

A NEW ION BEAM FACILITY FOR SLOW HIGHLY CHARGED IONS

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Abstract

A new ion beam facility for slow highly charged ions is presented that will provide low and medium energetic highly charged ions. An Electron Cyclotron Resonance (ECR) ion source delivers high currents of low and medium charged ions whereas very highly charged ions at lower ion currents are supplied by an Electron Beam Ion Trap (EBIT). The new ion beam facility will provide an experimental environment for basic research in atomic and solid state physics, as well as applied research in areas such as surface engineering, nanostructuring and nanobiotechnology.

INTRODUCTION

Slow highly charged ions (HCIs) are of increasing interest for a wide range of investigations in both basic and applied research. Fundamental studies in atomic physics, materials research, plasma physics and radiation physics are concerned as well as structuring, modification and analysis of solid surfaces and biological objects ([1, 2, 3]). HCIs are available from huge ion accelerators which supply high energetic ions, from Electron-Cyclotron-Resonance (ECR) ion sources, Electron Beam Ions Sources (EBISs), and Electron Beam Ion Traps (EBITs).

The physical properties of HCIs depend strongly on their charge state. Large amounts of potential energy are stored in the ion as a result of the ionization process. This energy increases with increasing ion charge state and can reach up to several hundred keV. The amount of stored energy of any charge state of any element up to uranium can be found at [4]. The potential energy stored in a HCI can be deposited into a surface with a lateral resolution of about 10 nm and a depth of about 1 nm, the interaction taking place within a few femtoseconds. This is equivalent to a deposited power density of up to 10^{14} W/cm². In order to investigate the role of potential energy deposition in solids experiments with ionic projectiles with the potential energies exceeding the kinetic energy must be provided. Hence, the ion beam must be decelerated to low kinetic energies.

A new ion beam facility, a cooperation project between the Forschungszentrum Rossendorf and the Dresden University of Technology, is presented that will provide both high currents of low and medium charged ions from an

ECR ion source and very highly charged ions at lower ion currents from an EBIT.

SET-UP OF THE TWO-SOURCE-FACILITY

The extraction of ions out of a plasma requires extraction voltages in the range of 10 to 100 keV. In order to reduce their kinetic energy the ions undergo a deceleration after selection of the required charge to mass ratio.

ECR ion sources as well as EBIT devices are producing ions with different charge states q by electron impact ionization. During the ionization process multiple electron-ion collisions lead to certain ion velocity distributions. In ECR ion sources this results in beam emittances of about $100 \cdot 10^{-6} \pi$ m rad at 25 keV [5, 6]. The energy of ions created in EBIT devices exceeds several 10 eV, established by both model calculations [7] and X-ray spectroscopic data from helium-like argon ions [8].

Beam formation and momentum analysis work better the more kinetic energy the ions gain in the acceleration gap. Finally, the separated ion beam needs to be decelerated to supply the potential energy of the ion species while suppressing the influence of the kinetic energy. Unfortunately, the beam spreads out according to its initial perpendicular velocity component. The beam emittance increases proportional to the ratio of the particle velocity before and after retardation v_{start}/v_{final} .

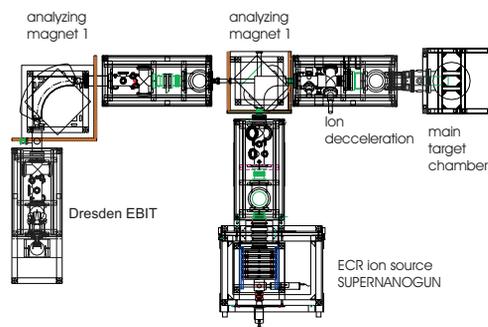


Figure 1: Schematic of the two-source-facility. Upper right: Potential distribution between S2 and target. ΔU is the potential difference between ion source and target.

The Rossendorf two-source-facility (Fig. 1) is based on an acceleration-deceleration principle. A pulsed ion beam from a room-temperature electron beam ion trap (Dresden

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EBIT; for a detailed description see [11]) and a continuous beam from an ECR ion source (SUPERNANOGAN; see [9]) are formed, magnetically analysed, and decelerated to a final energy of $q \times \Delta U$ entering a target at UHV conditions. If no deceleration is needed the device set-up allows to run experiments simultaneously with the extracted ion beams from the EBIT and from the ECR ion source. If the ion beam has to be decelerated the ions from the ECR ion source or from the EBIT can optionally be applied. Additionally, the interaction of ion beams from both sources with the same target can be realized.

The ECR ion source supplies beam intensities of 250 $e\mu A$ of Ar^{8+} ions, 30 $e\mu A$ of Xe^{17+} and 2 $e\mu A$ of Pb^{25+} [9].

The Dresden EBIT can supply bare nuclei of elements up to nickel, such as Fe^{26+} or Ni^{28+} , helium-like ions for elements with medium atomic numbers, such as Ge^{30+} or Kr^{34+} , and neon-like ions for high-Z elements, such as Xe^{44+} or Ir^{67+} . Typical ion currents extracted from the Dresden EBIT are in the range of enA per pulse [10].

