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PRODUCTION OF ION BEAMS WITH THE USE OF ECR ION SOURCES

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1. Introduction

About 28 year history of Electron Cyclotron Resonance Ion Sources (ECRIS) [1] based on the ECR has already shown that the ECRIS is an ideal tool for the production of multicharge ion states. Over the past years, the ECRIS has evolved into two directions: i) Production of higher charge states, more intense ion beams for accelerators and ii) development of a compact ECRIS with moderate performances for the production of radioactive ion beams and industrial ion implantation. All the existing sources are based on basic criteria with increasing magnetic fields, whereas the rf frequencies being used now range from 2.45 GHz to 18 GHz: radial hexapolar field, axial mirror field, interaction with an electromagnetic wave on a close surface so that $|B|\, e = m_e\omega_{rf}$, where B is the average value of the magnetic field in the region where the plasma lies [T], e the charge of the electron [C], m_e the mass of the electron [kg] and ω_{rf} the microwave frequency [Hz] matching the electron cyclotron frequency ω_c.

This paper is intended to make a survey of currently available ECRIS as well as to summarize the progress made in the last time.

2. ECR Principle

In order to produce ions in an ECRIS, microwave power is coupled by ECR heating into the plasma confined in a minimum B field magnetic bottle. The electrons spiral back and forth between the magnetic mirrors. They are heated in the thin zone on the egg-shaped ECR surface. In addition to the hot electrons are also cold electrons inside the plasma, which cause the step-wise-step ionization of the atoms and ions in the ECRIS. The ions and electrons are kept in a dynamic equilibrium. Then, the longer the average electron confinement is the longer the average ion confinement is. The average electron confinement time $<\tau_e>$ in an ECRIS can be expressed as [2]

$$<\tau_e> \approx \left(1+\frac{n_{eh}}{n_{ec}}\right) <\tau_{ec}> .$$

Here n_{ec} and n_{eh} are the cold and hot electron densities, and $<\tau_{ec}>$ the cold electron average confinement time. The cold electrons are not magnetically confined and tend to escape more rapidly from the plasma than the ions because of their much higher mobility. In order to increase the average electron confinement and thereby the average ion confinement time τ_i, it is necessary to produce a higher ratio of hot electrons to cold electrons or a longer cold electron confinement time τ_{ec}. For the production of high charge state ions, especially of ions with ionization potentials of tens of keV, the high hot electron density and the long ion confinement are very important.

Modern ECRIS usually consist of two stages. The first stage generates cold plasma and the second stage, which operates at a pressure of about $\leq 10^{-3}$ Pa, confine electrons and ions in order to strip the ions. The ECR plasma in the both stages always has tendency to be unstable if the microwave power is switched off at the low neutral pressure.

3. ECRIS Characteristics and Survey

A big advantage of ECRIS is the absence of filaments, which results in an unusually high stability and reliability. The high ion production efficiency reduces vacuum problems and also makes ECRIS promising sources for the production of beams of rare isotopes.

The most advanced ECRIS are compact devices (length and diameter are about 50 cm) using permanent magnets and coils at room temperature. The typical parameters of the ECRIS of different types developed at CEA (Grenoble) and JINR (Dubna) [3] are given in Table 1. Their performances are compared in Table 2a and 2b. In Table 3a and 3b are shown the parameters of the world best ECRIS of the year 1997. It is possible to see that the highest intensities and charge states are obtained with sources using high frequencies. The superiority of the source b' over the source b arises from its operation with a higher B field, which allows the existence of a second resonance structure (so called 2 ω mode). While operated at 10 GHz, it has the same performance as a 14 GHz source. A source of type b' may be the optimum choice for our purpose. An overview of its performance is presented in Fig. 1.

At extraction energies convenient for the injection into the Bratislava (Slovak Republic) cyclotron, the intensities are about 10 times smaller. According to our estimates, the accelerated current will be a few percent of the current observed at the source. These estimates have been confirmed by measurements performed at several laboratories. At KVI (Groningen) and PSI (Villigen), which are equipped with Philips Cyclotrons, a transmission of 3 % has been observed [3]. It can be expected that the intensities delivered to the target will be of the order of 1 % of those quoted in Table 2a, 2b and Fig. 1.

As for the energy range, it is given in principle by the lower limit of E/A $\approx$ 0.4 MeV/u and the maximum value of E/A = 75 (q^2/A^2) MeV/u = 75 MeV/u, where q is the charge of the ions and A the mass number. However, due to the rapid decrease in the intensity as a function of the extraction voltage of the source and to the missing experience in operating the cyclotron at the highest field, the practical range can be different. This range is between 6 and 60 MeV/u for ions of $^4He^{1+}$ to $^{238}U^{24+}$ for the cyclotron U-400M [5].

The expected ratios E/A versus the type of the accelerated ions for the Bratislava cyclotron are summarized in Table 4.

