J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Collisionless Electron Heating in a Very High Frequency Neutral Loop Discharge

Aleksey V. ARSENIN, Vladimir G. LEIMAN and Vladimir P. TARAKANOV

Department of General Physics, Moscow Institute of Physics and Technology (State University), Institutskii per. 9, Dolgoprudnyi, 141700 Russia

(Received: 6 September 2008 / Accepted: 19 March 2009)

We present two-and-a-half-dimensional particle simulation and analysis of the collisionless electron heating processes in a very high frequency neutral loop discharge (NLD) which is attractive plasma source for plasma processing. Results of numerical simulation allowed to reveal new type of collisionless heating – local electron cyclotron resonance (ECR). Simulation shown that regime of local ECR heating is realized at low gas pressure and negligible Coulomb collisions. Efficiency of local ECR is enhanced with decreasing pressure (collision frequency) or increasing driving frequency. The results of simulation are compared with available experimental data. We used a fully electromagnetic code KARAT based on the particle-in-cell Monte-Carlo collision (PIC-MCC) method.

Keywords: neutral loop discharge, collisionless electron heating, electron cyclotron resonance

1. Introduction

Neutral Loop Discharge (NLD) is variety of magnetic enhanced inductive coupled plasma (ICP) [1, 2]. The NLD plasma source is characterized by a high-density plasma (>10^{11} cm^{-3}) at low gas pressure (~ 10^{-3} Torr). Distinctive feature of NLD is magnetic field configuration with neutral loop (NL) that consists of continuous sequence of null magnetic field points connected in circle. The NLD is more efficient at low gas pressure in comparison with ICP due to existence of new type collisionless electron heating – stochastic heating around the NL [3].

The goal of this work is numerical simulation of the NLD plasma around the NL in order to determine effect of local electron cyclotron resonance (ECR) on electron heating in the very high frequency regime, when the electron collision frequency ν_e is much less than driving frequency ω.

2. Description of the model

A schematic diagram of the cylindrical NLD apparatus is shown in fig. 1. The stainless steel chamber was cylindrical, 30 cm in inner diameter. The left end and right end of the chamber are closed by a grounded metal end plate. The discharge was sustained by an azimuthal electric field induced by the rf single turn antenna which was placed inside the chamber. The magnetic system consists of three electromagnetic coils that are placed on the outside of chamber. The currents in first and third coils flow in the same direction and current in second coil flows in the opposite direction. These coils form necessary configuration of the magnetic field with neutral loop (fig. 2). Varying the current of the second coil can change the radius of the neutral loop.

Numerical simulation is performed in *r-z* cylindrical geometry of code KARAT [4 - 6]. Plasma is represented as a system of the charged super particles and any one particle substitutes a lot of ions or electrons, which move in self-consistent electromagnetic field and undergo both elastic and inelastic collisions. Electric and magnetic fields are three-dimensional. Magnetic field produced by three magnetic coils and the rf field of antenna are calculated.

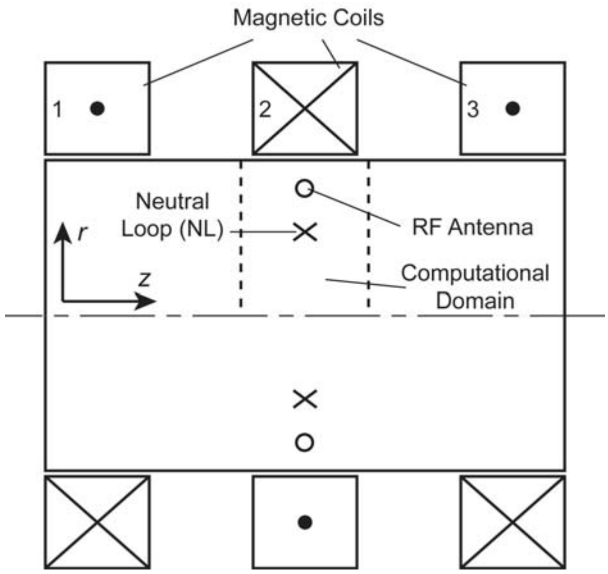

Fig. 1. Schematic diagram of the cylindrical NLD setup. A dashed line denotes computational domain for numerical simulation.

