Thomson-Rayleigh scattering in expanding plasmas

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THOMSON-RAYLEIGH SCATTERING IN EXPANDING PLASMAS

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Expanding plasmas are interesting from a fundamental as well as from a technological point of view. Nowadays expanding plasmas are used in plasma processing, e.g. plasma deposition [1, 2] and plasma spraying. The fundamental interest in expanding plasmas is the different behavior of the electrons and heavy particles due to their large mass difference. As a consequence, if the expansion is strong, charge separation can occur, which leads to a generated electromagnetic field [3]. This electromagnetic field in turn influences the behavior of the charged particles in the expanding plasma. Another interesting feature is the coupling between the ionization-recombination phenomena and the transport properties as electron temperature and electron density. In this respect the study of the equilibrium departure is essential, as it can help in the understanding of the kinetic processes involved.

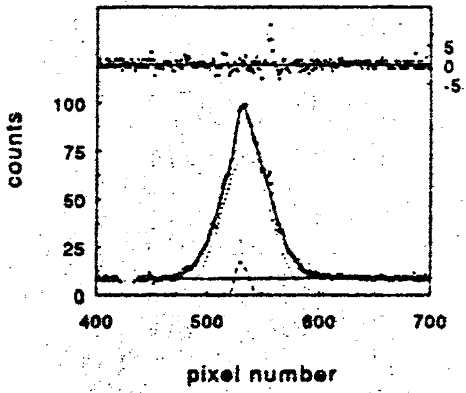

Figure 1: A measured Thomson-Rayleigh profile with least mean square fit and five times magnified residue.

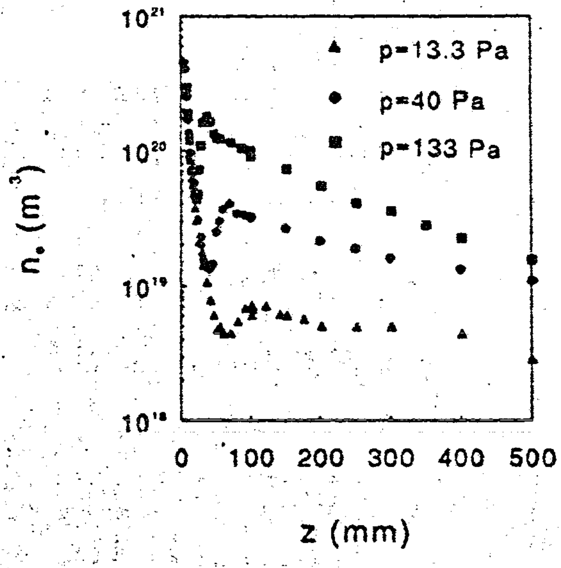

Figure 2: n_e on the axis as a function of the axial position for different background pressures. I_{cas} = 45 A, *Ar − flow* = 3500 ml/min.

The measurements discussed in this paper were performed on a plasma which expands freely from a sub atmospheric thermal plasma in argon (a cascaded arc, $T \approx 1$ eV, $n_e \approx 10^{22}$ m^{-3} and $n_0 \approx 10^{23}$ m^{-3}) into a low background pressure ($p \approx$ 10-100 Pa) [1, 2]. The electron density and temperature and the neutral particle temperature in the expansion part are measured locally by means of Thomson and Rayleigh scattering [4]. The main components of the scattering diagnostic are a frequency doubled Nd:YAG laser, a polychromator based on a holographic grating and a gateable light amplifier in combination with a linear photodiode array. Much attention is given to the suppression of stray light which is essential if one wants to measure Rayleigh scattering (stray light level 0.4 Pa argon at 300 K). For more details cf. Refs. [4, 5]. In fig. 1 a typical Thomson-Rayleigh profile is given, in which the different components can be distinguished: a broadened Thomson profile with a superimposed Rayleigh profile.

In figs. 2 and 3 the measured electron density and temperature and the neutral particle density on the axis are shown for different background pressures. The supersonic expansion can be clearly seen. After several mm, depending on the background pressure, a shock occurs, after which the plasma expands further subsonically. The behavior of the densities and the electron temperature in the first region will be treated here in more detail.

