EPJ Web of Conferences 187, 01017 (2018) https://doi.org/10.1051/epjconf/201818701017
30th Joint Russian-German Meeting on ECRH and Gyrotrons

Status of ECRH experiments at GDT mirror trap

A. G. Shalashov[1,2], P. A. Bagryansky[2], E. D. Gospodchikov[1,2], L. V. Lubyako[1,2], Z. E. Konshin[2], V. V. Maximov[2], V. V. Prikhodko[2], V. Ya. Savkin[2], O. B. Smolyakova[1,2], A. L. Solomakhin[2], D. V. Yakovlev[2]

[1]Institute of Applied Physics RAS, Nizhny Novgorod, Russia, ags@appl.sci-nnov.ru
[2]Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia

The paper summarizes the recent results of experiments on electron cyclotron resonance plasma heating (ECRH) and electron cyclotron emission (ECE) diagnostics at the GDT facility in Budker Institute, Novosibirsk. The design, physics of plasma confinement, and main goals of the machine are described in [1]. The gas-dynamic trap (GDT) is an axially-symmetric magnetic mirror device with a 7-m-long central cell and two expander cells at both ends (fig. 1). Previously we reported on plasma discharges with a very high temperature of bulk electrons achieved at this facility: up to 900 eV at the plasma density about 0.7×10^{19} m^{-3} [2]. This is more than a threefold increase with respect to previous experiments both at GDT and at other comparable machines. The breakthrough is made possible by the application of 0.7 MW 54.5 GHz ECRH in addition to standard 5 MW heating by means of neutral beam injection (NBI) [3-5].

While the previous experiments confirmed the core principles of longitudinal electron heat flux suppression in a gas-dynamic trap, it faced difficulties with mitigation of anomalous transport related to the development of MHD instability of the plasma column. In particular, when the microwave power was focused in a narrow axial plasma region thereby leading to a highly peaked electron temperature profile, the duration of effective heating was always limited to about 0.6 ms; later on, a flute instability developed preventing further absorption of microwaves.

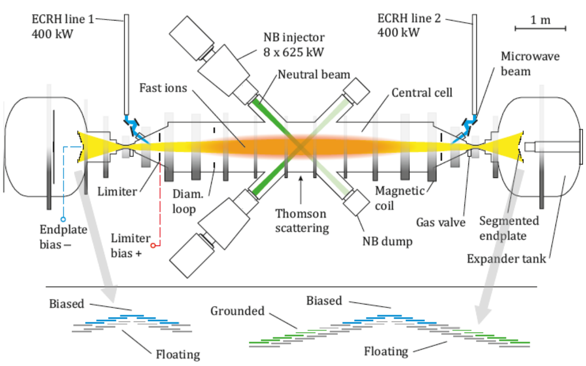

Fig. 1. Schematic of the GDT experiment. In the bottom we show new plasma-facing endplates for tuning of the radial distribution of plasma potential in the axial region.

During last experiments, we demonstrate the possibility of suppressing the MHD activity driven by localized ECRH using a new method for controlling the plasma differential rotation with the help of ring electrodes at the ends of the trap [6]. As a result, we demonstrate plasma discharges with parameters close to the reported record ones, but characterized by low MHD activity level and duration limited only by the available heating and magnetic confinement systems. In particular, a stable electron heating up to 450 eV during 1.5 ms period with ECRH power of 400 kW is attained for the first time at GDT.

A typical scenario is shown in fig. 2. The discharge is initiated in deuterium by electron cyclotron waves generated by second available gyrotron [7]. In the end of the start-up phase, the target plasma is heated with 5 MW NBI. At 7 ms, the additional 0.4 MW ECRH is switched on. Figure shows the evolution of on-axis electron temperature in the trap center for stabilized and non-stabilized discharges at otherwise identical experimental conditions. One see, when the end-plate potential U_{ep}<-400 V is applied, the electron temperature stays within the range of 350-450 eV for more than 1 ms while the plasma is MHD-stable throughout the whole ECRH duration, see "▲". Some decrease of the temperature at the end of the heating period is caused by detuning from optimal ECRH conditions due to the time variation of the magnetic field and drop in heating power at the end of the NBI pulse. Downward triangles "▼" illustrate cooling of bulk electrons immediately after ECRH is switched off while the stabilizing bias is still being applied. In agreement with previous observations, a discharge with on-axis ECRH but without the additional bias, ends in rapid degradation of plasma confinement. see "♦".

