HIGH POWER RF CONDITIONING OF THE ESS RFQ

O. Piquet, M. Baudrier, A.C. Chauveau, M.J. Desmons, P. Hamel
CEA-IRFU, University Paris-Saclay, Gif-sur-Yvette, France
E. Trachanas, B. Jones, D. Noll, A.G. Sosa, R. Zeng
European Spallation Source ERIC (ESS), Lund, Sweden

Abstract

The 352.21 MHz Radio Frequency Quadrupole (RFQ) for the European Spallation Source ERIC (ESS) has been delivered by the end of 2019 by CEA/IRFU. The RFQ is designed to accelerate a 70 mA proton beam from 75 keV up to 3.62 MeV. It consists of a 4-vane resonant cavity with a total length of 4.6 m. Two coaxial power loop couplers feed the RFQ with the 1.4 MW of RF power required for beam operation. This paper first presents the main systems required for the RFQ conditioning. Then it summarizes the main steps and results of this high power RF conditioning completed at ESS from June 9 to July 29, 2021 in order to achieve the nominal field for a pulse length of 3.2 ms at the repetition rate of 14 Hz.

INTRODUCTION

CEA/IRFU was in charge of the RFQ design [1], manufacturing [2], installation [3], and conditioning at ESS (Lund). An important step towards beam commissioning is the high power conditioning in order to achieve the nominal field for the proton acceleration. During this procedure where the power, width and repetition rate of the RF pulses sent to the cavity are increased gradually, confined gasses and water are released from the cavity surface and electrical sparks and discharges even out surface imperfections. The high power conditioning of RFQ (Fig. 1), was realized in 7 weeks following a period of extensive tests in the overall system chain.

Figure 1: ESS RFQ.

RFQ ANCILLARY SYSTEMS

RF System

The RF power system for the RFQ is comprised of the 660 kVA modulator (115kV/100A amplitude, 3.5 ms width and 14 Hz repetition rate), the klystron, and the RF distribution system. RF produced by the klystron is guided through waveguides (in addition to a power split towards a dummy load) to the symmetrically placed coaxial cavity couplers. The forward power requirements for operation are expected to be 1.4 MW (729 kW for cavity plus 225 kW beam loading and 30% margin for LLRF feedback evaluated during the bead-pull measurement campaign in December 2019 [3].

Low Level RF System

The Low Level RF system monitors and adjusts the amplitude and phase of the cavity. Stable operating frequency is achieved by tandem operation of LLRF and RFQ water system by regulation of the temperature in the 4 cooling loops. During RFQ conditioning, a feedback control loop adjusts the frequency of the provided RF power to compensate for cavity detuning during heating. Although in normal operations LLRF systems measures the detuning of the cavity and adjusts the water temperature to regulate cavity resonant frequency.

Vacuum System

In order to achieve nominal vacuum level (7 10^{-8} mbar) during beam operation, 10 turbo pumps are installed at the RFQ. Two cold-cathode gauges are installed at the beginning and the end of the cavity body and two at the couplers for monitoring the cavity vacuum levels during conditioning process.

Local Protection System

Local protection system (RF-LPS) is structured as a multistate machine to manage interlocks in the entire system chain with different response times: a slow interlock module with interlock times of some milliseconds and a fast interlock module with response times less than 20 microseconds. There are multiple interlock conditions that can lead to the shut-off of the RF power.

During conditioning the forward power from the klystron was limited to 800 kW or 400 kW for each arm feeding the two couplers. Electric breakdowns or sparks lead to significant power reflections monitored by the reflected power interlock. Because of the high reflection during the filling time of the cavity and at the end of the RF pulse this area is masked out and excluded from the interlock monitoring. Moreover electric field breakdown inside the cavity leads to a drop of the field with a speed faster than the usual field decay time. The RF decay interlock detects this slope with the pickup used by the LLRF and switch off the RF power.

Couplers are equipped with electron pickups (45 V voltage bias) to measure the current due to multipacting activity and RF power is switched off when electron activity transcends a defined threshold.

For the detection of arcs inside the couplers two viewports are mounted on the vacuum and air side, fitted with fibers going to an arc detection system. A fast interlock is triggered in case illuminance exceeds a threshold of about 1 lux un the coupler.

The cavity-local protection system is composed by 32 temperature sensors to monitor the surface temperature of each quadrant of the RFQ body and the couplers.

RFQ system status and interlocks are constantly monitored through the EPICS based control system graphical user interfaces (Fig. 2).

