DEVELOPMENT OF METAL ION BEAMS AND BEAM TRANSMISSION AT JYFL

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Abstract

The activities of the JYFL ion source group cover the development of metal ion beams, improvement of beam transmission and studies of Electron Cyclotron Resonance Ion Source (ECRIS) plasma parameters. The development of metal ion beams is one of the most important areas in the accelerator technology. The low energy beam injection for K-130 cyclotron is also studied in order to improve its beam transmission. It has been noticed that the accelerated beam intensity after the cyclotron does not increase with the intensity extracted from the JYFL 14 GHz ECR ion source, which indicates that the beam transmission efficiency decreases remarkably as a function of beam intensity. Three possible explanations have been found: 1) the extraction of the JYFL 14 GHz ECRIS is not optimized for high intensity ion beams, 2) the solenoid focusing in the injection line causes degradation of beam quality and 3) the focusing properties of the dipoles (analysing magnets) are not adequate. In many cases a hollow beam structure is generated while the origin of hollowness remains unknown.

INTRODUCTION

The research at the JYFL accelerator laboratory focus on the research in nuclei under extreme conditions, on accelerator based material physics and on the accelerator based applications in industry. The main tool for the studies is the isochronous K-130 cyclotron [1] equipped with two ECR ion sources [2,3] for heavy ion beams and a filament driven multicusp-type light ion source for negative ions. Typical energy needed for the nuclear physics programme is about 5 MeV/nucleon. This requirement is met with the q/A-ratio of about 0.2.

The requirements towards the use of heavier projectile elements and higher ion beam intensities have increased. These demands require the work for improving the performance of the ion sources, beam transport and methods for the production of metal ion beams. The efficient development of ion sources requires plasma studies in order to improve the understanding of plasma ignition and plasma-wave interaction, for example. In this R&D work the good availability of ion sources and different tests benches at JYFL plays an important role.

METAL ION BEAMS

At JYFL the solid ion beams are produced mainly by the MIVOC method [4] and with ovens. As a latest approach the sputter technique [5] has been adopted. Table 1 shows the solid elements available from the JYFL ECR ion sources, the method usually used and the intensity for the charge state giving the q/A-ratio of at least 0.2. In some cases the intensity shown in the table does not correspond to the maximum performance of the ion source – instead the value corresponds to intensity, which is high enough to meet the requirements set by the nuclear physics experiment.

Table 1: Solid ion beams by the JYFL ECRIS's. The beams have been produced with 14 GHz ECRIS if not mentioned otherwise

Element	Method	Intensity [µA] (q/m≈0.2)	Note
B	MIVOC	235	($C_2H_{12}B_{10}$)
C	CO_2	195	
F	SF_6	19	6.4 GHz
Mg	MIVOC	12	6.4 GHz
Al	Oven	9.5	6.4 GHz
Si	SiH_4	124	
S	SF_6	22	6.4 GHz
Cl	$TiCl_4$	23	6.4 GHz
Ca	Oven	75	CaO + Zr
Ti	MIVOC	45	$(CH_3)_5C_5Ti(CH_3)_3$
V	MIVOC	10	$V(C_5H_5)_2$
Cr	Ind. oven	20	
Mn	Oven	22.5	
Fe	MIVOC	115	$Fe(C_5H_5)_2$
Co	MIVOC	12	$Co(C_5H_5)_2$
Ni	MIVOC	55	$Ni(C_5H_5)_2$
Cu	Oven	7.5	
Zn	Sputter	5.5	6.4 GHz
Sr	Oven	30	ZrO + Zr
Y	Foil oven	5	
Zr	Sputter	12	
Ru	MIVOC	9.1	$Ru(C_5H_5)_2$
Ag	Oven	5.8	
Au	Oven	15	

MIVOC Method

The MIVOC method is based on the fact that some compounds including metal element have relatively high saturated vapour pressure already at room temperature. For example $Fe(C_5H_5)_2$ has the vapour pressure of about 10^{-3} mbar, which can easily give the feed rate of several

