ION BEAM RESEARCH AND DEVELOPMENT WORK AT JYFL

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Abstract

During the last year the main focus of the JYFL ion source group has been on the studies of the beam transmission, time evolution of Bremsstrahlung (will be presented elsewhere in this same proceedings by T. Ropponen) and on the development of metal ion beams. Comprehensive studies of the beam transmission efficiency at the Department of Physics, University of Jyväskylä have shown several problems concerning the injection line of the K-130 cyclotron. The experiments have shown strongly non-uniform and elliptical beam shape, which limits the beam transmission efficiency. The durability of the inductively heated oven has successfully been improved and it has been tested with the 14 GHz ECRIS for the production of titanium and chromium ion beams. The intensity level of about 20 μA was reached for the medium charge states, which is adequate for most of the nuclear physics experiments at JYFL.

INTRODUCTION

According to operation experience with the K130 facility at JYFL (University of Jyväskylä, Department of Physics) the beam transmission efficiency decreases when the beam intensity extracted from the ECRIS increases [1]. In some cases the available beam intensity after cyclotron even decreased when the beam intensity from the ECRIS was increased. As a result of this behavior the beam transmission project was initiated in order to over come the problem and to meet the beam intensity requirements. The extensive beam transmission measurements were started in 2007 with the beam line simulations in collaboration with NSCL/MSU. As a result of the simulations several bottlenecks concerning the beam transmission were found. As a next step the beam transmission experiments were started in order to confirm the results obtained by the simulations.

The most of the beams needed for the nuclear physics experiments are produced with the JYFL 14 GHz ECRIS. Figure 1 shows the beam line components used for the focusing and steering of the ion beams from the ECRIS to the cyclotron. In this case the beam is transported via three different dipole magnets: DJ1 is used as a mass spectrometer, SWI1 is used to select the ion source for the experiment (i.e. light ion source, 6.4 GHz ECRIS or 14 GHz ECRIS) and DI2, which is used to bend the beam into the vertical injection of the cyclotron. As the figure shows the focusing of the beam is carried out with solenoids, which generates different focus points for different q/m-ratios. The beam diagnostics includes Faraday cups, beam viewers and an Allison-type emittance scanner.

BEAM TRANSMISSION EFFICIENCY

The objective of the beam transmission experiments was to define the losses of different beam line sections including the K130 cyclotron. The beam intensities were measured from several locations: FCJ2, FCI5, inflector, outer radius of cyclotron, after deflector and finally from PFC. The Faraday cup FCJ2 is located after the analysing magnet, FCI5 in the vertical beam line before the cyclotron injection and PFC is the first Faraday cup after the cyclotron.

Figure 2 shows the tendency of the transmission efficiency as a function of the beam intensity extracted from the 14 GHz ECRIS. Here the efficiency is calculated from the ion beam currents measured by FCJ2 after the first dipole magnet (DJ1) and by PFC after the cyclotron. The transmission studies were carried out using $^{40}Ar^{8+}$ ion beam, which corresponds to the q/m-ratio normally needed for the nuclear physics experiments. The voltage of 9.66 kV was used for the extraction of ion beam from the ECRIS and the beam current was varied by changing the microwave power. The experiments were carried out with the second harmonic acceleration.

According to the experiments the transmission efficiency decreases strongly when the beam intensity extracted from JYFL 14 GHz aECRIS increases. As Fig. 2 shows the total transmission efficiency has the value of about 15 % for the beam intensities less than 25 μA (drain current ≈ 0.5 mA). The efficiency degrades almost linearly when the beam intensity increases being only about 6 % for the beam intensities above 100 μA (drain current ≈ 1 mA or higher). The corresponding drain current of high voltage power supply is presented in the same figure. The drain current roughly corresponds to the total beam current extracted from the ECRIS if secondary electrons from the puller are excluded.

