STRUCTURAL MECHANICAL ANALYSIS OF 4-ROD RFQ STRUCTURES IN VIEW OF A NEWLY REVISED CW RFQ FOR THE HLI AT GSI*

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Abstract

The High Charge State Injector (HLI) at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, serves as one of the two injector linacs for the UNILAC as well as dedicated injector for the upcoming cw linac project for super heavy element research. As the front end of the HLI is planned to be upgraded for cw operation a newly revised cw capable Radio Frequency Quadrupole (RFQ) structure with an operating frequency of 108 MHz is required. The existent 4-rod structure, which was commissioned at the HLI in 2010 [1], suffers from severe modulated rf power reflections originating from mechanical oscillations of the electrodes that both limit the achievable performance and impede stable operation [2]. Besides preceding vibration measurements that were done by GSI using a laser vibrometer [3], the structural mechanical behavior of the 4-rod geometry was extensively analyzed using ANSYS Workbench [4]. Thereby the crucial mechanical eigenmodes could be identified and their impact on the rf properties was investigated by simulations using CST MWS. A completely newly revised 4-rod RFQ design with optimized structural rigidity was developed [5] of which a 6-stem prototype is currently being manufactured.

INTRODUCTION

The currently operated HLI-RFQ was designed within the scope of an intended HLI cw upgrade under the guideline of a power restriction to 60 kW for being compatible with the existent power amplifier. Necessarily the overall capacitance had to be kept low, resulting in a thin electrode profile. In order to yield the resonance frequency of 108 MHz a rather large stem distance of 173 mm was used which facilitates the mechanical bending of the long inter-stem electrode sections as well as of the levitating electrode overhangs. As a consequence the structure turned out to be highly prone to mechanical vibrations of the electrodes. The periodic displacement of the electrode surfaces leads to a recurring change of the overall capacitance, hence causing an impedance mismatch. The resulting modulated power reflections to the amplifier limit the achievable pulse length and amplitude.

The modulation frequency of the reflected signal at the HLI-RFQ is at approximately 500 Hz. Measurements of the vibration velocity of the electrodes using a laser vibrometer (see Fig. 1) confirmed the electrode vibrations as source of the modulated power reflections and identified the edges of the rf pulse as their excitation. Additionally the measured frequency spectra revealed other major vibrational modes around 350 Hz that however do not affect the rf properties.

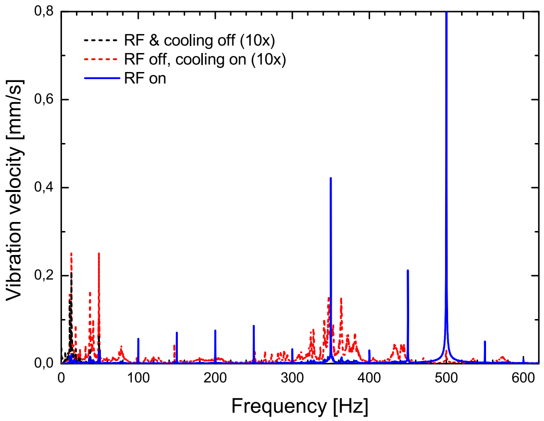

Figure 1: Measured frequency spectrum of the electrode vibration velocity (P. Gerhard *et al.* [3]).

Besides mechanical electrode vibrations the existent HLI-RFQ also suffers from a high thermal sensitivity since changes in thermal load have a significant and immediate effect on the resonance frequency. Overall operational stability is substantially impaired and the requirements for the upcoming cw linac project are not fulfilled.

Based on the gained experiences a completely newly revised 4-rod RFQ structure for the HLI was designed originating from the RFQ concepts that have been previously developed for FRANZ and MYRRHA.

ELECTRODE EIGENMODE ANALYSIS

Using the modal analysis solver of ANSYS Workbench the mechanical eigenmode spectrum of the electrodes was determined (see Fig. 4).

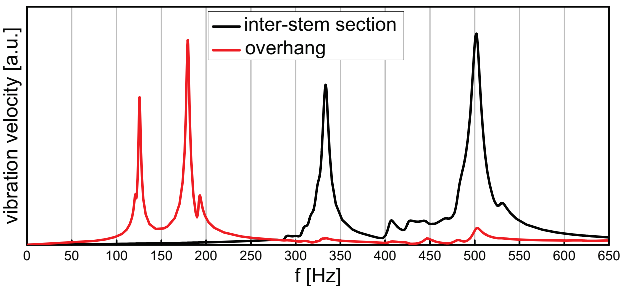

Figure 2: Simulated frequency spectrum for an inter-stem electrode section and the electrode overhang.

