ECRIS RELATED RESEARCH AND DEVELOPMENT WORK AT JYFL AND SOME FUTURE PROSPECTS*

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Abstract

Since the last ECR workshop the JYFL ion source group has focused on 1) development of metal ion beams, 2) ion beam formation and transport, 3) plasma studies and 4) photoelectric effect in ion sources. The MIVOC method and sputtering technique were further studied in order to produce intensive titanium ion beams. As a result, an intensive $^{50}Ti^{11+}$ ion beam was successfully produced with the MIVOC method. An improvement in ion beam transport of the JYFL K130 cyclotron facility was achieved as a result of the work performed on ion beam formation. This work will be described in more detail elsewhere in these proceedings (see V. Toivanen et. al). The plasma research can be divided into plasma breakdown processes, plasma and ion beam instabilities, afterglow processes and plasma-wave coupling. The afterglow and instability experiments will be presented elsewhere in these proceedings (see. V. Skalyga et. al. and O. Tarvainen et. al.). In addition, studies involving in the photoelectric induced electron emission and charge exchange reactions will be briefly discussed.

METAL ION BEAM PRODUCTION

The metal ion beams and their production techniques can be considered as one of the key factors in nuclear physics laboratories using stable isotopes. Also at JYFL increasing requirements towards the availability of some refractory elements, like Ti, Zr and Mo has been expressed. In the following the development work for the sputter and the MIVOC technique will be presented.

Sputtering Technique

The sputter technique makes it possible to produce ion beams from the elements exceeding the capabilities of high temperature ovens. The efficiency of the method depends on the mass of projectile, its energy, angle of incident and naturally the sputter yield of the material to be sputtered. Unfortunately, the sputter yield tends to be low in the case of refractory elements, as is demonstrated in Table 1. However, the method still offers the intensities not available using the other methods. The method was first adopted at ANL, and since that it has been used in several laboratories on a day-to-day basis (see for example ref. [1,2]).

At JYFL the sputter technique has mainly been used for the production of Zr ion beams. Recently, strong effort has been made to produce ^{50}Ti ion beams by placing enriched ^{50}Ti powder into a small hole drilled in a metallic titanium rod [3]. This hole, including the enriched material, is placed to the spot where the sputtering mainly takes place. A test sample (with natural abundances) was exposed to plasma via radial port of the JYFL 14 GHz ECRIS. During the tests up to 20 µA of $^{48}Ti^{11+}$ beam was extracted from the ion source. Unexpectedly, the titanium ion beam remained even if the sputter voltage was set to zero. This indicated that the power was coupled directly to the sample causing vigorous heating and consequently the evaporation of titanium. The substantial evaporation of titanium requires the temperature of about 1800˚C. At this temperature a remarkable fraction of heat losses are caused via thermal radiation. This generated a strong heat load on the adjacent permanent magnets.

After the sputter experiment a clear degradation of source performance was noticed. The measurement of hexapole magnets confirmed that magnetic field was decreased approximately by 10 % close to the radial port used for the experiment. The destroyed hexapole was replaced and more efficient cooling scheme to minimize the heat load of the permanent magnets was designed. The sputter experiments will be continued with the new cooling scheme during the last quarter of 2012.

Table 1: Sputter yield Y for some elements. The yield is calculated for Oxygen or Argon projectiles at 1000 eV. Values calculated with Simple Sputter Yield Calculator (http://www.iap.tuwien.ac.at/www/surface/sputteryield)

Element	Y (with O)	Y (with Ar)
Ag	1.8	3.7
Ni	0.9	1.7
Mo	0.4	0.9
Pb	2.3	4.9
Ti	0.4	0.7
Zr	0.4	0.8

MIVOC Method

The MIVOC method [4] is very efficient in the case of some metal ion beams like Fe, Ni and Ti. As an example, in the case of $^{48}Ti^{11+}$ion beam the intensity of 45 µA was produced using (trimethyl)pentamethylcyclopentadienyl-titanium)compound [5]. However, for the nuclear physics experiment at least 40 pnA of accelerated ^{50}Ti ion beam was needed. In order to meet this intensity requirement the afore-mentioned compound has to be synthesized using the enriched ^{50}Ti isotope. After an intensive development work the compound needed for the nuclear physics experiment was successfully synthesized by the Strasbourg group and subsequently tested using the JYFL 14 GHz ECRIS [6]. The $^{50}Ti^{11+}$ beam produced with the