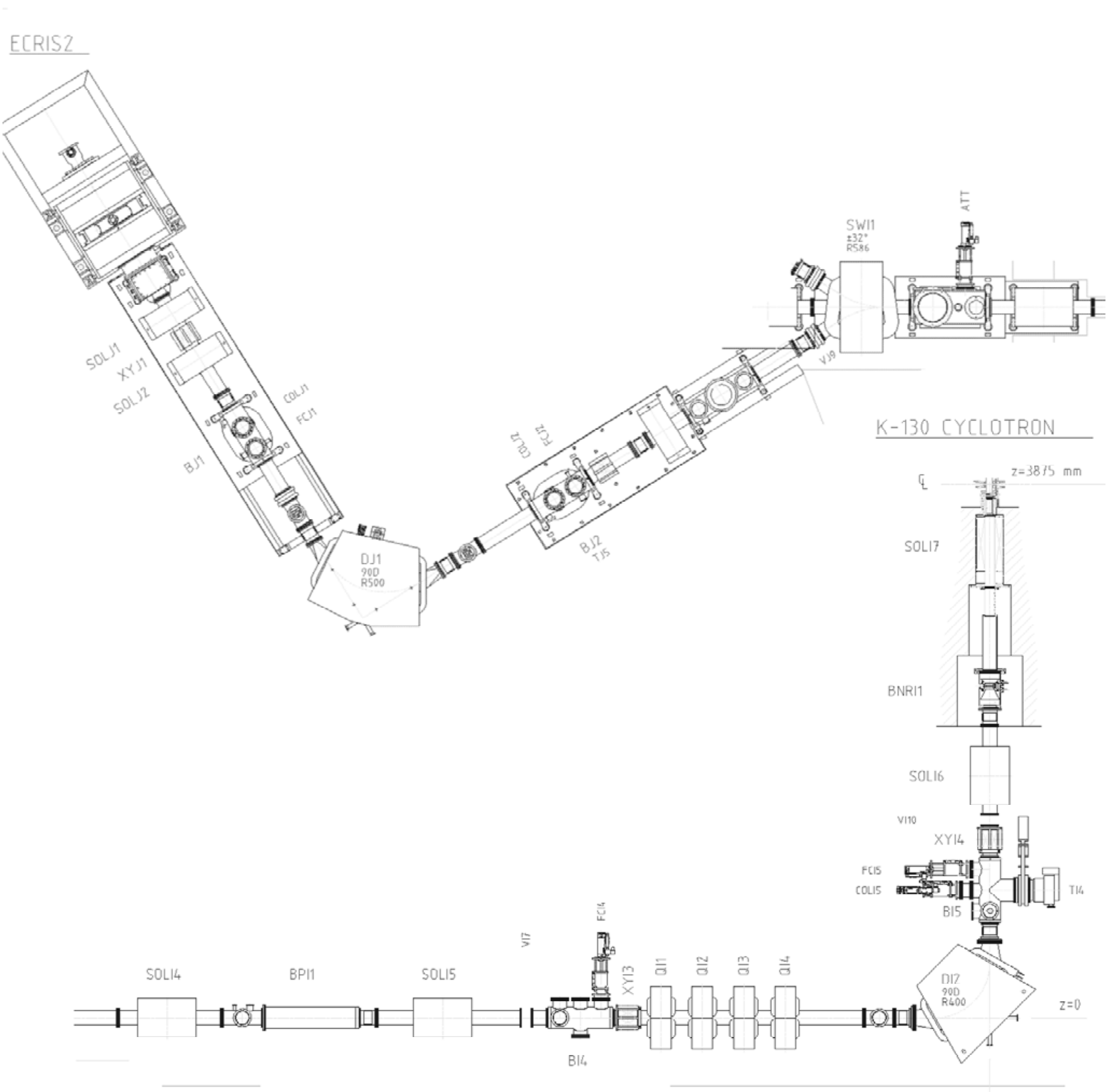

Figure 1: The JYFL beam line from the 14 GHz ECRIS (ECRIS2) to K130 cyclotron.

From Fig. 2 it can be estimated that about 6 μA of the $^{40}Ar^{8+}$ ion beam can be extracted from the K130 cyclotron when 50 μA is available from the ECRIS. Approximately the same accelerated beam current is available if the beam intensity from the ECRIS is doubled. Consequently, there is no ambition to improve the performance of the ECRIS before the reason for the behavior has been found.

As was mentioned earlier the beam currents were measured from different sections of the beam line. It was found that the tendency shown in Figure 2 can be seen only in the section between FCJ2 and FCI5 (see Fig. 3). The other sections have practically constant transmission efficiency or the intensity effect is of the order of 10 % or less. This indicates that the main problem in the case of the second harmonic acceleration exists before FCI5. As a next step it has to be defined if the main problem is the ECR ion source or the beam line.

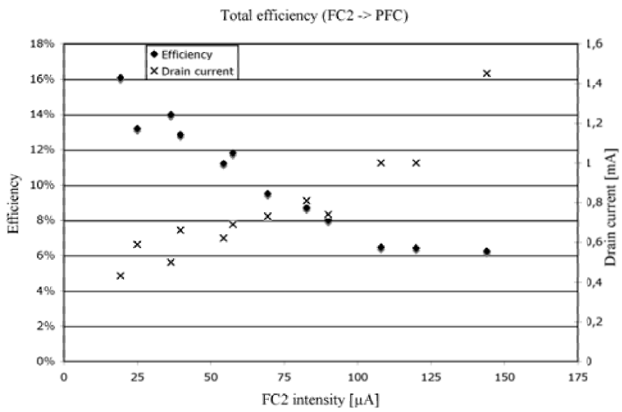

Figure 2: Total transmission efficiency of K130 cyclotron facility, i.e. (PFC/FC2), in the 2nd harmonic acceleration.

