OPERATION AND MAINTENANCE OF RF SYSTEM OF 520 MEV TRIUMF CYCLOTRON*

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Abstract

1 MW CW 23 MHz RF system of the TRIUMF 520 MeV Cyclotron has been in operation for over 40 years. Continuous development of the RF power amplifiers, the waveguide system and of the measurement and protection devices provides reliable operation and improves the performance of the RF System. In this article, operation and maintenance procedure 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 their effect on the protection of the RF system against RF breakdowns and sparks. We discuss the new version of 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 used in the future. The thermo-condition improvements of the Dee voltage probe's rectifiers are described.

INTRODUCTION

TRIUMF 520 MeV Cyclotron's high power RF system consists of three main parts – the 1.8MW CW RF amplifier, the transmission line (TL) and the resonator. 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 the TL's terminus.

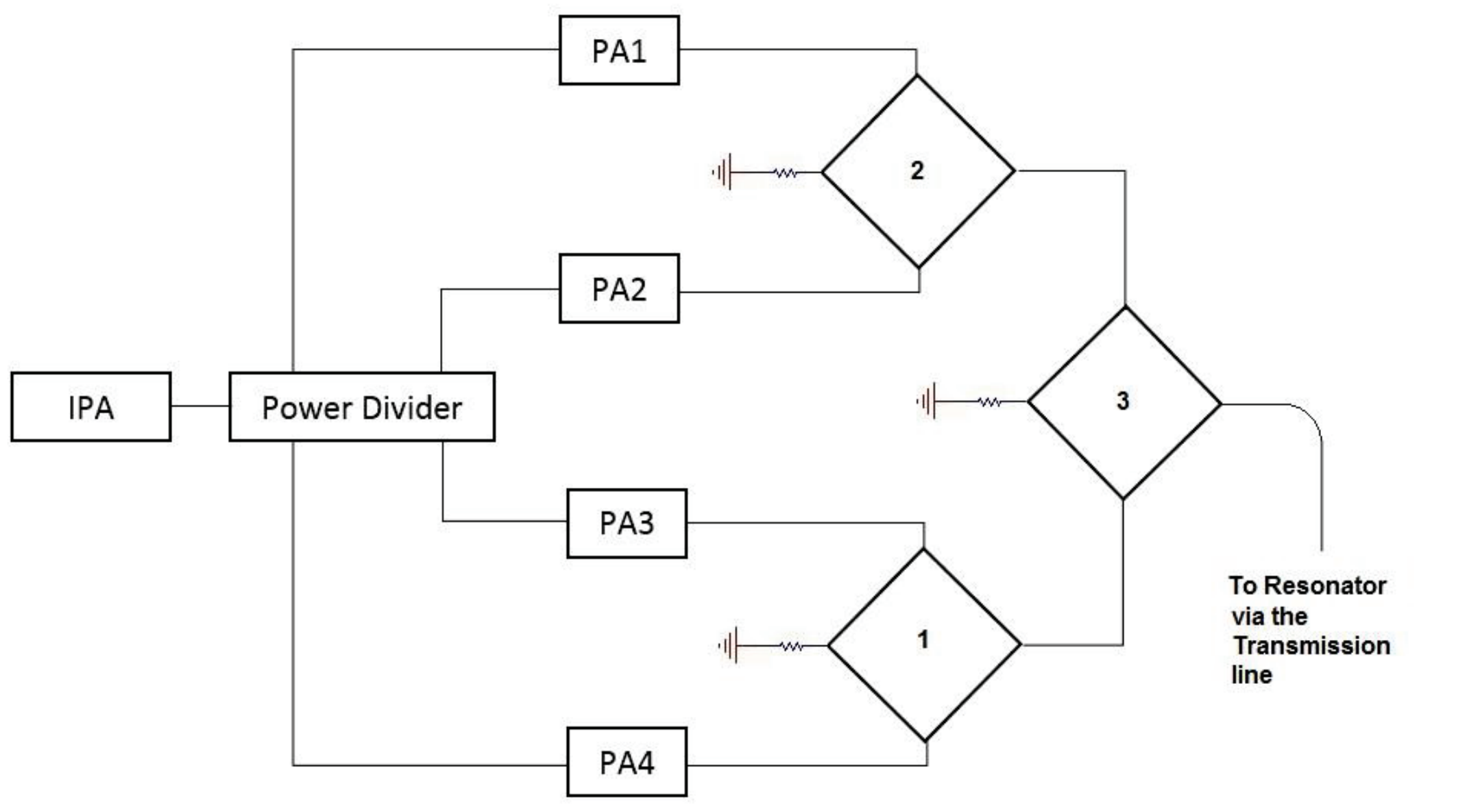


Figure 1: RF System of the 520MeV Cyclotron.

