June 1973 LRP 64/73

A LINEAR RF TURBULENT HEATING EXPERIMENT

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We consider here how one might change the rf experiment to try to produce hot, turbulent plasmas and also the feasibility of investigating the turbulence using the (CO_2) laser scattering technique.

A. General Considerations

The scheme for the experiment is simply to have a large rf current flowing in the plasma along the direction of a steady magnetic field.

Although it is difficult to predict the behaviour in a turbulent heating experiment, we have some guidance in what to expect from the results of somewhat similar experiments. A few years ago one might have dismissed such a proposal for heating a plasma from skin depth considerations. The classical skin depth for a hot, effectively collisionless plasma is only

$$\delta_c = c/\omega_{pe} = .05 \text{ cm}$$

at a plasma density of $n = 10^{20}\ \text{m}^{-3}$. However it is found in a number of experiments that the actual skin depth is more like

$$\delta \lesssim \delta_i = c/\omega_{pi}$$

which gives δ_i = 2 cm for a hydrogen plasma at $n = 10^{20}\ \text{m}^{-3}$. This behaviour, observed at densities $n \gtrsim 10^{20}\ \text{m}^{-3}$ in such experiments as Janus and Omega (Efremov Institute, Leningrad), NPR-2 (Kurchatov), Columbus 4 (Los Alamos), Tarantula (Culham), is discussed by Dubovoi et al. (1971).

The explanation of the large skin depth has been given by Breizman et al. (1970) and others. According to this explanation the electron drift velocity u cannot increase indefinitely. When it exceeds a critical velocity u_c ion acoustic waves begin to grow and this leads to an anomalous resistance which limits the drift velocity. At the same time the electrons are heated. Assuming (1) $u \sim u_c \sim c_s = (\kappa T_e/m_i)^{\frac{1}{2}}$ for $T_e \gg T_i$, and (2) negligible loss or transport of thermal energy, it can be shown that Maxwell's equations lead to the following relation for the externally applied electric field near the surface of a (one-dimensional) plasma

$$\frac{\partial^2 E}{\partial x^2} \sim \frac{\omega_{pi}^2}{c^2} E$$

Thus the skin depth is $\delta \sim c/\omega_{pi}$.

This kind of behaviour can also be expected in an rf experiment, and there is evidence for this from the Omega ($I_{rf} \sim 1$kA ; $\omega/2\pi = 1{\cdot}7$ MHz ; $n \sim 10^{20}$ m^{-3}) and Janus ($I_{rf} \leq 30$ kA ; $\omega/2\pi = 0.4$ MHz ; $n \sim 2 \times 10^{20}$ m^{-3}) experiments, as long as

$$\omega << \gamma$$

where $\gamma (\lesssim \omega_{pi})$ is the growth rate of the ion acoustic instability. For example at $n = 10^{20}$ m^{-3}, $\omega_{pi} = 1.3 \times 10^{10}$ sec^{-1} (hydrogen plasma) and it seems that the present frequency of the Lausanne rf generator, $\omega = 2\pi \times 2.7 \times 10^6$ sec^{-1}, should be sufficiently low. Reduction to half this value can be made without much difficulty (Lietti 1973) and may be advantageous.

Suppose now that we have an experiment which is current-limited or constant-current-amplitude as is the case in an rf discharge when the constant inductive reactance $\omega L > R$ the resistance. Then the current is

$$I = n e u A_{eff}$$

and

$$u \sim (K T_e / m_i)^{1/2} = \frac{I}{n e A_{eff}}$$

where $A_{eff} \sim 2\pi r \delta_i$ is the effective cross section for the current flow. Thus as the current turns on u increases to u_c . Then ion acoustic waves grow, limiting u to approximately u_c , but at the same time electron heating takes place up to a temperature T_e limited by the current. This estimate of T_e is only very rough because of uncertainty in u and A_{eff}. We can do a little better by making use of another experimental fact. First let us rearrange the above expression

