NEW DEVELOPMENTS WITH A HIGH-CURRENT ION SOURCE

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Introduction

The development of high-current ion sources at GSI is primarily aimed at delivering singly or doubly charged ions of virtually any species with beam intensities of some ten mA into an RFQ accelerator presently under construction as part of a new high-current injector for the UNILAC [1]. The required duty factors range around a few percent or even lower values. In parallel, the capacity of the source system CHORDIS (Cold or HOt Reflex Discharge Ion Source) to produce dc beams as well as pulsed ones is being cultivated, in view of other applications such as ion implantation.

The source system was presented some years ago, and results with some gaseous and metallic feeding materials are published in Refs. [2, 3]. The sources are of the multi-cusp/reflex type, with a thermionic cathode and a cylindrical anode lined by 18 permanent magnets. Both discharge chamber end plates are biased negatively with respect to the anode potential. There are four basic source versions which can easily be converted into each other, due to their modular construction: a cold one for operation with pure gases and three hot ones which are equipped either with an internal oven or with an external vapour supply bottle or with a sputtering electrode. All hot versions have an inner heat shield mounted within the anode, and the reflector electrodes are thinned out so as to run hot during operation. For a view of the version with oven, see Fig. 1.

All newer results are displayed in Tables 1 and 2 below, together with some older data that better outline the real performance limits of the sources.

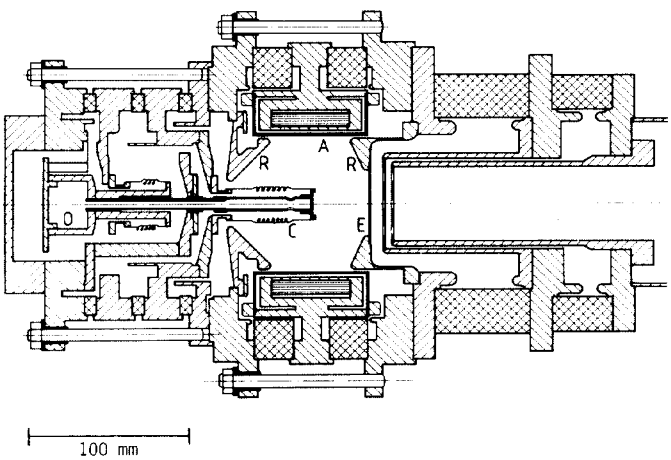

Fig. 1. Hot-running version of CHORDIS with internal oven. O, oven; R, reflector electrode; A, anode; C, cathode; E, extraction system.

Particle Feed

Depending on the vapour pressure of the material to be ionized, four different techniques are employed to feed particles into the source. For gases, a commercial membrane valve with feed-back stabilization is used, which allows to operate the source for several hours without supervision. The noble gases, hydrogen, and nitrogen had successfully been tried out with the cold source version [2, 3], and recently CO_2 was used in a test run with a hot source. No carbon deposits could be detected after a running time of some hours, and the filaments were only slightly corroded by the oxygen.

For the second feeding method a supply bottle is attached to the rear side of a hot-running source. It may be heated, and the vapour flow is regulated by a needle valve. This method is suited for materials with high vapour pressure like iodine, tellurium, or mercury, but also volatile chemical compounds such as chlorides, fluorides, or others. source version is the adequate choice With chemical compounds the beam current will always be shared among several ion species, including different ion molecules, but a test run with $TiCl_4$ showed that even with this high-melting material more than 10% of the beam current was carried by Ti^+ ions. Another successful test was made with H_2S.*

For solid elements with vapour pressures of more than 2 mbar at 1000 °C the source modification with internal oven is to be used. The oven is heated by an independent set of tungsten filaments, and above 350 °C its temperature is completely decoupled from cathode and discharge power. All other internal source parts are kept at higher temperatures than the oven itself, to avoid recondensation of the solid feeding material. Previously, beams of calcium, bismuth, and lithium had been produced by this method. When elements with low work function, like the alkalines, are used the extraction field strength must be kept lower by about 30% than the maximum values that are possible with inert gases.

For the extremely low melting element cesium, handling of the pure material with the oven is quite difficult. Here, a chemical reduction technique was successfully tried out, using a mixture of 1 part cesium chromate in 4 parts of titanium powder. At about 600 °C the cesium is reduced to its elemental state and easily evaporated. The remaining substances do not appear in the discharge or the ion beam [4].

The last method to feed particles into the discharge is the well known sputtering technique. The structure of the CHORDIS sources is well suited for it because the reflector electrodes are anyway biased negatively. By covering the outer zones of the outlet electrode with a ring of the desired material, a metal or a mixture of metal powder with a non-conducting element, and applying still lower potential values to this reflector one can obtain shares of about 20% of the interesting ion species, apart from the auxiliary gas ions that are needed to strike and sustain the discharge. The only test of this method so far was conducted with aluminum.

