ACCELERATION AND BUNCH FORMATION WITH TWO COUPLED RFQ's *

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Abstract

A combination of two RFQs with 50 MHz resp. 200 MHz is well suited to accelerate a high current beam from 6.5 keV to 320 keV with a bucket to bucket particle transfer. The proton beam from the plasma beam ion source is accelerated to 50 keV in a Split Coaxial RFQ with four rod electrodes. The second stage, a 200 MHz Four Rod RFQ accelerates the beam to the final energy. This accelerator, which couples two RFQs operating at different frequencies for the first time, is being built and first experimental results will be presented.

Introduction

In accelerator physics the interest in high current ion beams with specially shaped microbunch structure is increasing. A first experiment with two coupled RFQs working at different frequencies was done at our institute. For this a 50 MHz Split Coaxial RFQ (SCR) with four rod electrodes [1,2] and a new Four Rod RFQ [3] working at 200 MHz has been used.

This accelerator concept is well suited to form a "1 out of 4" microstructure of the accelerated beam, even at high space charge forces. It means that not all of the 200 MHz RFQ buckets are filled with particles. 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 RFQ. Fig. 1 shows the scheme of the accelerator complex and the "1 out of 4" philosophy.

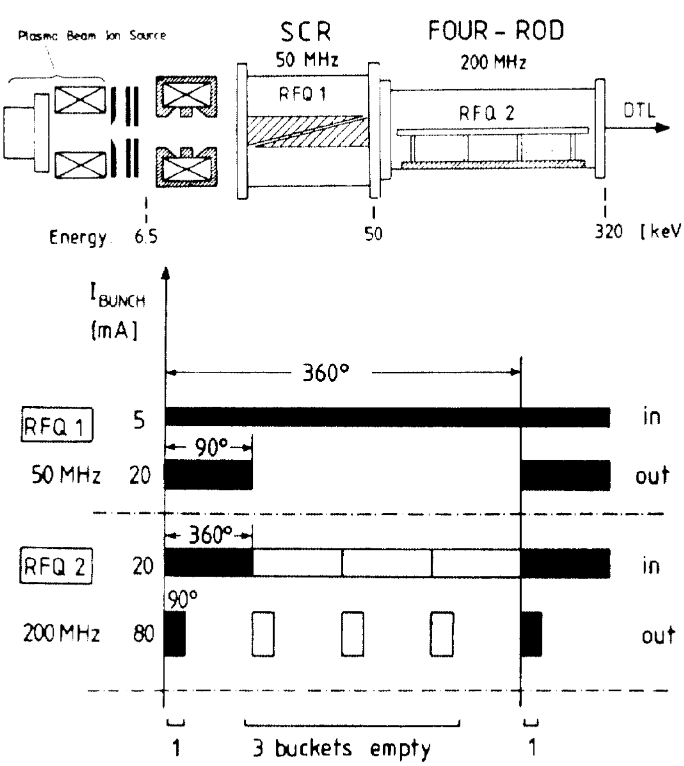

Fig. 1: Scheme of the accelerator-concept and the "1 out of 4" philosophy

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The idea of this concept was born for the European Hadron Facility (EHF) project [4,5]. The special bunch formation of the beam is necessary, since in this accelerator complex 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 need similar pulse structures.

Layout of the Accelerator-Concept

The dc-beam extracted from the ion source is injected into the first RFQ and transformed into a sequence of 50 MHz bunches with a phase width of $\Delta\varphi = 3\varphi_s$ (φ_s synchronous phase). Simultaniosly the 50 MHz SCR RFQ1 accelerates the high current proton beam from 6.5 keV to an energy of 50 keV. This resonator was further developed by using trapezoidally modulated continuous electrodes [1] and is operating reliably since several years. The main structure data and beam parameters are listed in table 1.

For the second stage a $\lambda/2$-Four Rod RFQ is used. This structure which was also developed at our institute [3] is well suited for the high frequency of 200 MHz. The mechanical and rf-construction follows the HERA Four Rod injector [6]. The RFQ2 is designed to accept the main part of the 50 MHz bunches in one rf-bucket and continues the bunching process of the ion beam ($\varphi_s = 80^0 - 30^0$). The final energy is 320 keV. The design current was increased by a factor of four because of the number of empty buckets. The main parameters of RFQ2 are also listed in table 1.