$$I = n e \frac{A_{eff}}{A} A \frac{u}{c_s} \sqrt{\frac{K T_e}{m_i}} ; \qquad A = \pi r^2$$

$$T_e = \frac{I^2}{n^2 e^2 \pi^2 r^4} \frac{m_i}{K} \left(\frac{A}{A_{eff}} \frac{c_s}{u} \right)^2 = \frac{I^2}{n K \pi^2 r^4 \epsilon_0 \omega_{pi}^2} \left(\frac{A}{A_{eff}} \frac{c_s}{u} \right)^2$$

$$= \frac{\mu_0 I^2}{n K \pi^2 r^2} \left(\frac{\delta_i}{r} \frac{A}{A_{eff}} \frac{c_s}{u} \right)^2$$

where r is the radius of the plasma column.

Information on the quantity in brackets can be obtained from the experimental result that

$$\beta_p = \frac{n K T_e}{B_\theta^2 / 2\mu_0} \sim 1$$

where

$$B_\theta = \frac{\mu_o}{2\pi} \; \frac{I}{r}$$

is the magnetic field of the plasma current. In some rf experiments (Janus, Berezin et al. 1972) β_p = 1 has been found; in the Omega experiment (Dubovoi et al. 1971) $\beta_p >$ 1. In recently reported pulsed current experiments on the other hand (Dubovoi et al. 1972) $\beta_p \sim$ 0.3 was found. Taking β_p = 1 as typical we have

$$T_e \sim \frac{\mu_o I^2}{8\pi^2 r^2 n K}$$

Comparison with the previous expression for T_e indicates

$$\frac{\delta_i}{r} \; \frac{A}{A_{eff}} \; \frac{c_s}{u} \sim \frac{1}{\sqrt{8}}$$

We probably should not look for new physics in the experimental result that $\beta_p \sim$ 1. At first sight, it seems to be a pressure balance condition but we note that there is an axial magnetic field $B_z (> B_\theta)$ in the experiments so pressure balance does not require β_p = 1. Evidently this result is just another expression of the physics discussed above. For example, substituting $A_{eff} = 2\pi r \delta$ where δ is the actual experimental skin depth we have

$$\frac{\delta_i}{r} \; \frac{\pi r^2}{2\pi r \delta} \; \frac{c_s}{u} \sim \frac{1}{\sqrt{8}}$$

$$\frac{1}{2} \; \frac{\delta_i}{\delta} \; \frac{c_s}{u} \sim \frac{1}{\sqrt{8}}$$

So the result $\beta_p \sim 1$ is consistent with $\delta \lesssim \delta_i$ and $u \gtrsim c_s$ and serves only to specify their values somewhat better.

We now have some idea of the electron temperature. The ions should be heated as well, due to the fluctuating electric field of the turbulence and/or electron-ion collisions. However as $T_i \rightarrow T_e$ ion Landau damping becomes important and tends to turn off the ion acoustic instability. Thus we might expect T_i to level off at a value somewhat below T_e. In fact one experiment (Berezin et al. 1972) shows a final temperature ratio

$$(T_i/T_e)_{obs} \sim \frac{1}{5} .$$

For the observed electron drift velocity

$$(u/c_s)_{obs} \sim \frac{1}{4}$$

this corresponds to the threshold for the ion acoustic instability.

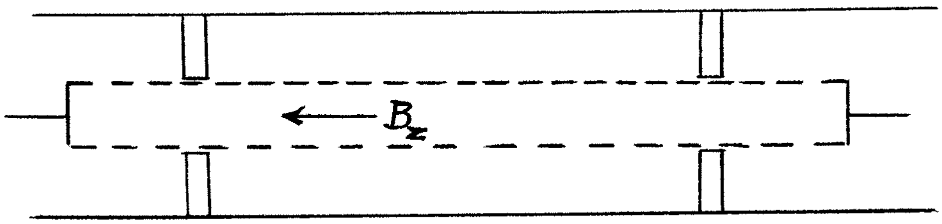
Assuming the same temperature ratio in the Lausanne experiment we might expect plasma temperatures determined by the current and Column radius according to the following table. The plasma density is assumed to be $n = 10^{20}\ m^{-3}$.