ECRIS have been developed at many places. The leading position in this field is held by CEA of Grenoble, which has developed more than 20 sources operated successfully at different accelerators like GANIL, GSI, CERN, KVI, RIKEN, etc. The sources listed in Tab. 1 are commercially available. They are simple, compact, and do not require excessive power or cryogenics. ECRIS of type b' are the best to fit the potential needs of the Bratislava cyclotron.

4. New Improvements in ECRIS

New technologies which maximize the performances of high charge state ECRIS are given. There are included: i) Multi - frequency plasma heating; ii) effects of extra cold electrons and iv) higher magnetic mirror fields.

4.1 Multi-frequency plasma heating

The minimum B field configuration in an ECRIS can provide many closed ECR heating surfaces for microwaves with different frequencies. If a single microwave frequency is used in an ECRIS, only one egg-shaped ECR heating zone is produced. The electrons are heated twice when they travel from one mirror point to the other.

Using two or more different frequencies which are matching the minimum B field, two or more well separated ECR surfaces will exist in the ECR plasma. Because a high charge state ECRIS typically runs with an underdense plasma microwaves of lower frequencies can propagate through the ECR plasma. Then the electrons passing through the ECR plasma can be heated four or more times in one passage from one end of the mirror to the other and this will lead to the higher density of the hot electrons. The higher the density of the hot electrons is the higher the production of high charge state ions is.

Tests with two frequency plasma heating on the LBNL AECRIS [10] have shown that the plasma was more "quiescent" than that in case of single frequency heating. Then larger total microwave power can be launched into the plasma. With such improved plasma stability, the source can run at lower neutral inputs, which indicates a lower neutral pressure. The higher microwave power and lower neutral pressure result in the higher hot electron density. It was shown [11] that the two frequency heating of ^{209}Bi shifted the peak charge state from 32+ to 33+ and enhanced the number of high charge state ions by a factor of 2 for high charge states 36+ to 40+. Two frequency heating shifts also the peak charge state of ^{238}U from 33+ to 36+ and increase the intensity by a factor of 2 to 4 for charge states from 35+ to 39+. Then two frequency heating produces the greater enhancements of the intensity of higher charge state ions than one frequency heating.

4.2 Effects of extra cold electrons

In order to enhance the production of high charge state ions, ECR plasma needs yet additional cold electrons besides the cold electrons arising from the ionization. With these additional cold electrons, high charge state ECRIS can run at a lower neutral pressure and higher microwave power, which are essential for the production of high charge state ions.

There have been used various active methods to provide extra cold electrons to ECR plasma, such as: i) Biased probe

[12]; ii) microwave - driven first stage [13]; iv) electron gun [2] and iu) plasma cathode [14]. The electrons injected by using these active methods are moving mainly along the magnetic field lines. Except the biased probe method, they are more complex and costly than plasma chamber surface coatings. In ECRIS the plasma chamber surface is parallel to the axis therefore a large portion of the secondary electrons emitted from the surface are perpendicular to the axis. Thus the electrons emitted from the surface can have the higher ratio of the transverse velocity to their longitudinal velocity and a higher probability of being trapped in the plasma compared to those of the electrons injected by using the other active methods. Therefore the surface coating method could be a more efficient method to provide extra electrons to the ECR plasma and result in better performance.

A good surface coating for an ECR source should have the following characteristics: i) High secondary electron emission; ii) long lifetime, i.e. a coating should resists plasma etching and iv) low material sticking coefficients to minimize the surface memory. Although the secondary electron emission of Al_2O_3 is not the highest, it is a good coating for an ECR source because it is strong against plasma etching. With such an Al_2O_3 coating and a biased probe the AECR [15] runs do not require gas mixing for the optimum performance of the ECRIS vacuum chamber in the production of the higher charge state ions of noble gases up to Xe. In general, an Al_2O_3 coating allows an ECRIS to operate at a lower neutral pressure and produces the strong enhancement of the highest charge state intensities, especially for heavier elements. Plasma potential measurements have shown that an Al_2O_3 coating yields the lowest average plasma potential and it is almost independent of microwave power. A lower

plasma potential reduces the ion sputtering and improves the plasma stability. All of these desirable characteristics make an Al_2O_3 coating the best one for high charge state ions. Listed in Table 5a and 5b are the performance data of a few ECRIS with an Al_2O_3 coating.

4.3 Magnetic mirror fields

A well-known rule of plasma physics says that the higher the mirror ratio of a magnetic trap is, the smaller the number of the particles lost from the confined plasma is. The confining trap in ECRIS is formed by the superposition of a mirror field and a hexapolar field. In high charge state ECRIS with one frequency the geometry of the minimum B field results in a closed, approximatelly ellipsoidal surface. The values of the ratios B_{max}/B_{min} and $B_{max}/|B|$ are also important for ECR heating. By means of $|B|$ the length of the plasma L is defined [6]. It holds that $L \approx |B|^2$. On the other hand the high B mode configuration increases not only the plasma length but also the mean electron temperature, the ion confinement time and the electron density.

