GYROTRON PUMPED ECR SOURCE OF MULTI-CHARGED IONS BUILT IN A CYCLOTRON

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Recent successful experiments on ECR ion sources with pumping by a millimeter wave gyrotron provide a hope for fast future development of such ion sources at high pumping frequencies. Gyrotron manufacturers guarantee elaboration of CW gyrotrons with frequencies ranging from 18 GHz to 100 GHz and power up to 30 kW. This project aims at developing an internal ECR source built in a cyclotron. Such sources have a significant advantage over external sources associated with the absence of ion losses during beam transmission. The project was developed for Dubna cyclotrons U-200, U-400, and U-400M. The cyclotrons have central cylindrical cavities that can be used as a mirror trap on proper modification. A magnetic field in these regions amounts to 1.5-2.1 T, so a gyrotron with the frequency of 40-60 GHz is needed to provide resonance heating conditions. An axial cyclotron tube will play a role of a wave-guide for quasi-optical millimeter wave beam. The ion extractor will be similar to the one that has been operating for a long time in Dubna for PIG ion source.

1 Advantages of internal ion source

Effective operation of a cyclotron accelerator depends significantly on parameters of the ion beam injected into acceleration space. An external ion source is mounted rather far from the accelerator, which gives rise to additional problems associated with the need to transport the beam. There are no such problems in the case of an internal ion source (built in a cyclotron) localized immediately in the central zone of accelerator [1]. Internal sources are much cheaper, they do not need their own magnetic system because they use the magnetic field of the cyclotron.

Internal arc sources of the PIG type have been employed in the Joint Institute for Nuclear Research in Dubna for injection of multi-charged ions into cyclotron accelerators U-200, U-400 and U-400M for about forty years [2]. Being free of the problems related to ion transport, these sources can operate in the regime of high plasma density and provide high current of accelerated ions. Principal shortcomings of PIG sources are:

a) small lifetime service due to sputtering of arc electrodes,
b) relatively low ion charge (for Xenon, for example, the charge does not exceed +16),
c) pulse-periodic operation only.

2 Can an ECR ion source be internal?

Creation of ECR sources of multi-charged ions has been advanced significantly in recent years [3, 4]. Such sources are used in numerous accelerators all over the world. By now, multi-charged ions of nearly all elements of the Periodic System have been obtained in ECR. Record currents have been achieved with ions of O^{6+} (the current of 1 emA) and of U^{48+} (the current of 1 eμA) at CW operation. ECR sources excellently meet the criteria of maximum possible current and maximum attainable ion charge.

A natural question arises: is it possible to combine the merits or internal arc PIG and ECR ion sources? Such a source has been realized quite recently after creation of reliable sources of microwave radiation at a frequency corresponding to the gyrofrequency of electrons in the field of cyclotron accelerators ($\omega_H = \omega$, where ω_H is electron gyrofrequency and ω is the frequency of microwave pump generator); the characteristics of such sources are given below. For instance, the U-200, U-400, and U-400M cyclotrons have a magnetic field of 2 T in the central zone. Consequently, the microwave pump frequency needed to provide electron cyclotron resonance condition for this field should be 56 GHz, which is much higher than the pump frequency of traditional ECR sources at the frequency of 10-18 GHz [5,7].

On the other hand, one of the tendencies towards perfecting the ECR sources of multi-charged ions is to increase the microwave pump frequency and, thus, obtain high-density plasma and high ion current with adequate ion distribution over charge states. Requirements to sources with high pump frequency were formulated in semi-empirical scaling [6]. According to the scaling, an increase of microwave pump frequency leads to enhanced efficiency of the source of multi-charged ions. Namely, ion distribution over charge states is shifted towards larger ionization states in proportion to log (ω), and average ion current increases substantially: $\langle I \rangle \sim \omega^2$.

Early experimental investigations of ECR sources of multi-charged ions with high-frequency pumping of gyrotrons were carried out in IAP RAS [4]. The experiments were aimed at determining the efficiency of generation of multi-charged ions in a mirror magnetic trap (without minimum B) at pulsed operation using gyrotron radiation at the frequency of 37.5 GHz with the power of 130 kW and pulse duration 1 ms.

Powerful gyrotron radiation allows one to produce ECR discharge plasma with unique parameters: electron density of about 10^{14} cm^{-3} and electron energy of about 1 keV that is optimal for multi-charged ion formation. An increase of plasma density changes plasma confinement in the trap: the so-called quasi-gasdynamic regime of confinement is realized, when plasma lifetime depends weakly on its density. Hence, the increase of plasma density provides better conditions for the formation of multi-charged ions (parameter $N\tau$, electron density, and plasma lifetime grow). All this results not only in enhancement of ion beam intensity in proportion to plasma density but also in the pronounced shift of ion charge state distribution towards higher ionization states.

