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MEASUREMENT OF THE ION TEMPERATURE IN THE DENSE PLASMA FOCUS BY LASER BEAM SCATTERING

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MEASUREMENT OF THE ION TEMPERATURE IN THE DENSE PLASMA FOCUS BY LASER BEAM SCATTERING

by

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A B S T R A C T

The spectrum of scattered ruby laser light due to collective electron motion has been used to measure the ion temperature in the dense Plasma Focus. Over a range of operating conditions the deuterium temperature in the dense pinch is between 0.7 keV and 3 keV, the highest values being obtained on only a few discharges in pure deuterium. Interpretation of the scattered light in terms of a near-thermal plasma is favoured for the dense pinch for two reasons. Firstly, the electron parameters derived from the scattered spectrum are in agreement with other independent measurements and secondly, the contribution to the spectrum by rare gas ions in the plasma can be quantitatively accounted for.

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1. INTRODUCTION

In plasmas of interest in fusion research the mechanisms by which the fusion reactions take place are determined uniquely by the ion energy distribution. The Plasma Focus device, Mather (1965), is a source of copious neutron emission when operated in deuterium and the temperature of the ions in the dense pinch, which is formed as a result of the imploding current sheath, is therefore of particular significance.

One of the few direct methods for measuring the ion energy distribution is from the spectrum of light scattered by the electrons moving collectively to shield the ions in the plasma. The form of the co-operatively scattered spectrum depends not only to the ratio of the electron to ion temperature, T_e/T_D, but also on the temperature of any other ion species present, Evans (1970). In our experiments scattering has been observed from a pure deuterium plasma and also from deuterium with a few percent by volume of rare gas additives such as neon. The spectrum of the scattered light is found to be significantly different for each case and the contribution from both ion species to the scattered spectrum has been included in the analysis of the results.

2. DESCRIPTION OF METHOD

The Plasma Focus discharge apparatus and its operating conditions have been described previously, Peacock, Speer and Hobby (1969), Peacock, Hobby and Morgan (1971). A 6 joule, 20 nanosecond pulse from a ruby laser irradiated the plasma on and transverse to the axis of symmetry of the electrodes and at a mean distance of 12.5 mm from the

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anode. The laser beam is focussed down to 3 mm diameter, which is
somewhat larger than the mean diameter of the pinch so as to accommo-
date variations in the location of the dense pinch from one dis-
charge to another. Scattered light is collected at 45° (θ) to the
incident beam as illustrated in figure 1. When the correlation
parameter $\alpha = (K \lambda_D)^{-1} > 0.5$ ($K = 4\pi \sin \theta/2 . \lambda_o^{-1}$, is the
scattering wave number; λ_o is the laser wavelength; and λ_D the
debye length) we expect the scattered spectrum to be determined by
density fluctuations due to the ion motion with frequency shifts
given by $\Delta\omega = K\bar{v}_i$. In the case that the ion motion is random, $\bar{v}_i$
is the mean velocity of the Maxwellian distribution, and the wave-
length shift is

$$\Delta\omega = 2 \sin \theta/2 \left(\frac{2k \, T_D}{M}\right)^{\frac{1}{2}} \frac{\lambda o}{c} \quad .$$

Thermal motion of the ions at temperatures of 1 keV or higher, give
rise to spectral shifts $\Delta\lambda \geq 6 \overset{\circ}{A}$, and an echelle grating spectrograph
is an appropriate instrument to analyse the scattered light, figure 1.
The total spectrum is recorded during the laser pulse by means of
fibre optic channels each recording over a wavelength interval of
1.8 $\overset{\circ}{A}$ units. Using this optical arrangement parasitic scatter
at the laser frequency has been found to be negligible.

3. THE SCATTERED SPECTRUM
FROM A NEON-DOPED DEUTERIUM PLASMA

Figure 2 shows the scattered light signals from the dense pinch
of Plasma Focus operated in deuterium with 4% neon added by volume.
The scattered spectrum is recorded mainly during the dense

pinch phase of the Focus. The time-history of the pinch, its
formation and break-up relative to the neutron and the thermal X-ray
emission has been described previously, Peacock et al (1971). It
is worth bearing in mind, with a view to the interpretation of the
results, that the dense pinch phase lasts $\sim$ 40 nanoseconds at the
end of which period the neutron emission has almost reached a
peak in intensity. The scattered light spectra shown in figure 2
corresponds to the time at which the current sheath first meets the
axis of symmetry (peak compression) and + 20 nanoseconds later.
Following Evans (1970) the form factor for the scattered spectrum S
(K, ω), has been calculated for a wide range of the parameters α,
T_e, T_D, T_{Ne}, % Ne. It is clear from a comparison of the calculated
form factor with the results shown in figure 2 that the spectrum
has a double-humped shape, symmetric about the laser frequency, and
this is characteristic of co-operative scattering with $T_e/T_D > 1$,
Farley (1971). The error bars in figure 2 represent an average
of the background noise fluctuations. The ion term contribution to
the form factor for the scattered spectrum can be expressed in terms
of the parameter,

$$\beta = \left[\frac{\alpha^2}{(1 + \alpha^2)} \frac{T_e}{T_D} \right]^{\frac{1}{2}} ,$$

neglecting for the moment the impurity contribution. By comparison
of the results in figure 2 with theoretical form factor curves,
Evans and Katzenstein (1969), β must lie between 1 and 2.