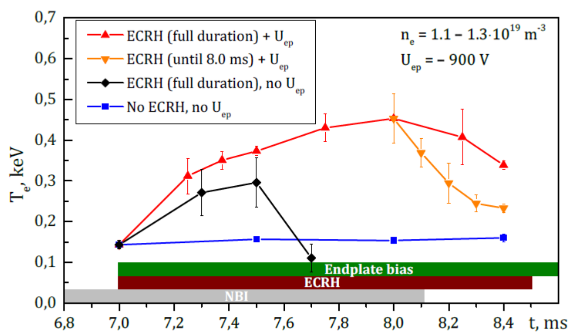

Fig. 2. On-axis electron temperature for: ▲stabilized full-time ECRH, ▼ stabilized ECRH with switch-off at 8 ms, ♦ not-stabilized ECRH, and ■ pure NBI discharges

Thus, we have shown experimentally that a local modification of the radial distribution of the plasma potential allows for a complete suppression of the MHD-instability caused by strong ECR heating and enables to maintain a high-T_e plasma in a large mirror trap. The minimum value of the external potential sufficient for stabilizing the plasma is quite modest (~400 V), so likely our technique may be extrapolated to higher temperatures and to larger devices without overwhelming engineering difficulties.

Attainment of quiescent discharges enables to perform more detailed studies of high-T_e transport physics not possible in MHD-unstable plasma. Of particular interest is the evolution of radial profiles of the electron temperature when ECRH is switched off, but the bias is maintained, see fig. 3 (top). In this case, the MHD effects in the core region of plasma can be excluded and the series of smoothly decaying profiles can be used to study plasma confinement [6]. An example for reconstructed radial profiles of electron energy fluxes, including ECRH "▲", electron heating from slowing-down of fast ions "▼" and gas-dynamic losses "■", recovered by fitting of transport equations to the experimental profiles is shown in fig. 3 (bottom). One finds that gas-dynamic losses are dominating, while the deposition of radial transport is less than 5% at each displayed point.

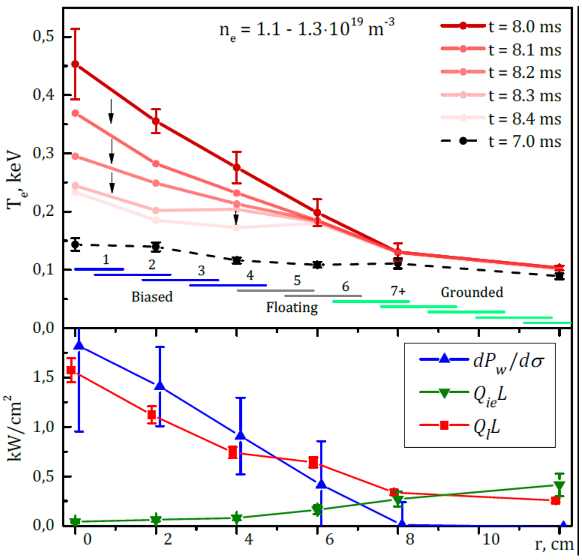

Fig. 3. Top panel: measured evolution of the electron temperature radial profiles at the trap center after ECRH switch-off. Bottom panel: reconstructed radial profiles of electron energy fluxes at $t = 8$ ms.

A new diagnostic system has been introduced at the GDT, allowing registration of plasma ECE at 75 GHz in a geometry corresponding to a possible scheme of ECR heating at the second harmonic of the extraordinary wave. With the help of this diagnostic, the spontaneous emission of fast electrons generated during microwave plasma heating is registered for the first time during the main phase of the plasma discharge, see fig. 4. According to the new data, the energy and lifetime of fast electrons are determined and the classical regime of their confinement is confirmed for the main phase of the plasma discharge. With the previous ECE system at the fundamental EC harmonic, these measurements were difficult since the emission of fast electrons was effectively screened by the bulk plasma [8].

