IN SITU MEASUREMENT OF MECHANICAL VIBRATIONS OF A 4-ROD RFQ AT GSI

P. Gerhard*, L. Groening, K.–O. Voss, GSI, Darmstadt, Germany

Abstract

A new 4-rod CW Radio Frequency Quadrupole RFQ was commissioned at the High Charge State Injector HLI at the UNILAC in 2009. It is in operation since 2010 [1,2]. At high rf amplitudes strong modulations of the rf reflection emerge, with a modulation frequency of approximately 500 Hz. They are attributed to mechanical oscillations of the rods, excited by the rf pulse. The high fraction of reflected rf power severely limits the pulse length and amplitude achievable. The frequency control is challenging due to the amplitude of the modulation and its variation with rf power level. Stable operation is hard to achieve. As these modulations could so far only be seen *during* the rf pulse by means of rf measurements, a direct observation of the mechanical vibrations was desirable. Such measurements have been conducted using a commercial laser vibrometer, allowing the investigation of the mechanical behavior of the RFQ *in situ* and independent of the presence of rf power. This paper gives a short introduction of the method, presents some important results and a comparison with rf measurements. Possible countermeasures are discussed.

INTRODUCTION

Fast modulations of the reflected rf power were already observed long ago at the first HLI RFQ [3], but with the new RFQ the impact on the operation became unacceptable. A number of investigations based on rf measurements were conducted. They all suffered from the fact, that the measurements were restricted to the timespan of the rf pulse. Another rf independent approach was required. The idea of using a laser, which could be directed into the cavity through a vacuum window, to monitor the movement of the RFQ electrodes, lead to the application of a laser vibrometer, which allows for remote, fast measurement of the movement of any (reflective) surface.

PRINCIPLE OF MEASUREMENT

The POLYTEC OFV-525 laser vibrometer exploits the Doppler effect of a laser beam reflected by the surface of interest. The laser beam is split into a probe and a reference beam. The Doppler frequency shift of the reflected light with respect to the reference beam, which is proportional to the velocity of the movement, is determined by a laser interferometer. In order to define the direction of movement relative to the vibrometer, the reference beam light frequency is modulated. The displacement of the surface, and hence the amplitude of the vibration, can either be measured directly by a second operation mode of the vibrometer, or calculated

---

* p.gerhard@gsi.de

from the velocity data. In principle, only oscillations in the direction of the laser beam can be monitored. For more details about the principles of vibrometry refer to [4].

By pointing the laser through a vacuum window onto e. g. the back edge of a rod between two mounting bridges, we were able to measure the vibration of the rods *in situ* for different operational states. The laser beam was pointing at the electrode at about 30° (60°) with respect to the principle axes of the electrode. This allowed for the measurement of oscillation modes along both axes. The vibrometer was placed on top the RFQ, and the laser beam was guided into the cavity by a motorized mirror. The beam spot was monitored by a video camera. By this, also other parts of the structure like the coupling loop, could be examined. Reference data were taken in order to exclude any perturbation of the vibrometer by the rf, X-rays, vibration of the mounting or the vacuum window.

RESULTS

In Fig. 1, measurements without rf, but with vacuum pumps and cooling water running, are shown as frequency spectra of the vibration velocity (black and red dashed curves, ten times enhanced). The vacuum pumps and other devices
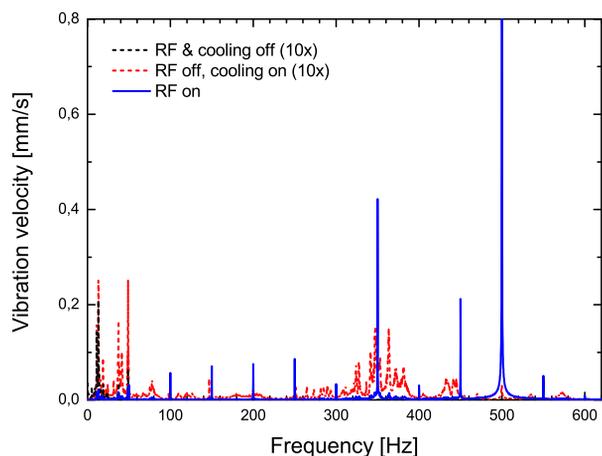

