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AN EBIS-BASED LOW-ENERGY ACCELERATOR FACILITY FOR FINE-FOCUSSED ION BEAMS

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Abstract

Technologies based on focused ion beams have become indispensable for research institutions as well as commercial laboratories and high-tech production facilities (micro- and nanotechnology, semiconductor technology). We report on a compact setup combining an Electron Beam Ion Source (EBIS), a Wien filter for ion species separation, and a fine focusing ion acceleration column capable of producing ion beams with beam diameters in the micrometer range at ion beam energies up to the MeV range. Almost all elements of the periodic system can be injected into the EBIS to produce a broad spectrum of ion charge states with only one ion source. The beam energy of a selected ion species can easily be varied by changing the electric potential of the EBIS drift tube in which the ions are generated, resulting in different implantation depths in various solids. We present studies on beam diameter and emittance, available charge states, and SEM imaging as application.

INTRODUCTION

A variety of previous studies have shown that fine-focused ion beams (FIB) are a powerful tool in various applications such as materials and surface analysis (HCI projection X-ray microscopy [1], HCI-SIMS [2]), micro- and nanostructuring [3], photonic structures, and radiation biology [4]. Together with additional nanoapertures focused ion beams can be applied in proof-of-principle experiments for the development of quantum computers [5] as well as in quantum cryptography [6].

Using an EBIS as the ion source in a FIB device has the advantage that ion beams of a wide ion charge state spectrum can be produced, beginning with singly or lowly charged ions up to highly charged ions (HCI) and bare nuclei. Depending on the ion charge state q different kinetic ion energies $E_k = eqU$ can be achieved with a given acceleration potential U and the elementary charge e. In addition, ions of higher charge states carry larger amounts of stored potential energy. In ion-surface interactions, this offers the possibility of introducing a certain potential energy into the surface besides the projectiles' kinetic energy. The potential energy of the ions can dissipate in very short time and nanometre regions with power densities of about $10^{12} \cdots 10^{14}$W/cm^2. Therefore, FIB systems including EBIS able to produce high ion charge states are of basic interest in different application fields, especially if the setup represents a compact, stable, and relatively low-cost machine as presented in this paper.

THE TECHNICAL SOLUTION

Traditionally, focused ion beam columns are equipped with liquid metal ion sources able to produce singly charged ion beams of high brilliance but with a limited range of available ion species [7]. With the development of room-temperature electron beam ion sources of the Dresden EBIS type compact and powerful sources of a broad range of ion species, i.e. elements and charge states, became available for this field of application [8]. Special features of the Dresden EBIS-M are its bakeable permanent magnet setup as opposed to solenoid coils, its table-top sized but still powerful design [9], and the specially designed third drift tube segment which is attached to the electron collector, providing excellent on-axis alignment.

As a first step of the EBIS-FIB development we coupled a Dresden EBIT with a standard nanometer FIB column provided by LPN/CNRS Marcoussis [10, 11]. This first attempt already demonstrated the potential of an EBIS-FIB and was the starting point for developing the simplified fine-focusing system described in this paper which is able to produce ion micro beams in a more stable and controlled manner.

Figure 1 shows an overall view of the setup. The micro beam system consists of an EBIS ion source, a Wien filter for ion charge state separation, ion-optical components and diagnostics, a target chamber, electrical supplies, as well as measuring and control electronics. The target chamber has a versatile design for the application of various detection systems such as electron and x-ray detectors or TOF-SIMS spectrometers and is equipped with a load-lock system for easy target exchange.

Figure 1: Overall view of the EBIS based low-energy fine-focus ion accelerator facility.

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During the development of the fine-focusing ion beam system care was taken to obtain an ion beam that was as free from aberrations as possible. This means keeping chromatic aberrations, geometric aberrations, as well as manufacturing and alignment errors as small as possible. For most applications of such setups it is desirable to separate the ion beam extracted from the source into its various components in order to achieve well-defined physical conditions. The separation of individual ion charge states can be realised with a Wien filter as shown in Fig. 2 (a). The functional principle of the used Wien filter is explained in detail in [12]. Characteristic resolutions for the used Wien filter are shown in Fig. 3.