The design of the second accelerator was optimized to the given parameters of the first RFQ. One problem is the transverse and longitudinal beam matching between the RFQs. Beam dynamic calculations with a special PARMTEQ-code (particles can be traced through RFQ1 and RFQ2 by giving the second RFQ exactly the output of the first one) show, that the direct coupling of both RFQs will operate well at high space charge forces, in contrast to other configurations with buncher and chopper systems inbetween. Only the radial matching sections are used for transverse beam matching. The drift space should be as short as possible to prevent an increasing of the 50 MHz bunch length. Although the divergent beam emittance of the first RFQ, which has to be injected into the convergent acceptance of RFQ2 causes considerable particle losses, a maximum calculated transmission of 60% at design current is achieved.

Experimental Results

A view of the experimental setup of the "1 out of 4" accele-

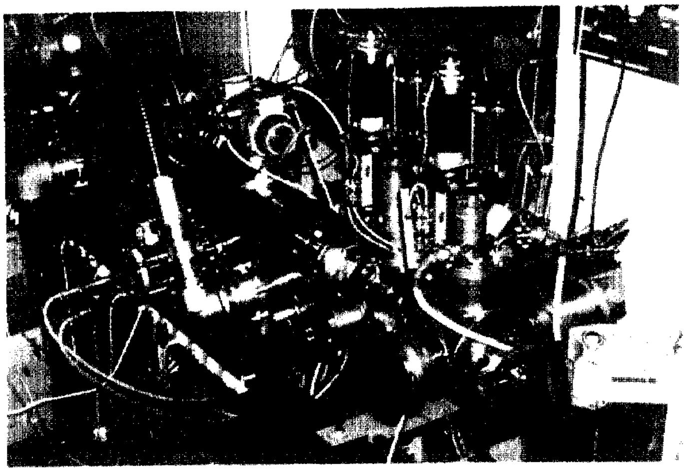

Fig. 2: View of the "1 out of 4" accelerator experiment

rator is shown in Fig. 2. The ions are extracted from a new Plasma Beam Ion Source [7], which supplies a high current ion beam with a proton fraction ≥ 90%. The beam is matched to the acceptance of RFQ1 by an iron capsuled magnetic solenoid lens. The second RFQ is flanged directly to the endplate of RFQ1. The drift length between the radial matching sections was minimized to 3.5 cm.

For beam analysis behind the RFQs a water-cooled faraday cup, a fast 50 Ω cup, a bending magnet and an emittance measurement device were used.

At first, beam measurements were made behind the SCR-RFQ1. The maximum transmitted H^+ current at design voltage of 9 kV is 3.6 mA. This corresponds to 90% of the theoretical current limit calculated with PARMTEQ.

The energy spectrum of the accelerated beam at the design voltage is shown in Fig. 3. As the measurements prove, the ions are accelerated to the calculated energy of 50 keV/N; the energy spread of ±6 keV is about 50% higher than calculated.

The 50 MHz microbunch structure was measured 3.5 cm (i.e.

Table 1.: Main beam parameters and structure data of RFQ1 and RFQ2.

	RFQ1	RFQ2
Type	SCR	Four Rod
Ion	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
φ_s (°)	60 - 30	80 - 30
σ_{ot} (°)	45	23
Length (m)	0.55	1.10
Cell number	36	93
I_{max} (mA) 100%	5	40
ε_{in} (π mm·mrad)	0.6	1.2
ε_{out} (π mm·mrad)	1.2	1.4

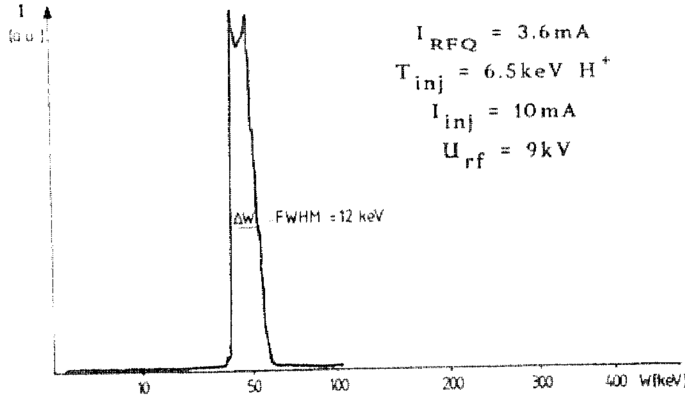

Fig. 3: Measured energy spectrum behind the 50 MHz SCR-RFQ1. (T_{design} = 50 keV/N)

