A High Current, High Energy RF-Implanter *

M. Sarstedt, J. Dehen, H. Deitinghoff, A. Firjahn-Andersch, H. Klein,
M. Kuhpour, A. Maaser, A. Schempp, R. Thomae, M. Weber
Institut für Angewandte Physik der Johann Wolfgang Goethe-Universität
Postfach 111932 D-6000 Frankfurt, FRG

Abstract

The interest in deep deposition of ions in the surface of solids is continuously increasing. Whether the ions are implanted in metals, ceramics or polymers to improve their surface properties, or into semiconductors to adjust the material conductivity (e.g. the formation of deep insulating layers), many of the newer applications require a large penetration depth corresponding to a particle energy in the MeV-range. Furthermore, some processes involve implant doses up to several 10^{18} ions/cm^2, which implies that high currents are needed as well. Both requirements - high ion energy and high beam current - can be satisfied by rf accelerators rather than the commonly used static machines. The experimental set-up discussed consists of bucket ion source, electrostatic injection system, Radio Frequency Quadrupole (RFQ) accelerator, Spiral Loaded Cavity (SLC) for energy variation, and target chamber.

1. INTRODUCTION

For the development of a high current, high energy implanter an accelerator system is under construction [1]. The facility is projected for Nitrogen ions with a final beam energy between 1.3 MeV and 1.7 MeV and beam currents up to 10 mA. Fig. 1 gives a schematic view of the implanter.

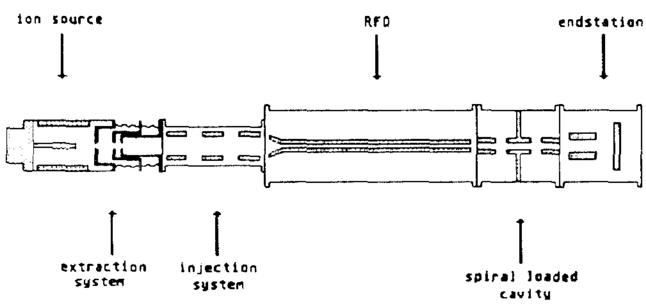

Figure 1. Schematic lay-out of a high current, high energy implanter based on an rf-accelerator system.

For the production of the ions a multicusp source is currently used. For beam formation either a triode or a pentode extraction system can be applied to the plasma generator [2]. The extraction voltage is determined by the fixed entrance velocity of the RFQ-accelerator of 3.57 keV/u.

Behind the extraction system the ion beam is usually divergent. For matching the beam to the entrance of the RFQ [3,4], which requires a convergent beam in both x- and y-plane, the beam has to be focused to a radius of 1.5 mm and an envelope angle of about -30 mrad.

As injection system electrostatic and magnetic quadrupole lenses, solenoidal lenses and einzel lenses were compared. A description of the selected einzel lens is given in section two.

For the acceleration of the ion beam an rf-system is projected, which has, compared to electrostatic accelerators, a lower efficiency, but allows higher beam currents and reduces voltage breakdown related problems, because high terminal voltages are avoided. The Radio Frequency Quadrupole (RFQ) is designed for the acceleration of high current beams and will be run with high duty cycles. The parameters of RFQ and Spiral Loaded Cavity (SLC) [5], which will be used to vary the final particle energy in the range of 90 and 125 keV/u, are given in section three.

When tests of the beam quality behind the rf system are finished, implantation experiments are planned. For these an endstation is placed at the end of the beam line, consisting of a scanner system and the target chamber. In section four plans for the experiments are discussed.

2. BEAM FORMATION AND INJECTION SYSTEM

2.1. Extraction system

For the extraction of the ion beam from the plasma generator usually a triode extraction system is used. The gap width has to be adjusted to the maximum extraction voltage, which amounts in our experiment to 50 kV in the case of Nitrogen (N^+) ions. To ensure good optical properties of the extraction system numerical simulations have been performed by means of the computer code AXCEL-GSI [6,7].

First experiments with a gap width of 5 mm showed that -in a triode system- the field strength between plasma electrode and screening electrode becomes critical with regard to high voltage breakdowns. Due to the potential of the screening electrode the voltage amounts to 55 kV. For reliable operation without breakdowns in our experience a gap width of more than 10 mm is necessary. On the one hand such a large gap width reduces the number of breakdowns, but on the other hand, for a constant aspect ratio, it leads to a higher gas flow into the vacuum chamber, which in view of the high voltages on the RFQ-electrodes is a critical aspect.

Therefore the experiments were done with a triode extraction system with a gap width of 16 mm and an aspect

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ratio of 0.25 only. This yields a beam current of 9 mA for a 50 keV Nitrogen beam. Results are summarised in [8]. After a drift space of 40 cm an emittance of about $\varepsilon = 70$ mm mrad was measured. These values are in good accordance with simulations, which predict a beam radius of 2 mm and an envelope angle of 20 mrad directly behind the extraction system.

