Transport of Ions in a RFQ Accelerator*

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Abstract

Up to now transport experiments have been performed in RFQ structures with unmodulated electrodes for the study of beam optics and space charge effects, e. g. [1]. Beam dynamic calculations show, that the transport of ions is also possible in RFQ accelerators with modulated electrodes without major lossses of beam quality as long as the ion velocity is outside of the longitudinal acceptance given by the velocity profile of the structure. Results from calculations and first measurements will be presented and discussed. One possible application is the variation of end energy in a RFQ accelerator, which is build up modular.

1. Introduction

As part of the upgrading program for the cluster facility at the Institute de Physique Nucleaire of the university of Lyon [2,3] an Radio Frequency Quadrupole (RFQ) accelerator has been designed and built for the post acceleration of clusters. The clusters are produced by a cryogenic cluster source and accelerated by a Cockroft - Walton machine with a maximum voltage of 500 kV. The RFQ has been designed to accelerate clusters up to mass 50 from input energies between 5 and 10 keV/u to an output energy, which is ten times higher [4,5]. For very light clusters the output energy out of the Cockroft - Walton is already higher than the design energy of the RFQ, very heavy clusters are to slow for being accepted by the RFQ. Therefore the question arose, whether the RFQ could be used as a transport element to the experimental area with high transmission and good beam quality. In addition there is an energy interval where both acceleration and transport are possible. Calculations with a slightly modified version of the PARMTEQ program have been carried out [6], in addition a small experiment has been performed in our lab with an existing RFQ [7] for comparison to the computational results.

2. Parameters of the Lyon RFQ

Normally RFQ structures like other rf accelerators have a fixed velocity profile and corresponding fixed input and output energies per nucleon for the accelerated ions. The main feature of this RFQ is the possibility of energy variation by changing the operation frequency [8]. The rf structure is of the 4 - rod - type, which allows a large tuning range by moving shorts in between the stems, such changing the length of the driving conducters [9]. With a design frequency range from 80 to 110 MHz the matched ion velocity can be varied by a factor of about 1.4, the energy by a factor of 2. For the highest frequency the design mass was chosen to 30 at a design electrode voltage of 80 kV, for fixed frequency the electrode voltage scale with mass wheras for fixed mass the electrode voltage and energy scale with f^2 The lowest and highest input or output energy are 5 and 10 keV/u or 50 and 100 keV/u resp.. The energy gain is as high as a factor of 10 at a length shorter than 2 m. To achieve this high gain the RFQ shaper and partly the buncher were omitted and the transverse focusing forces are rather low. Particle dynamics calculations for cluster acceleration [10] showed transmissions between 25 and 80% and small transverse emittance growth.

3. Transport of Clusters

Due to the high energy gain demanded the RFQ starts with modulated electrodes and synchronous phase of 50°. No radial matching in our section could be supplied, therefore for a bunched beam the RFQ acts transversely like a chain of quadrupole doublets with different shape and orientation of acceptance ellipses with a moderate time dependence over the bunch length. The injected dc cluster beam is round with constant emittance, which causes a certain degree of transverse mismatch. Fig. 1 shows a plot of transverse and longitudinal beam behavior of transported clusters with mass 3 and kinetic energy of 150 keV/u, f = 80 MHz.

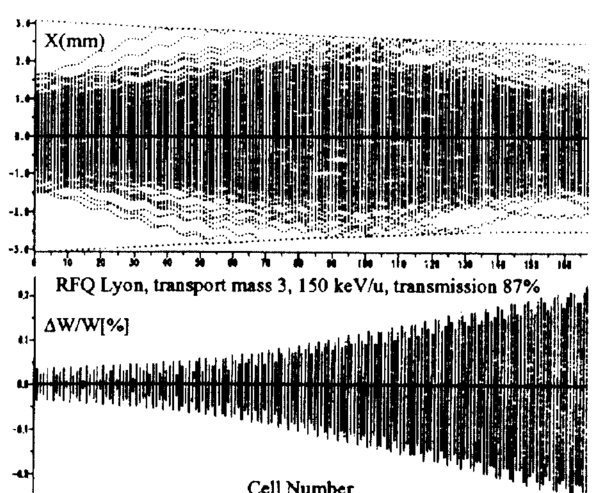

Fig. 1: Example of transverse particle motion and development of energy spread during transport

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The electrode voltage of 3 kV was chosen for minimum output emittance. Only a small energy spread of ± 0.2% is introduced to the beam, at a transmission of ≥ 80% the total transverse emittance growth is < 5%. Higher transmissions are achieved for higher electrode voltages which are causing also a proportionally higher energy spread. In fig. 2 transverse and longitudinal beam behavior can be compared for acceleration or transport of mass 7 with an final energy of 65 keV/u.