Best-fit curves to the experimental points show that over a
range of the correlation parameter, $1 < \alpha < 10$, the peaks are dis-
placed by a frequency $\Delta\omega = \pm 1.6 \, Kv_i$, where v_i is the mean velocity

of the deuterium ions at a temperature between 0.7 and 1.0 keV. For one set of experimental points, a best fit to the calculated spectrum is found for the following plasma conditions; 4% neon by volume, $N_e = 2 \times 10^{19}$ cm^{-3}, $T_e = 2.25$ keV, $T_D = 0.7$ keV and $T_{Ne} = 9$ keV. From the best fit parameter values above, $\beta = 1.39$ and $\alpha = 1.83$ are derived for the form factor and the correlation parameter respectively.

4. THE NEON ION TEMPERATURE

It is interesting to note that to account for the energy in the far wings of the observed spectrum, the neon ion temperature has to be at least an order of magnitude higher than that of the deuterium ions. This conclusion had been reached in a previous publication, using quite an independent approach to the problem, Peacock, Hobby and Morgan (1971). An analysis of the profiles of the NeX emission lines in the x-ray region has shown that the source function is doppler-broadened with an equivalent mean temperature of 9 keV during the dense pinch phase. This is in extremely good agreement with the neon ion temperature derived from the scattered light spectrum.

5. THE ELECTRON PARAMETERS

The electron parameters during the dense pinch have been sufficienctly well-documented in previous work, Peacock, Hobby and Morgan (1971), Morgan and Peacock (1972), to stand comparison with the data derived from S (K, ω).

Interferometric measurements in a plasma with 4% doping of argon show that the average density across the pinch colum is 8×10^{18} cm^{-3} with a peak density on the axis of symmetry of

3.5×10^{19} cm^{-3}. These values vary of course with operating conditions, with location in the pinch and from one discharge to another.

The electron temperature has been measured to be 2.0 keV $\pm$ 0.5 keV from the free-bound (Ar^{+18}, Ar^{+17}) continuum emission in the X-ray region and from the intensities of the lines of Li-like ions which are satellite to the He-like ion resonance lines in ionised argon, Peacock and Hobby (1973). These electron parameter values are also in remarkably good agreement with those derived from S (K,ω). Inserting them in the expression for the coherence parameter gives a value for α between 1 and 2, and the spectrum should, as is observed, be dominated by the ion motion.

For values of $T_D < T_e$, the spectrum should have peaks displaced approximately at $\omega \sim \omega_{ac}$, where ω_{ac} is the ion-acoustic frequency.

$$\omega_{ac} = K \left[(2 \ k \ T_e)/M_i \right]^{\frac{1}{2}}$$

$\sim 2.5 \times 10^{12}$ rad sec^{-1} for our experiment. This is within a factor of two of the observed frequency spread. From the ion shape factor alone it is difficult to judge therefore whether density fluctuations due to random motion of the ions are responsible for the scattered light or whether there is a supra-thermal energy content in the plasma. In the latter case, the effective scattering cross-section is

$$\sigma_s \ (K,\omega) = \ < \delta \ N_e^2 \ (K,\omega) > \ /N_e = S \ (K,\delta) \ \sigma_e \ ,$$

will be greater than the Thomson cross-section, σ_e. The total

scattered light intensity $S(K) = \int S(K,\omega) . d\omega$ is therefore a significant quantity and may be calculated, see for example, Evans (1970). The scattered light flux incident on the entrance slit of the spectrometer has been calculated after calibration of the spectrometer for absolute sensitivity using a standard lamp and after calibration of the incident laser pulse with a calorimeter. The scattered light flux corresponds to that from a thermal body of plasma, the total number of irradiated electrons viewed by the spectrometer being 1.0×10^{17}. This value compares with interferometric estimates (Morgan and Peacock, 1972) which are 5.3×10^{16} when the plasma compression front first meets the axis of symmetry to 2.0×10^{17} some 30 nanoseconds later. Since the experimental arrangement did not allow synchronous scattering and interferometry, large statistical variations, (of the order of four) in the local density, can be expected from one discharge to another. The error in the measurement of density from the absolute scattered signal is likely to be of the order of $\pm$ 50%. Considering the favourable agreement between the two estimates for the number of scattering electrons and the relatively large possible errors involved, it can be concluded that during the dense pinch the scattered light level is characteristic of a near-thermal plasma.

