*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.063 (2006)*

Properties of the electron energy distribution in plasma under pulsed magnetic fields

R. Doron[1], R. Arad[1], B. Rubinstein[1], A. Fruchtman[2], Y. Maron[1]
[1]*Faculty of Physics, Weizmann Institute of Science, Rehovot, Israel*
[2]*Holon Academic Institute of Technology, Holon, Israel*

Understanding the interaction of a propagating magnetic field with plasma is important in research of laboratory and space plasmas. Generally, the interaction of a propagating magnetic field with collisionless, or nearly collisionless plasma, is manifested through two competing processes. The first is plasma pushing with a characteristic velocity given by the Alfven velocity. The second, for plasmas that possess non-homogeneity in the electron density distribution, rapid magnetic field penetration via the electric Hall-field mechanism is possible; as described by the electron magneto-hydrodynamic (EMHD) model [1,2,3]. A fundamental aspect of the interaction is the dissipation of the magnetic-field energy by the plasma. In the first case, where plasma pushing is dominant, the part of the magnetic energy that is dissipated by the plasma mostly goes to the ions due to the electron low mass. In the other extreme case of an ideal EMHD model, where the ions are assumed to be essentially immobile, all the available magnetic energy goes into electron heating.

Previous laboratory studies, performed for multi-ion species plasma under pulsed magnetic fields, have shown that magnetic field penetration and plasma pushing can occur simultaneously [4]. In this phenomenon the magnetic field rapidly penetrates into the heavier ion component of the plasma, while the protons are pushed by the magnetic field. The present work focuses on the evolution of the electron energy distribution (EED).

A schematic description of the experimental platform is shown in Fig. 1. It consists of a system of pulsed currents driven through a plasma bridge between two electrodes. The currents generate magnetic fields of up to 10 kG with a rise time of ~300 ns. The initial parameters of the plasma, prior to the application of the currents, are an electron density (n_e) of ~5×10^{14} cm^{-3} and an electron temperature (T_e) of ~6 eV. The plasma is mainly composed of protons and carbon ions [5]. The diagnostics are mainly based on time-dependent, spatially-resolved, spectroscopic techniques. In order to obtain spatially-resolved measurements along the line of sight, the experimental setup includes the possibility to inject local impurities (doping) into various locations of the plasma volume.

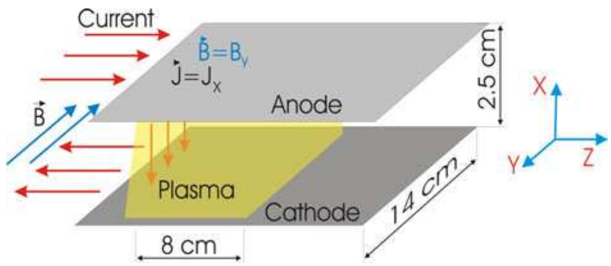

Fig. 1: Schematic description of the experimental system. The magnetic field is parallel to the Y axis and propagates in the Z direction.

Information on the EED evolution is first obtained by measuring the evolution of T_e-sensitive intensity ratios of spectral line pairs emitted from C^{2+}. An example of such a line pair consists the transitions 2s2p $^1P_1$ - $2p^2$ $^1D_2$ that falls at 2297 Å and 2s3d $^1D_2$ – 2p3s $^1P_1$ at 2982 Å. The upper level of the first transition lies at 18 eV, whereas the upper level of the second lies at 38 eV. Measurement of the evolution of this T_e-sensitive upper-level population ratio, together with a theoretical simulation, is given in Fig. 2. The term time 0 refers to the time of the application of the pulsed current.

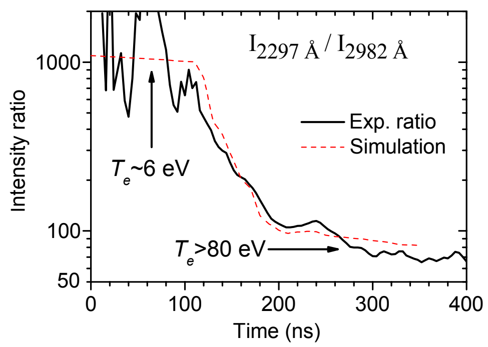

Fig. 2: Evolution of the temperature-sensitive line ratio I (λ=2297 Å)/I (λ=2982 Å) of C^{2+} observed roughly at the middle of the plasma volume.