Ionization

Cusp sources are among the most versatile types of plasma generators because they can be stably operated over a large range of plasma density values [6]. This

*These tests were performed on the site of Danfysik AS, Jyllinge, Denmark, in a collaboration with B.R. Nielsen.

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feature enables the user to concentrate on particular aspects such as gas efficiency, power efficiency, or shift of the ionization equilibrium towards either an optimum share of singly charged ions or higher shares of multiply charged ones. A look at the total ionization cross sections [7] immediately suggests that in order to efficiently create a certain ion species one should operate the discharge at a voltage about five times higher than the appearance potential of this ion. A list of calculated appearance potentials for singly and multiply charged ions was published in Ref. [8].

According to this rule, multiply charged ions of krypton and xenon have been produced in a CHORDIS source by applying discharge voltages up to 375 V. For the peak results, see Table 2, below. Surprisingly it turned out that, even though the extracted beam current was nearly constant, the discharge current had to be raised together with the voltage, in order to reach the matching plasma density for the applied extraction conditions. This fact apparently contradicts earlier observations with a similar source for singly charged ions where the discharge current was exactly proportional to the beam current [9]. The explanation for the unexpected behaviour could be that in optimizing the plasma for a copious production of multiply charged ions the ion temperature and maybe the electron temperature as well are raised, leading to lower density values for a given discharge current. The total discharge power of 21 kW, necessary to obtain the spectra shown in Table 2, cannot be withstood by the source continuously. The discharge has to be pulsed, and the maximum duty factor for this power load is 25 %. The actually used duty factor was 5 % during these experiments.

The 375-V limit for the discharge voltage was imposed by the available power supply. There is no doubt that by still increasing this voltage even higher charged ions could be produced. One should keep in mind, however, that there will always result a broad distribution over the various ion charge states, reducing the share of the one charge state selected for further transport to the order of 10 % or even less. Within this limitation, the experiments have demonstrated that the CHORDIS sources are well suited to yield high-current beams of multiply charged ions.

Beam Formation

All used extraction systems are of the accel/decel type, that is, they incorporate an electron screening electrode to keep secondary electrons within the beam and thus conserve space-charge compensation. The aperture contours are optimized relying on computer simulations by the code AXCEL-GSI [10]. The aim of such optimizations can be either a maximum current within a given acceptance or a minimum emittance for a given beam current. In the latter case, reduction of the beam halo is usually an implicit task.

For direct extraction at 100 kV, a new single-aperture accel/decel system was designed, but due to the lack of an adequate power supply it could be tested with voltages up to 30 kV only. At 100 kV, 110 mA of xenon will be delivered within 20 mrad half-angle, according to predictions of the computer code. The outlet electrode has an aperture diameter of 38 mm and the first gap a width of 15 mm, leading to an aspect ratio of 1.27 which slightly exceedes the usual limit of 1.0 [5]. However, for this system the definition of the gap width as the mechanical distance of outlet and screening electrodes is no more meaningful because both electrodes are deeply recessed on the sides facing each other in order to reduce aberrations. At the low extraction voltage used for the test, the source had to run at 4 A of discharge current only. The beam current transported over 0.7 m amounted to 13.5 mA; this corresponds to 82 mA to be obtained at 100 kV. The difference against the predicted value of 110 mA at 100 kV is most probably due to charge exchange of beam ions into neutrals because the background pressure in the beam line was quite high, 6.5 10^{-5} mbar.

The experiments anyway proved that the source can well be operated and a beam can be extracted with such a large outlet aperture. The simulations were therefore continued in order to find system contours that allow a convergent beam with little aberrations to be formed, for direct injection into an RFQ accelerator. The final geometry is shown in Fig. 2. The simulated emittance patterns, Fig. 3, represent two cases with different assumed plasma density values, leading to convergence half-angles of about 25 and 60 mrad for the core of the beam. The simulations demonstrate that direct injection of a convergent, high-current ion beam into an RFQ is feasible, but one should keep in mind that this method excludes any pre-separation of different beam constituents. This restriction seriously limits the choice of ion species in all cases where the spilled beam cannot be dumped within the RFQ itself.

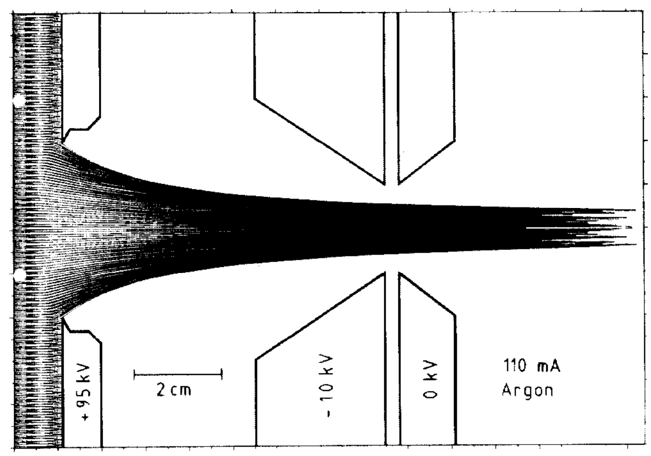

Fig. 2. Large-area, single-aperture extraction system for CHORDIS, producing a convergent beam. Computer simulation by AXCEL-GSI.

