HIGH CURRENT RFQ ACCELERATOR USING A SPLIT COAXIAL RESONATOR WITH A FOUR ROD STRUCTURE*

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Abstract

A split coaxial resonator with a trapezoidally modulated four rod accelerating structure has been built to accelerate high currents of protons or H_2^+-ions to an energy of 46 keV/N. It will be used to investigate RFQ funneling and to study beam loading effects. First experiments showed that 70 % of the current limit can easily be reached. Higher currents are expected by an upgrading of the RF power.

Introduction

The split coaxial resonator (SCR) concept[1,2] for RFQ accelerators was further developed at our institute[3]. In opposition to earlier designs, which employed drift tubes and focussing fingers (proton model, Maxilac)[4], the accelerating structure now consists of trapezoidally modulated[5] continuous electrodes (fig.1). These have the advantage of easier manufacturing, better cooling and mainly of much better mechanical alignment. An SCR accelerator of this type has been built to investigate RFQ funneling[6] and to study beam loading effects. In addition the computational programs for electrode profile design can be experimentally verified.

Technical Layout

The RFQ is designed to accelerate high currents of protons or H_2^+-ions from 6.15 keV/N to an energy of 46.8 keV/N at a resonance frequency of 49 MHz. As RF power at this frequency is presently limited to 1 kW, the design of the accelerator had to be chosen so that an RF voltage of 12 kV is sufficient to accelerate protons to the required energy. For this reason the synchronous phase ϕ_s has to start at a value of 60° in the bunching section to reach 30° at the acceleration part of the RFQ.

The R_p-value of 180 kΩ (Q_o = 4500) is relatively high for this type of resonator. This is achieved by the low capacitance of the continuous electrodes and by introducing spiral contacts between the inner and outer conductor. Structure data and beam parameters are listed in table 1.

Table 1 Parameters of the SCR-RFQ

ion	H_2^+, H^+
RF frequency	49 MHz
energy	6.15 - 46.8 keV/N
aperture radius	6 - 4.5 mm
modulation	1.16 - 1.88
RF voltage	8.6 kV/N
max. beam loading	30 %
synchronous phase ϕ_s	60° - 30°
σ_{ot}	45.5°
current limit ($I_t = I_l$)	8 mA (84 %) H_2^+
resonator length	0.5 m
structure length	26 $\beta\lambda/2$
R_p-value	∿ 180 kΩ
Q_o-value	4500

* supported by BMFT

The trapezoidal modulation (ϑ=0.4) of the electrodes[5] results in a higher acceleration rate A_{10} compared to the ideal profile. This permits a decrease of the RF voltage by 15 % and of the modulation by 20 % leaving the synchronous phase ϕ_s and the transverse phase advance σ_{ot} constant. The lower modulation ratio (r_{min}/r_{max} = 1.8) also contributes to the mechanical rigidity of the quadrupole structure. Fig.2 shows a comparison of the values of acceleration rate A_{10}, focussing strength A_{01}, modulation and aperture for ideal and trapezoidal profile along the RFQ[7].

The experimental set-up is schematically shown in fig. 3. The ions are extracted from a duoplasmatron ion source by a single aperture accel-decel-system. The focussing of the beam into the radial matching section of the RFQ was originally done with two electrostatic einzellenses[4]. Recently these were replaced by an iron capsuled magnetic solenoid lense[8,9] with specially shaped pole tips to reduce spherical aberrations. Also this lens gives a certain amount of mass separation. For beam analysis behind the RFQ a water-cooled Faradaycup, a fast 50 Ω cup and a bending magnet were used.

Experimental Results

The SCR-RFQ was operated with protons and H_2^+-ions at different RF voltages up to 14 kV (U_o = 8.65 kV for H^+). To test RFQ design and beam dynamics without space charge a low proton current (∿ 500 µA) was used. In this case the transverse phase advance σ_{ot} can be varied over a range from 27° - 70°. Figs. 4 a-e show the energy spectra for protons at different RF voltages. As the measurements prove, the protons are already accelerated at very low RF voltages. The energy increases slightly with the applied voltage and reaches 46.8 keV/N at the design value of 8.65 kV. At this point there is a significant increase in intensity and the energy spread is reduced to a minimum. This narrow spectrum only appears in a very small range (± 50 V) around the design amplitude. If the voltage is raised to higher levels, the energy spread increases again and also the beam energy is shifted to slightly higher values. The agreement with the corresponding calculated spectra as shown in figs. 5a-e is good. Also the energy distribution as a function of RF voltage takes a similar course.

