OPERATION AND RECENT DEVELOPMENT OF ECR ION SOURCES AT THE FLNR (JINR) CYCLOTRONS

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Recently the U-400M and U-400 cyclotrons of the FLNR JINR have been equipped with modern ECR sources at 14 GHz: DECRIS-14-2 (March, 1995) and ECR4M (November, 1996). DECRIS-14-2 (Dubna Electron Cyclotron Resonance Ion Source, 14 GHz) and ECR4M (GANIL) were built for accelerating heavy ions with energies from 0.5 to 100 MeV/n without making use of the tandem cyclotron complex U400 - U400M with a PIG ion source. Within the past three years the use of ECR ion sources at the FLNR qualitatively contributed into synthesis of superheavy elements, secondary beams and nuclear membrane production. A new technique for generating intensive beams of ions of metals with a relatively low melting point (Li, Mg, Ca) is described. Some latest results of production and acceleration of ^{48}Ca beams are presented.

1 Introduction

The FLNR JINR cyclotrons [1] have been lately operating with beams of ^{7}Li, ^{11}B, ^{24}Mg, ^{48}Ca, ^{86}Kr ions etc. which are mainly used for synthesis of the heaviest nuclei, production of secondary beams and nuclear membranes. Production of the ^{48}Ca ion beam is probably the key problem in synthesizing new nuclei [2]. The goal was to achieve the maximum intensity of the ^{48}Ca ion beam at a minimal consumption of this enriched and expensive isotope.

A few years ago at the U-400 cyclotron equipped with a PIG-type ion source, the beam of $^{48}Ca^{6+}$ with an intensity of about 0.1 pμA has been produced. Consumption of the working substance was in the range of 4 - 15 mg/h. These results were not satisfactory for achieving a beam dose of $\geq 10^{19}$ in long-term irradiations. For increasing the intensity by a factor of 5 - 10 and decreasing consumption of ^{48}Ca with a subsequent recuperation of the matter, it was necessary to change radically the concept of production and acceleration of highly charged ions of enriched isotopes.

With this in view, in 1995 - 1996 were created external ion sources of a ECR type and axial injection systems for the U400M and U400 cyclotrons with the aim of extending possibilities for experimental investigations at both the cyclotrons.

As for the U400 cyclotron with the ECR4M ion sourse of GANIL, the task was to achieve an extracted beam with an intensity of 0.5 pμA at the ^{48}Ca consumption of ~ 0.5 mg/h (over 50% of the matter was to be extracted from the source chamber).

By the end of 1996 technical work has been completed and the first experiment on the synthesis of superheavy elements was performed in November 1997.

2 Performance of the ion sources and the FLNR cyclotrons.

It is common knowledge that the final energy of a cyclotron can be increased by increasing the q/A ratio (where q is the charge state and A is the mass number) of the accelerated ions.

This can be done either in the ion source or by using strippers after a corresponding pre-acceleration of low charged ion beams.

The beam parameters and future development of the intensive and highly charged ion sources was discussed earlier in [3] from the point of view of potentiality of cyclotrons at the FLNR JINR.

The approach to the selection of the required ion sources for acceleration of intensive (10^{13} - 10^{14} pps) ion beams of all elements of the Periodic Chart using the U400 and U400M cyclotrons is explained by Fig.1.

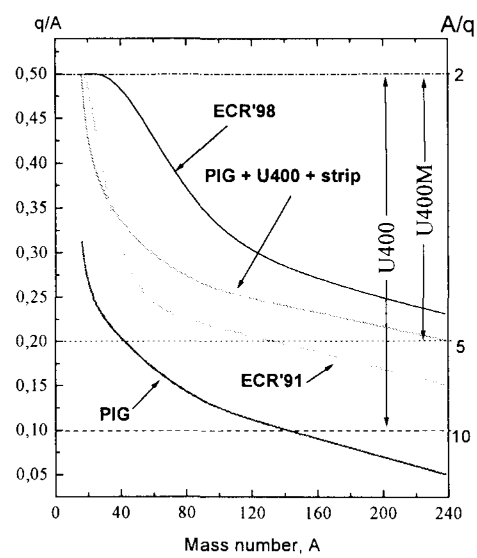

Fig.1 Potentialities of different high charge state and intensive ion sources for cyclotrons.