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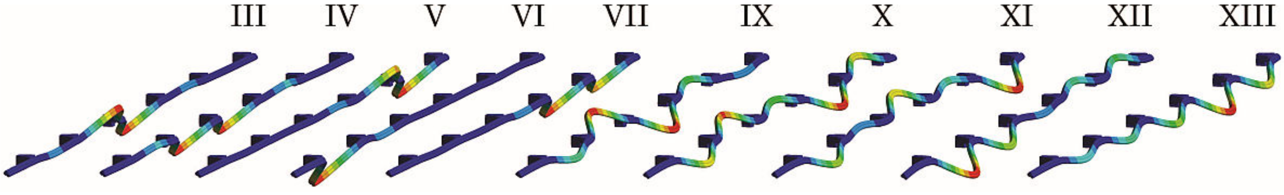

Figure 3: Transversal (III - VII) and radial (IX - XIII) mechanical electrode eigenmodes.

The obtained eigenmodes can be classified according to their vibrational planes that correspond to the symmetry planes of the rectangularly shaped electrodes (see Fig. 5). The main vibrational plane is either in radial or in tangential orientation to the beam axis. Eigenmode oscillations occur on the electrode overhang (modes 1, 2, 15 and 21) as well as on the entire electrode (modes 3-7, 9-13 and 16-20). The first order transversal and radial electrode eigenmodes are depicted in Fig. 3. Modes 8 and 14 are eigenmodes of the stems. Modes above 950 Hz include torsion modes of the stem arms.

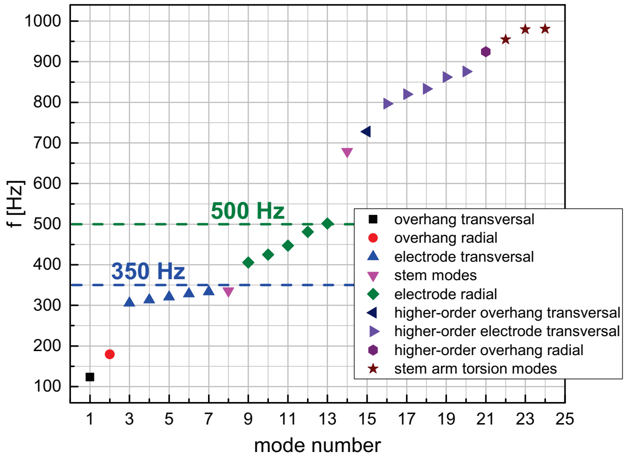

Figure 4: Simulated mode spectrum of the upper electrode.

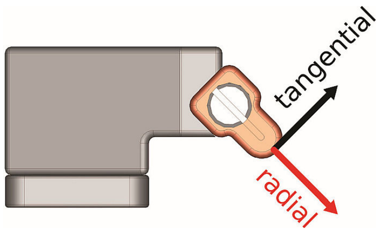

Figure 5: Vibrational planes of the electrodes.

Using the harmonic response analysis solver the resonance response was calculated following a predefined excitation that recreates the radial electric forces of the quadrupole field. The yielded results match the measured frequency spectra nicely (see Fig. 2). The radial electrode modes at 500 Hz are easily excitable by the quadrupole field whereas the tangential oscillations around 350 Hz are only excited by asymmetrically acting forces in horizontal direction that are introduced by e.g. an electric dipole component. Figure 7 shows the simulated frequency spectra for different orientations of the exciting force where λ is the ratio of vertical to horizontal excitation. For $\lambda \rightarrow 1$ the occurrence of tangential modes vanishes completely.

VIBRATION AMPLITUDES

For the estimation of the vibration amplitudes assumed deformation profiles of the electrode were used according to Fig. 6 since the actual oscillation pattern consists of a superposition of several eigenmodes that is not obtainable from the ANSYS simulations.

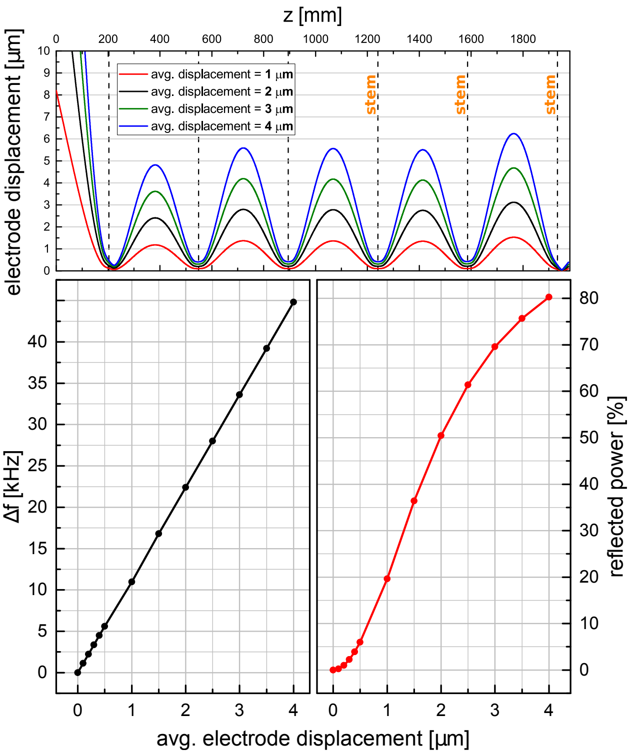

Figure 6: Electrode deformation profile (*above*), simulated frequency detuning Δf and reflected power as function of the average electrode displacement (*below*).

$$\frac{P_r}{P_f} = |\Gamma|^2 = \left|\frac{\beta - 1 - i\beta Q\delta}{\beta + 1 + i\beta Q\delta}\right|^2 \approx 1 - \frac{1}{1 + Q^2\frac{\Delta f^2}{f_0^2}} \qquad (1)$$

The frequency detuning Δf was calculated with CST MWS. Using Eq. (1) yields the relative amount of reflected power P_r/P_f with forward power P_f, coupling parameter $\beta = (f_0 - \Delta f)/f_0$, resonator quality factor Q and $\delta = f_0/(f_0 - \Delta f) - (f_0 - \Delta f)/f_0$.