Table I

I (kA)	r (cm)	T_e (keV)	T_i (keV)	$(W_{th})_{Max}$ (joules)
20	2.5	0.64	0.13	36
20	1.5	1.8	0.36	36
40	2.5	2.6	0.52	144

The thermal energy content $(W_{th})_{Max}$ has been calculated assuming uniform temperature and density throughout the plasma column. In any case it is not large. For available rf power of $\sim$ 100 MW these temperatures could be reached in t $\sim$ 1 μsec, i.e. within a few cycles of the rf current.

It should be possible to see if a hot, turbulent plasma can be produced without modifying the present rf experiment too drastically. One could first try to form a plasma at $n \sim 10^{20}$ m^{-3} in hydrogen at a pressure of a few microns. The column size could



be limited with the aid of quartz diaphragms and an axial magnetic field $B_z \sim$ 3-5 kG (large enough so that the ion Larmor radius is small compared with the column size). The z-rf circuit could be modified (Lietti 1973) to give $I_z \sim$ 20 kA through the plasma load of inductance $L \sim$ 250 nH.

The diagnostics in this preliminary experiment should include measurement of the discharge voltage and current, the plasma density n, electron temperature T_e, and the magnetic fields $B_\theta(r)$ and $B_z(r)$. From such measurements one could find out if the macroscopic behaviour is as expected and (a) heating occurs (b) $u \sim c_s$ (c) $\delta \sim c/\omega_{pi}$. From the measured anomalous resistance one could also estimate the level of turbulence (discussed below).

B. CO_2 Laser Scattering Measurements

If the results of this first experiment were positive, they would still not be very new since other experiments have already demonstrated such behaviour. The real chance to make an original contribution comes in studying the turbulence itself and relating it to such quantities as the rate of heating and conductivity. In the Leningrad experiments for example it is believed that ion acoustic turbulence is responsible for the heating and anomalous skin effect but no information is available on the frequency or wavelength of the fluctuations. Ideally one should measure the spectral intensity

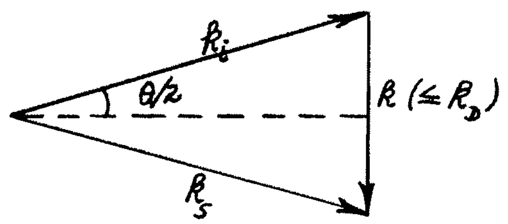
$$E^2(\omega, \vec{k})$$

of the fluctuating electric field. This has not yet been done satisfactorily in any turbulent heating experiment. Perhaps Paul and coworkers at Culham (Daughney et al. 1970; Paul et al. 1971; Paul et al. 1969) have come closest, in their ruby laser scattering experiments on the Tarantula device. However, the k-values investigated so far only cover the range from k_D ($= \lambda_D^{-1}$, the Debye wave number) down to $k_D/1.6$.

It seems that scattering measurements with the CO_2 laser could be used to obtain information on the spectrum of ion acoustic turbulence in the Lausanne experiment. According to the momentum and energy conservation laws, a laser beam $(\vec{k}_i, \omega_i)$ scatters from a plasma wave $(\vec{k}, \omega)$ to give

$$\vec{k}_s = \vec{k}_i \pm \vec{k}$$
$$\omega_s = \omega_i \pm \omega$$

We are interested in knowing first whether the $\vec{k}$ and ω shifts can be resolved and secondly whether the scattered signal is of sufficient intensity to be easily detectable. With regard to the first question the use of a CO_2 laser makes it desirable to work at somewhat higher densities than the value $n = 10^{20}\ m^{-3}$ assumed for Table I. If we take $n = 3 \times 10^{20}\ m^{-3}$, for example, then $T_e \rightarrow 0.2$ keV for I = 20 kA and r = 2.5 cm. We then have $k_D = \lambda_D^{-1} = 1 \cdot 6 \times 10^5\ m^{-1}$; for the CO_2 laser $k_i = 2\pi / \lambda_i = 6 \times 10^5\ m^{-1}$.