TRANSMISSION LINE RESONATOR OPERATION AND SPARK PROTECTION

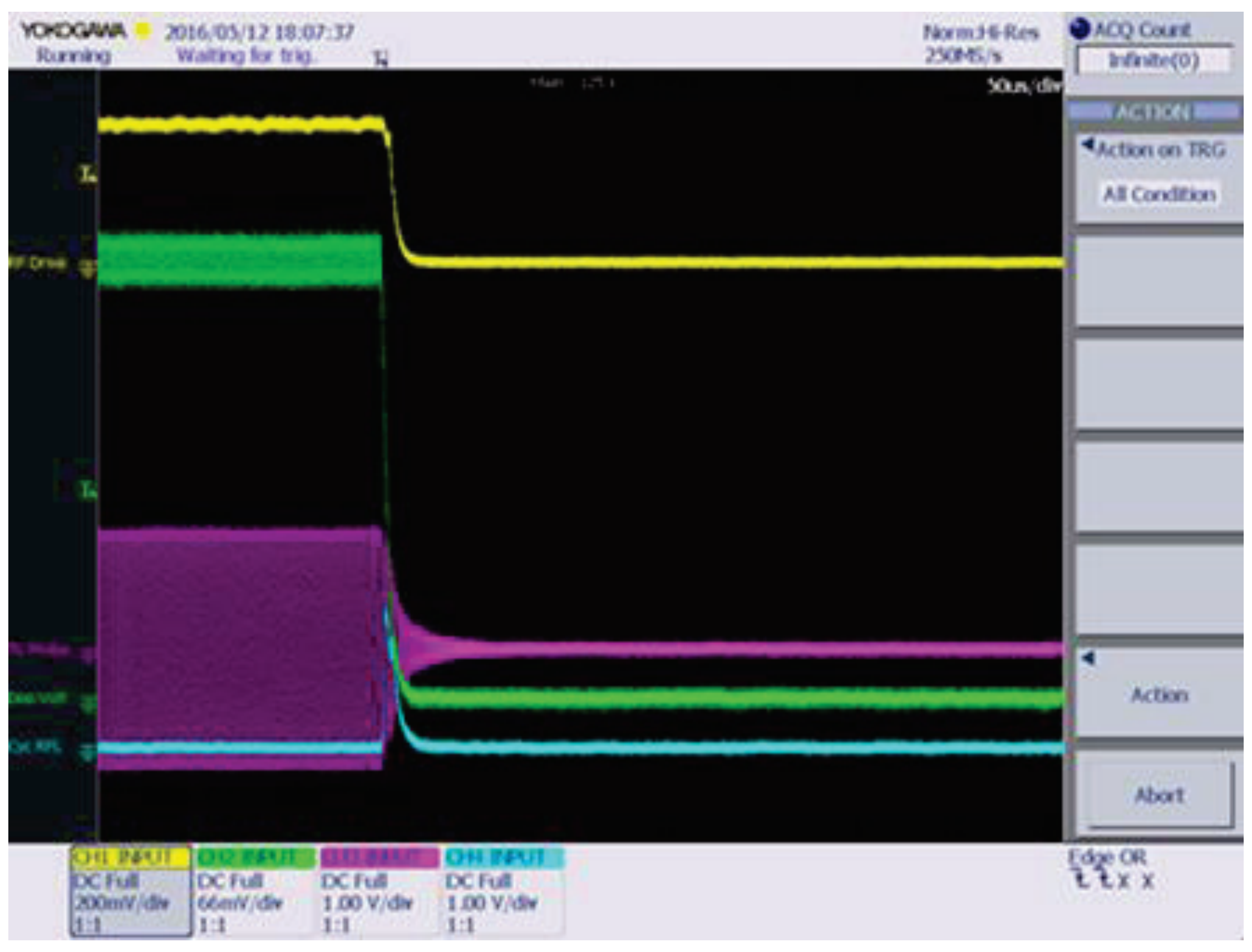


Figure 2: Resonator RF signals following a spark, when drive is OFF (yellow – drive amplitude, green – Dee voltage, pink – RF signal, blue – rectified voltage of the reflected signal).