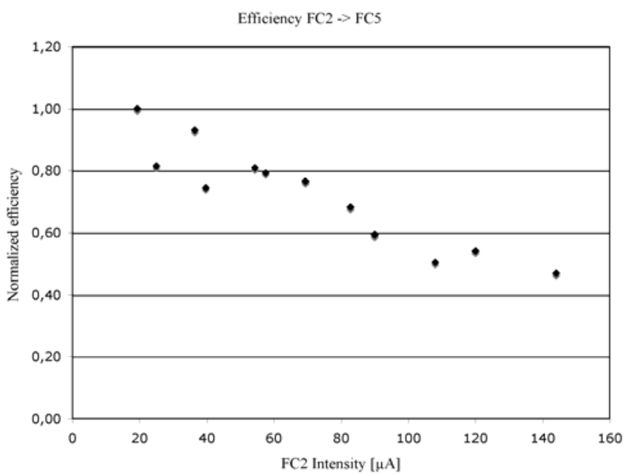

Figure 3: Transmission efficiency between FCJ2 and FCI5 (see Fig.1).

BEAM STRUCTURE

The beam line simulations were carried out by DIMAD code [2]. According to simulations the entrance and exit angle of dipoles in the beam line are not exactly correct (DJ1 and DI2). As a consequence, the focusing properties in different planes are not same, which results in an asymmetric beam profile. The 2D emittance of asymmetric beam can increase remarkably when focused by the solenoids making the beam injection into the cyclotron more inefficient.

In order to confirm the beam line simulations KBr beam viewers were installed before and after the analysing magnet (DJ1). As upper picture of Fig. 4 shows the beam profile after the analysing magnet is elliptical as was anticipated from the DIMAD simulations. In this case the $^{40}Ar^{9+}$ beam intensity was only 33 µA. In addition to elliptical shape a hollow beam structure (lower picture of Fig. 4) is present when the beam intensity exceeds the value of about 70 µA or strong solenoid focusing is used. This certainly decreases the beam quality and transmission efficiency. The hollow beam structure tends to be more pronounced when the beam intensity and the strength of the focusing power increases.

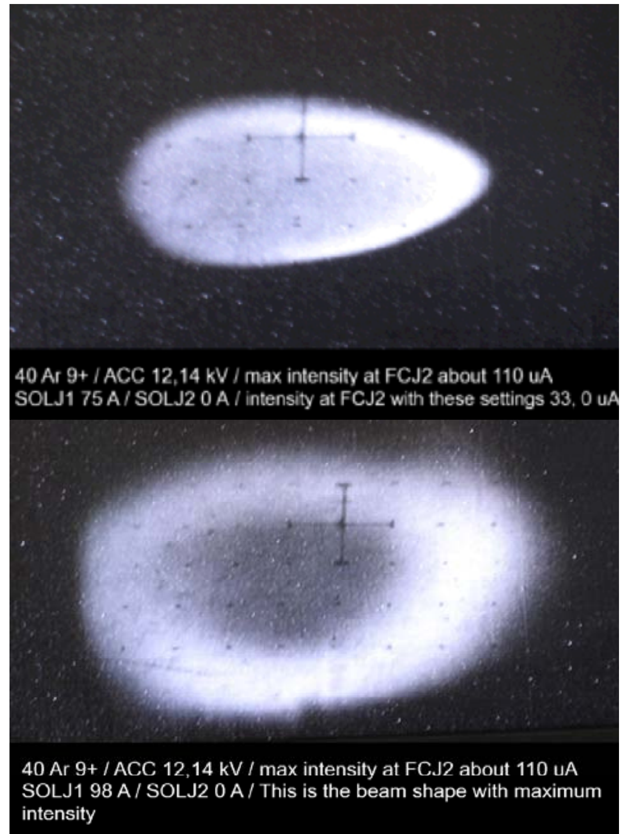

Figure 4: The beam profiles of Ar^{9+} ion beam after the analysing magnet.

TRANSMISSION EFFICIENCY WITH HIGHER INJECTION VOLTAGE

The effect of injection voltage on transmission efficiency was tested with Ar^{9+} ion beam using 9.75 kV and 12.14 kV. The injection voltage needed for the cyclotron operation is defined by the energy required for the nuclear physics experiments. Typical energy is slightly above the Coulomb barrier, i.e about 5 MeV/nucleon, which requires the injection voltage of about 10 kV. The use of higher injection voltage would then require geometrical changes into the central area of cyclotron in order to make the acceleration of ions possible.

