

# RECENT DEVELOPMENTS OF THE 520 MeV CYCLOTRON'S HIGH-POWER RF SYSTEM AT TRIUMF\*

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## Abstract

520 MeV Cyclotron's High-Power RF System has been in the state of continuous operation for over 50 years since its commissioning. This paper describes the recent upgrades of the RF System, the main goal of which was to improve reliability. Specially, we discuss the upgrades done to the RF Transmission Line (TL), the RF Power Amplifier (PA) components and their diagnostics tools. We upgraded the structure of Intermediate Power Amplifier (IPA), installed Solid State (SS) driver and are in the process of replacing tubes with a SS option for IPA and PA.

## INTRODUCTION

Upgrades to improve the RF system of 520 MeV cyclotron [1] are made on an annual basis. The main goal is reduction of RF system's downtime. Recently, we also began implementation of SS technologies, as in the future they are to make up the core of RF amplifiers.

## RF SYSTEM OF THE 520 MeV CYCLOTRON

The RF system of the 520 MeV Cyclotron consists of the 1.0 MW CW main resonator operating at 23.06 MHz and the 40 kW CW RF booster operating at 92.24 MHz (the 4th harmonics).

Main RF System layout is presented in Fig. 1.

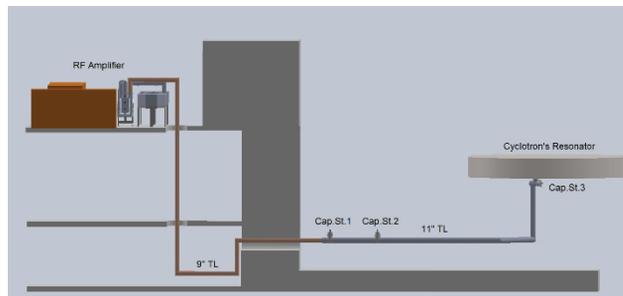


Figure 1: Main RF system layout.

RF amplifier of the main RF System consists of the IPA, the splitter and four 250 kW PAs. The output power of the 250 kW PAs is combined into a 1 MW output by the means of a 2-stage combiner system which consist of three combiners in total (Figure 2).

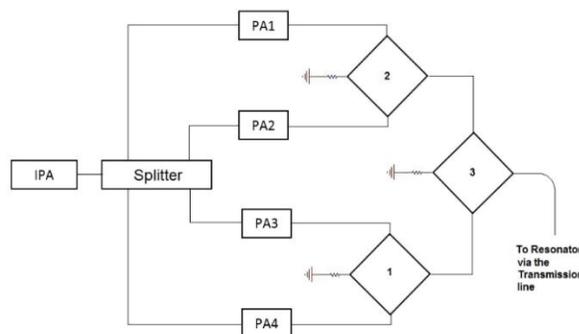


Figure 2: RF amplifier of the 520 MeV Cyclotron.

RF power is transmitted from the RF amplifier by the means of a 9" coaxial line followed by a 11" transmission line (TL) loaded with an inductive coupler and 3 variable capacitors for matching tuning.

## UPGRADE OF THE POWER AMPLIFIER

### Development of SS Driver for IPA

The original IPA consists of four stages: the SS preamplifier (SSPA), the driver, the pentode stage and the tetrode stage. We are in a process of replacing the pentode stage by SS amplifiers in the IPA. 2 kW SS driver will replace the pentode stage. The SS driver was installed and tested during Cyclotron's operation, yet at the same time, the pentode stage has not been decommissioned. A simple reconnection of cables in the IPA could return the IPA to the original configuration that uses the pentode. Figure 3 shows block diagram IPA with the 2 kW SS Driver.

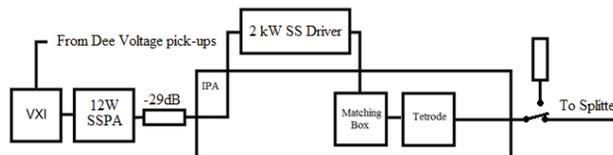


Figure 3: The block diagram of IPA for testing 2 kW SSA during cyclotron operation.

Before operational test of 2 kW SS driver, it was tested it in the IPA loaded with dummy load for power over 45 kW.

2 kW SS driver phase change never exceeds a 38.5-degree change at outputs that are above the minimal power of the RF system (SS output at 230 W, which corresponds to 40 kV of Dee Voltage). Figure 4 depicts the plot of phase change given the output power of the 2 kW SS driver; two horizontal markers show the range of phase change as output power increases from 230 W to 475 W.

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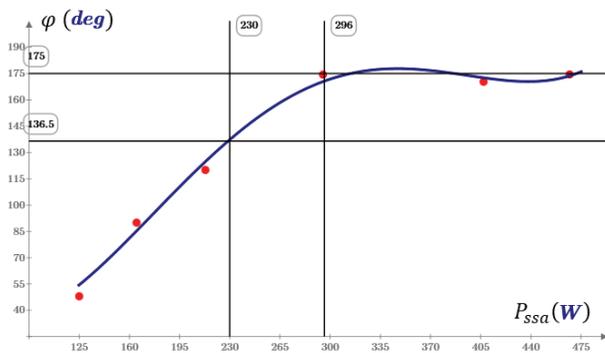


Figure 4: The dependence of the phase shift between input and output on the output power of the 2 kW SS driver.