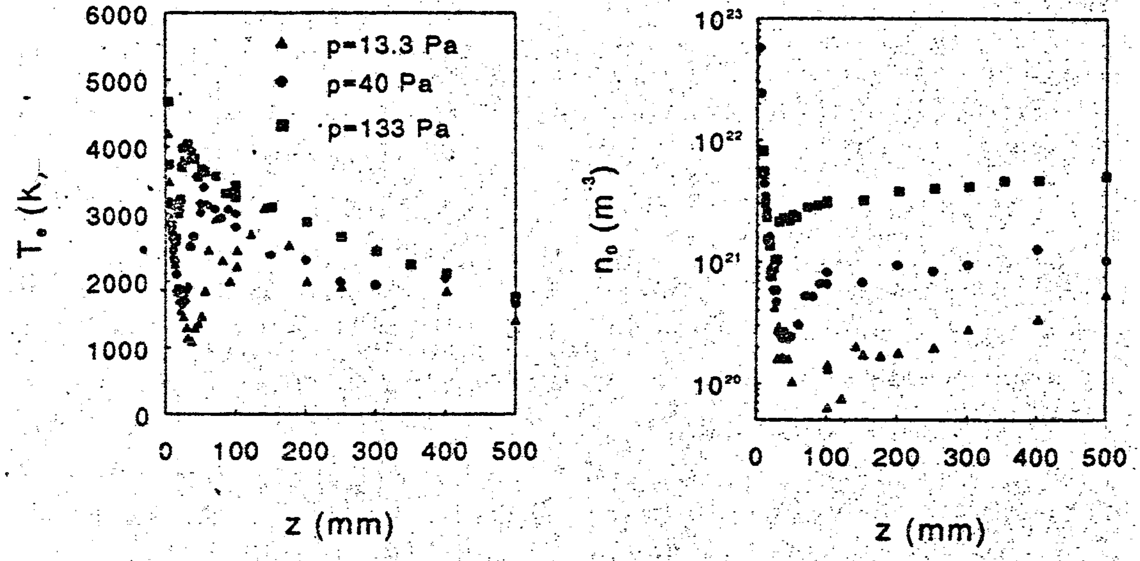

Figure 3: T_e (left) and n_0 (right) as a function of the axial position (cf. fig. 2).

In figs. 4 the measured electron and neutral particle densities in the expansion are compared with the model of Ashkenas and Sherman [6] developed for an adiabatic supersonic expansion of a gas. Following this model the densities should scale for $z > z_0$ as

$$n = \frac{n_{res} z_{ref}^2}{(z - z_0)^2} \qquad (1)$$

Equation 1 is the well known source expansion with n_{res} the reservoir particle density and z_0 the origin from which the particle trajectories seem to originate. z_{ref} is a reference length. As can be seen from figs. 4 the agreement with the easurements of n_0 and n_e is excellent ($z_0 \approx 1.5$ mm, $n_e = 1.3 \cdot 10^{22}$ m^{-3} and $n_0 = 3 \cdot 10^{23}$ m^{-3}). Equation (1) can be interpreted as follows. During the expansion thermal energy is converted into directed kinetic energy. Since the thermal energy is limited by the total enthalpy in the reservoir the velocity v_{axis} along the axis saturates and becomes finally constant. From flux conservation this means that the product $n v_{axis} A = constant$. Since the surface A scales as z^2 for large z, the densities scale as z^{-2} (cf. (1)). But the flux of particles is only constant if recombination can be neglected. This means that from figs. (4), it can be concluded that argon does not recombine on the particle level during the strong expansion or to put it in other words, the recombination is smaller than can be measured using the Thomson-Rayleigh scattering diagnostic.

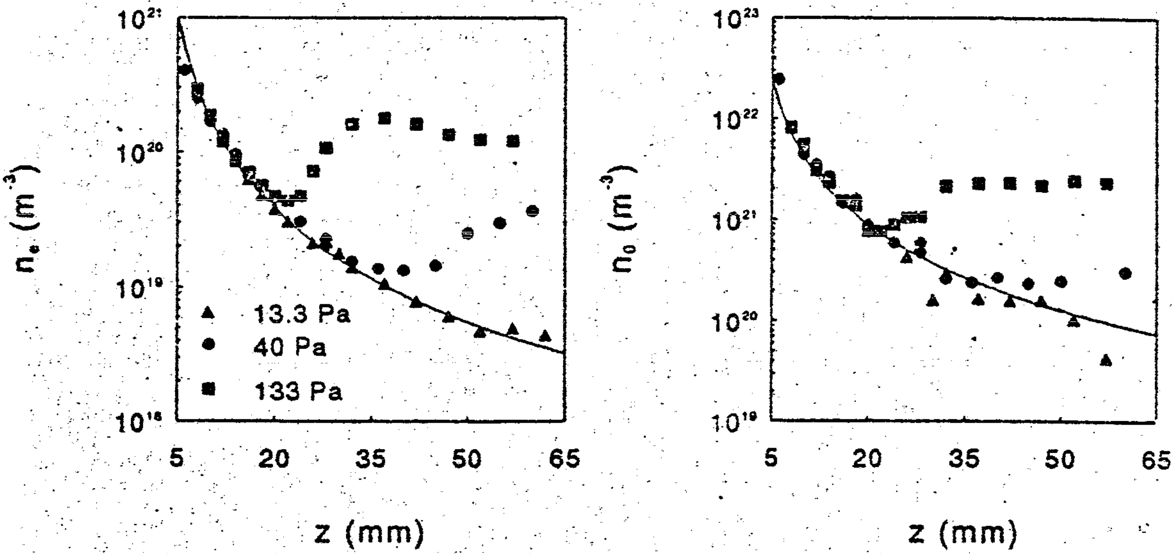

Figure 4: n_e and n_0 on the axis as a function of the axial position for different background pressures compared with the model of Ashkenas and Sherman (lines) [6]. $I_{cas} = 45$ A, $Ar - flow = 3500$ ml/min.

