ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THOGA3

USING P-SPICE MODEL FOR SPARK DETECTION IN TRIUMF'S MAIN CYCLOTRON SYSTEM

R. Leewe, T. Au, K. Fong, TRIUMF, Vancouver, V6T 2A3, Canada

Abstract

Sparks in TRIUMF's main cyclotron have to dissipate a lot of energy due to the large volume of the RF cavity, causing a trip of the system, resulting in down time of the machine and provide a risk of damaging the system if not reacted to immediately. A spark detection system evaluating the rate of change of the reversed power signal within the cyclotron when a spark occurs is employed but can currently not provide any information about its location.

Simulations with a detailed P-Spice model including the entire RF infrastructure from the amplifier, the combiner station, the waveguide system, and the rather big cyclotron with a diameter of 18 meters will provide the necessary information whether the location of a spark in the system can be located. The evaluated signals are the rate of change of the falling DEE voltage and the RF signals in different locations of the RF system. These results and actual measurements of sparks in the system can then in the future be used to train a Machine Learning model to implement a real time spark detection and reaction system. Such a system provides fast diagnostics and enables preventative maintenance during scheduled maintenance times and hence can reduce the machine downtime significantly.

INTRODUCTION

The current spark detection system classifies spark into small, medium, and large sparks based on RF drive level, fall times, and reflected power on the transmission line. A spark is recognized when the cyclotron voltage drops abruptly and an increase in reflected power [1]. Depending on the type of spark, RF is turned off to prevent equipment damage. Due to thermal imbalance, shutting the RF off will cause 4-5 minute downtime. In order to minimize downtime, real time fault diagnostic tools will be beneficial.

Another fault diagnostic tool that is available to identify different types of spark is a database of oscilloscope screenshots of over 68000 abnormal events (triggered by fast rise and fall times) that have been collected over the years. The goal of this work is to study the cyclotron RF system and gain more insight on the location of the spark.

The development of a P-Spice model will be presented, along with simulation results when a spark occurs at different locations in the RF system, such as inside the resonator or at the amplifier/transmission line system. The simulation results will be used to compare with actual captured events from the database. A summary of results will be presented, along with a future outlook.

P-SPICE MODEL

TRIUMF's cyclotron consist of 80 resonator segments that is powered by a RF system amplifier capable of delivering 1.8 MW of power at a fixed frequency of 23.06 MHz. The output of the amplifier is connected to a 9" transmission line and then an 11" transmission line. Three vacuum capacitors (capacitor stations) are used to match the impedance of the resonator to 50 Ω. They are located at both ends and one in the middle. This results a peak voltage of 100 kV at the resonator tips.

A P-Spice model based on the simplified blocks shown in Fig. 1 was developed. The resonator can be modeled as a paralleled resistor, capacitor, and inductor. While the coupler is modeled as a mutual inductance.

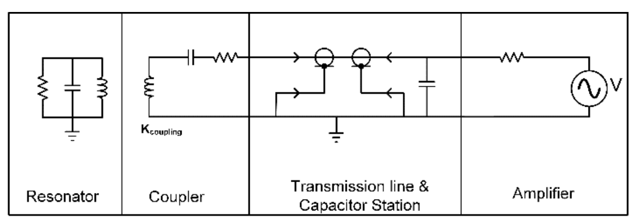

Figure 1: Simplified block for RF system.

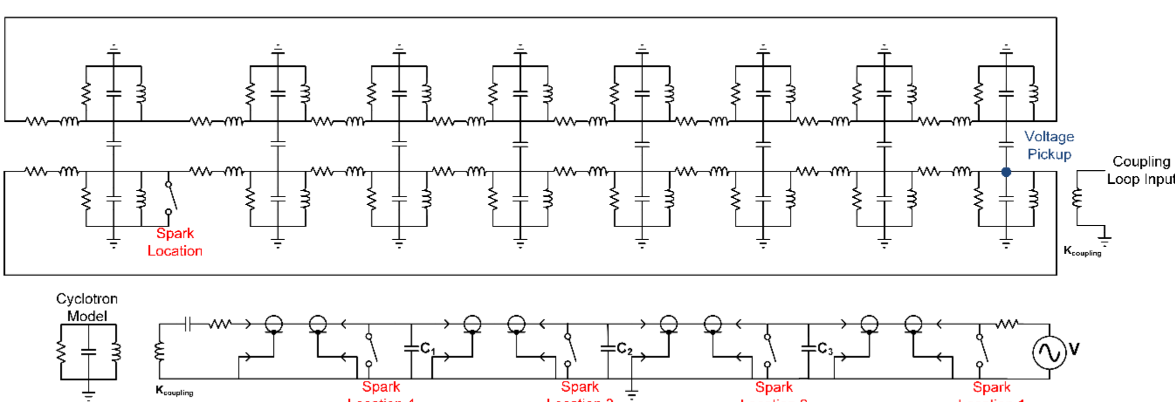

Figure 2: Full P-Spice model of TRIUMF's cyclotron RF system for spark studies.

