SIMULTANEOUS TRANSPORT OF N^+ AND N_2^+ BEAMS THROUGH A F0D0 CHANNEL

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Abstract: The transport of space-charge dominated ion beams, which contain both N^+ and N_2^+ ions, through a periodic focusing quadrupole channel has been investigated for 20 keV and 40 keV beam energies, various injected currents and for a wide range of the zero-current phase advance per cell, μ_0. The partial N^+ and N_2^+ beam currents have been measured at the entrance and exit side of the transport channel, which is part of the MEQALAC experiment. Both the measurements and the theoretical model show that the transport of a mixed beam is similar to the transport of a beam which contains one type of ions, when the cross sections and the emittances of the partial beams are identical at the entrance of the transport channel.

Introduction

The objective of the MEQALAC experiment (Multiple Electrostatic Quadrupole Array Linear Accelerator), which is carried out at the FOM-Institute in Amsterdam, is to accelerate intense N^+ beams from 40 keV to 1 MeV. In this type of accelerator, originally proposed by Maschke[1], the ions are accelerated in rf-gaps while the radial space charge forces are opposed by miniaturized electrostatic quadrupole lenses. The set-up of the experiment is schematically shown in fig. 1. It consists of a bucket-type plasma source, a Low Energy Beam Transport section (LEBT) and the accelerating structure.

The ion source is a so-called bucket type plasma source. Rows of CoSm magnets, which form a line-cusp magnetic field, are mounted on the walls to reduce plasma losses to the walls. The source is equipped with a four-grid extraction system. Typical operating parameters are : a gas pressure between 1×10^{-3} and 6×10^{-3} mbar, an arc voltage between 60 V and 150 V and an arc current of 10 A. The source produces both N^+ and N_2^+ ions, in roughly the same amount.

The LEBT section serves as drift-space for a buncher and provides space for a vacuum pump between the high-pressure extraction region and the low-pressure acceleration region. It consists of four parallel channels while each channel consists of 34 quadrupole lenses[2], which are arranged in a F0D0 lattice. The first five quadrupoles can be biased independently and serve to match the extracted rotationally symmetric beam to the acceptance of the F0D0 channel. Typical dimensions of the quadrupoles are the length of 10 mm and the channel radius of 3 mm.

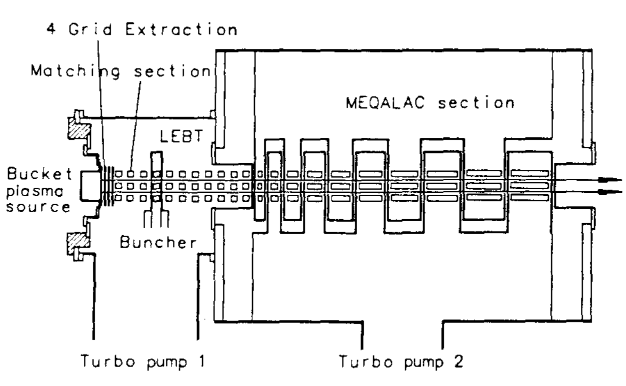

Fig 1. Schematic drawing of the FOM-MEQALAC experiment.

The ions are accelerated in a modified interdigital-H-resonator, excited in the TE_{111} mode. The accelerating structure has 32 gaps. The resonator has a rectangular cross-section, which offers the possibility to vary the inductance of the resonator. This way, the resonance frequency can be varied upto a factor $\sqrt{2}$, which means that the final energy of the accelerated ions can be varied by a factor 2 (ref. 3). For example, at 25 MHz and 17.7 MHz, N^+ ions can be accelerated from 40 keV to 1 MeV and form 20 keV to 500 keV, respectively. Therefore, the extraction and transport of 40 keV and 20 keV nitrogen ion beams has been investigated. More information about the resonator can be found in ref. 4.

The MEQALAC project consists of two stages. In Stage I, which was a proof-of-principle experiment, four He^+ beams have been accelerated from 40 keV to 120 keV. The time-averaged beam current was 2.2 mA[5]. The resonator used for this experiment contained 20 rf-gaps and was operated at 40 MHz. The first objective of Stage II is to accelerate four N^+ beams from 40 keV to 1 MeV.

In this paper we investigate the simultaneous transport of N^+ and N_2^+ beams through the LEBT section.

Theoretical background

In our experiment, ion beams which contain various types of ions are transported through a periodic focusing channel. The force which acts on the individual ions is the sum of the external focusing forces and the space charge forces of the partial ion beams, where a partial ion beam is defined as a beam which contains one type of ions. Because electrostatic quadrupole lenses are used, the external focusing forces are determined only by the channel dimensions and the applied quadrupole voltage, the ion mass plays no role. On the other hand, the space charge forces are determined by the charge density of the various partial ion beams, i.e., by the partial beam current and emittance, the ion energy and the various ion masses present in the beam.