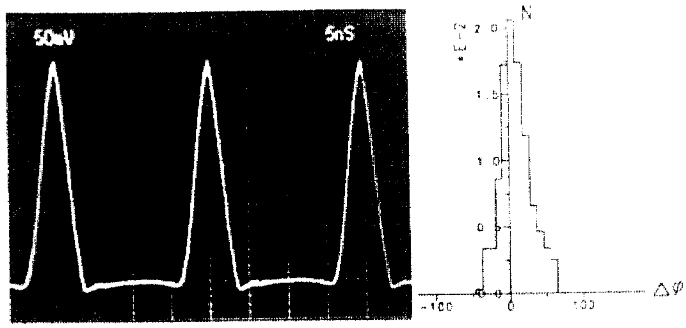

Fig. 4a,b: Measured and calculated bunch structure behind RFQ1. (U_0 = 9kV), bunch length: 5 ns

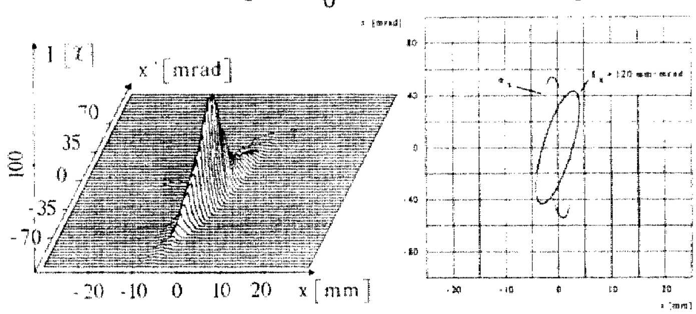

Fig. 5a,b: Measured xx'-emittance of the 50 keV H^+-beam (---: calculated acceptance α_x of RFQ2)

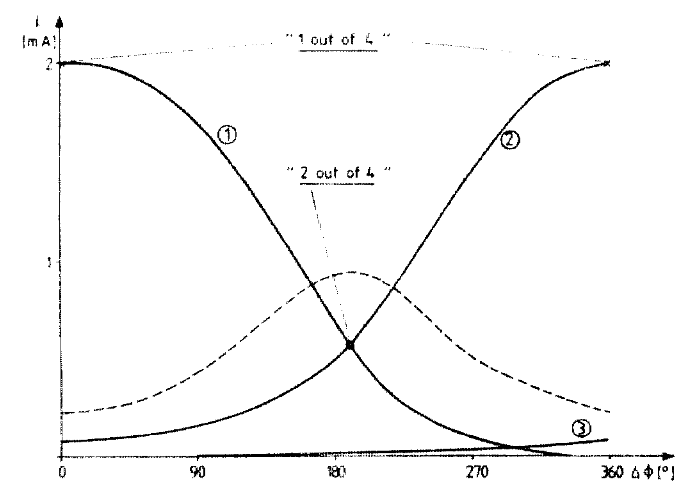

Fig. 6: Calculated bunch currents as a function of the rf-phase shift ΔΦ. (---: Fraction of none accelerated ions)

the drift length between the RFQs) behind the RFQ (Fig. 4a). The bunches are well separated and the bunch length of 5 ns corresponds to the sychronous phase $\varphi_s = 30^0$ in the acceleration part of the RFQ1. For comparison the calculated bunch structure is shown in Fig. 4b.

To verify the transverse beam matching between the RFQs, the beam emittance was measured (Fig. 5a,b). The value of $\varepsilon_x = 120$ mm·mrad at the maximum current of 3.6 mA agrees well to the calculated emittance of $\varepsilon_x = 125$ mm·mrad. The dotted line in Fig. 5b indicates the acceptance α_x of the 200 MHz RFQ2.

In the second stage of the experiment the bucket to bucket particle transfer from RFQ1 to RFQ2 was achieved immediatly. To investigate beam dynamics, beam parameters are measured as a function of the rf-phase shift $\Delta\Phi$ between both RFQs. As theory predicts, at $\Delta\Phi = 0^0$ resp. 360^0 nearly all particles of the 50 MHz bunch are accepted by one 200 MHz bucket (Fig. 6 curves 1 and 2), only a few percent populate the neighbouring bucket (curves 2 and 3). The maximum transmission of the accelereated beam is 2 mA in the main bunch; the measured H_2^+ current of 1.6 mA corresponds to 80% of this calculated value. By increasing the rf-phase shift the 50 MHz bunch is more and more 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.

Fig. 7 (a-c) shows the measured bunch structures as a function of the rf-phase shift. As calculated one gets a fine "1 out of 4" bunch separation with a narrow bunch length of 1.25 ns at $\Delta\Phi = 0^0$ and a "2 out of 4" pattern at $\Delta\Phi = 190^0$.