The structure of the beam bunches (figs. 6a-e) was measured at the same voltages as the energy spectra. At the voltage of 6.4 kV the bunches are already well separated, which confirms that the ion beam is already accelerated. With an increase of the applied voltage there is a raise in intensity and the bunch length decreases. At the design voltage a very symmetrical and narrow bunch with a high intensity is observed. The bunch length of 5 ns corresponds to the synchronous phase ϕ_s = 30° in the acceleration part of the RFQ. The two maxima of the bunch structure indicate that the spiral shaped particle distribution stands just upright in the separatrix. For higher RF voltages there is a decrease in intensity and an increase of the bunch length due to the higher synchronous phase ϕ_s.

For measurements near the space charge limit H_2^+-ions with an injection energy of 12.3 keV were used, since the ion source can be operated in a mode, where 80 % H_2^+ are extracted. Fig. 7 shows a measured energy spectrum of an accelerated H_2^+-ion beam with an output current of 3.4 mA. Although only 60 % of the design voltage could be applied here an energy of 92.8 keV is reached. This effect could be predicted from the experiments with protons.

The transmitted H_2^+-current as a function of RF voltage for different injected currents (1.5 - 8.5 mA) is shown in fig. 8. For low currents the transmission is high and the accelerated current remains constant over a wide range. With an increase of the injected beam current beam loading rises up to 30 % (beam power = 300 W), which reduces the maximum RF voltage from 14 kV to 10 kV, as the RF power is presently limited to only 1 kW. The dotted line in fig. 8 indicates the voltage, at which the transmitted current starts to be accelerated (ϕ_s = 0°). Theoretically with a starting phase of ϕ_s = 60° 50 % of the injected DC beam can be accelerated. For an injection current of 8.5 mA the measured output current of 3.6 mA corresponds to 85 % of the theoretical current limit.

All the described measurements were done in cw operation. The influence of beam loading can, however, be investigated, if the RF is pulsed. A macropulse of the beam with a length of 700 µs is shown in fig. 9. There is a significant breakdown in beam current at beginning of the pulse. The depth of this minimum is a function of the injected beam current.

To make measurements with a proton beam near the space charge limit possible, a new ion source with a high proton yield will be installed soon. Also an upgrading of RF power is planned in the near future. Thus the split coaxial principle combined with a four rod accelerating structure has proved that high current ion acceleration is possible with a relatively moderate effort.

References

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[2] H. Klein et al., GSI-85-21 (1985) p. 16
[3] P. Leipe et al., GSI Annual Report on Inertial Fusion 1985, to be published
[4] W. Neumann et al., Proc. 1984 Lin. Acc. Conf. Seeheim, GSI-84-11 (1984) p. 80
[5] P. Junior et al., GSI-81-3 (1981) p. 11
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[7] H. Deitinghoff, Univ. Frankfurt, Inst. f. Angew. Physik, Int. Rep. 85-29
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[9] K. Langbein et al., GSI Annual Report on Inertial Fusion 1985, to be published

Computations were carried out at the HRZ of the University of Frankfurt and at GSI Darmstadt.