For the situation of a homogeneously filled cylindrical ion beam, the electrical field is proportional with the distance from the axis (r) for $r<R_{beam}$, where R_{beam} is the beam radius. Outside the beam the electrical field is proportional with 1/r. The electrical field of a quadrupole lens is proportional with the distance from the axis. When the various partial ion beams have identical radii, the sum of the electrostatic forces experienced by the ions, are proportional with r. All ions, irrespective of their mass, experience the same lens action. On the other hand, when the partial beams do not have identical radii, the ions in the region between the beam with the smallest diameter and the beam with the largest diameter experience non-linear forces. The ions in this region are not properly focused. In this case, separation of the various partial beams in phase space will take place.

In general, when the emittances, the cross sections and the energy of the partial beams are identical at the entrance of an electrostatic transport channel, the cross sections of the various partial beams will remain identical with respect to each other during transport. For this situation, a mixed beam behaves like a beam which contains only one type of ions. No separation in phase space of the various partial beams will take place.

Experimental results

The partial-current fractions and the beam profiles of the N^+ and N_2^+ beams have been measured behind the extraction system and behind the LEBT section. These measurements have been performed with an emittance measuring device, which has a movable square entrance aperture and an array of 40 parallel wires to measure the beam current. The partial N^+ and N_2^+ beams are separated by means of a magnetic field. The device is scanned through the ion beam to measure the beam profiles of the two partial beams. However, the disadvantage of this device is that the 40 wires are always at earth potential, due to technical constrains. Due to the different secondary electron yields of the various ions, these measurements do not give the N^+ current fraction accurately. Therefore, the N^+ and N_2^+ currents have also been measured with a beam sweep device which consists of a single wire which is swept through the separated partial ion beams. The wire is at a potential of 40 V and secondary electrons are kept at the wire. This method however, has the disadvantage that the beam profile can not be measured accurately because the wire integrates the current in one direction. Therefore, both the emittance measuring device and the beam sweep device have been used to measure the various beam profiles and the partial current fractions.

A typical result of a measurement performed with the beam sweep device is shown in fig. 2. The right and left peak correspond with the N^+ and N_2^+ beams respectively. Integration of the curves shows that the N^+ current fraction is roughly 60 %. For this measurement the source parameters are in the center of the tuning range.

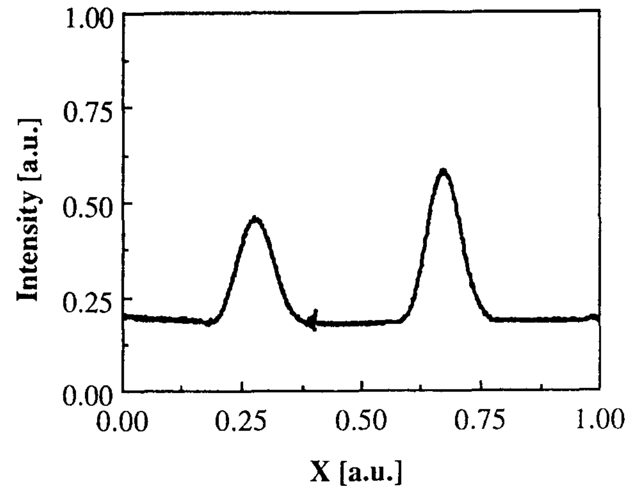

Fig. 2. Beam profiles measured with the beam-sweep device. The right and left peak correspond with the N^+ and N_2^+ beam, respectively. Integration of the curves shows that the partial N^+ and N_2^+ ion currents are 60 % and 40 %, respectively. The source parameters for this measurements are : an arc voltage of 120 V, arc current of 10 A and a gas pressure of $3{\times}10^{-3}$ mbar. The extraction voltage is 40 kV, the extracted total ion current is 5.1 mA.

