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RESULTS OF THE HIGH POWER TEST OF THE 325 MHZ 4-ROD RFQ PROTOTYPE*

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Abstract

For the FAIR proton linac at GSI a 325 MHz 4-rod RFQ prototype has been built. On this prototype RF measurements have been carried out. After low power conditioning in cw mode the structure was high power tested in pulsed mode. During the performance tests the 6 stem prototype was optimized and has shown the feasibility of a dipole free 4-rod RFQ at high frequencies and was testet up to 120 kW per meter. In this tests the input power and the electrode voltage was observed using gamma spectroskopy. From this the shunt impedance was calculated and compared to other methods of measurements. The power test results are presented in this paper.

PROTOTYPE

Overview

The 325 MHz 4-rod RFQ prototype (see Fig. 1) for the FAIR proton linac is a 6 stem model made in the in-house workshop of the Goethe University Frankfurt. The structure is made from copper and has a water-cooled ground plate. The low level RF measurements and the low power conditioning is described in [1].

After low power conditioning some problems occur with the prototype. The cooling channel was made with a milling machine on the top of the ground plate and brazed with a copper lid (see Fig. 2). The cooling water was not available at the time of the low power conditioning. This has lead to problems with the structure during low power conditioning or at the beginning of the hight power tests. Either to much temperature or RF sparking due to the rough surface of the simple copper model has led to a dissolving of the brazing solder and sprinkling it to the stems of the prototype. As long as this was undiscovered the high power conditioning was continued up to power of 12 kW. Then a second problem occurred at the circulator. Between a forwarded power of 8 kW to 12 kW sparking inside the circulator stopped the high power test. While the circulator was repaired by the manufacturer the break was used to optimize the RFQ structure.

Figure 1: 4-rod RFQ Prototype after optimization.

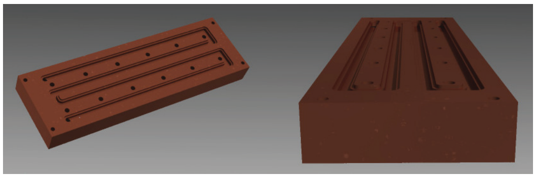

Figure 2: Autodesk drawing of the groundplates water channel.

Optimization

The water cooling was not tight anymore, due to the sprinkling of the brazing solder. Since the brazing of the cooling channel was very complicated and the duty cycle of the structure is anyway below 1 % it was decided to replace the ground plate with one made of solid copper without cooling possibilities. Also the tuning blocks that have brazed silver springs to contact the stems have been replaced by new ones. The solder sprinkles on stems needed to be removed by the workshop. The whole prototype was dismantled and polished. After reassembling the prototype the RF setup needed to be done again and was optimized as well. Table 1 shows the RF parameters before and after the optimization. An improvement of the RF behavior could be reached through successful tuning of the longitudinal voltage distribution (flatness) and the dipole adjustment. Also the polishing and cleaning of the connections of the structure lead to an better conductivity and improved the quality factor and the shunt impedance. Also the coupling of the power coupler was enhanced from -20 dB to -30 dB reflection.

Table 1: RF Parameter of the Prototype before and after Optimization

Parameter	**before Optimization**	**after Optimization**
Flatness	± 1.6 %	± 0.02 %
Dipole	3 %	2 %
Quality Factor	2400	2800
Shunt Impedance	46,8 $k\Omega$	54,6 $k\Omega$

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The low power conditioning was carried out with a 50 W amplifier in cw operation starting in the mW region rising the power levels very slow over several days up to 50 W.

High Power Test

The high power test was done with a 40 kW amplifier by DB Elettronica in pulsed mode. The RF pulses had a length of 1 ms with a 300 ms pause time. The duty cycle of the proton Linac at GSI would be even lower. The long lasting power conditioning lead to an improved behavior of the structure by switching to higher power levels in pulsed mode. The RFQ was accepting RF power over 30 kW without any sparking or other problems. This could also be recognized by a very stable pressure during rising the input power, due to a better cleaning of the parts. During the high power tests also no sparking was recognized at the circulator anymore. While this tests the electrode voltage was determined using gamma spectroscopy at different power levels to calculate the shunt impedance. Since the RFQ was not water cooled, the frequency needed to be adjusted according to thermal behavior of the resonator. Except this no weakness of the prototype was observed during high power operation.