Thus from the scattering diagram (shown for the case $\vec{k}_s = \vec{k}_i + \vec{k}$) we find that we can expect scattering angles up to

$$\theta_{Max} = 2 \sin^{-1} \frac{k_D}{2 k_i} = 15^\circ$$

By choosing scattering angles from $\sim 15^\circ$ down to some resolvable lower limit (4 or 5° say) one could cover a range of k-values from k_D to $k_D/3$ or $k_D/4$.

The frequency shift of the scattered radiation is in the range (for $k_D/4 \lesssim k \lesssim k_D$, and assuming the dispersion relation $\omega/k = (\omega_{pi}/k_D)(1 + k^2/k_D^2)^{-\frac{1}{2}}$)

$$\frac{\omega_{pi}}{4} \lesssim \omega \lesssim \frac{\omega_{pi}}{\sqrt{2}}$$

where $\omega_{pi} = 2 \cdot 3 \times 10^{10}\ sec^{-1}$ for a hydrogen plasma and $n = 3 \times 10^{20} m^{-3}$. The corresponding wavelength shift is

$$\frac{\lambda_M}{2\sqrt{2}} \lesssim \Delta\lambda \leq \Delta\lambda_H$$

$$\frac{\Delta\lambda_H}{\lambda} = \frac{\lambda}{c}\, \Delta f_H = \frac{10 \cdot 6 \times 10^{-6}}{3 \times 10^8} \times \frac{2 \cdot 3 \times 10^{10}}{\sqrt{2} \times 2\pi} = 0.9 \times 10^{-4}$$

This is comparable with the shift that the group at Culham hopes to observe in a CO_2 laser scattering experiment presently underway on the Tarantula device.

Use of the linear dispersion relation implies a δ-function shape for the frequency spectrum $E_k^2(\omega)$ at a given value of k. Nonlinear effects can lead to finite breadth however and it is therefore of considerable interest to have good measurements of the frequency spectrum. No such measurements have been made so far although Paul et al. (1970) have observed a finite breadth for the spectrum, contrary to the theory of Kadomtsev (1965), even though their measured k-spectrum (integrated over frequency) appears to agree with the Kadomtsev theory.

Finally we would like to know if the level of turbulence will be sufficiently high to give an easily measurable scattered signal. Since we cannot predict the level of turbulence in the Lausanne experiment, let us assume the value found in the Janus experiment (Berezin et al. 1972)

$$\frac{W_E}{W_{th}} \simeq 10^{-4}$$

where W_E is the energy density in the electric field of the fluctuations and $W_{th} = \frac{3}{2}\, n\, \kappa T_e$. This value was found both by measuring the effective collision frequency

$$\nu_{eff} \sim \omega_{pe} \frac{W_E}{W_{th}}$$

and by measuring the Stark shift of H_β lines in hydrogen due to turbulence whose spectrum has not been measured but which is believed to be due to the ion acoustic instability.

The differential scattering cross section per electron is determined by the Fourier transform of the electron density fluctuation (Paul et al. 1969; Bekefi 1966)

$$\sigma_s(\omega, k) = \frac{\langle n_e^2(\omega,k)\rangle}{n} \sigma_T = S(\omega,k)\sigma_T$$

where

$$\vec{k} = \vec{k}_s - \vec{k}_i \quad , \quad \omega = \omega_s - \omega_i \ , \ \text{and } \sigma_T$$

is the Thomson cross section. Integrating over frequency at a given value of k gives

$$\sigma_s(k) = \frac{\langle n_e^2(k)\rangle}{n} \sigma_T = S(k)\sigma_T$$

For a stable, homogeneous plasma with $T_e \gg T_i$, $S(k) \leq 1.0$. For a turbulent plasma S(k) can be larger however. We want to determine its value in terms of the level of turbulence. To do this we need to relate $\langle n_e^2(k)\rangle$ to $\langle E^2(k)\rangle$. For an ion acoustic wave (ω, k) the balance between kinetic and potential (electrostatic and pressure) energy gives

$$W_K = W_P + W_E$$

where

$$W_K = \frac{1}{2} m_i n v_i^2$$

$$W_P = \frac{1}{2} m_e n\, c_e^2 \frac{n_e^2}{n^2} \quad \text{for } T_e \gg T_i$$

