LOW-β ION ACCELERATION WITH A MEQALAC

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In a Multiple Electrostatic Quadrupole Array Linear ACcelerator (MEQALAC) a number of parallel beams is accelerated simultaneously. This device is useful for exit energies up to 1 MeV per nucleon. Radial stability is provided by electrostatic quadrupole lenses placed between successive acceleration gaps. The proof-of-principle MEQALAC presently available at FOM features four He$^+$ ion beams which are accelerated to an energy of 120 keV. The resonator cavity has a modified Interdigital-H-structure and contains 20 acceleration gaps. Its resonance frequency is 40 MHz. We present transmission measurements on injected beams with currents ranging from 1 to 15 mA. The transverse phase advance per cell of the quadrupole channels is varied between 43° and 114°. A maximum current of 2.2 mA per channel has been accelerated. A design for a MEQALAC which will be used for acceleration of N$^+$ ions to 1 MeV is presented. This accelerator will be operated at various frequencies to allow for a variation of the exit energy.

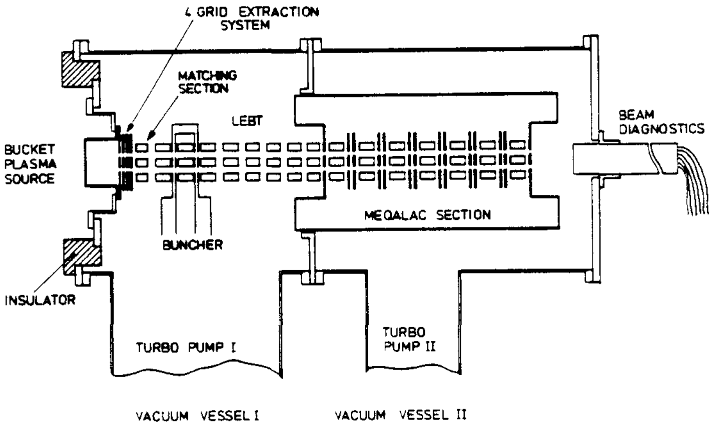

Fig. 1. Set-up of the MEQALAC experiment.

Introduction

Intense ion beams with a current in the mA range and a MeV energy are of growing importance for many fields of physics. Among those are diagnostics of fusion plasmas and surface treatment of metals. Furthermore, there are applications in the fabrication of semiconductor devices. The motivation to produce this type of beams with a RF accelerating field, instead of with a DC field, is obvious: a MeV energy is realized without the presence of a MV voltage. In many laboratories Cockcroft-Walton injectors are being replaced by RFQ's for this reason.

At the FOM-Institute a new type of RF-accelerator is studied, namely the Multiple Electrostatic Quadrupole Array Linear ACcelerator (MEQALAC). This device was invented by Maschke[1]. It features the simultaneous acceleration of a (large) number of ion beams. They are focused with electrostatic quads, and accelerated in a sequence of RF-gaps. This way the power which is needed to build up the RF field can be made an order of magnitude smaller than in a RFQ, in which device both acceleration and focusing are done with the RF field. The total accelerated current in a MEQALAC is increased via an increase of the number of channels. The output energy is limited to a value smaller than 1 MeV per nucleon due to the use of electrostatic quads.

Experimental set-up

A schematic of our present proof-of-principle experiment is shown in Fig. 1. This device has been used to accelerate four He$^+$ ion beams from 40 to 120 keV. It consists of a bucket-type ion source, a conventional 40 kV extraction system, a Low Energy Beam Transport (LEBT) section and the MEQALAC section. The latter is a modified Interdigital-H-resonator of the $\beta\lambda/2$-type, which contains 20 RF gaps. It is excited in the TE$_{111}$ mode. Its resonance frequency, parallel resistance and quality factor are $f_0 = 40$ MHz, $R_p = 16$ MΩ and $Q = 1800$, respectively. The resonator is designed to be operated at a synchronous phase ϕ_s of -38°. Electrostatic quadrupole lenses are placed in the field-free drift regions between the gaps. They are arranged in a FODO structure. The cavity length is 65 cm. The diameter is 40 cm. The channel diameter is 6 mm.