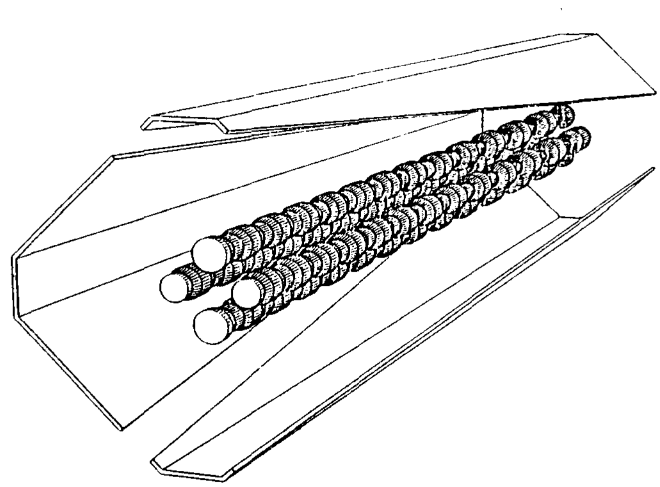


Fig. 1 Trapezoidally modulated SCR-RFQ electrodes

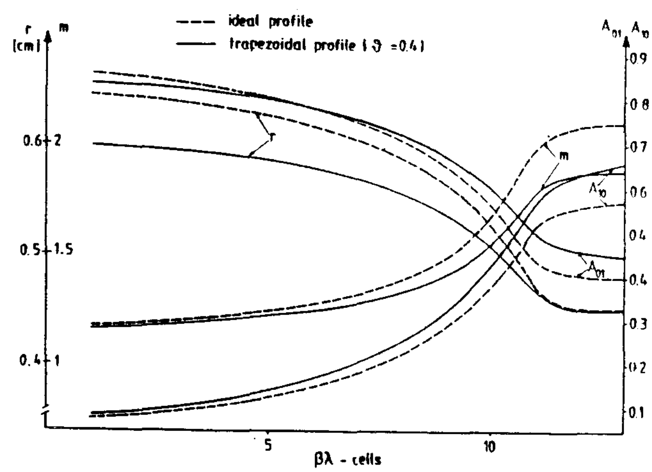


Fig. 2 Coefficients of ideal and trapezoidal (ϑ = 0.4) electrode profile versus section number ($\beta\lambda$) of the SCR-RFQ

