Transport of Ions in RFQ - Accelerators*

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Abstract

Radio Frequency Quadrupole (RFQ) structures [1,2] are well suited to accelerate all kinds of ions at low particle energies with high transmission efficiency even at high beam currents. Like other rf-accelerators they normally have a fixed velocity profile and corresponding fixed input and output energies per nucleon of the accelerated ions. But - due to the strong transverse focusing - the RFQ-accelerators can also capture and transport very efficiently ions with energies and specific charge states even far away from the design values [3]. Results of calculations will be presented and compared to measurements.

I. INTRODUCTION

RFQs serve today in manifold functions as pre- and postaccelerators, injectors, implanters for light and heavy ions, for low and high currents with small duty cycles up to dc operation [4]. Also RFQs with unmodulated electrodes have been built for beam transport experiments [5] to investigate current limits and instabilities. Here the beam behaviour of transported beams will be described in RFQs, which were designed and built for the acceleration of ions. The RFQ design has to be made for the lowest charge to mass ratio of the ions to be accelerated, input and output specific energy or velocity resp. are fixed and the cell length of the RFQ must fulfill the Wideroe resonance condition $l = v_p/2f = \beta_p\lambda_0/2$. Energy variable RFQs [6] can be built, when the frequency varies with the particle velocity $v_p \sim f$. The electrode modulation will be adjusted for simultaneous transverse focusing and longitudinal bunching and acceleration along the RFQ. The applied electrode voltage depends on the specific charge and is chosen in such way, that $\zeta/AU\cos\varphi_s$ is matched to the designed v_p of the RFQ cell considered. Small deviations U will be automatically corrected by the ions slipping to another rf phase φ_s. Ions with input energies much higher or smaller than the design value cannot fulfill the Wideroe condition and get out of the acceleration process, the same happens for too small electrode voltages. The beam behavior for these cases has been studied and some possible applications are discussed.

II. TRANSPORT EXPERIMENTS

Transport experiments have been carried out with a small proton RFQ [7]. The experimental setup is shown schematically in fig. 1. The proton beam is extracted by an accel-decel-system from a plasma beam ion source, which deliveres a high fraction (80%) of protons. The focusing of the beam into the RFQ is done by a solenoid. The RFQ which is of the split coaxial type [8] consists of 32 cells only and bunches and accelerates protons from 6.5 to 50 keV at an design electrode voltage U_{des}= 9 kV. The shaper is omitted for a shorter length, which causes longitudinal losses. The RFQ operates at 50 MHz, the total length is 58 cm.

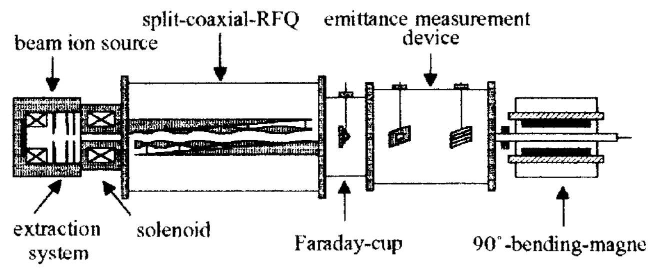

Fig. 1. Schematic drawing of the experimental setup

For the beam diagnosis behind the RFQ a Faraday cup, a bending magnet and an emittance measurement device could be used. First the operation at design values has been checked. Fig. 2 shows the measured transmission curve as function of electrode voltage for the design input energy of 6.5 keV.

