ECR plasma heating experiment in the GDT magnetic mirror

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Open magnetic systems for plasma confinement are suitable for a number of nuclear fusion applications. The near term one is a high-power D-T fusion neutron source (see for example [1,2]) capable of producing neutron flux of several MW/m^2. Such neutron flux is required for full-scale neutron-material interaction research, aimed at design of first wall and other structural elements of future fusion reactors. Furthermore, high-power neutron source can be used as a driver for subcritical fission reactors including devices for burning of long lived radioactive wastes [3,4,5]. Finally, a series of studies has shown that open magnetic traps with reasonably improved axial confinement are completely consistent with reactor-level fusion projects with power gain factor $Q \gg 1$. Improvement of axial confinement can be achieved, for example, through the use of ambipolar plugs [6,7] or multimirror end-sections [8]. The most attractive from engineering and physical standpoint are axisymmetric magnetic mirrors. The simplicity of design, intrinsic capability of sustaining high beta plasmas ($\beta \approx 1$), natural channel of impurities and thermonuclear ashes removal, possibility of direct power conversion with near-unity efficiency are crucial benefits of open magnetic systems for plasma confinement.

However, lack of experimental data for the electron temperatures suitable for nuclear fusion applications significantly diminishes the advantages of open systems mentioned above. Low electron temperature, most probably, is caused by high level of axial energy losses which was observed in many experiments. This circumstance accounts for today`s relatively low level of research activity in the field of open systems for magnetic plasma confinement.

This paper presents the first results of auxiliary electron cyclotron plasma heating (ECRH) experiment, which is presently under way on the gas-dynamic trap (GDT, Budker Institute, Novosibirsk) machine – an axisymmetric magnetic mirror with high mirror ratio [9,10]. The plasma confined in GDT consists of two components with different mean energies. First one is so-called warm ions with isotropic Maxwell velocity distribution. These ions are confined in a gas-like (gas-dynamic) regime and thus have isotropic speed distribution due to high collision frequency. The second component is a population of hot ions, which is produced as a result of oblique injection of hydrogen or deuterium neutral beams into the plasma. The hot ions are confined in adiabatic regime which means that their movement is governed by conservation of adiabatic invariants. As a result they are bouncing within the region between two turning points near the magnetic mirrors.

One of the main issues is the magneto-hydro-dynamic (MHD) stability of the bulk plasma, for which the current configuration of the GDT is inherently unstable. To suppress the anomalous transverse transport caused mainly by flute MHD modes, we use a novel technique, which we call “vortex confinement” [11]. Strictly speaking, this method is not meant to suppress MHD modes, but rather to saturate them at a relatively low level by the differential rotation of outer plasma layers induced by an externally applied radial electric field. This produces a vortex-like structure with essentially closed flux lines. In the GDT, the vortex confinement technique is realized by applying a biasing potential between the ring-shaped radial plasma limiters and the central sections of plasma-facing end plates. The vortex confinement results in a stable confinement of hot plasma in the central core region, which appears to be unaffected by peripheral convection. The main conclusion based on the theoretical analysis [11] and experimental results [12] is that the transverse power losses can be limited to the level of 10−15% of the longitudinal (gas-dynamic) losses. Implementation of the vortex confinement in GDT allowed achieving a record value, for axisymmetric traps, of $\beta \approx 0.6$ [12, 13]. To provide an optimal confinement the biasing potential should be of the order of T_e. This condition is easily violated during the fast rise of the electron temperature in ECRH experiments. Thus, to stabilize plasma we need to apply additional voltage to the plasma periphery during the ECRH phase.

Energy confinement times of hot ions as well as their velocity spread are determined mostly by the collisional slowing-down on the bulk electrons. Since the collisional time $\tau_{ei} \propto T_e^{3/2}$, the electron drag force is rapidly decreasing with increasing electron temperature. For this reason, electron temperature is the main factor limiting the

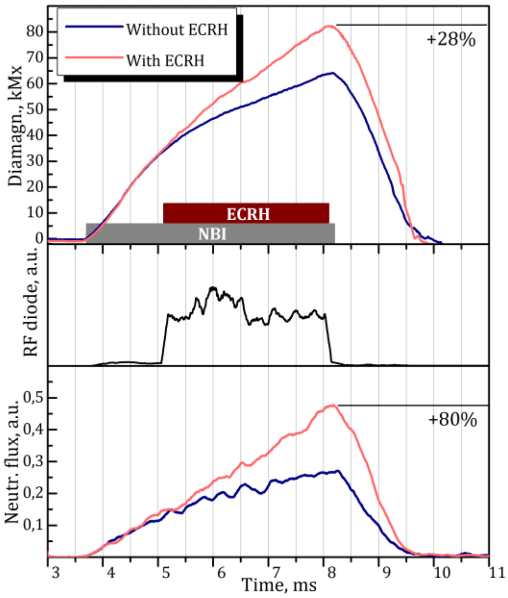

Fig. 1. Diamagnetic signal of fast ions with and without ECRH in magnetic configuration with broad power deposition (top). Stray radiation signal (middle) illustrating steady absorption of microwave power. D-D neutron flux signal (bottom) [18].

