A Compact High Brilliance Ion Source For RFQ Injection

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Abstract

The **HI**gh **EF**iciency Source (HIEFS) is a compact high brilliance ion source designed to supply intense ion beams as needed, e.g., for the injection into RFQ-accelerators. One aim of its development was the generation of nearly pure atomic ion beams with a single charge state only (e.g. N^+, Ar^+, He^+). Additionally, oxygen resistant cathodes enable an operation with oxygen and a production of nearly pure O^+ ion beams. In order to investigate different possibilities of magnetic confinement, the source was operated either with cusp magnets or with a solenoid. For operation with nitrogen (N^+-fraction > 95%) with an arc power of 2 kW, a current density of 220 mA/cm^2 (full beam) has been achieved.

Measurements have been performed concerning the ion beam composition, the beam current density, the beam emittance and the electron and ion distribution. It has been shown that the source and the extraction system are operating near the theoretical limits with respect to perveance and emittance. By using Helium as operation gas, the 80% normalized 4rms-emittance was measured to 0.003π mmmrad, which corresponds to an ion temperature of 300 K only.

1. INTRODUCTION

In the field of ion implantation, there is a growing interest in heavy ion beams with high brightness and low energy. In particular, nitrogen ion beams are necessary for ion implantation into metals. When operated with nitrogen, most ion sources produce two species, N^+ and N_2^+. For several reasons it would be advantageous to have an ion source which produces the required ion species with only a single charge state. This way, additional space charge forces by the undesired ions are avoided. A mass-to-charge separation between ion source and accelerator is not necessary, which is undesirable for the beam optics at large ion currents

2. EXPERIMENTAL SETUP

A schematic drawing of the HIEFS is shown in Fig. 1. The source consists of a water cooled cylindrical copper chamber (6.0cm diameter, 10.5cm depth). The front end of the chamber is closed by the plasma electrode, which is negatively biased with respect to the anode. In order to investigate various magnetic plasma confinements the source can be operated either with cusp magnets or with a solenoid. Near the plasma electrode an electro-magnet is installed as a filter to provide a transverse magnetic field (B_y).

The source is equipped with a single aperture accel/decel extraction system designed for 22keV beam energy. The distance between the plasma electrode and the screening electrode is 2.4mm, the diameter of the outlet aperture (plasma electrode) is 2.5mm or 3mm respectively. The screening electrode is 2kV negatively biased with respect to ground potential and serves as a barrier for secondary electrons from the beam line. According to Kilpatrick[2], the maximum extraction field strength of 10kV/mm has been used.

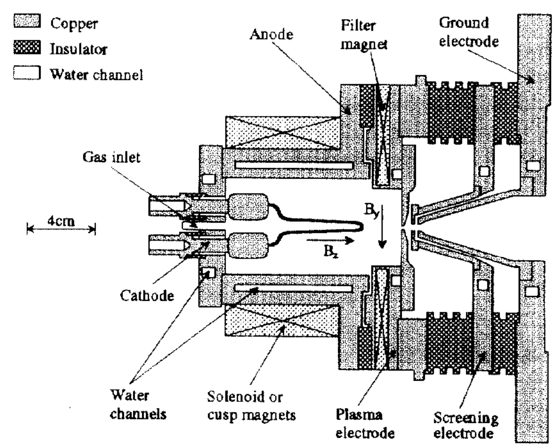

Fig. 1 Schematic drawing of the source and the extraction system.

3. EXPERIMENTAL RESULTS

In order to determine the optimum conditions for the generation of a high percentage of N^+ ions, the effect of the magnetic filter field strength (B_y), and the source pressure (p_S) on the ion distribution were investigated. The other source parameters such as arc voltage or plasma electrode potential hardly influence the N^+ percentage.

Fig. 2 illustrates the relationship of the N^+ percentage to the transverse magnetic field strength for three different source pressures. The arrangement of the filter magnet is of fundamental importance for the N^+ percentage and the extracted current density. In addition, the filter magnet field extends into the extraction region. As a result, the extracted ions are deflected. Consequently, there is an angle between the beam axis and the z-axis. Therefore the filter magnet arrangement and the source geometry near the extraction region were optimized initially. An N^+ fraction above 90% can be achieved for a filter field magnitude of only 3.5mT at the axis. For higher arc currents or higher source gas pressures the filter field can be reduced to 2.5mT. This way, the extracted current density increases while the beam angle decreases. Even for a beam energy of 13keV and transverse filter field strength of 4mT the beam angle is less than 1 degree.

It can be seen that the N^+ fraction increases with increasing arc power. Even for a source pressure of only 7Pa, it is possible to enhance the N^+ percentage up to 90% by increasing the arc power above 2kW.