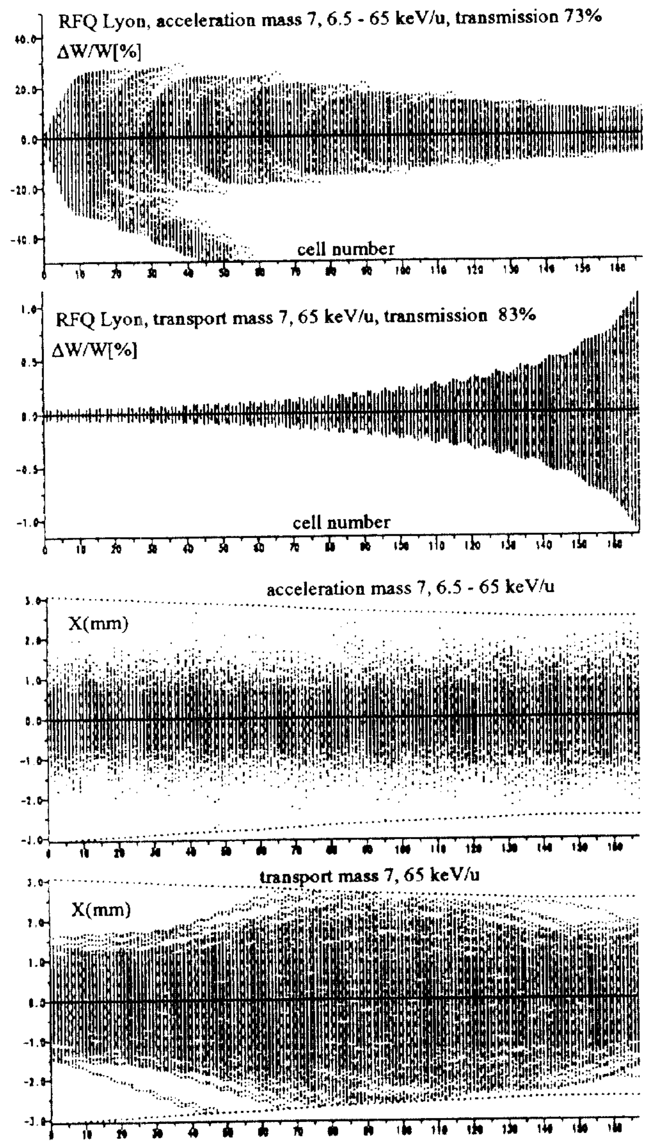

Fig 2: Beam behavior for acceleration and transport

While for acceleration at 91.2 MHz an electrode voltage of 33 kV is needed, transport is done with 3.5 kV at 80 MHz. Therefore concerning energy spread, transmission and emittance growth transport is clearly more favourable, on the other hand the accelerated beam is bunched, which allows to set time windows e.g.. Fig. 3 shows calculated longitudinal output emittances and relative energy spectra for both cases. Computations for the transport of heavy clusters below the input energy gave similar results, which have been checked in a small transport experiment. All calculations were done for an injected dc beam without energy spread, transverse waterbag distribution and constant normalized emittance.

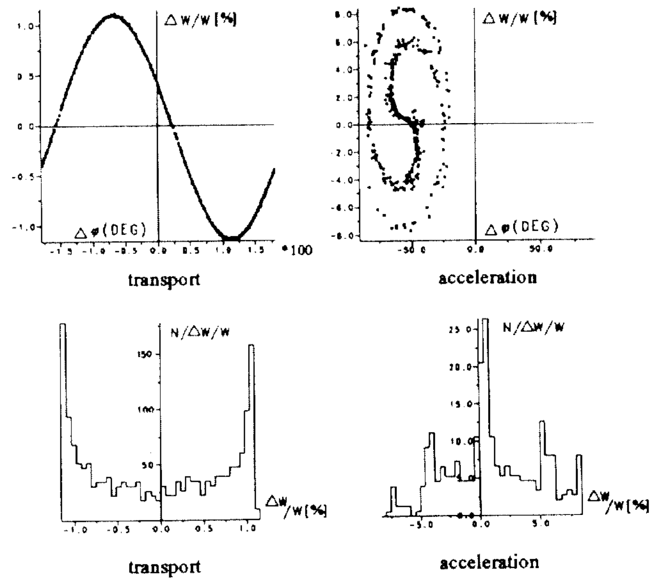

Fig 3: Longitudinal output emittances (upper part) and corresponding relativ energy spectra

4. Transport Experiment

Measurements have been carried out on transport and acceleration [11] with an experimental setup, consisting of ion source, magnetic lens, 50 MHz Split-Coaxial-Four-Rod RFQ, Faraday-Cup, emittance measurement device and 90° bending magnet for mass/energy separation.

At the design electrode voltage of 9 kV protons are accelerated from 6.5 up to 50 keV. For transport the input energy was reduced to 5.5 keV. Fig. 4 shows the transmitted current as a function of the electrode voltage.

Fig 4: Beam current versus electrode voltage

Due to the short length (12 $\beta\lambda$ = 50cm) 100 μA get through the RFQ at U = 0. Raising up the electrode voltage the transported current increases to a first maximum at 4 kV, now some ions already are accelerated, the second maximum at 11 kV contains 50% of ions with an energy of 50 keV.