It is clear that today the level of the ECR ion source parameters allows accelerating the ions of all elements to an energy of more than 6 MeV/nucleon at the FLNR cyclotrons. The U400 cyclotron with a PIG source can accelerate Xe ions to energies of up to 6 MeV/nucleon, whereas the

U400M cyclotron can accelerate to the above-mentioned energy only Ar ions.

Nevertheless, PIG ion sources are one of the suitable choice because they are capable of producing the most intensive (10^{16} pps) ion beams of light elements.

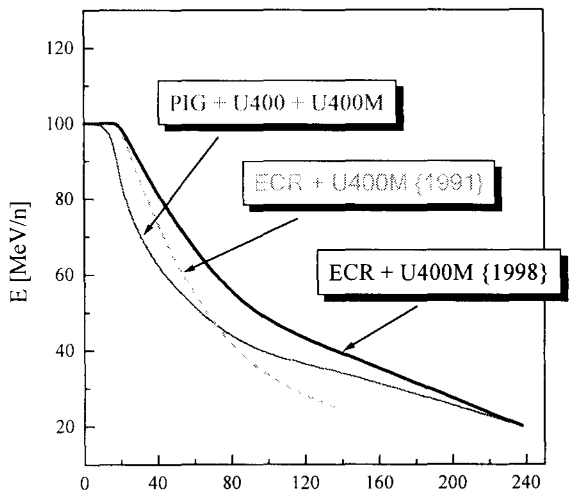

Fig.2 Dependence of the U400M ion energies on the ion mass.

The possibilities of the ECR ion source development for the acceleration of ion beams from the DECRIS and ECR4M ion sources at the U400M cyclotron are illustrated in Fig.2 in comparison with the old project involving tandem cyclotrons and a PIG ion source.

3 Status of the ECR ion source programme at the FLNR.

For the first time modern ECR ion sources (the DECRIS-family) have been developed at the JINR during 1990 - 1998. Since 1996 the U400 and U400M cyclotrons have been equipped with modern ECR ion sources of a new generation such as ECR4M (GANIL) and DECRIS-14-2 (FLNR JINR).

3.1 The DECRIS-14-2 and ECR4M ion sources

The FLNR's DECRIS programme was started in 1990.

This programme provided R&D of modern universal ECR ion sources which could produce ions (in gaseous and solid states) of all elements of the periodic chart [4,5].

The unique character of DECRIS-14-2 is explained by a high level UHF system, a new design and a new procedure for assembling the multipole magnet system used for the first time in the world.

At the same time it was decided to take into account a very well-known and positive GANIL-FLNR experience in production and acceleration of ^{48}Ca ion beams [6] and employ the unique results gained by GANIL in the work with ECR ion sources in the process of creation of a new generation ion source specially for the FLNR and, thus, provide physicists with ion beams of record parameters. It means, for example, that at the intensity of $^{48}Ca^{14+}$ of about 5×10^{12} pps achieved at ECR4M, a unique research programme can be started.

3.2 A new method for feeding the solids into ECR ion sources

In parallel with creation of the ECR ion sources at the FLNR, methods for production of ion beams of metals and compounds with low evaporation temperatures, such as Li, B, Mg, Ca etc. were developed and technical possibilities investigated. This R&D of new technologies for an efficient feeding of gasses and solids, enriched stable and radioactive isotopes into multicharged ion sources was supported by the INTAS'96 grant. The work has been performed in collaboration with the Universite Catholique de Louvain-la-Neuve and GSI, Darmstadt.