In the case of "2 out of 4" operation (Fig. 6, 7c) the transmitted current of the accelerated beam is decreased to 1.1 mA (0.55 mA/bunch). The splitting of the 50 MHz bunch causes, that more ions cannot be longitudinally accepted by the second RFQ. These particles can be partially focussed through the RFQ or accelerated to energies below the design value. The dotted line in Fig. 6 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. This fact can be verified by measurement of the correspnding energy spectrum.

Fig. 8a,b shows the measured energy spectra at design voltage (45 kV) for "1 out 4" and "2 out of 4" operation. In the first case one gets only one narrow accelerated energy peak at the design value of 320 keV/N with an energy spread of $\pm$ 3.5%. At the "2 out of 4" operation the intensity of the accelerated beam decreases and particles at lower energies are measured.

The beam emittance behind the second RFQ was measured in the xx'-phase space. The value of $\varepsilon_x = 65$ mm·mrad ($\varepsilon_n = 1.4\pi$ mm·mrad) agrees well to the calculated emittance of $\varepsilon_x = 60$ mm·mrad and is as small as required for the beam "painting" process in the EHF accelerator concept.

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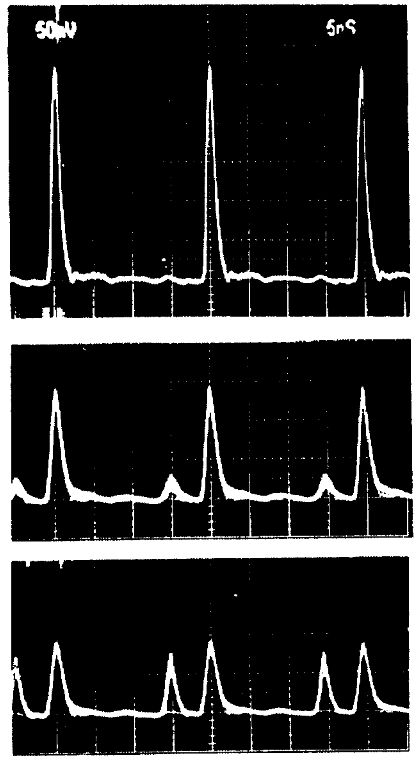

a) $\Delta\Phi = 0^0$
"1 out of 4"
bunch length: 1.25ns

b) $\Delta\Phi = 135^0$

c) $\Delta\Phi = 190^0$
"2 out of 4"

Fig. 7a-c: Measured microbunch structure behind RFQ2 at different rf-phase shift $\Delta\Phi$.

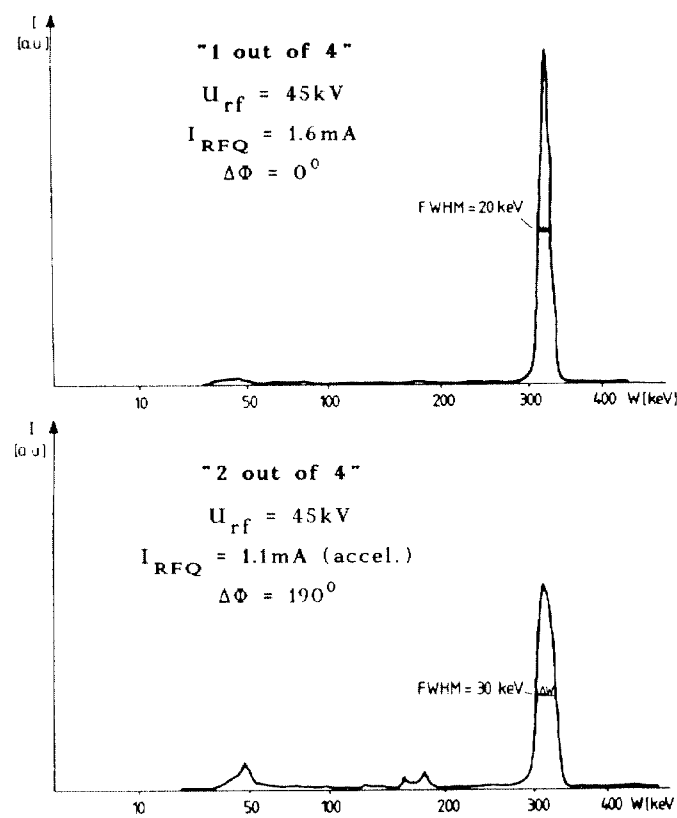

Fig. 8a,b: Measured energy spectra at design voltage (45kV) at "1 out of 4" and "2 out of 4" operation. $T_{design} = 320$ keV/N