The authors of [4] attribute to such a regime the shift towards higher ionization states of charge distribution of the ions escaping the plasma along the magnetic field. (The position of the maximum in the distribution corresponded to the ion charge 11-12 for discharge in Argon.) The magnitude of expected ion extraction current was estimated from measurements of saturation current on a flat probe placed behind the trap's plug, that amounted to 1 A. Measurements of plasma density and temperature by X-ray bremsstrahlung and by diagnostic microwave signal cutoff give direct evidence of a quasi-gasdynamic regime of plasma confinement. These investigations showed that plasma density amounts to about 10^{14} cm^{-3}, $T_e \approx 300$ eV [8], when the loss cone is filled, i.e., a quasi-gasdynamic regime of plasma confinement is realized. The research indicates that creation of ECR source with millimeter radiation pumping is quite promising.

3 Gyrotrons

Gyrotrons - powerful sources of microwave radiation at millimeter and submillimeter wavelengths - are produced commercially in the Institute of Applied Physics of the Russian Academy of Sciences [9]. Gyrotrons are broadly employed today in different branches of science and technology. Data for some CW gyrotrons operating in different installations are listed in Table 1.

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

Most popular are the gyrotrons generating at the second gyrofrequency harmonic, which allows one to use a lower magnetic field in 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.

Gyrotrons with superconducting solenoids are much more expensive in service but provide much higher frequencies. The experience of the Institute of Applied Physics verified feasibility of fabricating a gyrotron with superconducting solenoid at frequencies 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 technology 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.

4 Project of an internal ECR ion source

Elaboration of an internal ECR source demands solution of the following tasks:

4.1. Creation of magnetic trap inside a cyclotron

For formation of a magnetic trap in an internal ECR source of multi-charged ions one needs to modify the magnetic field in the center of the cyclotron. Towards this end, it is intended to add a ferromagnetic ring concentrating the magnetic field in the upper portion of the cyclotron cavity and a disk in its lower portion. In this fashion one can form a magnetic trap with the mirror ratio of 1.7.

Such a trap has no external system for stabilization of magneto-hydrodynamic plasma instabilities. (Most popular today are the so-called magnetic systems with minimum B.

These are mirror magnetic traps supplied with auxiliary magnets producing an additional radial field component.) It is intended to stabilize magneto-hydrodynamic instabilities in the internal source by forming a special spatial distribution of energetic electrons (rings or disks of fast electrons). Such a stabilization was verified in the experiments [8], in which stable operation of an ECR multi-charged ion source during the pulse of microwave radiation was demonstrated and inhomogeneous distribution of fast electrons was detected with the aid of an X-ray pin-hole camera.

Acceleration of ions having different masses demands a change in the magnitude of the cyclotron magnetic field. For Dubna accelerators these magnitudes were matched as follows:

U200	1.95	- 2.0 T,
U400	1.95	- 2.1 T,
U400M	1.50	- 1.9 T.

The necessary condition for ECR source operation is the existence of a zone of ECR discharge inside the trap, with the resonance zone being outside the plug area (see [10]). Thus, the optimal generation frequencies (in GHz) for microwave pump accelerators are:

U200	61,
U400	65,
U400M	56.

4.2 Electrodynamic system for the input of millimeter wavelength radiation into a plasma

It is anticipated that microwave radiation will be input through the central cyclotron opening that will operate as an oversized wave-guide section. Note that creation of such an electrodynamic system is a specific task. Microwave radiation is conventionally transmitted into ECR ion sources via single-mode waveguides. IAP RAS has gained experience in transmitting powerful millimeter wavelength radiation when systems of ECR plasma heating were elaborated for nuclear fusion installations.

4.3 Extraction system

The extraction system of internal ECR source differs from traditional ones. On the one hand, the use of internal source eliminates the need to form an ion beam to be transported at long distances. On the other hand, plasma density is much higher in internal sources that in conventional ones. This specifies additional requirements to extraction system. The proposed extraction system will be based on the system elaborated in Dubna for PIG sources that has been operating successfully for rather a long time [11].

4.4 Pulse-periodic operation

The U-200, U-400, and U-400M cyclotrons can also operate in a pulse-periodic regime with repetition rate 2-3. As was shown in [12], the average current of high-charge ions in ECR source pumped by a gyrotron-type generator operating in a pulse-periodic regime at quasi-gasdynamic plasma confinement may be higher than in a CW regime.

4.5 Expected parameters of internal source

Plasma size: 2 cm in diameter and 10 cm long.
Plasma density - about 10^{14} cm^{-3}.
Electron temperature - about 1 keV.
Expected charge state distribution of ions will have the maximum for the ion charge +15 for Argon and +25 for Krypton.
Total current of multi-charged ions - about 0.1A.

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