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Highly Charged Ion Injector in the Terminal of Tandem Accelerator

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Abstract. A highly charged heavy ion injector using an all permanent magnet type electron cyclotron resonance ion source (ECRIS) has been constructed in the high voltage terminal of the vertical and folded type 20UR Pelletron tandem accelerator at Japan Atomic Energy Agency at Tokai. The new in-terminal injector made it possible to accelerate highly charged heavy ions which have not been obtained from the tandem accelerator. Beam energy and beam intensity have been remarkably increased and the noble gas ion beams have become available.

1. Introduction
The tandem accelerator efficiently works on high energy heavy ion acceleration with an electron stripping carbon foil in the terminal which changes negative ions to multi-charged positive ions. However, carbon foils are short-lived under an intense heavy ion beam. It is difficult to greatly increase the beam intensity without loosing long time stability. On the other hand, charge states and intensities of the highly charged heavy ions from a high performance ECRIS are larger than those obtained after a charge exchange by carbon foil. In figure 1, charge states of ions with an intensity of several eµA expected for an ECRIS are compared with the most probable charge states obtained by electron stripping at a terminal voltage of 16 MV. For ions over a mass number of 100, the charge states higher than 20+ can be available from a 14.5 GHz ECRIS, compared to 13+ from the foil stripping. This fact motivated us to develop an in-terminal ECRIS (TECRIS) injector. Problems with stripper foil, such as short life time, energy straggling, emittance growth and beam intensity reduction could be cleared away also. We started with a 10 GHz compact ECRIS for this TECRIS project in 1998 [1], and succeeded in increasing the beam intensity and accelerating noble gas ions for many experiments. The TECRIS using a high performance 14.5 GHz ECRIS was newly developed as a second phase of this project.

2. Description of the TECRIS injector
The high voltage terminal is in a severe environment, i.e. it is filled with the pressurized insulation gas to 0.55 MPa(abs) and itself is held at a voltage of 20 MV at maximum. Therefore, the capability to withstand the high pressure and electrical discharges is indispensable to the in-terminal injector. We use a 14.5 GHz high performance all permanent magnet type ECRIS SuperNanogan [2], so that it can work within the limited electricity and installation space in the high voltage terminal. We considered the following in the design of the TECRIS injector;
1) the system be simple, 2) the injector should coexist with the conventional tandem acceleration system, 3) the injector and related equipments be as compact as possible, 4) every thing be securely resistant against pressure and electrical discharge, 5) the system should work certainly, simply, stably and safely, 6) every thing should work for a long time without maintenance, at least for a period of the beam time of about four months.

2.1. Layout and device control
The layout of the TECRIS injector is illustrated in figure 2. In usual tandem acceleration, the negative ions enter from the low energy (LE) side acceleration tube, charge exchanged to a multi-charged positive ion by a foil stripper, charge-selected by the 180° bending magnet and re-accelerated by the high energy (HE) side acceleration tube. The injector was horizontally connected to the LE side beam line by the 90° injection magnet in order to coexist with the tandem acceleration mode. A schematic diagram of the TECRIS injector is shown in figure 3. There is an 80 kV deck for pre-acceleration. Power supplies for the 30kV extraction, einzel lens, steerer and 90o injection magnet, source gas provided by means of an insulating transformer. The high voltage power supply for pre-acceleration, control circuits and gas bottles were put in the 80 kV deck. All devices in the high voltage deck are controlled through an optically linked CAMAC communication system. The electric power is supplied at 16 MV.

Figure 1. Charge states of ions with an intensity of several µA expected for compact ECRISs are compared with the most probable charge states obtained at a terminal voltage of 16 MV.

