KDP [26] with Q-switched pulses extrapolates to $\sim 5\text{GW}/\text{cm}^2$ for 100 ps pulses. The 10 GW of $1.06\text{ }\mu\text{m}$ light therefore requires $\sim 2\text{ cm}^2$ of nonlinear material.

In the glass laser itself, power densities of at least $25\text{GW}/\text{cm}^2$ have long ago been obtained. [26,27] Using a conservative number of only $10\text{GW}/\text{cm}^2$ implies a diameter of $\sim 1\text{ cm}$ for the output amplifier rod, which is commonplace. An oscillator plus 2 amplifiers have been shown to be sufficient to achieve the required energy levels in mode-locked operation. [26,27]

Typically, a passively mode-locked laser produces a train of pulses over a period of some tens of nanoseconds. Extraction of a single pulse using a laser triggered spark gap and pockels cell [28] is now a standard technique. However permitting scattering of the entire train can enhance the signal to noise ratio by at least the square root of the number of pulses integrated. Thus the bulk of the pulse train is usable. The width of the pulses from a mode-locked oscillator can be varied over a very large range. By using an etalon inside the cavity to restrict the number of longitudinal modes, it has been shown possible to vary the pulse width from 10 ps to over 1 ns [26,29].

d. Nonlinear Effects

Possible nonlinear effects must be considered for several reasons. These include the alteration of the plasma by heating during the pulse, and anomalous induced scattering by the plasma.

As can be verified from the work of DeSilva and Goldenbaum, [19] even if thermalization were to occur during the .1 ns pulse, the temperature increment due to inverse bremsstrahlung absorption is totally negligible for these plasma conditions.

Concerning induced plasma scattering several observations are in order. On the one hand, induced scattering requires the presence of operating nonlinear mechanisms in the plasma. One criteria by which the degree of nonlinearity is judged is the amplitude of the ac electron velocity in the electric field of the wave, compared to the thermal velocity. For keV electrons, $V_{th} \sim 10^9\text{ cm/s}$. The ac velocity is $V_{ac} = eE/m\omega$, which, for $E \sim 20\text{ MV/cm}$ corresponds to $\sim 10^7\text{ cm/s}$. This is definitely small, and would only start becoming appreciable at temperatures of $\sim 10\text{ eV}$.

On the other hand, effects which are small from a gross plasma or energy balance point of view, may not be small on the scale of Thomson scattering. In other words, an induced wave structure may exist with only minor energy density and transport features, but which may have a significant scattering cross section. However the conditions conducive to stimulated scattering usually entail much higher densities and longer pulses [30], as well as a predominance of backscatter rather than sidescatter, which would be of interest here. We thus approach the possibility with optimistic caution and plan to check for it during the experiment. As a 1st resort, the power density can be reduced by either increasing the

focal area or reducing the beam power. The very favorable detection conditions can tolerate a factor of 10 loss in signal, provided the assumptions are valid.

e. Extensions

Various extensions to this technique suggest themselves. For example a continuous train of mode locked pulses, over the duration of the experiment, could be used to map the profile in time. One need only be able to read the samples with the A-D converters between pulses. In light of the present state of the art in fast converters (100 MHz range) this is straightforward, and in fact is being pursued at Los Alamos. Another possibility is spectral analysis for temperature determination. With the scattered pulse widths only 0.1 ns, delays between the channels are easy to achieve. Combining this with the previous concept leads to a system that measures both temperature and density profiles as a function of time, all with a single detector.

Acknowledgment

The author wishes to acknowledge the vital contributions of Martin A. Leif in the design, construction, and testing of the scanning interferometer, as well as helpful discussions with P.R. Forman and F.C. Jahoda on the scattering concepts.

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FIGURE CAPTIONS

1. Acousto-optic cell operating modes.
2. Basic two beam heterodyne configuration.
3. Technique for slewing frequency offset scene and reference beams.
4. Conceptual schematic of scanning and beam collection technique. f_s --scan lens focal length, f_c --collecting lens focal length.
5. System optical schematic.
6. (a) Normal scene beam scans; (b) resolution test grill in object plane, 10 mm/LP (11 spots across field); (c) 5 mm/LP (21 spots); (d) 2.2 mm/LP (50 spots). Object plane ~ 17 cm from return mirror.
7. (a) Heterodyne scanning at low speed ($f_{rot}=0.94$ kHz) with quartz windows on vacuum chamber in scene beam. (b) through (d) same resolution test grills as in Fig. 4.
8. (a),(b) High speed (9.6 kHz) heterodyne scanning through quartz windows under vacuum. Lower trace--heterodyne scan; upper trace--acoustic signal. (c),(d) scene beam return mirror tilted by ~ 0.25 mrad; (e),(f) mirror tilted ~ 0.25 mrad in opposite direction.
9. Measured phase profiles for Figs. 8(d) and (f) (data scans) using Fig. 8(b) as the reference scan.
10. Sequential high speed scans on CO_2 gas jet in air. $f_{rot} = 9.5$ kHz (105 μs frame interval). Pressure in (a) is higher than in (b). Reference frequency may be seen to be decreasing across the field (due to instrumental phase shift) while the data frequency increases across the field.
11. Analysis of Fig. 10b.
12. Short pulse scattering system beam transport configuration.
13. Signal acquisition techniques: (a)--single channel sampling, (b) multiple channel sampling.

SPATIAL RESOLUTION

$f_{\text{rot}} = .93 \text{ kHz}$

(a)

(b)

(c)

$.5 \mu\text{s}/\text{div}$

$f_{\text{rot}} = 9.5 \text{ kHz}$

$50 \text{ ns}/\text{div}$

SLOW HETERODYNE SCANNING

(a)

(b)

(c)

(d)

FAST HETERODYNE SCANNING,
LINEAR PHASE OBJECT (MIRROR TILT)

50ns/div

(a)

20ns/div

(b)

REF.

(c)

(d)

POS. TILT

(e)

(f)

NEG. TILT

LINEAR PHASE OBJECT (MIRROR TILT, $\approx 1/4$ mr)

FOUR SEQUENTIAL SCANS,
 CO_2 GAS JET

REF.

(A)

(B)

DATA

CO₂ GAS JET

BEAM TRANSPORT CONFIGURATION

(a)

(b)