2.2. Injection system

In principle there are various types of lenses, which can be used for matching the divergent beam to the acceptance of the RFQ.

Quadrupole lenses have strong focusing forces and allow an adjustment of the beam parameters (envelope radius and angle) in the x- and y-plane independently, when four quadrupole elements are used. However, since the acceptance of an RFQ in x- and y-plane is almost identical, it is possible to use cylindrical symmetric lenses, where two elements only are needed for independent adjustment of the beam radius r and its derivation r'. The main difference between magnetic and electrostatic systems is the degree of space charge compensation in the beam. In magnetic fields the effective space charge is reduced by the presence of secondary electrons, whereas in strong electrical fields, these electrons are accelerated out of the beam and the space charge induces a beam blow-up. Therefore such decompensated beams require stronger focusing forces, but the problem of sudden decompensation of the beam in front of the RFQ is avoided.

Calculations done for various lens systems show that quadrupol lenses as well as solenoidal lenses exceed their technological limits with regard to the diameter of the structure and the necessary field strengths. To achieve the required convergence angle in quadrupole lenses the beam radius becomes too large and thus the ratio of effective length to aperture diameter becomes unacceptable small. Additionally, in the electrostatic case, the necessary voltages become too high. For cylindrical symmetric lenses it is calculated, that for solenoids, in the case of two elements, the field strength on the axis exceeds 1 T, which is only possible with superconducting coils. Alternatively the beam can also be focused by several solenoids successively. Both solutions, however, demand great technological efforts.

The electrostatic einzel lens usually has the disadvantage of strong aberrations. However, under certain conditions these aberrations can be kept small. Calculations show that it is possible to use an einzel lens directly behind the extraction system. That way the beam radius stays small. By using a ring lens, as proposed by Anderson et al., aberrations are minimized [9,10]. With a triode extraction system however, only one of the two beam parameters, i.e. the envelope radius r or the angle r', can be adjusted. Therefore, a combination of such a lens with a pentode extraction system is proposed. This system has two advantages. Firstly an additional degree of freedom is achieved, secondly the necessary extraction voltage is divided between two gaps, thus increasing the operational reliability. Computer simulations show that such a system has good optical properties.

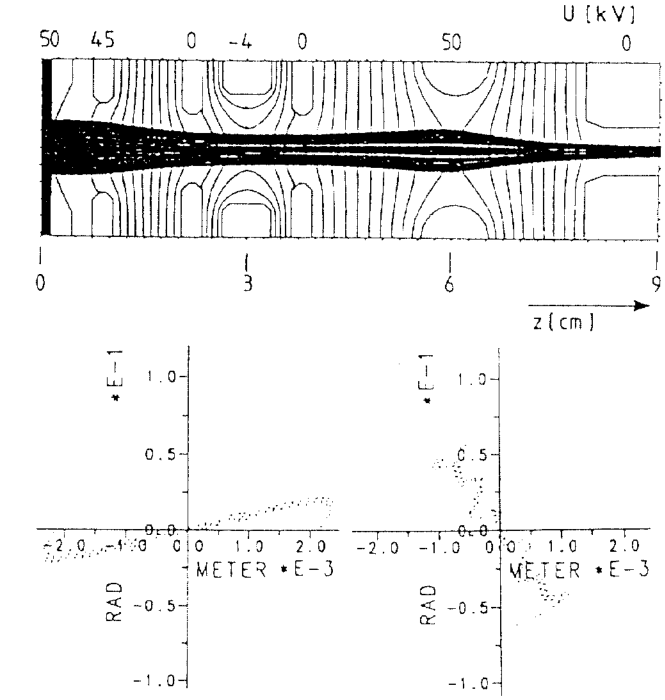

Figure 2. Combination of pentode extraction system and einzel lens for beam injection into the RFQ. Potential distribution and trajectories for a 50 keV Nitrogen beam (N^+) are shown. Below, the emittance diagrams behind the extraction system (z = 4 cm) and behind the lens (z = 8 cm) are given.

An example of the simulations is given in Fig. 2. Shown is the beam extraction for a 10 mA, 50 keV Nitrogen beam. The aperture diameter in the plasma electrode is 8 mm. In the extraction region the gap widths are 3 mm and 10 mm, respectively, the potential of the formation electrode is 45 kV. The dimensions of all electrodes and gaps are choosen in a way that the maximum field strength is less than 45 kV/cm. The overall length of the system amounts to 9 cm. In the case shown here the potential of the einzel lens is 50 kV, resulting in a beam radius of 1.5 mm and an envelope angle of -50 mrad at the exit. Because of the shortness of the system, pumping of the injection system is rather difficult. In consequence, the relatively high pressure in the RFQ tank may cause sparking between the electrodes.