author's e-mail: a.arsenin@mail.ru

©2009 by The Japan Society of Plasma Science and Nuclear Fusion Research

Size of the computational domain: radius of discharge chamber is $R = 15$ cm and length is $L = 10$ cm. Number cells of the computational grid: $N_r = 201$ and $N_z = 135$. The radius of the one-turn rf antenna is 13 cm. Position of neutral loop is defined by characteristics of magnetic coils 1, 2 and 3. Configuration of the magnetic field is calculated by code KARAT and showed in the figure 2. Parameters of NL: $r_{NL} = 11$ cm and $z_{NL} = 5$ cm. Discharge chamber is filled by argon at a pressure of $P = 3.3$ or 6.6 mTorr. Initially, uniform plasma with a density of $n_e = 10^8$ cm^{-3} fills incompletely discharge chamber and only its part in the neighbourhood of neutral loop. Therefore, we have used a simple boundary condition. The boundary conditions are $\phi(r,0) = \phi(r,L) = \phi(R,z) = 0$ and $(\partial\phi/\partial r)_{r=0} = 0$, where ϕ is the potential. The average number of PIC particles (ions and electrons) is about 500000. All ions and electrons reaching the wall are absorbed. Model takes into account electron-Ar collisions such as elastic, ionizing and exciting collisions on the basis of the cross section data [7]. Electron-Ar collisions are described by null-collision method [8]. The differential cross section is determined for all collisional events by Surendra et al. [9]. The calculation of ion-Ar collisions is omitted. The electron densities are low enough that the effect of Coulomb collisions is negligible.

The time step for the calculation of electron motion and electron collision is typically $1.3 \cdot 10^{-12}$ s, less than the smallest time scale in the discharge.

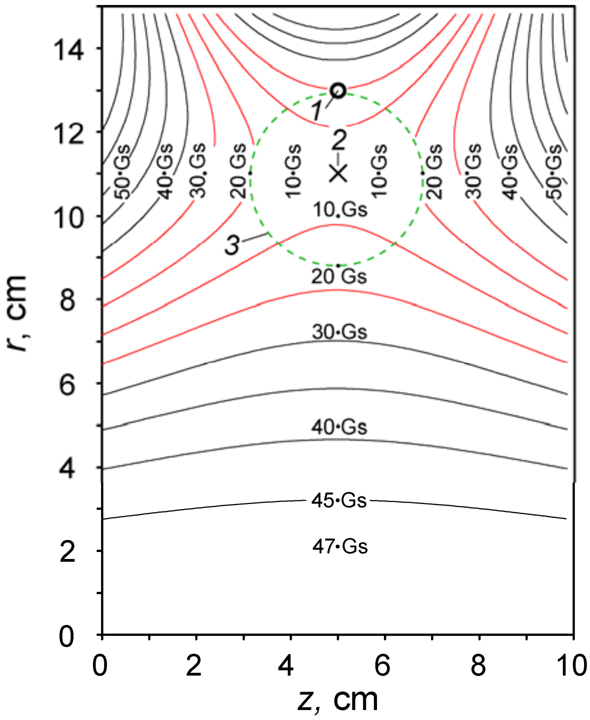

Fig. 2. Magnetic field lines and magnetic field strength in computational domain (r-z plane). 1 – rf antenna; 2 – position of neutral loop ($r = 11$ cm and $z = 5$ cm) and 3 – contour of local ECR. Red lines denote location of the magnetic trap.

3. Results and discussion

The NLD plasma is examined for an antenna frequency: $\omega / 2\pi = 54$, 48, 40 and 27 MHz. The results of the numerical simulation show that NLD has sufficiently complicated structure in the field of neutral loop (fig. 3). Spatial distribution of plasma density in the neighbourhood of neutral loop is non-homogeneous as in longitudinal direction and in radial direction. Positions of maximum plasma density coincide with positions of magnetic traps that is necessary to take into account when solving the problem of dynamical control for plasma parameters in the case of its technological application. The presence of these magnetic traps is typical for NLD magnetic configuration. Trajectories of plasma electrons in magnetic traps are presented in figure 4.