The LEBT section provides space for pumping and a drift length for the buncher. The latter device is used to match the longitudinal emittance of the ion beams to the acceptance of the accelerator cavity. It contains two gaps and has an R_p of 70 kΩ and a Q of 330. The four channels, which each contain 34 singlet quad lenses, have a similar FODO structure as in the MEQALAC section. The quad length is 10 mm. The length in between successive quads is 7.5 mm. All lenses carry the same (absolute) potential except for the first five. These are biased independently and serve to match the transverse emittance of the extracted beams to the acceptance of the channel.

In the following, we present measurements on ion transport and acceleration through the LEBT and the MEQALAC section, respectively. For a more detailed description of the experimental set-up we refer to Granneman et al.[2]

Transport through the LEBT section

We first discuss transport measurements on the LEBT section. The buncher is not excited. These measurements offer the possibility to study the transverse limits to charged-particle transport (i.e. the current limits related to the magnitude of the transverse focusing fields) in isolated form. In the MEQALAC section also longitudinal limits play a role.

The current measured at the exit of a single channel of the LEBT section is shown in Fig. 2 as a function of the zero-current phase advance per cell μ_0. The corresponding quad voltage varies from 1.75 to 4 kV. The current which is injected into the matching section is varied from 7 to 16 mA.

It is seen that the output current rises with increasing μ_0 for $\mu_0 < 90°$. This is consistent with calculations employing Reisers "smooth approximation"[3]. How-

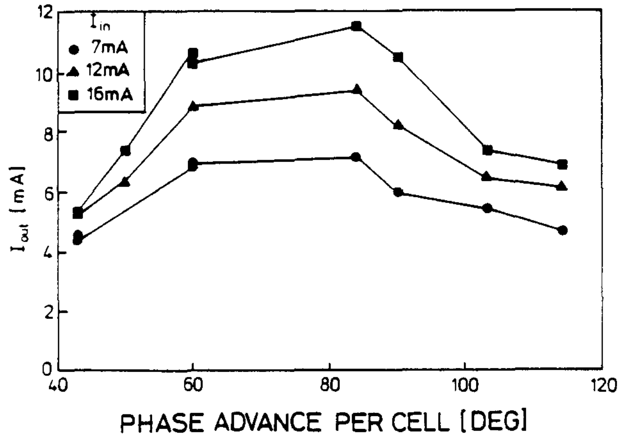

Fig. 2. The current measured at the exit of a single channel of the LEBT section, as a function of the zero-current phase advance per cell μ_0.

ever, the measured current is a factor of 2-3 smaller than the Reiser limit, as calculated for a filling factor of 70% of the channel cross-section. Furthermore, the output current decreases with increasing μ_0 for $\mu_0 > 90°$. This probably is related to the occurance of (parametric) instabilities[4]. The current has its maximum value for $60° < \mu_0 < 90°$. This maximum is higher at a higher value of the injected current. Note, that the particles losses also increase, so that the transmission decreases. A transmission of 100% has been obtained for injected currents smaller than 7 mA, and a μ_0 in the mentioned range. The smallest injected current that we have investigated amounts to 0.8 mA.

We have also measured the RMS-emittance at the exit of the LEBT section, and compared it to the initial value. A typical increase of a factor of two is observed. There is no correlation with the injected current or with μ_0.

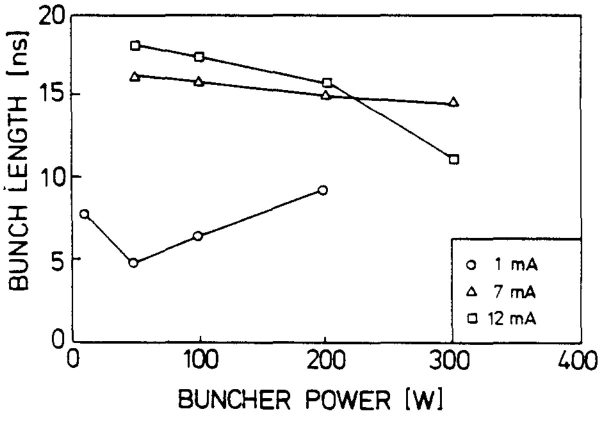

Fig. 3. The FWHM bunch length measured at the exit of a single channel of the LEBT section, as a function of the buncher power.

