ACCELERATION OF NITROGEN IONS WITH A 1-MeV MEQALAC

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In the MEQALAC (Multiple Electrostatic Quadrupole Linear Accelerator) multiple N^+ ion beams are accelerated in a number of gaps which carry a rf voltage. The transverse focusing of the intense ion beams is achieved by means of sets of miniaturized electrostatic quadrupoles. Results are presented which show that the ion beams are accelerated to 1 MeV with an energy spread of less than 8 %. The maximum beam current measured so far in a single channel is 200 μA. This is considerably less than the theoretically predicted current. It is shown that the smaller transmission is due mainly to misalignment of the quadrupole lenses.

Introduction

At the FOM-Institute in Amsterdam a MEQALAC for the acceleration of four intense N^+ ion beams has been built and is now in operation. In this type of rf accelerator, which is originally proposed by Maschke [1], the ions are accelerated in rf gaps, while the transversely-directed space charge forces of the intense ion beams are opposed by the focusing forces of miniaturized electrostatic quadrupole lenses. These quadrupoles are mounted in the field-free drift spaces in between the rf gaps and arranged such that a large number of beams can be stacked into a small area, thus resulting in a high accelerated current. A further advantage of the MEQALAC set-up is that the rf power is used only for acceleration and not for transverse focusing, as it is, for example, the case in RFQ accelerators. Therefore, the acceleration efficiency of a MEQALAC is generally higher than for a RFQ [2].

A schematic set-up of the FOM-MEQALAC experiment is schematically shown in fig. 1. The experiment consists of a bucket-type plasma ion source with a four-grid, four-channel extraction system, a matching section, a Low Energy Beam Transport (LEBT) section with a buncher, and the rf accelerator section. The ion source produces both N^+ and N_2^+ ions, in a ratio of 3:2. The LEBT section serves two purposes. Firstly, it provides space for a vacuum pump in between the high-pressure extraction region and the low-pressure accelerator region. Secondly, the LEBT section provides the necessary drift space for a buncher which matches the extracted dc beams to the longitudinal acceptance of the rf accelerator [3]. The LEBT section consists of arrays of electrostatic quadrupole lenses, which are arranged in a periodic focusing (F0D0) channel [4]. The quadrupole channel radius is 3 mm. The matching section in front of the LEBT section consists of five independently-biased quadrupole lenses [5], it matches the transverse emittance of the extracted rotationally symmetric beams to the transverse acceptance of the periodic focusing structure.

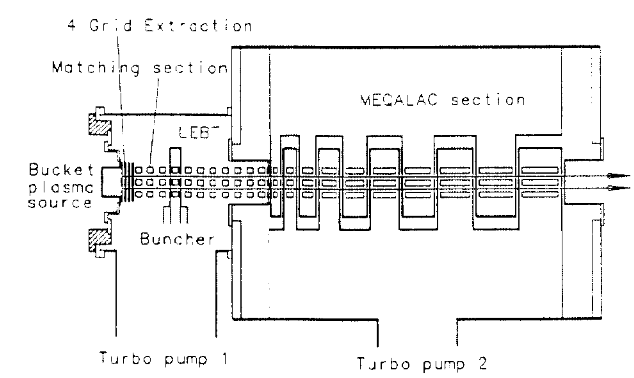

Fig. 1 Set-up of the FOM-MEQALAC experiment.

Acceleration from 40 keV to 1 MeV of the N^+ ion beams takes place in the 32 rf gaps of the accelerator section. The distance between the gaps is such that ions pass this distance in half a rf period and experience an accelerating field in all gaps. A MEQALAC is thus a fixed velocity maschine. The rf gaps are part of a modified interdigital-H-resonator, which is excited in the TE_{111} mode [6,7]. The resonance frequency is 25.4 MHz. The length, width and height of the resonator are 1.7, 0.5 and 1.0 m, respectively, and the length of the acceleration structure is 1.4 m. The rectangular cross-section of the resonator offers the possibility to vary the resonator width. This way, the inductance and thus the resonance frequency can be varied such that the ion energy can be varied. For example, at a resonance frequency of 17.5 MHz N^+ ions are accelerated from 20 keV to 500 keV [7].