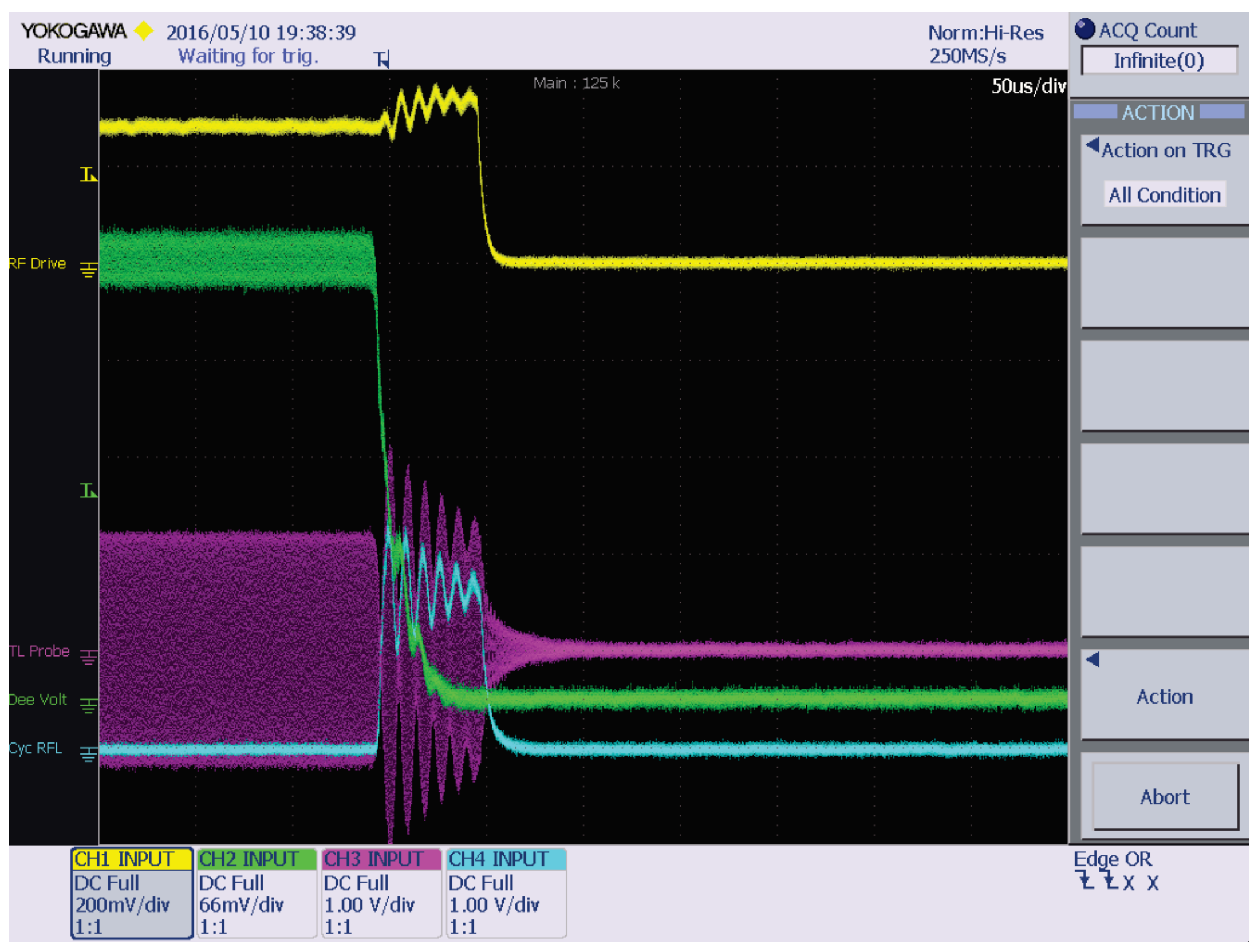


Figure 3: RF beat signals following a spark in the oscilloscope, when the drive is ON (yellow – drive amplitude, green – Dee voltage, pink – RF signal, blue – rectified voltage of the reflected signal).

Instability in the RF system's operation appears when there are sparks, electrical breakdowns and multipactor discharge in the resonator. 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 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.

The rate of 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 TL could reach double amplitude of the original signal (Fig. 3). As a result, some parts of the TL such as the matching capacitors, the water feedthrough or the TL conductors and insulators could be damaged.

To prevent the case demonstrated in Fig. 3 and to protect cyclotron equipment, the RF switch was built into the VSWR monitor to disconnect the RF drive from the RF amplifiers.