As a result, in the FLNR a new method for the Li, Mg and Ca intensive ion beam production was suggested and developed. The combination of a microoven with a hot tantalum sheet inside the discharge chamber [7] allowed production of intensive beams of ions of metals with a relatively low melting point. Ion yields for metals from the DECRIS-14-2 and ECR4M ion sources are presented in Table 1 and Figures 3, 4.

The spectrum of ^{11}B ions from the DECRIS-14-2 ion source obtained with the use of the MIVOC method is presented in this work together with the spectrum of Ca obtained with the use of the hot screen method. It is clear that the spectra in both sets of data have the same order of intensity.

4. The ion source development and acceleration of the ^{48}Ca ion beam

The members of the FLNR ion source group made their major effort in solving the following problems:

Table 1. Ion yields (eμA) from the DECRIS-14-2 and ECR4M (*) ion sources at 17 and 13 kV extraction voltage, correspondently.

I/Q	1+	2+	3+	4+	5+	6+	7+	8+	9+	10+	11+
^{7}Li	138	290	50								
^{11}B	20	55	100	50							
^{24}Mg*		80	259^	175	140	65	17				
^{40}Ca*			132	315	245	200^	165	125	80	52	14
^{48}Ca*				60	90&	120	100	60	30	15	5

^ - intensity optimisation; & - intensity and consumption optimisation

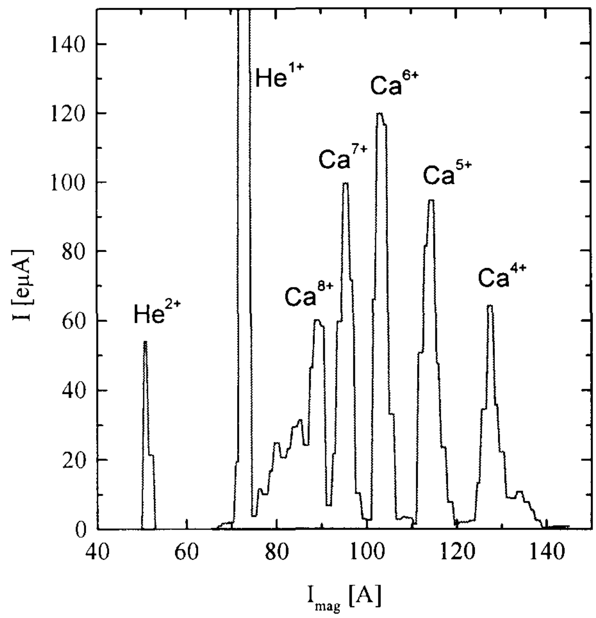

Fig.3 The spectrum of ^{48}Ca ions optimised for production of $^{48}Ca^{6+}$.

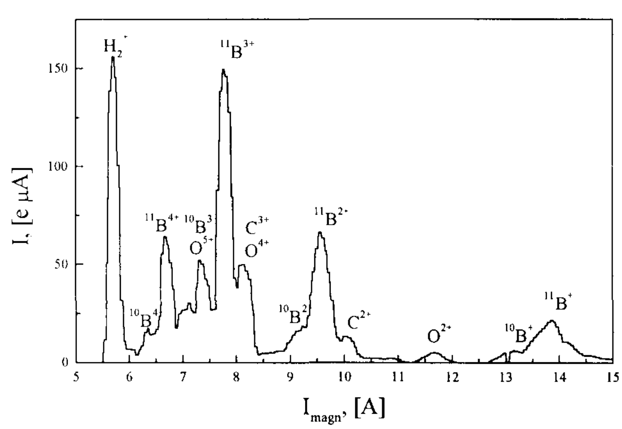

Fig.4 The spectrum of ^{11}B ions produced from the $C_2B_{10}H_{12}$ compound.

- production of a stable ion beam at a target during a long-term (few months) operation;
- increasing the $^{48}Ca^{5+,6+}$ ion beam intensity;
- optimisation of the working substance consumption at the maximal beam intensity.