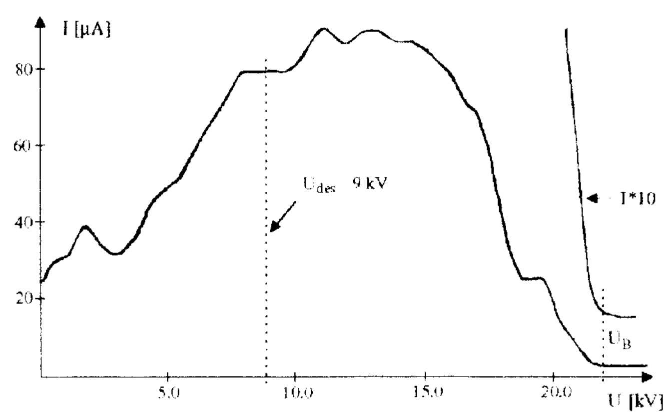

Fig. 2. Measured transmission vs. electrode voltage for design input energy, T_{in}= 6.5 keV

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As can be seen from the plot some fraction of the beam is transmitted already, when no electrode voltage is applied, due to the short total length. With increasing voltage the transmitted beam rises already before acceleration starts (U_{des}=9 kV), the protons being transported through the RFQ. At high voltages the beam motion gets transversally instable and the transmission is breaking down at U_B. The same behaviour can be observed in fig. 3, where the measured transmission is plotted as function of the electrode voltage for proton beams with input energies far lower than the design value of 6.5 keV.

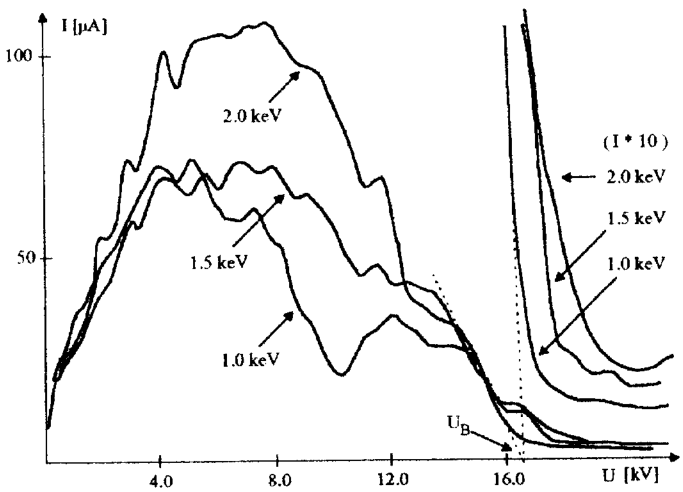

Fig. 3 Transmission vs. electrode voltage for three beam input energies: 1.0, 1.5 and 2.0 keV

Again the transmission first rises and drops at high voltages, but now the break-down voltage U_B is only 16.4 kV instead of 21.7 kV as before. This lower voltage can be explained by the change in the transverse rf defocusing, when the beam is transported instead of being accelerated. Fig. 4 gives a plot of the measured energy spectra for three different electrode voltages and T_{in} = 1.5 keV. At the low voltage of 5.4 kV only some energy spread had been introduced into the beam, at the high voltages a partial acceleration to 10 keV (T_{des}=50 keV) took place.

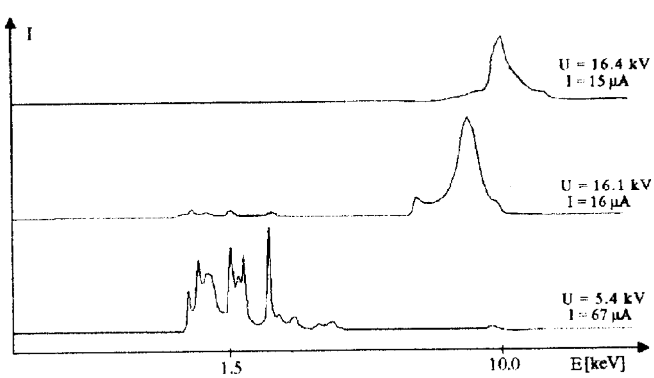

Fig. 4 Energy spectra for different electrode voltages and T_{in} = 1.5 keV

At the point of breakdown of the transmission the transverse phase advance is 180°, to which a certain focusing gradient belongs. If the radius is known precisely, from this value the electrode voltage can be determined. This could be an additional method for checking the shunt impedance and efficiency of a RFQ [9]. As a final example the measured energy spectra for the transport of protons as function of the electrode voltage are presented in fig. 5 for constant input energy.