The ion optics downstream from the Wien filter consist of the following components (see Fig. 2): b) Entrance aperture. The entrance aperture collimates the incoming ion beam with respect to maximum transmission (large aperture, up to 1 mm) or highest resolution (small aperture, down to 100 µm), respectively. c) Einzel lens. The lens focuses the pre-collimated ion beam down to a few microns. d) Electrostatic octupole deflector. The octupole acts as stigmator and directs (scans) the focused ion beam to match a subsequent target assembly. With the octupole deflector elements having a set maximum voltage the maximum scan field is determined by the working distance to the target. At usual distances the irradiation area's dimensions lie in the range of a few mm^2 up to about 1 cm^2.

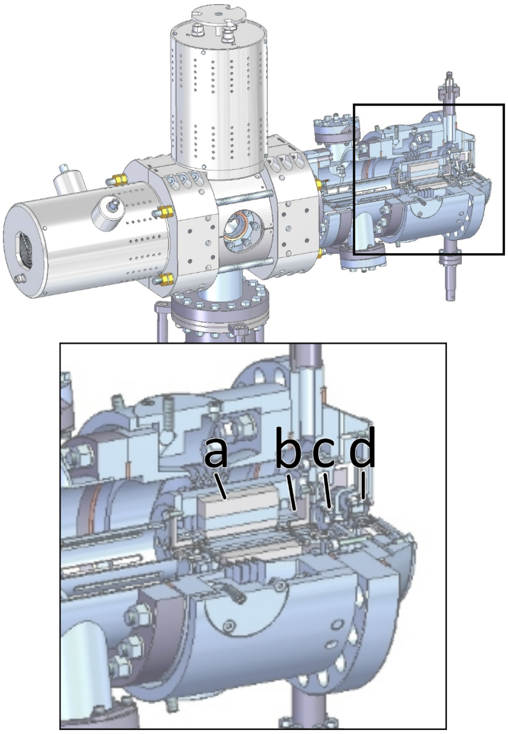

Figure 2: 3D cross-sectional view of the overall structure of the fine-focussing ion beam system for HCIs including an integrated mass and charge state separating Wien filter.

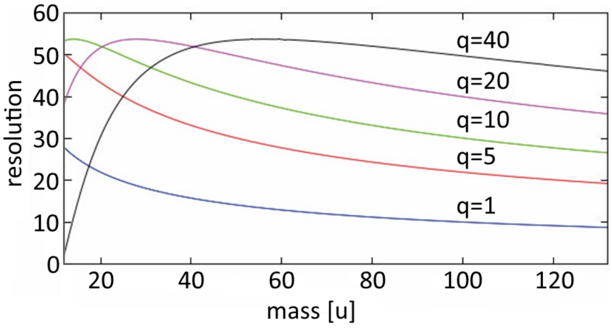

Figure 3: Wien filter resolving power for various projectile masses and ion charge states q with an effective Wien filter length of 50 mm, an ion drift length of 20 mm and a diaphragm diameter of 0.5 mm.

EXPERIMENTAL RESULTS

In the following we report results for first measurements with the facility described above.

SEM Imaging. Figure 4 shows an SEM image of a wireframe measured with fine-focused helium ions. Two meshes with different wire distances are displayed. The highest beam quality in terms of beam width comes with the downside of lower transmitted ion beam currents in the range of 10 pA when the 100 µm aperture is used.

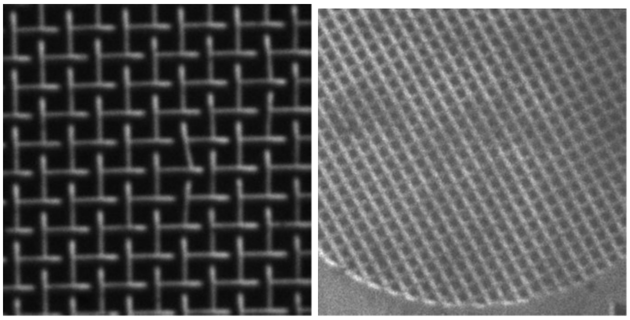

Figure 4: SEM picture of a wireframe of 35 µm wire thickness and 106 µm gap (left) and a wireframe with distance from wire center to wire center of 63.5 µm (right).

Beam Diameter. The technique for measuring the ion beam diameter is shown in Fig. 5. An ion beam scans over a chessboard pattern with 0.1 mm × 0.1 mm fields to create an SEM image (left side). Subsequently the intensity distribution along the red line is taken and a script determines the beam diameter by fitting integrated Gauss functions to the slopes in the distribution and analysing them (right side). In case of an aperture diameter of 100 µm we deducted beam diameters below 20 µm. A more detailed description of the procedure can be found in [13].

