STATUS OF THE MODULATED 3 MeV 325 MHz LADDER-RFQ*

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Abstract

Based on the positive results of the unmodulated 325 MHz Ladder-RFQ from 2013 to 2016, a modulated 3.3 m Ladder-RFQ is currently under construction and will be tested with beam at GSI FAIR, Darmstadt.

The unmodulated Ladder-RFQ showed a very constant voltage along the axis. It could withstand more than 3 times the operating power of which is needed in operation at a pulse length of 200 μs. That corresponds to a Kilpatrick factor of 3. The 325 MHz RFQ is designed to accelerate protons from 95 keV to 3.0 MeV according to the design parameters of the p-linac at FAIR. This particularly high frequency for a 4-Rod – type RFQ creates difficulties, which are challenging in developing an adequate cavity. The results of the unmodulated prototype have shown, that the Ladder-RFQ is a suitable candidate for that frequency. Inspired by the successful RF power test, the nominal vane-vane voltage was increased from 80 kV to 96 kV.

The basic design and tendering of the RFQ has been successfully completed in 2016. Electrodynamic simulations of a modulated full structure, especially in terms of field-flatness and frequency tuning, are shown. Furthermore, the mechanical design, which includes a direct cooling of the structure for duty cycles up to about 5%, will be discussed.

INTRODUCTION

The idea of the Ladder-RFQ firstly came up in the late eighties [1, 2] and was realized successfully for the CERN Linac3 operating at 101 MHz [3] and for the CERN antiproton decelerator ASACUSA at 202 MHz [4]. Within the 4-Rod design the challenge is to minimize dipole components and to have geometrical dimensions which are suitable for mechanical manufacturing and assembling. At frequencies above 250 MHz the 4-Vane-type RFQ is used so far, and many versions for low and high duty factors have been realized successfully until now. Draw backs are the high costs per meter, the complexity as well as the challenging RF tuning procedure of that structure: The dipole modes tend to overlap with the quadrupole mode. Safe beam operation conditions result in ambitious mechanical vane tolerances. In the proposed Ladder-RFQ version, the ladder spokes have a significant vertical width, which increases the resonance frequency and results in an homogeneous current flow towards the mini-vanes. The mini-vanes are embedded via precisely machined carrier rings into the copper shells (Fig. 1). It is even possible to exchange the ring-mini-vane-structure completely by an improved electrode system as demonstrated successfully at the GSI High Current RFQ [5]. To proof the mentioned advantages and the realizability of the Ladder-RFQ, an unmodulated prototype was designed and built from 2013 until 2016. Further details of the mechanical layout can be seen in [6, 7]. The successful high power measurements are presented in this paper. The very good results motivated the design and manufacturing of a modulated prototype at its full length of approximately 3.3 m. The status of its design as well as field simulations including a modulation of the electrodes are also shown in this paper.

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HIGH POWER MEASUREMENTS OF THE UNMODULATED PROTOTYPE

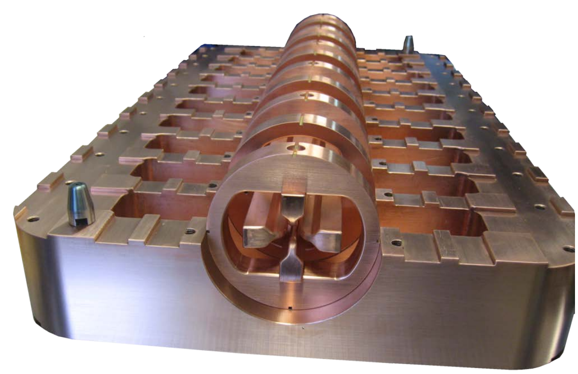

Figure 1: Front view of the ring-electrode-system of the unmodulated prototype. The steel-tank and the upper half-shell are removed. Ladder dimensions: LxHxB: 650x150x365 mm.

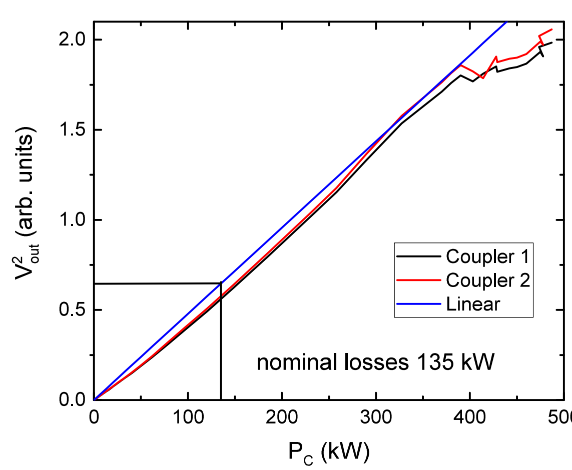

Figure 2: Results of the high power tests of the unmodulated prototype. The forward power up to 487 kW is shown in black. The RFQ accepted the power as the reflected power is stable along the flat top being lower than 3.34 kW. The RFQ is slightly over-coupled.

