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Beam Interactions with Materials & Atoms

The Frankfurt ECRIS-RFQ facility for materials research with highly charged ions[1]

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Abstract

The new accelerator for the production of highly charged heavy ions, presently installed at the Institut für Kernphysik consists of a 14 GHz ECR source in combination with an variable-energy RFQ post-accelerator. It is designed to deliver highly charged ions in the energy range between 1 keV/u (the ECRIS beam) and 100–200 keV/u with the (Variable-Energy Radio Frequency Quadrupole) VE-RFQ. Investigations of transient processes with ns time constants will be possible by a single bunch system. Another attractive feature for materials research is the combination with ion beams from the 7 MV Van de Graaff. The status of the project and first results of beam measurements will be presented.

1. Introduction

Slow highly charged ions, due to the potential energy stored in their atomic shells, are able to induce electronic transitions in collisions with atoms or solids, even at kinetic energies far below the threshold for dynamic ionization. Dependent on the charge state, this potential energy can exceed several 10 keV, enabling the liberation of numerous target electrons during collisions of one such ion with surfaces or single atoms (gas targets). At low ion velocities these electron transfer and emission processes only depend on the stationary properties of the colliding ion–atom/ion–surface system. If the ion velocity exceeds that of the electrons bound at the surface or in the bombarded atom, the dynamical aspects become more and more important. Thus, being able to vary the ion velocity over a sufficiently wide range (0.1 to 3 a.u.) both aspects of the ion–surface or ion–atom interaction can be studied. For these investigations a novel accelerator has been constructed and is almost completed [1,2]. This facility consists of a combination of a 14.4 GHz ECR ion source and a Variable-Energy Radio Frequency Quadrupole accelerator (VE-RFQ). The facility is shown in Fig. 1. The first analyzing magnet is designed to simultaneously separate two charge states from the charge-state spectrum delivered by the ECR source. Thus, one of the maximum-intensity charge states is injected into the RFQ, while a higher charge state can be deflected simultaneously into one of the low-energy beamlines. There are two electric quadrupole triplets in the beamline as focussing elements, one before and one behind the analyzing magnet. Two electrostatic einzel lenses are used for the injection into the RFQ.

2. The 14 GHz ECR ion source

This source was developed in close cooperation with a number of other groups [3–6]; especially the support by the group of Lyneis at LBL has to be acknowledged here. The outline of IKF-ECR, as presently installed, is given in Fig. 2. In the present design all inner parts of the source, like a plasma chamber, hexapole, disk, etc., can be dismounted without opening the structure of the magnetic solenoid.

As a radial electron trap, a magnetic hexapole was constructed following a design of Halbach [7]. It is a closed structure of 24 pieces [8,9] optimized for maximum field strengths. The field measured at the inner surface of the hexapole of the source amounts to 1,3 T. The system has a total length of 190 mm, the inner diameter of the plasma chamber is 58 mm.

Insulation is achieved via two epoxy pipes of 150 mm length separating the extraction region and the pump of the

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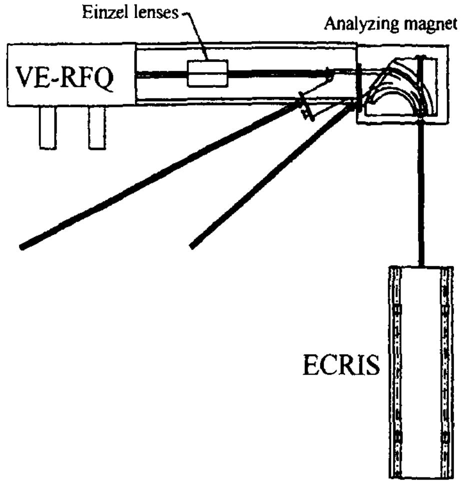

Fig. 1. Schematic of the ECRIS/VE-RFQ facility.

injection region (not shown in Fig. 2) from the high voltage components of the source. One large pipe separates the plasma region from the solenoid. Although all insulators are designed to allow source voltages of $U > 60$ kV, the operation voltages are limited at $U = 30$ kV because of the microwave insulator. Large cross sections for pumping are obtained by using CF-150 cross-pieces at both ends of the plasma chamber. Two 360 l/s turbomolecular pumps are used on the injection side and in the beamline, respectively. In addition, during operation of the source the extraction region is pumped via a 800 l/s cryogenic pump. After maintenance a vacuum of better than 3×10^{-7} mbar is reached using only the two turbo pumps. The X-ray emission of the source was minimized distinctly below permitted values by inserting special absorbers into the injection chamber.