(see Denisse and Delcroix 1963)

$$W_E = \frac{\epsilon_0}{2} E^2$$

and $c_e^2 = K T_e/m_e$, n_e is the electron density perturbation, E is the electric field of the wave, v_i is the oscillatory ion velocity. Since for negligible ion pressure ($T_e \gg T_i$)

$$-i\omega v_i = \frac{e}{m_i} E \ ,$$

the total wave energy is

$$W_T = 2\,W_K = \frac{n\,e^2}{\omega^2 m_i}\;E^2 .$$

From the dispersion relation for ion acoustic waves

$$\omega^2 = k^2\,\frac{KT_e}{m_i}\left(1+\frac{1}{\alpha^2}\right)^{-1} \qquad T_e \gg T_i$$

$$\alpha = \frac{k_D}{k}\;;\quad k_D = \lambda_D^{-1} = \frac{n e^2}{\epsilon_o K T_e}$$

Thus

$$\frac{W_E}{W_T} = \frac{1}{2(1+\alpha^2)}$$

Now

$$W_p + W_E = \frac{1}{2}\,W_T$$

$$\frac{W_p}{W_E} = \frac{1}{2}\,\frac{W_T}{W_E} - 1$$

So we obtain

$$\frac{W_p}{W_E} = \alpha^2$$

Therefore*

$$\frac{\langle n_e^2(k)\rangle}{n} = \frac{2}{m_e c_e^2}\,\alpha^2\,\frac{\epsilon_o}{2}\,\langle E^2(k)\rangle .$$

Now let us assume a spectrum of turbulence with the same shape as that calculated by Kadomtsev, for which there is some experimental evidence, chiefly from the work of Paul et al. on the Tarantula device. Then

$$\langle E^2(k)\rangle = \frac{C}{k}\,\ln\frac{k_D}{k}$$

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*Although $T_e \gg T_i$ has been assumed in deriving this result, it also holds for $T_e \gtrsim T_i$.

where the factor C can be defined in terms of the level of turbulence. Thus

$$W_E = \frac{1}{(2\pi)^3} \frac{\epsilon_0}{2} \int d^3k \, \langle E^2(k) \rangle$$

Assuming isotropic turbulence within the k-space hemisphere $0 < \beta < \frac{\pi}{2}$ (β = angle between $\vec{u}$ and $\vec{k}$) we have

$$d^3k = 2\pi k^2 \, dk$$

$$W_E = \frac{1}{(2\pi)^3} \pi \epsilon_0 C \int_{k_c}^{k_D} k \ln \frac{k_D}{k} \, dk$$

The cutoff wave vector k_c, determined by the dimensions of the plasma, is normally $\ll k_D$ and its value is not critical. The integral gives $k_D^2/4$ and we have

$$C = (2\pi)^3 \frac{6 n K T_e}{\pi \epsilon_0 k_D^2} \frac{W_E}{W_{th}}$$

$$\frac{\langle n_e^2(k) \rangle}{n} = 48 \pi^2 n \frac{W_E}{W_{th}} \frac{1}{k^3} \ln \frac{k_D}{k} .$$

