EXPERIENCE WITH A 4-ROD CW RADIO FREQUENCY QUADRUPOLE

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Abstract

The High Charge State Injector (HLI) provides heavy ion beams for the linear accelerator UNILAC at GSI [1]. After 20 years of successful operation its four–rod Radio Frequency Quadrupole (RFQ) was replaced in 2010 [2]. Besides higher beam transmission, the principal intention of this upgrade was to raise the duty factor up to 100%. Commissioning and operational experience from the first years revealed that this goal could not be reached easily. After serious problems with melting of rf contacts were overcome, operation is still restricted. There is strong, modulated rf power reflection, most likely due to mechanical instabilities of the structure. In this paper we present the RFQ design, commissioning results, operational experience and future activities.

INTRODUCTION

The HLI is equipped with an ECR ion source and an RFQ-IH linac which accelerates highly charged ion beams with high duty factor of up to 30% to 1.4 MeV/u for further acceleration in the Alvarez DTL of the UNILAC. Since 1991 main user of these beams is the Super Heavy Element (SHE) research, one of the outstanding projects at GSI [3]. Experiments like TASCA and SHIP strongly benefit from the high average beam intensities. A dedicated cw linac for SHE research at GSI is seriously proposed, with the HLI as its injector. The existing HLI is not designed for cw operation. The replacement of the RFQ in 2010 was the first step towards a cw capable injector.

DESIGN & COMMISSIONING

Due to the high average rf power caused by the cw operation, all parts of the new 4-rod RFQ (electrodes, stems, tuning plates, plungers and coupling loop) had to be directly water cooled. This results in 72 connections and vacuum feedthroughs for cooling water, equipped with pre-vacuum sealing, making the mechanical engineering rather complex. More design properties are given in Tab. 1.

Table 1: Design properties of the new HLI RFQ.

Injection / extraction energy [keV/u]	2.5 / 300
RF frequency [MHz]	108.408
A/q (cw / max.)	6.0 / 8.5
Power (max. avg. / max. pulse) [kW]	60 / 120
Intervane voltage (cw / max.) [kV]	55 / 78
RMS emittance in / out [π mm mrad]	0.1 / 0.1009
Electrode length [m]	2.0

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The new RFQ was delivered to GSI in autumn 2009. RF and beam commissioning was finished in spring 2010. Achievement of the design beam parameters (transmission, energy, emittance) could be demonstrated (Fig. 1 and [4]). Extensive beam measurements at different locations of the HLI beam line were performed.

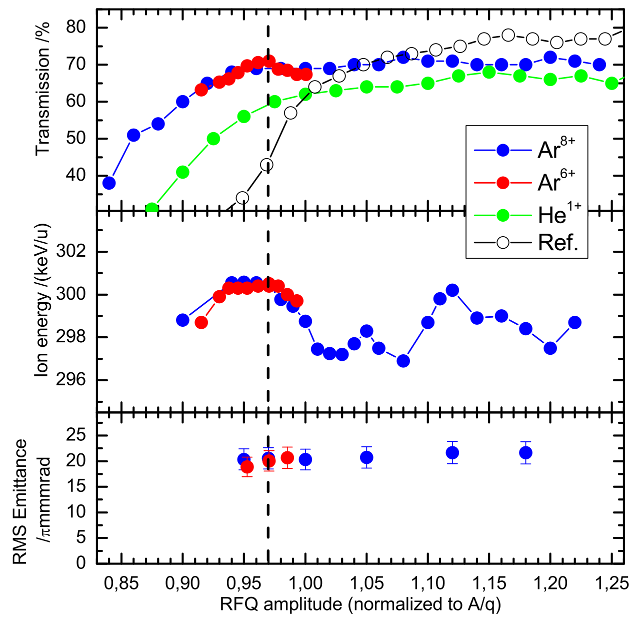

Figure 1: Beam commissioning results (top to bottom): Transmission, ion energy and beam emittance for different ions as a function of the rf amplitude, normalized to the mass-to-charge ratio. Reference data: Old RFQ; dashed line: Derived working point.

THERMAL ASPECTS

During rf commissioning two issues were discovered:

- Insufficient rf contact springs and
- the thermal instability of the 4-rod structure.

