Experimental Study of Coupling of Low-Frequency Electromagnetic Waves with Plasma in Strong Magnetic Field

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Abstract. Helicons (circularly-polarized electromagnetic waves) propagate in a plasma with density exceeded cut-off for its frequency, and provide effective energy delivery to plasma. Accordingly, helicon discharge is one of the most suitable way for production of high-density low-temperature plasma. Helicon plasma sources, operating in the MHz frequency range and respectively low magnetic fields (0.01-0.1 T), capable to create plasma with density up to 10^{13} cm^{-3}. At the same time, next generation of linear plasma facilities for both for PMI studies and fusion applications requires production of plasma with density above this limit. Theoretical studies predict that such increasing of density can be achieved by application of powerful microwave sources of GHz range frequency. The aim of the presented experiments is experimental verification of theoretical predictions and search of conditions for effective delivery of electromagnetic power to plasma towards development of stationary source of dense plasma for linear facilities. Interaction of 2.45 GHz electromagnetic radiation with low-temperature plasma column, confined in a strong magnetic field, was studied on the GOL-3 facility. Plasma was created by external source (arc plasma gun) placed on the edge of the facility. Microwave power is transferred from moderate power (1.4 kW) magnetron source to o-ring antenna, separated from plasma column by quartz tube. Coupling of antenna with plasma (reflected-to-direct wave ratio) are measured for various magnetic fields in the facility. First results of the measurements are presented in the paper.

INTRODUCTION

Linear magnetic traps with intensive neutral beam injection are considered as a perspective scheme of a neutron source for material testing or fusion-fission reactor control [1-6]. Such a traps should confine two-component plasma, consisting of population of sloshing fast ions, provided by the beam injection, and warm target plasma. The later is required for a beam capture and suppression of instabilities. Up to now, such target plasma is created by plasma guns, mounted on the ends of a trap. In particular, GDT facility, operating in Budker INP, use this approach [7,8], and it is planned to apply on the novel facilities GOL-NB [9,10] and SMOLA[11], that is now under construction. At the same time, arc plasma guns have several disadvantages, which prevent their use in next generation of linear fusion facilities. Main problem is strong heat sink to arc generator and corresponding plasma cooling, which cause loss of energy confinement of fast ions. Additional problem is limitation of pulse duration of arc generators by several milliseconds due to overheating of electrodes, which makes them irrelevant for the quasi-stationary systems like GDMT project [12,13]. Promising way to overcome these problems is the application of electrodeless microwave discharge for creation and sustaining of target plasma. Recently electron-cyclotron (ECR) breakdown and start-up was successfully

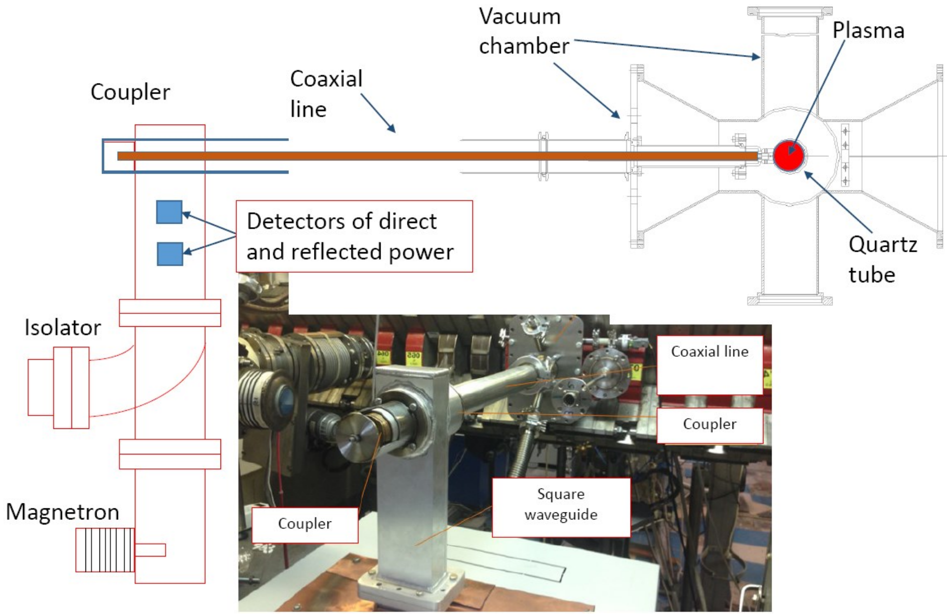

FIGURE 1 Scheme of connection of microwave generator

demonstrated on GDT facility [14]. Another possible technique, that is not required sophisticated and expensive mm-wave radiation sources – gyrotrons, is the use of helicon discharge.