Another important parameter of plasma is the kinetic plasma pressure p_{pl} [Pa], which is written as

$$p_{pl} = k(n_{ec}T_{ec} + n_{eh}T_{eh}) \approx |B|^x , \qquad (1)$$

where $1 \leq x \leq 2$, k is the Boltzmann constant [J/K], T_{ec} and T_{eh} are the cold and hot electron temperatures [K] and n_{ec} and n_{eh} are the cold and hot electron densities [1/m^3], respectively. In order for the plasma confinement in a magnetic trap to be stable, the following condition has to be fulfilled

$$\beta = \frac{p_{pl}}{|B|^2/2\mu_0} < 1, \qquad (2)$$

where β is the parameter characterizing the ECRIS magnetic configuration and μ_0 the permeability of vacuum ($\mu_0 = 4\pi$

10^{-7} N s^2/C^2). It may be concluded that the achievement of the high electron density and consequently of the high ion density of various charge states is subject to condition (2) strongly depending on the magnetic field.

The recent development of ECRIS has demonstrated that the nominal magnetic mirror field with a maximum mirror ratio of 3 is not yet optimized [17].

5. Conclusions

The output characteristics of ECRIS developed all over the world in the last years are surveyed. The recent results concerning the production of high charge state $^{14}N^{q+}$ and $^{16}O^{q+}$ ions are presented. Also is given a summary of 10 GHz CEA (Grenoble) CAPRICE ECRIS, which are still progressively improving their performances. All the existing sources are based on the same basic criteria with respect to the configuration of magnetic fields and rf frequencies, only frequency varying from 6 to 18 GHz. Their performances can be regarded very good and some of them are also suitable enough for accelerator applications.

Some attention is given to the progress of ECRIS aimed at maximizing the performance of high charge state ECRIS and including multi-frequency plasma heating, aluminum oxide surface coating to provide extra cold electrons into the plasma, and improved plasma confinement with higher magnetic mirror fields. Furthermore, given is the long-awaited ratio E/A as a function of the accelerated beam for the Bratislava cyclotron. It is demonstrated that the intensities delivered to the target will be of the order of 1 % of those quoted in Tab. 2a, 2b and Fig. 1.

Table 1. Typical parameters and prices of ECRIS including the prices of power supplies [3 - 4].

Type of ECRIS	RF frequency [GHz]	RF power [kW]	B structure	$\langle B_{av.} \rangle$ [T]	Total power [kW]	Price [M$]
a	8	1	only permanent magnet	0.35	3	0.89
b	10	2	permanent magnet + coils	0.45	50	0.81
b'	10	2	permanent magnet + coils	0.90	80	0.89
c	14.4	2	permanent magnet + coils	0.70	70	1.00
d	16.6	10	permanent magnet + coils	0.80	120	2.33
DECRIS-14 -2	14	2	permanent magnet + coils	0.8	60	

Table 2a. Output parameters of ECRIS commercially available in France [3]. Currents are in [eμA].

Ion	^{16}O				^{40}Ar				^{84}Kr			
Type of ECRIS	a	b	c≅b'	d	a	b	c	d	a	b	b'	d
q 6	50	150	200	300								
7	2	15	40	60								
8	0.1	1	4	10	80	300	300	300				
9					25	100	140	200	25	50		
11					3	15	110	120	15	50		
13					0.1	2	20	35	10	30	30	
16						0.1	<1	2	1	12	30	50
17								0.1		6	20	40
18								0.005		4	15	30
20										1	5	12
24												3
26												1
28												0.1
30												
32												
34												

Table 2b. Other output parameters of ECRIS commercially available in France [3]. Currents are in [eμA].

Ion ^{130}Xe																	Type of ECRIS
q	6	7	8	9	11	13	16	17	18	20	24	26	28	30	32	34	
						12	10	8		2							a
						40	32	27	20	15	5	2					b
								30	25	25	12	7	2	1			c≅b'
								50	40	40	20	10	3	2	1	0,1	d

Table 3a. Short survey of the world best ECRIS of the year 1997 [2,6-9]. Currents are in [eμA].

