Tornado type closed magnetic trap for an ECR ion source

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I.   INTRODUCTION

At present time the most widely used sources of multicharged ions (MCI) are ECR sources that exploit a mirror magnetic trap for plasma confinement and microwave radiation for plasma heating at electron gyrofrequency. Such devices sustain sufficiently high electron temperature for multiple gas ionization as well as provide a fairly long-duration plasma confinement for achievement of high ion stripping rate. In addition, they enable one to extract an ion beam, which is then transported for a few tens of meters to the consumption region [1]. If ideal, plasma losses from such a trap are determined by plasma leakage along the axial magnetic field through the trap plug where an extractor is set. Longitudinal losses limit the ion lifetime in a trap and, consequently, the stripping rate of multicharged ions [2].

The use of traps with a closed structure of magnetic field lines seems alluring for increasing plasma confinement time that can be essentially greater (as a ratio of longitudinal and transverse, in respect to the magnetic field, rates of plasma diffusion) than in a simple mirror trap. An apparent shortcoming of closed traps is complicated ion extraction. Tornado type closed magnetic traps [2] can solve this contradiction. They allow for using a supplementary coil that partially destroys the closeness of magnetic field lines but yet does not alter drastically the over-all plasma confinement time. This allows for regulation of plasma outflux by varying the magnetic field of the supplementary coil, i.e. there appears an opportunity to control a plasma flux into the extractor and govern, within certain limits, the ion confinement time.

In the present paper we propose to use a closed Tornado type trap for creation of an ECR source of MCI. We describe a scenario of cyclotron plasma heating and present the ion charge state distribution (CSD), which can be obtained in Tornado-322 trap. Tornado-322 trap has been fabricated this year and is now being tested [3].

II. TORNADO TRAP

The feasibility of creating a closed magnetic system with a magnetic field increasing towards the periphery was shown nearly 40 years ago. Then a device, which enables one to create such a magnetic field, was proposed. The magnetic structure, which was called Tornado, can be used as a magnetic trap for confinement of hot dense plasmas. The Tornado type magnetic field can be produced by two currents flowing through a couple of concentric helical conductors connected at the poles by two jumpers (Fig. 1).

Fig.1. External appearance of Tornado-322 trap

Later realization of such a field was demonstrated analytically. Its magnetic configuration has got a spherical separatrix that divides the magnetic field into two regions. The magnetic field lines inside the separatrix encircle the inner helical conductor and keep to the volume confined by the separatrix, whereas, outside the separatrix the magnetic field lines encircle the outer helical conductor and can go to the infinity. The volume within the separatrix is used for plasma confinement [2]. This volume includes a region of reduced magnetic intensity surrounded by a magnetic barrier. The magnetic field forms a regular and stable system (Fig. 2).

A series of independent experiments on the system confinement properties have been performed. They have convincingly proved the following: the magnetic structure is closed; the plasma confinement time reaches its maximum when the values of conductors'

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[1] A project of a built-in ECR MCI source is discussed in Ref. [1]. The MCI source, installed inside the cyclotron accelerator, is free from the system of ion transfer.

[2] The efficiency of multicharged ions generation in a plasma is determined by the plasma confinement time,

currents meet the condition of the spherical separatrix existence; the major channels of plasma losses (for plasmas with the electron temperature of 2-5 eV) are the classical diffusion and recombination. It should be emphasized that in the present paper we assume that the latter statement is still valid over much greater electron temperatures.
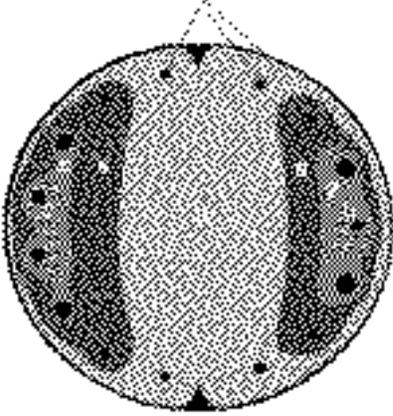

Fig. 2. Regular field - line structure inside the separatrix. 1, 2, 3, 4 - regions built of generalised magnetic lines; 5 - region built of individual magnetic lines.

