# EXPERIMENT ON BEAM FORMATION WITH TWO COUPLED RFQ'S.*

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## Abstract

*In accelerator physics there is an increasing interest in high current ion beams with specially shaped microbunch structure. We present an experiment, in which for the first time two RFQ's, a 50 MHz Split Coaxial Four Rod resonator (SCR) and a 200 MHz λ/2 Four Rod structure, are coupled directly. This accelerator concept is well suited to form a "1 out of 4" microbunch structure of the accelerated high current ion beam. The repetition of full buckets is determined by the low frequency of the first RFQ, while the bunch length corresponds to the higher frequency of the second one.*

*The $H^+$ dc-beam extracted from the Plasma Beam Ion Source is bunched and accelerated from 6.5 to 50 keV in the SCR RFQ and up to 320 keV in the Four Rod structure. A final bunch length of 1 nsec (FWHM) is obtained. The peak current amounts to 32 mA (time averaged current 1.6 mA).*

## Introduction

In several accelerator layouts special time structures of high current ion beams are necessary. One is the European Hadron Facility (EHF) project (1), where a bunch repetition frequency of 20 Hz is required, since the cavities of the booster ring have to work at 50 MHz, whereas the frequency of the main injector linac is about 1 GHz. Other proposals, e.g. the SSC injector (2), need similar pulse structures. The RFQ accelerator, which is under investigation at our institute (3), is capable of simultaneous bunching and acceleration of intense low energy ion beams. Therefore we propose a concept in which two RFQ's with different frequencies are coupled to produce special time structures of high current ion beams.

A first experiment with two coupled RFQ's working at different frequencies was carried out. Here a 50 MHz Split Coaxial Four Rod RFQ (SCR) (4,5) and a λ/2 - Four Rod structure (6) working at 200 MHz has been used. This accelerator concept is well suited to form a "1 out of 4" microbunch structure of the accelerated beam, even at high space charge forces. In this concept one populated bucket is followed by a void of three 200 MHz periods. The repetition of full buckets is determined by the low frequency (50 MHz) of the first RFQ, while the bunch length corresponds to the higher frequency (200 MHz) of the second one. This new concept can replace conventional buncher - chopper systems, which don't work properly at low β, high intensity beams.

## Beam dynamics

A scheme of the "1 out of 4" accelerator concept is shown in Fig.1. The dc-beam extracted from the ion source is injected into RFQ1 and transformed into a sequence of 50 MHz bunches with a phase width of $\Delta\varphi \approx 3\varphi_s$ ($\varphi_s$ synchronous phase). RFQ2 is designed to accept a 50 MHz bunch in one 200 MHz rf-period and continues the bunching process of the ion beam ($\varphi_s = 80^0 - 30^0$). RFQ2 has to be designed so that the current limit is more than four times larger than in RFQ1, due to the number of empty buckets.

An important aspect of this accelerator concept is the transverse and longitudinal beam matching between the RFQ's. In Fig. 2(a-d) simulation results of the longitudinal bunch formation ("1 out of 4") are shown. The special PARMTEQ-code (7) allows for tracing of particles through RFQ1 and RFQ2, where the particle distribution at the end of RFQ1 gives the input for RFQ. In (a) and (b) the well known adiabatic bunching process of a monoenergetic dc ion-beam is seen, as it is done in RFQ1. $\Delta T/T_s$ is the energy spread related to the energy of the synchronous particle and $\Delta\varphi$ denotes the phase distance to the synchronous particle. The obtained particle distribution of the 50 MHz bunch is used as an input for RFQ2 by increasing the phase distance

