The Frankfurt ECR-RFQ facility

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An ion beam facility for high-intensity beams of highly charged ions in the energy range between 1 and 200 keV/u has been funded and will be installed in 1992 at the Institut für Kernphysik, Frankfurt am Main, Germany. The facility is based on a 14.6 GHz ECR ion source and a variable-energy RFQ as postaccelerator. The facility is intended for atomic-physics and materials research.

I. INTRODUCTION

Highly charged ions are able to induce electronic transitions in collisions with atoms or solids, even at kinetic energies far below the threshold for dynamic ionization or charge transfer. This fact is related to the potential energy stored in their atomic shells. Dependent on the charge state, that potential energy can exceed 10 keV, enabling the liberation of numerous target electrons during collisions of one such ion with surfaces or single atoms (gas targets). Moreover, by changing their kinetic energy and/or their charge states this "ionizing power" can be varied over a wide range. Therefore slow highly charged ions can be used as a unique probe for materials analysis and materials modification as well as for basic atomic research.

An important parameter for atomic ionization and excitation mechanisms is the ratio λ of the target electron velocity (v_e) to the ion velocity (v_I) ("adiabaticity parameter"). The transition probabilities vary drastically, when λ changes from 0.2 to 5. For typical electron binding energies in atoms near a surface this demands a variation of the kinetic energy of the ions from a few keV/u up to 200 keV/u. In order to experimentally investigate this especially interesting velocity regime, an ECR ion source in connection with a variable-energy RFQ accelerator will be installed. This facility is described below.

II. THE ECR–RFQ FACILITY

The facility, including the planned experimental beamlines, is shown in Fig. 1. The first analyzing magnet (double focusing for deflection angles in the range of 90°–137°) is especially designed to simultaneously analyze two charge states from the charge-state spectrum delivered by the ECR source. Thus the high-intensity charge state (e.g., $q_{\max} \simeq 11^+–13^+$ for Ar ions) is injected into the RFQ and postaccelerated, while a higher charge state (e.g., hydrogenlike Ar) can be deflected simultaneously into the "low-energy" beamline, where collisions between nearly completely stripped ions and atoms under single-collision conditions will be studied.

A. The 14.6 GHz ECR-ion source

The source design is shown in Fig. 2. It is based on the LBL–AECR (Berkeley, CA).[1,2] It is very similar to that design described elsewhere in these proceedings.[3] We refer to this paper for more technical details.

In order to obtain the necessary high preacceleration, the whole inner vacuum part of the source can be set on terminal voltages between 50 and 100 kV. The insulation consists of a circular, completely closed structure, where surface sparks are strongly suppressed.

Pumping and observation flanges in the center of the source are connected to the high voltage part via 15–20 cm long ceramic tubes. The magnetic trap is formed by a solenoidal magnetic field, generated by copper coils ("pancake" shape) superimposed on the field of a magnetic sextupole system (permanent magnets NeFeB). Altogether, 22 pancake coils are assembled in three packages, each being supplied separately with cooling water and electric power. The experience in many other laboratories is that, the radial field generated by the sextupole system should be as strong as possible. A similar sextupole configuration to

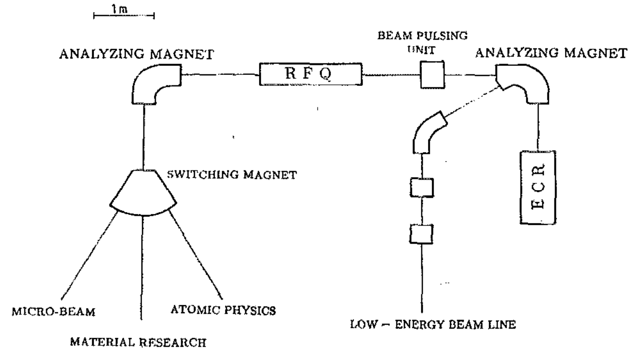

FIG. 1. The Frankfurt ECR–RFQ facility.

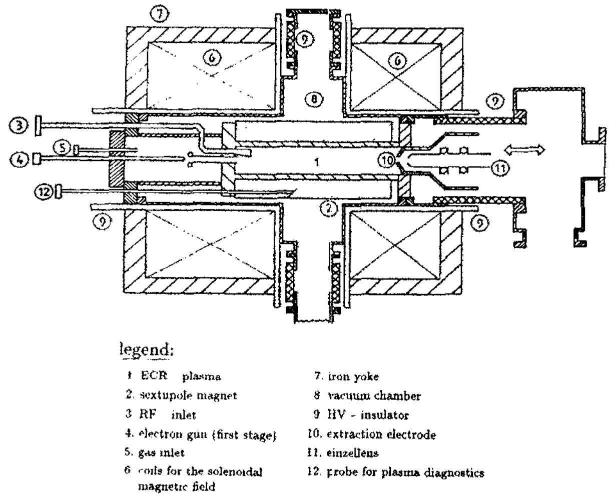

FIG. 2. Delineation of the ECR ion source.