Figure 2. 14.5 GHz TECRIS injector developed for the tandem accelerator. The ion beam generated by the ECRIS is bent with 90° injection magnet and 180° bending magnet, and then accelerated through the main 20 MV acceleration tube toward the earth potential.
2.2. Ion source
The operating conditions of the ECRIS were optimized prior to the installation in order to obtain a simple and reliable operation. The ion source is controlled only by adjusting the RF power and the voltage of the bias electrode and by selecting the source gas. A gas mixing method is used for the source gas. The gas bottles are filled by the mixed gas of the main gas (Ar, Kr, Xe or etc.) and the support gas (N$_2$ or O$_2$). A calibrated leak source with a shut-off solenoid valve was employed for simplification. Eight gas bottles with a calibrated leak valve were installed on the 80 kV deck, and each gas pressure was adjusted to the best flow rate through the leak valve. These gas flow rates were about 1~3 $\times 10^{-5}$ Pa·m$^3$/sec. Though the maximum performance was not always obtained, this fixed flow method was quite effective to make the ion source operation easy and certain. The beam current adjustment was mainly done by RF power control. The beam intensities were increased by a factor of ten using the bias method that applied a negative dc voltage to the center conductor of RF guide adjustment was mainly done by RF power control. The beam intensities were increased by a factor of ten using the bias method that applied a negative dc voltage to the center conductor of RF guide inserted into the plasma chamber. In addition to these gas bottles, one gas line has been installed with a thermo-mechanical-leak valve connected to motor driven sliding transformer for the gas flow control so that the condition is tuned to a high charge state more than 25+ for Xe etc.

![Diagram of the TECRIS injector.](image)

2.3. RF source
The RF source is composed of a dielectric oscillator, a 200 W traveling wave tube amplifier and a variable attenuator. They were set in an airtight container to keep them an atmospheric pressure and prevent them from electrical discharges. The circulator to protect the amplifier from the reflected RF power was connected to the output port on the container. The RF amplifier of which power consumption is 1 kW is cooled by water. The plasma chamber of the ECRIS is cooled by SF$_6$ gas flow.

2.4. Pumping station
Since the ion pumps do not work for noble gases, a turbo molecular pump (TMP) of a pumping speed of 450 l/sec and a rotary pump (RP) were employed for pumping out the gas from the source. These pumps have a protection against high pressure. The TMP was directly attached to the vacuum chamber without a gate valve. An electro-magnetic valve for the vacuum partition was located between the TMP and RP. The exhaust gas from the pumps was designed to accumulate in a closed vessel. The TMP driver was set in an airtight vessel to keep it atmospheric pressure and protect the complicated electric circuit from electric discharge. The system was arranged to work in fail-safe. Even when the pumping system fails, the high vacuum is held by the ion pump which is installed for holding the vacuum while the source is off.
2.5. Magnetic shielding for ECRIS
For an ECRIS with powerful permanent magnets, the influence of a leakage of magnetic flux on an ion beam can not be ignored. The magnetic field on vertical beam line was 2 mT at maximum. We made a shield panel which covered up the ion source and its extraction and focus chamber with 3.2 mm thick iron plates. With the iron shield, the leakage magnetic field was suppressed to about 1/10 and there was no beam steering problem in actual acceleration of negative ion beams.

3. Acceleration results and performance
Highly charged noble gas ions were accelerated from the TECRIS by the terminal voltage of 15 MV. The intensities of these ions are shown in figure 4. Ions of Ne^{8+}, Ar^{12+}, Kr^{15+} and Xe^{22+} were obtained with a beam intensity of 100 pnA or more, and these charge states agreed with the curve for the 14.5GHz ECRIS in figure 1. The ion source operation and beam handling of the new injector was easily carried out. The accelerated ion beams were stable and the beam transmission efficiency was nearly 100% for acceleration from the terminal to the exit of tandem accelerator. The intensities of highly charged heavy ions were increased by a factor of 10~100 compared with the 10 GHz ECRIS or the tandem acceleration mode. Xenon ion energy reached 420 MeV which was the highest energy this tandem accelerator has ever had, and it is possible to provide beams in a wide energy range of 50~500 MeV. The beam quality was greatly improved compared with the tandem acceleration mode because there was neither the energy spread nor the beam divergence due to the carbon foil.

![Figure 4. Charge state distributions of noble gas ions from 14.5 GHz TECRIS injector. Beam intensities were measured at the exit of tandem accelerator.](image-url)

4. Conclusion
A 14.5GHz TECRIS injector was constructed at the high voltage terminal of the JAEA tandem accelerator. Highly charged heavy ions which were not obtained by the tandem acceleration mode in the past were successfully accelerated. We can use a high energy and intense beam without the problem with stripper foils. Highly charged and intense beams from TECRIS have become available for studying atomic and nuclear physics and radiation effects [3].

References
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