3. RF-ACCELERATOR

3.1. Radio Frequency Quadrupole

The beam is then accelerated by an rf system. The main part of the set-up, the RFQ, makes use of the concept of spatial homogeneous focusing. Four modulated copper rods are placed in a resonator cavity. The rf power coupled to the resonator is converted into an electric field between the electrodes, which has both a transverse

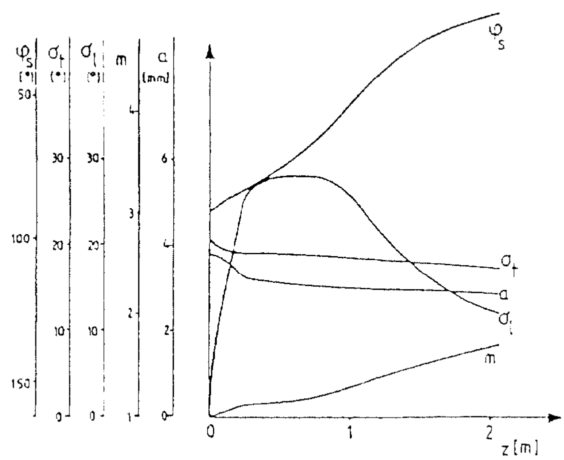

Figure 3. Design parameters for the RFQ along the structure. m: electrode modulation, φ: synchronous phase, a: aperture, σ_r and σ_l: radial and longitudinal phase advances per cell.

and a longitudinal component. These focus and accelerate the ions, respectively.

The projected RFQ is designed for the acceleration of N^+ from 50 keV to 1.5 MeV [4]. Fig. 3 shows an example of the design parameters along the structure. The electrodes of the four rod structure are alternately supported by 12 stems, which are mounted onto a supporting plate. The final goal is to operate the RFQ at high duty cycles up to 100 %, which requires good cooling. All elements (electrodes, rods and supporting plate) are therefore water cooled. The top lid of the vacuum tank can be opened to allow easy handling, mounting and alignment of the electrodes. In Table 1 the parameters of the RFQ are listed. For a mass to charge ratio of 14 beam currents up to 10 mA can be accelerated.

Table 1
Parameters of RFQ

Injection - final energy	3.57 - 107.1 keV/u
Mass to charge ratio	14
Frequency	108.5 MHz
Electrode voltage	80 kV
Rf - power	80 kW
Aperture radius	4.0 - 3.0 mm
Modulation	1 - 1.65
Tank diameter, length	35 cm, 2.0 m
Radial acceptance (norm.)	0.75 mm mrad
Input/output emittance (norm.)	0.2/0.3 mm mrad
Longitudinal emittance (95 %)	5.5^0 keV/u

3.2. Spiral Loaded Cavity

The SLC [5] is a short and compact rf structure giving high voltage gain. It consists of a spiral λ/4 - resonator connected at one end over a common leg with the cylindrical outer tank, and is equipped with a drift tube at the free end. The tank is terminated by end plates, each carrying a drift tube at the center and thus forming the two acceleration gaps. Due to its large energy acceptance it is well suited for the postacceleration or deceleration of ions.

In this experiment the SLC is coupled to the RFQ to vary the beam energy in a range of +/- 200 keV. For that reason the matching out section of the RFQ is designed in a way that the beam fits into the SLC's acceptance. In Table 2 the parameters of the SLC are summarised.

Table 2
Parameters of SLC

Energy variation	+/- 200 keV
Frequency	108.5 MHz
Gap voltage	125 kV
Rf - power	20 kW
Aperture radius	20 mm
Tank diameter, length	50 cm, 29 cm

4. FUTURE PLANS

Before ion implantation experiments will start, the high power, high duty cycle properties of the resonators as well as the current capability and the beam quality will be determined.

Implantation experiments with various elements are planned. Of special interest is the deep implantation of Nitrogen and Oxygen into Silicon. Hereby the formation of deep buried layers of Si_3N_4 and SiO_2, especially considering self-annealing processes, will be studied. Ion implantation into metals requires a good temperature control of the targets to prevent phase transitions. For this reason a target chamber is required, which allows cooling of the targets as well as preheating.

Furthermore it has to be studied what influence a beam of high power density has on different targets. Here, the possibility of pulsing the accelerators is advantageous, because the average beam current can be varied via the duty cycle. In addition experiments on the influence of a variation of the beam energy during the implantation are planned.

Implantation experiments at low ion energy of 50 keV have already been started. Experiments with MeV ion beams are scheduled for 1993.

5. REFERENCES

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