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RFQ PERFORMANCE DURING RF CONDITIONING AND BEAM COMMISSIONING AT ESS

R. Zeng†, B. Jones, D. Noll, R. Miyamoto, A. Svensson, G. Fedel, E. Trachanas, D. Nicosia, A. Garcia Sosa, European Spallation Source ERIC (ESS), Lund, Sweden
O. Piquet, M. Desmons, M. Baudrier, A-C. Chauveau, P. Hamel
CEA-IRFU, University Paris-Saclay, Gif-sur-Yvette, France
F. Grespan, INFN, Italy

Abstract

The RFQ at ESS has been successfully gone through RF conditioning, RF re-conditioning and low duty cycle beam commissioning. The RFQ fulfils all required functions and overall performance is satisfactory. RF conditioning, three RF re-conditionings after LEBT interventions and beam commissioning will be reported and RFQ performance during these periods will be described. RFQ performance in a large extent is reflected by dynamics and interactions between RF, cavity and beam. Thanks to advanced hardware capabilities and flexible software intelligence, observation of those dynamics and interactions are done at a detailed level. Analysis of those dynamics and interaction will be introduced. Some techniques to deal with challenges resulting from those dynamics and interactions will also be discussed.

INTRODUCTION AND RFQ OVERALL PERFORMANCE

RFQ has been installed and tuned in the ESS tunnel following its delivery to ESS in 2019. The overall parameters are listed in Table 1. RFQ high power conditioning started in June 2020 and after 7 weeks RFQ was conditioned up to full duty cycle (14 Hz and 3.2 ms) at 800 kW (corresponding to 776 kW net power in cavity). After high power conditioning, the RFQ reached stable operation condition and RF breakdown rates reduced to 1~2 times per hour at full duty cycle, compared to 200 times per hour in the peak of conditioning. After a trip when RF power is shut down completely, it takes around 3 minutes for RFQ to thermally stabilise with nominal power nominal power and full duty cycle [1].

In late 2021 and early 2022 when there were three interventions in the LEBT to fix and exchange components, the RFQ end flange had to be disconnected. During these periods, nitrogen gas was purged through RFQ to avoid exposure to air. RF re-conditioning was performed immediately after each intervention to enable RFQ to recover to its full capacity. It was noticed that the longer intervention time it took, the longer re-conditioning time it required for RFQ to recover. During the beam commissioning phase (beam destinations to Faraday cup in MEBT and Faraday cup after DTL1), beam pulse length is limited to be less than 50 µs, and RFQ was set to run in low duty cycle (1 Hz and 100 µs) to avoid damage of Faraday cups in case of chopper failure in LEBT. RFQ performance has been very stable and robust throughout this low duty cycle beam commissioning phase, and very few RF breakdown occurred.

Table 1: RFQ Overall Parameters

RFQ	Design	Measured
Frequency (MHz)	352.21	
Beam Duty Cycle	4% (14 Hz, 3.2 ms)	
P_{cu} (kW)	713-1375	713
P_{beam} (kW)	241 (67.5 mA)	200 (58 mA)
Vane Voltage (kV)	80~120	118 (max.)
Max. E field (Kilpatrick)	1.9	
Power Coupler	2	
Coupling factor (beta)	1.337-1.175	1.321
Phisync (deg)	-43.4	-43
Q_0	4055-7821	7436
W_in (MeV)	0.075	
W_out (MeV)	3.62	3.60
3 dB bandwidth (kHz)	±52.4	±55.0
Cooling skid stability at full duty cycle (deg.)	±0.1 @30° (Vane) ±0.1 @30° (Body)	±0.04@28.81° (Vane) ±0.06@28.80° (Body)

RF AND CAVITY INTERACTION

Transient Thermal Effect

The RFQ experiences a transient thermal effect that induces significant frequency shift when RF power is on or off. The RF power does not heat up directly the whole RFQ body and vane, instead it affects first only 3.5 µm thick skin of RFQ body and vane. The transient temperature rise, especially over vane surface, can be very high when RF is on. In the case of RF off due to interlock trips, it leads to significant frequency due strong RFQ frequency sensitivity to temperature. A frequency jump up to 50 kHz over seconds was observed during conditioning when RF is suddenly triggered off from full power at full duty cycle. This value is also consistent with thermal simulation of RFQ and its cooling system [2]. To deal with the issue of frequency jump, a dedicated RF ramp up procedure using RF frequency tracking method has been developed, which adjusts RF frequency to track cavity resonance, instead of adjusting cavity resonance to track RF frequency. In this way,

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nominal power level can be established in quite a short time. After conditioning, RF power can be recovered to nominal level in less than 3 minutes. Further improvement was also made during subsequent re-conditionings, and the recovery time to nominal level was improved to less than 1 minute.