We can check this relationship against data given by Paul et al. (1971) for their ruby laser scattering experiment on Tarantula. They give $n = 10^{21}\ m^{-3}$, $k = 7{\cdot}1 \times 10^5\ m^{-1}$, $k_D/k = 1{\cdot}3$, $W_E/W_{th} = 0.53 \times 10^{-3}$ (computed from the given values $E_{rms} = 7 \times 10^5$ V/m and $T_e \sim 20$ eV in the shock). We then find

$$\frac{\langle n_e^2(k) \rangle}{n} = 180$$

in good agreement with their measured value of 230. If we consider a cone of turbulence limited to $\beta_{max} = 50^o$, for which they have some experimental evidence, we find

$$\frac{\langle n_e^2(k) \rangle}{n} = 510$$

Let us now consider the conditions anticipated in the Lausanne experiment. If we are looking at scattered light corresponding to $k = k_D/2 = 0.8 \times 10^5\ m^{-1}$, with $n = 3 \times 10^{20}\ m^{-3}$ and $W_E/W_{th} = 10^{-4}$ (as in the Janus experiment) we find

$$\frac{\langle n_e^2(k)\rangle}{n} = 1.9 \times 10^4$$

This is to be compared with the "thermal" or stable-plasma value (Salpeter 1963)

$$\frac{\langle n_e^2(k)\rangle}{n} = \frac{1+\alpha^2\left(1+\frac{T_e}{T_i}\right)+\alpha^4}{(1+\alpha^2)\left\{1+\alpha^2\left(1+\frac{T_e}{T_i}\right)\right\}} = 0.33$$

for $\alpha = 2$ and assuming $T_e/T_i = 5$. The level of turbulence $W_E/W_{th} = 10^{-4}$ thus leads to an enhancement in the scattered light by a factor 5.8×10^4 over the thermal value !

The dependence of $\langle n_e^2(k)\rangle/n$ on k^{-3} is important to us. Since the expected value of k_D (and therefore k) in the Lausanne experiment is nearly an order of magnitude lower than that in the ruby laser scattering experiments on Tarantula; we can expect a relatively good enhancement in the scattered signal even at low levels of turbulence.

These conclusions are not restricted to the shape of spectrum assumed. If, instead of a Kadomtsev spectrum, we assume a peaked spectrum

$$\langle E^2(k)\rangle = \frac{C}{(k-k_0)^2+\frac{1}{L_k^2}}$$

$$k_0 = k_D/2$$

$$L_k = 2\pi/k_0$$

we find

$$C = (2\pi)^3\ \frac{3nKT_e}{20\pi\epsilon_0 k_D}\ \frac{W_E}{W_{th}}$$

$$\frac{\langle n_e^2(k)\rangle}{n} = \frac{6}{5}\pi^2 n \frac{W_F}{W_{th}} k_D \frac{k^{-2}}{(k-k_0)^2+\frac{1}{L_k^2}}$$

For the same conditions as before ($k_D = 1{\cdot}6 \times 10^5$ m^{-1}, $n = 3 \times 10^{20}$ m^{-3}, $W_E/W_{th} = 10^{-4}$) we then have

$$\frac{\langle n_e^2(k_0)\rangle}{n} = \frac{384}{5}\pi^4 \frac{n}{k_D^3}\frac{W_F}{W_{th}} = 5{\cdot}5 \times 10^4$$

compared with $1{\cdot}9 \times 10^4$ for a Kadomtsev spectrum shape. Thus the results are not very sensitive to the shape of spectrum assumed.

The power P_s scattered into a solid angle element Ω is given by

$$P_s / P_i = L\, n\, \sigma_T \frac{\langle n_e^2(k)\rangle}{n}\Omega$$

where P_i is the power of the incident laser beam and L is the scattering length.

