520 MEV TRIUMF CYCLOTRON RF SYSTEM: MAINTENANCE, TUNING AND PROTECTION*

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Abstract

1 MW CW 23 MHz RF system of the TRIUMF's 520 MeV Cyclotron has been in operation for over 40 years. Continuous development of the RF power amplifiers, the waveguide system and the measurement and protection devices provides reliable operation and improves the performance of the RF System. In this article, operation and maintenance procedures of this RF system are analysed and recent as well as future upgrades are being analysed and discussed. In particular, we discuss the improvements of the transmission line's VSWR monitor and its effect on the protection of the RF system against RF breakdowns and sparks. We discuss the new version of the input circuit that was installed, tested and is currently used in the final stage of RF power amplifier. We analyse various schematics and configurations of the Intermediate Power Amplifier (IPA) to be deployed in the future.

INTRODUCTION

TRIUMF 520 MeV Cyclotron's high power RF system consists of three main parts – the 1.8 MW CW RF amplifier, the transmission line (TL) and the resonator [1]. The TL itself is composed of two coaxial lines with wave impedances of 50 and 30 ohm. The second part of the TL has three capacitor stations that match 50 ohm impedance of the TL's first part with the coupling loop port of the resonator that is at TL's terminus.

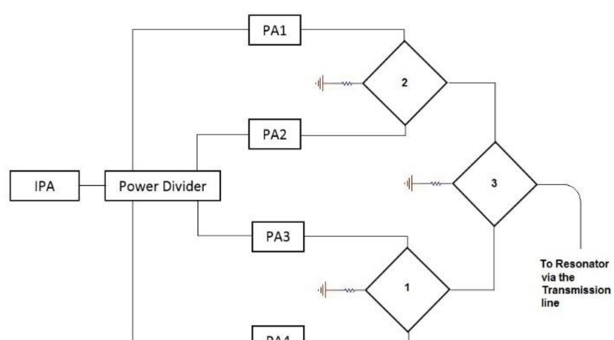

Figure 1: RF System of the 520 MeV Cyclotron.

TRANSMISSION LINE RESONATOR OPERATION AND SPARK PROTECTION

Instability in the RF system's operation appears when there are sparks, electrical breakdowns, multipactor discharge in the resonator and a presence of an essential screen current in the vacuum tubes. The VSWR monitor is used to protect the RF system. This monitor turns off the RF system, if the reflected power in one of the 12 channels exceeds a specified threshold value. The RF control system analyses the rate of the Dee voltage drop, classifies the events and then tries to recover the system. The follow up analysis of where sparks and electrical breakdowns took place is done using an oscilloscope. The oscilloscope operates in stand-by mode otherwise. An example of a typical signal pattern that illustrates a spark inside the resonator is presented in Fig. 2.

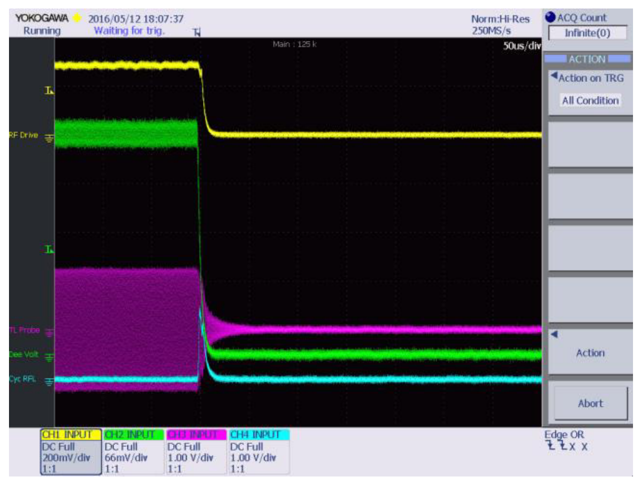

Figure 2: Resonator RF signals following a spark, when the drive is OFF (yellow – drive amplitude, green – Dee voltage, pink – RF signal, blue – rectified voltage of the reflected signal).