Multipacting

Multipacting was frequently observed at two power couplers in the power band 10~200 kW and 300~400 kW (5~100kW and 150~200kW for each power coupler). One challenge thing is that multipacting grows gradually with time if there is not enough RF power in cavity. Sometimes this leads to difficult RF ramping up to nominal field after long break (weeks to months). Restarting RF from long break period when there is no RF at all in cavity, multipacting is often not visible from electron current pickup measurement. However, electron current interlock is triggered immediately whenever RF pulse length increases to certain level. It seems adequate pulse length is required for electron to be resonant with RF. A good practice of multipacting trigger is to use multiple micro-pulses during RF pulse. As long as multipacting gets triggered, it appears all over the RF pulse, as indicated in Fig. 1. It is also indicated from electron pickup measurement that, at certain conditions, multipacting patterns vary with power levels. By keeping constant RF power on, multipacting goes away gradually.

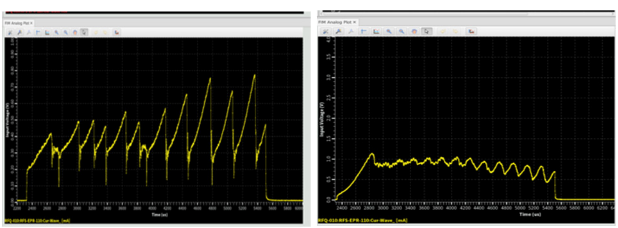

Figure 1: Multipacting patterns vary with RF power level. (Left: electron pickup read at 110 kW, Right: electron pickup read at 80 kW).

Breakdown

During RFQ conditioning, more than 50,000 reflected power interlocks occurred (mostly caused by breakdowns). The reflected power interlock is designed in such a way that it masks the peak reflection at both beginning and end of RF pulses. For very short RF pulses less than 20 µs, reflect interlock is not able to protect the system due to masking effect. A cavity decay interlock, designed as redundancy for reflected power interlock, was then re-enabled. An automatic RF power recovery feature called RF "auto-reset" is also implemented in IOC (in the RF Local Protection System), to allow quick recovery of RF field in next RF pulse after reflected power or cavity decay interlock trip. RF breakdown usually happens one after another in the cavity, and sometimes appears intensively over several consecutive RF pulses.

RFQ is divided into 5 sections, and section 1 is close to LEBT while section 5 is close to MEBT. There are in total 20 pickup antennas all along RFQ, with 4 for each section.

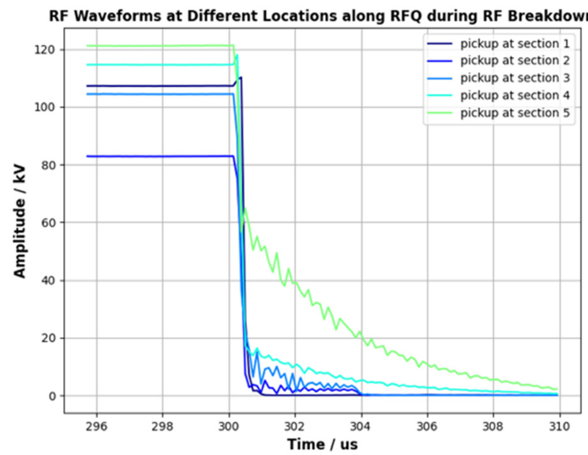

Figure 2: Cavity field measured by pickups located in different sections of RFQ during RF breakdown.

By plotting the RF waveforms sampled by pickup along RFQ, it is able to locate approximately where the breakdown happens [3]. Cavity field close to breakdown location drops sharply to zero, while cavity field further away drops with a decay curve, as shown in Fig. 2. This means the energy stored in cavity is not absorbed immediately by breakdown if it is away from the occurrence place. It provides a useful tool for breakdown location identification in future.

For normal breakdown scenario, RF cavity field usually goes back to stable state after a couple of interlocks, as shown in the left of Fig. 3. After first breakdown, the second one usually starts at lower cavity field as indicated by the green curve in the left of Fig. 3 and the blue curve in the right. For intensive breakdown scenario, RF cavity field becomes hard to back to stable state, as shown in the right of Fig. 3. To prevent intensive breakdown from further escalating, maximum number of breakdowns is limited and RF is shut off when the number is over the limit.

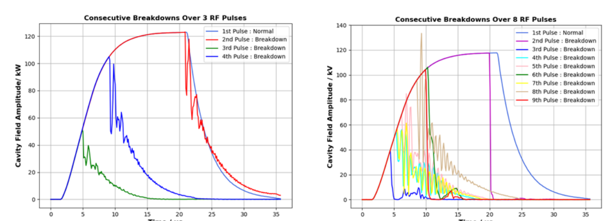

Figure 3: Normal breakdown scenario (left) in which RF goes back to stable after a couple of interlocks, and intensive breakdown scenario (right) in which RF is hard to back to stable state.

BEAM AND CAVITY INTERACTION

Beam Loss with RF On and RF Off

There was a wide discussion at ESS about sending very low duty cycle (1 Hz and 5 µs) and low beam current beam to RFQ when RF is off. For short term effect, simulation in Fig. 4 indicates the beam loss is more evenly distributed along the wall during RF off, while more concentrated on vane tip when RF is on.

