

## Inversion of population in an expanding H<sub>2</sub> plasma

**Citation for published version (APA):**

Qing, Z., Sanden, van de, M. C. M., Otorbaev, D. K., Eerden, M. J. J., Graaf, de, M. J., Wevers, J. C. A., & Schram, D. C. (1994). Inversion of population in an expanding H<sub>2</sub> plasma. In *ESCAMPIG 94 : European Sectional Conference on Atomic and Molecular Physics of Ionized Gases, 12th, Noordwijkerhout, The Netherlands, August 23-26, 1994* (pp. 434-435). (Europhysics conference abstracts; Vol. 18E). European Physical Society (EPS).

**Document status and date:**

Published: 01/01/1994

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

**Take down policy**

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

# INVERSION OF POPULATION IN AN EXPANDING H<sub>2</sub> PLASMA

Zhou Qing, M.C.M. van de Sanden, D.K. Otorbaev, M. Eerden  
M.J. de Graaf, J.C.A Wevers and D.C. Schram

Department of Physics, Eindhoven University of Technology,  
P.O.Box 513, Eindhoven 5600 MB, The Netherlands

The inversion of atomic hydrogen level population of an expanding nonequilibrium dense plasma has already been demonstrated experimentally by emission spectroscopy [1,2]. An atomic collisional-radiative model has been attempted to explain the experimental data [2,3]. This paper shows an experimental determination of the atomic hydrogen excited levels population in a magnetized expanding cascaded arc plasma.  $n_e$  and  $T_e$  are measured by Langmuir double probe diagnostics and the classical Langmuir probe theory is used to interpret the probe characteristic. An explanation to the presented situation in which a large discrepancy is found between the outcome of the model and the measured population densities is given based on the presence of rovibrationally excited molecules.

Fig.1 show  $n_e$  and  $T_e$  as function of the axial distance to the exit of the cascaded arc as measured by the Langmuir double probe diagnostics.  $n_e$  is much larger than in the absence of a magnetic field [4]. The accuracy in  $T_e$  is estimated up to 50% and in  $n_e$  about 25%. It should be noted that in the measured  $n_e$  and  $T_e$  ranges the plasma is still recombining in nature and that the excitation and the ionization from the ground state can be neglected. Fig.2 show the absolute population densities  $n_p/g_p$  and the  $b_p$  factor on the plasma beam axis as a function of the ionization potential  $I_p$  of the level  $p$ . A population density inversion appears for the levels  $3 < p < 7$ . In general the inversion is more pronounced downstream in the plasma jet and the maximum of  $n_p/g_p$  occurs for the higher quantum numbers. In the  $b_p$  plot, a maximum value occurs for the level  $p_{max}$  at which the inversion is found in Boltzman plot. Furthermore, the  $b_p$  values for smaller  $I_p$  values decrease directed to 1, as expected for levels close to the continuum for which the population is ruled by electron collisions [5]. Another aspect of the  $b_p$  plot is the fact that the  $b_p$  values for high  $p$  are much larger than 1, indicating that a large population source is present. The negative slope of  $b_p$  vs.  $I_p$  for levels with  $p < p_{max}$  means that these levels are recombining since for these levels the optical decay at the given  $n_e$  and  $T_e$  is dominant over the collisional excitation. Alternatively, the positive slope for  $p > p_{max}$  means that these excited levels are ionizing.

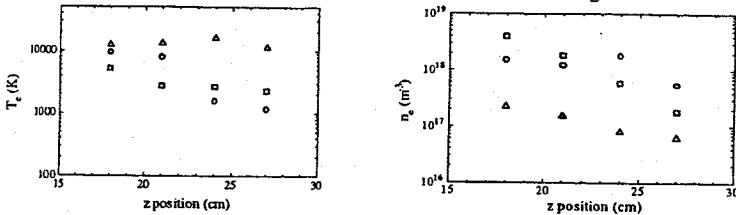


Figure 1  $T_e$  and  $n_e$  of a cascaded arc expansion hydrogen plasma  
plasma conditions: H<sub>2</sub> = 0.5 slm,  $I_{arc}$  = 50 A,  $p$  = 0.05 mb,  $z$  = 24 cm  
□: B = 40 mT, ○: B = 24 mT, △: B = 8 mT

For an explanation, a mechanism which can lead to the observed large population and should at least populate levels up to  $p_{max}$  is required. The purely atomic processes of which the three particle recombination ( $e+e+H^+ \rightarrow e+H^*$ ) is the main population mechanism can not explain

the large overpopulation since e.g. for  $p = 4$  the calculated density is a order of 4 lower than the measured density at the present condition. Therefore the molecular processes should be included.