MEASUREMENT OF THE SHUNT IMPEDANCE

The shunt impedance R_p is an important RF parameter of RFQ structures. It correlates with the maximal electrode voltage U_{max} and the average dissipated power $\overline{N}$.

$$R_p = \frac{U_{max}^2}{\overline{N}} \tag{1}$$

The shunt impedance describes the efficiency of the structure to convert RF power into the electric field between the electrodes. A high shunt impedance is associated to high efficiency.

The R_p-value is a length dependent value. With

$$R_p = \frac{2Q}{\omega_0 C} \tag{2}$$

it depends on the total capacitance and increases with the length of the electrodes. In order to compare RFQs of different lengths a parameter which does not depend on the length is necessary. Often the R_{pL}-value is used

$$R_{pL} = R_p \cdot L \qquad [\Omega m] \tag{3}$$

Perturbation Capacitor

The shunt impedance of an RFQ can be measured at low RF level by adding a known perturbation capacitance onto the electrodes [2]. This leads to a change of the resonace frequency

$$\omega_0^* = \omega_0 - \Delta\omega = \frac{1}{\sqrt{L(C + \Delta C)}} \tag{4}$$

and can be written as

$$\frac{\Delta\omega_0}{\omega_0} = \frac{\Delta W}{W} = 1 - \frac{1}{\sqrt{1 + \frac{\Delta C}{C}}} \approx \frac{\Delta C}{2C} \tag{5}$$

With formula (2) and the definition of the quality factor the equation can be written as

$$R_p = \frac{2 \cdot Q \cdot \Delta f}{\pi \cdot \Delta C \cdot f_0^2} \tag{6}$$

The perturbation capacitance has to be small in comparison to the electrodes capacitance. Capacitances of 1 pF, which are the smallest commercial capacitances, have rather big production variation of 20 % [3]. Furthermore the 325 MHz region makes the RFQ quite sensitive to the additional perturbance, which leads to large errors of this measurements. Measurements gave a shunt impedance of 123.4 $k\Omega$. This is quite unrealistic because the shunt impedance of RFQ structures scales with $R_p \propto f^{(-3/2)}$. From comparison of many different operating RFQs the shunt impedance should be clearly below 100 $k\Omega$ (see [1], [4]).

This high value of the shunt impedance is due to a large perturbation of the capacitance. Usually this measurements fit with the energy consumption of the RFQ structures. But measurements have been mostly carried out at structures that are less sensitive to perturbation due to frequencies below 200 MHz and much larger electrode capacitance not only due to larger electrode length. The perturbation of the capacitance was about 7 MHz at the very short 325 MHz prototype however it is usually at least clearly below 2 MHz or even around 200 kHz.

To verify the shunt impedance further methods to determine the R_p-value have been investigated.

Gamma Spectroskopy

At high RF level one can determine the shunt impedance directly by measuring the intervane voltage and the RF power level using formula (1). The voltage can be measured by gamma spectroscopy. Electrons that are produced at one electrode by residual gas ionization are accelerated by the electric field of the intervane voltage. When these electrons hit the copper of the other electrode bremsstrahlung is generated. This continuous γ-spectrum is measured with a semiconducting detector, which was calibrated with an Am^{241}-probe. Americium emits photons with energies of 26.4 keV and 59.6 keV.

Measurements of the intervane voltage have been carried out at different RF power levels. These measurements are summarized in Fig. 3.

