MEQALAC, A 1 MeV MULTI-CHANNEL RF-ACCELERATOR FOR LIGHT IONS

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Abstract: The MEQALAC (Multiple Electrostatic Quadrupole Array Linear Accelerator) project deals with multi-channel RF acceleration of light ions in a resonator cavity. The ions are accelerated in RF-gaps and the space-charge forces of the intense ion beams are opposed by arrays of electrostatic quadrupoles. An advantage of the MEQALAC over the RFQ is its higher acceleration efficiency. Moreover, in a MEQALAC, the total accelerated current can be increased via an increase of the number of beams. In a proof-of-principle experiment we accelerated four He^+ beams of 2.2 mA per channel from 40 keV to 120 keV. The objective for the present experiment is to accelerate four N^+ beams from 40 keV to 1 MeV. With the same acceleration structure both the ion mass and the exit energy can be varied up to a factor of 2. This accelerator is presently under construction; performance tests on various components are presented.

Introduction

At the FOM-Institute in Amsterdam a MEQALAC for the acceleration of intense ion beams to MeV energies is under construction. In this type of accelerator, originally proposed by Maschke [1], the ions are accelerated in RF-gaps and the radial space-charge forces are opposed by miniaturized electrostatic quadrupoles between these gaps. The special arrangement of the quadrupoles makes it possible to stack many beams within a small area, so that the total accelerated current can be increased via the number of channels. An advantage of this set-up in comparison with an RFQ accelerator is that in a MEQALAC the RF power is used only for the acceleration of the ions, while in an RFQ the RF power is also used for transversal focusing; therefore, the acceleration efficiency of a MEQALAC can be roughly one order of magnitude higher.

The experimental set-up of our experiment is schematically shown in fig. 1. It consists of a bucket-type ion source, equipped with a 40 kV four-grid extraction system, a matching section, a Low Energy Beam Transport (LEBT) section, and an accelerating section. The LEBT section consists of four parallel quadrupole channels. Each periodic focusing channel consist of 29 quadrupoles which form a F0D0 structure. The channel radius is 3 mm and the length of the quadrupoles is 10 mm. A buncher is mounted in the LEBT section; it matches the longitudinal emittance of the transported ion beams to the longitudinal acceptance of the accelerator. So, the LEBT section provides the necessary drift length for the buncher and the space for pumping between the high-pressure ion source region and the low-pressure acceleration region. The matching section consists of five quadrupole singlet lenses, which are independently biased [2], and serves to match the transverse emittance of the extracted rotationally-symmetric ion beams to the acceptance of the periodic channels of the LEBT section. Acceleration takes place in a modified Interdigital-H-resonator, excited in the TE_{111} mode [3]. The accelerating structure has 32 gaps.

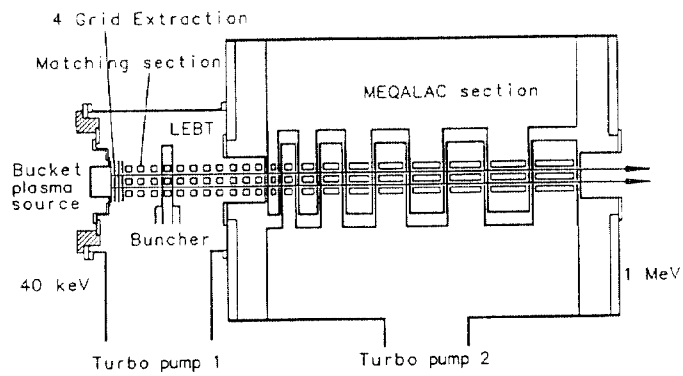

Fig. 1. Set-up of the FOM-MEQALAC experiment.

Our project consists of two stages. In a proof-of-principle experiment a resonator with a cylindrical cavity, operated at 40 MHz, is used. The cavity has a length of 0.7 m and a diameter of 0.4 m, the accelerating structure contains 20 RF-gaps. At a constant synchronous phase of -40°, a maximum He^+ current of 2.2 mA per channel was accelerated from 40 keV to 120 keV through four parallel channels [4].