Measured ECE data from thermal (bulk) electrons measurements is in reasonable agreement with theoretical expectations. However, to reproduce thermal ECE with a ray-tracing modeling, we must reduce the electron density as compared to the value measured independently at the central cross-section with TS diagnostics. This may indicate the influence of the ambipolar potential barrier formed by sloshing fast ions in the GDT conditions.

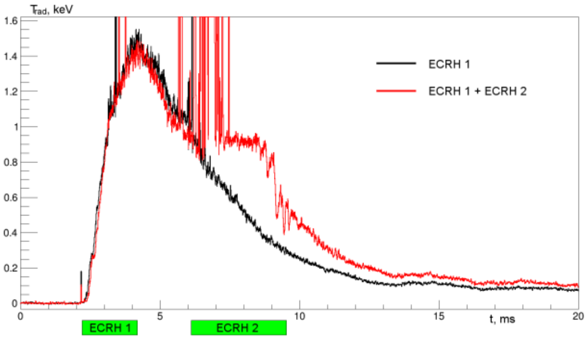

Fig. 4. Example of X2 ECE signal from fast electrons generated by one and two consecutive ECRH shots.

Next experimental campaign will be aimed at essential increase of fast ion confinement and neutron flux. New scenario is proposed theoretically with very flat ECRH power deposition profile that eventually provides high average T_e [9,10]. A new plug-in unit has been designed, manufactured and tested for GDT magnetic system upgrade for the planned experiment on ECR heating with the wide power deposition.

The work is supported by the Russian Scientific Foundation (pr. 14-12-01007).

References

1. *Ivanov A. A., Prikhodko V. V.* Gas-dynamic trap: an overview of the concept and experimental results // Plasma Phys. Control. Fusion. 2013. V. 55. P. 063001.

2. *Bagryansky P. A., Shalashov A. G. et al.* Threefold increase of the bulk electron temperature of plasma discharges in a magnetic mirror device // Phys. Rev. Lett. 2015. V. 114. P. 205001. (arXiv:1411.6288).

3. *Bagryansky P. A., Kovalenko Yu. V., Savkin V. Ya. et al.* First results of an auxiliary electron cyclotron resonance heating experiment in the GDT magnetic mirror // Nucl. Fusion. 2014. V. 54. P. 082001.

4. *Bagryansky P. A., Gospodchikov E. D., Kovalenko Yu. V. et al.* ECR heating experiment in the GDT magnetic mirror: recent experiments and future plans // Fusion Sci. Technol. 2015. V. 68. P. 87.

5. *Bagryansky P. A, Anikeev A. V., Denisov G. G. et al.* Overview of ECR plasma heating experiment in the GDT magnetic mirror // Nucl. Fusion. 2015. V. 55. P. 053009.

6. *Yakovlev D. V., Shalashov A. G., Gospodchikov E. D. et al.* Stable confinement of high-electron-temperature plasmas in the GDT experiment // Nucl. Fusion. 2018. (https://doi.org/10.1088/1741-4326/aacb88)

7. *Yakovlev D. V., Shalashov A. G. et al.* Electron cyclotron plasma startup in the GDT experiment // Nucl. Fusion. 2016. V. 57. P. 016033. (arXiv:1607.01051).

8. *Shalashov A. G., Solomakhin A. L. et al.* // Phys. Plasmas. 2017. V. 24. P. 082506. (arXiv:1611.09137).

9. *Shalashov A. G., Balakin A. A. et al.* Quasi-optical theory of microwave plasma heating in open magnetic trap // Phys. Plasmas. 2016. V. 23. P. 112504.

10. *Shalashov A. G., Balakin A. A., Khusainov T. A. et al.* Quasi-optical simulation of the electron cyclotron plasma heating in a mirror magnetic trap // JETP. 2017. V. 124, No 2, P 325.