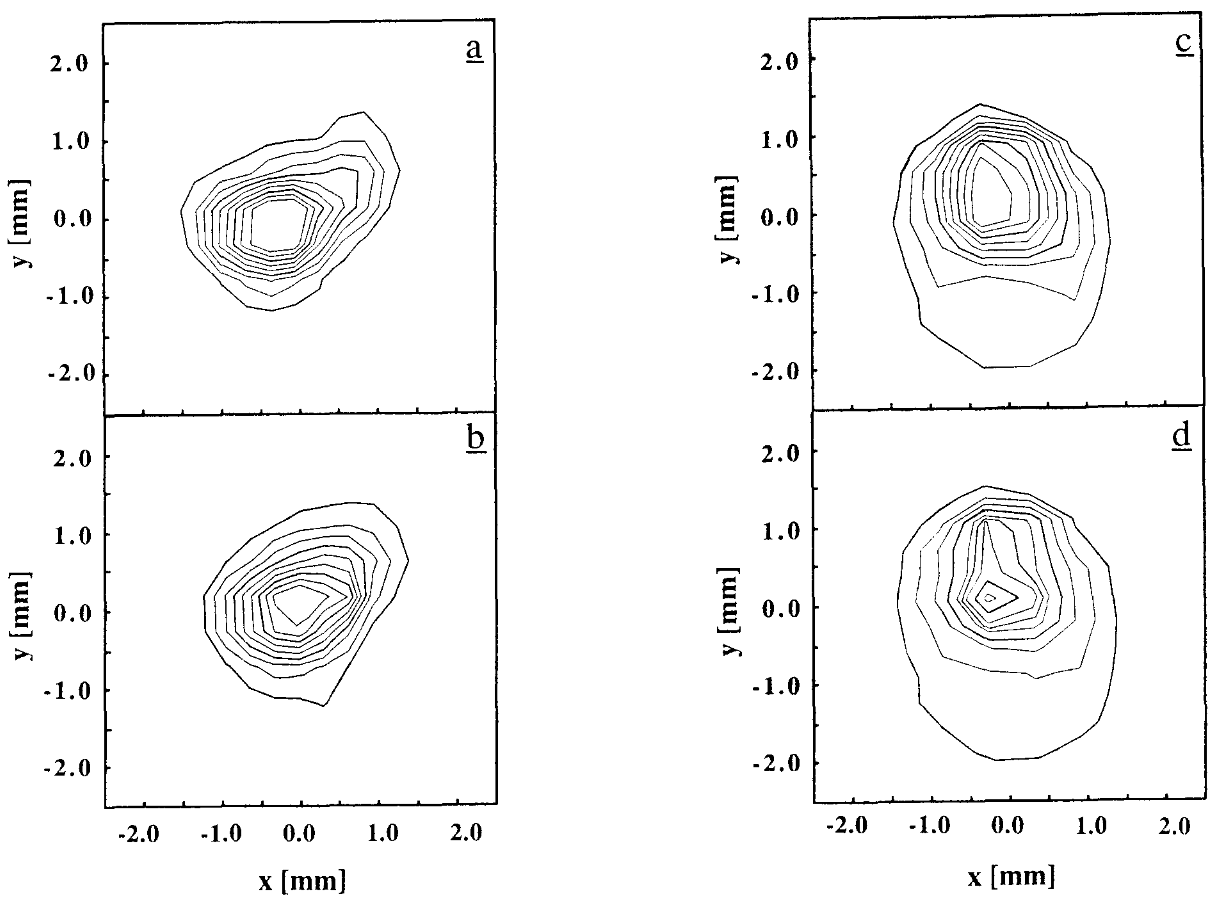

Fig. 3. Beam profiles of the N^+ and the N_2^+ beams as measured behind the extraction system (fig. 3.a and 3.b, respectively) and behind the LEBT section (fig 3.c and 3.d, respectively). The contours are shown at a 10 % interval; the outer contour is the 10 % intensity-curve. The source parameters are identical to those given in fig. 2.

Beam profiles as measured with the emittance measuring device are shown in fig. 3, for an injected 40 keV-5.1 mA nitrogen ion beam. The source parameters are identical to those given in fig. 2. Typical beam profiles of the N^+ and the N_2^+ beams as measured behind the extraction system are shown in fig. 3.a and 3.b, respectively. At this position the profiles of the two partial beams are roughly identical. Behind the LEBT section the profiles of the N^+ and the N_2^+ beams are roughly identical too, as shown in fig. 3.c and 3.d, respectively. Moreover, integration of the profiles presented in fig. 3.a to 3.d learns that the N^+ current fraction has not changed during transport.

Measurements performed for μ_o=45°, 84° and 105° and measurements performed for smaller injected beam current show the same results; the N^+ current fraction does not change during transport and the beam profiles of the various partial ion beams remain identical with respect to each other.