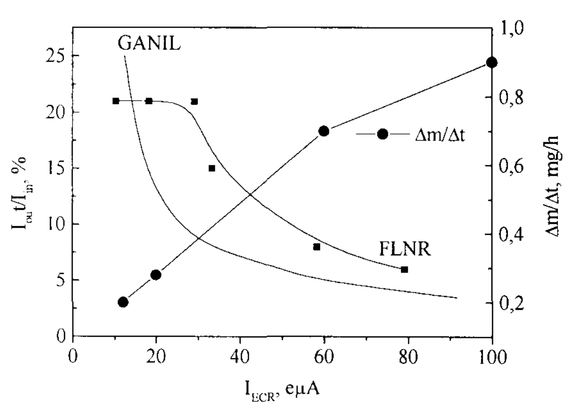

Fig.5 Experimental results for the bunching effect and consumption of metallic ^{48}Ca versus the ion beam intensity from the ion source.

Finally the best results concerning stable and intensive ion beams were achieved with the use of metallic calcium. Using this method we can provide a very stable intensity of the ion beam at a physical target during one week.

Taking into account the efficiency of a buncher versus the ion beam intensity, which has been obtained by the GANIL [8] and FLNR [9] groups, the transmission being several times higher at a decrease in the injected current, we have defined the working area for the optimal intensity of the ^{48}Ca beam from the ECR ion source. Fig.5 shows that for the optimal consumption of working substance from the oven the intensity should be of about 30 - 40 eμA. In this case good efficiency of the source can be provided at a relatively low (about 0.4 mg/h) consumption of ^{48}Ca. The efficiency of this experiment is presented in Fig.6. One can see that the total efficiency equal to about 2×10^{-3} was provided by means of a relatively high efficiency (about 4%) of the ion source.

In this case out of 1.4×10^{15} pps of Ca atoms fed into the source we produce about 6×10^{13} pps of $^{48}Ca^{5+}$ ions from ECR4M. As a result, in such mode of the ion sourse operation it is possible to provide about 2500 hs of the target irradiation using one gramm of ^{48}Ca. Information on the ^{48}Ca ion beam parameters is presented in Table 2.

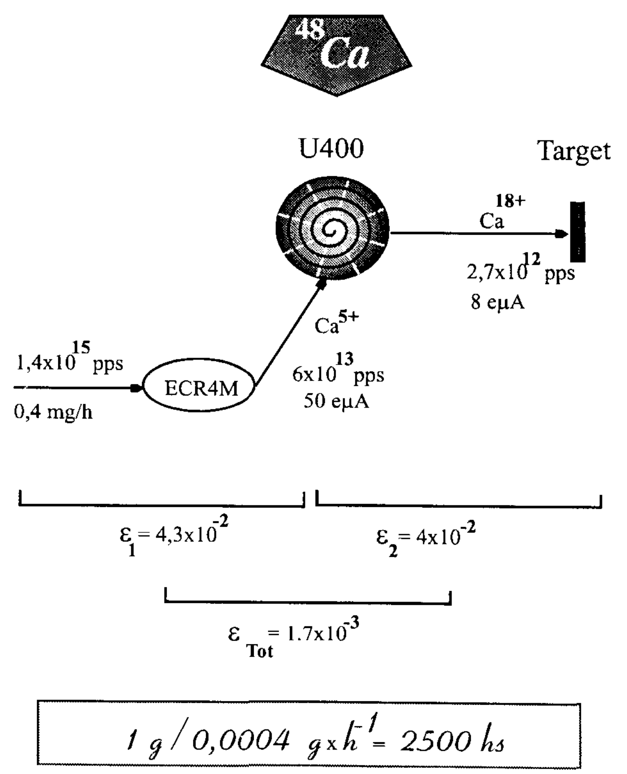

Fig.6. Efficiency of the ECR4M ion source and the U400 cyclotron with the ^{48}Ca ion beam.

Table 2. ^{48}Ca ion beams from different ECR ion sources.