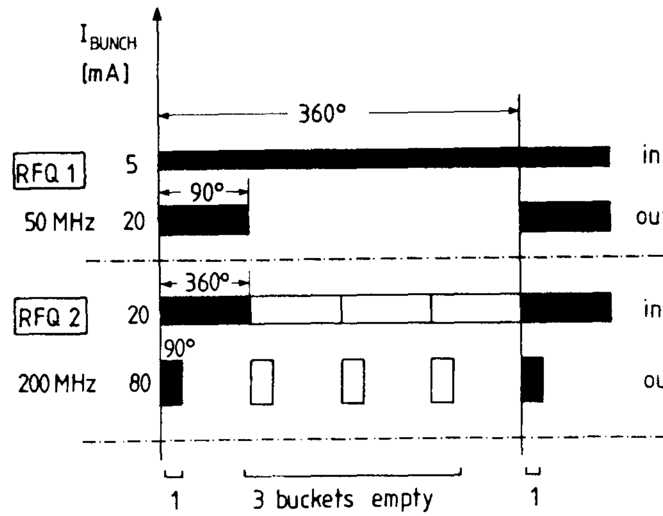


*Fig. 1: Scheme of the "1 out of 4" accelerator concept.*

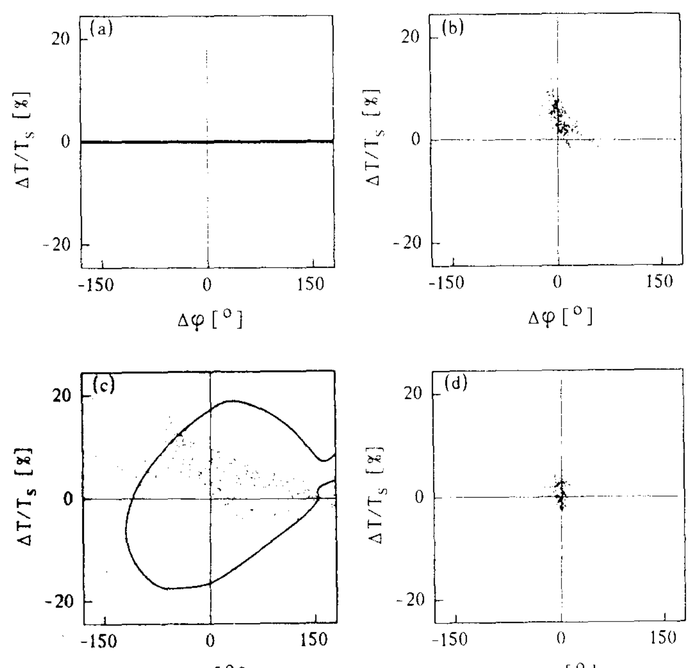


*Fig. 2: Simulation results for longitudinal bunch formation in the "1 out of 4" accelerator concept ($\Delta\varphi - \Delta T/T_s$ phase plane) with the multiparticle code PARMTEQ. In (a) and (b) the adiabatic bunching of the monoenergetic dc ion-beam in RFQ1 is seen. The synchronous phase is $\varphi_s = -30^0$ at an rf voltage of 9 kV. (c) and (d) shows the bunching process of the RFQ1 output beam in the 200 MHz RFQ2. A very short phase width of $\Delta\varphi = 18^0$ relative to the 50 MHz time structure is obtained.*

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$\Delta\varphi$ and the beam current by a factor of 4, corresponding to the higher frequency (c). In comparison to the usual injection (as shown in (a)), here the beam has an energy spread $\Delta T$ and an inhomogeneous distribution in the $\Delta\varphi$-range. The line indicates the calculated $\Delta\varphi - \Delta T/T_s$ acceptance of RFQ2. Finally, in (d) the shape of the output beam is shown. The ion beam is further compressed to a bunch length of 1 nsec (FWHM), which corresponds to a very short phase width of $\Delta\varphi = 18^0$ relative to the 50 MHz time structure.

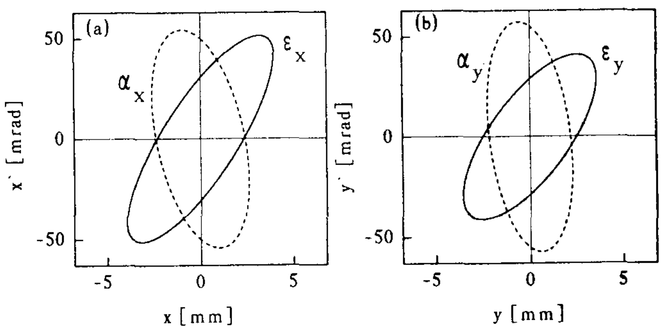


*Fig. 3: Calculated xx'- and yy'-emittances (rms-values) behind RFQ1 and corresponding acceptances of RFQ2 (dashed lines). The emittances are 125 and 100 πmm·mrad resp., the xx'-and yy'-acceptances of RFQ2 are 130 and 125 πmm·mrad. The maximum calculated transmission is 60 %.*

The transverse beam matching between the RFQ's was only done with the radial matching sections. This keeps the drift space short and prevents a transverse and longitudinal blow up of the intense ion beam. The calculated xx'- and yy'-emittances behind RFQ1 and the corresponding acceptances of RFQ2 (rms-values) are compared in fig. 3. In this design a maximum transmission of 60% is calculated, which results in a peak current of 40 mA (time averaged current 2 mA).

