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DESIGN OF THE 325 MHz 4-ROD RFQ FOR THE FAIR PROTON LINAC*

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Abstract

Investigations on the 325 MHz 4-rod RFQ prototype for the FAIR proton linac have confirmed the feasibility of a 4-rod RFQ to work at frequencies above 300 MHz. This RFQ will accelerate protons from 95 keV to 3 MeV [1] within a length of 3.3 m and will be powered by a 2.5 MW klystron. The mechanical and rf design of this RFQ are presented in this paper.

325 MHz 4-ROD RFQ R & D

In simulations the dipole field, the fringe fields and higher order modes were investigated to find a solution for an rf design to fit a 4-rod RFQ to an operation frequency of 325 MHz. Based on this simulations a copper prototype was built and investigated as well. The results of the low level rf measurements confirmed the simulation work quite well and are presented in [2,3]. After the rf measurements the 6 stem prototype was power tested with 40 kW and a duty cycle of 0.3% that refers to a cw power of 400 W/m. At the FAIR project the 3.3 m RFQ will be powered at a duty cycle < 0.1% [4]. This tests have shown the feasability of the prototype to meet the FAIR requirements. Apart from this the input power was measured in comparison to the maximum electrodes voltage using gamma spectroscopy. From these measurements results the shunt impedance was determined and compared to other methods of determination of the shunt impedance to confirm their reliability. In summary these tests have demonstrated a working 325 MHz 4-rod RFQ without a dipole component that meets the FAIR requirements.

Challenges

Since higher frequencies refer to smaller dimensions of the resonant structure a 4-rod RFQ at 325 MHz becomes very small and sensitive with respect to parametric changes. This filigree and sensitive structure is very challenging for the engineering and requires very tight tolerances in manufacturing of every single part of the RFQ. In respect to rf this transversally small structure leads to a dipole component much stronger than at lower frequencies. In longitudinal direction the RFQ has a length above 3 m with approximately 60 rf cells. This leads to higher order modes in the region of the operation frequency that usually can be neglected at 4-rod RFQs. In addition this large number of rf cells makes the tuning procedure much more elaborate than usual.

ENGINEERING AND DESIGN

To reach a higher precision of the RFQ in the manufacturing process changes of the mechanical design, that worked very well over the last years on 4-rod RFQ at lower frequencies, were crucial. To reach a higher precision the idea was on the one hand to simplifiy all parts of the RFQ with respect to machining reasons and on the other hand to reduce the number of connected surfaces to increase the precision after assembly.

For example the stems and ground plate will be made of one piece of copper. This combination will be segmented in only few segments to form the support and resonant structure for the electrodes. To build this out of one or few pieces allow not only a higher precision in machining the surfaces that mount and connect the electrodes. In addition it provides also a better thermal and electrical connection of the single parts. Also the shape of the electrodes will be kept more simple to increase precision and stabillity of the filigree parts.

TUNING

General Tuning Process

In general the tuning of a 4-rod RFQ is an iterative process were a perturbance capacitor is placed on every single rf cell of the structure. From the frequency shift caused by this additive capacitance the longitudinal voltage distribution of the RFQ can be calculated. Then the tuning plates will be moved in such a way to minimize the longitudinal voltage deviation. This process has to be repeated several times to find a best match of the operating frequency and simultaneously a minimum longitudinal voltage deviation.

Additional to the large number of rf cells the frequency of 325 MHz causes a high sensitivity of the tuning plates that have to be placed very accurate (in sub millimeter range).

Simplification of the Tuning

In order to simplify and hence abbreviate the above mentioned process one can reduce the number of rf cells. This can be done by increasing the thickness of the stems but it only allows a limited reduction of the number of rf cells.