Figure 1: Frequency spectra of the measured vibration velocity. Black: Vacuum pumps running, cooling water and rf switched off. Red: With cooling water. Blue: With RF on at 50 Hz pulse repetition rate. (Black and red are 10x enhanced.)

lead to vibrations of the electrode rods in the range from a few to about 100 Hz, with noticeable signals around 12 and at 50 Hz. Switching on the cooling water, which runs directly through the electrodes and other parts of the structure, adds a broad background up to 600 Hz, with higher amplitudes between 300 and 400 Hz and below 50 Hz.

The third curve (blue compact) shows a frequency spectrum of the vibration velocity with rf power at moderate levels. The data were taken unsynchronized at a pulse repetition frequency of 50 Hz, and the spectrum is shown as calculated by the vibrometer software. This leads to artefacts in the FFT (narrow side bands every 50 Hz). Besides this, two strong peaks at 500 and 350 Hz emerge when rf power is transmitted. The 500 Hz peak is in very good agreement with the rf observations made earlier and clearly identifies the rf pulses as the source of the vibrations which modulate the rf signals. The peak at 350 Hz was not known from the rf measurements, details will be discussed later. The velocity of the vibration at 500 Hz corresponds to an oscillation amplitude on the order of 1 μm.

Results from Standard Operation Conditions

After this first affirmative result, specific investigations on the correlation between the excitation and operational parameters, like pulse length and repetition rate, were conducted. Figure 2 shows the variation of the vibration velocity at 500 Hz for different rf pulse lengths at 50 Hz pulse repetition rate. One can see immediately the periodic behavior of
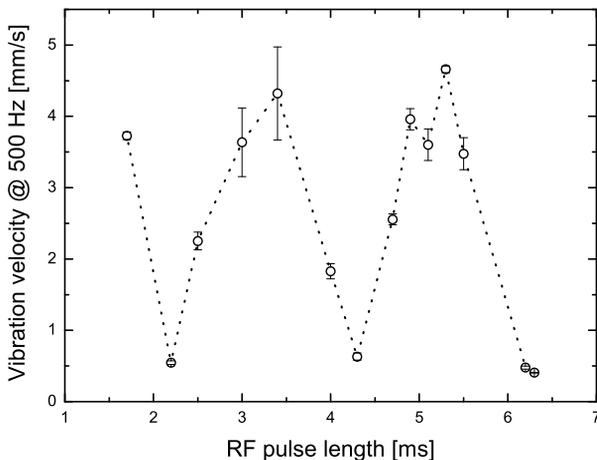
Figure 2: Vibration velocity at 500 Hz for different rf pulse lengths at 50 Hz pulse repetition rate.

the velocity. From operational experience and rf observation it was known, that at rf pulse lengths of roughly 2.3, 4.3 and 6.3 ms, corresponding to 1.15, 3.15 and 5.15 ms beam pulse length respectively, stable operation was possible, while at other pulse lengths, only unstable or no operation at all was possible, depending on the power level. This observation corresponds nicely to the periodicity and the position of the minima of the vibration velocity in Fig. 2.