To investigate beam dynamics of the bucket to bucket particle transfer, calculations on bunch formation were done as a function of the rf phase-shift $\Delta\Phi$ between both RFQ's. As the results show (fig. 4.), at $\Delta\Phi = 0^0$ resp. $360^0$ nearly all particles of the 50 MHz bunch are accepted by one 200 MHz bucket, only a few percent populate the adjacent bucket (curve 1 and 2, resp. 2 and 3). By increasing the rf phase-shift the 50 MHz bunch is splitted into two 200 MHz buckets. At $\Delta\Phi = 190^0$ a "2 out of 4" operation with an equal current in both bunches is achieved. In this case the transmission is decreased to 1.1 mA (time averaged current), because only a smaller fraction of the ion beam can be accepted longitudinally by RFQ2. Nonaccepted particles are partially focused and accelerated to energies below the design value. The dotted line in fig. 4. shows the fraction of the undesired particles as a function of $\Delta\Phi$, and indicates a maximum value at the point of "2 out of 4" operation.

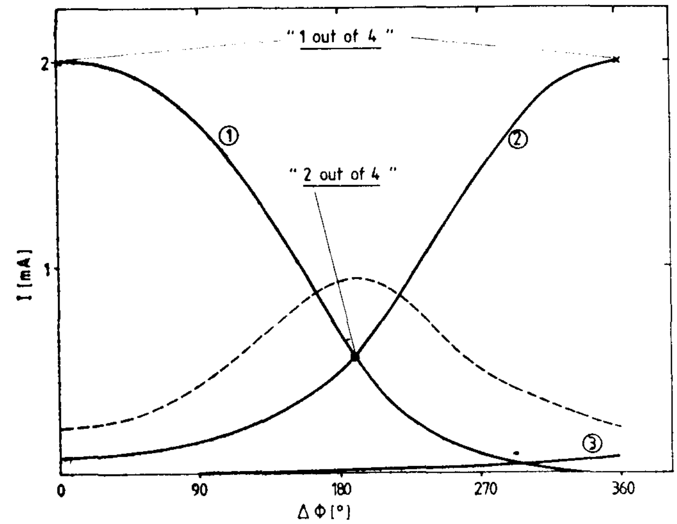


*Fig. 4: Calculated bunch currents (time averaged) as a function of the rf phase-shift $\Delta\Phi$ between the RFQ's. (---: fraction of not accelerated ions)*

**Table 1.:** Design parameters and structure data of the Split Coaxial (SCR) and the Four Rod RFQ.

| Type | SCR | 4-Rod |
|---|---|---|
| Ion | $H^+$ | $H^+$ |
| f (MHz) | 50 | 200 |
| Voltage (kV) | 9 | 45 |
| $T_{in}$ (keV) | 6.5 | 50 |
| $T_{out}$ (keV) | 50 | 320 |
| Aperture (mm) | 6 - 4.5 | 5 - 3.2 |
| Modulation | 1.16 - 1.88 | 1.06 - 2.0 |
| $\varphi_s$ ($^0$) | 60 - 30 | 80 - 30 |
| $\sigma_{ot}$ ($^0$) | 45 | 23 |
| Length (m) | 0.55 | 1.10 |
| Cell number | 32 | 95 |
| $I_{max}$ (mA) PARMTEQ | 4.2 | 34 |
| $R_p$ - value (kΩ) | 180 | 40 |
| $Q_0$ - value | 4500 | 3000 |

## Experimental results

A schematic view of the experimental arrangement is shown in fig. 5. The high current ion beam with a proton fraction ≥ 90%, which is extracted from the Plasma Beam Ion Source (8) is matched to the RFQ by an iron capsuled magnetic solenoid lens. This lens also gives a certain amount of mass separation, and the