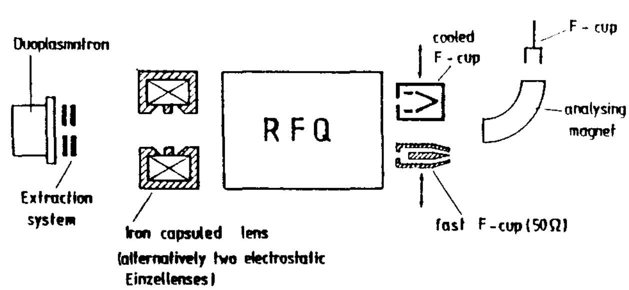


Fig. 3 Scheme of the experimental set up of the SCR - four rod RFQ

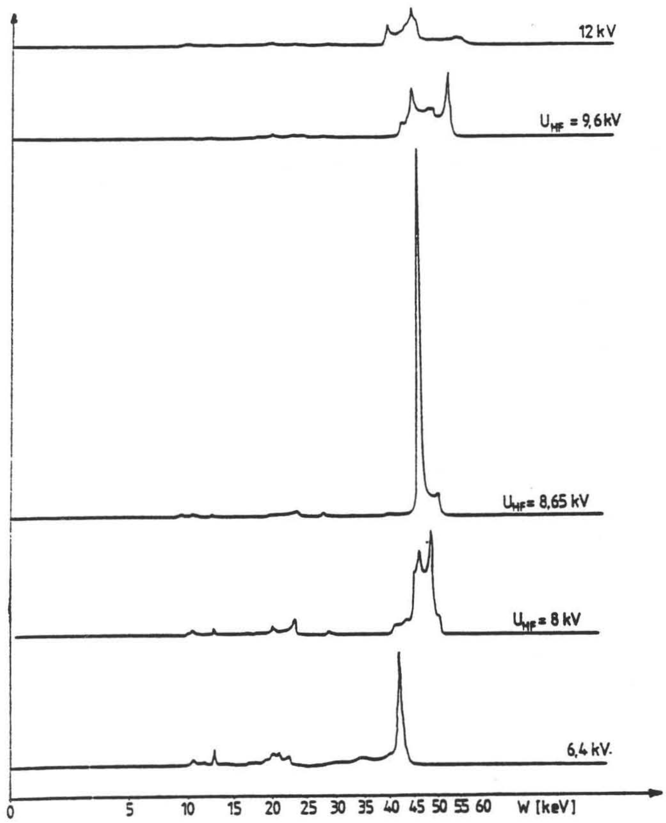


Fig. 4 (a-e) measured

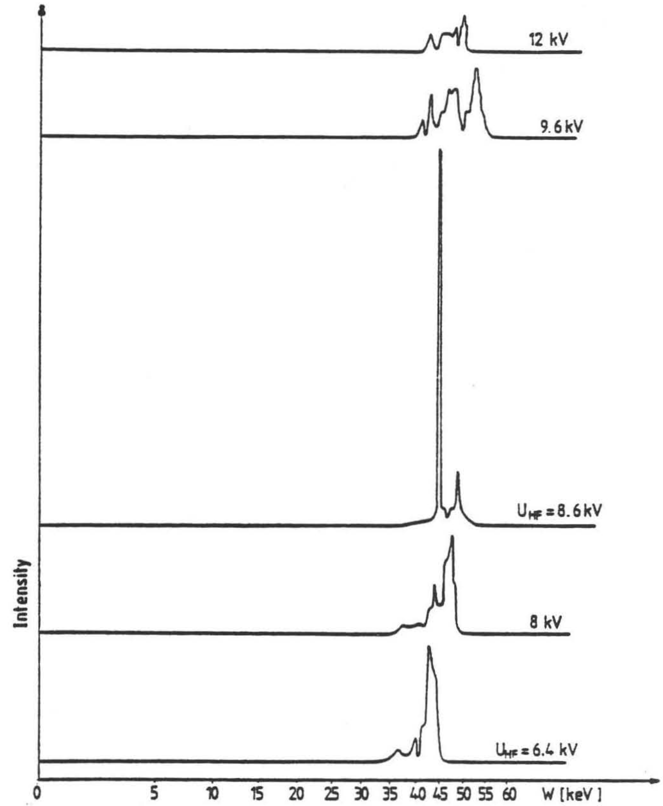
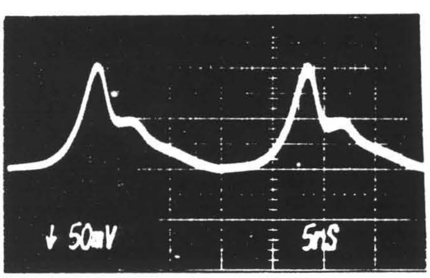
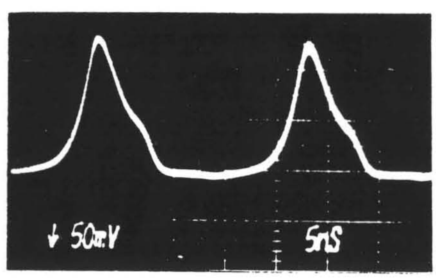


Fig. 5 (a-e) calculated

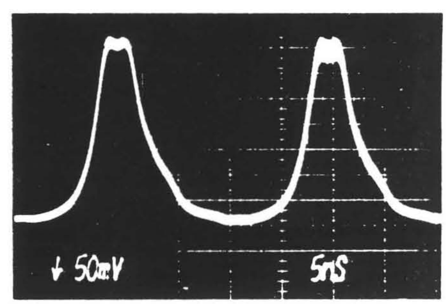
Meassured and calculated H^+-energy spectra at different RF-voltages
design voltage: 8.65 kV, design energy: 46.8 keV/N, σ_{ot}: 21° - 70°



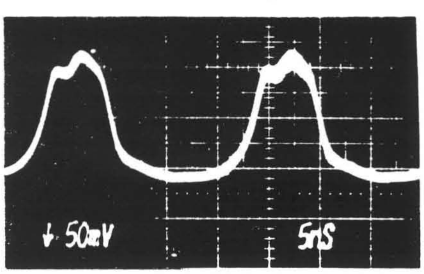
a) U_{rf} = 6.4 kV



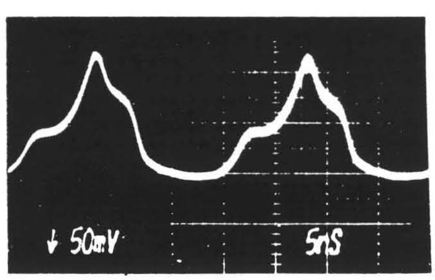
b) U_{rf} = 8.0 kV



c) U_{rf} = 8.65 kV (design)
ϕ_s = 30°
bunch length: 5 ns



d) U_{rf} = 9.6 kV



e) U_{rf} = 12 kV

Fig. 6 (a-e)
measurement of the bunch-structure of the accelerated beam at different RF-voltages.
ion: 46.8 keV H^+
RFQ-frequency: 49 MHz