Helicons - left-hand circularly polarized waves with frequencies below cut-off plasma frequency – can propagate in the plasma confined in the magnetic field [15]. Several effects cause effective absorption of the energy of these waves by plasma. Therefore, helicons is widely used for production of low-temperature plasma in different applications, but majority of these systems restricted by plasma density below 10^{13}cm^{-3} and magnetic field on the range 10^{-2} T with the use industrial 13.6 MHz RF generators. Features of fusion applications is strong magnetic field (0.1-5 T) and high plasma density (~10^{14}cm^{-3}). Scaling low and simulations shown, that radiation with frequencies of GHz range and power in order of 100 kW are required for excitation of helicon waves and sustaining of such plasma. Fortunately, 915 or 2450 MHz magnetrons with mentioned power are routine equipment widely used in industry, that open possibility to consider helicon discharge as a tool for generation of a target plasma in novel facilities. Another possible application of such system is steady-state linear plasma facility for fusion material testing.

Since the proposed scheme is novel and there are no information about helicon discharge systems operated in chosen parameter range (high density, high magnetic field, high frequency), preliminary experiments required before designing of full-scale discharge system. Main challenge of the design is a choice of configuration of an antenna, which should provide coupling of microwave power with plasma. Preliminary tests of antenna can be done in the

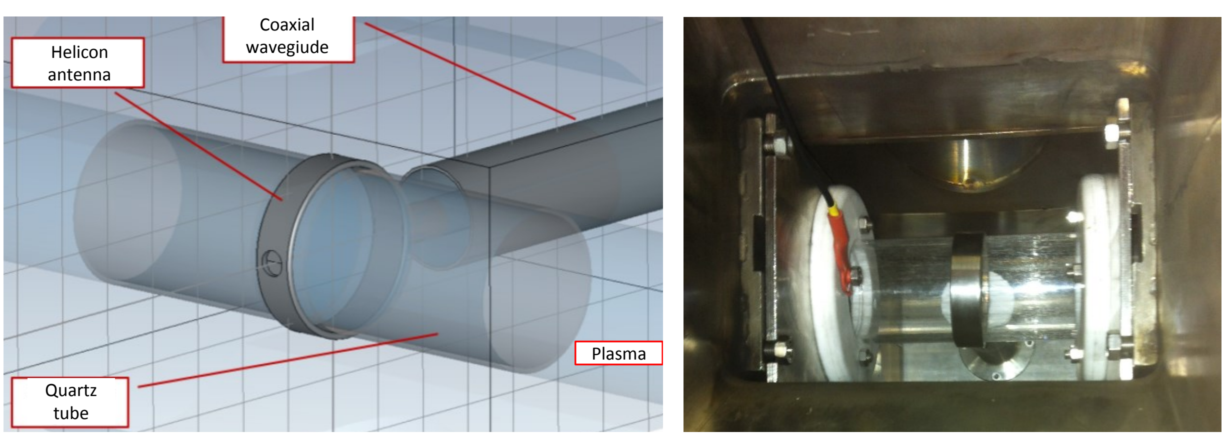

FIGURE 2 Microwave antenna unit in the vacuum chamber of GOL-3 facility

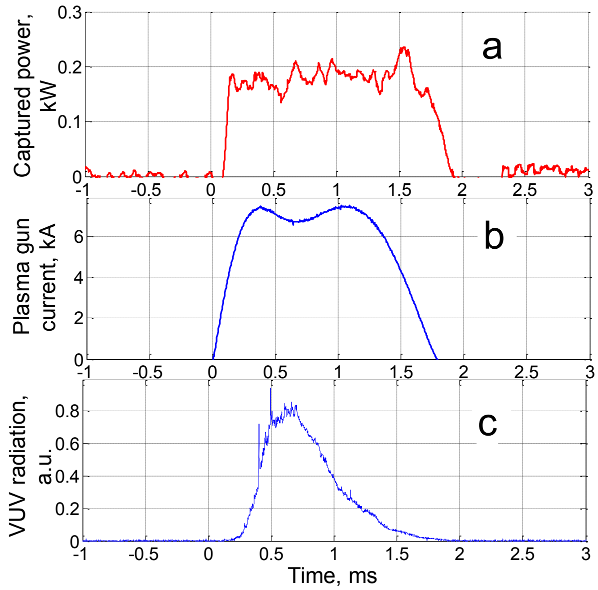

FIGURE 3 Waveform of captured microwave power (a), current of plasma gun (b), and VUV radiation from plasma, measured by wide range X-ray photodiode; magnetic field 0.3 T, plasma density 10^{14}cm^{-3}

"cold" experiments on GOL-3 facility. Main idea of these experiments is measurements of coupling of antenna with plasma column with controlled density created by external source. Experimental configuration and first results of measurements of interaction of EM wave with plasma are presented in the paper.

EXPERIMENTAL SETUP