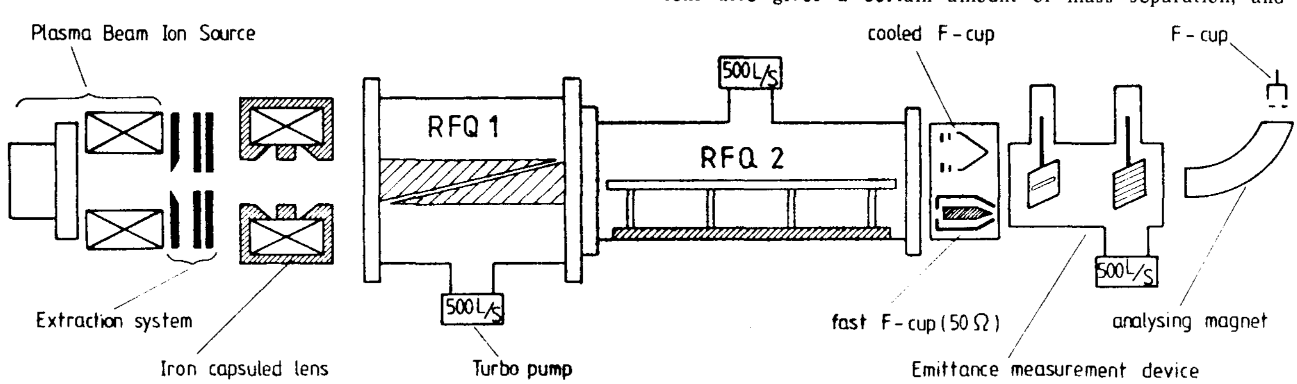


*Fig. 5: Schematic view of the experimental arrangement of the "1 out of 4" accelerator concept.*

special shape of pole tips reduces spherical aberrations considerably. The RFQ1 accelerates the $H^+$-ion beam from 6.5 to 50 keV at an electrode voltage of 9 kV. The final energy at the end of RFQ2 is 320 keV at an rf voltage of 45 kV. This $\lambda/2$-Four Rod structure is flanged directly to the endplate of RFQ1. The drift length between the electrodes is only 3.5 cm. Table 1. summarises the design parameters of both RFQ's.

For beam analysis behind the RFQ's a Faraday cup, a $90^0$-bending magnet ($\pm 0.5\%$ resolution), an emittance measurement device, and a fast ($50\,\Omega$) Faraday cup were used. The bandwidth of 1.7 GHz allows for a resolution of the bunched beam down to 600 psec.

Fig. 6 (a - d) shows the measured bunch structures at design voltage behind RFQ1 and RFQ2. The 50 MHz microbunch structure (a) was measured 3.5 cm (i.e. the drift length between the RFQ's) behind the SCR RFQ. The bunches are well separated, and the current free period between the pulses indicates a good beam matching. The bunch length of 3.5 nsec (FWHM) corresponds to the synchronous phase of $\varphi_s = -30^0$ and agrees well with calculations (fig. 2b). The transmitted current of 3.6 mA is 86 % of the theoretical current limit calculated with PARMTEQ (see table 1).

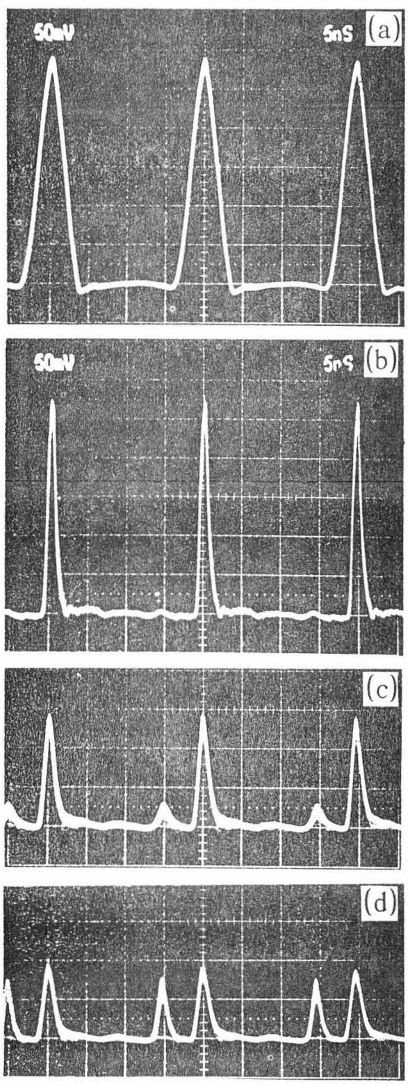


*Fig. 6: Measured microbunch structures behind RFQ1 and RFQ2. In (a) the 50 MHz pulses are shown, the bunch length defined as FWHM is 3.5 nsec ($\varphi_s = -30^0$). In (b - d) the microbunches behind RFQ2 for different rf phase-shift $\Delta\Phi$ are shown. In (b) the shortest bunch length of 1 nsec (FWHM) is obtained at "1 out of 4" operation ($\Delta\Phi = 0^0$). (d) shows "2 out of 4" operation at $\Delta\Phi = 190^0$. The bunch structure for an intermediate value ($\Delta\Phi = 135^0$) is shown in (c).*