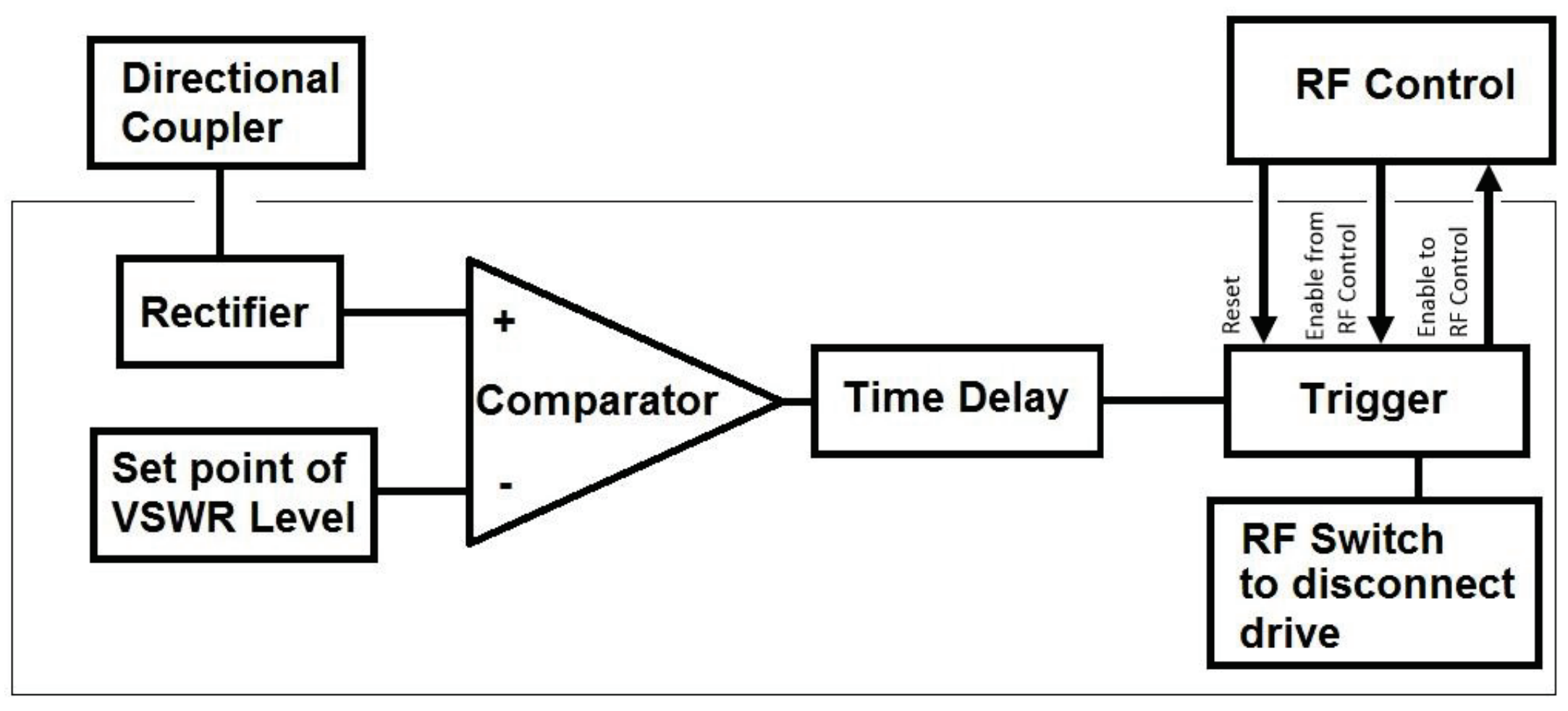
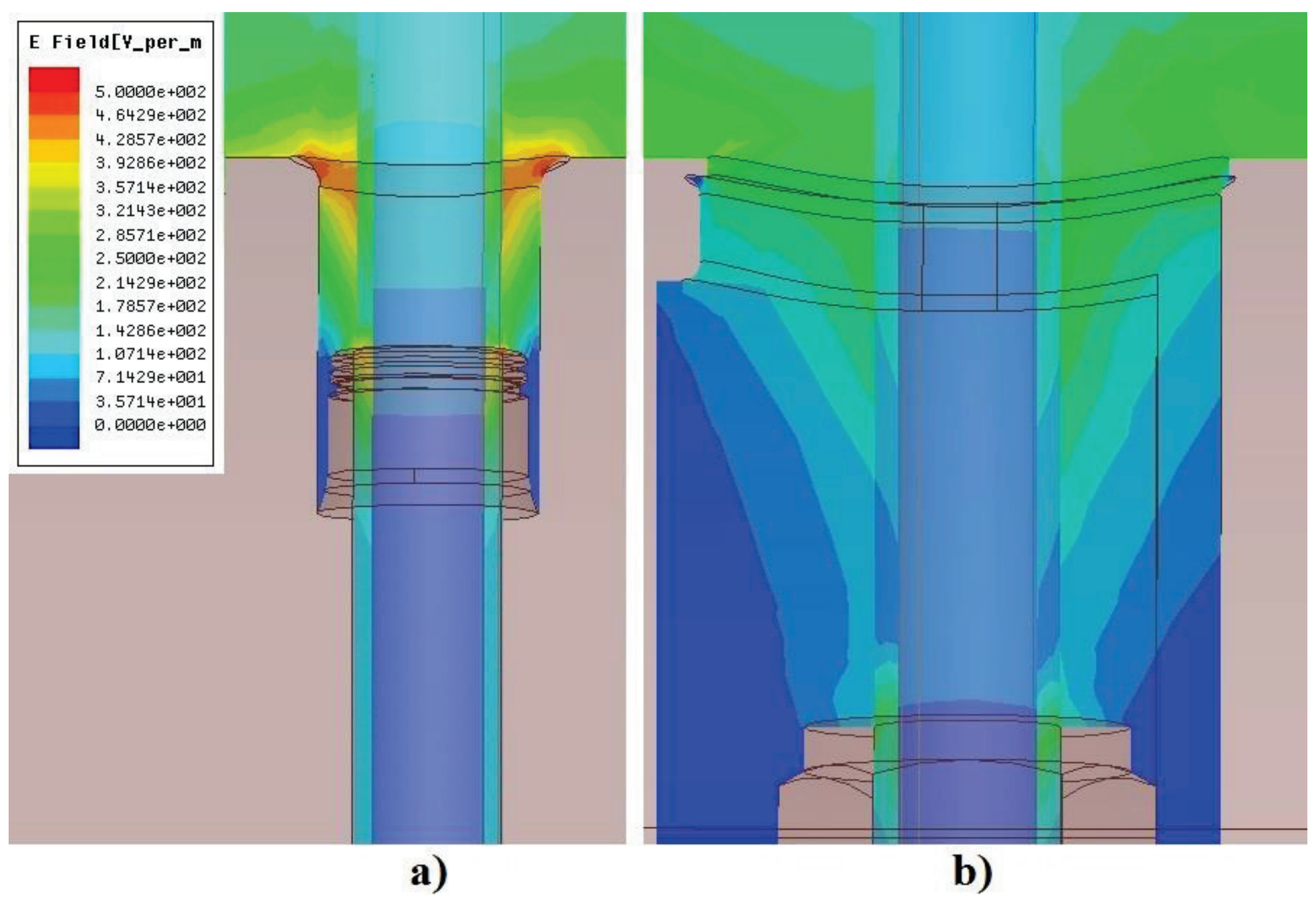