There is some evidence for more intense scattering, perhaps a factor of 2 or 3 above thermal, at times later than $\pm$ 50 nanoseconds, figure 3, i.e. during the late time-history when the pinch breaks up. These spectra retain the double-humped characteristic for $S(K,\omega)$ but have a higher peak to valley ratio indicating an increase in T_e/T_D. However, the theoretical profiles, which assume thermal distributions of the various particle species, do not provide a good

fit to these experimental points. For any realistic value of the
neon ion temperature, T_{Ne}, and for T_e/T_D fixed by the peak to valley
ratio, there is an excess of energy in the far wings of the spectra.
The intensities of these later profiles are cited therefore with the
caution that it is not altogether meaningful to compare the observed
intensities with those from a thermal plasma, the parameters of which
are inadequately known.

6. CONSEQUENCES OF A THERMAL MODEL

On a thermal model then, the energies of the separate ion
species, Peacock, Hobby and Morgan (1971) are found to scale as

$$\varepsilon \ (Z/M) = 1.5 \ (\frac{Z}{M})^{2.1} \ .$$

The approximation to a Z^2/M scaling is consistent with some level of
turbulence in the plasma.

This postulate has several immediate consequencies. Firstly
the intensity of the scattered light should exceed that from a
thermal plasma. We have shown however, that the scattered light
level is, within fairly large statistical errors, appropriate to
that of a thermal plasma. Nevertheless, in view of the errors
involved let us postulate a level of turbulence perhaps with an
energy content a factor of two higher than the plasma kinetic energy;
then it is appropriate to examine the mechanism by which the energies
and the different ion species remain separate. The deuterium ion
temperature is seen for example to be an order of magnitude less
than that for neon. The energy relaxation time between these
particles τ_{D-Ne} is readily calculated to be 0.9 nanoseconds. The
rate of loss of energy from the neon ions is therefore,

$$\int\limits_{}^{\text{Vol}} \varepsilon \cdot \frac{N_{Ne}}{\tau_{D-Ne}} \quad dV \quad ,$$

where ε for neon is approximately 10 keV. This amounts to 6 joules/
nanosecond in comparison with a total kinetic energy in the plasma
of about 60 joules. The energy drain from the rare gas ions could
therefore be supported by turbulence whose energy content is a
factor of two or so higher than thermal. On the other hand the
doubling time for the deuterium ion temperature is only 2 nanoseconds
and one has to invoke a rapid energy loss rate, τ_{D-loss}^{-1}, for the
deuterium ions so that their temperature remains at around 1 keV.
In the steady state, energy balance gives

$$\frac{\varepsilon_D \, N_D}{\tau_{D-loss}} \underset{\sim}{} \frac{\varepsilon_{Ne} \, N_{Ne}}{\tau_{D-Ne}} .$$

Inserting the experimental values for $\varepsilon_D/\varepsilon_{Ne} \sim 0.1$ and $\frac{Ne}{N_D} = 0.02$,
we have $\tau_{D-loss} = 4$ nanoseconds.

This loss mechanism has not been identified but the time
corresponds approximately to the local m = 0 instability growth time
in the pinched plasma.

7. ALTERNATIVE INTERPRETATIONS TO THERMAL MODEL

There are alternative explanations to the scattered spectrum
and these have to be considered.

The finite transit-time of the electrons in a bounded plasma
can result in frequency broadening as pointed out by Pechacek and
Trivelpiece (1967). At a temperature of 3 keV a plasma dimension
of the order of 100 microns would be required to explain the observed

broadening by electron transit-time effects. Although plasma structure of this scale length has been observed in the Focus, Peacock et al (1971) the mean diameter of the irradiated plasma is more, nearly 2 or 3 mm, and scattering occurs everywhere inside this wider region. Only that component of the collective electron motion which follows the drift of the ions is responsible for the observed spectrum in the present experiments. The thermal velocity of the ions cannot therefore give rise to appreciable transit-time broadening for any realistic plasma dimensions.