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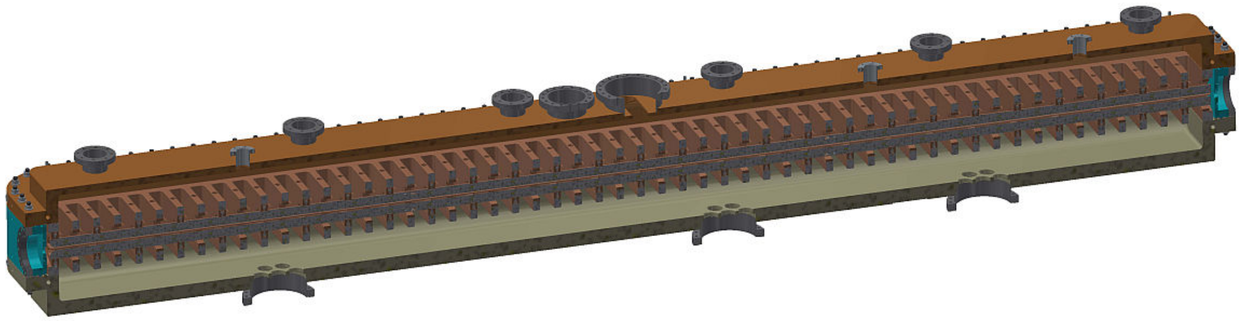

Figure 3: Isometric view of the 3.3 m modulated Ladder-RFQ prototype. The copper carrier-rings guarantee the electrode positioning as well as the RF contact. The ladder structure consists of bulk copper components. Any brazing or welding processes were avoided for the assembly of the main components. In total three TMP700 at the lower side of the RFQ provide a vacuum in the 10^{-8} mbar range. The entrance and exit flanges are milled out to achieve a shorter distance for the integration of cone and steerer preventing an emittance growth.

At the GSI 325 MHz klystron test stand the unmodulated Ladder-RFQ prototype with an electrode length of 630 mm was tested with a forward power up to 487 kW at a repetition rate of 2 Hz and a pulse duration of 200 µs (Fig. 2) [8] [1]. That exceeds the designed RF power at an electrode voltage of 80 kV during normal operation by a factor of 3.6. The averaged power reached 200 W, which is about 50% more than the thermal loss during normal operation. The Kilpatrick factor went up to 3, compared to 1.6 at design level. As anticipated, the stored energy increases linearly with the forward power up to 400 kW. At higher energies up to 487 kW, the stored energy begins to rise slower due to field emission. During the power tests it was clearly recognized that more time for conditioning can further reduce the dark current levels. In nine days of high power measurements the surface of the copper structures has changed its color slightly but has not been damaged. The surface remained smooth and non abrasive. The successful power tests of the prototype justify an increase of the electrode voltage from 80 kV to 96 kV for the modulated version. The low-level RF measurements such as frequency spectra, frequency tuning and field flatness for the unmodulated cavity were presented in [9]. The first HOM of the prototype is measured at 378 MHz.

MECHANICAL LAYOUT OF THE MODULATED PROTOTYPE

The mechanical design consists of an inner copper ladder structure mounted into an outer stainless steel tank. The tank is divided into three parts: A lower half-shell carrying the inner resonating structure, a middle frame and the upper half-shell (Fig. 3). The lower half-shell will carry and fix the position of the resonating ladder structure. The ladder structure is machined from solid copper blocks. It consists of two lower and two upper half-ladder elements, which are precisely aligned via guide pins (cf. Fig. 1). The RF features are mainly determined by the resonating structure, while the dimensions of the tank have no significant influence on the frequency. Based on the successful high power tests of the unmodulated prototype it was decided to develop a new beam dynamics with an increased electrode voltage of 96 kV [10]. The basic physical and mechanical parameters of the Ladder-RFQ results are shown in Table 1. Besides water-cooling channels within the upper and lower tank half-shells, the RFQ is equipped with a direct cooling of the ladder side rails. Along the side of all half-ladders a groove is milled (8 channels in total). The groove will be closed by a cover bar from copper with stainless steel connection pipes at the ends. All weldings on the ladder-structure apply electron beam technology to reduce heat and deformation during manufacturing. Pursuant to temperature simulations the RFQ can be operated with the advanced cooling system up to a duty factor of 5%.