The recombination of argon can be better examined by combining measurements of the excited state densities with Thomson-Rayleigh measurements using the Saha equation. In fig. 5 the calculated b_p-factor [7, 8] is given using the locally measured $\frac{n_p}{g_p}$ and n_e and T_e. The b_p-factor is defined as the ratio of the measured excited state density to the excited state density according to the Saha equation for the given n_e and T_e. If the b_p-factor is smaller than one the plasma the plasma is recombining. As can be seen from fig. 5, the b_p-factor approaches one for the highly excited states, revealing the fact that the highly excited states are collisionally dominated, and is much smaller than one for the lower excited states. In fact from fig. 5 one can conclude that the plasma is recombining and from the gradient in the b_p-factor space the recombination rate can be calculated [5, 7].

Another way in which one can research the recombination phenomena is by means of the electron energy balance. In fig. 6 n_e as a function of T_e is given in the expansion for different conditions. As can be seen a simple scaling law is found which reads $n_e = C_0 T_e^{\chi}$ with $\chi \approx 3.7$. A similar result was found by Stevefelt and Collins [9] for a laser produced carbon plasma. The explanation is the fact that although the three particle recombination can be neglected, it can *not* be neglected on the energy level, i.e. it has to be taken into account as a heat source for the electron gas. Therefore the electron gas does not expand adiabatically (corresponding with $\chi = \frac{3}{2}$. Using a quasi-one dimensional model for the expansion and using the Ashkenas and Sherman result (cf. (1)), it can be shown that the determined χ corresponds to a three particle recombination coefficient which reveals the

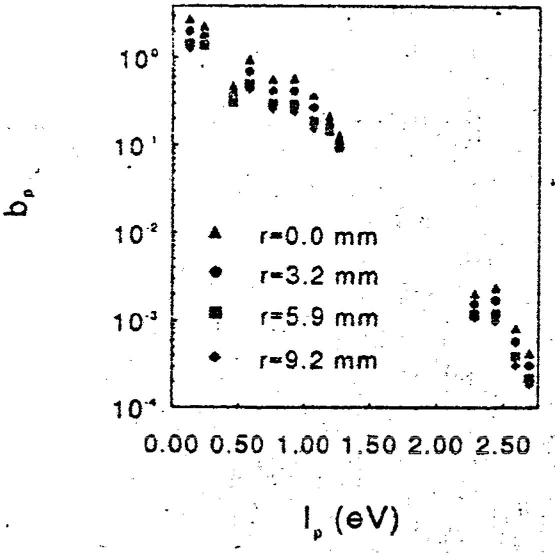

Figure 5: b_p as a function of the ionization potential I_p for different radial positions at $z = 40$ mm. $I_{cas} = 45$ A, $Ar - flow =$ 3500 ml/min, $p = 40$ Pa.

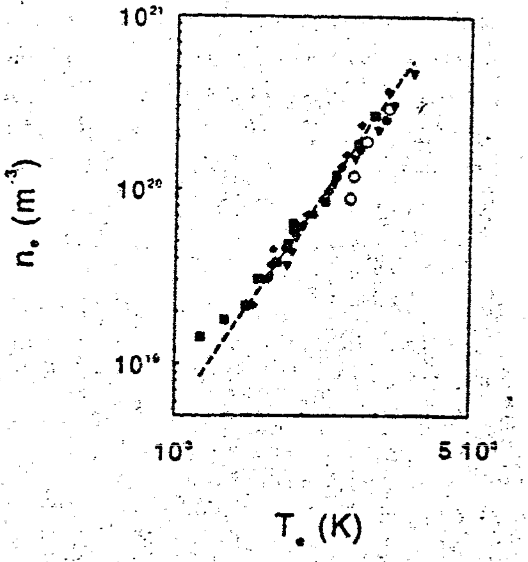

Figure 6: n_e as a function of T in the expansion for different conditions of the cascaded arc and background pressure.

well know $T_e^{-9/2}$ dependence on the electron temperature.

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References

[1] J.J. Beulens, A.J.M. Buuron, and D.C. Schram, Surface and Coatings Techn. **47** 401 (1991)

[2] G.M.W. Kroesen, D.C. Schram and J.C.M. de Haas, Plasma Chem. Plasma Proc. **10** 531 (1990)

[3] H.J.G. Gielen and D.C. Schram, IEEE Trans. Plasma Sci. **18** 127 (1990)

[4] M.C.M. van de Sanden, J.M. de Regt, G.M. Janssen, D.C. Schram, J.A.M. van der Mullen, B. van der Sijde, accepted for publication in Rev. Sci. Instr. (june 1992)

[5] M.C.M. van de Sanden, thesis University of Technology of Eindhoven, the Netherlands (1991)

[6] H. Ashkenas and F.S. Sherman, Rarefied Gasdynamics **4**, Ed. J.H. de Leeuw (Academic Press, New York, 1966)

[7] J.A.M. van der Mullen, Phys. Rep. **191** 109 (1990)

[8] L.M. Bibermann, V.S. Vorob'ev and I.T. Yakubov, *Kinetics of Nonequilibrium Low Temperature Plasmas*, (Plenum, New York, 1987)

[9] J. Stevefelt and C.B. Collins, J. Phys. D **24** 2149 (1991)