According to Child-Langmuir law the improvement of about 40 % can be anticipated when the injection voltage is increased from 9.75 kV to 12.1.4 kV. However, the improvement of about 100 % was obtained (see Fig. 5). This indicates that the beam intensity within the acceptance of the cyclotron increases drastically with the injection voltage. A possible explanation is that the effect of the hollow beam structure shown in Fig. 4 decreases dramatically with the injection voltage. This can be due to decreased space charge effect. The same effect can possibly be obtained with the lower beam intensity (i.e. lower space charge effect). This will be studied later.

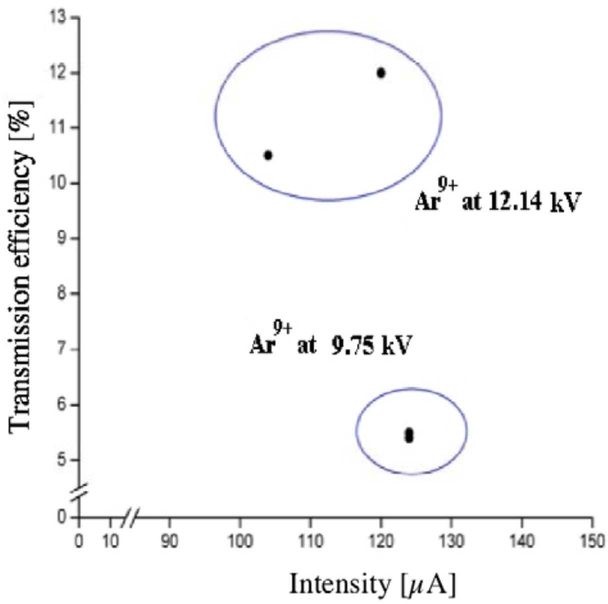

Figure 5: The effect of injection voltage (= extraction voltage of ECRIS) on the beam transmission efficiency.

TESTS WITH QUADRUPOLES

Quadrupole magnet focuses ion beam in one plane and defocuses it in the perpendicular plane. Thus it is possible to alter the shape of the beam profile by using quadrupole magnets. An experiment was carried out to determine if the beam quality at JYFL could be improved by reshaping the beam profile this way. To achieve this, a quadrupole doublet was temporarily installed before the analysing magnet (DJ1) of JYFL 14 GHz ECRIS and the beam shape was observed with a beam viewer after the analysing magnet. The beam was focused through a 20 mm aperture after the beam viewer and its intensity was measured with Faraday cup (FCJ2). Just after the FCJ2 (see Fig. 1), the beam emittance was measured with Allison-type emittance scanner.

The quadrupole magnets proved to be effective in the reshaping of the beam, especially in the case of fixing a strong elliptical profile to a more circular one. Reshaping of the beam caused considerable increase in the beam intensities measured in FCJ2. These changes are probably caused by the 20 mm aperture in the beam line. Previously the aperture had caused more beam losses because of the elliptical shape of the beam. With quadrupole magnets it is possible to focus more beam through the collimator. The measured intensities after the analysing magnet increased on average over 14 % when quadrupole magnets were used. Intensities after the cyclotron increased on average almost 10 %.

