TUNING OF A 4-ROD CW-MODE RFQ ACCELERATOR*

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Abstract

A four-rod RFQ accelerator has been built which operates in CW mode with a power consumption of 250 kW. The assembly of a high power RFQ structure requires a precise mechanical alignment and field tuning of the electrode field. The field distribution must be very flat to enable a proper operation with few losses. Adjusting of the field distribution is critical in long structures. Simulations and the status of the tuned structure 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 at many experiments. There, the beam current is low and the energy is limited. Current and energy can get much higher by the use of a RFQ structure. In common, RFQs are driven in a duty cycle, they operate with high power for i.e. 5% of the time and then get swiched off. In that way, the structure does not get to hot. Difficult at the built-up 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 ($U^2 \propto N$) – is required for proper particle 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 extend 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.

Comparing a RFQ in CW-mode with one driven in duty cycle mode concerning the whole beam line gives another advantage: all beam line elements must be designed for the highest possible beam currence. Thus, elements for a beam line in duty cycle mode are more extensive than those of a CW-mode beam line with the same mean currence.

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 is in progress [1]. All mechanical work and the electrodynamic set-up is done, water cooling system tests, vacuum tests and the conditioning process as well.

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FUNDAMENTALS

Electrode Voltage

Adjusting of the electrodynamic properties is important for high power or temperature critical structures, because errors or inaccuracy of the adjustment must be compensated by rising the input power. Main part of the electrdynamic adjustment is the assuring of a constant voltage distribution along the electrodes. The voltage between the electrodes causes the electric field in the beam volume, it is responsible for the beam acceleration and focussing. The principle of particle acceleration in a RFQ structure allows some inaccuracies of the electrical field, because of self-controling mechanisms. This applies up to a specific point from where particles will be lost because of insufficient field strength. The loss of particles can be caused by a single RFQ cell where the voltage is to low. This cell can be seen as a bottle neck for the beam.

The simulation picture in figure 1 demonstrates a case, where one of 40 RFQ cells is detuned - 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 to nealy all particles - the bunch blows up, beam quality decreses. At that point, the transmission falls off from 99% to 85%.

Table 1: Characteristics of the four-rod RFQ for CW-mode.

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 %

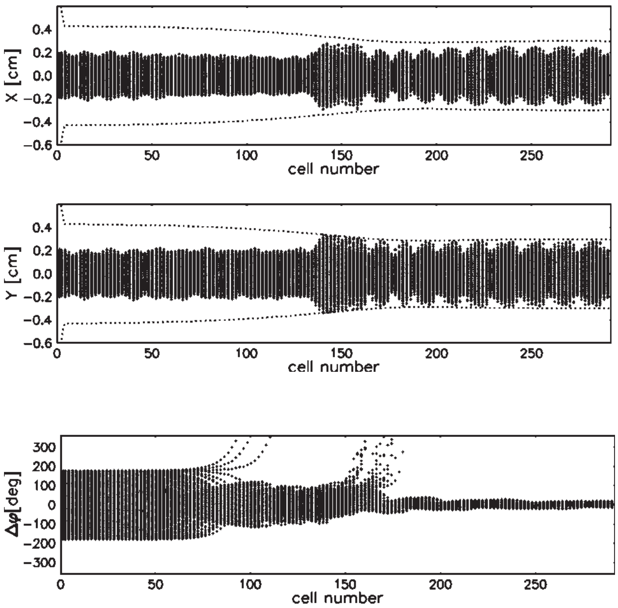

Figure 1: Here, the effect of an unconstant electrode voltage distribution can be seen. In the middle of the structure, the voltage was reduced to 70% in a small range. This causes particle losses that can be seen in the lower picture where particles get out of phase. These particles get stuck in the electrodes because of insufficient focussing forces, see picture in the middle. From that point on, many particles are out of phase, the beam volume grew. The label "cell number" on the y-axis corresponds to particle dynamic's cells, not the RF cell.

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

RF Behaviour

Values of the electrode voltage can be explaned by taking the RFQ as a construct of many coupled resonant circuits. There, current oscillates in each cell from one pair of electrodes (which are of the same polarity) to the other via the stems and the base plate. Thus, each cell can be seen as a resonant circuit consisting of a capacity given by the electrodes and an inductivity in terms of the stems and the base plate. Then, the magnetic field arises in the cell's volume between the stems, the electric field is located between the four electrodes as a quadrupole field. Given by geometric data, a cell has its own fixed frequency of resonance.
The RFQ structure is driven in the π-0-mode. That means, neighbour cells are driven in opposite phase, the difference is 180°. All circuits are coupled by their collective capacity, neighbour cells are also coupled by the magnetic field which comes out as a circle around each stem.
In fact, all cells have a separate, little differing resonant frequency. The capacity, given by the electrode's distance - the aperture, changes along the structure. Also at the ends of the RFQ structure, where the electrodes project a little, this additional capacity changes the resonant frequency. At all, the RFQ operates at a mean frequency of all cell's resonances. Thus, each cell is more or less detuned and that causes a different voltage on their capacity in terms of the electrodes. Altogether, the flatness is not constant.