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JYFL 14 GHz ECRIS was subsequently accelerated to the energy of 242 MeV in order to produce ^{256}Rf (Z = 104) evaporation residues. This enabled the first prompt spectroscopy of a superheavy element using the JUROGAM2/RITU/GREAT experimental set-up [7]. During the experiment the intensity of 15 - 20 µA was extracted from the ion source over the period of three weeks giving the required beam-on target intensity of 40 - 45 pnA. In order to meet the requirement for the next ^{50}Ti experiment the beam-on target intensity of higher than 200 pnA has to be produced. The requirement is 5 fold compared to the previous experiment in the fall 2011. In order to meet this requirement the intensity of Ti ions has to be increased and the transmission of the JYFL LEBT has to be improved.

BEAM FORMATION AND TRANSPORT

In the case of the JYFL K130 cyclotron facility the typical injection voltage is as low as about 10 kV, dictated by the cyclotron injection, making the low energy beam transport challenging. The emittance of the low energy beam is typically high and it tends to increase further during the beam transport due to the aberrations caused by different ion optical components and due to the space charge.

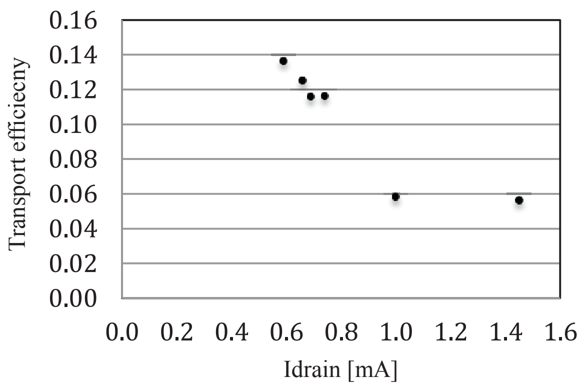

Figure 1: The Ar^{8+} transport efficiency from the first Faraday cup downstream the JYFL 14 GHz ECRIS mass separation to the first Faraday cup after the K130 cyclotron as a function of the drain current of the ion source high voltage power supply (U = 9.66 kV).

The typical behavior concerning the JYFL ion beam transport efficiency is presented in Fig. 1. The graph shows that the transport efficiency decreases when the total ion beam current from the JYFL 14 GHz ECRIS increases.

Comprehensive studies and development work have been performed in order to increase the ion beam intensity available after the K130 cyclotron (see for example [8, 9]). As a result of the studies it was realized, for example, that the beam emittance increases vigorously in the ion source extraction when the beam intensity exceeds the value of about 1 mA. A new extraction for the JYFL 14 GHz ECRIS was designed using a new ion beam simulation code IBsimu [10]. The first results have shown that the beam intensities after the K130 cyclotron have increased even by a factor of 2. This work and the results are presented elsewhere in these proceedings (see ref. 11).

PLASMA STUDIES

Intensive research of ion source plasmas has been performed at JYFL. This work can be divided into four different categories: 1) plasma breakdown, 2) plasma instabilities, 3) plasma afterglow and 4) plasma-wave coupling. This work will be presented in the following.

Plasma Breakdown

Plasma breakdown process has been studied extensively at JYFL with the aid of x-ray/gamma diagnostics (see for example [12, 13]). The most recent experiments were performed in collaboration with the LBNL, NSCL/MSU and IAP/RAS ion source groups using CdTe detector (1.5 – 400 keV) with 100 µs temporal resolution. The experimental setup and results are extensively presented in ref [14].

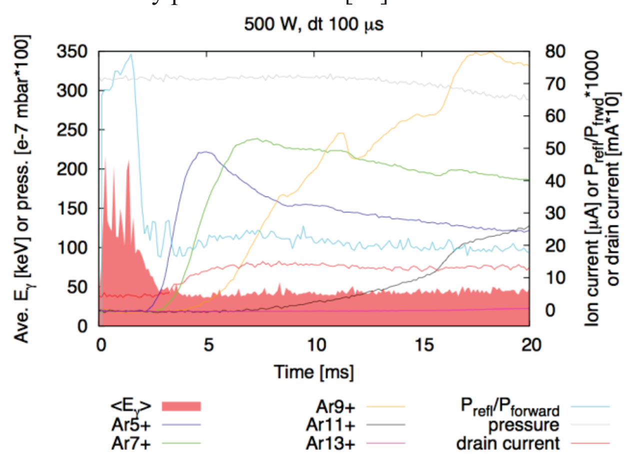

Figure 2: The time evolution of average bremsstrahlung energy during the plasma breakdown process. Pulse length of 500 ms with 1 Hz repetition rate was used.