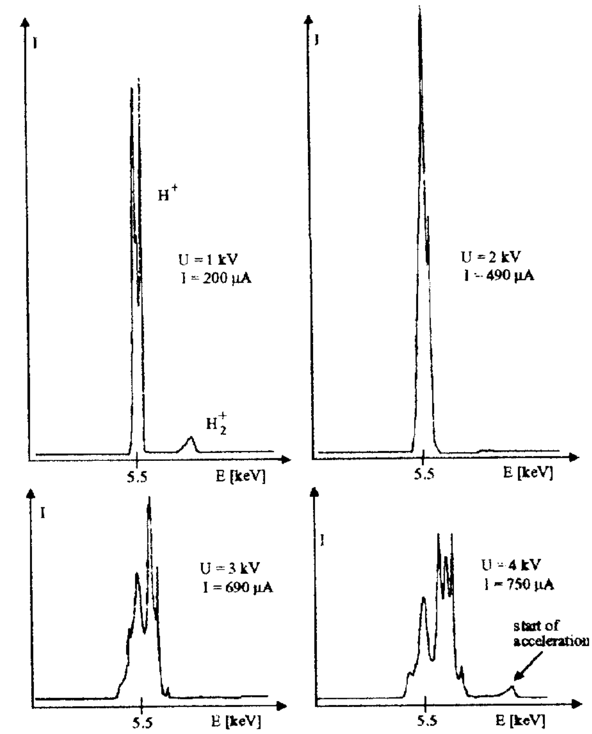

Fig. 5 Measured energy spectra for the transport of a proton beam with T_{in}= 5.5 keV for different electrode voltages below the design voltage.

As can be seen from this curves the output energy is constant, which means that transport takes place. The width of the curve, i.e. the energy spread, is directly proportional to the applied electrode voltage.

III. RFQ WITH DIFFERENT OUTPUT ENERGIES

In the measurements steps in the output energy of the beam could be observed, when the electrode voltage was varied from low values to the design value for a beam with design input energy. These steps could be reproduced for certain constant voltages and were better marked at voltages closer to the design voltage. This effect can be explained as follows: for voltages below the design voltage the ions must change to a lower synchronous phase to be stable accelerated. If the voltage is such low, that no stable phase could be found, particles can no longer reach the design energy. For a bunched beam with a small bunch width the whole bunch will be decelerated and can loose once, twice ore even more often the electrode voltage times charge state times acceleration factor in energy. PARMTEQ calculations came out with the same results. This effect could be used for the design of a RFQ with different output energies. Fig. 6 shows as an example the longitudinal and transverse beam behaviour along a RFQ. In the first part the beam is mainly captured and bunched before acceleration can start.