At the electron density less than 10^{13} cm^{-3} the experimentally observed plasma confinement time was found to be directly proportional to the magnetic intensity H squared and inversely proportional to the electron density N_e: $\tau_i^D \sim H^2 ?N_e^{-1}$. Thus, the plasma confinement time in this regime can be written as follows:

$$\tau_i^D \approx \frac{R^2}{D^{ef}} \approx \frac{?R^2H^2T_e^{3/2}}{AN_e\left(T_i + \langle Z\rangle T_e\right)}, \qquad (1)$$

where D^{ef} is the transverse diffusion coefficient; R (cm) is the magnetic barrier width; T_e and T_i (eV) are the electron and the ion temperatures, respectively; Z is average ion charge, $\_ \ 3 \ 10^{-4}$ is a numerical factor; H is given in Tesla; and is the correction factor, which accounts for the complexity of the magnetic field structure. The value of can be derived from comparison of (1) with results of accurate calculations. For numerical simulation was taken to be equal to 1/6, relying on the experience of Tornado trap handling.

Investigations conducted on Tornado-X trap verified these results for the plasma density up to 10^{14}cm^{-3} and 0.25 T magnetic field with a pulse duration up to 2 ms.

At high electron densities, the plasma confinement time, measured experimentally, was restricted by recombination. In this case we have:

$$\tau_i^R \approx \left(?N_e\right)^{-1}, \qquad (2)$$

where is the recombination rate coefficient.

Thus, all the measurements performed on different

structure closeness and stability of the trap in relation to magnetohydrodynamic perturbations. However, for long-duration confinement of a hot plasma it is necessary to increase the magnetic field strength and pulse duration. None of the former models allowed both conditions to be met simultaneously. That's why a new advanced device (Tornado-322) was elaborated and fabricated. Experiments on Tornado-322 have already been started this year [3].

The confinement of relatively hot and dense plasma in Tornado-322 trap must be provided by the following characteristics: 1) The helices are assembled of two elements: a tube maintaining the helical shape of the conductors and conductors inside the tube. 2) The stainless steel tubes contain insulated current-carrying copper wires. This allows one to refuse any insulating materials inside the vacuum chamber and to lower the background pressure. 3) The current-carrying wires are cooled down with a nitrogen vapor. This decreases their conductivity approximately four-fold and increases the magnetic field pulse duration. 4) Turns of the inner helix are placed between those of the outer helix. This moderates pondermotive interaction between the helices' turns and provides an opportunity to raise the magnetic field strength.

The advantage of closed magnetic traps over the mirror traps in terms of plasma confinement could be evaluated as a ratio of the plasma confinement times (for a mirror magnetic trap we use an expression for the classical regime of plasma confinement [4], conventionally exploited in ECR MCI sources):

$$\frac{\tau_i^D}{\tau_i^C} \approx \frac{R^2 ?_{ei}}{D^{ef}} \sim \frac{R^2 ?H^2}{T_e} . \qquad (3)$$

The advantage is the most apparent for high magnetic intensities. For instance, this ratio amounts to 10^5 for Tornado-322 trap (the magnetic field strength is about 2 T) with the electron temperature taken as 100 eV.

III.   ECR PLASMA HEATING

ECR heating of the electron component is the most efficient way to produce strongly nonequillbrium plasmas with parameters optimal for MCI stripping, namely, with hot electrons having the temperature of 1-5 keV and with relatively cold ions having the temperature of several electron-volts. Unfortunately, no experiments have been conducted on microwave plasma heating in Tornado trap, relying on which we could measure the efficiency of ECR heating in this trap. The structure of magnetic field lines in the trap is fairly intricate and, therefore, a detailed analytical study of microwave radiation absorption seems impossible at the present. Nevertheless, some conclusions concerning feasibility of plasma heating can be made form general considerations.

Features of the structure of magnetic field lines do not allow longitudinal launching of microwave radiation (when a wave vector is parallel to the magnetic

terms of radiation absorption in small laboratory devices.

Estimates have shown that at nonlongitudinal launching the one-pass absorption of cyclotron microwaves is weak (plasma is optically thin for normal waves [ ]). One might expect a considerable augment in microwave absorption due to a multi-pass effect (the trap is set into the vacuum chamber, which is a resonator) and, perhaps, under the conditions of upper-hybrid resonance absorption. Aniway, microwave radiation is believed to be absorbed in a broad range of frequencies due to a strong inhomogeneity of the magnetic field in the trap.