Figure 4: The Block Diagram for one channel of the high VSWR detector in the VSWR Monitor.

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



a)
b)

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) into the central conductor. As a solution, the compression fitting was moved deeper into the central 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, the ability of the high power RF capacitors to operate in high RF voltage and on the condition of the DC power supplies.

PA Tuning, Operation and Development

Each of the four PA amplifiers are 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 is now beyond 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.

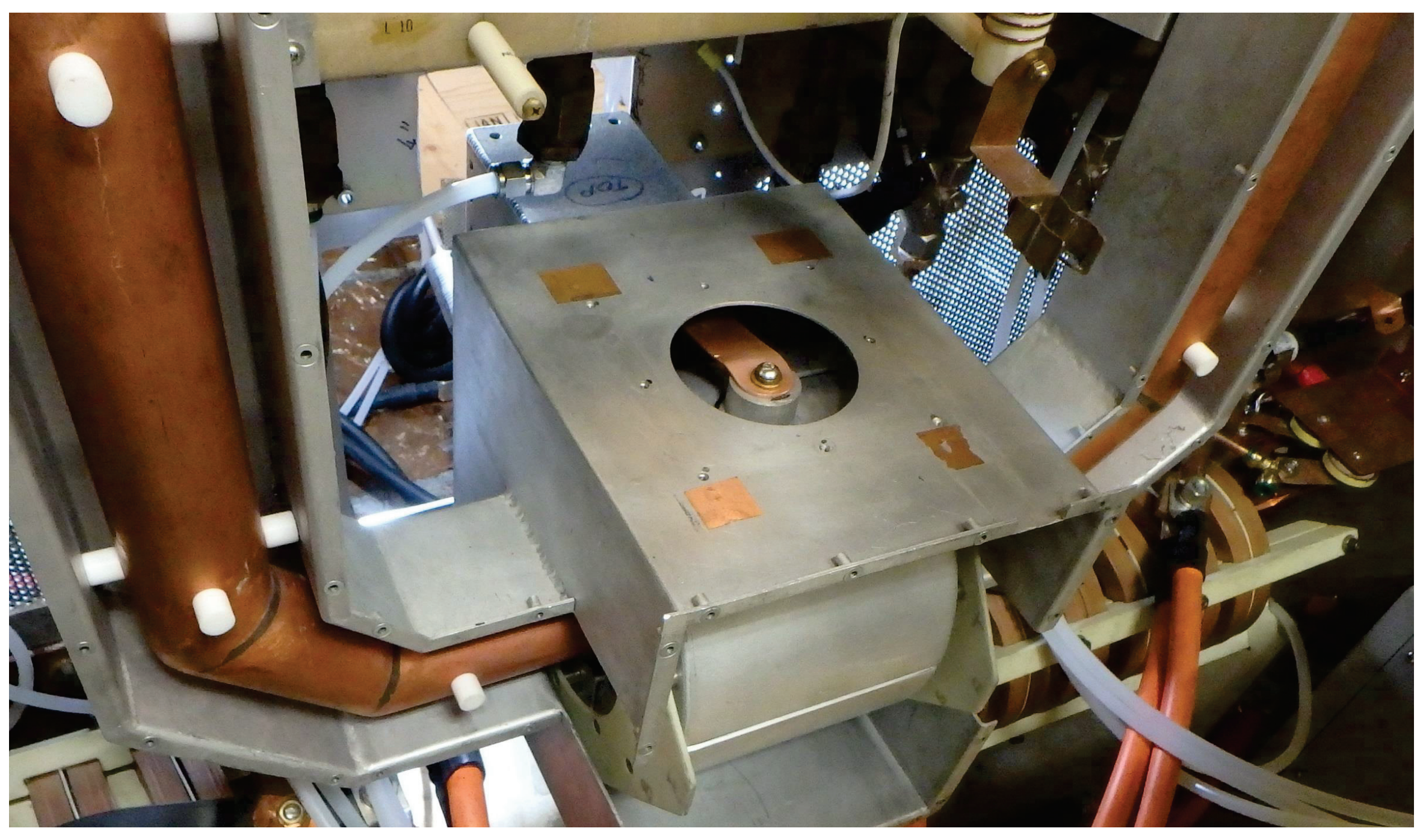


Figure 6: Installation of a new PA4 Input circuit.

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 reach 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 was applied to the Pi-network. Independent variations of C37, C40 (Fig. 7) from the original values allow to derive five equations for resonance conditions with C37, C40 and L19 being the unknown variables.