Measured energy distributions for variation of electrode voltage in steps of 1 kV are shown in Fig. 5a - d.

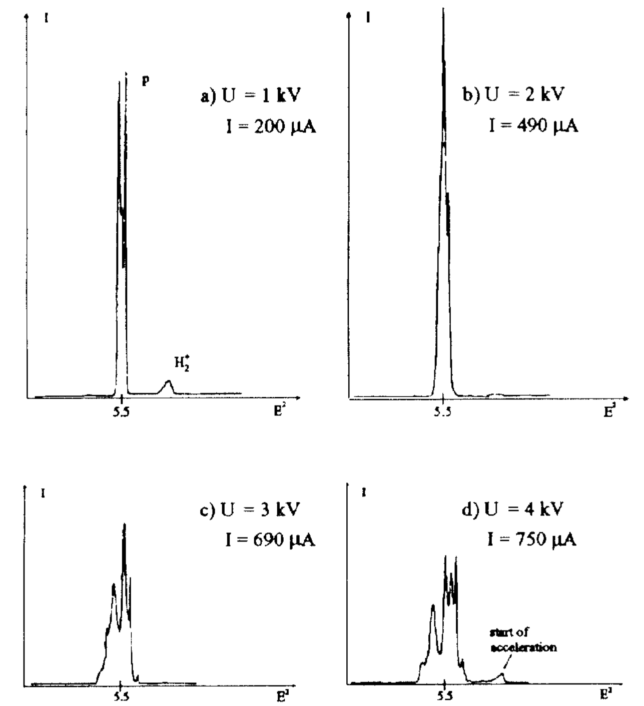

Fig.5: Measured energy spectra for transport of p at 5.5 keV

The energy spread increases with total electrode voltage, in fig. 5b the beam was measured to be 5.5 ±1.0 keV. As can be seen in fig. 5d, a small fraction of the beam was accelerated. Therefore transport of 5.5 keV protons is limited to voltages less than 4 kV, due to the matching-out section of the RFQ the transverse emittance-growth is less than ± 10%.

5 .SPLITTET RFQ WITH DIFFERENT OUTPUT ENERGIES

Calculations were performed with a data set at hand [12] for a maximum mass over charge state ratio of 9, f = 108.48 MHz, input/output energy of 2.5/300 keV/u, length about 3m. The data set was splittet at 200 keV/u into two sets for 2 RFQ's of length 2.1 and 0.9 m resp., with a drift space of 5 cm in between. Calculations of particle dynamics show three possibilities: By proper phasing of the bunch coming from the first RFQ with respect to the synchronous phase of the second RFQ, in addition to acceleration, as indicated in fig. 6, the particles can be transported or slightly decelerated.

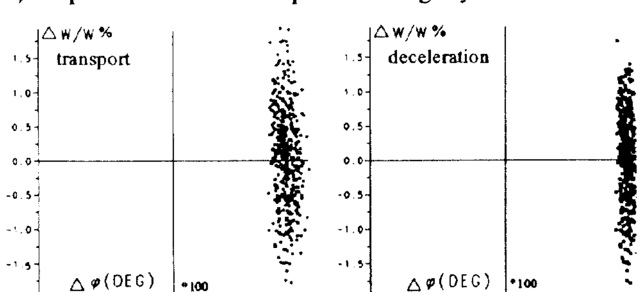

Fig 6: Input phase into RFQ2 for transport and deceleration

The corresponding output energies from RFQ2 are then 185, 200 or 300 keV/u. The transmission in all cases is more than 90%, the transverse emittance growth due to some mismatch from the coupling is less than 50%. Fig. 7 shows the calculated beam sizes at the end of the second RFQ. The technical feasibility of such device has been already demonstrated in an experiment some time ago [13].

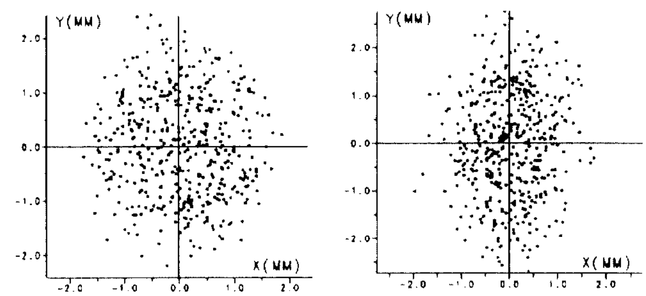

Fig 7: Calculated beam size for transport (left) and deceleration at the output of second RFQ part

6. CONCLUSION

Beam dynamic calculations show, that the transport of ions in a RFQ accelerator is possible. In first experiments the results of calculations could be verified with good accuracy. Possible applications are the use as transport element in beam lines besides its main purpose as accelerator. An RFQ which is build up modular can provide different output energies with a rather large gap in between. Total transmission and beam quality will not fall short in such a device.

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