The simulation indicates an initial average T_e of ~6 eV, consistent with previous measurements of the prefilled plasma. At these early times the experimental curve is very noisy due to the very weak signal from the higher energy transition. Only when the propagating magnetic field arrives to the observed volume, the ratio indicates rapid heating. As T_e increases the ratio decreases, but when T_e corresponds to ~ 4 or 5 times the energy gap, the temperature-sensitivity winds down. Therefore, one can only determines a lower limit for T_e, which is around 90 eV.

Unfortunately, lines of C^{2+} are the only candidates that offer such a straightforward determination of T_e using intrinsic lines of the prefilled plasma. Taking advantage of the fact that the prefilled plasma is well studied [5], we can try to gain a dipper insight into the EED by not limiting our measurements solely to intensity ratios involving the same ion. In this approach, we expand our measurements to include transitions with much larger differences in excitation energies. We measure three transitions with excitation energies of 18, 56, and 304 eV, belonging to C^{2+}, C^{3+}, and C^{4+}, respectively. Fig. 3 shows the inferred evolution of the absolute populations of the upper levels of these three transitions. Also shown, is an attempt to simulate the measurements using a time-dependent Maxwellian EED model. It can be seen that this model provides a good fit to the C^{4+} transition, but it strongly disagrees with the transitions of C^{2+} and C^{3+}. When one uses a different Maxwellian model that best describes the data of the lower charge states, a clear disagreement with the experimental C^{4+} data is obtained. These results indicate that the EED significantly deviates from a Maxwellian distribution. Indeed, if instead of considering a single T_e at each time step in our simulation we assume a combination of a Maxwellian population plus a beam of hot electrons, it is possible to obtain a good fit for all three line intensities simultaneously.

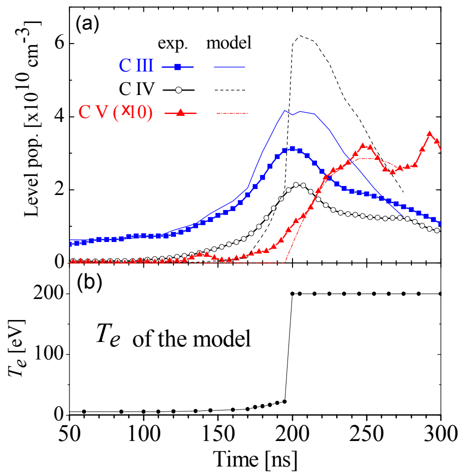

Fig. 3: (a) Time evolution of the upper level population of the transition of the C ions. (b) The time-dependent T_e used for the modeling presented in (a)

In order to avoid integration along the line of sight and refine our measurements we make use of He dopant injection. In He, the intensity ratio I (λ=6678 Å)/I (λ=5876 Å), corresponding to the transition upper levels known as "singlet 3d" and "triplet 3d", is T_e-sensitive. The left panel of Fig. 4 presents the measured evolution of the ratio I (λ=6678 Å)/I (λ=5876 Å) observed in a 2-cm wide column of He gas, injected into the middle of the plasma volume. The numbers in red give the calculated temperatures corresponding to several chosen ratios. The right panel of Fig. 4 presents the evolution of the absolute population of the singlet 3d level, together with an attempt to simulate the experimental curve on the basis of the temperatures inferred from the ratio. The clear discrepancy seen in the figure provides a compelling evidence for the non Maxweillian nature of the EED. We note that opacity effects, neglected in the present work, may somewhat change the inferred T_e values (by ~15%); but not the main result regarding the EED.

