TUNING A CW 4-ROD RFQ*

P.Fischer†, A.Schempp, IAP, J.-W.-Goethe-University
Max-von-Laue-Str. 1, 60438 Frankfurt, Germany

Abstract

A four-rod RFQ has been built, which operates cw and will accelerate 5mA D beams up to 3 MeV The length of the structure is 3.8 m, the power consumption as high as 250kW. The tuning of a four-rod RFQ with 30 RF-cells at the frequency of 176 MHz is difficult, so procedures have been developed to facilitate this work. The properties of the RFQ accelerator, the tuning procedure and the status of the project will be discussed.

INTRODUCTION

Classical continuous beam facilities do particle acceleration with electrostatic machines i.e. Tandem-van-de-Graff accelerators. The beam DC beam offers precise energy as needed for many experiments. But the beam current is low and the energy is limited. Beam current can get much higher by the use of a RFQ structure as injector. But like most room temperature RF accelerators, RFQs are driven in pulsed operation mode. They operate with high power for a short time and then get swiched off, i.e. $50\mu s$ - $1ms$ operation and repeat rate 0.1 - $50Hz$. The duty factor is mostly below 1%.

Difficult point of a CW-RFQ is the cooling. The power fed into the RFQ must be dissipated by a water cooling system. Reducing the input power is possible, but limited. A minimum electrode voltage – the electrode voltage U depends on the input power N by $(N \propto U^2)$ – is required for proper particle transport, focussing and acceleration. Thus, a CW-RFQ with low electrode voltage still needs a good power dissipation by a good water cooling system.

CW-RFQs can be used to upgrade conventional tandem-using or similar experiments that require a continuous beam. Some set-ups for i.e. coincidence or cross section measuring have detectors that get an overflow by the compact beam intensity of a RFQ in duty cycle mode. They require a lower, but constant beam.

The RFQ driven in CW-mode has another advantage: the design of beam line elements is done for the current peak value, which is lower at a CW-beam than at a pulsed beam, concerning the average beam current.

Furthermore, the development of high power machines like CW-RFQs leads to solutions for experiments or facilities with need of high mean beam currents. These could be accelerator driven fusion experiments or nuclear waste transmutation projects.

At the Institute of Applied Physics (IAP) in Frankfurt, Germany, the assembly of a four-rod RFQ structure for CW-mode operation was done [1]. The parameters are listed in Table 1. All mechanical work and the electrodynamic set-up is completed, water cooling system tests, vacuum tests and the conditioning process as well.

Table 1: Parameters of the CW 4-rod RFQ.

Injection/output energy	20 / 1500 keV/u
Isotope	deuterium
Frequency	176 MHz
electrode voltage	65 kV
RFQ length	3.8 m
inner diameter	280 mm
min. aperture	2.7 mm
max. modulation	2.7
power consumption	250 kW
input emittance $\epsilon_{x,y}$	160 π mm mrad
a / b	0.85 / 0.28 mm mrad^{-1}
number of cells	199
number of stems	40
long. output emittance ϵ_l	75 π deg. keV/u
transmission 0 / 5mA	98 / 96 %

RF TUNING

Electrode Voltage

Adjusting of the electrodynamic properties, e.g. a homogenious field distribution, is important for high power structures, because errors or inaccuracy of the adjustment must be compensated by rising the input power. Main part of the RF tuning is to get of a constant voltage distribution along the electrodes as assumed in the beam dynamics design of the RFQ. The voltage between the electrodes it is responsible for the beam acceleration and focussing. The principle of particle acceleration in a RFQ structure is tolerant to inaccuracies of the electrical field distribution. It applies up to a point from where particles will be lost because of insufficient focussing strength. The loss of particles can be caused by several modulation periods in which the voltage is to low. This acts as a bottleneck for the beam.

The simulation result in Figure 1 demonstrates a case, where the RFQ is detuned in a range of 10 cm which accords to 5 beam dynamic cells - the voltage there is only 70% of the mean electrode voltage. Focussing forces to the particles are to weak, some particles get lost and there is an immense rise of the phase error for nearly all particles - the bunch blows up, beam quality decreases. The transmission falls off from 99% to 85%. This causes particle losses that can be seen in the lower picture where particles

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† P.Fischer@iap.uni-frankfurt.de