The mechanism [4] based on the charge exchange with rovibrationally excited  $H_2^{v,J}$  molecules which could be presented in the recirculating plasma flow is also unlikely because it requires large amount of very high rovibrational excited  $H_2$  molecules to reach the population level between 5 and 7. In our experiment, the background pressure is only a few pascal which is an order lower than that in the case in Ref. [4] and the reionization could be occurred in our case due to the application of a magnetic field.

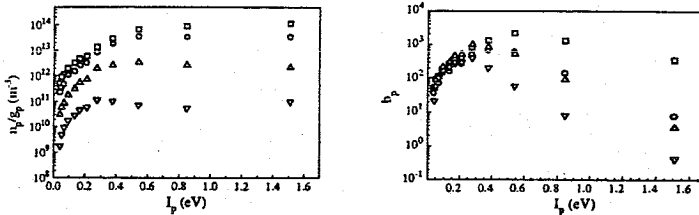


Figure 2 Boltzmann plot and  $b_p$  plot of a cascaded arc expansion hydrogen plasma  
plasma conditions:  $H_2 = 0.5$  slm,  $I_{arc} = 50$  A,  $p = 0.05$  mb,  $B = 40$  mT

□:  $z = 18$  cm,  $T_e = 5150$  K,  $n_e = 3.9 \cdot 10^{18} \text{ m}^{-3}$ ,    ◻:  $z = 21$  cm,  $T_e = 2710$  K,  $n_e = 1.8 \cdot 10^{18} \text{ m}^{-3}$   
▲:  $z = 24$  cm,  $T_e = 2610$  K,  $n_e = 5.8 \cdot 10^{17} \text{ m}^{-3}$ ,    △:  $z = 27$  cm,  $T_e = 2250$  K,  $n_e = 1.8 \cdot 10^{17} \text{ m}^{-3}$

An alternative mechanism is the mutual recombination of  $H^+$  and  $H^-$  which is formed by dissociative attachment, but only this is also difficult to explain the large population at  $p \geq 4$  since recombination rate for  $p \geq 4$  is negligible small. A more probable mechanism is the mutual recombination of  $H^-$  and  $H_2^+$  which could be either formed by charge exchange in the expansion [4] or generated in the arc), i.e.



this mechanism can explain the population of highly excited states since the ionization energy of  $H_2^+$  is about 15.6 eV. Furthermore, it generates rovibrationally excited molecules, which means that there is no need for high vibrational temperatures (or equivalent rotational temperatures). A simplified calculation based on the assumptions of comparative rate of formation of  $H^-$  and  $H^+$  and the time limiting step is still the charge exchange and the electron attachment reaction and the molecular states of  $v \geq 4$  or equivalent rotational states leads to  $n(H^-) = n(H_2^+) = 6 \cdot 10^{17} \text{ m}^{-3}$ . This means that if the assumptions made are true, the potential of the expanding magnetized hydrogen plasma as a negative hydrogen source is large. Note that there is still competition from dissociative and mutual recombination. Another interesting aspect is that if the proposed mechanisms Eqs.(1)-(2) are correct, this would enable an optical detection technique of the negative ions: by performing laser photodetachment the light emission originating from the excited levels in the range  $3 \leq p \leq 6$  should disappear.

- 1 G.A. Lukyanov, V.V. Nazarov and N.O. Pavlova, Opt. Spectrosc. 26 (1978)
- 2 H. Akatsuka and M. Suzuki, Phys. Rev. E 1534 (1994)
- 3 D.R. Bates, A.E. Kingston and R.W.P. McWhirter, Proc. Roy. Soc. Lond. A. 297 (1962)
- 4 M.J. de Graaf, R.J. Severens, R.P. Dahiya, M.C.M. van de Sanden and D.C. Schram, Phys. Rev. E. 2098 (1993).
- 5 J.A.M. van der Mullen, Phys. Rep. 109 (1990)