IV. FORMATION OF MULTICHARGED IONS IN A TORNADO-TRAPPED PLASMA

Pulse duration of the magnetic field in Tornado-322 trap is less than the plasma confinement time. Thus, in order to investigate formation of the ion CSD, one has to solve a nonstationary set of differential equations for ionization balance of electrons, neutral atoms, and ions of all charge states. Density N_i of ions in the ith charge state is determined by ionization, recombination, charge exchange processes, and by the rate of transverse plasma diffusion:

$$\frac{fN_i}{ft} = (k_{i-1,i}N_{i-1} - k_{i,i+1}N_i + k^r_{i+1,i}N_{i+1} - k^r_{i,i-1}N_i)?N_e$$

$$+ (k^{ex}_{i+1,i}N_{i+1} - k^{ex}_{i,i-1}N_i)?N_0 - \frac{N_i}{}, \quad (4)$$

where $k_{i,i+1}$ is the electron impact ionization rate coefficient (Lotz formula [5] was employed in computations), $k^r_{i+1,i} = k^{rr}_{i+1,i} + k^{dr}_{i+1,i}$ is the sum of radiative recombination [6] and dielectronic recombination [7] rate coefficients, and $k^{ex}_{i+1,i}$ is the rate coefficient of charge exchange process [8] due to collisions with neutral atoms. In a computer simulation the time of transverse diffusion   was assumed to be equal for ions of all charge states and was calculated from (1).

Let us suppose that the electron distribution function is Maxwellian with temperature T_e which depends on plasma density N_e and the power P of microwave radiation absorbed by a plasma. Therefore, the balance of the electron temperature is given by the equation:

$$\frac{fT_e}{ft} = \frac{P}{N_e V} - \sum_i {}_{ei}(T_e - T_i) - \sum_i k_{i,i+1}N_i(U_i + T_e). \quad (5)$$

Here, $= 2m_e/M_i$; U_i is the ionization potential of an ion with the charge i; and V is the trap volume.

Temporal distribution of the magnetic intensity in the magnetic barrier of Tornado-322 trap is shown in Fig. 3. This curve was obtained in testing experiments. As a pulse current is flowing through the trap coils, the ECR zone, which corresponds to the given frequency of microwave radiation, is moving over the trap volume. This may provide a quasi-uniform plasma heating in different internal trap regions. For simplicity's sake, the injected microwave power is assumed to be totally absorbed by a plasma if there is a
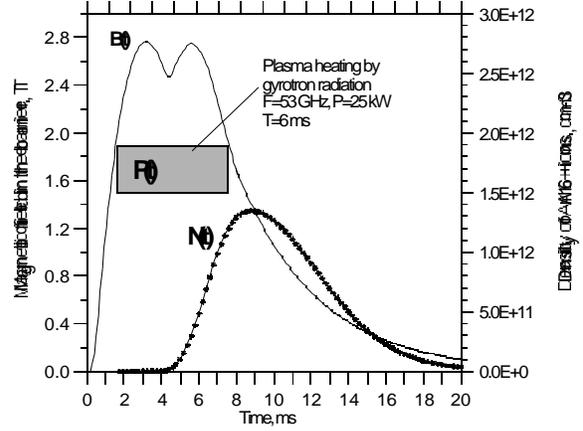

Fig. 3. P(t) is a model block diagram of microwave radiation absorption, which was used in the numerical simulation. Curve B(t) is a pulse of the magnetic field in Tornado-322 trap. Curve N(t) is the calculated temporal evolution of the density of ions Ar^{16+}; $P_{ini} = 6 \ 10^{-5}$ Torr.

plasma heating lies between 30 GHz and 60 GHz. Microwave radiation of this frequency range can be absorbed in the separatrix area with the magnetic field from 1.06 T up to 2.12 T. The corresponding powerful generators – gyrotrons – are presently manufactured in IAP RAS (Appendix A). The numerical simulation was carried out for the 53 GHz frequency.

The time of plasma confinement in the trap exceeds the magnetic field pulse duration. Therefore, temporal limitation of resonance plasma heating by the pulse duration of the magnetic field is a crucial factor that determines a possibility to attain ion CSD with a high mean charge. To shorten the stage of plasma ignition while the gyrotron pumping is applied, it is proposed to produce a pre-plasma with a density of about $10^{10} \div 10^{11}$ cm^{-3} before the switching on of a gyrotron. Calculations indicate that the pre-plasma density should be much greater than that of the background plasma. On the other hand, computed results are weakly dependent on a further rise in the initial ionization rate if the pre-plasma density exceeds 10^{10} cm^{-3}. When solving the set of equations (4) the pre-plasma density of 10^{10} cm^{-3} was taken as the initial condition. In experiments, it is suggested to produce pre-plasmas by ECR break-down of neutral gas at the 2.45 GHz frequency. Generators for this frequency exert a power up to several kilowatts at moderate device cost.