To reduce the sensitivity of the tuning plates the influence of plunger tuners instead has been investigated. While tuning plates change the inductivity of an rf cell by changing the length of the shortcut, plunger tuners are suppressing the field inside one rf cell. These kind of tuner have been used already as additional tuning possibilities at the FNAL RFQ [5]. Simulations of piston tuners have shown a strong reduction of the tuning range. The fact that the frequency is less sensitive on these plungers leads to a much higher precision of adjustment by keeping still enough frequency

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range to properly tune the RFQ. In Fig. 1 the usual tuning plates influence on the resonant frequency and on the dipole field is compared to plunger tuners.

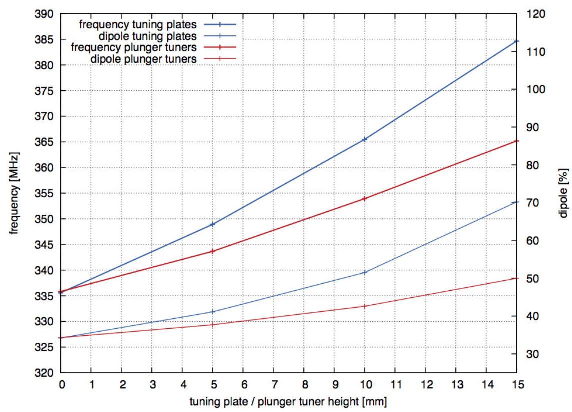

Figure 1: Comparison of common tuning plates with plunger tuner in respect to their influence on the resonant freqeuncy and the dipole field of the RFQ.

By considering a tuning range of 5 mm the tuning plates change the frequency about 13.34 MHz while the plunger tuners change the frequency by about 7.84 MHz. A further benefit is that the influence on the dipole growth with the tuner height is much less with the plunger tuners than with the tuning plates. In the 5 mm tuning range the plungers increase the dipole of about 3.3 % while it is about 6.4 % with the tuning plates. By regarding this graph it should be mentioned that this model was not dipole compensated yet in order to study the compensation procedure. In summary the influence on the frequency and on the dipole field of the tuning plates is about twice as much than of the plunger tuners.

Usually the tuning plates are connected to the stems with silver plated copper springs. When the final setting is reached through the tuning process their correct placement is fixed with distance blocks under the tuning plates. This adjustment is very coarse im comparison to the plunger tuners. The plunger tuners are just put in the rf cells. They can be machined very accurate and in addition different heights, sizes and shapes can be chosen to match the best tuning results. While or after the tuning they will be fixed in the rf cells with silver-plated screws.

Fig. 2 shows different possible plunger tuners, which influence on the frequency and the dipole field have been simulated with CST Microwave Studio®.

According to the size of the tuners the strength of the influence can be varied. The results have also shown a very linear influence on the frequency with the hight of the tuner, that have a flat top. This linear behavior makes it easier for calculating and predefining its influence during the tuning process, but this can also be increased, if needed, by a more spheric shape of the tuners.

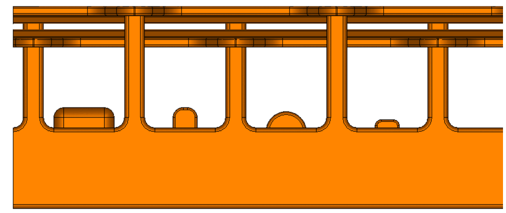

Figure 2: Different size and shapes of plunger tuners.

As an example, if it would be required to tune the frequency about 2 MHz to the objective frequency with the smallest plunger tuner in 50 cells, it would increase the dipole by about 1 %. By previously determining this the structure can be built dipole overcompensated, which can result in a dipole close to zero after tuning.

DIPOLE

The dipole field results from intrinsic asymmetries of a 4-rod RFQ, but it is an effect that can often be neglected at lower frequencies. An rf cell of a 4-rod RFQ can be described by capacitively shortened $\lambda/4$ resonator. As one can see in Fig. 3 the voltage distribution of a 4-rod RFQ stem is an almost linear function of the stems height. That means the upper two electrodes gain more voltage than the lower ones.