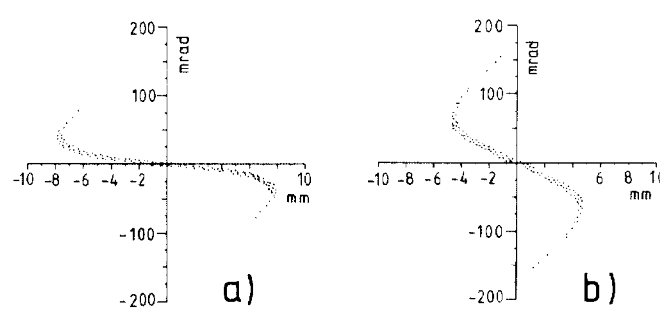

Fig. 3 a and b. Emittance patterns of convergent ion beams, produced by the extraction system according to Fig. 2. Ion species: argon; beam energy: 95 keV. Transported currents: 114.5 mA (case a) and 110 mA (case b).

Results

The new results and some older ones obtained with all source versions are displayed in Tables 1 and 2 below. Other results which give a more complete picture of the source performance can be found in Refs. [2, 3]. As to a general formula that may describe the peak beam currents, the CHORDIS sources are able to deliver ion beam currents up to the modified space-charge limit [5] that applies to low-divergence beams extracted from a single round aperture and reads as follows:

$$I_{n,tr} = P^* U^{3/2} S^2/(1+aS^2) \qquad (1)$$

with $I_{n,tr}$, normalized transported beam current (proton equivalent), $I_{n,tr} = I_{tr} (A/\zeta)^{1/2}$; A, atomic mass number; ζ, ion charge-state; P^*, perveance for low S values, $P^* = 6\times10^{-8}$ $(A/V^{3/2})$; S, aspect ratio of the circular outlet aperture, S = r/d; r, aperture radius; d, mechanical extraction gap width; U, extraction voltage, defining the beam energy; and a, aberration factor with the empirical value a = 1.7.

Proper reductions have to be made, however, if the beam current is shared among different ion species in cases where multi-component discharges are being utilized or multiply charged ions produced.

The beam emittances vary largely, due to the wide range of possible extraction conditions. However, assuming a divergence half-angle of 20 mrad that can easily be reached in praxis and further assuming that the beam waist is about half as wide as the outlet aperture one can derive two first-guess formulas for the emittance values to be expected from either single- or multiple aperture extraction systems:

$$\varepsilon_{sing} = 50\ (F)^{1/2} \qquad (2)$$

and, with a linear dilution factor of 3.5:

$$\varepsilon_{mult} = 175\ (F)^{1/2} \qquad (3)$$

with ε, absolute (measured) emittances (π mm mrad) and F, total open area of the outlet electrode (cm^2).

Table 1. Results with the CHORDIS ion source system for singly charged ions. All shown results can be obtained under dc conditons. El, element. I_{tr}, transported beam current (mA). U, extraction voltage (kV). N, number of outlet apertures. F, total outlet area (cm^2). Rem, remarks, see below the table.

El	I_{tr}	U	N	F	Rem
He	120	47	7	0.51	
N	52	25	7	2.69	(1)
Ar	42	50	1	1.33	(2)
Xe	71	50	7	1.98	
Bi	37	36	7	1.98	
Al	2.4	20	1	0.79	(3)
C	6.1	18	7	1.37	(4)
O	2.7	18	7	1.37	(4)
S	3.3	25	1	0.64	(5)
Ti	0.8	25	1	0.64	(5)
Cs	1.9	14	1	0.64	(6)

Remarks:
(1) N_1/N_2 = 10.4/9. (2) Pentode extraction system. (3) Sputter source, Al/Ar = 1/4; extraction system could sustain 45 kV, 8.1 mA Al current expected. (4) Extraction system could sustain 50 kV, beam current higher by a factor of 4.6 expected. (5) Extraction system could sustain 50 kV with gases, but probably 40 kV with this material. Beam current higher by a factor of 2 expected. (6) Extraction system could sustain 50 kV with gases, but probably 40 kV with Cs. Beam current higher by a factor of 4.8 expected.

Table 2. Results with the CHORDIS ion source system for multiply charged ions: transported beam currents of xenon and krypton ions, given in mA (electrical, pulse height). Extraction voltage: 30 kV (50 kV could have been applied to this system, leading to twice the measured current values). Seven outlet apertures with 2.7 cm^2 total area. Discharge voltage: 375 V. Discharge current: 57 A. Pulse duty factor: 5 % (the necessary discharge power could be sustained up to duty factors of 25 %).

Charge state	1	2	3	4	5	6
Xenon	11.6	10.2	5.0	2.2	0.8	0.11
Krypton	15.8	9.9	3.4	0.44	0.16	0.06

Acknowledgements

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