Figure 5 shows the dependence of the gain of the 2 kW SS driver on its output power. The vertical markers (at 230 W and 437 W) show the operational range of the driver during operation of the 520 MeV Cyclotron.

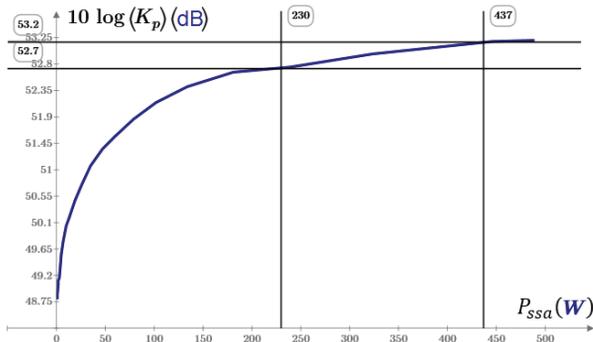


Figure 5: The dependence of the gain of the 2 kW SSA on its output power.

Figure 6 illustrates the dependence of the Cyclotron resonator's Dee Voltage on the outer power of the 2 kW SS driver. The plot confirms the appropriateness of using the 2 kW SS driver during regular Cyclotron operation.

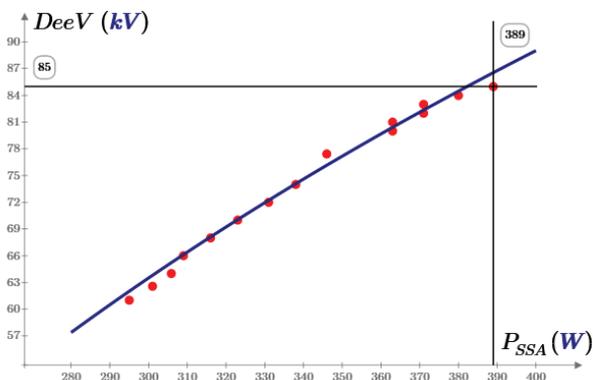


Figure 6: The dependence of the Dee Voltage given the output power the 2 kW SS Driver.

### Redesign of Water-cooling for the IPA

The water-cooling system of the high-power tetrode (4CW100,000E) in IPA requires use of plastic hoses in high power RF field, right above the top of the tetrode assembly.

The original design employed polyethylene hoses (to minimize RF losses) and copper shielding rings connected to the tetrode plate. After two years of operation, the hoses become fragile due to the high RF field. As a result, there was a potential for water leaks and even splashes of water onto components at high DC and RF voltage, followed by sparks and big damages to the IPA. Our goal for the redesign was to reduce the RF field near hoses and to use stronger and more elastic hoses.

To reduce the RF field, we decided to replace the copper lid of the tetrode top assembly and the shielding copper rings with a simple Teflon lid. Figure 7 shows the photos of the original design (a) and of the new design (b).

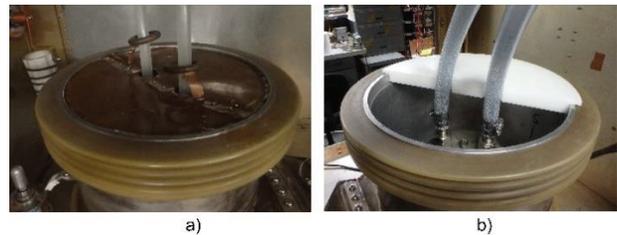


Figure 7: The blocking capacitor of the tetrode with different lids.

Simulation of the RF field in Comsol 2D showed the field distribution of the electrical component of the EM field near polyethylene hose. Fig. 8 a) shows the simulation for the original design and Fig. 8 b) shows the simulations for the new design. According to the simulation results, the new design reduces electric component of the EM field near hoses by a factor of at least two in comparison with the original design.

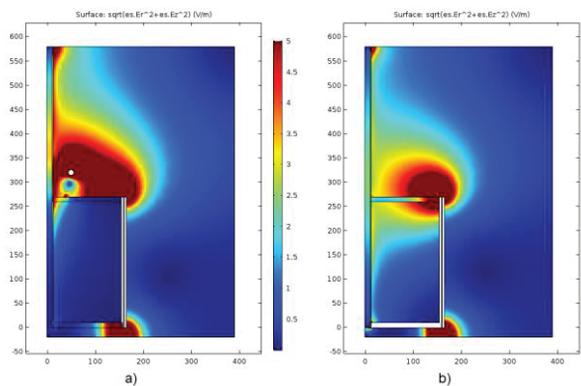


Figure 8: The results of simulations of the electrical field near the top of the blocking capacitor.

### The Upgrade of Water Supply for the PAs

One of the essential causes of a water leak in the PAs is a crack in the metal bellows that provide water-cooling for power tubes, caused by water cavitation in those bellows. The original bellows were made of beryllium copper (BeCu). To avoid these problems, we installed stainless steel bellows that should sustain against water cavitation (see Fig. 9).