Beam Emittance. The emittance was determined by measuring the ion beam diameter at three subsequent positions in the field-free region of the target chamber via SEM images and by estimating the emittance of the beam from these results. The basic mathematical procedure is explained in [14, ch.4].

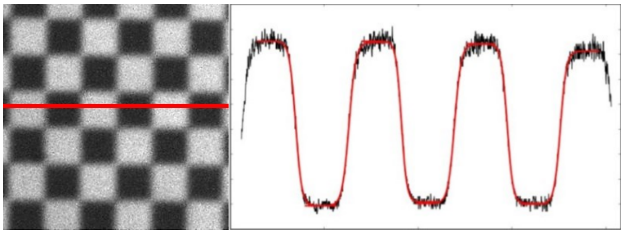

Figure 5: Determination of the beam diameter of a nitrogen ion beam (explanation see text).

For a nitrogen beam accelerated by a drift tube potential of 10 kV an emittance of 0.1 mm mrad was estimated with a corresponding brilliance of at least 1 nA mrad^2/mm^2. The ion beam was not charge state separated and was analysed directly after the ion beam extraction system.

Beam Energy. As stated before, the energy of ion beams from our EBIS-FIB setup covers a wide range starting at some keV and reaching up to more than one MeV. This is possible since the projectile energy can be controlled via charge state selection by the Wien filter as well as by controlling the overall acceleration potential in the ion optical column between about 5 kV and 20 kV with a resolution in the eV range. For singly charged xenon ions, e.g., we start with 5 keV and can reach highly-energetic ion beams with 1 MeV projectile energy for Xe^{50+}. Higher energies would be available when combining the EBIS with an acceleration platform.

Beam Currents. Depending on the EBIS operation regime (see [8]) it is possible to operate the facility with DC ion beams as well as with pulsed ion beams. In case of pulsed beams pulse widths of some tens of ns up to a few µs at pulse repition rates from subseconds up to 1 kHz are possible.

As an example, an argon ion spectrum measured for a collimated ion beam with a diameter of about 20 µm for an electron energy of 13 keV, an electron beam current of 42 mA, and an argon gas pressure of 2×10^{-8} mbar is presented in Fig. 6. The diameter of the aperture used in the setup was 100 µm and the EBIS was operated in leaky mode (DC ion beam). For this operation regime typically some pA were measured after the ion beam fine-focusing optics.

Ion Charge states. With a standard Dresden EBIS a wide variety of ion charge states can be produced. In Table 1 we give some examples of achievable ion charge states and the possible final kinetic ion beam energies for the case of a total acceleration potential of 20 kV. Below the given maximum kinetic energy each kinetic energy can be realised by tuning the acceleration potentials of the facility.

It should be noted here that because of the basic physics of ion production higher ionic charge states can only be generated with lower ion beam currents. Thus, compared to singly charged ions, the beam currents for ions with ultimate charge states can be reduced by several orders of magnitude. Also the ion source parameters have to be adjusted for each ion species to achieve the respective maximum output.

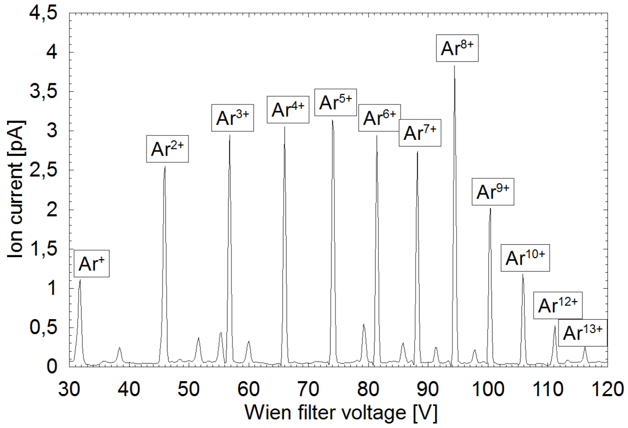

Figure 6: Measured ion extraction spectrum for argon ions produced with a Dresden EBIS in leaky mode using an aperture of 100 µm, measured after the fine-focusing ion beam optics.

Table 1: Maximum kinetic energies E_k for ions of the ultimate derivable ion charge state q.

element	max. q	max E_k / keV
C (Z=6)	6	120
Ne (Z=10)	10	200
Ar (Z=18)	18	360
Ge (Z=32)	30	600
Xe (Z=54)	44	880
Ir (Z=77)	67	1340

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