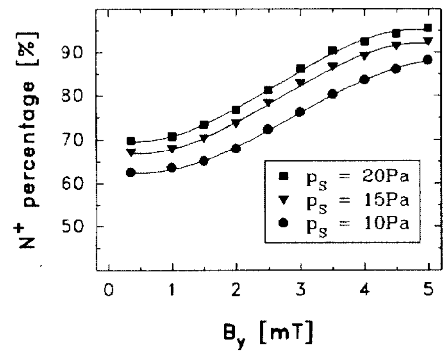

Fig. 2 N^+ percentage as a function of transverse magnetic field strength. (P_A = 1kW)

The species dependence on source pressure (p_S) is plotted in Fig. 3. The results show that the N^+ fraction increases with the source pressure. N^+ fractions of 98% can be obtained for a source pressure of 30Pa (measured in the gas inlet). Also for a source pressure of only 7Pa, it is possible to enhance the N^+ percentage up to 90% by increasing the arc power above 2kW.

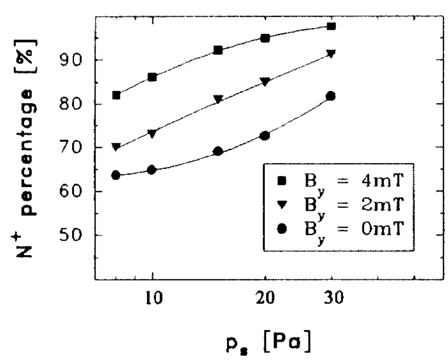

Fig. 3 N^+ percentage as a function of source pressure. (I_A = 10A, U_A = 100V)

To compare different kinds of magnetic confinements, the dependence of the extracted current density on the magnetic field configuration was investigated. Fig. 4 illustrates the relation of the extracted current density (J_{SO}) to the solenoidal field strength (B_z) for a constant arc power (P_A) of 1kW in case of a nitrogen plasma. It can be seen that the extracted current density is directly proportional to the field strength of the solenoid.

In a second step, the source was operated with cusp magnets. The source chamber was surrounded by 10 samarium-cobalt magnets, forming a longitudinal line cusp field. In this magnetic arrangement B_z is zero. To compare the current densities for both magnetic field arrangements, the source was operated with the same parameters. The current density with cusp magnets is marked as (J_{CU}) on the y-axis.

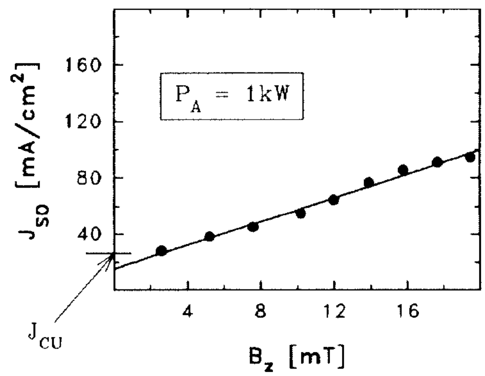

Fig. 4 Extracted current density as a function of solenoidal field strength. (p_S = 15Pa)

A comparison shows that the plasma confinement for an operation with a solenoid is up to four times higher than an operation with cusp magnets. Consequently, the power efficiency, i.e. the extracted current density for a given arc power, is up to four times higher.

For an arc power of 2kW only, current densities of 220 mA/cm^2 can be obtained in nitrogen operation (N^+ percentage 90%, dc, total beam).

In Tab. 1 the current density of the HIEFS is compared to the current density of other single-stage ion sources. The values are scaled to an operation with nitrogen and 2kW arc power. In comparison to other single-stage ion sources, the table indicates the excellent power efficiency of the HIEFS. This allows a reliable production of high current densities at low arc power, reducing instabilities for high arc currents and cooling problems.

Source		Current density [mA/cm^2]
HIEFS	[1]	220
ECR	[3]	212
Penning	[4]	168
CHORDIS	[5]	111
Multicusp	[6]	58

Tab. 1 Comparison of the power efficiency for different single-stage ion sources. (Arc power = 2kW, operation gas = nitrogen)

The energy distributions of ions and electrons have been measured by an electrostatic 127° cylinder spectrometer. Compared to measurements with Langmuir probes, this method has the advantage that the plasma potential is not disturbed. Note that for all distribution measurements no transverse magnetic filter field was applied. In addition the energy spectra represent the distribution near the anode hole and thus near the plasma electrode.

Fig. 5 shows the energy distribution of the electrons for three different source pressures in nitrogen operation. For these measurements the potential between anode and plasma electrode U_{PE} is zero. According to their energy, the electrons can be divided into two groups. The electrons of the first group originate from the plasma near the anode and have an energy of approximately 10eV. The intensity of this peak strongly increases with increasing source pressure, its energy spread is approximately 9eV. Note that this peak is slightly shifted to higher energies with decreasing source pressure. The second group of electrons (B) consists of electrons originating at the cathode or the plasma between cathode and plasma electrode. Its energy spread is approximately 50eV. In contrast to group A neither its intensity nor its energy is influenced by the source pressure.

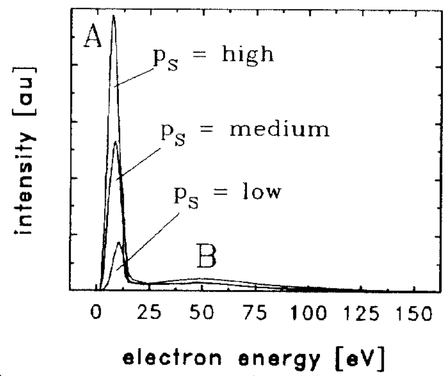

Fig. 5 Electron energy spectra for three different source pressures.