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mg/h for iron into the ECRIS plasma chamber if the conductance of feed line between the sample and plasma chamber is adequate. The MIVOC method can provide very intensive ion beams for some elements as is shown in Table 1. In addition the consumption rate of metal element is usually very small, which is very important factor in the case of enriched materials. However, compounds from enriched materials are not commercially available, which means that the user has to have a know-how to synthesize the compound of interest (for example $Fe(C_5H_5)_2$). The lack of convenient compound including the element of interest also gives a limitation for the use of the method. The other drawback is the carbon existing in the compound causing the contamination of the plasma chamber. Often the ECRIS plasma chamber is made out of aluminium, which behaves as a good source of secondary electrons strongly increasing the intensity of highly charged ions. Consequently, the carbon contamination on the surface of the plasma chamber decreases the performance of the ECRIS. However, similar effect is seen with some other metal elements like Zr for example.

JYFL Evaporation Ovens

The MIVOC method was not able to provide all metal ion beams needed for the cyclotron. Consequently evaporation ovens were chosen to increase the variety of available metal ion beams. Presently, three different evaporation ovens are available for the metal ion beam production at JYFL: miniature oven, foil oven and inductively heated oven. The use of the most appropriate oven is chosen according to requirements.

JYFL Miniature Oven

The miniature oven has been used at JYFL for the metal ion beams since 1997. It is a modified copy of the MSU design [6] and layout of one version is shown in Figure 1. The oven has been tested up to 1400˚C without any signs of failure. The limitations come from the maximum temperature for the surface-to-surface stability between the tungsten filament and Al_2O_3 insulator ($T_{max} \approx$ 1700˚C). In addition, the vapour pressure of Al_2O_3 is about 1E-5 mbar at 1763˚C [7]. The oven has successfully been used - especially with the JYFL 6.4 GHz ECRIS [2] - for the production of several metal ion beams like Al, Ca and Cu. However, the capability of the oven was not adequate for the production of metal ion beams needing evaporation temperature significantly higher than 1400˚C. This excluded several metal ion beams needed for the nuclear physics program at JYFL. Consequently, an active development work has been performed to develop both the resistively and inductively heated ovens. The most difficult problem concerning the oven development work comes from the surface-to-surface interaction of different materials, which limits the maximum usable temperature (see Ref. 7).

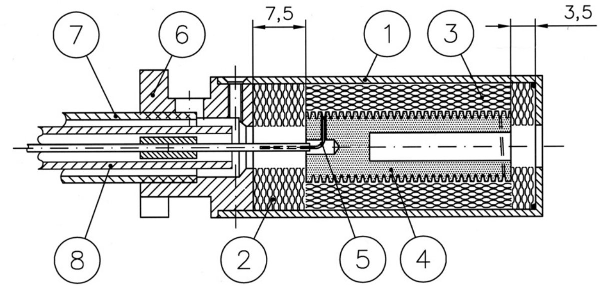

Figure 1: The JYFL miniature oven. 1) outer Mo body (OD = 20 mm), 2 and 3) Mo radiation shielding, 4) Al_2O_3 inner body, 5) W/Re filament, 6 and 7) stainless steel parts, 8) Al_2O_3 insulation.

JYFL foil Oven

The structure of the foil oven is presented in Figure 2. It is capable of operating close to temperature of 2000˚C. The current is conducted through the copper stem (1) and Mo crucible (2) to Ta heater foil (3), which thickness is 25 µm. The current of close to 80 A is needed to reach the temperature of 1900-2000˚C. The heater foil is pressed using parts 4) and 5) which can cause temperature variation of even 50 ˚C depending on the contact of the foil. The material to be evaporated is inserted into the crucible, which is heated by the heat radiation from the heater foil. The current loop is closed via Mo-body (8) and stainless steel tube 9). The inner part is electrically insulated from the outer part by Al_2O_3 insulator (7).