Figure 9: PA2 with stainless steel bellows.

Cold measurements showed that Q-factor of the output resonator of the PA was less than the original one by about 3 % due to the change of BeCu to SS. We successfully tested upgraded PA in regular operation at 200 kW power.

## UPGRADE OF THE TRANSMISSION LINE

### Redesign of the Inner Conductor of the 11-inch TL near the Main Coupling Loop

The original inner conductor of the 11" coaxial TL consisted of two parts that were made of aluminium (see Fig. 10, a)). Only the left part of the conductor had water-cooling, and the right part was cooled just by the means of poor thermal contact with the left part. The inner conductor was made from aluminium cast that is prone to deterioration from water cavitation followed by leaks. In the summer of 2017, a water leak on the inner conductor surface caused to a strong RF discharge that heavily damaged the TL.

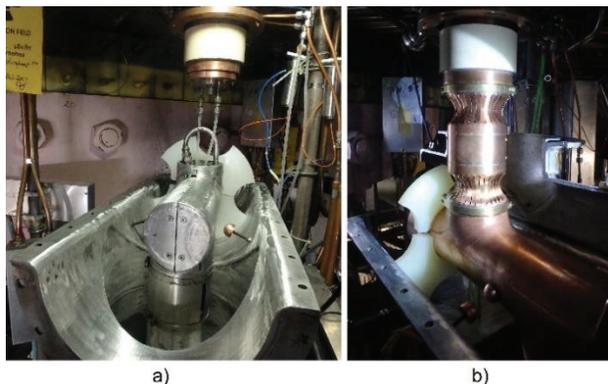


Figure 10: 11-inch TL near the main coupling loop before and after the upgrade of the inner conductor.

To make the inner conductor sustainable to exposure to water and to avoid any damage of the TL in the future, we came up with the new design of TL near the main coupling loop of the cyclotron resonator. New inner conductor is now made of a copper plated stainless-steel welded structure, which is resistant to water cavitation and has better cooling properties (Fig. 10 b)). The rest of 11" TL is made of aluminium. We connected the new copper plated inner conductor to the rest of the TL with aluminium foil that is copper plated at one end to avoid corrosion problem. In this

winter shutdown, we manufactured and installed new parts of the TL.

### Interlock Based on Verification Standing Wave in the Matching Section of the 11-inch TL

The TL has 41 RF pick-ups in 11-inch TL. These signals allow determining the standing wave in the TL for Xtpage measurement system. The results help with monitoring the operation of TL and of the cyclotron resonator. We are now considering development of a diagnostics system to be used for protection of the RF system (see Fig. 11).

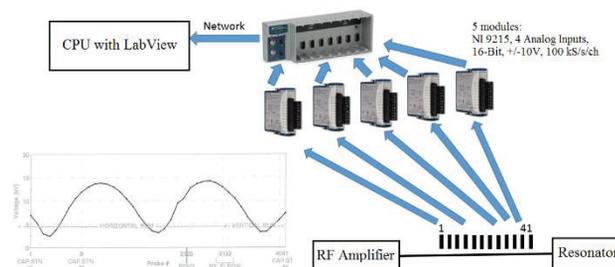


Figure 11: The block diagram of the interlock based on the waveform of the standing wave in the TL.

### Water Leak Detectors and Interlocks of the TL

To protect RF TL from water leak damage, we built the water interlock system that is based on water sensors placed underneath all critical parts of the TL (see Fig. 12). Those sensors trigger this interlock.

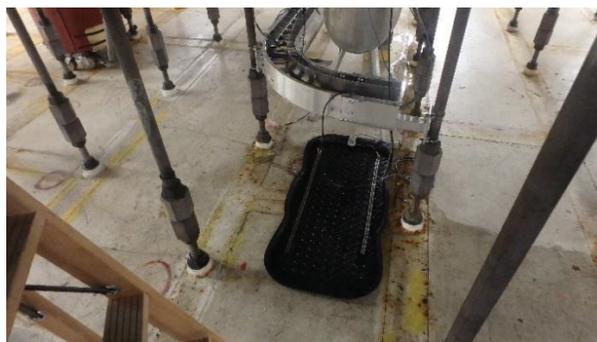


Figure 12: Photo of water leak sensors tray.

## CONCLUSION

The current upgrades involved many critical components of the TRIUMF Cyclotron's RF system: replacement of pentode with the SS driver, improvements of water-cooling for PA and IPA, TL upgrade with new components and water interlock. Those upgrades should provide more reliable operation of the 520 MeV cyclotron.

In the future, we are looking to gradually substitute tube RF power amplifiers for SS RF power amplifiers.

## REFERENCES

- [1] N.V. Avreline, V.L. Zvyagintsev, I.V. Bylinskii, C. Bartlett, B. Jakovljevic, T. Au, Operation and Maintenance of RF System of 520 MeV TRIUMF, in *Proc. Cyclotron2016*, Zurich, Switzerland, 2016, paper THP03.