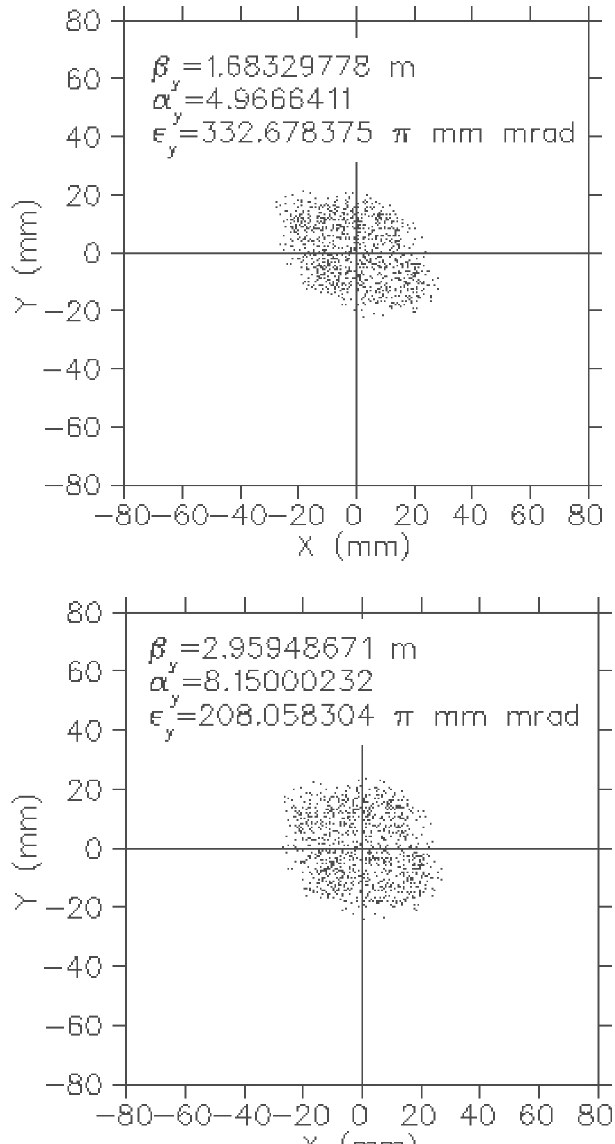

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Figure 6: Upper picture: Beam profile and emittance without the quadrupoles. Lower picture: Beam profile and emittance with the quadrupoles.

Reshaping of the beam had a significant impact on the beam emittance. The emittance decreased with the use of quadrupole magnets over 25 % on average. Aberrations, which can be seen as 'S'-shape in the emittance phase space plots, were reduced. A similar decrease of emittance was also seen in computer simulations (see Fig. 6). According to the results of these simulations, the beam is more symmetric at the emittance scanner due to the use of quadrupole magnets. This results in a smaller value of beam emittance.

Although it was assumed that the reshaping of the beam would improve the beam transmission efficiency, this was not observed. It is possible that the beam quality degrades during the remaining transmission line so much that there is no clear improvement in the transmission efficiency even if the starting conditions have become better. With higher intensities the beam also becomes hollow which further decreases the beam quality and transmission efficiency. This may hide some improvements, which otherwise could be gained from reshaping the profile of a higher intensity beam. It is also possible that the beam intensity within the acceptance of cyclotron does not increase although the emittance has decreased (i.e. only some aberrations have decreased due to more circular shape of the beam).

METAL ION BEAMS

The titanium and chromium ion beams have been developed with the inductively heated oven [3]. The oven can reliably be operated at the temperature of 1700 ˚C, which is needed for the production of Ti ion beam (the oven has been tested up to 2000 ˚C). In the case of $^{nat}Ti^{10+}$ the intensity of 20 µA and 1 µA were extracted from the JYFL 14 GHz ECRIS and the K130 cyclotron, respectively. During the experiment the consumption rate was slightly less than 2 mg/h. Oxygen was used as a buffer gas and clear getter effect was seen in operation. The intensity level after the ECRIS was about 20 µA for the medium charge states like Ti^{10+}. After the test a clear degradation of ECRIS performance was found. The other experiment was carried out using helium as a buffer gas. In this experiment the same intensities and consumption rates as with oxygen plasma were achieved. In the case of chromium similar intensities were obtained as with titanium. However, the consumption rate was remarkably lower (≈ 0.5 mg/h) and a clear effect in the subsequent performance was not seen.

FUTURE PLANS

The main focus of the work of the JYFL ion source group will be in the beam formation and transmission. According to measurements the main problem is the hollow beam structure, which is more visible with higher beam intensities. Several different solutions will be considered and tested. The higher injection voltage would certainly be the most effective solution. However, in this case a new central area for the cyclotron has to be designed and constructed. The higher injection voltage decreases the space charge effect. A smaller charge density can easily be achieved with a smaller extraction aperture of ECRIS, which will be tested at JYFL. This decreases the total beam current but probably the decrease is more pronounced for the low charge states as is indicated by some experimental results (for example by the LBNL ion source group [4]). However, the beam quality can improve faster than the beam intensity decreases due to the smaller extraction aperture, which can result in a higher ion beam current after the cyclotron.

The simulations in order to see the effect of Wien-filter have been started. The first results indicated that the size of the filter might be too large to be installed in the extraction area of ECRIS. However, the simulations will be continued. The Wien-filter would be beneficial because it would make it possible to remove all unwanted elements – i.e decreases the total current - from the extracted beam. In addition, focus points of different q/m-ratios before the analysing magnet can be avoided. The relocation of the JYFL ECRIS closer to analysing magnet will be considered. It is also possible that the successful project concerning the electrostatic focusing performed at the NSCL/MSU [5] will be carried out at JYFL. The Bremsstrahlung experiments will be continued.

ACKNOWLEDGEMENTS

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