The rate of the Dee voltage drop allows to determine whether this spark happened inside the resonator or inside the TL and how large the spark was. The RF control system has sensors to determine the Dee voltage drop and if zero Dee voltage is detected. If either case is detected, the RF control system generates the signal to turn OFF the RF drive and to determine the time when RF system's recovery should be attempted.

However, if these sensors didn't respond properly or responded with some delay, the standing beat wave in the TL could reach double amplitude of the original signal (Fig. 3). As a result, some parts of the TL, such as matching capacitors, the water feedthrough or the TL conductors and insulators could be damaged.

To protect cyclotron's equipment in such an event, the RF switch was built into the VSWR monitor to disconnect the RF drive from the RF amplifiers (Fig. 4).

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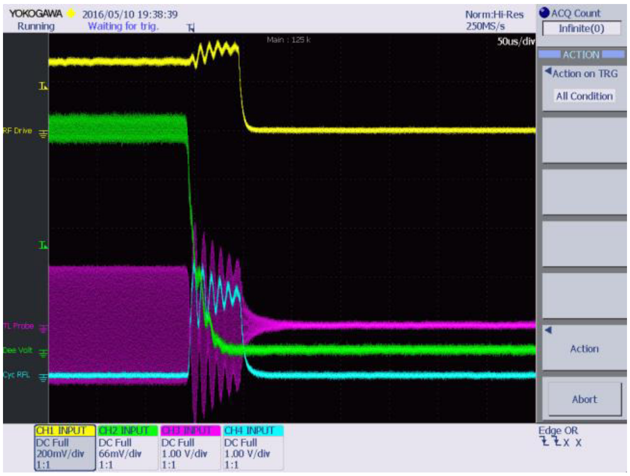

Figure 3: RF beat signals following a spark in the oscilloscope, when the drive is ON (yellow – drive amplitude, green – Dee voltage, pink – RF signal, blue – rectified voltage of the reflected signal).

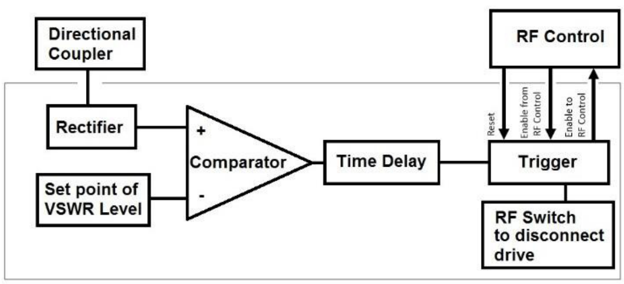

Figure 4: The Block Diagram for one of the channels of the high VSWR detector in the VSWR Monitor.

Some of the weakest parts of the TL susceptible to damage following a spark are the water hoses between the outer and the inner conductors of the TL. The water entrances into the inner conductor are simulated in HFSS v15.0 (Fig. 5).

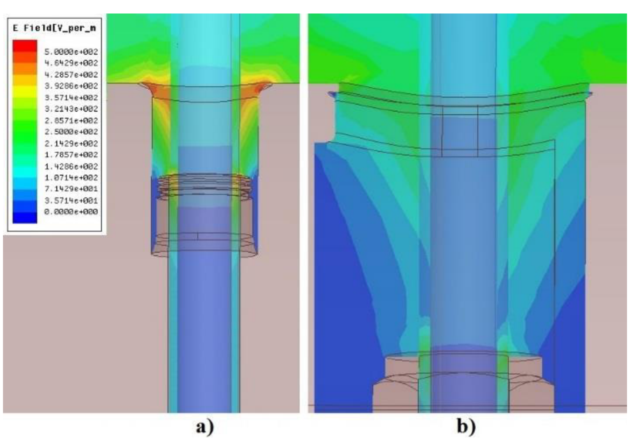

Figure 5: Simulation of the RF field near the water feedthrough in the TL for the original (a) and the new design (b).