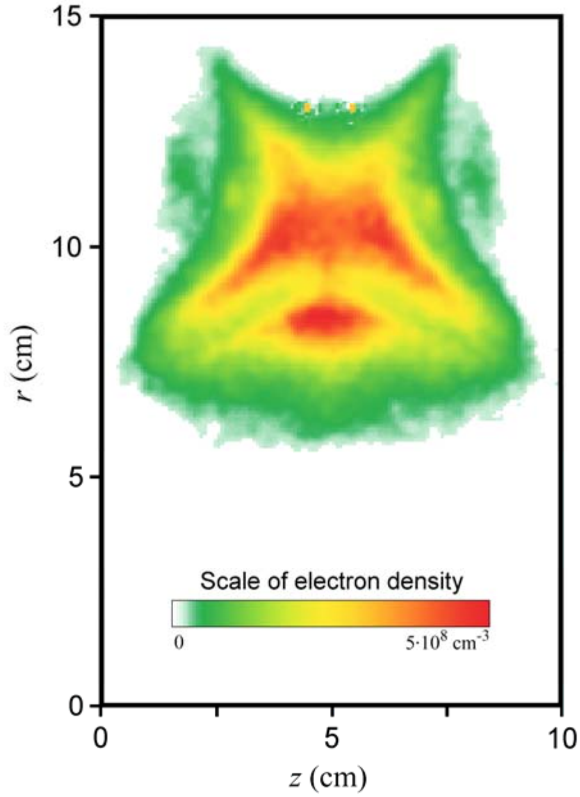

Fig. 3. Distribution of electron density in r–z plane.

We examine the effect of the driving frequency and the gas pressure on the discharge. Figure 5 shows the dependence of the electron temperature on the distance from the axis of the discharge chamber in the plane of the NL for several frequencies of the rf field (27, 40, 48, and 54 MHz). The results of the simulation show that, when the condition of a collisionless plasma $\nu_e / \omega < 1$ is satisfied (where $\nu_e \approx 6 \cdot 10^9 P\sqrt{T_e} + 3 \cdot 10^{-5} n_e / T_e^{3/2}$, T_e is the electron temperature in eV), the NLD is transformed into a regime that is characterized by a shift of the temperature maximum relative to the neutral loop. In this case, the position of the maximum coincides with the region in which the ECR condition is satisfied at the frequency of the external rf field. Location of electron temperature maximum coincides with the region of radio frequency ECR heating when driving frequency is 40, 48 or 54 MHz and pressure is 3.3 mTorr. The existence of electron temperature maximum in the neighbourhood of local ECR is confirmed by both our numerical simulation and experimental investigations (fig. 6) [10]. The coincidence of the location of the temperature maximum and the ECR region allows the assumption that the ECR heating is realized in this region. For a frequency of 27 MHz and a pressure of 6.6 mTorr, we have $\nu_e / \omega \approx 1$, so that dependence $T_e(r)$ does not exhibit a maximum in the region where the ECR condition is satisfied.

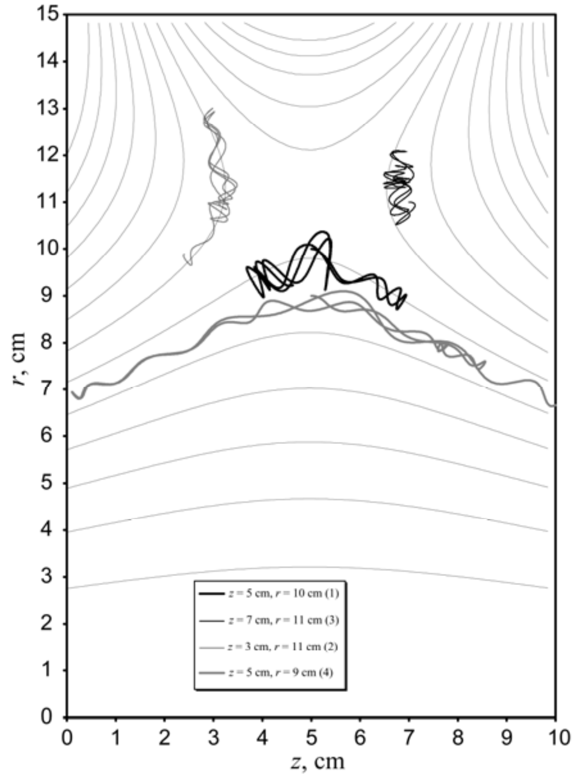

Fig. 4. Trajectories of plasma electrons in magnetic traps.

Recently, existence of ECR in a weakly magnetized rf inductive discharge has been evidenced [11 and 12]. It was shown that electron temperature is at maximum near ECR condition. In addition, results of our numerical simulation show that the efficiency of the NLD is defined by one more type of collisionless electron heating – local ECR. The regime of local ECR heating is realized at low gas pressure and negligible Coulomb collisions. The dominance of local ECR is enhanced with decreasing pressure (collision frequency) or increasing driving frequency. Location of electron temperature maximum coincides with the region of stochastic heating (neutral loop) [3] when driving frequency is 27 MHz (low frequency) and pressure is 6.6 mTorr (high pressure) (see fig. 5).