Figure 2 shows the average bremsstrahlung energy during the plasma breakdown process. At the beginning of the microwave pulse the reflected power is high indicating the absorption of microwave power is low and consequently the plasma density is also low. At this moment, the electromagnetic field amplitude is high making a vigorous heating of electrons possible. As a result of this, the bremsstrahlung emission has relatively high average energy. The electron density increases exponentially and after some threshold density the microwave power is too low to maintain the high average energy of electrons. As a result of this also the average energy of measured photons decreases. During this transition also the reflected microwave power decreases vigorously (see Fig. 2) and the first ions are extracted from the plasma. In addition, at this point the preglow peak [15], normally attributed to low charges, can be observed.

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Plasma and Ion Beam Instabilities

The ion beam instabilities have been studied with VENUS [16] at LBNL and with JYFL 14 GHz ECRIS. The motivation of the studies was to define the fast scale beam instability behavior and the parameters affecting the amplitude and the frequency of the instabilities. The work was performed in collaboration with the LBNL ion source group and the experimental setup and the results are presented in ref. [17].

Afterglow

The afterglow behavior [18] is a well-known phenomenon in pulsed operation mode of ECR ion sources. The decay of afterglow peak with high temporal resolution was studied in collaboration with the IAP-RAS ion source group. The experimental setup and related results are presented in ref. [19].

Plasma-Wave Coupling

Frequency tuning effect has been found and studied by the □INFN-LNS□ ion source team [20]. In this technique the microwave frequency is varied in order to select the efficient heating mode inside the plasma chamber of ECRIS. This plasma-wave coupling was studied also with the JYFL 14 GHz ECRIS by measuring the behavior of S_{11} parameter with the aid of a Rohde & Schwarz network analyzer using dual port technique. In this experiment the plasma was heated with TWTA (f = 11.56 GHz) and the other waveguide was used to define the behavior of S_{11} parameter by scanning the frequency of the low power probing signal of the network analyzer around 14 GHz. Waveguide effects were removed by calibrating the network analyzer with two different waveguide offset shorts and a load element in order to measure only the combined properties of the plasma and the cavity.

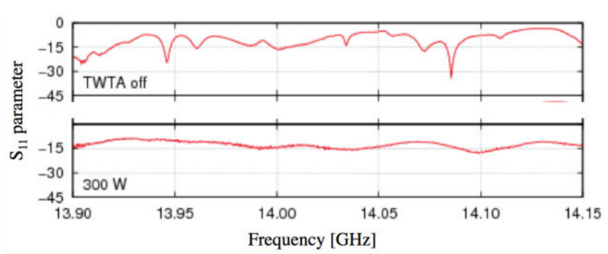

Figure 3: Plasma chamber S_{11} behavior with empty plasma chamber and with plasma maintained with the TWTA microwave power of 300 W at 11.56 GHz.

As a first step the properties of the empty plasma chamber (i.e. no plasma) was measured (see upper picture of Fig. 3). Next, the plasma was ignited and maintained with the TWTA at the microwave frequency of 11.56 GHz (lower picture of Fig. 3). As Fig. 3 shows, a fairly strong behavior of S_{11} parameter is present with the empty plasma chamber. This indicates that the quality factor Q of the empty plasma chamber is relatively high. In this case the quality factor was calculated to be of the order of 10^3. The Figure also shows that the plasma-loaded cavity strongly damps the mode behavior and consequently decreases the quality factor Q. This is due to the absorption of electromagnetic field. In this case the quality factor was estimated to be of the order of 10^2. A comprehensive report about the experimental setup and results are given in ref. [21].

PHOTOELECTRIC EFFECT AND ION SOURCES

The intensity of highly charged ions can be increased by increasing the product of $n_e\tau_i$, where n_e is the electron density of plasma and τ_i the confinement time of ion. The ion confinement is mostly governed by the ambipolar diffusion affected by the plasma potential. The confinement time can be increased by increasing the magnetic confinement, the size of the plasma and by decreasing the kinetic energy of ions. The electron density increases, for example, with the microwave power and microwave frequency used for electron heating (see for example ref. [22, 23, 24]). In addition, the secondary electron emission can increase the electron density and consequently the performance of ECR ion sources [25].