Theoretical Background

In a rf accelerator the ion beam current is limited either transversely or longitudinally. The transverse current limit is determined by, amongst others, the space charge forces of the ion beam, the external transverse focusing forces of the electrostatic quadrupole lenses, and the channel acceptance which is a function of the channel dimensions and the quadrupole voltage [8]. A measure for the external transverse focusing forces is the so-called zero-current phase advance per cell, μ_{0T}, which is proportional to the quadrupole voltage. The transverse current limit, I_T, for our MEQALAC is shown in fig. 2. First I_T increases with μ_{0T} because the external focusing forces increase allowing a higher space charge density in the beam, and for $\mu_{0T} > 90^o$ I_T decreases due to the decreasing acceptance.

The longitudinal current limit is a function of, amongst others, the synchronous phase, ϕ_s [8]; the stable region, $\Delta\phi$, in the longitudinal phase space is given as $\Delta\phi \approx |3\phi_s|$. At the phase ϕ_s of the rf field the so-called synchronous particle enters a rf gap. The relation between the gap voltage, U_g, and the synchronous phase is $\delta E = U_g \cos \phi_s$, where δE is the energy gain per gap. In other words, for a large gap voltage and thus for a large rf power coupled into the resonator $|\phi_s|$ is high, which results in a large longitudinal current limit. This is also illustrated in fig. 2, which gives the longitudinal current limit for ϕ_s = -20°, -30° and -42°. This figure shows that for typical operating values, e.g. ϕ_s = -42° and μ_{0T} = 60°, the current is trans-

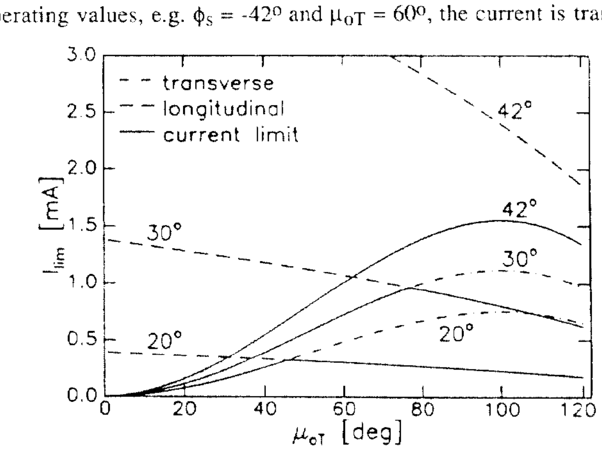

Fig. 2. The transverse, the longitudinal and the resulting total current limit for the MEQALAC 1-MeV N^+ accelerator, according to equations as given by Reiser [8]. For ϕ_s = -42° the current is always transversely limited.

versely limited.

The energy and the energy spread of the accelerated ion beam have been simulated by means of PARMILA multi-particle simulations. In fig. 3 energy spectra are given for various values of the maximum gap voltage. It is seen that for the proper gap voltages the ion energy is indeed 1 MeV and that the energy spread is some 5 %.

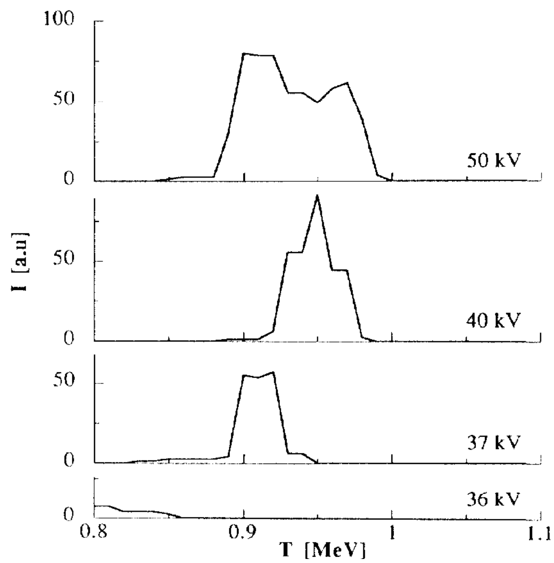

Fig. 3. Energy spectra of the accelerated beam as simulated by means of PARMILA multi-particle simulations for various maximum gap voltages. In these simulations the injected N^+ current is 3 mA and the unnormalized rms emittance of the injected beam is some 20 π mm mrad. The injected beam is not bunched.

Experimental Results

The beam current and the ion energy are measured by a water-cooled Faraday cup, which can handle four 1.5-mA, 1-MeV ion beams, and an electrostatic energy analyzer, respectively, see fig. 4. The energy analyzer can accept an ion beam with an energy width $\Delta E/E$ of 20 %.