A follow-up experiment is planned to reach higher exit energies with heavier particles. In view of possible applications the use of different ion species and acceleration to different exit energies is desired. In principle, this can be done while maintaining the same accelerating structure. The distance from one RF gap to the adjacent gap is given by $\beta\lambda/2$, where β is the design velocity (normalized to the speed of light) and λ is the corresponding wave length of the resonance frequency f_0. Thus, for a velocity-matched acceleration of the ions f_0 must be adapted. This frequency is dependent on the inductance which itself depends on the free volume of the cavity and the accelerating structure. This way, f_0 is adaptable via the width of the cavity. Therefore, the resonator cavity has a rectangular cross section and exchangeable side plates [5].

As a first step the acceleration of N^+ ions from 40 keV to 1 MeV is planned through four channels at a resonance frequency of 25 MHz. The width and the height of the resonator are 0.5 m and 1.0 m, respectively, its length is 1.7 m and the length of the accelerating structure is 1.4 m. By the choice of this small resonator width the frequency is tuneable over a wide range, for instance a reduction of f_0 by a factor of $\sqrt{2}$ is easily obtained. At 17.7 MHz, N^+ ions can be accelerated from 20 keV to 0.5 MeV. Therefore the extraction of nitrogen ions has been measured for an extraction voltage of both 20 kV and 40 kV. The new accelerator is presently under construction; design tests on various components have been done.

Extraction and transport of nitrogen ions

The nitrogen ions are produced in a bucket-type plasma source with a diameter of 14 cm and a depth of 11 cm. Rows of CoSm magnets form a line-cusp magnetic field at the source walls. This field reflects the electrons emitted by the filaments which ionize the neutral gas; the average lifetime of the electrons is drastically increased. In the front plate no magnets are mounted; this electrode is at a slightly negative potential with respect to the source to reflect the electrons. The four-grid extraction system consists of two earth electrodes with a negative electron repelling plate in between and an intermediate electrode mounted in between the source front-plate and the earth electrode. The extracted ion current and the beam emittance can be influenced strongly via the voltage at this intermediate electrode. For both 5.1 mA-40 keV as well as 1.8 mA-20 keV nitrogen ion beams a minimum unnormalized rms-emittance of about 20π mm mrad can be obtained, which is sufficiently small to match and transport the beams without severe losses in the LEBT section.

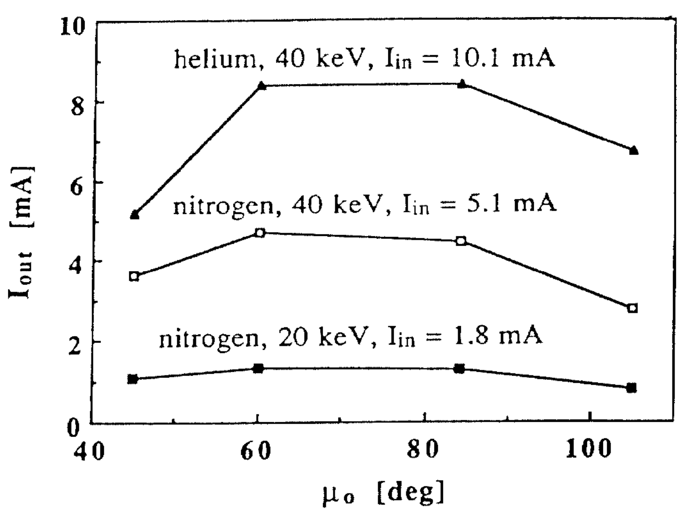

Fig. 2. The ion current transported through the LEBT section as a function of the zero current phase advance per cell (μ_o).

