J. Plasma Physics (1998), *vol.* 60, *part* 2, *pp.* 447–448. Printed in the United Kingdom

© 1998 Cambridge University Press

Letter to the Editor

Reply to 'Comment on "Collective effects in bremsstrahlung in plasmas"'

V. N. TSYTOVICH,[1]† R. BINGHAM,[1] U. de ANGELIS[2] and A. FORLANI[2]

[1] Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
[2] Department of Physical Sciences, University of Napoli, Italy

(Received 16 February 1998)

We reply here to a criticism of our paper (Tsytovich *et al.* 1996) by Iglesias (1997).

In our paper we present a very general formulation of collective effects in bremsstrahlung that is valid for any non-equilibrium non-Maxwellian particle distribution. This result is given in (2.20) early in the paper. The standard treatments of bremsstrahlung found in books like Bekefi (1966) are only for thermal plasmas, where the fluctuation–dissipation theorem is valid. Note that the fluctuation–dissipation theorem cannot be used for non-thermal or non-dipole fields, and in this respect the method we use is more general. Our method is the more complex of the approaches used, but, as stated, it can handle situations that cannot be treated by the standard approach. Our main result is the formula (2.20), which is valid for any non-equilibrium non-Maxwellian particle distribution, and which cannot be found anywhere else in the literature. Furthermore, we find new qualitative effects indicating that the ion–ion bremsstrahlung (which is always neglected in the literature) is not small in the case where the collective effects are taken into account, and is in fact, for certain frequencies, of the order of the electron–electron bremsstrahlung. The other qualitatively new result is that, where collective effects are important, the electron–electron bremsstrahlung is not of the order v_{Te}^2/c^2, as it is for the case in the absence of collective effects, but of the order ω_{pe}^2/ω^2 times less – which, for example in the solar interior, where ω_{pe}^2/ω^2 is of the order of v_{Te}^2/c^2, is then of the order of v_{Te}^4/c^4.

In our paper we describe the modern concept of bremsstrahlung, giving references to original papers where the new physics and its mathematical description were proposed, and stress once more than one should not use the incomplete description given in previous textbooks such as Ichimaru (1973) and Bekefi (1966). Concerning the Bekefi treatment, one can turn back one or two pages in his book to find (see his formula (5.6) that in his approach only the dipole approximation is used and only the correlation of electric fields is taken into account. Further on he uses the fluctuation–dissipation theorem, which can only be used for thermal plasmas. Here again we stress that (2.20) in our

† Permanent address: General Physics Institute of the Russian Academy of Sciences, Moscow, Russia.

https://doi.org/10.1017/S0022377898006953 Published online by Cambridge University Press

paper is valid for any distribution: thermal or non-thermal, with or without beams, etc. All three assumptions used in standard texts are not made in our paper, in which we obtained more general expressions valid for any multipole emission and for non-thermal plasmas, where one cannot use the fluctuation–dissipation theorem. The most important improvements come from the fact that our approach shows that in the case where one considers only the electric field correlations, as Bekefi (1966) does, one loses terms that, for a certain range of frequencies, are of the same order of magnitude as those terms that are proportional to the correlations of electric fields.

We have explained this point clearly in the paper, but we can here refer to the book by one of the authors (Tsytovich 1995) to point out what is incomplete in Bekefi's formula (5.6). A more complete fluctuation approach given in Tsytovich (1995) shows that not only should the correlations of electric fields be taken into account (see (12.14) in Tsytovich 1995), but so also should correlations between particles and fields (see (12.20), (12.22), (12.28) and (12.31)). All four additional contributions to the dielectric function are of the same order of magnitude as the electric field fluctuation term. In Chap. 13 of Tsytovich (1995) it is shown for the case of bremsstrahlung of longitudinal waves that all contributions are important. Our paper deals with brems strahlung of electromagnetic waves in a range where collective effects are important.

Considering the approach by Ichimaru (1973), one should first look not at his formula (9.130) or (9.132) but rather at the starting equations, where he does not take into account the nonlinear plasma response, while in Chaps 12 and 13 of Tsytovich (1995) it is clearly stated and explicitly shown how the bremsstrahlung effects depend on the plasma nonlinear response. We have used well-known expressions for the nonlinear plasma response, and use an appropriate approximation for the case of electromagnetic waves ($v/c \ll 1$) to derive the results. In obtaining his (9.132), Ichimaru neglects particle–field correlation terms, which are now taken into account in our paper for arbitrary non-thermal particle distribution and for non-dipole emission. We give (46) as an example only, but (46) is not the our final result even for this example, since by using the correct treatment of the classical and quantum expressions, we get an additional term in (55). Equation (55) is the final result, which cannot be interpreted in the simple way proposed by Iglesias.

References

Bekefi, G. 1966 *Radiation Processes in Plasmas*. Wiley, New York.

Ichimaru, S. 1973 *Basic Principles of Plasma Physics: A Statistical Approach*. Benjamin, Reading, MA.

Iglesias, C. A. 1997 *J. Plasma Phys.* **58**, 381.

Tsytovich, V. N. 1995 *Lectures on Nonlinear Plasma Kinetics*, Chaps 12 and 13. Springer-Verlag, Berlin.

Tsytovich, V. N., Bingham, R., de Angelis, U. and Forlani, A. 1996 *J. Plasma Phys.* **56**, 127.

https://doi.org/10.1017/S0022377898006953 Published online by Cambridge University Press