Scattering from plasma boundaries, moving with velocity U_f will give rise to frequency shifts of the scattered spectrum up to

$$\Delta\omega_s = \pm \ \overline{K}.\overline{U}_f \ .$$

Time lapse, nanosecond, transmission photography of the imploding plasma shell, Peacock et al (1971) indicates that U_f is between 2 and 3×10^7 cm sec^{-1}, i.e. of the right order to explain the frequency shift in the scattered light spectrum. Since the ion species with different charge/mass ratios (Z/M) have a common velocity U_f in the plasma shell, their energies due to mass motion will scale as

$$\epsilon \ (Z/M) \ \alpha \ M \ .$$

Taking a mean value of 0.7 keV for the deuterium ion energy and $U_f = 2.65 \times 10^7$ cm sec^{-1}, then for neon, ϵ (10/20) = 7 keV, and for argon, ϵ(17/40) = 14 keV. These values are just outside the probable errors of the ion energies derived from X-ray profile measurements, Peacock et al (1971). Scattering from moving plasma

fronts appears at first sight therefore to be a plausible explanation.

A consideration of the geometry of the imploding plasma in our experiments (Morgan and Peacock, 1972) and of the number of scattering electrons which contribute frequency shifts $\underset{\sim}{\simeq} \bar{K}_o . \bar{U}_f$, shows that, due to mass motion, $S(K,\omega)$ should change with the radial position of the plasma. The shape factor, figure 3, remains remarkably constant however before, during and even after the formation of the dense pinch. A hump at $\Delta\omega = 1.6 \ KU_f$ cannot be produced by purely radial plasma motion. Furthermore, radial implosion velocities will have randomised well within the duration of the dense pinch, which is of the order of 40 nanoseconds. The explanation for $S(K,\omega)$ based on scattering from a near-thermal, quasi-static plasma is therefore to be preferred.

8. THE SCATTERED SPECTRUM FROM A PURE DEUTERIUM PLASMA

The scattering experiments were repeated in a deuterium plasma at 3 torr pressure with no rare gas addition. This 'pure' deuterium plasma was found to be considerably less reproducible and it was not possible to obtain a comprehensive time sequence for the scattered light profiles. As illustrated by the two examples shown in figure 4, the spectrum has now quite a different form factor from that of the neon-doped plasma. The flat-topped and bell-shaped symmetry about the laser frequency is characteristic of $T_e/T_D \leq 1$. Best fit curves to the experimental points give deuterium ion temperatures between 2 keV and 3 keV, figure 4, depending on the time of observation of the dense pinch. The intensity of the scattered light from the pure deuterium plasma is a factor of about two above that from a thermal plasma.

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9. DISCUSSION AND CONCLUSIONS

While there is a firm base of direct measurements of the electron parameters in the dense pinch, Morgan and Peacock (1972), Peacock and Hobby (1973), with which the scattering results can be compared, and satisfactory agreement obtained, the same is not true for the deuterium ions. It is of interest however to compare the deuterium temperature derived in this paper with ab initio calculations using a 2-D fluid code, Potter (1971). Using the same Focus geometry, but with a slightly lower filling pressure of pure deuterium, the ion and electron temperatures during the pinch are computed to have closely similar values, around 1.6 keV. These calculated particle temperatures are in reasonable agreement with the parameters derived from scattering during the middle of the dense pinch phase, figure 4, lower curve.

However, in deuterium doped with neon, the deuterium temperature is _less_ than that predicted by these computations and is a factor of almost three less than the electron temperature and a factor of about ten less than that of the neon ions. While the code has not been run for exactly these gas filling conditions it is not apparent why this situation should arise except perhaps if there is turbulent heating as suggested in section 6.

In a doped plasma also, the neutron emission from the dense pinch has been estimated, Peacock et al. (1972), as

$$\gamma_n = <\sigma v>^{DD}_{\cdot} \cdot \tau_{pinch} \cdot \int_o^R \int_o^z \pi r \cdot n_D^2 (r) \, dr \cdot dz.$$

where $<\sigma v>$, the fusion reaction rate, is a sensitive function of temperature and where R, z are the radial and axial dimensions

of the cylindrical pinch. In order to account for all the total
neutron emission on this basis, the deuterium ions must have a
minimum temperature of 3.5 keV. But, using the value for T_D
derived from scattering in a doped plasma, only a small fraction,
of the order of a few percent of the total emission, can be due to
thermonuclear reactions in the pinch. Maisonnier (1972) has proposed
a model in which the bulk of the fusion reaction takes place by
thermonuclear collisions during the break-up of the pinch. Whether
this would hold for our geometry and operating conditions is
an open question.

Bernard et al (1971), (1972), have also observed light
scattered from a less-powerful Focus at 90° ($\alpha < 1$) and at 7° ($\alpha \gg 1$)
to the incident laser. An analysis of their results shows that the
scattering vectors lie in the plane which includes the current and
is orthogonal to that chosen for the present work. Bernard's
spectra indicates that, contrary to our results, the ion form factor
$\beta < 1$ and that $T_e/T_D \gtrsim 1$, with ion temperatures even lower than
those reported here.