The foil oven has been tested for the production of Au, Y and Ti ion beams. Especially in the case of Y and Ti evaporation a strong surface-to-surface reaction was seen (depends only on the materials in contact). The drawback of the foil oven is a difficult handling because it has to be disassembled when the evaporated material is changed.

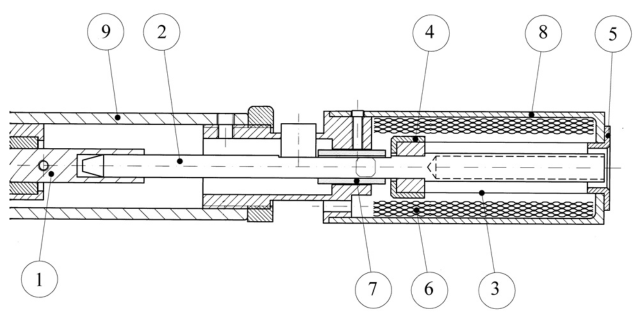

Figure 2: Resistively heated foil oven: 1) Cu rod, 2) Mo crucible, 3) Ta heater foil 4-5) Mo foil holder, 6) Ta radiation shielding, 7) Al_2O_3 insulator, 8) Mo body, 9) stainless steel outer tube.

JYFL Inductively Heated Oven

An inductively heated oven is very efficient for the production of metal ion beams requiring high temperature. Figure 3 clarifies the operation principle of the final version of the home-made control unit, which makes the oscillation of the circuit at resonance frequency possible. The gate voltage of the transistor is controlled with the integrated signal generator at the resonant frequency of the circuit. Proceeding this way the voltage of the circuit provided by -50 V power supply is changed. The amplitude of the oscillation is controlled by the voltage of the power supply. The oven has intensively been tested at the test bench up to 2000˚C. No failure of the oven - including control unit – have occurred during the tests of several days. The oven has been used for the production of Cr and Ti ion beams. The structure of the oven is shown in Figure. 4.

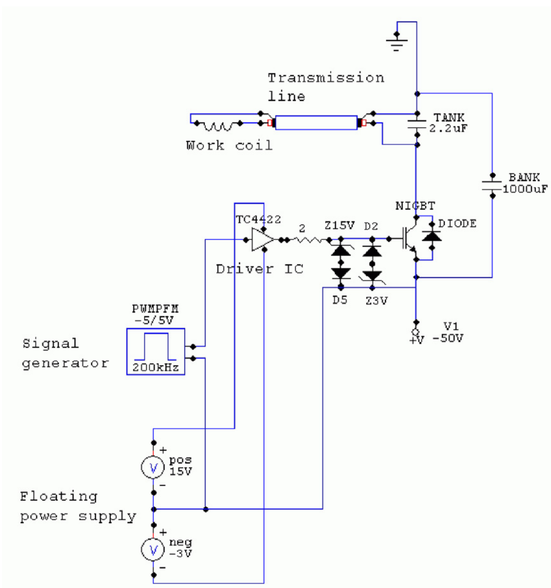

Figure 3: Control unit layout of the inductively heated oven at JYFL.

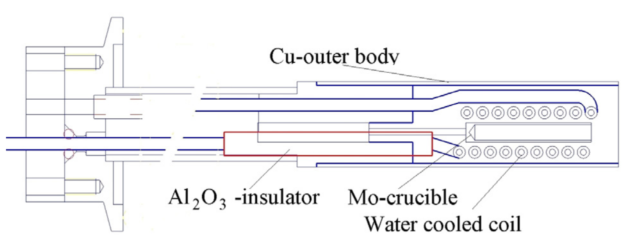

Figure 4: The JYFL inductively heated oven.

Sputter Technique

The sputter technique is beneficial especially for elements requiring very high temperatures to be vaporized. In this method the surface of the material is bombarded by the ions originating from the ECRIS plasma to give an extra energy to the atoms at the crystal lattice of the material. With the aid of the adequate energy the atoms of the target material are removed from the bulk material. The erosion of the material is measured by the sputtering yield, which is defined as *(removed atoms)/(projectile atom).* The yield depends on the properties of the target material, the mass and the energy of projectile atoms and the angle of incidence (with respect to the normal of the bombarded surface). Information about the sputter yields can be found for example from ref. [8]. There it can be seen that Ag, Au, Cu and Pd are among the most easily sputtered materials.