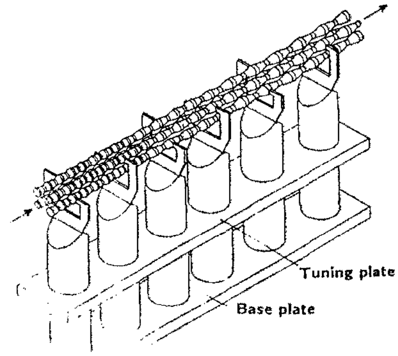

FIG. 3. Principle of the tunable four-rod RFQ structure.

that for the Groningen ECRIS ion source[4] will be used here. In addition, a second sextupole system will alternatively be installed, which, at the cost of maximum magnetic field strength, has an open structure (longitudinal open slits between the sextupole bars). The purpose of this choice is to allow optical observation of the plasma at any position in the plasma region of the second ECR stage. Therefore, the sextupole systems will be installed inside the vacuum chamber and sealed in a separate housing, which at the same time serves as a cooling system.

Space is provided in the extraction region and near the gas inlet, where the iron rings can be mounted to correct the solenoid field configuration to obtain the best source performance. The whole construction is planned as an "experimental" source, which allows an easy and fast change of the inner parts of the source, e.g., from a two-stage to a one-stage ECR source. For the two-stage source the rf power is divided and fed into the two plasma regions separately. In region one an electron gun can be mounted to replace the first, rf powered plasma region.[2]

B. The variable-energy RFQ

This device is a special development to be used in combination with the above ECR ion source.[5] In order to provide the large range of ion velocities at different charge states the radio frequency quadrupole structure (RFQ) is designed to allow variation of the operation frequency between 80 and 110 MHz, which corresponds to an energy variation of a factor of 2. The principle of operation is depicted in Fig. 3. The resonance frequency of the system is adjusted by changing the effective length of the driving conductor by means of movable shorts. The system is designed for a minimum specific input charge of $q/A = 0.15$, and will provide ion energies between 100 and 200 keV/u. The maximum electrode voltage will be 70 kV and the total length of the structure is 1.5 m. At a duty cycle of 25%the electric power consumption will be 50 kW for the highest energy.

The bunching capability of the RFQ will be used to provide a time trigger for the time-of-flight detection technique and controlled materials modification (pulsewidth $\Delta\tau \approx 1$ ns, basic repetition frequency $\nu_{\mathrm{RFQ}} \approx 100$ MHz). For this purpose additional chopping devices will be installed (beam pulsing unit), allowing the reduction of the repetition rate of the beam pulses over a wide range in order to adjust this trigger to the demands of the experiment. For time-of-flight experiments, for instance, single pulse rates can be generated with the long time separation needed for the comparatively slow particles to reach the detector systems. For applications in materials science the implantation of a certain dose (n pulses with a few 10 ns distance) can be followed by a variable time interval for relaxation of the material (no beam). At an ion source current of about 10 particle μA each bunch of $\Delta\tau \approx 1$ ns contains approximately 10^6 ions.

In Table I the available beam energies are given.

III. RESEARCH PROGRAM

A. Atomic physics

In atomic physics the single collision charge transfer as function of initial ionic charge and projectile velocity will be measured as a function of the projectile scattering angle. Using two-dimensional position sensitive detectors, projectile and recoil will be detected in coincidence, determining both final charge states. For these experiments the multiparameter detection system has already been tested in first experiments at the ECR sources at LBL, Grenoble and

TABLE I. Beam energies available at the "low-energy" beamline (ECR) and after the RFQ.

	ECR (keV)	RFQ (MeV)
N	10–420	1.4–2.8
O	10–480	1.6–3.2
Ne	10–600	2.0–4.0
Ar	10–1080	4.0–8.0
Kr	10–1800	8.5–17.0
Xe	10–2400	13.5–27.0
Bi	10–2400	21.0–42.0

Jülich.[6,7] In particular, the emission of quasimolecular x rays and electrons will be studied as functions of the initial and final charge states. In these experiments the radiation pattern with respect to the scattering plane will be measured to investigate dynamical alignment effects during the adiabatic collision.

B. Materials research

For materials research an UHV system is being prepared that will allow the study of the scattering of highly charged ions from aligned single crystals. Here the capture of surface electrons by the ions will be studied under well defined kinematical conditions by detecting the backscattered ions as a function of their final angle, their final energy, and charge state. Also, the stopping power of highly charged slow ions in the first layers of solids and their inner shell charge exchange in layers at or close to the surface are of interest and will be investigated. First experiments have shown[6] that the inner shell charge exchange cross section of such ions is in the order of one atomic unit. Thus the highly charged ion will capture electrons and fill its shell system after penetrating a few Å into the solid.

For future applications the installation of a μ beam is envisaged. With this additional feature in combination with the beam pulsing system, detailed studies of solid surfaces as well as the controlled modification of target materials (crystals, semiconductors, and insulators) will become possible on the scale of μm to sub-μm.

For the purpose of controlled materials modification a "double-beam" scattering chamber will be added to the facility. By combining two beamlines, one from the ECR–RFQ (for modification of the material, e.g., implantation) and one from the 7.5 MV Van de Graaff accelerator at the same experimental location "*in situ*" modification and analysis of the modification can be performed.

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