Finally, the significance of the present results is that the
collective scattered light spectrum from plasmas with ion tempera-
tures of 1 keV or more has been measured. The effect of different
ion components in the plasma can be accounted for quantitatively
following theoretical predictions, Evans (1970). The temperature of
the rare gas ions agrees with that derived from x-ray line profiles.
The electron parameters derived from the scattered light spectrum
and assuming a thermal plasma are in good agreement with those
derived previously using quite different measuring techniques.

Acknowledgement

REFERENCES

BERNARD, A. and CESARI, G. et al, (1971) Plasma Physics and Controlled Fusion Research, Vol. 1, pp. 553-560. Published IAEA Vienna.

BERNARD, A. et al (1972) Proc. 2nd Topical Conf. on Pulsed High Beta Plasmas. Paper E1. Published by Max-Planck-Inst. Garching IPP 1/127 July 1972.

EVANS, D. E. (1970) Plasma Physics, Vol. 22, pp. 573-584.

EVANS, D. E. and KATZENSTEIN, J. (1969). Reports on Progress in Physics 32 No. 2, 207-271.

FARLEY, D. T. (1971) Methods of Experimental Physics. Vol. 9, Plasma Physics, Part B, p. 139-186. Editors, Loveberg and Griem. Published by Academic Press.

MAISONNIER, Ch. et al (1972) Proc. 5th Eur. Conf. Controlled Fusion. Vol. II. pp 183. Published CEA Grenoble.

MATHER, J.W. (1965) Physics Fluids 8, pp 336-377.

MORGAN, P.D. and PEACOCK, N.J. (1972). Proc. 2nd Topical Conf. on Pulsed High Beta Plasmas. Paper E9. Published by Max Planck Inst. Garching I.P.P. 1/127 July 1972.

PEACOCK,. N.J., HOBBY, M.G. and MORGAN, P.D. (1971) Plasma Physics and Controlled Fusion Research, Vol. 1, pp. 537-551. Published IAEA Vienna.

PEACOCK, N.J. et al (1972) Proc. 5th Europ. Conf. on Controlled Fusion and Plasma Physics. Vol. 1, pp. 66. Published CEA - Grenoble.

PEACOCK, N.J. SPEER, R.J. and HOBBY, M.G. (1969). J. Phys. B. 2, p. 798-810.

PEACOCK, N.J. and HOBBY, M.G. (1973) to be submitted to J. Phys. B.

PECHACEK, R.E. and TRIVELPIECE, A. W. (1967) Phys. Fluids 10, No. 8 1688-1696.

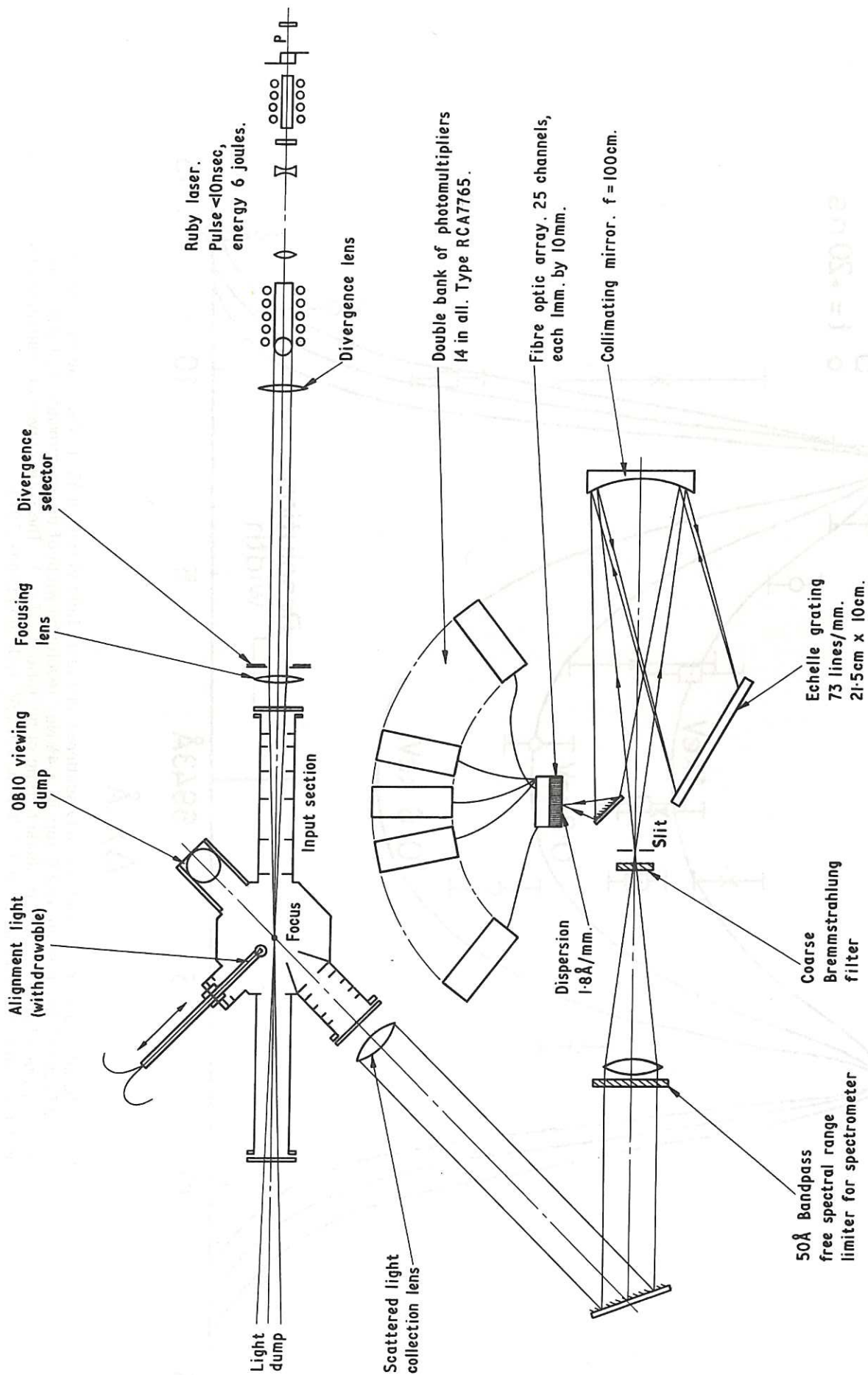POTTER, D.E. (1971) Physics Fluids Vol. 14, No. 9, pp. 1911-1924.