The influence of the plasma electrode voltage on the electron energy distribution is shown in Fig. 6 for helium operation. By means of this voltage the plasma potential in the plasma electrode can be influenced. A negative plasma electrode voltage leads to a negative plasma potential (with respect to the anode) which functions as a potential barrier for low energy electrons from group A. Consequently, with decreasing plasma potential an increasing number of low energy electrons is reflected at this potential barrier.

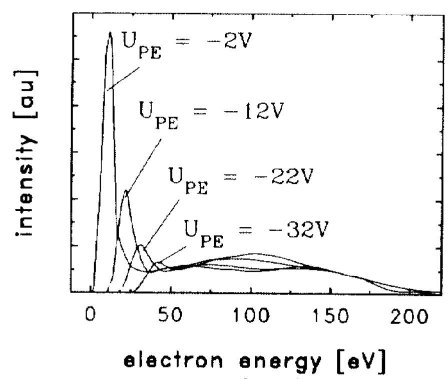

Fig. 6 Electron energy spectra for different plasma electrode potentials.

The emittance of the source was measured in case of matched beam with a high resolution emittance measurement device (0.25mm, 0.74mrad). A 2D-emittance diagram for a 17keV helium beam is presented in Fig. 7. The unnormalized 80% 4rms emittance is 1.2π mmmrad (normalized: 3.0 * 10^{-3}). Compared to He^+ ions, the mean energy transfer on N^+ ions after ionization is much higher (He^+: 0.04eV, N^+: 0.19eV). Therefore the mean transverse energy of N^+ ions in the beam is higher; this leads to a higher emittance of the N^+ beam. As a result, in operation with nitrogen the unnormalized 80% 4rms emittance is 6.4π mmmrad (normalized: 1.0 * 10^{-2}). The measurements show that the resulting minimum emittance size is predominated by the plasma temperature alone. Emittance growth due to aberrations in the extraction system is obviously negligible.

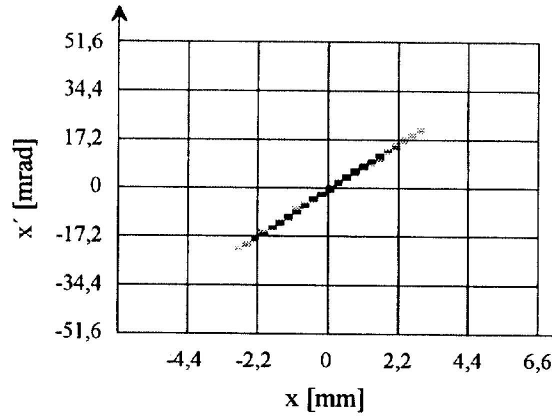

Fig. 7 2D-emittance diagram of the extracted beam. (U_{EX} = 17kV, I_{EX} = 9mA).

Based on these results, a new ion source is being built for the ESS project (European Spallation Source). In contrast to HIEFS the plasma will be generated by means of rf. The source is designed for the generation a 35keV 35mA H^- beam with a very low emittance. Fig. 8 shows schematic drawing of the source and the extraction system.

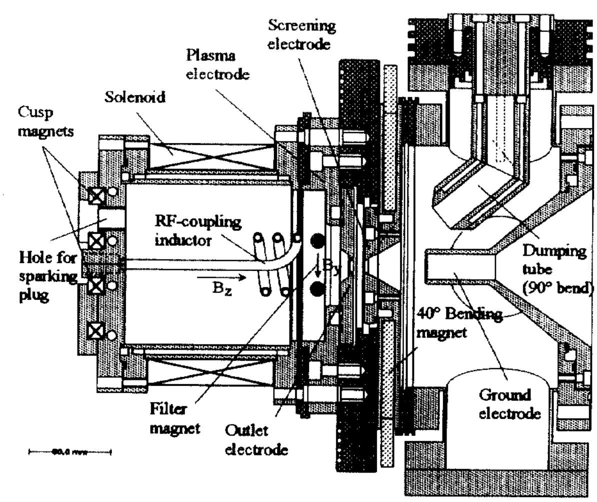

Fig. 8 Schematic drawing of the source and the extraction system.

4. References

[1] K. Volk, Dissertation Univ. Frankfurt, Frankfurt (1993).

[2] W. D. Kilpatrick, *Rev. Sci. Instrum.* **28,** 10, 824 (1957).

[3] Y. Torii et al., *Rev. Sci. Instr.* **61**, 253 (1990).

[4] R.P. Vahrenkamp, R.L. Seliger, IEEE Trans. Nucl. Sci., NS-16, 3101 (1979).

[5] R. Keller, *The Physics and Technology of Ion Sources,* John Wiley, New York, 1989.

[6] K. Volk, H. Klein, K.N. Leung, *Proceedings of Int. Con. on Ion Sources,* Bensheim, Germany, 2607 (1992).