Ion	I_{ECR}, pps	Consumption mg/h	Consumption mg/(h•pμA)	Working subst.	ECRIS
$^{48}Ca^{5+}$ (78%)	6×10^{13}	0.4	0.04	Metal	ECR4M FLNR'98
$^{48}Ca^{11+}$	2×10^{12}	0.015	0.045	CaO+Zr	RTECR MSU
$^{48}Ca^{10+}$	1.6×10^{12}	0.06	0.25	CaO+Al	ECR4 GANIL'97
$^{48}Ca^{10+}$ (54%)	1.5×10^{11}	0.03	1.2	Metal	AECR LBL'96

As a working substance both metallic calcium [10] and calcium oxide mixture with Al [11] or Zr [12] have been used. Very low consumption of ^{48}Ca was achieved at the MSU [12] at a relatively high intensity of the RTECR ion beam. But in this case a higher temperature of the oven (~1400 ^{0}C) is required than that in the case of the CaO+Al technology (~1100 ^{0}C) [11]. The most intensive ^{48}Ca ion beam was produced by ECR4M. The ^{48}Ca consumption using the hot screen method amounts to 0.4 mg/h without collection and regeneration. In order to evaluate and compare the efficiency of different ^{48}Ca ion sources specific consumptions are presented in Table 2. In the fourth column of Table 2 one can see that the specific consumptions are quite low at both Laboratories, the FLNR and MSU.

The intensity of the accelerated ^{48}Ca ion beams from the FLNR's ECR and PIG ion sources and the calcium consumption are presented in Figure 7 and Table 3.

Due to the limitation in the physical target current the service life of the source was about a week at a physical target current of 8 eμA. The quantity of metallic calcium loaded in a crucible is usually about 50 - 70 mg.

As it can be observed from Fig.7, in the process of work with the PIG ion source the sputtering electrode containing ^{48}Ca substance should be replaced every day. As it is illustrated by Table 3, the ECR ion source at the U400

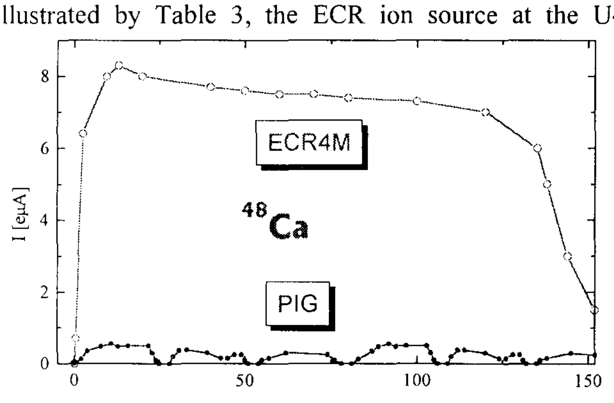

Fig.7 Intensity of the accelerated ^{48}Ca ion beams from the PIG [13] and ECR ion sources at a physical target.

Table 3. Comparision of the efficiency of PIG and ECR ion sources.

	PIG	ECR4M	Factor
Beam intensity eμA	0.5	8	16
Consumption mg/h	4 ÷ 15	0.4	> 10
Total			> 160

cyclotron provides a drastic increase in the efficiency of the experiments. The total factor of the increase equals to ~ 100. This is the result of the optimisation of both the beam intensity from the source and ^{48}Ca consumption.

5. Conclusion

Since 1996, the U400 and U400M accelerators have been equiped with modern ECR ion sources of a new generation, namely ECR4M (GANIL) and DECRIS-14 (FLNR JINR).

In the FLNR a new method for the Li, Mg and Ca intensive ion beam production has been suggested and realized. The combination of a microoven with a hot tantalum sheet inside the discharge chamber allowed production of intensive beams of ions of metals with a relatively low melting point.

The efficiency of the ^{48}Ca ion beam production with the use of a new injector at the U400 cyclotron is more than 100 times higher compared with that in the case of a PIG source.

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