Measure of the Voltage Distribution

The flatness can be measured by the frequency shift of the whole strucure caused by a field perturbation. Placing a very small capacitor or just some dielectrical material with $\epsilon_r >> 1$ and $\mu_r = 1$ between two electrodes changes the domain frequency depending on the strength of the perturbated field. A small electrode voltage and a weak field cause a small frequency shift. This shift lets one calculate[1] the local electrode voltage from the linear relation $\Delta f \propto U^2$. For an absolute value of the electrode voltage, a precise capacitor is needed. But the calculation is only valid for small perturbations, and capacitors with small capacity have big tolerances. Thus, absolute measureings of the electrode voltage usual have a big error. 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 measureings.
For a complete flatness measure, the perturbated and the not perturbated domain frequency is taken for each cell. The capacitor is placed above the first cell, then the frequency shift is acquired, implying the local voltage. Then this step is repeated for each cell. Finally, the voltage distribution for the whole structure is avaliable and the correction progress can be started.

Tuning

Adjusting of the voltage distribution is done by a frequency tuning in each cell. This frequency tuning is realised by a reduction of the magnetic field. A short cut is inserted into the cell, current passes now the so called *tuning plate* - see figure 2 - insead of the base plate. Depending on the width of the plate, the current path can be reduced at will, the resonant frequency changes and thus the electrode voltage at this place. But the effect of the tuning plate is not reduced to cell where the plate is built in, its effect can be seen all over the structure[2]. A good combination of tuning plates must be choosen to get a configuration that results a flat field distribution.

[1] The calculation of the voltage requires to know the R_p-value of the structure. It is $R_p = \frac{2Q\Delta f}{\pi f_0^2 C_s}$ 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 are to find in [4].

[2] Calculations concerning the effect of a perturbation in a RFQ cell were done by J. X. Fang and A. Schempp in [2]. There, the frequency change of each cell and the effect on the flatness were approximated by the use of an equvalent circuit.

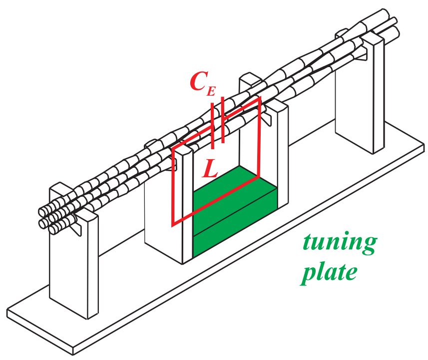

Figure 2: Scematic view on a RFQ. Each cell's resonant frequency is defined by the capacity (electrodes) and the inductivity (stems and base plate). The resonance can be changed by inserting a tuning plate.

RFQ TUNING

Tuning plates are the most heat critical part of a RFQ structure. The biggest power dissipation is located at the surfaces of the highest current density. Thus, cooling of the base plate or, if in use, the tuning plates is a main thread of the cooling system. Aggravating, tuning plates need to be flexible to enable a good electrodynamic adjustment process.

The RFQ structure built up at the IAP includes a tuning plate for each cell. All 39 plates are separately water cooled and have a sliding contact at both sides. The contacts have special material properties, flexibility needs to be preserved also at high temperatures. For the better electrical and thermal contact, the sliding contacts are silverplated. Publication [3] gives a view on the thermal development and critical states of a tuning plate.

From the initial tuning plate configuration, where no tuning plates are built in, a state could be 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 width of 15 mm, this is the minimum built-in height that is possible.

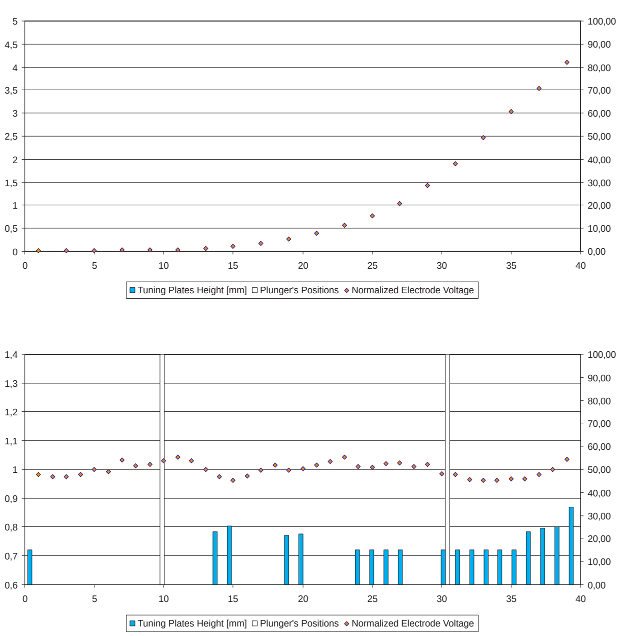

Figure 3: The electrode voltage distribution in the untuned, initial state and, below, the final tuning plate configuration with tuner plungers built in and high power coupling loop.

CONCLUSIONS

It was possible to advance the flatness from a very unconstant initial state to a flat distribution with only little deviation by the actual tuning plate configuration. From this state, R_p-value, electromagnetic energy and the estimated input energy for an electrode voltage of 65 kV could be acquired. The results are resumed 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 has been successful, also a test of the water system was positive. A conditioning operation was performed with low input energy up to 100 W.

Outlook – The next step will be a high power performance test to verify the functionality of the cooling system, studies on the temperature developement will be done. After this preparal step, an ion source can be connected and first beam tests will be performed.

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[4] A. Bechtold, "Aufbau eines Schwerionen-RFQ-BNeschleunigers mit hohem Tastverhaeltnis", diploma thesis, August 1997, IAP, Frankfurt, Germany, p.61.

Table 2: Final parameters after low energy measurings.

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