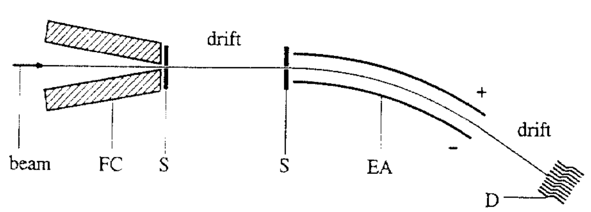

Fig. 4. The diagnostic equipment for the MEQALAC experiment, which consists of a Faraday cup (FC), an electrostatic energy analyzer (EA) with its detector (D). The detector consists of 21 parallel copper plates. The slits (S) limit the beam divergence in order to obtain a sufficiently high energy resolution.

For all given measurements only a single beam channel is used and the beam is not bunched prior to injection into the accelerator. The accelerated beam current is shown in fig. 5, for an injected current of 5 mA, which contains N^+ and N_2^+ ions. The unnormalized rms emittance of the injected beam is some 20 π mm mrad. The current is shown as a function of the quadrupole voltage of the last 16 cells of the MEQALAC section. In the first 15 cells the quadrupole voltage is kept around 4 kV since measurements showed that this voltage gives the highest transmission through the first 15 cells. Results are given for normal polarity, which means that the first quadrupole is focusing in the x-direction, and for inverse polarity, when the first quadrupole is focusing in the y-direction.

In fig. 6 the accelerated current is shown as a function of the rf power coupled into the resonator. This measurement is done for the same injected current as given at fig. 5 and for optimum setting of the MEQALAC quadrupole voltages.

Fig. 7 shows energy spectra of the accelerated beam for various values of the rf power coupled into the resonator. The injected beam current is 5 mA. The figure shows that the energy spread of the beam is less than 8 % and that the ion energy is indeed 1 MeV for a rf power of 24 kW.

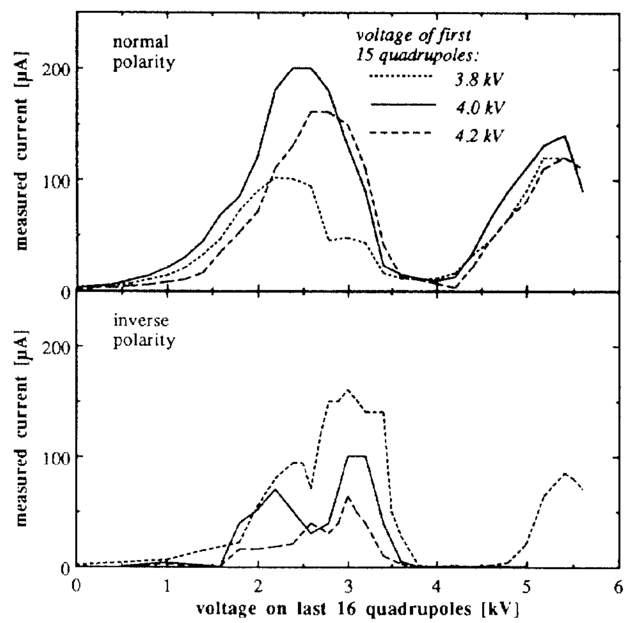

Fig. 5. The measured current of a single accelerated beam as a function of the quadrupole voltage in the last 16 cells of the MEQALAC. The quadrupole voltage in the first 15 cells is indicated. The total injected current (60 % N^+, 40 % N_2^+) is 5 mA and the unnormalized rms emittance of the injected beam is some 20 π mm mrad. The injected beam is not bunched.

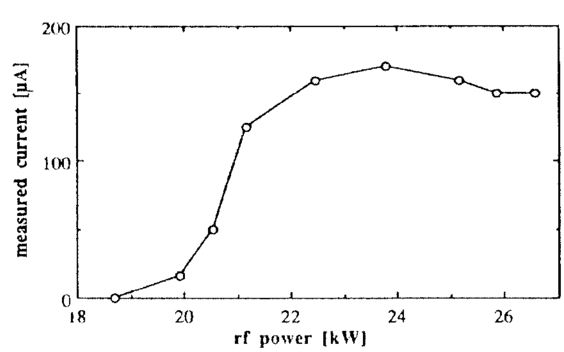

Fig. 6. The measured accelerated current as a function of the rf power coupled into the resonator. The beam properties are as given in fig. 5.