The JYFL ion source group has studied the VUV-light emission of different plasmas. The motivation towards the studies was to 1) define the power dissipation of different plasmas through the visible light and VUV- light emission and 2) find out if the light emission can yield a remarkable amount of photon induced electron emission from the plasma chamber walls. This would affect the performance of the ECR ion source. The third motivation was to find out if the light diagnostics can be used as a fault-finding tool. This subject is very complicated and will be studied later after more experience regarding the light spectroscopy has been gained.

A dedicated setup for studying the photon induced electron emission from different surfaces was designed and constructed (see Fig. 4). In this arrangement, a deuterium lamp is placed in front of a collimator structure. The cathode surface coated by the material of interest is exposed to photons emitted from the lamp. The photon-induced electrons are collected by the positively biased anode. The entire experimental setup is placed in vacuum in order to make the propagation of photons and induced electrons possible.

An Au cathode was chosen to be a target material in order to minimize different chemical surface reactions. The work function of the Au surface is 5.1 – 5.5 eV and the highest emission yield in VUV-region is reached at the photon energy of about 20 eV whilst the second maximum is reached at the x-ray energy of about 500 eV (see for example ref. [26] for quantum efficiency of Au). The optimization of the experimental setup, for the further studies with ion sources, was performed by using a deuterium lamp as a source of photons. The quartz structure of the lamp stops the photons exceeding the wavelength of about 160 nm. Consequently, the usable photon spectrum covers the range of 5.1 – 7.8 eV. As a next step, rotatable target system will be used in order to

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make the studies of different materials without breaking the vacuum possible.

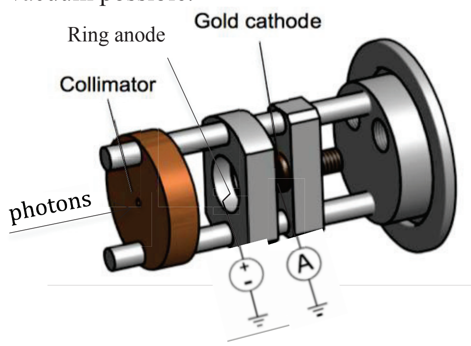

Figure 4: Setup for the studies of photoelectric effect.

The first results using deuterium lamp are presented in Fig. 5 showing the photon induced current as a function of anode voltage. During the experiment the photon emission current was measured to be of the order of 0.32 nA, whilst the VUV light power was measured to be 0.7 µW. This corresponds to the current to power ratio of about 0.5 mA/W. Here it should be noticed that the afore-mentioned efficiency is obtained with the narrow range of photon energies (5.1 – 7.8 eV), which does not correspond to the optimum spectrum for photon-induced emission. As can be estimated from ref. [27] this ratio can be remarkably higher (≈ 10 fold) if a more optimum spectrum of light is available. In this optimum case the photon-induced emission current can exceed the value of 5 mA/W.

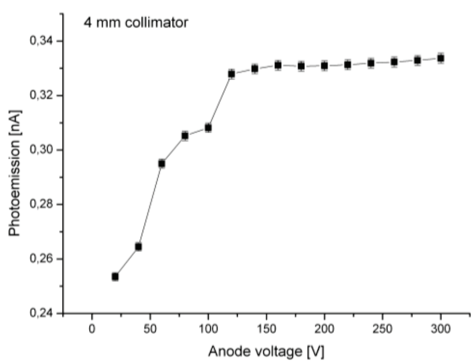

Figure 5: Photon induced electron emission measured from an Au cathode. Photons were produced by a deuterium lamp.

As a next step the experiments will be continue with the microwave ion source using a hydrogen plasma and later by using ECRIS plasma. The experiments at JYFL have indicated that the power dissipation of microwave ion source plasma via VUV light emission can be approximately up to 30 % of the microwave power fed into the plasma chamber [27]. Although the power of VUV light emission from the ECR ion source plasma is still unknown it probably is much lower than in the case of microwave ion source. This estimation is due to the operation pressure, which is 2 - 3 orders of magnitude lower in the case of ECR ion source. However, in the case of ECR ion sources the power dissipated via low energy x-ray emission (some hundreds of eV) can be at the level of W. This makes it possible that the photon induced electron emission can have an effect on the performance of ECR ion sources.