At two points of the beamline, emittance measurements were carried out. The first one was done directly behind the ECR source. The ECR source was able to produce charge states for argon from $q = 2+$ to $q = 16+$; the maximum was reached at Ar^{8+}. The lowest value of the emittance measured was $\varepsilon = 102.14$ π mm mrad. This measurement was carried out with a beam energy of $T = q \times 20$ keV. These results are very good also if compared with measurements at other ECR sources, e.g. at GSI and LBL. The second group of measurements were done behind the analyzing magnet at the entrance of the einzel lenses. Used charge states were Ar^{3+} to Ar^{8+} extracted with 30 kV. The emittances measured varied between 17 and 50 π mm mrad (The normalized emittance $\epsilon_N = \epsilon \times v/c$ was $\epsilon_N < 0.3$ π mm mrad) with currents between 30 and 40 μA. Fig. 3 shows the emittance of Ar^{4+} with a current of 34 μA; the emittance was $\epsilon = 17.5$ π mm mrad ($\epsilon_N = 0.1$ π mm mrad).

3. The VE-RFQ

The VE-RFQ is shown in Fig. 4. The RFQ is basically a homogenous quadrupole transport channel with additional acceleration. The mechanical modulation of the electrodes adds an acceleration axial field component, resulting in a linac structure which accelerates and focuses with the same rf fields [10]. Usually the operating frequency of an accelerator is fixed. This means a fixed input energy per nucleon and a fixed output velocity. In order to provide the large range of ion velocities at different charge states this RFQ structure is designed to allow a variation of the operation frequency between 80 and 110 MHz, which corresponds to an energy variation of a factor of 2. The resonance frequency of the system is adjusted by changing

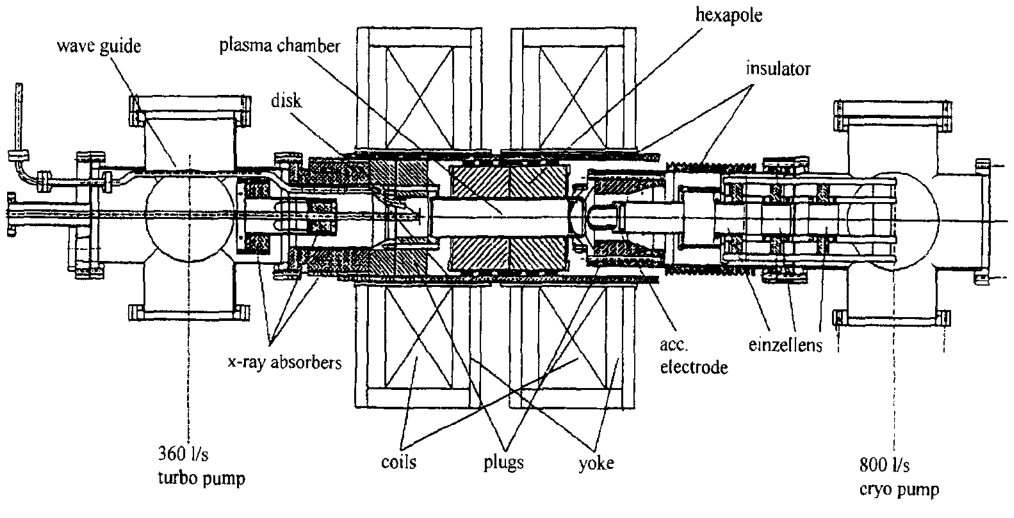

Fig. 2. The ECRIS.

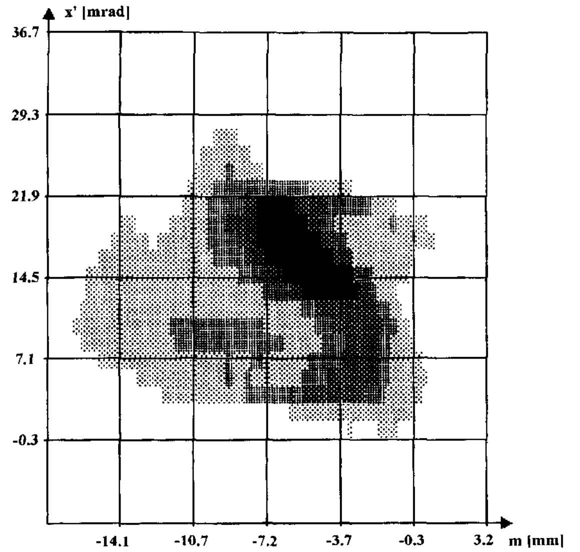

Fig. 3. ECRIS emittance of 17.5 π mm mrad, measured with a Ar^{4+} beam of 34 μA (darker shading: higher particle density).