Figure 3 shows the same data as Fig. 2, but in the time domain. The diagram spans 3.5 rf cycles. For any pulse length, a strictly periodic progression of the velocity arises, with a period of 20 ms corresponding to the repetition rate of 50 Hz. The data show, that for the pulse lengths where stable operation is possible, the vibration amplitude is low not only during the rf pulse, but all the time.
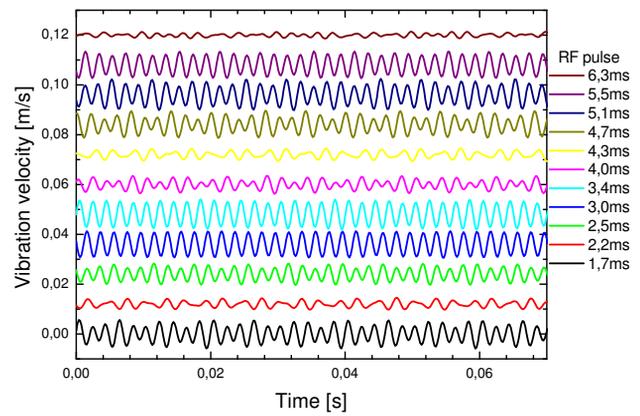
Figure 3: Comparison of the vibration velocity as a function of time for different rf pulse lengths at 50 Hz pulse repetition rate.

Ring–Down Investigations

As a substantial improvement, the laser vibrometer enables the analysis of the vibration before and after the rf pulse, i. e. the ring–down of the free mechanical oscillation after the excitation by the rf pulse. In Fig. 4 and 5 only the data of this free decay, taken at 1 Hz pulse repetition rate, is shown. Due to the long break between two pulses, the
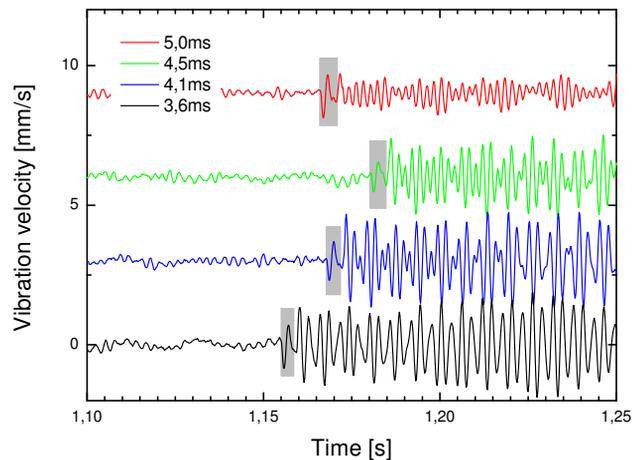
Figure 4: Vibration velocity as a function of time for different rf pulse lengths, measured at 1 Hz pulse repetition rate. The grey fields mark the time of rf transmission.

vibration has nearly vanished before a new rf pulse (grey field) is transmitted. The start of the vibration clearly shows when the rf pulse excites the vibration, but the exact time where the rising edge is placed can not be determined without synchronization to the rf cycle. For the first vibration period, the amplitude is always the same. After that a phase jump can be seen, which probably marks the second excitation by the falling edge of the rf pulse. At this point, the vibration changes its amplitude to higher values at 3.6 and 4.1 ms, while at 5.0 ms the amplitude is considerably lower after the pulse than within.
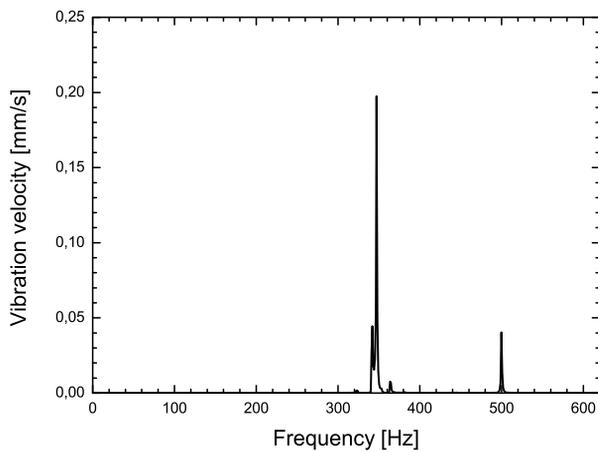
Figure 5: Frequency spectrum of the measured vibration velocity at 1 Hz rf pulse repetition rate. Here only the free decay of the vibration after the rf pulse is considered.