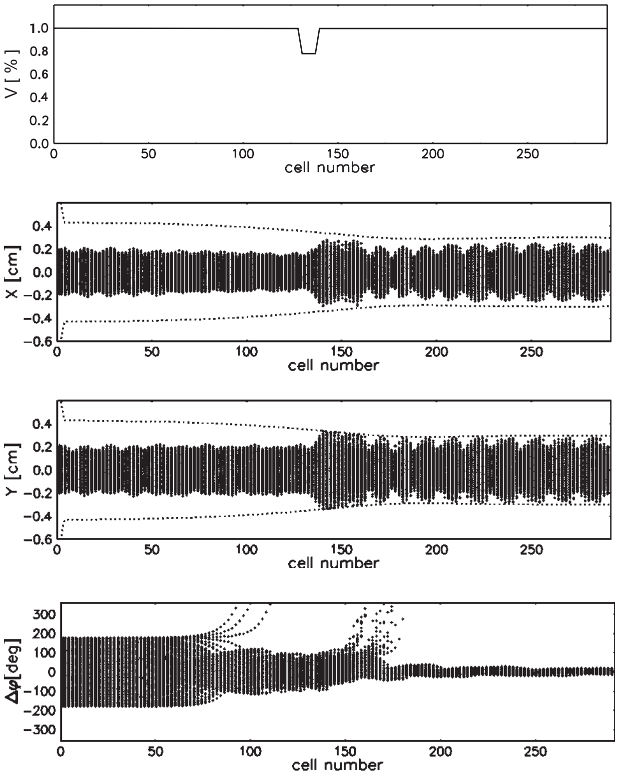

Figure 1: The effect of a perturbationin the electrode voltage distribution (first graph). In the middle of the structure, the voltage was reduced to 70% in defined range.

get out of phase. These particles hit the electrodes because of insufficient focussing forces, see picture in the middle.

The voltage distribution along the electrodes is called *flatness*. The goal of the adjusting progress is a constant flatness to avoid particle losses like shown in Figure 1.

RF Properties

Variations of the electrode voltage can be explained by taking the RFQ as a chain of coupled resonant circuits. There, current oscillates in each cell from one pair of electrodes with the same polarity to the others via the stems and the base plate. Thus, each RF-cell can be seen as a resonant circuit consisting of a capacity given by the electrodes and an inductivity loop of the stems and the base plate. Given by geometric data, a RF-cell has its own fixed resonance frequency.

If RFQ structure operates in resonance, currents and the magnetic field of neighbour cells are in opposite phase, the difference is 180. All circuits are coupled by their collective capacity, neighbour cells are also coupled by the magnetic field around each stem.

All cells have different resonant frequencies. The capacity, given by the electrode's distance - the aperture and modulation, changes along the structure. Especially at the ends of the RFQ structure, where the electrodes overlap a little, the additional capacity changes the resonant frequency. The RFQ operates at an average frequency of all cell's resonances. Thus, each cell is more or less detuned and that causes a different voltage on their electrode section. Generally, the flatness is not constant.

The flatness can be measured by the frequency shift caused by an additional field perturbation. Placing a small capacitor or just some dielectrical material between two electrodes changes the local frequency depending on the strength of the local field. A small electrode voltage and a weak field cause a small frequency shift. This shift allows the calculation of the local electrode voltage from the linear relation $\Delta f \propto U^2$. The R_p-value of the RFQ structure is

$$R_p = \frac{2Q\Delta f}{\pi f_0^2 C_s} \tag{1}$$

with the perturbation capacity C_s. With the mean input power $\bar{N}$, one gets $U^2 = R_p\bar{N}$. More information, studies and samples can be found in [4].

For the tuning progress, the goal is a constant voltage distribution. A relative distribution is sufficient and can be obtained by the method of perturbation capacitor measurings. For a complete flatness measurement, frequency shift Δf caused by a perturbation is taken for each cell. Then the voltage distribution for the structure is available and the correction progress can be started to tune all cells to the same frequency.

For an absolute value of the electrode voltage, an exact value for the capacitor is needed. But the calculation is only valid for small perturbations, and capacitors with small capacity have big tolerances. Thus, absolute measurements of the electrode voltage usual have a big error.

Tuning

Adjusting of the voltage distribution is done by a frequency tuning in each cell. A cell's resonant frequency is defined by the capacity of the electrodes and the inductivity of the stems and the base plate. The resonance can be changed by inserting a tuning plate. This frequency tuning is realized by a reduction of the inductivity. A *tuning plate* - see Figure 2 - is inserted into the cell which reduces the inductivity. Depending on the height of the plate, the resonant frequency changes and thus the electrode voltage at this RF-cell. But the effect of the tuning plate can be seen all over the structure[1] due to the coupling of the cells. A proper combination of tuning plates must be chosen to get a flat field distribution.

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Tuning plates have the highest power dissipation in the RFQ structure [3]. Thus, the base plate and the tuning plates are important parts of the cooling system. Aggravating, tuning plates need to be flexible to enable a good electrodynamic adjustment process.

[1]Calculations concerning the effect of a perturbation in a RFQ cell were done in [2]. The frequency change of each cell and the effect on the flatness were approximated by the use of an equivalent circuit.