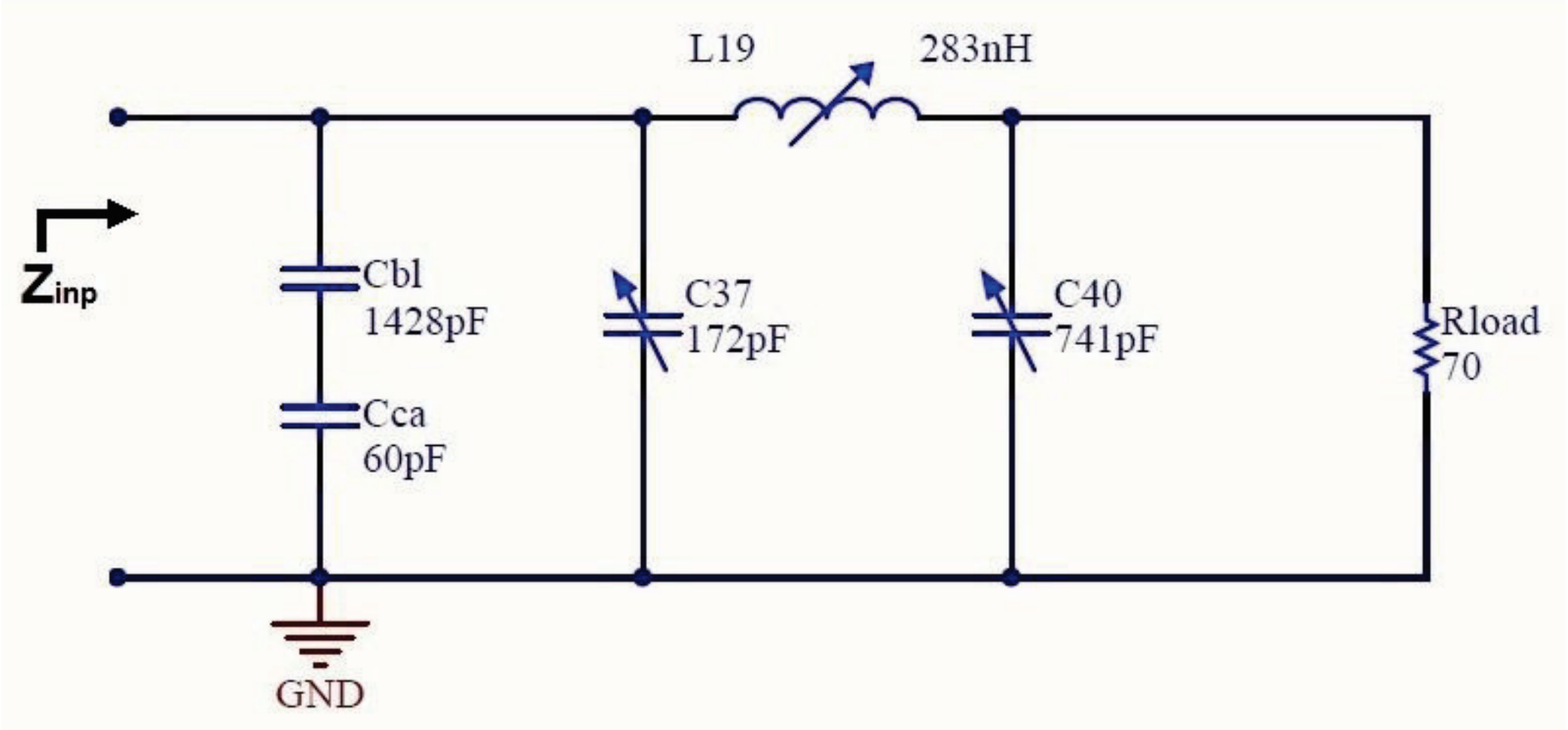


Figure 7: The load schematics setup for the variable capacitance method.

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

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

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

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

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

where $\omega_1,\ \ \omega_2,\ \omega_3, R_{load}, C_{bl}, C_{ca}$ are the measured values, values of $C37$, $C40$, $L19$ are the unknowns.