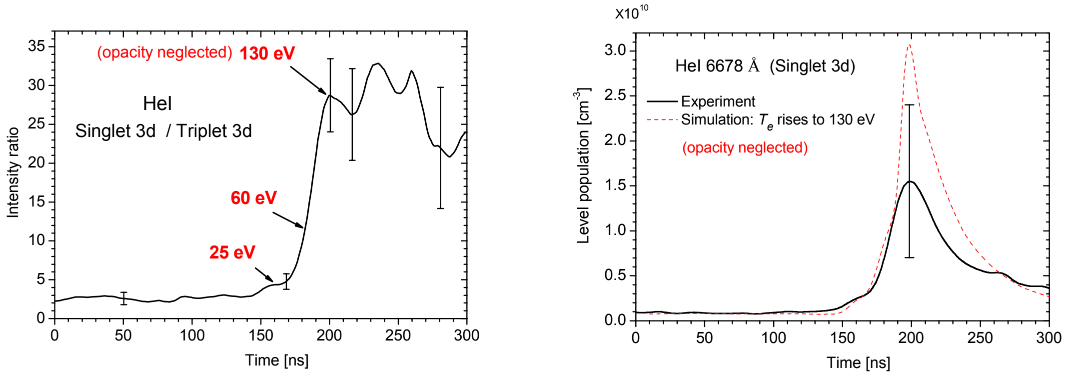

Fig. 4: (Left) Evolution of the ratio I (λ=6678 Å)/I (λ=5876 Å). The numbers in red are calculated T_e corresponding to chosen ratios. (Right) Evolution of the singlet 3d population.

Similar to the case of the carbon ions, it is possible to obtain a good fit both for the measured ratio and the absolute intensities by using a model consisting of a two-component electron population; a relatively cold temperature electron population and a beam of 250 eV, with an increasing fraction up to 70%. These simulations are presented in Fig. 5.

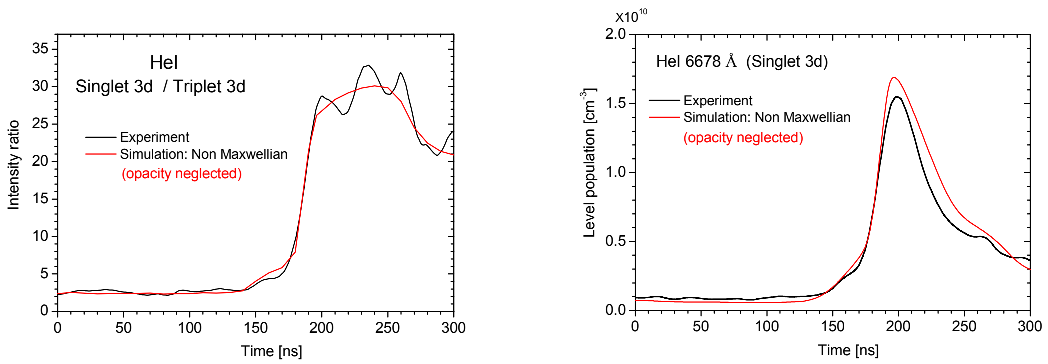

Fig. 5: Same as Fig. 4, but with a model with non Maxwellian EED

Further measurements involving higher energy transitions and a discussion on the meaning of these results will be given in future publications.

Refernces

[1] A. S. Kingsep, Yu. V. Mohkov, and K. V. Chukbar, Sov. J. Plasma Phys. **10**, 495 (1984); A.S. Kingsep, K.V. Chukbar, and V.V. Yankov, in Reviews on plasma Physics, edited by B. Kadomtsev (Consultants Review, New York, 1990), Vol. 16, P. 243.

[2] A. Fruchtman, Phys. Fluids B **3**, 1908 (1991)

[3] A. V. Gordeev, A. S. Kingsep, and L. I. Rudakov, Physics Reports, vol. **243**, 215 (1994)

[4] A. Weingarten, R. Arad, A. Fruchtman, and Y. Maron, Phys. Rev. Lett. **87**, 115004 (2001)

[5] R. Arad, K. Tsigutkin, Yu. V. Ralchenko, and Y. Maron, Phys. Plasmas **7**, 3797 (2000)