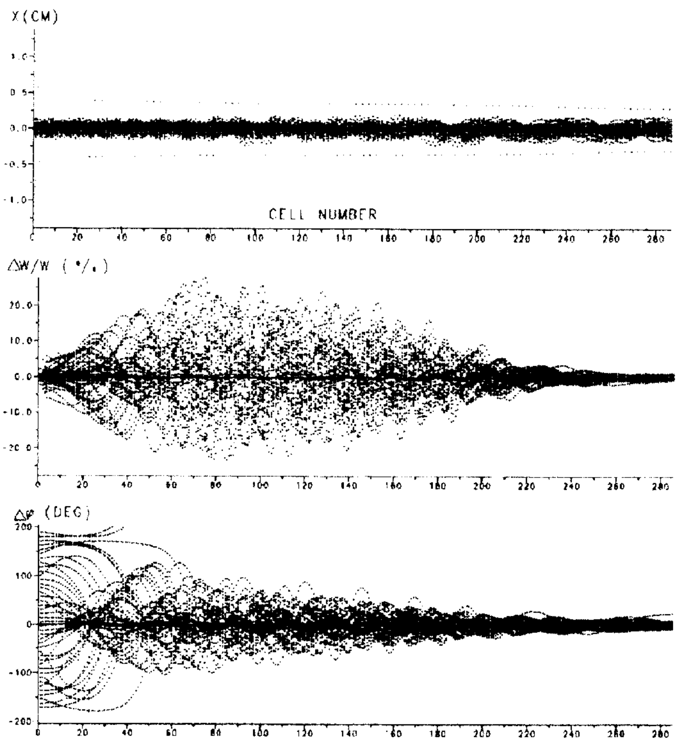

Fig. 6. Transverse and longitudinal beam behaviour along a RFQ

If the RFQ at the end of the bunching process is cut into two pieces, already two final energies are available: The bunched beam can be transported with the output energy of part 1 through part 2 at low electrode voltages to maintain transverse focusing, or can be accelerated in part 2 to the original final energy at design voltage. Two more intermediate energies can be adjusted, when the voltage in part 2 is varied. Fig. 7 a shows the result of PARMTEQ calculations for $U_{el} = 0.8U_{des}$, fig. 7 b for $U_{el} = 0.62U_{des}$. The final energies in these examples are 30 and 40% lower than the energy with acceleration. Together with the transport energy of 50% beyond, four different output energies are available with high transmission and good beam quality.

IV. CONCLUSION

Measurements and calculations show, that transport of ions with good beam quality in RFQ accelerators is possible. One possible application is the design of RFQs with different end energies without frequency variation e.g. for ion implantation.

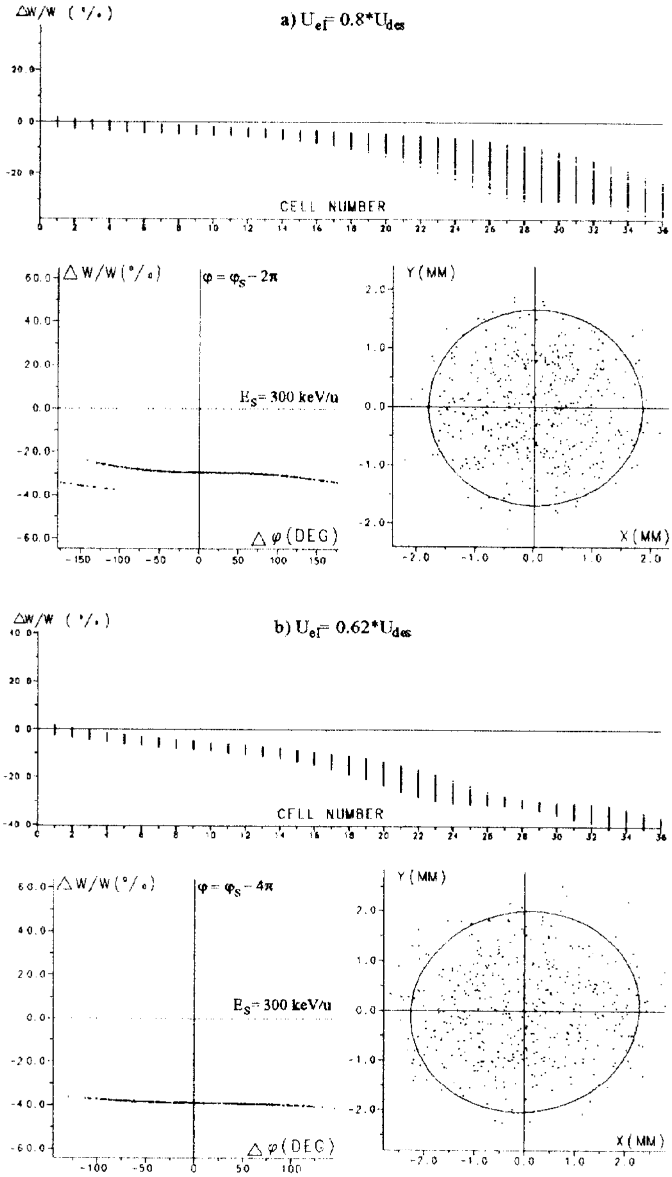

Fig. 7. Example of longitudinal motion and output emittances for lowered electrode voltage

V. REFERENCES

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