Fig. 1 Schematic of optical arrangement for measuring collective spectrum of light scattered at 45° from a ruby laser beam incident on the Plasma Focus. The incident beam and viewing optics lie in a plane transverse to the axis of symmetry of the Focus.
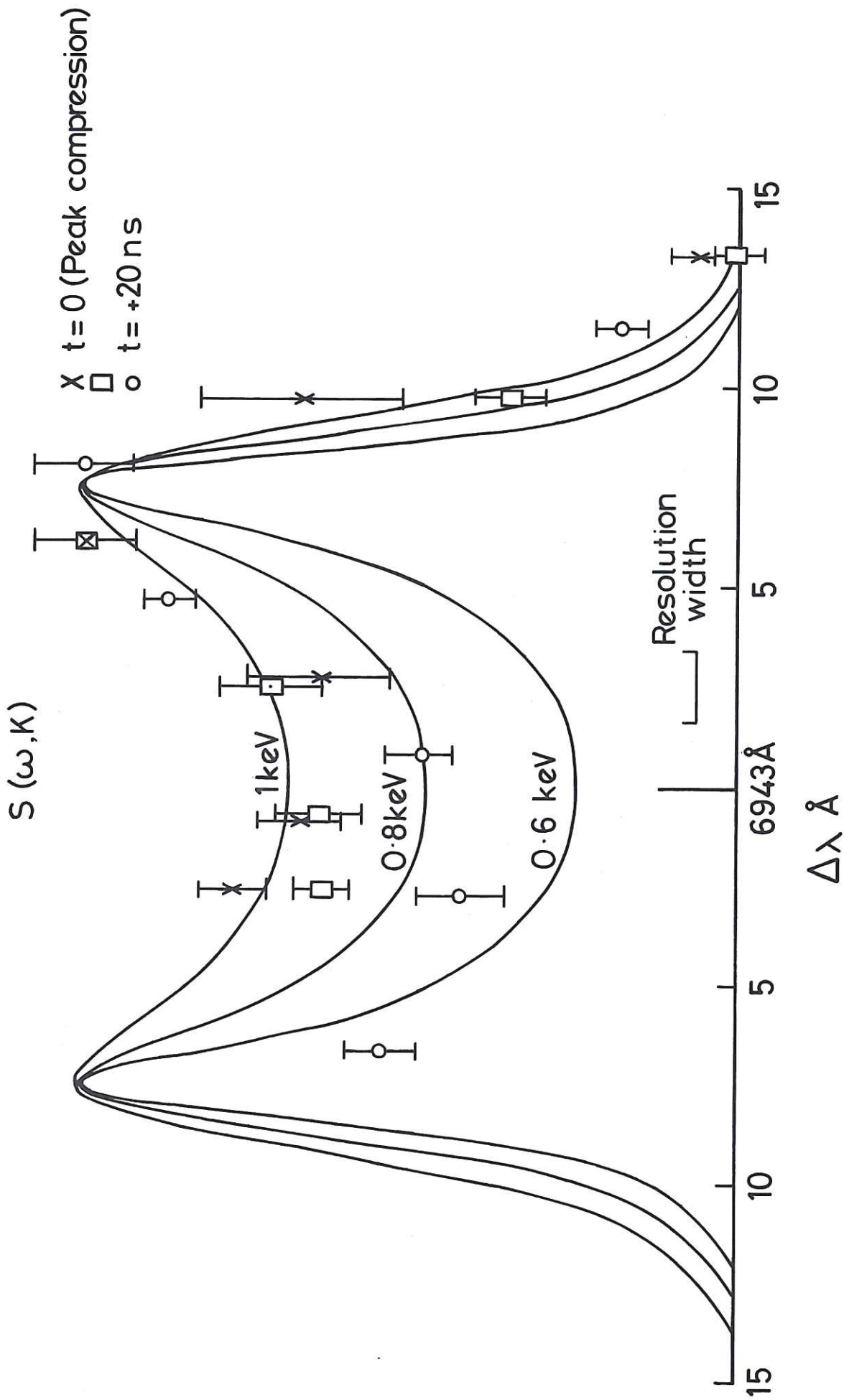
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Fig. 2 Spectra, $S(\omega, K)$ of co-operatively scattered ruby laser light viewed at 45° to the incident beam. The Plasma Focus filling pressure is 2.5 