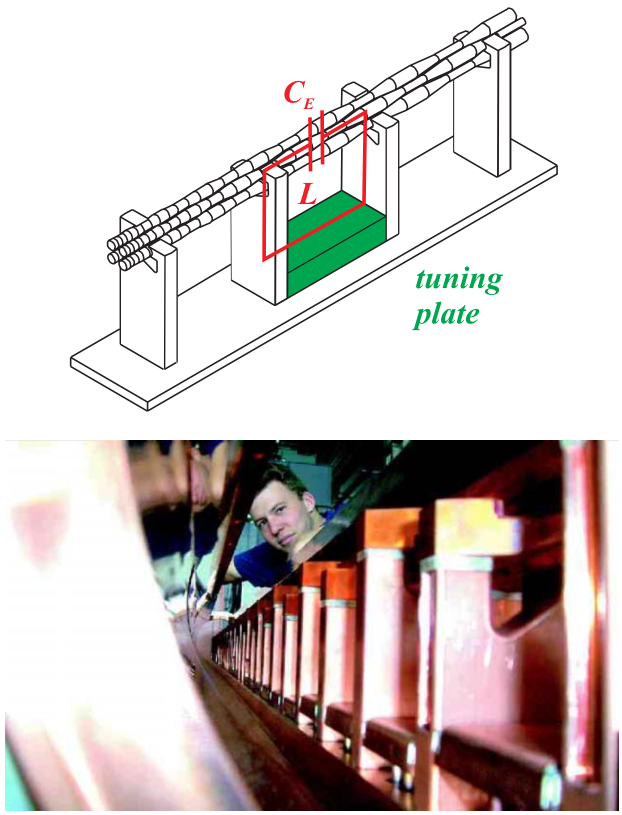

Figure 2: RFQ with 39 RF-cells and a tuning plate in each cell.

The CW-RFQ structure uses a tuning plate for each cell. They are individually water cooled and have silverplated sliding contacts at both sides for good electrical and thermal contact.

From the initial configuration without tuning plates, a arrangement has been found, that reduced the mean deviation of the electrode voltage to a minimum. Initial and final configuration are shown in Figure 3. In this structure, a tuning plate has a height of 15 mm.

CONCLUSIONS

It was possible to improve the flatness of the field distribution to a deviation of $< 2.5\%$. For this structure, R_p-value, electromagnetic energy and the estimated input energy for an electrode voltage of 65 kV could be measured. The results are summarized in Table 2. In the final state, tuner plunger's frequency shift was taken, transmission and reflexion at power coupler and pick-ups as well. A vacuum test and a test of the water cooling system were done. A RF-cleaning operation was performed with low input power up to 100 W.

The next step will be a high power test to operate with the design field levels which is planned for the 3. quater of 2006. Following, an ion source will be connected and first beam tests will be performed.

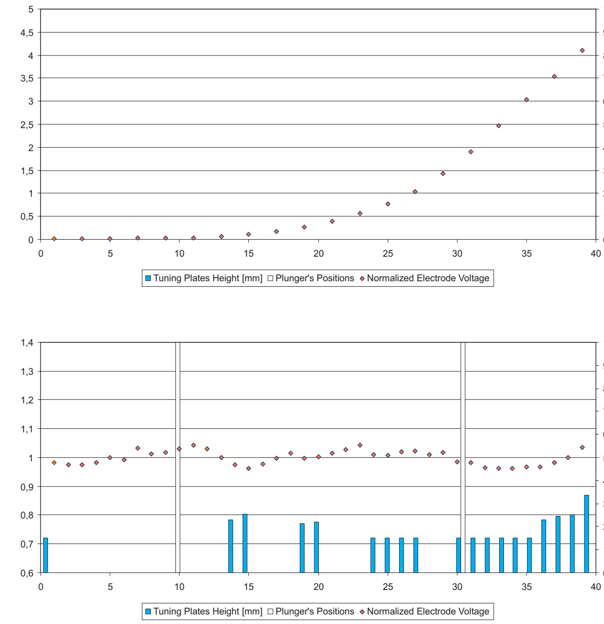

Figure 3: The electrode voltage distribution in the untuned, initial state and, below, the final tuning plate configuration with tuner plungers built in and high power coupling loop.

Table 2: Final parameters from low power measurements.

Duty factor Q	3750
R_p · length	106.4 kΩm
input power @ 65 kV	≈ 150 kW
electromag. energy (expected)	≈ 3 J
π-0-mode frequency	176.0 MHz
next HOM	180.6 MHz
Flatness mean error	< 2.5%
Tuner plunger shift (total)	1.1 MHz
Reflection power coupler	-43 dB
Transmission pick-ups	-55 dB

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