The bunch structure behind RFQ2 was measured as a function of the rf phase-shift. At $\Delta\Phi = 0^0$ a "1 out of 4" bunch separation is obtained (b) with a short pulse length of 1 nsec (FWHM) and a repetition frequency of 50 MHz. The measured current of 1.6 mA (peak current 40 mA) corresponds to 80 % of the calculations shown in fig. 4. By increasing the phase-shift a "2 out of 4" pattern is obtained (d) at $\Delta\Phi = 190^0$.

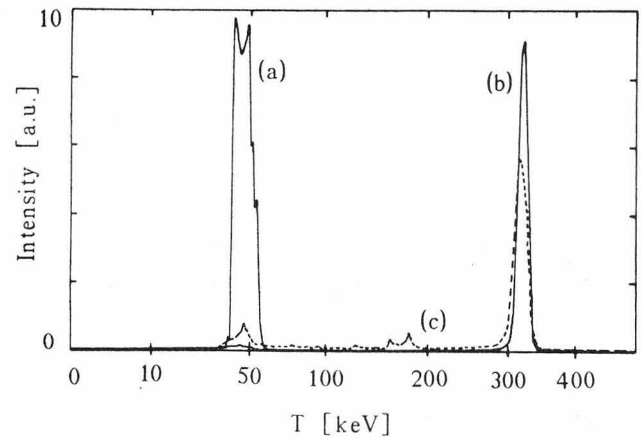


***Fig. 7:** (**a**) Energy distribution measured behind RFQ1 at design voltage (9 kV). The output current amounts to 3.6 mA. The design energy is 50 keV. (**b**), (**c**) Energy spectra behind RFQ2 at design voltage (45 kV) at "1 out of 4" and "2 out of 4" operation ($T_{design}$ = 320 keV).*

The measured energy spectra behind the RFQ's at design voltage (9 resp. 45 kV) are shown in fig. 8. In the first step (a) the $H^+$ beam is accelerated to the design energy of 50 keV; the energy spread of $\pm$ 6 keV is about 50 % higher than calculated. Behind RFQ2 one gets one narrow accelerated energy peak at the design value of 320 keV (energy spread $\pm$ 3.5 %) for "1 out of 4" operation (b). In the case of "2 out of 4" operation, the intensity of the accelerated beam decreases and fractions of lower energies are measured, as predicted by theory (see fig. 4.)

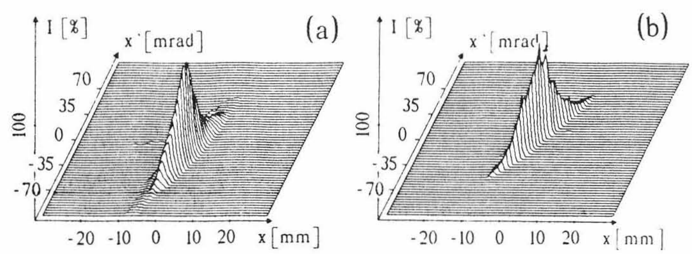


***Fig. 8:** Measured beam emittances in xx' phase-plane behind RFQ1 (a) and RFQ2 (b). The values are $\varepsilon_x(90\%) = 120$ in (a) and $65\,\pi$ mm · mrad respectively in (b). The overall emittance growth is 2.3. $I_{RFQ1}$ = 3.6 mA and $I_{RFQ2}$ = 1.6 mA.*

Fig. 9 shows the obtained emittances behind the RFQ's in the xx'-phase space at design voltage. The measured values are $\varepsilon_x(90\%) = 120\,\pi$ mm · mrad ($\varepsilon_n = 1.2\,\pi$ mm · mrad) behind RFQ1, resp. $\varepsilon_x(90\%) = 65\,\pi$ mm · mrad ($\varepsilon_n = 1.4\,\pi$ mm · mrad) behind RFQ2. With an input emittance of $\varepsilon_n(90\%) = 0.6\,\pi$ mm · mrad this results in an overall emittance growth of 2.3. This first beam experiments, which were operated successfully, proved that the proposed two coupled RFQ accelerator concept is well suited to produce high current ion beams with special shaped pulse structures.

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