The deceleration is performed in two steps. As the target is grounded and the ion sources are on the voltage ΔU the beam guiding system is set to a negative potential. The quantity $q \times \Delta U$ mainly determines the final kinetic energy of the selected ion species whose potential energy depends on the charge state q . The facility allows to supply ion species with potential energies that are significantly higher than their kinetic energies. Furthermore, both potential and kinetic energy can be chosen in a wide range.

After extraction from the ion sources the ions are guided by ion-optical elements to the analysing magnets which separate the ion charge states according to their charge to mass ratio. After passing the magnet the separated ion beams are focused on the target.

ION OPTICAL SIMULATION OF THE ION BEAM DECELERATION

The layout of the two-source-facility was designed in regard to the above-cited emittance value of the ECR ion source. To our knowledge, no exactly measured values of the EBIT emittance have been reported so far. The process of ion beam formation at the end of the trap was simulated using the spectroscopic data from [8] on the ion velocity distribution inside the trap and the geometrical and magnetic features of the Dresden EBIT. The simulation was performed using the SIMION code [13, 14]. A typical simulation result of the ion beam formation in the Dresden EBIT is shown in Fig. 2.

Preceding simulations showed a potential gradient of about one Volt along the trap axis. In the simulation the ions start with different initial transversal and longitudinal velocity components from the center of the drift tube ensemble 0.2 mm off the axis. The resulting beam emittance is $\varepsilon = 125\pi \cdot 10^{-6}$ m rad at a beam energy of about $q \times 5$ keV (see Fig. 2). At 25 keV the emittance of the EBIT ion beam increases up to one half of the ECR beam

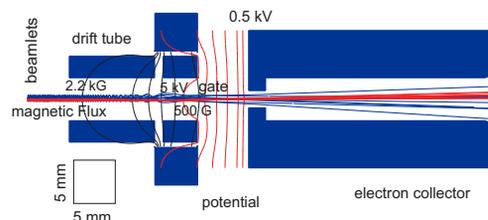


Figure 2: Example of ion beam formation in the Dresden EBIT. Beamlet energy 1 eV (inner beamlets) resp. 30 eV (outer beamlets), magnetic flux density inside the trap region < 500 Gauss, drift tube potential: 5.2 kV, gate potential: 5.0 kV.

emittance.

For this reason, the common deceleration system was simulated, using an emittance value of $100 \cdot 10^{-6} \pi$ m rad at the beam entrance. The potentials of the final deceleration lens are chosen to reduce the kinetic energy to a value of about $q \times 5$ eV (see Fig 3). The final deceleration lens had been developed several years ago and has been successfully used to proof the retention of the potential energy of multiply charged argon ions incident on copper [15].

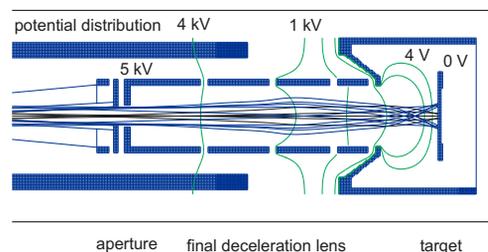


Figure 3: Details of the beam propagation through the final deceleration lens.

Figure 3 shows selected potential values of some electrodes and equipotential lines, respectively. Reducing the kinetic energy from 25.000 eV to 5 eV yields an increase of the beam spot diameter by a factor of about 1.5 and an increase of the beam angle by a factor of about 50.

SIMION calculations allow realistic assessments of the influence of beam energy and aberrations on beam size and angular distributions during beam deceleration. The space charge of intense ECR beams is expected to set a practical limit at high ion current density conditions.

Figure 3 illustrates that the aperture at the entrance of the final deceleration lens cuts low quality parts of the beam off. As a result smaller angle distributions are realised accepting a loss of ion current at the target.

ION EXTRACTION SPECTRA

With the facility described above ions of a wide spectrum of charge states can be extracted. First tests of the beam extraction at the ECR ion source with argon result in the extraction of ion currents of up to 170 $e\mu A$ of Ar^{8+} ions.

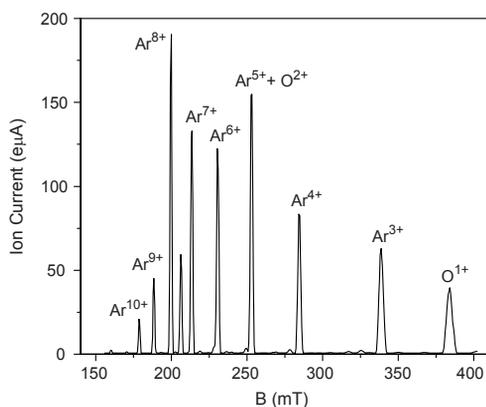


Figure 4: Extraction spectrum of argon ions measured at the SUPERNANOGUN ECR ion source.