the effective length of the driving conductor by means of movable shorts. The structure is designed for a minimum specific input charge of $q/A = 0.15$ and input energies between 2 and 4 keV/u. It will provide ion energies between 100 and 200 keV/u. For the highest energy the electric power consumption will be 60 kW. The maximum electrode voltage is 72 kV and the length of the electrodes is 138.6 cm. The number of cells of the structure is 158, the length of the cells is growing from 3.9 mm at the beginning of the structure to 13.98 mm at the end of the structure. The diameters of the electrodes are between 4.5 and 8.6 mm, while the aperture radii are between 3 and 5 mm. Accepted normalized emittances of the RFQ are between 0.2 and 0.5 π mm mrad. The structure is mounted in a vacuum chamber which has a length of 150 cm and a diameter of 50 cm. The parameters of the RFQ are shown in Table 1. During first tests at the IAP, with a frequency of 108 MHz and a low duty cycle, the rf power could be increased up to 80 kW (electrode voltage 79 kV). With a duty cycle of 10% and a rf power of 40 kW, an electrode voltage of 55 kV was reached.

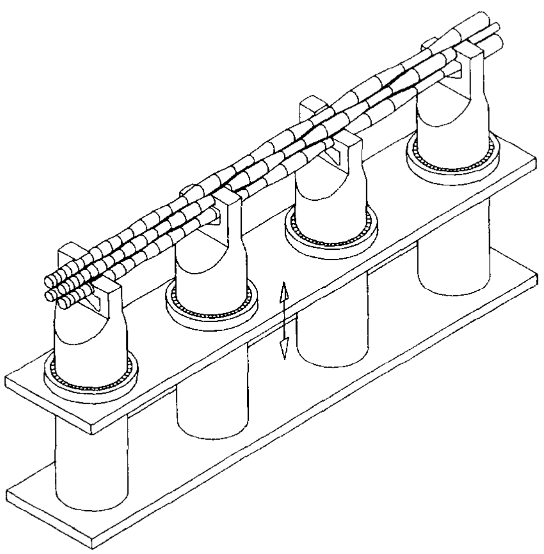

Fig. 4. The VE-RFQ.

Table 1
RFQ parameters

Length of tank [mm]	1548
Diameter of tank [mm]	500
Number of stays	10
Number of cells	158
Lenght of cells [mm]	3.9–13.9
Length of electrodes [mm]	1386
Diameter of electrodes [mm]	4.5–8.6
Aperture radius [mm]	5.0–3.0
Modulation	1–2.25
Injection energy [keV/u]	2.0–4.0
Ion energy [keV/u]	100–200
Specific charge	0.2–1
Rf frequency [MHz]	80–110
Maximum electrode voltage	72
Maximum rf power [kW]	60
Duty cycle [%]	25
Normalized acceptance [π mm]	0.2–0.5

4. Status

At present the RFQ is in place, the rf transmitter (80–115 MHz), the injection lenses, the remote control and the water cooling are installed and ready for operation. The low-power conditioning with a 400 W amplifier is in progress. The injection in the RFQ will be performed by the two electrostatic einzel lenses. The complete length of the two lenses is 60 cm, the apertures of the electrodes are 60 mm. The lengths of the second, third and fourth electrodes are 120 mm. Calculations of the injection in the RFQ were executed with IGUNe [11]. Fig. 5 shows a calculation of a parallel beam with a radius of 12 mm, of Ar^{4+}, which was extracted with 28.6 kV. The potentials of the second and the fourth electrodes are both 17 kV, the other electrodes are on earth potential. The best results

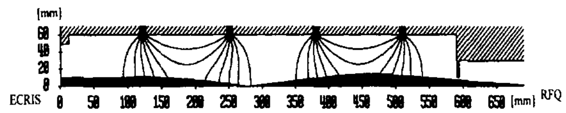

Fig. 5. IGUNe simulation of RFQ injection.

were obtained with parallel beams: A beam with a radius of 15 mm can be focused very well with equal potentials at the second and the fourth electrode. Different potentials at these electrodes will be necessary if the diameter of the beam is larger than 30 mm.

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