EPJ Web of Conferences **149**, 03005 (2017) DOI: 10.1051/epjconf/201714903005
10th International Workshop 2017 "Strong Microwaves and Terahertz Waves: Sources and Applications"

Electron-cyclotron waves in large-scale open traps: new questions highlighted by recent experiments

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The absorption of electromagnetic waves under the electron cyclotron resonance (ECR) conditions is widely used for heating of high-temperature plasmas in tokamaks and stellarators. However, for many years the use of this method in open magnetic traps has been limited either by plasma heating in compact technological devices, such as ECR sources of multiply-charged ions and X-ray radiation [1–3], or by stabilizing of low-density plasma in fusion-relevant experiment, first of all, in GAMMA-10 at Tsukuba University [4]. This tandem mirror trap is equipped with a complicated ECRH system, including five 28 GHz high-power gyrotrons. The plug and barrier ECRH generate the axial ion-confining potential and the thermal barrier potential for electrons, respectively; thus, ECRH power is utilized to increase the confining potentials and to control of internal transport barrier formation [5]. The central-cell ECRH is aimed at increase of the bulk electron temperature, but this feature has not been demonstrated convincingly.

Until recently, the only example of the bulk electron heating in the large mirror trap was TMX-U experiment at LLNL. There the electron temperature up to 0.28 keV was obtained with ECRH at 28 GHz, but these studies were concluded soon [6]. The ECR heating of a dense plasma, comparable to those in toroidal devices, has been demonstrated in a large-scale mirror trap only in 2013. We mean successful experiments on combined plasma heating by neutral beams and 54.5 GHz fundamental harmonic X-mode ECRH performed at the Gas Dynamic Trap (GDT) in Budker Institute [7–10]. Here, a highly-localized heating of the bulk electrons leads to achieving the record for open traps electron temperature of 1 keV [8]. These studies demonstrate good prospects for the use of simple axially symmetric open traps as a powerful source neutron for fusion applications [11]. Therefore, GDT may be considered as a prototype of the next-step fusion reactors.

Note that GDT, being comparable to GAMMA-10 in dimensions and confining magnetic fields, is operated at about an order of magnitude more dense plasma, what results in very different electrodynamics conditions in these two devices. Namely, $\omega_{pe}/\omega \sim 0.8$ in GDT and $\omega_{pe}/\omega \sim 0.15$ in GAMMA-10 with ω_{pe} and ω being, correspondingly, the electron Langmuir frequency and ECRH frequency (which is close to the fundamental electron cyclotron harmonic, $\omega_{ce} \sim \omega$). In this sense, the plasma is rarefied in GAMMA-10 and relatively dense in GDT. The latter makes the refraction of radiation essential at the GDT conditions.

Implementing the efficient heating of a dense plasma at large open traps requires a revision of the prevailing ideas about the physics of cyclotron absorption [12] as well as the subsequent transport of energy and MHD stabilization of a plasma column [13]. In compact traps, millimeter wave radiation of a high-power gyrotron is usually launched from the trap end along the ambient magnetic field; such scheme allows matching the radiation and dense plasma at the plasma interface [14]. However, in a large device, this option is not possible due to obligate expander elements at the trap ends where radiation meets a cut-off. Thus, the heating radiation may be launched only through side walls of a vacuum chamber. Because of very different magnetic topology, none of the well-understood ECRH schemes developed for the toroidal plasma works well in a large open trap.

The primary ECRH scheme at GDT relies on a radiation trapping by a non-uniform plasma column [12]. This effect is caused by the dependence of the plasma refraction on the magnetic field strength. The radiation is launched obliquely through a side of a plasma column at high magnetic field (close to the magnetic mirror). As the microwave beam propagates in plasma in the direction of the trap center, the magnitude of the magnetic field decreases resulting in conditions for an internal reflection from the plasma-vacuum boundary. The plasma column acts as a kind of waveguide, heterogeneous in both transverse and longitudinal directions, whereby the radiation is delivered to the fundamental ECR surface with **k**-spectrum and polarization favorable for absorption.