Thus, the observed increase in the electron temperature in the very high frequency NLD in the region where the ECR condition is satisfied confirms that electron heating can be attributed to not only a well-known stochastic mechanism [3], but also the local ECR heating.

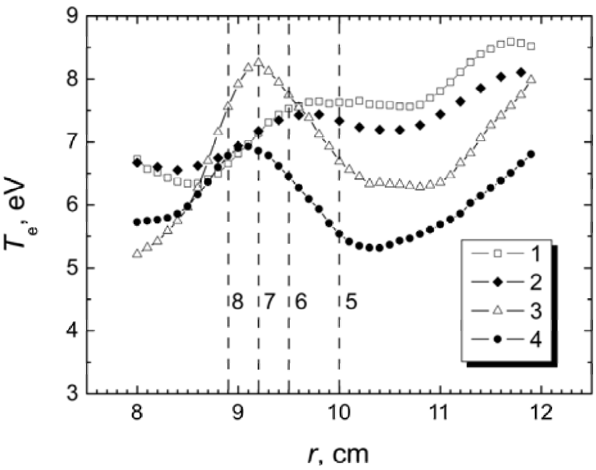

Fig. 5. Radial distribution of the calculated electron temperature as parameters of the frequency and pressure. 1 – $\omega = 27$ MHz, $P = 6.6$ mTorr; 2 – $\omega = 40$ MHz, $P = 3.3$ mTorr; 3 – $\omega = 48$ MHz, $P = 3.3$ mTorr; 4 – $\omega = 54$ MHz, $P = 3.3$ mTorr. Lines 5, 6, 7 and 8 denote radius corresponding to the ECR condition at the rf of 27, 40, 48 and 54 MHz, respectively. Radius of neutral loop is 11 cm.

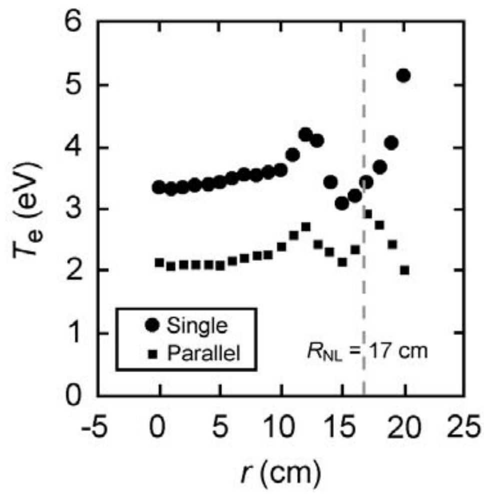

Fig. 6. Radial distribution of the measured electron temperature in NLD plasma using a single turn and parallel turn rf antenna [10]. The operating pressure is about 0.2 Pa (1.5 mTorr), rf is 13.56 MHz and 1 kW.

4. Acknowledgments

This work was supported in part by the Russian Foundation for Basic Research (grant No. 07-08-00497) and the Russian Federal Agency of Education (grant 2.1.1/236) and grant of the President of the Russian

Federation for young scientists No. MK-4082.2007.2.

5. References

[1] H. Tsuboi, M. Itoh, M. Tanabe et. al., Japan. J. Appl. Phys. **34** (1995) 2476.
[2] T. Uchida, S. Hamaguchi, J. Phys. D: Appl. Phys. **41**, 083001 (2008).
[3] Z. Yoshida, H. Asakura et. al., Phys. Rev. Lett. **81**, 2458 (1998).
[4] V.P. Tarakanov. User's Manual for Code KARAT. Springfield, VA: Berkley Research, 1992.
[5] A.V. Arsenin, V.G. Leiman and V.P. Tarakanov, Bulletin of the Lebedev Physics Institute **4**, 15 (2003).
[6] A.V. Arsenin, V.G. Leiman and V.P. Tarakanov, Journal of Communications Technology and Electronics **52**, 906 (2007).
[7] ftp://jila.colorado.edu/collision_data
[8] K. Nanbu, IEEE Trans. on Plasma Sci. **28**, 971 (2000).
[9] M. Surendra, D.B. Graves, I.J. Morey, Appl. Phys. Lett. **56**, 1022 (1990).
[10] W. Chen, K. Sugita et. al. J. Vac. Sci. Technol. A **19**, 2936 (2001).
[11] ChinWook Chung, S. S. Kim et. al., Phys. Rev. E **69**, 016406 (2004).
[12] V.A. Godyak, B.M. Alexandrovich, Physics of Plasmas **11**, 3553 (2004).