An average electrode displacement of 1 µm, corresponding to oscillation amplitudes on the inter-stem electrode sections of roughly 1.2 µm, causes 20 % of reflected power.

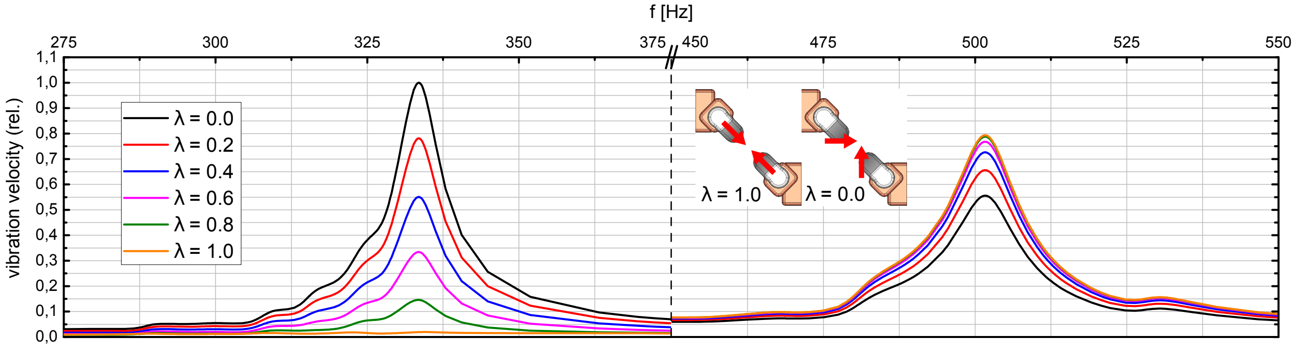

Figure 7: Simulated frequency spectra of the resonance response for different orientations of the exciting force.

PROTOTYPE DESIGN

Figure 8 depicts the developed prototype design. The stem distance was significantly decreased to 120 mm whereby the stem height had to be increased to 283 mm. The mechanical eigenmode frequencies could be increased by a factor of 4 compared to the existent HLI-RFQ while mostly preserving the value of the shunt impedance of about 100 kΩm. The electric dipole is compensated entirely.

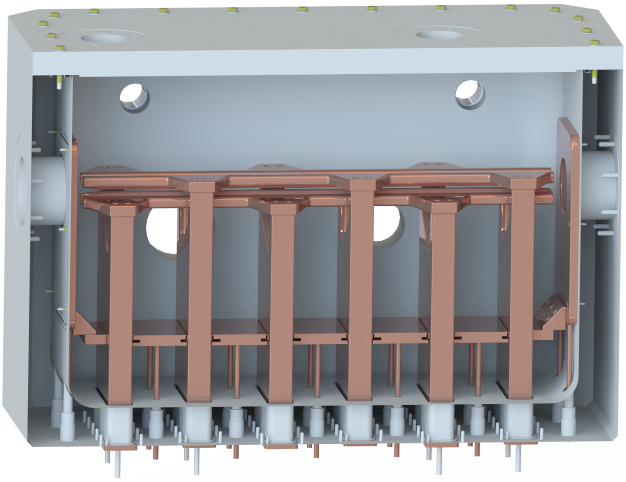

Figure 8: 6-stem prototype design.

CONCLUSION & OUTLOOK

The rf affecting radial mechanical electrode oscillations are excited by the basic quadrupole field configuration and need to be suppressed by mechanical stiffening of the 4-rod structure. Tangential eigenmodes are excited by asymmetric excitations like the electric dipole component, which can be compensated completely.

Based on the FRANZ/MYRRHA-RFQ concept (175/176.1 MHz) a completely newly revised design for the HLI-RFQ (108 MHz) was developed. A 6-stem prototype structure is currently being manufactured by Neue Technologien GmbH, Gelnhausen, Germany. The completion of manufacturing is expected in Q3 2017.

A more in-depth analysis of the thermal sensitivity of the HLI-RFQ is still pending. Basic thermal simulations have already been done with CST MPHYSICS. More sophisticated simulations with ANSYS like already done for the MYRRHA-RFQ [6] are planned.

Because a complete new revision of the HLI-RFQ would offer the opportunity to deploy longer electrodes (in the range of about +20 cm) also the beam dynamics concept is planned to be optimized using the PARMTEQM code with regard to the future requirements for the cw linac project as well as the UNILAC.

ACKNOWLEDGEMENT

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