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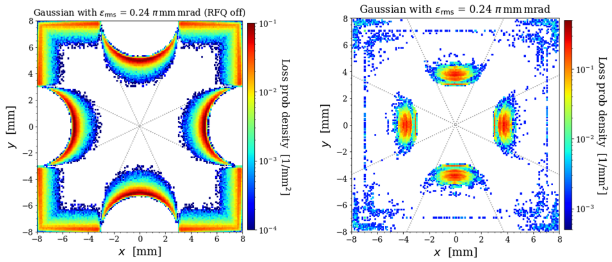

Figure 4: Beam loss distribution simulation in RFQ (left: RF off, right: RF on).

The simulation agrees with observation of RFQ operation in IPHI and CSNS. In IPHI, beam passes through RFQ regularly when RF is off. Experience from IPHI [4] indicates that RFQ performance seemed not degraded much in short term and spark rates did not increase too much. However, it was observed that vacuum pressure increased almost two magnitudes higher due to too much beam loss in RFQ. In CSNS, experience [5] indicates that there is some beam loss concentrated on RFQ vane tip during normal operation with RF on. The beam chopper angle was not correctly set in LEBT and beam hit the same area too often. Without understanding much about the long-term effect of beam loss on RFQ, cautions need to be taken not only for cases with RF off but also for RF on.

Beam Loading and its Compensation

An effective way to characterize beam loading is to pass beam through cavity in open loop and measure the beam induced voltage drop. In open loop, beam induced voltage drop is around 11% for beam at 58 mA and 20 µs. For short beam pulse less than 5 µs, feedback alone is not effective and thus close loop compensation was not applied at beginning of beam commissioning. For longer beam pulses, both feedback and adaptive feedforward ILC (Iterative Learning Control) have been applied. Figure 5 shows the case of beam loading and its compensation for 20 µs beam at 58 mA by different methods. It can be seen from Fig. 5 that there is still some small residual overshoot (±1%) in the beginning and end of beam pulses, even with feedback and adaptive feedforward compensation.

Beam Transmission under Different Beam Loading Compensation Methods

Perturbation in cavity field acts back on beam and leads to change in beam transmission, as indicated in Fig. 6. In open loop without beam loading compensation, beam transmission degraded by 1.5% (from 94.5% to 93.0%), compared with close loop operation with feedback and adaptive feedforward.

Effective Beam Phase Variations under Different Beam Loading Compensation Methods

RFQ is a special device from which beam phase originated. To describe overall effect of beam phase, the term effective beam phase is employed and defined as:

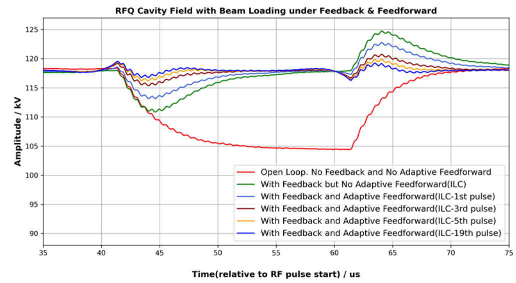

Figure 5: Beam loading compensation by feedback and adaptive feedforward.

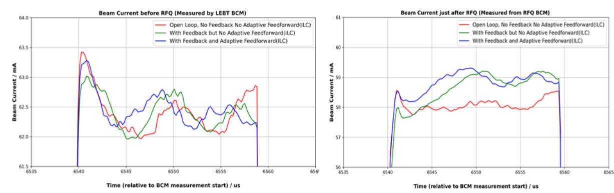

Figure 6: Beam current before(left) and after (right) RFQ under different beam loading compensation methods.

$$\varphi_{eff} = atan\frac{\sum_i V_i T_i sin\varphi_i}{\sum_i V_i T_i cos\varphi_i}, \quad (1)$$

where V_i, T_i and φ_i are the accelerating voltage, transit factor and synchronous phase of each cell.

Effective beam phase varies a lot between uncompensated beam loading operation (open loop with big cavity field drop) and compensated beam loading operation (cavity field is flat), as shown in Fig. 7. It reflects the fact that beam phase from RFQ is sensitive to field perturbations.

In this paper, beam phase is calculated directly from RF cavity field (vectors with/without beam loading), without taking into account effect from detuning. Further improvement is ongoing to enable effective beam phase measurement in close loop and with wide detuning range [6].

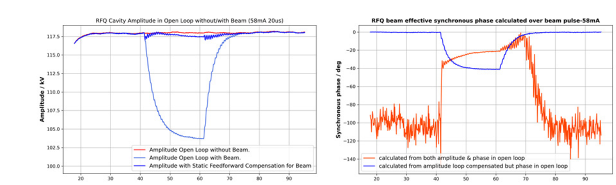

Figure 7: Uncompensated and compensated beam loading (left) and their effects on beam phase (right).

CONCLUSION

The RFQ and its supporting system such as cooling, vacuum, diagnostics and software applications have been demonstrating stable performance over conditioning, reconditionings and low duty cycle beam commissioning. Stable operation of RFQ system has enabled systematic observation of interactions between cavity, RF and beam, which in turn allow us to gain insight into system limits and find a way to operate RFQ at its full capacity.

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