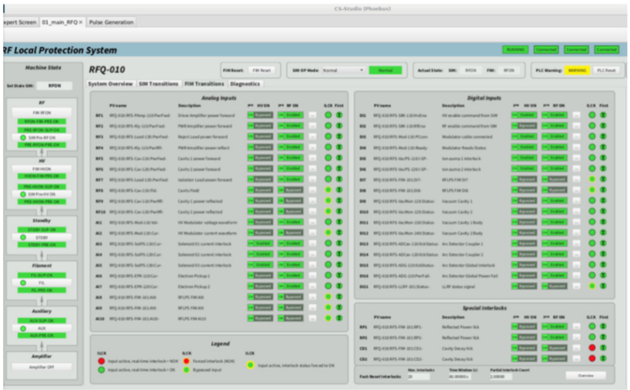

Figure 2: EPICS view of Local Protection System.

RFQ CONDITIONING

The RFQ conditioning campaign can be divided in three phases: 1. low power conditioning, 2. high power conditioning and 3. nominal operation. During these phases the power level, pulse width and repetition rate are adjusted by monitoring the vacuum levels, spark rates and overall system interlocks. Sparks and breakdowns are essential for the procedure of the cavity conditioning. Although, the interlock thresholds and conditioning strategy have to be carefully fine-tuned in order to protect system components from damage. RF power supplied to cavity is switched off in less than 20 µs under the presence of sparks, vacuum pressure increase due to outgassing or any other sort of interlock.

Low power conditioning (100-300 kW zone) focuses on the conditioning of the couplers and was firstly performed at a dedicated test bench at CEA-Saclay. This power zone is mainly dominated by electron activity in the 2 coaxial couplers due to multipacting effects. Multipacting is also linked to outgassing and a small amount of light is sometimes measured by the arc-detectors located in the vacuum side.

Conditioning strategy included power sweeps to detect multipacting areas and outgassing through monitoring electron current and vacuum pressure. In order to eliminate electron current at a specific power level and reduce outgassing, the repetition rate was increased up to 14 Hz. Once stability achieved, the pulse width was also increased gradually to 3.2 ms. Subsequently power levels are increased until the detection of next multipacting zone. It is notable that, the elimination of multipacting areas had to be redone after any conditioning pause for several days.

During high power conditioning, coupler activity was negligible and progress was limited by vacuum hardware interlocks inside the cavity.

In order to facilitate and accelerate the conditioning procedure, an automatic conditioning application was used in combination with start-up and auto reset scripts. Depending on the nature and/or the severity of the interlock the RF power was restored for the next RF pulse or after several seconds either at the same power level before interlock or reduced.

Gradually the frequency of all interlocks were reduced (Figs. 3 and 4) and system achieved nominal field with stable operation (Fig. 5).

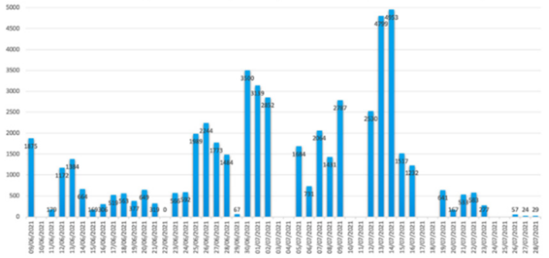

Figure 3: Number of reflection interlocks vs time.

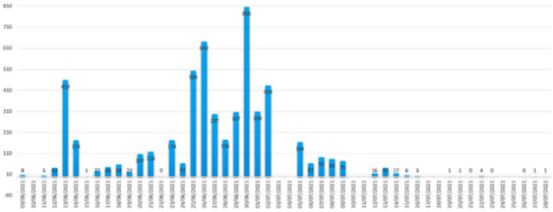

Figure 4: Number of hardware vacuum interlocks vs time.

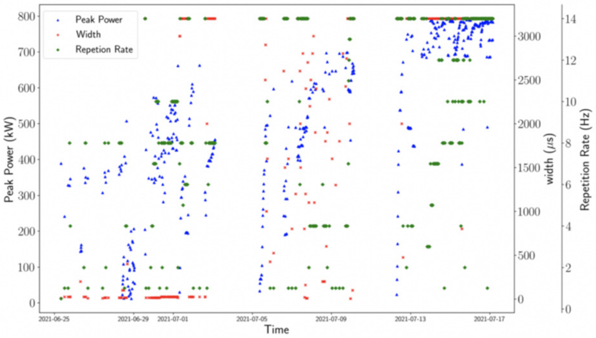

Figure 5: Peak vs Average Power during conditioning.