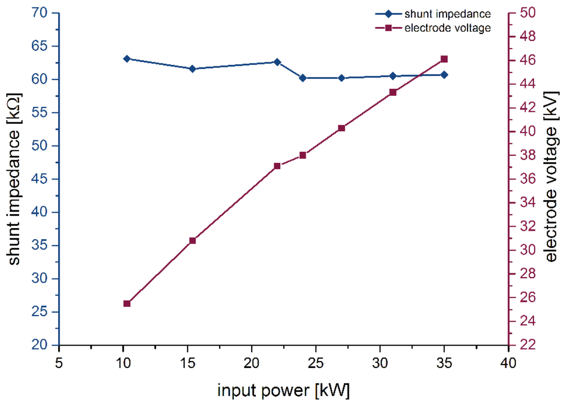

Figure 3: Measurements of the electrode voltage and shunt impedance using gamma spectroscopy on different input power levels.

From these measurements the shunt impedance was determined using formula (1). A mean value for the R_p-value is $(61.3 \pm 7)\ k\Omega$. The errors in these measurements are due to a slight thermal drift of the resonator which was not cooled resulting in instabilities of the RF power amplitude.

R/Q-*Value*

A another way determining the shunt impedance is the comparison of the R/Q-ratio of CST Microwave Studio® simulation results with measurements. By experience this gives one quite accurate results because the ideal behavior of simulations is reduced in the fraction R/Q. This ratio in addition with an accurate measurement of the quality factor gives one the shunt impedance.

$$\frac{R_{sim}}{Q_{sim}} = \frac{R_{meas}}{Q_{meas}} \Rightarrow R_{meas} = \frac{R_{sim}}{Q_{sim}} \cdot Q_{meas} \tag{7}$$

With this method the shunt impedance of the 325 MHz 4-rod RFQ prototype was calculated to 54.6 $k\Omega$. This value fits quite well with the results of the gamma spectroscopy measurements.

Summary

The R_p-values determined by the different measurement methods are summarized in tabular 2.

Table 2: Comparison of Shunt Impedance Measurements

Method	**R_p-Value**	**Error**
Perturbance Capacitance	123.4 $k\Omega$	± 61.7 $k\Omega$
Gamma Spectroscopy	61.3 $k\Omega$	± 6.7 $k\Omega$
R/Q-Comparison	54.6 $k\Omega$	± 4.4 $k\Omega$

By experience perturbation capacitance method works quite well if the disturbance is small in comparison to the overall electrode capacity. In this case a perturbation of several MHz results in errors of 30 % in addition with the error of 20 % of the small capacitance of 1 pF. This measurement is not usable for this prototype but might work if the RFQ would be build with a length of 3 m. This would increases the electrodes capacitance by a factor of 10 bringing back the requirement of a small perturbation over the total capacitance.
The R/Q-comparison delivers good results that fit with the values from gamma spectroscopy. Optimization of the measurements could be done by improving the determination of the dissipated power in the resonator. By cooling the RFQ the frequency would be more stable as well as using calibrated power meters might deliver even more sufficient results. Altogether a shunt impedance of around 60 $k\Omega$ fits with the comparison of many operating RFQs worldwide in [1, 4] and is a quite good result for the prototype.

CONCLUSION

The 325 MHz 4-rod RFQ prototype has been revised what successfully enhanced the RF performance of the structure. A slow and persisting low power conditioning has lead to an acceptance of high RF levels without any difficulty. With the determination of the gamma spectra at different RF levels the shunt impedance was calculated. These results have been compared to other methods to determinate the R_p-value. In addition high power tests have shown that the prototype accepts power levels of about 120 kW/m without any problems.

REFERENCES

[1] B. Koubek, H. Podlech, A. Schempp, J. Schmidt, “Power Tests of the 325 MHz 4-rod RFQ Prototype”, IPAC’13, Shanghai, May 2013, THPWO018 (2013) `http://jacow.org`

[2] A. Schempp “Beiträge zur Entwicklung der Radiofrequenz (RFQ)-Ionenbeschleuniger”, Habitilationsschrift 1989

[3] J. M. Maus “Development of RFQ Particle Dynamics Simulation Tools and Validation with Beam Tests”, Dissertation 2010

[4] T. Sieber, “Entwicklung von 4-Rod- und IH- Radio- Frequenz-Quadrupol (RFQ)-Beschleunigern für radioaktive Ionenstrahlen bei REX-ISOLDE und MAFF”, PhD Thesis, 2001, München, Germany

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