In order to improve TL's reliability, the configuration of the conductors in the area with the highest RF field was modified. A simulation in HFSS determined that the RF field is three times higher near the water feed (ε=81) and the sharp edge of the inner conductor. As a solution, the compression fitting was moved deeper into the inner conductor.

HIGH POWER RF AMPLIFIER

The high power RF amplifier is composed of the intermediate power amplifier (IPA), the splitter, four high power amplifiers (PA) and three combiners (Fig.1). The performance and the stability of the RF system is dependent on the quality of vacuum tubes, on the amplifier fine tune and on the suppression of parasitic oscillations.

PA Tuning, Operation and Development

Each of the four PA amplifiers is composed of two 4CW250,000E tetrodes that operate in push-pull mode. Those amplifiers are designed to operate up to 450 kW CW. In order to increase the life time of these tubes they are operated at a 50% lower power and 10% lower filament current (with respect to the nominal values). As a result the tetrodes' lifetime can now reach 135,000 hours.

During the last maintenance period, the PA4 amplifier was upgraded. A new input circuit was installed in order to improve its accessibility and to reduce the downtime involved in troubleshooting as well as during input capacitor replacement.

Figure 6: Installation of a new PA4 Input circuit.

IPA Operation, Tuning and Development

The IPA consists of two stages: a pre-amplifier pentode and a final tetrode. The maximum power that could be reached under the current design is 100 kW. However, in order to increase the life time of the IPA tubes, a 4CW100,000E tetrode is used at the output stage to provide only 50 kW and is operated at 10% lower filament current.

The tetrode stage is loaded with the Pi-network which is connected to the 4-way splitter. This splitter distributes the output power between PAs inputs. To determine the impedance of this load, the method of variations of capacitances [2] was applied to the Pi-network. Independent variations of C_{37}, C_{40} (Fig. 7) from the original values allow to derive five equations for resonance conditions with C_{37}, C_{40} and L_{19} being the unknown variables.

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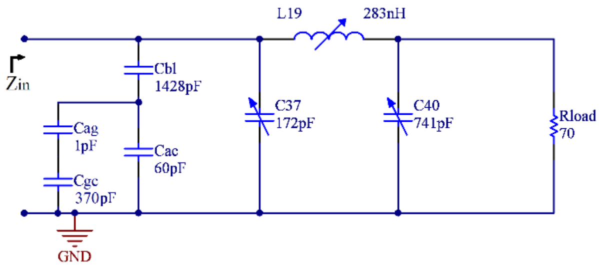

Figure 7: The load schematics setup for the variable capacitance method.

$$Im\left(Z_{inp}(\omega_1, R_{load}, C_{bl}, C_{ac}, C_{ag}, C_{gc}, C_{37}, C_{40}, L_{19})\right) = 0$$

$$Im\left(Z_{inp}(\omega_2, R_{load}, C_{bl}, C_{ac}, C_{ag}, C_{gc}, C'_{37}, C_{40}, L_{19})\right) = 0$$

$$Im\left(Z_{inp}(\omega_3, R_{load}, C_{bl}, C_{ac}, C_{ag}, C_{gc}, C_{37}, C'_{40}, L_{19})\right) = 0$$

$$C'_{37} = C_{37} + \Delta C_{37}$$

$$C'_{40} = C_{40} + \Delta C_{40} ,$$

where ω_1, ω_2, ω_3, R_{load}, C_{bl}, C_{ac}, C_{ag}, C_{gc} are the measured values, values of C_{37}, C_{40}, L_{19} are the unknowns. MathCAD Prime 3.1 has been used to solve this system of equations.

This more precise measurement of load impedance allowed to determine the regime of tubes. As a result, the screen current was reduced, which allowed more stable tube operation.