Discussion and Conclusion

We have demonstrated that our MEQALAC accelerates N^+ ions to 1 MeV. The energy spread corresponds well with values predicted by PARMILA simulations, see fig. 3 and fig. 7. With respect to the accelerated current we mention that, so far, the measured current is less than the current as predicted by a theoretical model and by

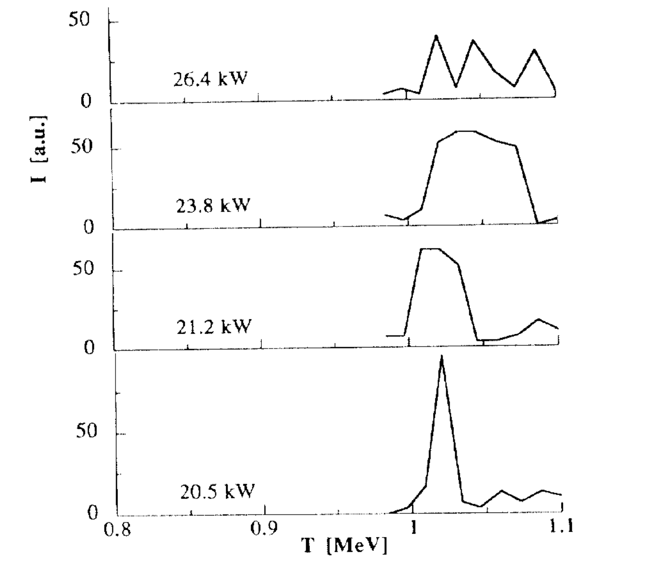

Fig. 7. Measured energy spectra as a function of the rf power coupled into the resonator. The resolution of the detector is 13 keV/channel. The beam properties are as given in fig. 5.

PARMILA simulations, which are performed for a perfectly aligned system. Further, we mention that optimum beam current was reached when the quadrupole voltages are higher (4 kV) in the first half of the accelerator section than in the second half (2.4 kV), which can be explained as follows.

In the MEQALAC both N^+ and N_2^+ ions are injected but only the N^+ ions are accelerated in successive rf gaps. These N_2^+ ions are lost during transport. Furthermore, also the N^+ ions outside the longitudinal acceptance are lost rapidly. Therefore, the space charge density of the beam strongly decreases within a few cells. As a result, the space charge depressed phase advance per cell, μ, changes during transport, which causes mismatch. However, by adjusting the external focusing forces, i.e. the quadrupole voltages, the phase advance per cell can be kept roughly constant.

The dependency of the transmitted current of the misalignment of the quadrupoles has been investigated by a simple simulation model which treats the quadrupole lenses as thin lenses and does not take space charge into account. In fig. 8 the transmission as a function of the quadrupole voltage is shown for an average misalignment, $\sqrt{<x^2>}$, $\sqrt{<y^2>}$, of 0.1 mm and 0.2 mm. Without misalignment the radial transmission is 100 % for quadrupole voltages between 2 kV and 5 kV; for lower voltages the focusing forces are too weak, and for higher voltages overfocusing occurs.

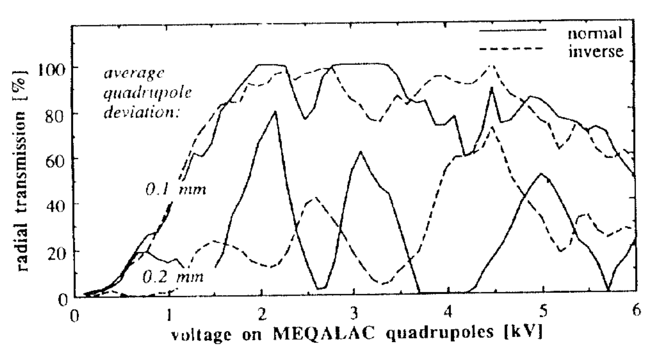

Fig. 8. Simulated transmission taking misalignment into account, as a function of the quadrupole voltage of the MEQALAC. The average misalignment in x and y-direction, $\sqrt{<x^2>}$ and $\sqrt{<y^2>}$, respectively, is indicated. The solid and dotted curves refer to various polarities of the quadrupole lenses, see text.

For a misalignment of 0.1 mm the transmission in the optimum focusing region reaches values between 60 % and 100 %. For a misalignment with twice that value the transmission in the same voltage region is considerably less and changes drastically from 0 % to 80 % for only small differences in quadrupole voltage. The strong dependency of the transmitted current on the polarity indicates that misalignment plays an important role.

Comparison of the simulated beam current and the measured current (see fig. 5) shows that in spite of the limitations of the model the measured beam current as a function of the quadrupole voltages is properly explained as being a result of imperfect alignment. It is therefore reasonable to assume that a higher current can be obtained once the alignment of the system is improved.

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