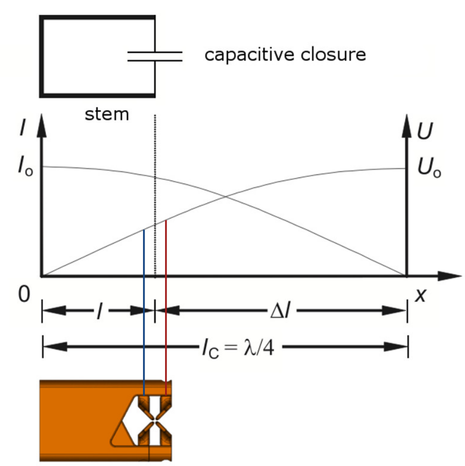

Figure 3: Description of one rf cell of an 4-rod RFQ as capacitively shortened $\lambda/4$ resonator.

With a larger resonant frequency and hence smaller geometric dimensions this effect gets relatively more relevant. To reduce the dipole field the stem shape needs to be varied in a way to provide more space for magnetic field that can evolve to increase charge transport to the undersupplied lower electrodes. This is described in more detail in [6]. Another approach is to adjust the current paths of the upper and lower electrodes to the same length like it is shown in Fig. 4 on the left side. As a third possibility this can also be

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realized by a stem displacement to the left and right side in an alternating way of the adjacent stems (see Fig. 4 right).

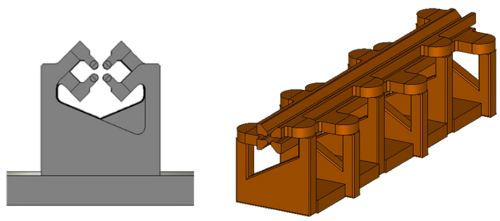

Figure 4: Approaches on dipole compensation. Adjustment of the current paths (left) and stem displacement (right).

Simulations have shown that this is not only reducing the dipole fraction, in addition it helps to separate the first higher order mode above the operating mode. Within a certain range the displacement leads to an increase of the first HOM and a decreases of the operating mode. This can provide an additional mode separation up to 500 kHz. Another advantage of the stem displacement is that is supplies more freedom for the design surrounding the electrodes area. The inner stem shape can be less steep what leads to less capacitances at the lower electrodes backsides. The smaller electric fields in this area results in less losses during operation.

TUNING AND ASSEMBLY PROCEDURE

In order to have only less tuning effort it is planned to manufacture first a full scale RFQ model made of aluminum including the real modulation of the electrodes[1]. On this aluminum RFQ first the influence of the different plunger tuners will be determined and compared with the simulations results. Then the tuning will be executed in a way, that the shape of every rf cell can be determined and adapted to the later copper model. The result of the full scale copper RFQ should then be an RFQ that has almost its final longitudinal voltage distribution and operation frequency. Only less fine tuning will be required for the rf setup. This, in addition, has the advantage that the shape of the rf cells is optimized to its current paths and the surface currents are only disturbed by a small number of plunger tuners.

CONCLUSION

The advantages are that the tuning iterations of final copper model, that will be assembled in a tank with limited access, can be minimized. This is realized by the pre-tuning and the higher accuracy of determination of the needed tuners distribution. Also the adjustment of a frequency change of a single rf cell has an unprecedented accuracy for 4-rod RFQs and the growth of the dipole field by tuning is kept as low as possible due to the small plunger tuner sizes.

OUTLOOK

The optimized mechanical design including the calculations to rf and dipole fields is planned to be finished by the middle of 2015. Then the machining and assembly of the full scale aluminum 325 MHz 4-rod RFQ model is planned to be finished by the first half of 2016. After the rf pre-tuning the pLINAC RFQ copper structure will be finished by the beginning of 2017.

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[1] In oder to save calculation time and increase accuracy of the calculation results, most calculation are made without a modulation of the electrodes but a mean and weighted aperture and electrodes radius calculated from the beam dynamic design instead.