This entirely new ECRH scenario substantially depends on a magnetic configuration and plasma inhomogeneity. Although successful ECRH experiments evidence for the reliability of such heating mechanism, a new electron cyclotron emission (ECE) diagnostics has been installed to improve understanding of complex wave physics in GDT [15]. The idea is to exploit the reciprocity principle: conditions favorable for the ECRH should manifest themselves as an increased ECE level of thermal electrons along the same line of sight. Thus, the new ECE diagnostics operates near the heating frequency in the geometry reversed to the ECRH one. Measured thermal emission for different discharge scenarios has essentially validated the existing physical conceptions about the microwave heating in the machine [16]. Somewhat against our expectations, it has been found that ECRH may start from weakly absorbing plasma, but during the discharge the evolution of the electron temperature leads to an eventual transition to optically thick plasma; before we believed that ECRH always starts with optically thick plasma.

Numerical modeling of the propagation and absorption of electromagnetic waves plays an important role both in preparing and understanding of the last ECRH/ECE experiments. Until recently, such modeling was only possible in the framework of the geometric optics approximation also known as ray-tracing. Combined with the Fokker-Planck quasi-linear kinetic equation for the

ECRH-driven electron distribution function, the ray-tracing works perfectly well for the low-density plasma [17]. However, for the new high-density scenario, the geometric optics may not be valid in a vicinity of wave reflection surface due to formation of caustics, and near ECR surface due to a sharp inhomogeneous damping of waves. Straightforward simulation of these effects for large devices within a complete set of Maxwell's equations is not practical, in particular, because of smallness of the wavelength. A good alternative is the consistent quasi-optical approach based on the paraxial asymptotic expansion of Maxwell's equations in an inhomogeneous dissipative media with spatial dispersion [18], recently adopted for open traps [19, 20]. New approach lets to adjust the magnetic configuration to improve the rf-power deposition profile.

Another important issue is related to fast electrons and plasma micro-instabilities generated by strong ECRH. The fraction of fast electrons in GDT is moderate compared to other devices. Indeed, an efficient power deposition into the thermal plasma component is considered as one of the major achievements of this experiment. Nevertheless, suprathermal electrons play an essential role in ECR plasma start-up recently implemented at GDT: electrons with energies about 10 keV are entirely responsible for the gas ionization and plasma pressure at initial stages of gas breakdown and seed plasma build-up [21]. Measured non-thermal ECE have unambiguously confirmed the existence of suprathermal electrons generated during the ECR heating of the main plasma [16]. Explanation of time dependence of ECE level observed in the varying magnetic field and decaying plasma is a rather challenging task. Our current hypothesis is based on the concept of stimulated micro-instabilities that cause fast losses of suprathermal electrons. Such instabilities are observed at GDT as broadband electromagnetic pulses in 5–50 GHz band and synchronized precipitations of fast electrons. Despite some similarities to kinetic EC instabilities in small traps [22], detailed explanation of such events is still a matter of our efforts.

A high-power neutron source based on GDT concept will operate at higher relative pressures β and densities [23]. In this context, ECRH at the second harmonic is attractive; however, it is efficient only in combination with heating at the first harmonic providing the initial high electron temperature. Possibilities to test such regime in GDT are discussed [24].

Another class of next-step devices, advanced reversed-field-configurations [25, 26], is characterized by even more high values of $\beta \sim 1$. For electrodynamics, this implies $\omega_{ce} << \omega_{pe}$. A convenient way to heat such overdense and weakly magnetized plasma is based on a linear transformation of high-frequency electromagnetic waves into quasi-electrostatic waves near the plasma upper-hybrid resonance. Surprisingly, the correct theory of such coupling in high-β plasma was developed just recently [27]. A rigorous approach based on exact Maxwell's equations not only correct the traditional qualitative views on wave coupling but reveals some new options for the efficient transformation of electromagnetic waves into damped quasi-electrostatic oscillations in high-β plasmas.

The author thanks to all colleagues from IAP and BINP involved in this study. The work was supported by the Russian Science Foundation (pr. 14-12-01007).

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