CHARGE EXCHANGE

The motivation towards the charge exchange studies was to estimate the effect of neutral pressure to the production rate of the highly charged ions. The maximum life-time of highly charged ion can be estimated if the cross section for the charge exchange reaction, the neutral pressure inside the volume of interest and energies of particles are known. This can be compared to the production times of highly charged ions for example in the pulsed operation mode of the ECRIS. The volume production rate of different charge states can be estimated with the aid of the balance equation (1). The production rate depends on the following parameters

$$\frac{dn_q}{dt} = n_e\langle\sigma_{q-1,q}v_e\rangle n_{q-1} + n_0\langle\sigma_{q+1,q}v_i\rangle n_{q+1} - n_0\langle\sigma_{q,q-1}v_i\rangle n_q - n_e\langle\sigma_{q,q+1}v_e\rangle n_q - \frac{n_q}{\tau} \quad (1)$$

where the third parameter is linked to the charge exchange reaction. In the case of highly charged ions its cross section can be several orders of magnitudes higher than related ionization cross section. Consequently, the charge exchange can strongly limit the production of highly charged ion beams.

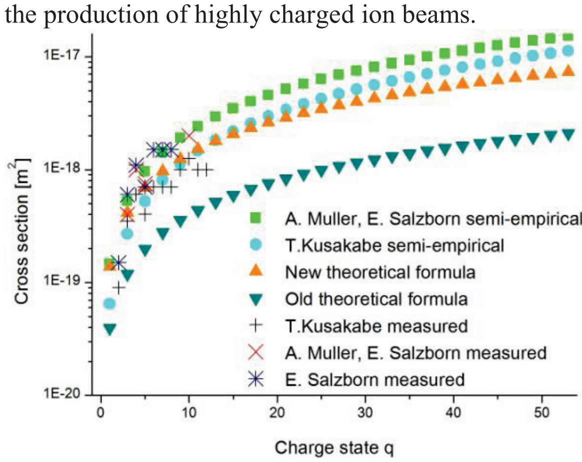

Figure 6: The charge exchange cross section σ for different xenon charge states.

During the literature study a fairly limited amount of experimental data regarding the charge exchange reactions for the highly charged ions, like Xe^{10+} or higher, was found. This is demonstrated in Fig. 6. In order to estimate the charge exchange cross section of high charge states, like Xe^{30+} or higher, semiempirical or fully theoretical equation has to be used. One generally used theoretical equation has been derived using the Bohr model of atom. The approach presented in [28] assumes that in the case of low energy ions the cross section of charge exchange reaction is independent on the ion velocity. As Fig. 6 shows there

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is a remarkable difference between the results obtained by the semiempirical models (based on the experimental data) and classical model. Very good agreement with the experimental data was achieved when we included the shielding of electrons in the old theoretical formula. The charge exchange cross section using a new theoretical formula is also shown in Fig. 6.

FUTURE PROSPECTS

The JYFL LEBT will be studied with the aid of simulations to further improve its performance. One option is to move the 14 GHz ECRIS closer to the dipole (to its object point). In addition, the first section of the LEBT, including the dipole, could be negatively biased making it possible to transport the beam through this section with higher beam energy. Both changes could decrease the space charge problems existing before the q/M separation. In addition, a new central area configuration for the cyclotron will be considered in order to make the use of higher injection voltages possible. This would also mitigate the space-charge problems in the JYFL LEBT.

Different radiation-hard ion source schemes, needed by RIB-ISOL facilities, will be studied by simulations. A so-called double helix structure is interesting option especially with the quadrupole multipole configuration. This configuration produces quadrupole-type plasma flux, which would have a perfect match between the beam properties and ion beam optics with quadrupole focusing. This structure can be considered as an intermediate step in the process of designing and constructing a more advanced ARC-ECRIS [29, 30]. This ion source can possibly be used as a radiation hard ion source and a beam merger. The project to design and construct a 18 GHz ECRIS for the future needs of the JYFL nuclear physics program will be also initiated. In addition to afore-mentioned projects the intensive program for plasma related experiments will be continued in strong international collaboration.

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