The sputter technique was adopted because some of the elements cannot be evaporated by the ovens (like Mo, W, etc). The most of the information and know-how needed was received from ANL ion source group. Figure 5 shows the sputter device at the JYFL 14 GHz ECRIS. The sample to be sputtered is inserted through a radial pumping slot (width ≈ 6 mm) of plasma chamber. The face of the sample is approximately at the level of plasma chamber surface and its position can be adjusted. The ion beam production is very sensitive to the position of the sample – even the movement of less than 0.5 mm can have a drastic effect. The stem of the sputter sample is insulated from the plasma chamber wall by Al_2O_3 tube.

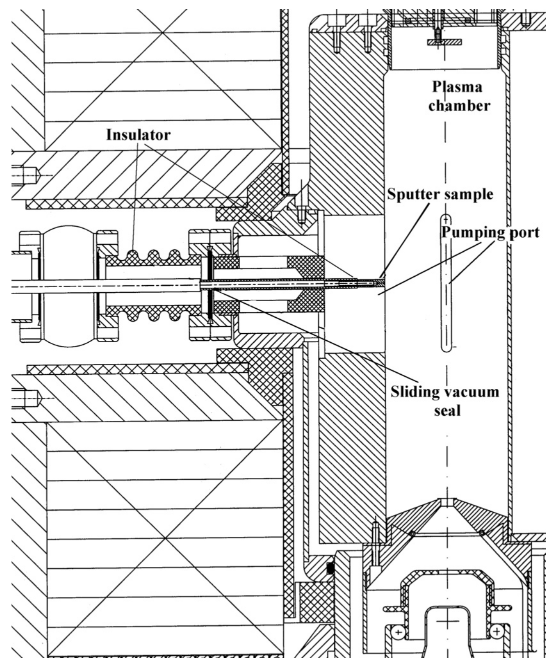

Figure 5: Radial sputter device at the 14 GHz ECRIS.

The development work concerning the sputtering was carried out with Zirconium, which has relatively low sputter yield. In the first tests the diameter of the sputter sample was 5 mm, but due to frequent sparking and short-circuits (happened after few hours operation) the width of the sample was reduced to 3.5 mm. The new sample geometry increased the operation hours but vacuum seal failures started to appear as a new problem. This happened especially when the beam intensity was maximized. It was expected that failure took place because of excessive heat load, which damages the sealing. However, the problem did not disappear when the cooling for the sputter stem was added. The problem disappeared when an adequate tantalum radiation shielding for the sliding vacuum seal was provided. The zirconium beam has successfully been used for nuclear physics experiments and the intensity varied between 4-8 μA (14 GHz ECRIS). The consumption rate has been about 1 mg/h. The sputter voltage of about 1.3 kV is required with the sputter current of 1-1.5 mA.

BEAM TRANSMISSION

Ion beam transmission plays a crucial role in the operation of cyclotron facility. For example in the operation of the JYFL K-130 cyclotron facility it was noticed that in some cases no positive effect in the accelerated beam intensity was seen when the extracted beam intensity from the JYFL 14 GHz ECR ion source was increased. In some cases the ion beam intensity after the cyclotron even started to decrease. The behaviour indicates that the beam quality decreases from the ECR ion source or/and the beam quality degrades by the inadequate properties of the beam line in the case of high ion beam intensities. Several experiments to understand the behaviour have been performed.