confinement time of fast ions and thus the power efficiency of a beam-driven fusion reactor based on a magnetic mirror. To significantly raise the electron temperature and thus the overall energy confinement time of the hot ion component, an electron cyclotron resonance (ECR) heating system based on two 450 kW/54.5 GHz gyrotrons was designed and installed. The crucial part of the heating scheme [14] is the strong refraction of the microwave beam in the inhomogeneous magnetized GDT plasma, which allows the beam to reach the ECR region. Technical details of ECRH system at the GDT are described in Ref. [15].

Two distinct modes of ECR heating were established which we call the "core heating" and the "broad heating". In the core heating mode the electron temperature increased only within a few centimetres from the device axis and the ECR heating started after 2 ms of NB injection. After approximately 0.3 ms the electron temperature, measured by laser scattering on the axis of the machine, increased from 200 eV (without ECR) to 400 eV, while the scattered spectrum indicated that the electron velocity distribution remained Maxwellian [16]. Shortly after this we observed an MHD activity, which dramatically increased the radial losses. In the broad heating mode the ECR surface had been shifted by 3 cm towards the mirror and the heating started 1 ms earlier. This resulted in a much wider power deposition and much more stable plasma (was stable during the whole time of NB operation). There was also a strong rise both in diamagnetic signal and in the neutron flux from D-D reactions (see Fig.1.), which might be of impotance in thermonuclear applications of the GDT device. In the next experiment the core heating mode was essentially stabilized by appling an additional (two-step) biasing voltage to the limiter to provide more optimal regime of vortex confinement. The sceme allowed adding limiter voltage during the shot at a specified time moment. The time of stable ECR heating was increased up to 0.6 ms what resulted in the record electron temperature more than 900 eV registered at the GDT to date. Plasma density in this mode was $0.65 \cdot 10^{19}$ m^{-3}. Even though

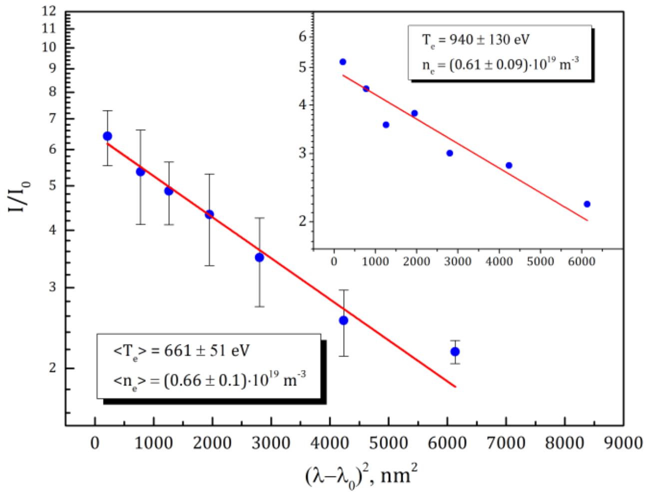

Fig. 2. Electron energy spectrum measured by Thomson scattering on the axis and averaged over 7 consecutive shots. Fit of these data suggests a Maxwellian electron distribution function with an electron temperature of 660 ± 50 eV and a density (0.66 ± 0.10) × 10^{19} m^{-3}. The same data for one of the shots with an electron temperature above 900 eV is shown in the insert [17,18].

the MHD activity is still present, it no longer leads to the dramatical loss of the entire plasma and tends to become less destructive with the increase of the limiter potential jump. The energy spectrum of heated electrons is close to Maxwellian (see Fig. 2.). We find that our theoretical understanding of resonant plasma heating has been proven experimentally, thus the proposed novel ECRH scheme works quite robustly. The measured increase of electron temperature to nearly 1 keV along with the previous experiments, which demonstrated plasma confinement with β ≈ 60%, provide a firm basis for extrapolating the gas dynamic trap concept to fusion-relevant applications [17,18].

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