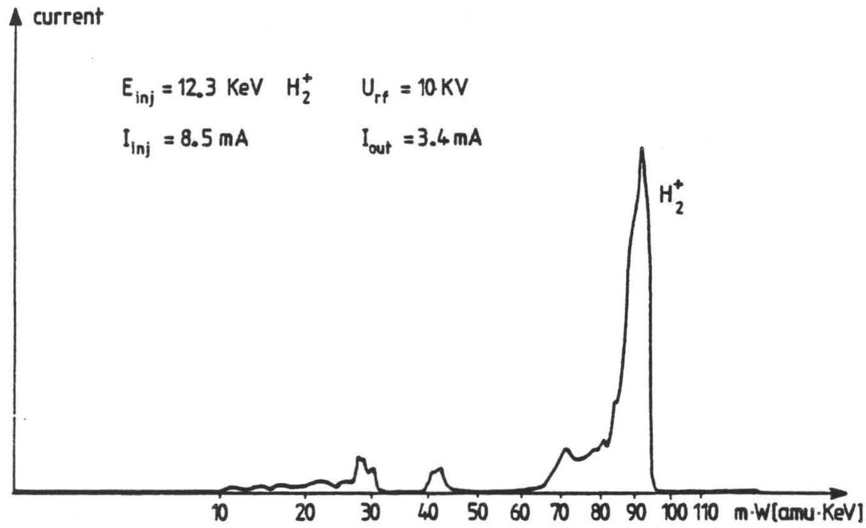


Fig. 7 Measured energy spectrum of an accelerated H_2^+ - beam

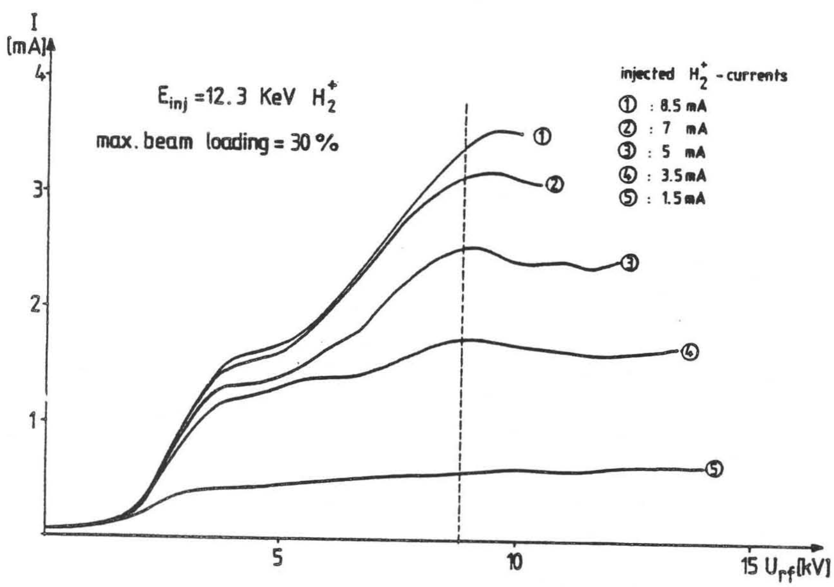


Fig. 8 Transmitted H_2^+ - current versus RF-voltage at different injection currents

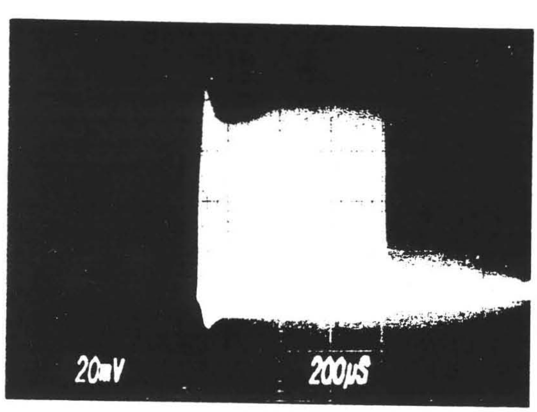


Fig. 9 Macropulse-measurement with beam loading

ion:	93.6 keV H_2^+
RF-voltage:	14 kV
pulse length:	700 µs
current:	2 mA
beam loading:	20 %