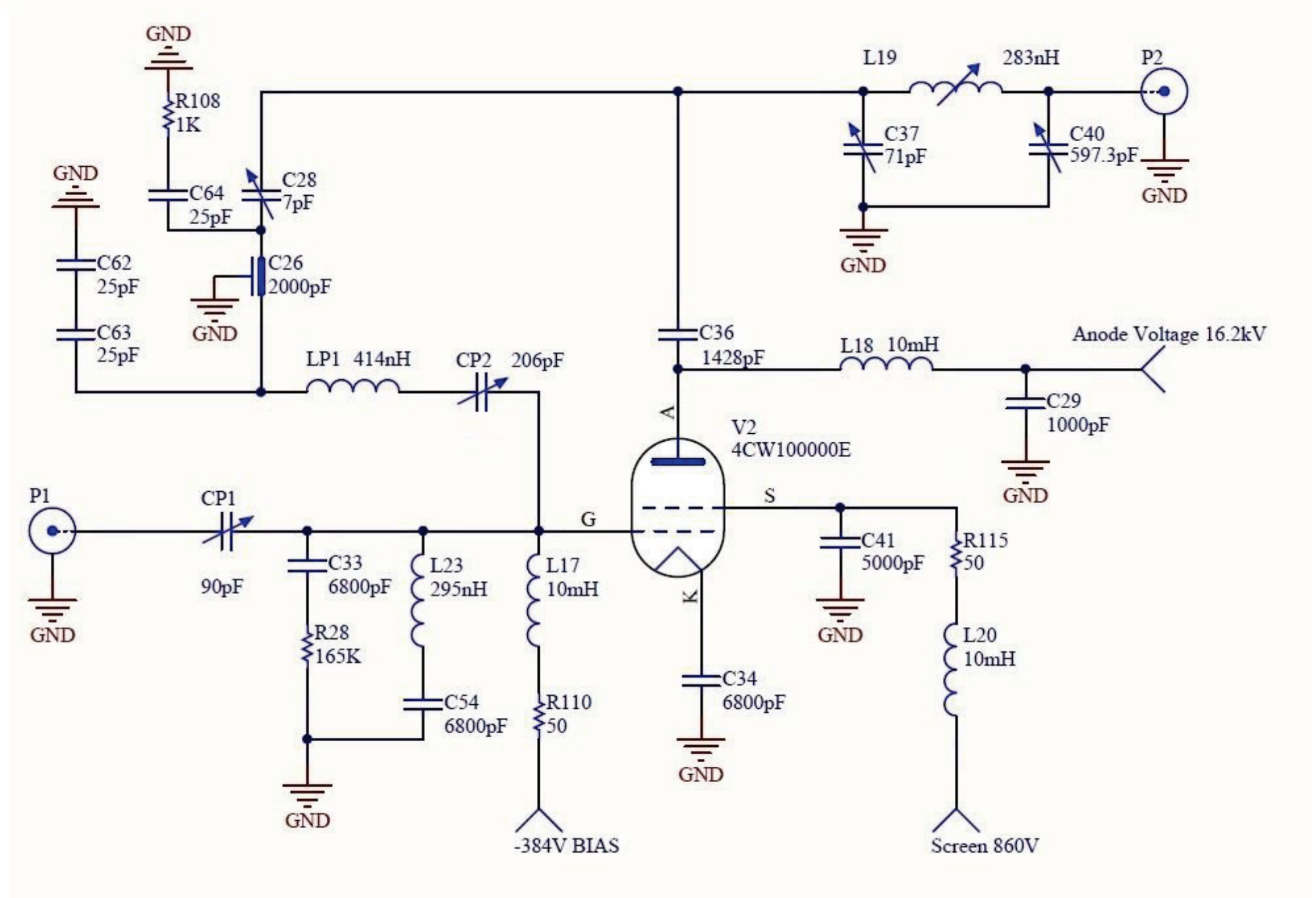
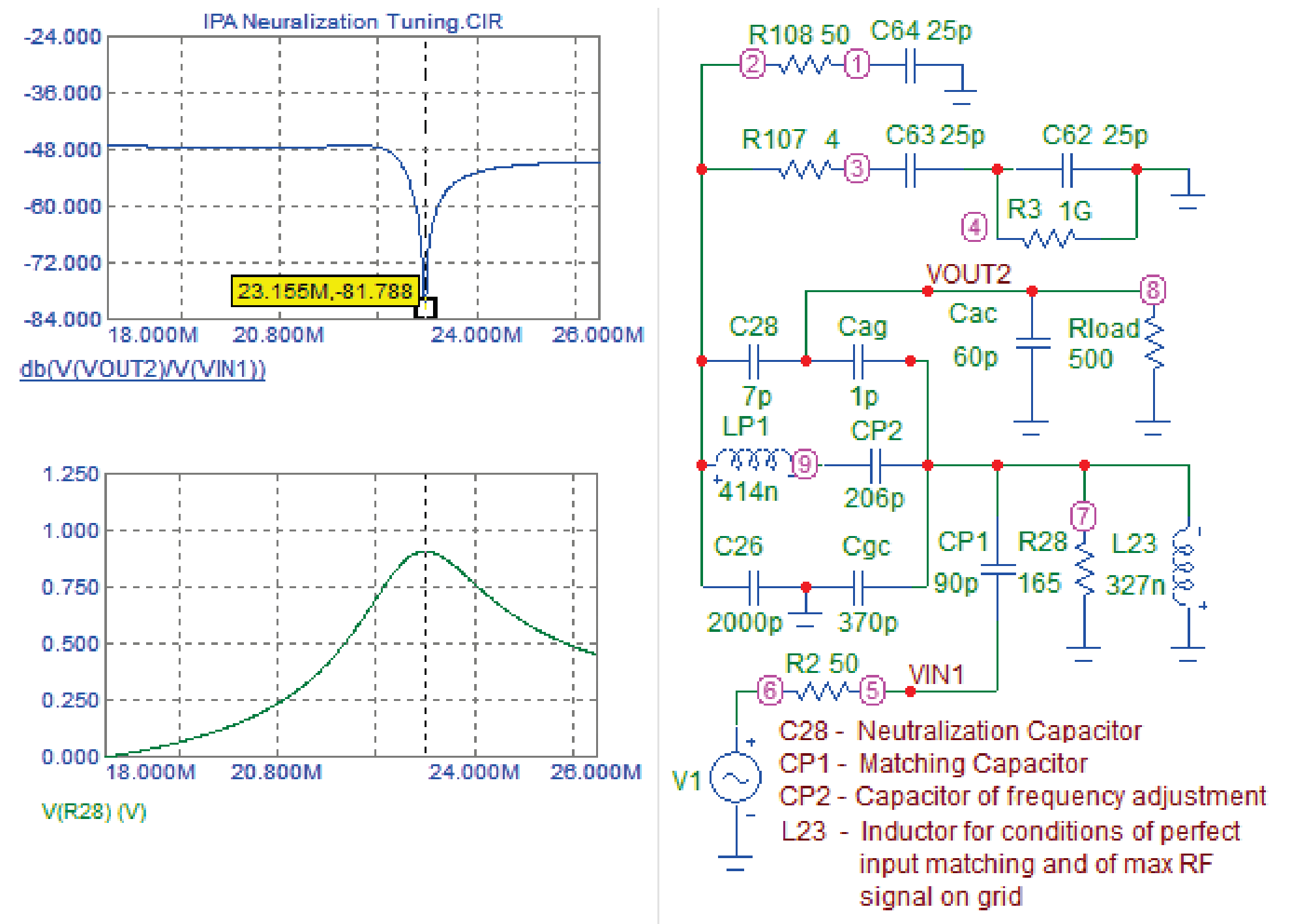


Figure 8: The tetrode stage with a new neutralization.



C28 - Neutralization Capacitor
CP1 - Matching Capacitor
CP2 - Capacitor of frequency adjustment
L23 - Inductor for conditions of perfect input matching and of max RF signal on grid

Figure 9: Simulation of neutralization tuning.

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