Rf contact springs

Several breakdowns of contact springs between the tuning plates and the stems occurred at rf power levels far below the design (s. Fig. 2). The first burning occurred at 16 kW avg. power, possibly due to incorrect mounting of the springs. After two breakdowns, complete renewal with more robust contacts and careful mounting was employed. Nevertheless, damages were found after operation at 24 and 30 kW. Obviously this type of contacts could not handle enough power safely in routine operation. Therefore it was decided to introduce a different contact mechanism using

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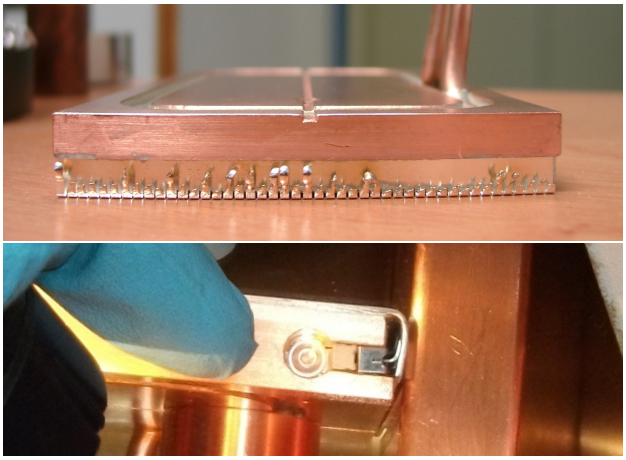

Figure 2: Tuning plate with burnt contact springs (top) and new contacts (bottom). The thick silver foil is pressed against the stem by spring steel foil and steel wedges.

solid silver foils (Fig. 2) [5]. After the new contacts were mounted in November 2010, 30 kW avg. and 110 kW pulse power were reached. Due to other limitations, the avg. design power could not be demonstrated so far.

Thermal instability

Although all relevant parts of the structure are directly water cooled, the structure reacts rapidly to changes of the thermal load. The frequency changes by approx. 200 kHz from rf off to 50% design power; elaborate estimates as well as tests with warm water indicate a temperature change of 10-20 K. Even small changes of the thermal load ($\ll 1\%$) have a significant and almost immediate effect, posing a challenge for the frequency or plunger controller. In normal operation, the average power can only be changed in small steps to allow the controller to follow. After rf breakdowns (sparking), the RFQ immediately cools down and is off resonance. It has to be restarted manually after the plungers have moved to the 'cold' position.

MECHANICAL ASPECTS

Observations

It was known from similar 4-rod RFQs, that the rf power reflected by the cavity can show a modulation [6]. In this case, the magnitude of the modulation turned out to be a major problem (Fig. 3). While the amplitude controller is still able to provide a perfect flattop (at its reference probe), the plunger controller is severely affected, since it relies on the phase difference between forward and reflected rf, which is also modulated. At higher power, it also leads to a significant fraction of the power being reflected. Besides heating up the transmitter, this limits the rf amplitude.

Most probably this modulation originates from mechanical vibrations of the electrode rods or the coupling loop. These vibrations may affect the rf resonance and rf matching. Rf power is then reflected due to the mismatch. The

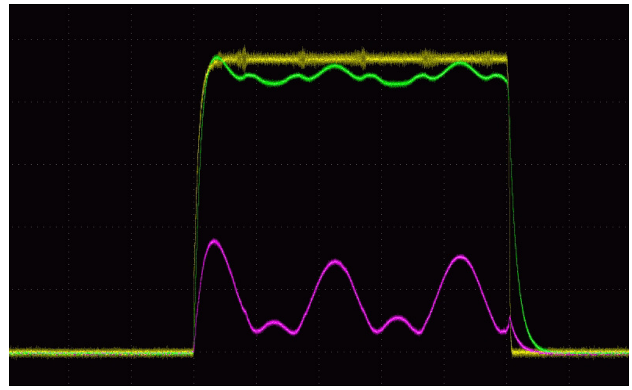

Figure 3: Modulation of the rf tank signals. Magenta: Reflected power; green: Forward power; yellow: Tank amplitude (read out).

modulation has a frequency of about 520 Hz, which is confirmed by simulations considering mechanical vibrations of the rods. A more detailed analysis of the rf signals revealed that the modulation is damped with a time constant between 6 and 10 ms. In order to identify the origin, we tried to increase the damping by putting Vespel clamps on every cell of the RFQ (Fig. 4). Operating the RFQ up to

Figure 4: RFQ structure with mounted Vespel clamps. A plunger is moved in from the top right corner.

moderate rf levels, we found the damping of the modulation to be slightly faster (5–6 ms), but also the modulation frequency slightly higher.

The RFQ is typically operated at 50 Hz pulse repetition rate and pulse lengths of up to 6 ms. During commissioning it turned out, that the RFQ can only be operated at certain pulse lengths, which have to be adjusted carefully in order to minimize the amplitude of the modulation (s. Fig. 5, left, curve 1, 5 and 9 from top). At other values, phase error exceeds the dynamic range of the control loop, rf behavior becomes unstable, reflected power increases and sparking occurs. The behavior changes when the RFQ is operated at 1 Hz. Now every pulse duration is possible and gives the same signal shape. Fig. 5 shows a comparison between the 50 Hz and the 1 Hz operation.