Computer simulation of ion CSD formation in Tornado trap was done for Argon plasmas. The model diagram (Fig. 3) of microwave radiation absorption at 53 GHz frequency was used in calculations. The curve N(t) in Fig. 3 represents temporal evolution of the density of ions Ar^{16+}. This time dependence was obtained under the following conditions: initial pressure of neutral gas $P_{ini} = 6 \ 10^{-5}$ Torr and gyrotron output power P = 25 kW. For the same initial conditions, the ion CSD, which has the highest over time average charge, is shown in Fig. 4. This ion CSD is formed in
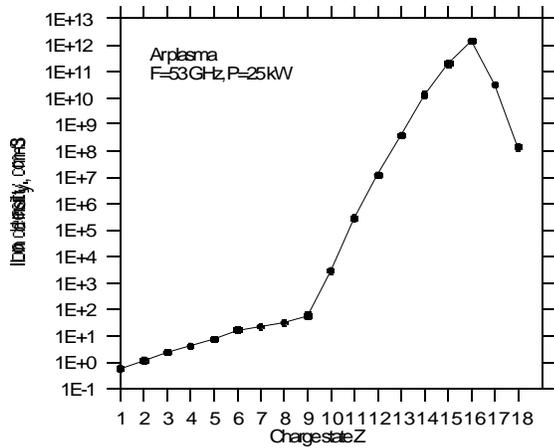
Fig. 4. Calculated ion CSD for initial parameters the same as in Fig. 3.

crowave pumping has been switched off. At high power absorption, the electrons gain the energy T_e of $1\div3$ keV and keep stripping multicharged ions effectively for some time after the end of a microwave pulse due to a rather great plasma confinement time.

In a regime illustarted in Fig. 3 – Fig. 4, the maximum electron density in a discharge during the ECR heating is $\{N_e(t)\}_{max}$ 2.3 10^{13} cm^{-3}, which is less than the cut-off plasma density for the 53 GHz frequency (N_c=3.47 10^{13} cm^{-3}). This, in principle, solves a problem of microwave radiation reflection from the boundary of a plasma with the density nearing the cut-off value.

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APPENDIX A.

Most popular gyrotrons are those generating at the second gyrofrequency harmonic, which allows one to use a lower magnetic field in a generator cavity and renounce superconducting magnets that make microwave sources very costly. Gyrotrons with "hot" magnets tested at the frequencies of 24 GHz and 30 GHz may be tuned to any frequency ranging from 20 GHz to 40 GHz.

Table 1. The best Russian CW Gyrotrons [9] (updated)

Frequency GHz	Output power, kW	Magnetic field, T	Type of magnet
30	25	0.55	Ns[a]
37.5	20	1.45	SCM[b]
83	20	3.2	SCM

a - Normal solenoid
b - Superconducting magnet

Gyrotrons with superconducting solenoids are much more expensive in service but provide much higher frequencies. The experience of the Institute of Applied Physics RAS verified feasibility of fabricat-

quencies from 30 GHz to 140 GHz with the power of 20 kW and higher.

Gyrotrons may operate both in the CW and pulse-periodic regime. Pulsed power may be much higher than the one indicated in Table 1, but average power is limited to about 20 kW. Parameters of the pulsed gyrotrons fabricated in IAP RAS for nuclear plasma heating at ECR are listed in Table 2.

Table 2 Russian Pulsed Gyrotrons [9] (updated)

Frequency GHz	Output power kW	Pulse duration s
28	500	0.1
53	500	0.2
83	500	2
100	2100	$3\ 10^{-5}$
110	1300	10^{-4}
110	6000	2
140	550	3
140	500	2
168	500	0.7

Thus, available data and technologies allow for fabricating a gyrotron with a frequency in the interval from 15 GHz to 140 GHz with the power of 20 kW and higher in the CW regime and with the power exceeding 500 kW in the pulse-periodic regime.

References:

[1] S.V. Golubev, V.G. Zorin, G.G. Gulbekian and V.B. Kutner. Proceedings of the Int. Conf. on Cyclotrons and Their Applications (Caen, France, June 1998).

[2] G. A. Galechyan and B. P. Peregood. Sov. Phys. Tech. Phys., **14**, 1272 (1970); K. B. Abramova et al, Tech. Phys., **42** (2), 134 (1997).

[3] K.V. Abramova et al. Trans. of Fusion Technology, **35**, 263 (1999).

[4] V. P. Pastukhov. Nucl. Fusion, **14** (3), 68 (1974).

[5] Lotz W. Zeit. fur Phys., 216, 241 (1968).

[6] P. Mazzotta et. al. Astron. Astroph. Suppl. Ser., **133**, 403 (1998).

[7] J.M. Shull, M. Van Steenberg. Astroph. J. Suppl. Ser., **48**, 95 (1982).

[8] Muller A., Salzborn E. Phys. Lett., **62A**, 391 (1977).

[9] A.L. Goldenberg and A.G. Litvak. Physics of Plasmas, **2**, 2562 (1995).