The beam current and its emittance have also been measured behind the matching and LEBT section. Behind the matching section no current losses are observed; fig. 2 shows the current transported through the LEBT section for injected 1.8 mA-20 keV and 5.1 mA-40 keV nitrogen ion beams and a 10.1 mA-40 keV helium ion beam. The transported currents are slightly less than the theoretically maximum transportable current. The optimum transmission is always about 90% at a zero current phase advance per cell (μ_o) of 60°-84°. At smaller values of μ_o the beam losses are more severe because of the larger beam envelope; at $\mu_o > 90°$ the beam is unstable and the losses increase. The measurements show that the emittance growth, measured behind the matching section is typically 60%, independent on μ_o. This emittance growth is a result of space charge effects; the gaussian current distribution changes to a KV-distribution [6]. During transport through the LEBT section the beam emittance slightly decreases due to current losses.

The ion source is fed with nitrogen gas, and produces N^+ as well as N_2^+ ions, which are both transported through the LEBT section. Only one kind of ions will be accelerated because MEQALAC is, like any RF accelerator, a fixed velocity machine. Therefore, the fraction of the N^+ current has been measured for various source parameters. The extracted N^+ and N_2^+ beams are separated by a small magnet system. The fraction of the two currents has been measured by a thin wire (at a potential of 40 V to suppress secondary electrons) swept through the separated beamlets. The fraction of the N^+ current is typically 60% of the total current, independent on the source parameters like gas pressure and arc voltage and current. Behind the LEBT section the same percentage is measured; all the forces acting on the particles are radially-directed electrostatic forces and thus the N^+ and the N_2^+ particles are transported in identical ways.

Resonator and acceleration structure

Our initial idea was to give the voltage in the first RF-gaps of the 1 MeV MEQALAC the same value as in the rest of the structure to minimize the overall length of the accelerating structure. However, simulations with the multi-particle code PARMILA have shown that this gives rise to severe particle losses, which are due to three effects: (1) the strong compression of the bunch in the longitudinal direction causes a space-charge induced beam blow-up in the transverse direction, (2) the transverse component of the RF field at the entrance and the exit side of an RF gap form a strong defocusing lens and (3) the large energy spread in the bunch causes an increase of mismatch. A solution for these problems is to reduce the gap voltage at the entrance of the cavity. This way, the particle energy is significantly above the injection energy once the 'full' gap voltage, which is 48 kV, is encountered.

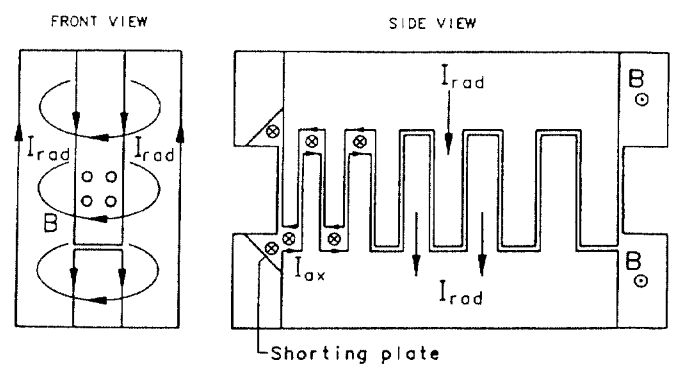

Fig. 3. Accelerating structure. The magnetic field lines surround the accelerating structure, leading to radial currents. Shorting plates force the field lines through the free area, leading to additional axial currents.

RF measurements on a scale model [5] indicate that such a voltage ramp can be obtained at reasonable loss power by mounting shorting plates at the entrance of the accelerator, while providing for additional free space in the accelerating structure, see fig. 3. With a set of dummy blocks in the full scale resonator three iteration steps to the final design of the acceleration structure are investigated. The voltage distributions along the RF-gaps are obtained by perturbation measurements, see fig. 4.