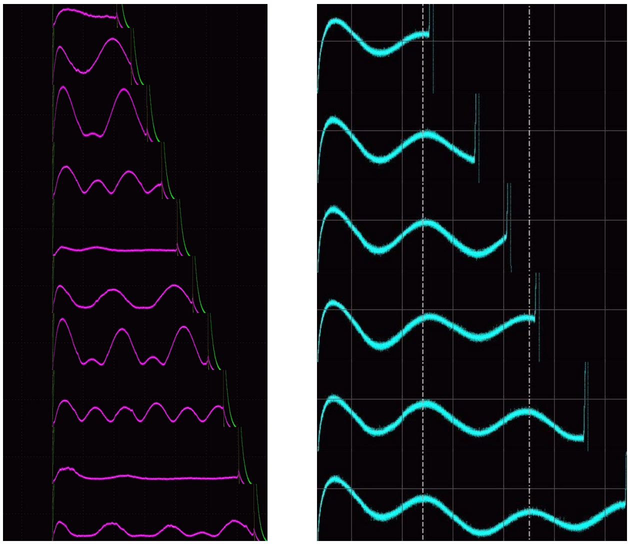

Figure 5: Rf signal modulation at 50 Hz (reflected power, left) and 1 Hz (phase difference forward/reflected, right) pulse repetition rate for pulse lengths of appr. 2-6 ms.

Discussion

The comparison shows, that 15-20 ms after the rf pulse a feedback between successive pulses is observed, while the damping has eliminated the modulation after 1 s. At 50 Hz, the remaining mechanical oscillations interfere with the excitation by the next pulse, leading to different appearances of the modulation for different pulse sequences. This fits nicely to the damping time of 5-10 ms found above. The unexpected rise of the modulation frequency with the Vespel clamps attached can be explained by a raised stiffness of the oscillator, i. e. the electrode rods, when they are pressed by the clamps. The changes induced by the clamps are indicating towards mechanical vibrations of the rods as the origin of the modulation, but they are not significant enough to prove this.

The rf field oscillates 5 orders of magnitude faster than the modulation observed, making it impossible to excite the vibrations. This is supported by the fact, that during the flattop the oscillation is damped. However, the envelope of the rf pulse is of almost rectangular shape. Therefore the rising and falling edges contain a broad frequency spectrum, which could be the origin of excitation. Tests with a trapezoid pulse shape showed a reduction of the modulation, on the cost of rf power used up outside of the flattop.

PULSED & CW OPERATION

After the serious breakdowns in the beginning, beam times with up to 30% duty cycle were conducted successfully in the past years. Handling of the RFQ is complicated due to the fast thermal reactions and the high, modulated power reflection. This also limits the applicable rf amplitude, depending on the duty cycle. A high risk of damage to the rf (pre-)amplifier is obvious. Interruptions like sparking cause long breakdowns, because the rf has to be raised slowly by hand from low levels. Pulsed operation requires absolutely stable repetition of identical pulses (length of pulse and pause, amplitude) at certain pulse lengths, which have to be fine adjusted to the thermal conditions.

So far no cw operation could be established. This is partly due to the low level rf, which is tailored to pulsed operation at 50 Hz rep. rate and 50% duty cycle at most. During a test period, the LLRF was reconfigured to enable cw operation. It turned out that no steady state could be reached. One would have expected that the perturbing modulation was damped out, but this was not the case.

In cw mode the thermal load is much higher than in pulsed mode at the same rf amplitude, hence rf power changes lead to larger thermal and consequently resonance frequency changes. The resonance changes much faster than the reaction time of the frequency controller. This leads to severe fluctuations of the power reflected and, despite the rapid compensation by the amplitude controller, of the power coupled into the cavity, too. The (slow) movement of the plungers also affects the amplitude controller. Finally, the rf amplitude is constantly changing, the system never reaches a steady state and the modulation is excited all the time, in spite of the cw operation.

CONCLUSION AND OUTLOOK

The new RFQ was intended to enable cw operation and enhance operational stability. Both aims could not be reached so far. Pulsed operation is possible with restrictions and special handling instructions. Cw operation has to be established in the framework of the upcoming cw linac.

In order to improve the situation, more tests and simulations are planned concerning the mechanical stability of the rods and the coupling loop. New electrodes with enhanced vibrational resistivity and cooling will be developed and implemented. Tests concerning the thermal stability have to be conducted in order to decide whether the stems and tuning plates have to be redesigned, too.

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