Transmission measurements have been performed for various injected currents and beam energies. Fig. 4 shows the transmitted current for injected 5.1 mA-40 keV and 1.8 mA-20 keV nitrogen ion beams and a 12.0 mA-40 keV helium ion beam. The source parameters and the parameters of the extraction system are set such that all beams have an unnormalized rms-emittance of roughly 20 π mm mrad. The beams have roughly the same generalized perveance too, which is 1.9×10^{-3}. The three parameters which determine the beam transport, i.e., the emittance the generalized perveance and the external focusing forces are identical for the three beams, for given values of μ_o. The same beam behaviour is expected. For all beams, the transmission reaches 85 % for μ_o=60°-84°. For μ_o=45° and μ_o=105° roughly 40 % of the injected beam current is lost during transport. For μ_o=45° these losses are due to the large beam-envelope maximum of the matched beam, which is roughly 2.5 mm. The channel radius is only 3 mm and thus a slight mismatch or misalignment causes current losses. For μ_o=105° the maximum of the matched envelope is only 1.2 mm and current losses are most probably due to unstable beam behaviour.

According to the equation for the current limit (I_T) of a F0D0 channel as given by Reiser[6], I_T is proportional with $V^{3/2}m^{-1/2}$, where m and qV are the particle mass and energy, respectively. In the case that the injected beam current is larger or equal than I_T, the three curves presented in fig. 4 should be identical after scaling with $V^{3/2}m^{-1/2}$. These normalized currents are presented in fig. 5. The difference between the normalized current for 40 keV-helium and 40 keV-nitrogen ion beams is roughly 30 % for μ_o=45° and is less than 20 % for larger values of μ_o. The differences are partly due to mismatch and misalignment of the ion beams, which strongly influences the transmitted beam current, especially for small values of μ_o.[7] However, in general the three curves show roughly the same beam behaviour, i.e., severe current losses are observed for μ_o=45° and μ_o=105°, while the transmission for μ_o=60° and μ_o=84° is roughly identical.

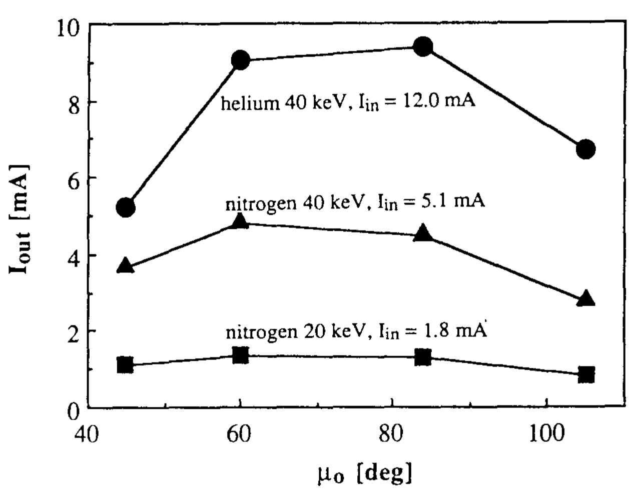

Fig. 4. The ion current transported through the LEBT section as a function of μ_o for various injected currents, as indicated in the figure. The unnormalized rms-emittance of the injected beams is roughly 20 π mm mrad.

As mentioned before, the N^+ current fraction is always 60 %, independent on μ_o. Also in the case of severe current losses N^+ and N_2^+ current is lost in the same amount. This indicates too that a mixed beam indeed behaves like a beam which contains just one type of ions, provided that the emittances and cross sections of the partial beams are identical at the entrance of the transport channel.

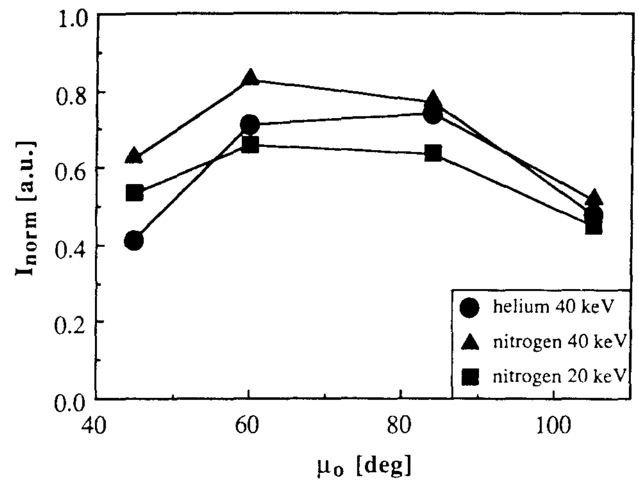

Fig. 5. The normalized current (I_{norm}) as a function of μ_o. The curves are calculated from the results presented in fig. 4, by scaling the current with $V^{3/2}m^{-1/2}$.

Acknowledgements

This work is part of the research program of the association agreement between the Stichting voor Fundamenteel Onderzoek der Materie (FOM) and EURATOM, with financial support from the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), the Nederlandse Ministerie van Onderwijs en Wetenschappen and EURATOM.

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