The values of L and Ω depend on the optical arrangement and the spectral resolution desired. For the Lausanne experiment let us take L = 0.5 cm and $\Omega = 0.4 \times 0.4/8^2 = .0025$ steradian. (These compare with L = 1 cm and $\Omega = .001$ steradian in the CO_2 laser scattering experiment now underway on Tarantula). For the scattering angle $\theta_s = 7.6^\circ$, corresponding to $k = k_D/2$ in the proposed Lausanne experiment, we find (Bekefi 1966) $\sigma_T = 7.9 \times 10^{-30}$ m^2. With $\langle n_e^2(k)\rangle/n = 1.9 \times 10^4$ as estimated for a Kadomtsev spectrum shape we then obtain

$$P_s/P_i = 0{\cdot}5 \times 10^{-2} \times 3 \times 10^{20} \times 7{\cdot}9 \times 10^{-30} \times 1{\cdot}9 \times 10^4 \times 2{\cdot}5 \times 10^{-3}$$

$$= 5{\cdot}6 \times 10^{-10}$$

With $P_i \sim 100$ MW available from the CO_2 laser we have

$$P_s = 5{\cdot}6 \times 10^{-2} \text{ watts.}$$

If a CMT detector of the kind constructed by SAT were used (operating at liquid N_2 temperature; response time down to ~ 1 nsec; area $A \sim 10^{-4}$ cm^2; $D^* \sim 5 \times 10^9$ cm Hz$^{\frac{1}{2}}$/watt), together with a pulse amplifier of bandwidth B = 180 MHz, the noise equivalent power would be

$$NEP = (AB)^{\frac{1}{2}} / D^*$$

$$= (10^{-4} \times 1{\cdot}8 \times 10^8)^{\frac{1}{2}} / 5 \times 10^9 = 2{\cdot}7 \times 10^{-8} \text{ watts.}$$

This is comparable with the NEP in the Culham experiment, which uses the same amplifier but a Mullard CMT detector whose poor response time (~ 500 nsec) results in a reduction of the scattered signal by a factor of ~ 50. This would be avoided by use of the SAT detector. On the other hand, the small area of the SAT detector element (5 times smaller than the Mullard detector) makes it more difficult to focus the scattered power on it. For example, if the scattered beam were focussed down to 1 mm^2 only a fraction 10^{-2} of the scattered power would strike the detector. Even so the estimated effective scattered power

$$P_{s\ eff} = 10^{-2} \quad P_s = 5{\cdot}6 \times 10^{-4} \text{ watts}$$

is more than a factor of 10^4 above the NEP.

These estimates of course depend on our assumed value of $W_E/W_{th} = 10^{-4}$ for the level of turbulence, as found in the Janus experiment. This value is not very high however and should not be too difficult to reach, if necessary by going to a Janus-type power source (400 kHz; 10 kA). Thus it seems feasible to measure the spectrum of turbulence by observing the scattering of the CO_2 laser radiation.

Acknowledgments

This work has benefitted greatly from discussions with several people, particularly E.S. Weibel, A. Lietti, A. Pietrzyk and A. Heym.

References

1) G. Bekefi (1966) Radiation Processes in Plasmas (Wiley, New York) Chap. 8.

2) A.B. Berezin, L.V. Dubovoi, B.V. Lyublin and D.G. Yakovlev (1972) Sov. Phys. Tech. Phys. 17, 750.

3) B.N. Breizman, V.V. Mirnov and D.D. Ryutov (1970) Sov. Phys. Tech. Phys. 14, 1365.

4) C.C. Daughney, L.S. Holmes and J.W.M. Paul (1970) Phys. Rev. Lett. 25, 497.

5) J.F. Denisse and J.L. Delcroix (1963) Plasma Waves (Interscience, New York).

6) L.V. Dubovoi, V.P. Fedyakov and V.P. Fedyakova (1971) Sov. Phys. JETP 32, 805.

7) L.V. Dubovoi, V.P. Fedyakov and A.V.K. Komin (1972) Sov. Phys. JETP 35, 703.

8) B.B. Kadomtsev (1965) Plasma Turbulence (Academic Press, London) Chap. IV.

9) A. Lietti (1973) private communication.

10) J.W.M. Paul, C.C. Daughney and L.S. Holmes (1969) Nature 223,822.

References (cont.)

11) J.W.M. Paul et al. (1971) in Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971 (IAEA, Vienna, 1971) Vol. III, p. 251.

12) E.E. Salpeter (1963) J. Geophys. Res. 66, 982.