Fig. 4 shows an argon charge state spectrum measured at a microwave power of 100 W and at a gas pressure of $4 \cdot 10^{-5}$ mbar inside the source.

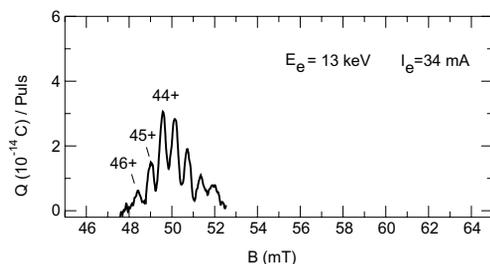


Figure 5: Extraction spectrum of xenon ions measured at the Dresden EBIT at an electron energy of 13 keV and an electron current of 34 mA.

In Fig. 5 an extraction spectrum of xenon ions from the Dresden EBIT is shown. The maximum intensity is at neon-like xenon ions, i.e. ions with a potential energy of about 51 keV. Up to now, ions as summarized in table 1 have been extracted at the Dresden EBIT.

A comparison of the ion production in the two types of ion sources shows that the ionization factor in the ECR ion source is in the order of $(5 \dots 10) \cdot 10^{19} \text{ cm}^{-2}$, whereas in an EBIT the ionization factor reaches values up to $(2 \dots 5) \cdot 10^{21} \text{ cm}^{-2}$. As mentioned above, the ions can be slowed down to energies of about $q \times 5 \text{ eV}$. On the other hand, ion energies of up to $q \times 25 \text{ keV}$ are possible, too. As an example, Xe^{44+} has a kinetic energy of 1.1 MeV or an energy of 8.4 keV per nucleon at $q \times 25 \text{ keV}$. In dependence on the requirements of the current experiment all energies within the mentioned limit can be applied.

CONCLUSION

The new ion beam facility will allow principal investigations on different physical and technical aspects in order to make high resolution nanostructuring with charged particles possible. It will provide the basis for studies on

Table 1: HCIs produced with the Dresden EBIT. The derived charge states are identified for ions each with the highest atomic number.

Charge state	Ion
bare nuclei	Ni^{28+}
hydrogen-like ions	Ge^{31+}
helium-like ions	Kr^{34+}
carbon-like ions	Xe^{48+}
oxygen-like ions	Ce^{50+}
neon-like ions	Ir^{67+}

novel tool concepts for nanometer-structuring using highly charged ions at very low kinetic energy. Therewith various applications in micro- and nanoelectronics, biomedical nanotechnology and other fields can be addressed.

First studies at different laboratories in the world have shown that the use of highly charged ions complements classical ion beam applications, which usually operate with acceleration potentials of 1 - 100 kV. Covering the range of kinetic energies significantly below $q \times 1 \text{ keV}$ requires a new innovative ion-optical setup.

REFERENCES

- [1] R. W. Schmieder and R. J. Bastasz; VIth Int. Conf. on the Physics of Highly Charged Ions, AIP Conference Proceedings 274, AIP, New York, 1993, p. 675.
- [2] J. Gillaspay; *Trapping Highly Charged Ions: Fundamentals and Applications*, Nova Science Publishers, New York, 2001 and references therein.
- [3] J. Gillaspay; J. Phys. B: At. Mol. Opt. Phys., 34 (2001) R93.
- [4] <http://www.physik.tu-dresden.de/apg>.
- [5] <http://www.panttechnik.com>.
- [6] C. Bieth, J. L. Bouly, J. C. Curdy, S. Kantas, P. Sortais, P. Sole, and J. L. Vieux-Rochaz; Rev. Sci. Instr. 71 (2000) 899.
- [7] I. Kalagin, D. Kuchler, V.P. Ovsyannikov, and G. Zschornack; Plasma Sources Scien. Technol., 70 (1998) 441.
- [8] U. Kentsch, G. Zschornack, F. Grossmann, V.P. Ovsyannikov, and F. Ullmann; Nucl. Instr. Meth., B205 (2003) 266.
- [9] The Panttechnik Catalogue, August 2001 Edition, Caen 2001, France.
- [10] U. Kentsch, S. Landgraf, M. Schmidt, H. Tyrroff, G. Zschornack, F. Grossmann, V.P. Ovsyannikov, and F. Ullmann; Nucl. Instrum. Methods, B216 (2004) 196.
- [11] V.P. Ovsyannikov and G. Zschornack; Rev. Sci. Instr., 70 (1999) 2646.
- [12] <http://www.dresden-ebit.de>.
- [13] M. Schmidt; Diploma Thesis, Institut für Kern- und Teilchenphysik, TU Dresden, Dresden, 2003.
- [14] D.A. Dahl; Simion 3D Version 7.0, User's Manual, Idaho Engineering and Environmental Laboratory, 2000.
- [15] U. Kentsch, H. Tyrroff, G. Zschornack, and W. Möller; Phys. Rev. Lett. 87 (2002) 105504-1.