GOL-3 facility is an axially-symmetric linear trap initially intended to study plasma heating by relativistic electron beams and it's confinement in a multimirror magnetic field. Recently, deep upgrade of facility was started, the main aim of which is creation of new facility GOL-NB, capable to provide experimental verification of enhanced confinement of gas-dynamic trap with multimirror end plugs. On the present day, the facility represents 8-meter long solenoid with an arc plasma gun attached at the one end. Facility can be switched between uniform and multimirror magnetic field with magnetic field value arranged from 0.5 to 4.5 T. Plasma gun produces plasma column with density up to 10^{14}cm^{-3}. Diameter of the plasma can be varied from 0.5 to 4 cm by changing of relation between magnetic fields on the plasma gun and in the solenoid.

Experimental study of EM wave interaction with plasma was performed in the special cell in the center of the facility. The cell, initially designed for neutral beam injection, represents 20-cm-long section of vacuum chamber with diameter, increased to 146 mm. One coil of the solenoid was taken away for increasing of dimensions of ports, so magnetic field on the cell represents local mirror trap with mirror ratio 1.8.

The scheme of microwave generator connection is shown in Fig.1. Microwave power was produced by 1.4 kW household 2.45 GHz magnetron, mounted in the R26 square waveguide. Magnetron is separated from antenna unit by ferromagnetic isolator to avoid influence of coupling efficiency to generation of microwave power. Direct and reflected power are measured by DD112 detectors from S-Team lab, mounted in the waveguide after isolator. Magnetron unit is connected to antenna by coaxial transfer line via specially designed waveguide-coaxial coupling unit. Experiments shown that power transfer line, connected to matched load, provide reflection below 5% of input power.

Simple circular antenna with capacitive coupling with plasma is used in the first experiment. The reason of choosing of such simplest geometry is that this antenna can excite wide range of modes in plasma, therefore it should be nonselective according plasma density and magnetic field.

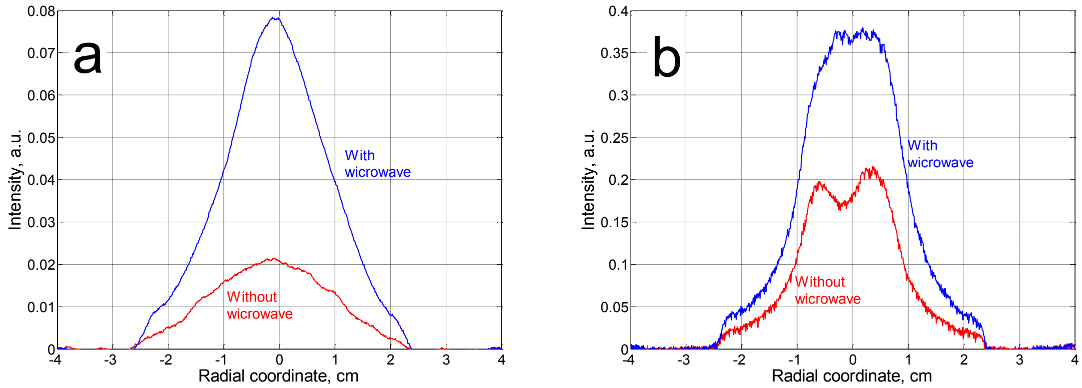

FIGURE 4 Profiles of plasma radiation in visible range with and without microwave power; a – magnetic field 0.3 T, b – magnetic field 1.7 T.