Table 1: Main RF and Geometric Parameters of the Modulated Prototype Ladder-RFQ

No. of cells	55
Q Value (simulated)	6800
Loss (with sim. Q)	675 kW
Thermal Loss (measured Q)	1360 W
Shunt Impedance (sim.)	45 kΩm
Electrode Voltage	96 kV
Frequency	325.224 MHz
Repetition Rate	4 Hz
Pulse Duration	200 µs
Total Length	3410 mm
Cell Length	40 mm
Spoke Thickness	20 mm
Spoke Height	280 mm
Spoke Width	150 mm
Aperture	2.96 mm
Electrode Radius ρ	2.22 mm
Electrode Length	3327 mm

[1] The authors would like to thank A. Schnase, G. Schreiber and B. Schlitt from GSI for the facilitation of the measurements.

SIMULATIONS

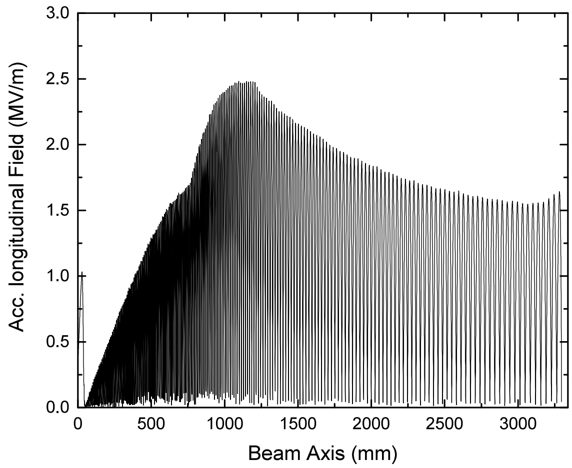

Figure 4: Longitudinal electric field distribution on the beam axis of the modulated Ladder-RFQ.

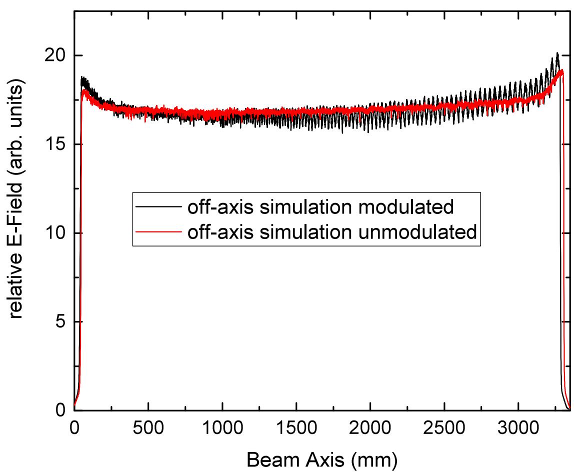

Figure 5: Field flatness along the beam axis of the modulated (black) compared to the unmodulated (red) simulation.

All simulations are additionally performed with including modulated electrodes, which is indispensable for the tuning process. Accordingly, the longitudinal accelerating electric field component along the beam axis could be evaluated (Fig. 4). The study has shown that the simulation is in accordance with the beam dynamics calculation. Furthermore, it has been confirmed that the field flatness and the electrode voltage, respectively, of the modulated model is equivalent to a model without a modulation but a varying mean aperture (Fig. 5). As in the case of the unmodulated RFQ it is sufficient to tune the field flatness by merely adjusting the first and last three cell heights (i.e. in cells 1-3 and cells 53-55), which is the clear distance between the side rails in a ladder cell. Nevertheless, the first and last four cells will be adjusted to reach the optimum field flatness. The first neighboring HOM is approx. 9 MHz above the operating mode.

CONCLUSION

All measurements of the unmodulated Ladder-RFQ such as frequency spectra, tuning, field flatness are in a good agreement with the simulations. The vacuum properties and pump ability has been verified. Accordingly, the Ladder-RFQ seems to be a good candidate for the acceleration of protons at typical frequencies above 250 MHz. Based on these results, the design and construction of a full length modulated Ladder-RFQ, which will be tested with beam at GSI, is currently on-going. The current design of the modulated Ladder-RFQ remains on-schedule. Semi-finished goods are already delivered encouraging the production release in Q2/2017 once the preliminary examination has been approved. The completion of manufacturing is aimed until the end of 2017, to be ready for first RF tests in early 2018.

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