The vibration during the break was not accessible by rf observations. It is of high interest, because it allows to study the interference of the excitations by the two edges of the rf pulse. Using a slow repetition rate, it also allows for the observation of the mechanical oscillation for a longer period of time and by this an exact analysis of the spectrum and damping times is possible. The frequency spectrum shows four modes at 341, 347, 364 and 500 Hz. The decay times for all frequencies are about 0.3 s.

DISCUSSION

The initial objective of the measurements described above was to verify independently, that

- the rf pulses are the source of the excitation of the vibrations, and
- these mechanical oscillations are responsible for the modulation of the rf properties.

These results were achieved quickly and without doubt. The enhanced opportunities of the laser measurement technique enabled further investigations of the properties of the vibrations. One important result is the determination of the decay times. From the rf observations, decay times on the order of 10 ms were derived, owed to the fact, that only data from the short time span of the rf pulse was available [2], which is additionally distorted by the rising edge of the rf pulse. The new data, taken at 1 Hz pulse repetition rate, gives decay times on the order of 0.3 s. Together with the analysis of the time resolved data of the movement at 50 Hz pulse repetition rate, the explanation of the different behavior at different pulse repetition rates has to be revised. From Fig. 2 it shows, that the perturbation within the rf pulse is minimal for pulse lengths t_P in the vicinity of 2 ms and integer multiples of this, which is exactly the period t_V of the mechanical vibration. The excitation of the rods by the electrical force due the rf voltage changes sign for the rising and falling edge of the pulse. When $t_P = n \cdot t_V$, $n = 1, 2, \ldots$, the two excitations match the same phase of the vibration and

therefore cancel out. When $t_P = \frac{2n+1}{2} \cdot t_V, n = 0, 1, \ldots$, both the excitations and the vibration phase change sign and interfere positive. Figure 3 reveals, that in the first case, the oscillation amplitude is always low. There is no strong oscillation, which could cancel out the excitation from the rising edge. A synchronization between the rf cycle and the measurement is necessary to explore this in more detail.

The direct measurement of the mechanical movement of the electrodes also revealed, that different oscillations modes are excited. Some of which have an effect on the electrical properties of the structure, while others obviously have not — and are therefore not discoverable by rf measurements. This can be explained by different orientations of the oscillation modes.

OUTLOOK

In order to understand the connection between the vibrations and their impact on the rf properties, simulations of the vibrational modes and their effect on the electrical parameters of the structure are initiated and have to be extended. The main goal will be to identify the vibrational mode at 500 Hz, which perturbates the rf properties and impairs stable operation of the RFQ. Based on this, strategies to mitigate the problems have to be developed. A new set of electrodes with a modified profile, which is less susceptible to the vibrations identified as the source of the perturbation, would obviously be the most consistent, but also most expensive solution in terms of time and cost. However, it will be necessary to build new electrodes with enhanced cooling capabilities anyway in order to enable cw operation, for which the RFQ was initially foreseen [1].

The knowledge gained by the measurements described here may also open easier ways to reduce the vibrations. One way could be to modify the existing electrodes only in some parts, for instance the long free ends. A completely different approach is to modify the rf pulses in such a way, that the vibrations within the accelerating part of the pulse are cancelled out. This requires a better understanding of how the rf pulses and the electrodes interact mechanically, which can be provided only by the vibrometer data. Further measurements with synchronization to the rf cycle could help analysing the details of the excitation process. Such investigations will be accompanied by implementing new rf pulsing schemes.

REFERENCES

[1] P. Gerhard *et al.*, "Commissioning of a new CW Radio Frequency Quadrupole at GSI", IPAC'10, Kyoto, Japan, May (2010), MOPD028, p. 741.

[2] P. Gerhard *et al.*, "Experience with a 4-Rod CW RFQ", LINAC'12, Tel Aviv, Israel, Sept. (2012), THPB035.

[3] W. Vinzenz, "Resonanzfrequenzanalyse HLI RFQ", GSI internal report (1997).

[4] Polytec website: http://www.polytec.com/us/solutions/vibration-measurement/basic-principles-of-vibrometry/