RESULTS OF EXPERIMENTS

Without presence of plasma the antenna unit reflects about 90% of microwave power. A power, captured by plasma, was calculated as a difference between power, being reflected with and without plasma. Waveforms of captured power and related signals are shown in Fig.3 The value of captured power – about 200 W or 15% of incoming power – practically independent on magnetic field of facility in the range 0.3-2.5 T. Duration of observed pulse of absorption correspond to duration of plasma gun operation and existence of plasma in the facility.

Influence of microwave power to plasma was indentified on the images of plasma radiation taken by CCD camera. Profiles of plasma radiation across the plasma column are shown in Fig.4 for magnetic field 0.3 T (Fig. 3a) and 1.7 T (Fig.3b). Despite captured microwave power sufficiently less than power, released in the plasma gun, microwave cause valuable increasing of light emission and also transformation of the radial profile of emission.

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REFERENCES

[1]. A.Anikeev, V.Prikhod'ko, D.Yurov, "Progress in Mirror-Based Fusion Neutron Source Development" Materials **8**, 8452-8459 (2015)

[2]. A.Anikeev V.Prikhod'ko, D.Yurov, "Parameters of a Fusion Neutron Source Based On The Recent GDT Experimental Data And Possible Applications" Fusion Sci. Technol. **68**, 70-75 (2015)

[3]. A.Anikeev et al, "Mirror based fusion neutron source: current status and prospective" AIP Conf. Proc. (these proceedings)

[4]. D.Yurov and V.Prikhod'ko, "Hybrid systems for transuranic waste transmutation in nuclear power reactors: state of the art and future prospects" Physics-Uspekhi, **57** 1118-1129 (2014)

[5]. D.Yurov *et al.*, "Recent Calculation Results for a Fission-Fusion System with Gas Dynamic Trap Neutron Source" Fusion Sci. Technol. **68 (1T)**, 313-315 (2013)

[6]. A.Arzhannikov et al., "Subcritical assembly with fusion neutron source as a device for studies of neutron-physical characteristics of thorium fuel" AIP Conf. Proc. (these proceedings)

[7]. A.Anikeev et al, "The GDT experiment: status and recent progress in plasma parameters" Fusion Sci. Technol. **68** , 1-7 (2015)

[8]. E.Soldatkina et al.,"Study of plasma electron thermal conductivity in themagnetic mirror" AIP Conf. Proc. (these proceedings)

[9]. I.Ivanov et al., “Transportation of plasma jet in GOL-NB multiple-mirror trap” AIP Conf. Proc. (these proceedings)
[10]. V.Postupaev et al., “Experiments on the transportation of a magnetized plasma stream in the GOL-3 facility” Plasma Physics Reports, **42**, 319-326, (2016)
[11]. A.Sudnikov et al., “Concept Exploration Helical Mirror Device: Design and Status” AIP Conf. Proc. (these proceedings)
[12]. A.Beklemishev et al., “Novosibirsk project of gas-dynamic multiple-mirror trap” Fusion Sci. Technol. **63** (1T), 46-51 (2013).
[13]. S. Polosatkin et al., “GDMT-T: superconducting linear device for PMI studies” Fusion Sci. Technol. **63** (1T), 184-187 (2013).
[14]. D.Yakovlev et al., “ECR discharge startup in the Gas Dynamic Trap” AIP Conf. Proc. (these proceedings)
[15]. S. Polosatkin, *et al.*, Rev. Sci. Instrum. **85**, 02A707 (2014).
[16]. F.Chen “Helicon discharges and sources: a review” Plasma sources science & technology **24** 014001 (2015)