Torr D_2 + 4%Ne; resolution width of the spectrometer is 1.8 Å. The double-humped form of $S(\omega, K)$ is characteristic of the ratio $T_D/T_e < 1$. The solid curves are calculated for deuterium ion temperatures, T_D, of 0.6, 0.8 and 1.0 keV, following Evans (1970).
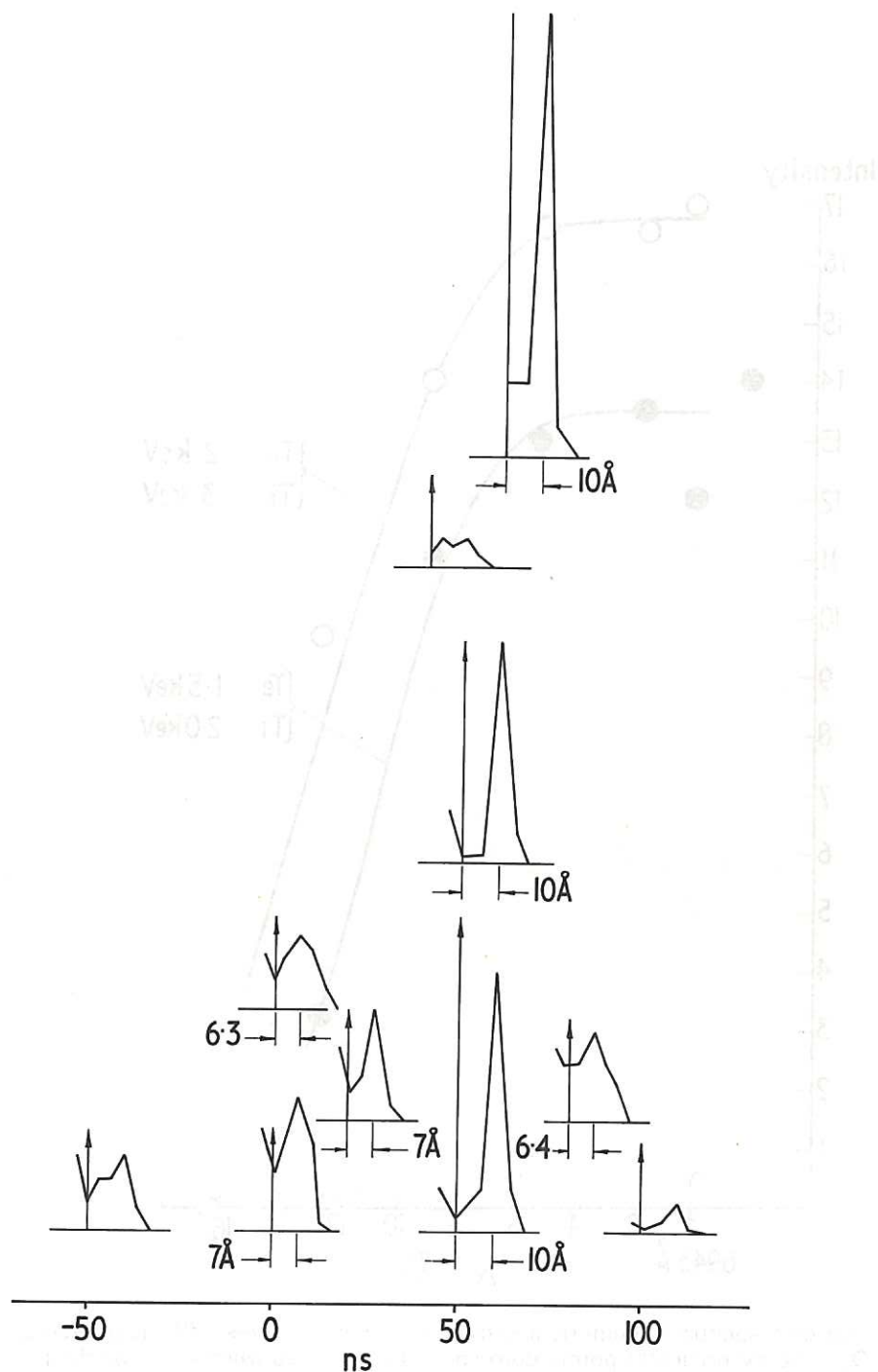
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Fig. 3 Scattered spectra from several separate discharges. Each spectra is taken at a different time during a Focus discharge. Time zero