August 1997	SF-ECR INS Japan	ECR-6.4 VECC India	SC-ECR MSU USA	NEOMA-FIOS RCNF Japan	NIRS-ECR NIRS Japan	ECR-2 Caprice IMP China	ECR-3 KVI Netherlands
f [GHz]	6.1	6.4	6.4	10	10	10	14
N^{2+}	195				790		
N^{3+}	195				590		
N^{4+}	190	25		110	340		
N^{5+}	160	12	245	65	220		
N^{6+}	35	1	115	6	25		
O^{2+}					660		
O^{3+}	200				590		
O^{4+}		65		180	440		
O^{5+}	150	27		85	280		100
O^{6+}	130	15	930	35	130	200	220
O^{7+}	12	1.2	205	2	15	44	55
O^{8+}			18				11
HF power [W]			700 - 1300	650			

Table 3b. Continuation of short review of the best ECRIS all over the world in 1997 [2,6-9]. Currents are in [eμA].

August 1997	DEC-RIS-2 FLNR Russia	Hyper ECR TRC Japan	ECR 4-M GANIL France	Caprice -New CEA France	Caprice IPCHR-RIKEN Japan	AECR LBNL USA	MINIMAFIOS CEA France
f [GHz]	14	14	14.5	14.5	14.5	14+10	18
N^{1+}				1000	1000		
N^{2+}					1100		
N^{3+}	465				700		
N^{4+}	570	315			680		
N^{5+}	640	300		660	560	123	
N^{6+}	70	57		325	95	41	
N^{7+}				40			
O^{1+}				1220	1430		
O^{2+}				1120	1310		
O^{3+}	290			920	1000		
O^{4+}	340	500		770			
O^{5+}	660	500	550	650	700		
O^{6+}	300	490	1000	760	500	570	800
O^{7+}	68	60	120	100	130	306	180
O^{8+}			18	3		75	
HF power [W]	200		1000			2100	

Table 4. Expected ratios E/A as a function of the type of the accelerated ions for the Bratislava cyclotron.

Ion	$^{1}H^{1+}$	$^{16}O^{2+}$	$^{16}O^{7+}$	$^{40}Ar^{3+}$	$^{40}Ar^{11+}$	$^{84}Kr^{9+}$	$^{84}Kr^{28+}$	$^{130}Xe^{13+}$
E/A [MeV/u]	75	1.2	14.5	0.4	5.7	0.9	8.3	0.7

Table 5a. Performance data of a few ECRIS with an Al_2O_3 coating. Currents are in [eμA] [2].

Ion	$^{16}O^{6+}$	$^{16}O^{7+}$	$^{40}Ar^{14+}$	$^{40}Ar^{16+}$	$^{84}Kr^{18+}$	$^{84}Kr^{25+}$
LBNL AECR-U 14+10 GHz	570	306	77	21	100	19.4
Grenoble CAPRICE 14 GHz	760	100	15	1	55	2
RIKEN ECR-18 18 GHz	500	130	25	5		

Table 5b. Others data of a few ECRIS with an Al_2O_3 coating. Currents are in [eμA] [2].

Ion	$^{136}Xe^{28+}$	$^{136}Xe^{31+}$	$^{238}U^{36+}$	$^{238}U^{39+}$	$^{238}U^{48+}$
LBNL AECR-U 14+10 GHz	21	7	13.3	9.3	1.1
Grenoble CAPRICE 14 GHz	10		1.4	0.17	

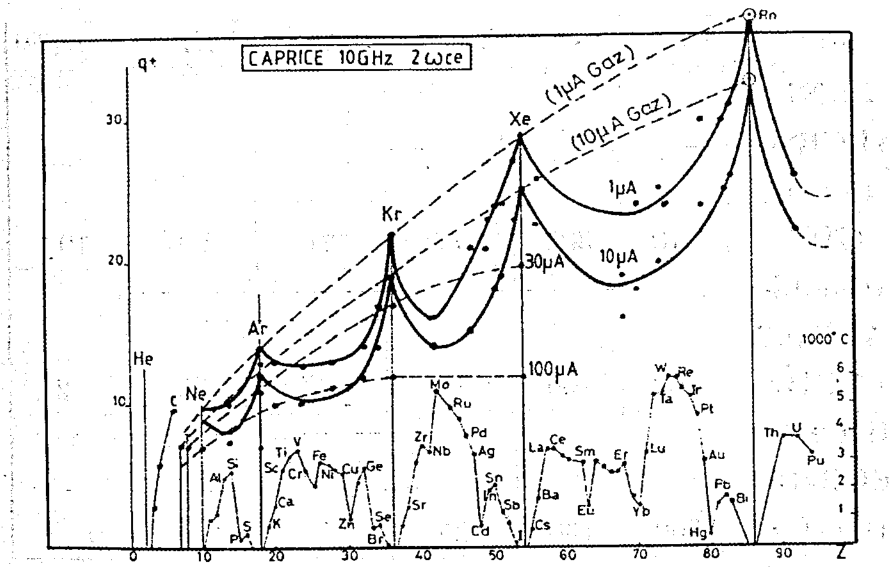

Fig. 1. Attained yields of multicharge ions produced by the CAPRICE 10 GHz ECRIS [3] (• - measured values and ⊙ - extrapolated values).

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