The capacitance at the entrance side of the accelerating structure is relatively high due to the small distance between two adjacent gaps. As a result, the resonator without shorting plates (a) has a high voltage at the entrance and a low one at the exit, instead of the other way around as desired. Shorting plates between the entrance plate and the supports of the accelerating structure reduce the free area at the entrance of the resonator from 100% to 5%, so the anticipated voltage ramp is obtained (b). The resonance frequency f_0 is still below the anticipated 25 MHz, so that in a second modification (c) f_0 is adapted via a reduction of the size of the first blocks. The final design is slightly modified; the number of RF-gaps is increased from 30 to 32. The gap voltage increases from 9 kV in the first gap to 48 kV in gap 28, while the electric field strength is the same for all gaps via an increase of the gap widths (12.5 MV/m = 1 Kilpatrick) .

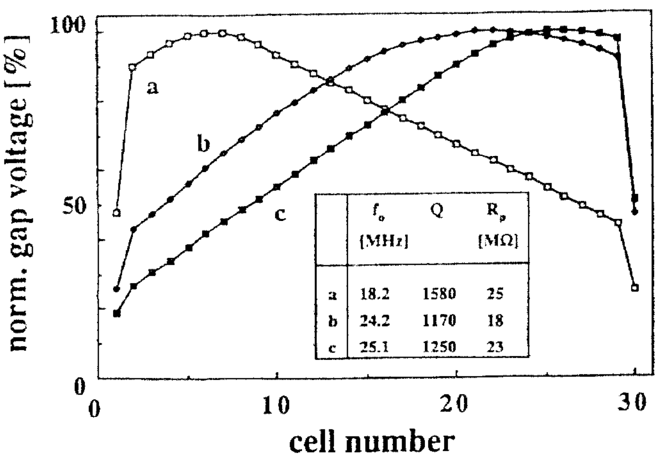

Fig. 4. The measured voltage distribution, normalized to the maximum gap voltage, along the RF-gaps for different structures: (a) conventional set-up, (b) with shorting plates and (c) tuned to the final resonance frequency by a reduction of the gap capacitance at the entrance.

The perturbation measurements predict a maximum loss power of 60 kW. This RF power and the additional heating by beam losses must be safely handled by the cooling system. An estimation of the local power dissipation shows that roughly half of the power (27 kW) is dissipated in the accelerating structure. There are three currents of interest, see fig. 3 : (1) the radial current (due to the axial magnetic field), (2) the axial current (caused by the shorting plates forcing the magnetic field through the accelerating structure) and (3) the beam current (due to particle losses). An estimated distribution of the total power dissipation along the accelerating structure is given in fig. 5. It is seen that the additional heating by radially lost particles P_{beam} is only of minor influence. The sum of P_{rad}, P_{ax} and P_{beam} amounts to the already mentioned 27 kW. In the first cells a maximum power loss of 2 kW per cell is expected.

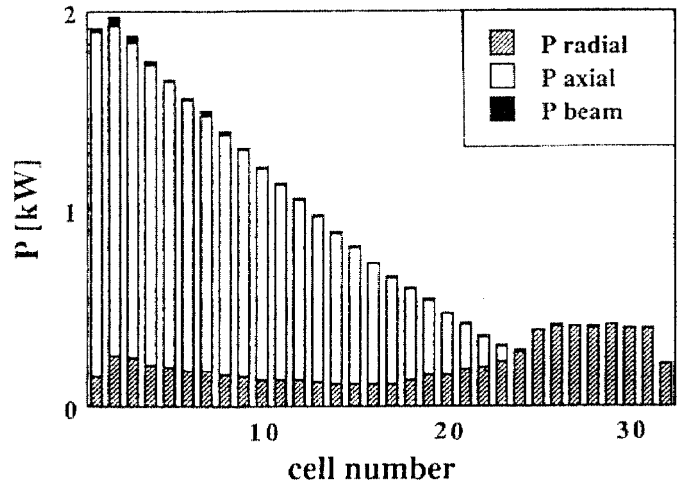

Fig. 5. The estimated distribution of the power dissipation P along the axis in the accelerating structure of the final design of the resonator cavity.

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