refers to the moment when the imploding shock meets the axis of symmetry of the Plasma Focus.
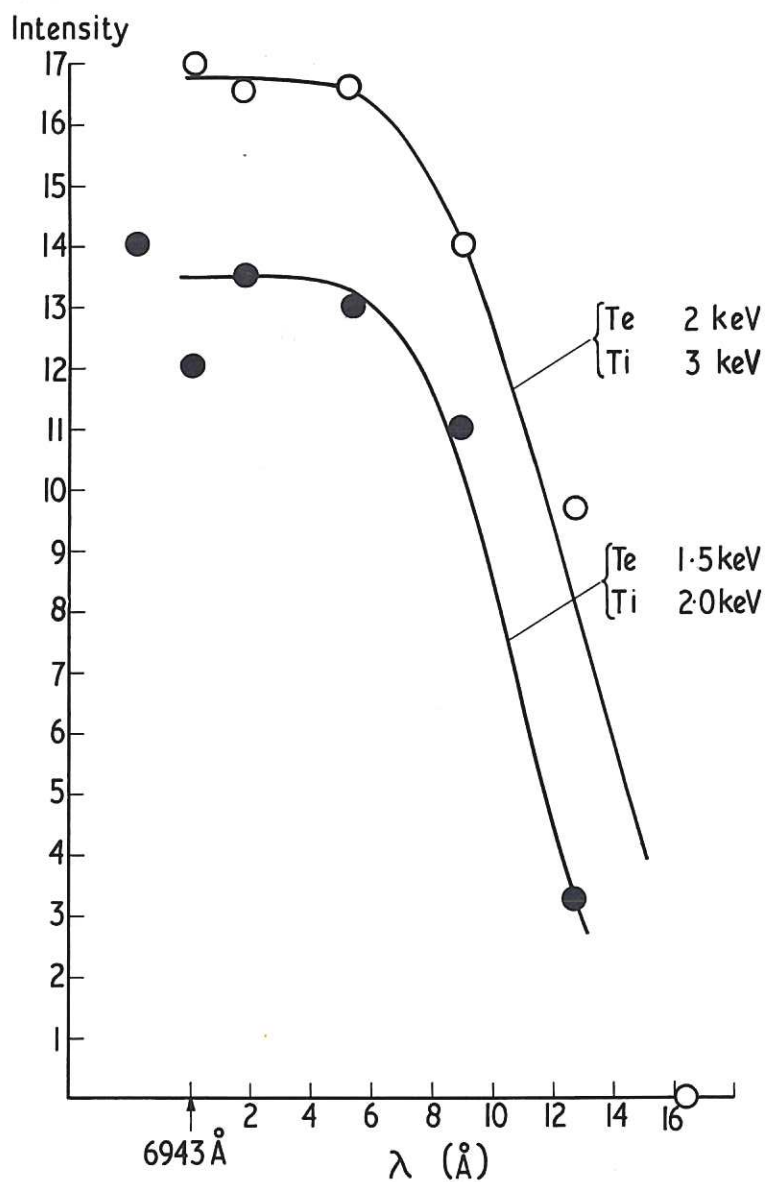
Fig. 4   Scattered spectra in deuterium with no rare gas additives; filling pressure,
3.0 Torr D_2. The experimental points correspond to the times when the imploding
shock reaches the axis of symmetry (upper set) and 30 nanoseconds later (lower set).
The solid curves are calculated for the values of electron and ion temperature indicated,
following Evans (1970).