Next, we discuss measurements on bunched beams. In Fig. 3 the bunch length at the exit of the LEBT section is shown as a function of the buncher power, for an injected current of 1-12 mA per channel. It is measured with a 50-Ω Faraday cup. The buncher is excited at 40 MHz, so that the "bunch length" of a continuous beam is 25 ns. The transverse phase advance per cell μ_0 is 60°.

It is clear from Fig. 3, that the formation of a sharp longitudinal focus is more difficult with increasing space charge. At a current higher than 7 mA the beam is hardly compressed in our range of buncher powers. In contrast to this, a compression of a factor of 5 can be obtained for an injected current of 1 mA. The required buncher power is 50 W, which result is consistent with an elementary calculation on the bunching of ion beams with negligible space charge.

For injected currents upto 12 mA per channel, we have investigated if the transmission is altered when the buncher is excited. Only a very small decrease is observed.

Acceleration with the MEQALAC system

Results on acceleration with the MEQALAC section are presented in Fig. 4. Shown is the current measured at the exit of a single channel of the accelerator cavity, as a function of the RF-power coupled into it. The synchronous phase varies with varying RF power. The injected current is 0.84 mA. The transverse phase advance per cell μ_0 is 84° for all measurements presented in this section. According to the results of Fig. 2 this is in the range where the transverse limits to charged-particle transport are weakest.

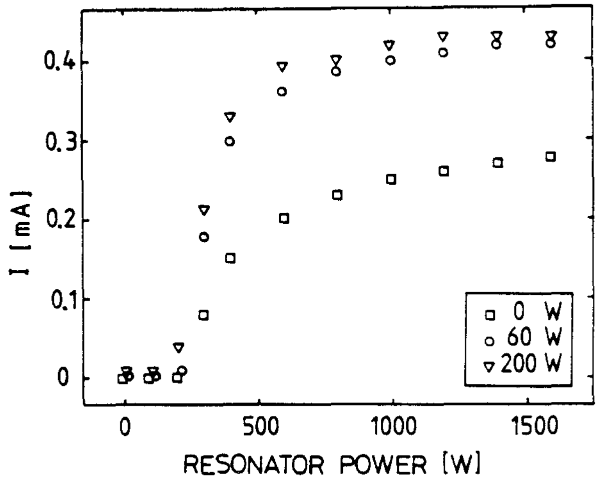

Fig. 4. The current measured at the exit of a single channel of the MEQALAC cavity, as a function of the RF-power coupled into it. The injected current is 0.8 mA. The buncher power is varied from 0 to 200 W.

It is seen in Fig. 4 that the accelerated current increases with 50% when the buncher is excited with 60 W; a higher buncher power does not lead to a further increase. This is in sharp contrast with the measurements in Fig. 5, where the results for an injected current of 6.4 mA per channel are shown. In this case the buncher hardly has any influence. This behaviour is consistent with the measurements in Fig. 3, which have shown the limits to longitudinal focusing. Thus, it is worthwhile to increase the longitudinal acceptance of the accelerator. This will be done in a follow-up experiment.

It is deduced from Figs. 4 and 5 that also in the MEQALAC section a higher accelerated current is obtained at a higher injected current, at the expense of a smaller transmission. The maximum current which we have accelerated is 2.2 mA per channel. The current accelerated through four parallel channels is within 20% equal to four times the values in Figs. 4 and 5. This 20% discrepancy is attributed to mechanical misaligmment.