Beam Transmission of Different Beam Line Sections

The injection line from the JYFL 14 GHz ECRIS to cyclotron has been divided into two different sections for the studies: injection line from the 1) extraction of JYFL 14 GHz ECRIS to the analysing magnet and 2) first Faraday cup after analysing magnet (FC2) to the last Faraday cup before the cyclotron. The first section has been studied only by simulations because the transmission of total ion beam including all charges cannot be measured due to inadequate bending capability in the case of low charge states. Figure 6 shows the simulated beam behaviour from the JYFL 14 GHz ECRIS to the analysing magnet with two different Ar^{8+} intensities. The simulations have been performed by TRANSPORT-code using the extraction voltage of 10 kV and initial emittance of 200 π mm mrad. The code can include only one charge state and consequently, the measured charge state distribution was converted to Ar^{8+} beam, such a way that equivalent beam potential is obtained (corresponds to 1.5 mA of Ar^{8+}). As figure shows such beam intensity cannot be transported through the analysing magnet at 10 kV, which is a typical injection voltage for the K-130 cyclotron. The intensity has to be decreased to the value of 0.6 mA before the transmission of 100 % through the section 1 is obtained. The highest Ar^{8+} intensity measured after the analysing magnet of the JYFL 14 GHz ECRIS at 10 kV is about 350 µA. The results indicate that the available beam intensity for the cyclotron is strongly limited by the first section of the injection line.

The beam behaviour in section 2 was studied experimentally by measuring the intensity in several locations. Figure 7 shows the behaviour between the analysing magnet after 14 GHz ECRIS and the last Faraday cup before the cyclotron. As figure shows the transport efficiency of section 2 decreases dramatically when the beam intensity from the ion source increases. The further measurements demonstrated that behaviour is seen only in the last part of section 2.

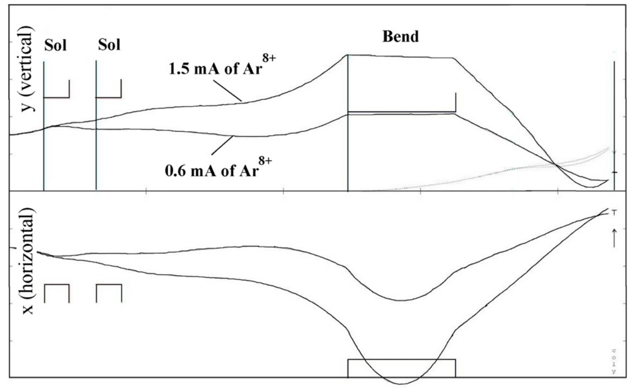

Figure 6: Beam transport simulations from the extraction to the bending magnet using two different Ar^{8+} intensities.

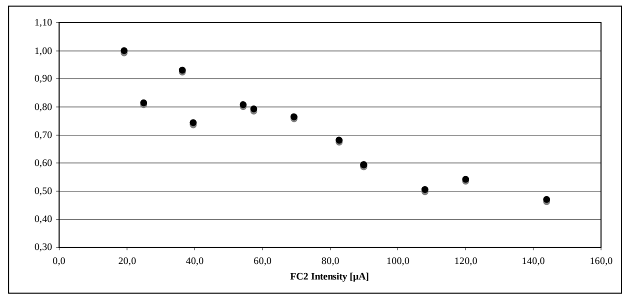

Figure 7: The normalized transmission of Ar^{8+} ion beam as a function of beam intensity from the JYFL 14 GHz ECRIS after the first dipole to the last FC before the cyclotron (i.e. section 2).

Asymmetric Beam Shape

The beam viewers have shown that the ion beam profile after the analysing magnet is elliptical as is shown in Figure 8. The aberration can come for example from the wrong entrance-exit angle of the analysing magnet, which causes different focusing properties in different planes. The elliptical beam can have remarkable difference in the Twiss parameters in different planes, which will result in high value of mismatch factor. This will increase 2D emittance in solenoid focusing as is shown by Eq. (1)

$$\varepsilon_x^2 = \varepsilon_x^2 \left[\left(1 + \frac{\Delta\varepsilon}{\varepsilon_x} \sin^2\theta \right)^2 + \frac{M}{4} \left(1 + \frac{\Delta\varepsilon}{\varepsilon_x} \right) \sin^2 2\theta \right] \qquad (1),$$

where $\Delta\varepsilon = \varepsilon_y - \varepsilon_x$ is the difference in the 2D emittances between the two transverse phase spaces and $M = \beta_x\gamma_y + \beta_y\gamma_x - 2\alpha_x\alpha_y - 2$ [9]. The rotation angle is close to 45˚ in the case of JYFL solenoids giving the highest effect on emittance increase.