X-RAY MEASUREMENTS

Throughout the conditioning process, an effort was made to evaluate cavity vane voltage by detecting and analysing the bremsstrahlung x-ray radiation emitted by the electrons released and accelerated into the RFQ [4]. The measurements were performed using an AMPTek XR-100CdTe X-Ray Gamma Ray detector installed on a vacuum flange close to the end of the RFQ, where the design cavity voltage reaches 120 kV, and calibrated with known radioactive sources (251Am 125 Eu). X-ray measurements were performed for multiple power levels and the spectra were acquired, processed and compared with voltage pick-up measurements. Results disclosed a consistency with the designs specification and the power levels estimated during RFQ tuning (Fig. 6).

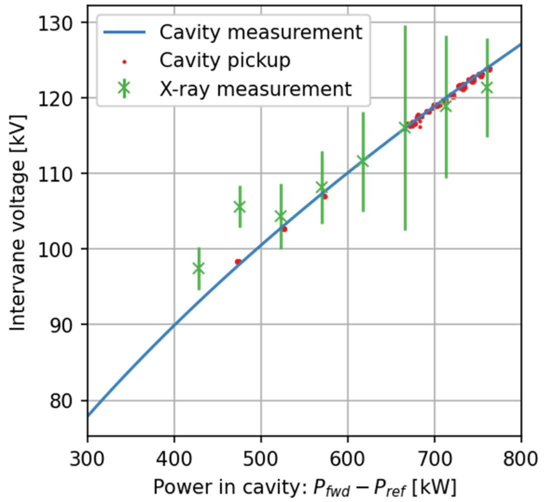

Figure 6: X-ray based voltage measurements.

LONG RUN TESTS

After the achievement of stable cavity field, long run tests and studies were conducted with the aim of observing cavity stability in case of an interlock. For high-power operation, all the temperature setpoints for the cooling loops are set at 28.8°C. In this mode, with stable power, the cavity frequency is maintained to within ±1.5 kHz of the RF frequency. However, when power is interrupted, a variation of ±40 kHz was observed and the power must be ramped in steps and LLRF frequency tracking is required to restore power. This agrees well with thermal simulations of the cavity [5]. In any case, power is restored to the cavity at nominal level in a time period of 3 minutes.

CAVITY VOLTAGE MEASUREMENTS

Field acquisition is performed with 20 RF pickups distributed on each quadrant of the RFQ body along with an additional RF-pickup is saved for LLRF system feedback. These 20 measurements are used to reconstruct inter-vane voltages vs. abscissa along the RFQ and to evaluate field perturbation. Several measurements were made and processed (from short pulse at low power to the nominal pulse at the maximum power). These measurements have been done after about ten minutes of thermal stabilization for the cavity.

The first lower power record (data from 27/07/2021 at 50 kW, 1 Hz, 300µs) is used for calibration with the last beadpull measurement and all the next measurements are compared to this one. Figure 7 shows that the reconstructed voltage varies smoothly over the full power range. Therefore, the RFQ is stable at all power levels and the cavity voltage stays in the 2% requirements. These measurements will be used to periodically check the RFQ field profile in order to detect potential cavity deformation.

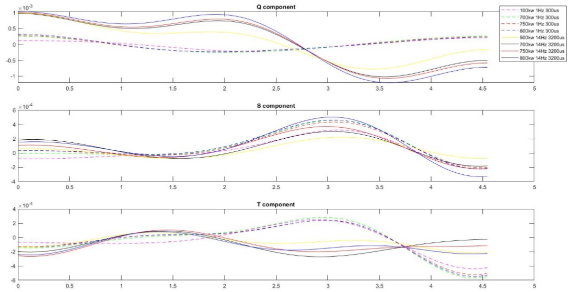

Figure 7: Error of voltage profile for different RF pulse configurations.

CONCLUSION

A seven week period was held at ESS for RF conditioning of the RFQ. At the end of this period, it was successfully demonstrated that the RFQ can stably operate at 112% of the required RF power. At nominal power, 96% of availability is achieved.

It was also demonstrated that the cooling skid performance exceed design specifications and was able to maintain the cavity frequency to ±1.5 kHz during stable operation. Following a period of downtime, full RF can be restored within 3 minutes.

Since October 2021, the RFQ has been undergoing beam commissioning [6, 7]. Further development and testing are in progress to determine optimal operating parameters for LLRF, interlocks and skid control loops.

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