We next discuss measurements on the energy distribution of the accelerated particles. These measurements

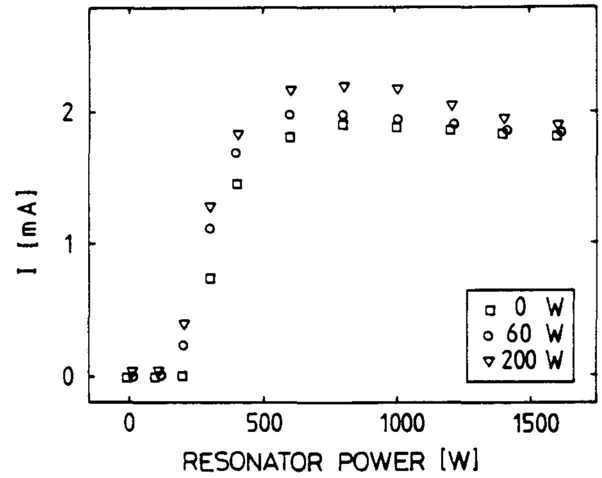

Fig. 5. Accelerated current for an injected current of 6.4 mA per channel. See Fig. 4.

are done with a magnetic analyzer. The distribution for an injected current of 3.6 mA per channel is shown in Fig. 6, for two values of the resonator power. The buncher is not excited. The central peak is seen to shift to the low energy side with an amount of 10 keV when the resonator power is increased from 400 to 600 W.

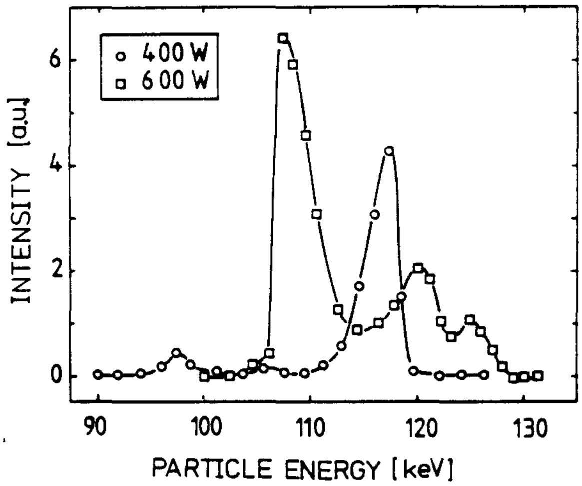

Fig. 6. Energy distribution of the accelerated particles, for a resonator power of 400 and 600 W.

A distribution with a single peak at 120 keV is measured at a power of 400 W. The width of this peak is of the order of 5 keV, which is slightly higher than the gap voltage. The interpretation of the energy spectra is still under debate, so that we will not give a further discussion.

Future plans

In the next stage of our experiment we shall build a new MEQALAC, with which four N^+ ion beams are accelerated from 40 keV to 1 MeV. The total current is 5-10 mA. The same device can be used to accelerate Li^+ ions to 500 keV. In this section we briefly discuss its essential features.

The present experiment clearly shows the limits to bunching of low energy ion beams. These limits will be less severe at a higher particle energy. Therefore, in the next stage the "gentle bunching" mechanism will be employed; the synchronous phase ϕ_s then smoothly increases from the first towards the last accelerator gap. This is achieved via a proper choice of the drift lengths in between the gaps. With this approach, bunch formation is completed at an energy which is significantly above the injection energy of 40 keV. Thus, space-charge related limitations are weaker. An additional advantage is that a separate buncher is superfluous. We remark that the longitutinal acceptance can have the same value in all gaps. This is due to the fact that at a higher particle energy, a given acceptance is obtained at a higher ϕ_s. The acceptance increases with increasing energy in the present experiment, in which ϕ_s amounts to -38° in all gaps.

We shall investigate the possibility to vary the exit energy of the ion beams. A change of the resonance frequency is required for this. This will be achieved via a change of the resonator width, which is equivalent to a change of its inductance. Our resonator shall have a rectangular cross section for this purpose. The width is changed by mounting different side plates. Measurements on a scale model have shown, that a frequency decrease of the order of a factor of $\sqrt{2}$ is feasible. The width is enlarged with a factor of 2 to achieve this. The corresponding reduction of the exit energy is 50%.

Finally, the characteristic parameters of the new resonator are given: resonance frequency 25 MHz, resonator length 170 cm, width 50 cm, height 100 cm, RF loss power 35 kW, number of gaps 25, gap voltage 50 kV.

Acknowledgements

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