Currently the IPA is being planned for upgrade. The new IPA configuration will have four independent 12 kW solid state amplifiers connected directly to the inputs of PA amplifiers. The amplitude and the phase will be fixed before each IPA input. The development of a new IPA design will be carried out in several stages. Currently, the IPA is based on pentode and tetrode vacuum tubes, where the tetrode has the neutralization circuit via the pentode load. The goal of the first stage of the upgrade is to make these tubes independent. In the second stage, the pentode will be replaced by a 2 kW solid state amplifier. In order to decouple the pentode and the tetrode, a different neutralization circuit is proposed for the tetrode (Fig. 8). This circuit has been developed using the prototype that is currently used as a part of TRIUMF's ISAC-1 particle accelerator. The mechanical design and the series of simulations in Micro-Cap and Altium Designer 10 have been completed. The equivalent circuit for neutralization and the results of simulation in Micro-Cap presented on Fig.9. The current timeline is to rebuild and test IPA in the winter shutdown of 2017.

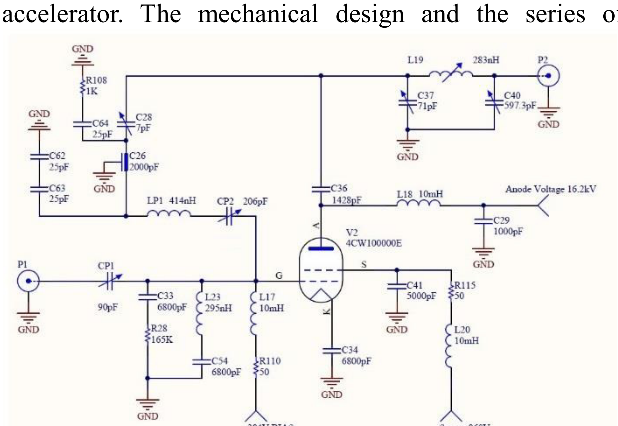

Figure 8: The tetrode stage with a new neutralization.

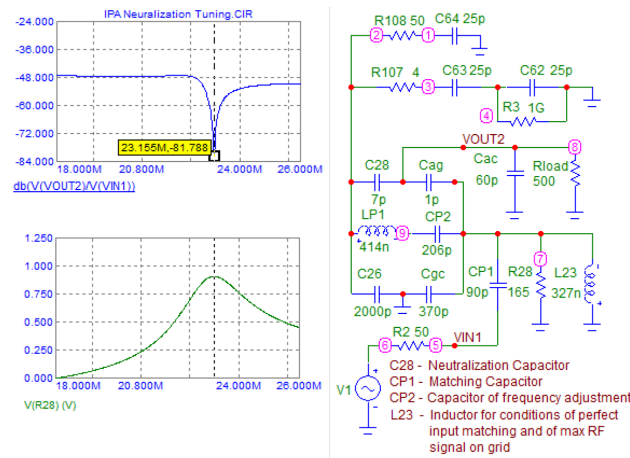

Figure 9: Simulation of neutralization tuning.

MAINTENANCE OF RF SYSTEM

All high power RF components such as vacuum capacitors of the amplifier, combiners and the TL have an annual maintenance service carried out during the 4-month winter shutdown or during 10 days of the autumn mini shutdown. A hi-pot test for the capacitors and the vacuum tubes, inspection and cleanup of the RF components, a low and high power level tunings are carried out during those maintenance periods. An inspection of the TL, the vacuum capacitors of the matching stations, the booster resonator, the water cooling pipes and hoses in the vault are also performed during every winter shutdown.

CONCLUSION

Fine tuning of PAs and the IPA, installation of the RF switch in the VSWR monitor, thermo-stabilization of the Dee voltage rectifiers improved the stability of the high power RF system.

REFERENCES

[1] Y. Bylinski, S. Calic, K. Fong, R. Poirier, "TRIUMF Cyclotron RF System Refurbishing", presented at the 17th International Conference on Cyclotrons and their Applications, Tokyo, Japan, Oct. 2004, pp. 326-329

[2] E.L. Ginzton, "Resonant-cavity characteristics: Measurements of R_o/Q_o ", in Microwave Measurements, Leonard I. Schiff, Consulting Editor, McGRAW-HILL BOOK COMPANY, INC, New York, Toronto, London, 1957, pp. 435-438

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