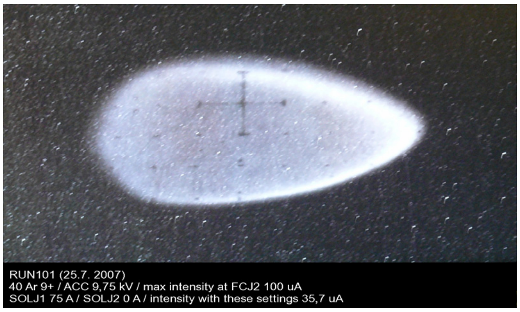

Figure 8: Asymmetric Ar^{9+} beam after the dipole magnet.

Hollow Beam Structure and Space Charge Compensation

Probably the most severe transport problem at JYFL is related to the hollow beam structure, most evident with low and medium charge states (see Figure. 9). This makes the beam transport difficult and increases beam losses. Possible reasons for the hollowness include strong solenoid focusing and consequent space charge effects between the ECR ion source and analyzing magnet, the spatial charge state distribution inside ECR plasma and possible flaws in the ion source extraction geometry.

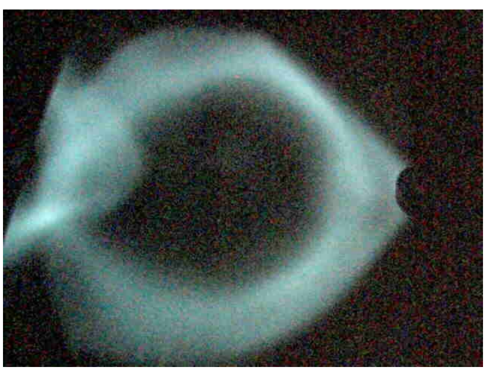

Figure 9: A hollow Ar^{8+} ion beam after dipole.

Studies by L. Celona et. al. [10] with Caprice ion source have revealed that the shape of the beam profile is dependent on the microwave frequency, i.e. on the mode structure, which can cause the hollowness of the beam. Similar behaviour has recently been measured with the JYFL 14 GHz ECRIS [11]. This indicates that at least part of the hollowness can be due to plasma phenomena inside the ECR ion source. It has also been noticed, that with high beam currents the beam becomes increasingly hollow. Increasing the acceleration voltage of the ion source reduces the effect and strongly improves the beam transmission. These indicate that the at least part of the hollow beam structure is generated inside the beam line due to space charge effect. Recent studies have also shown that the beam shape has strong dependency on the pressure at the beginning of the beam line. This can be due to space charge neutralization effects and thus is an indication of space charge problem.

The beam compensation with the residual gas is well-known method in the light ion source community to decrease the space charge effect. This has been tested at JYFL with highly charged Ar ion beams (Ar^{6+} - Ar^{11+}) by feeding nitrogen into the beam line upstream from the analysing magnet where all beam components are still included. It was observed that the hollow beam structure started to disappear and emittance decreased as a function of beam line pressure. The brightness of the beam reached the maximum value around the pressure of $5 \cdot 10^{-6}$ mbar [12]. Later different residual gases will be tested and the results will be confirmed with the cyclotron. As a consequence of lower emittance and higher brightness it is assumed that the beam transmission efficiency will increase substantially in the case of high beam intensities.

FUTURE PLANS

New metal ion beams will be required with the inductively heated oven and with the aid of sputter technique (especially Ti, Gd, Mo, and W). The improvement of beam quality will be continued by testing different residual gases in the beam line and as a next step to use a filament to introduce extra electrons for the beam neutralization. The possibility to have the first section of the beam line at high voltage (including analysing magnet) with adequate electron traps will be studied.

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