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The values of each of the components can be calculated based on the resonant frequency of 23.06 MHz and a quality factor 7000 [2]. The electrical length of the transmission line can be calculated based on the physical length. Finally, the capacitance of the capacitor stations are measured. The model was then expanded to include 16 segments as shown in Fig. 2 for a better representation of what happens inside the resonator when a spark occurs.

In order to determine which mode of operation (push-pull mode and push-push mode), a frequency sweep was performed. Note that the push-pull mode is useful for accelerating ions in the cyclotron. The result of the simulation shows the push-pull frequency at approximately 23.08 MHz and push-push frequency at 23.80 MHz in Fig. 3.

Next, the transient response of the model was simulated at the resonant frequency.

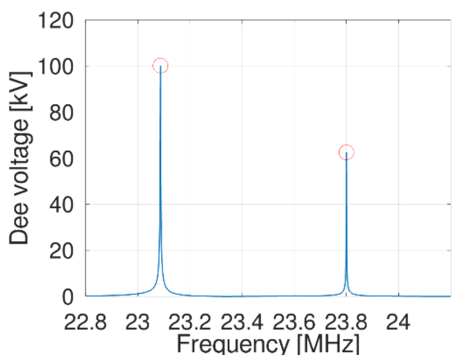

Figure 3: Simulated frequency response for full model.

Spark Simulation

As seen from Fig. 4, steady state value is achieved at approximately 1.50 ms. The spark is introduced after steady-state value of 1.55 ms. To simulate a spark in the P-Spice model, a short-circuit switch with a residual resistance of different values are added at different locations in the model, which includes: at the amplifier, after the first capacitor station, second capacitor station, third capacitors station, and at one segment of the resonator. A spark is dependent on charge carrier mobilities, ion and electron temperature, space charge effects and many more. Furthermore a vacuum spark inside the resonator further depends on the quality of vacuum and surface contamination, making the value residual resistance of a spark difficult to calculate and very irreproducible [3].

We ran several simulations to estimate the residual resistance for a spark inside the resonator. By changing the residual resistance between 10 Ω to 100 Ω, we can see that the time response of the decay varies from 10 to 50 microseconds in Fig. 5. The results of the simulation was used to overlay a spark event from the oscilloscope image database shown in Fig. 6. A residual resistance of 10 Ω with a fall time of approximately 15 microseconds closely resembles an actual spark event captured by the oscilloscope.

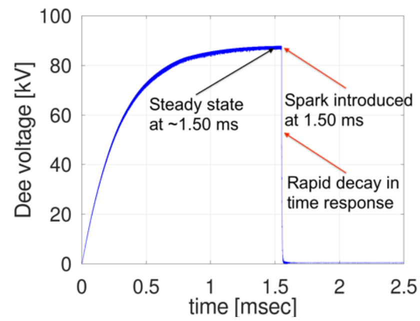

Figure 4: Simulated transient response.

Similarly, several simulations with various residual resistances were performed by introducing a spark at capacitor station #3 (closest to the amplifier). The results of this simulation shows that the time response decay for a spark along the transmission line or at the amplifier is much longer, by a factor of 10 times or more, shown in Fig. 7. Furthermore, the final stabilized voltage is a non-zero value, which is proportional to the residual spark resistance.

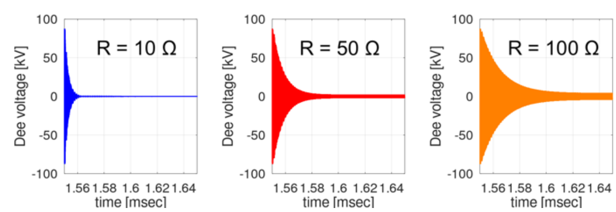

Figure 5: Simulated transient response with different residual resistance for a spark inside the resonator.

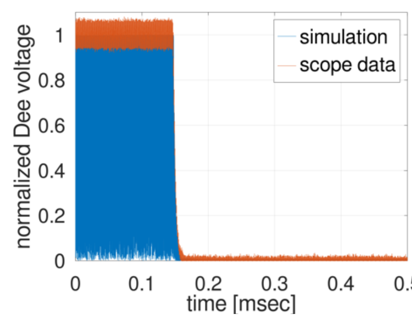

Figure 6: Simulation results overlaid with a spark event from oscilloscope trace.

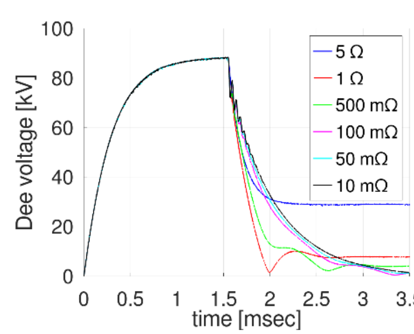

Figure 7: Simulated transient response with different residual resistance for a spark at capacitor station #3.

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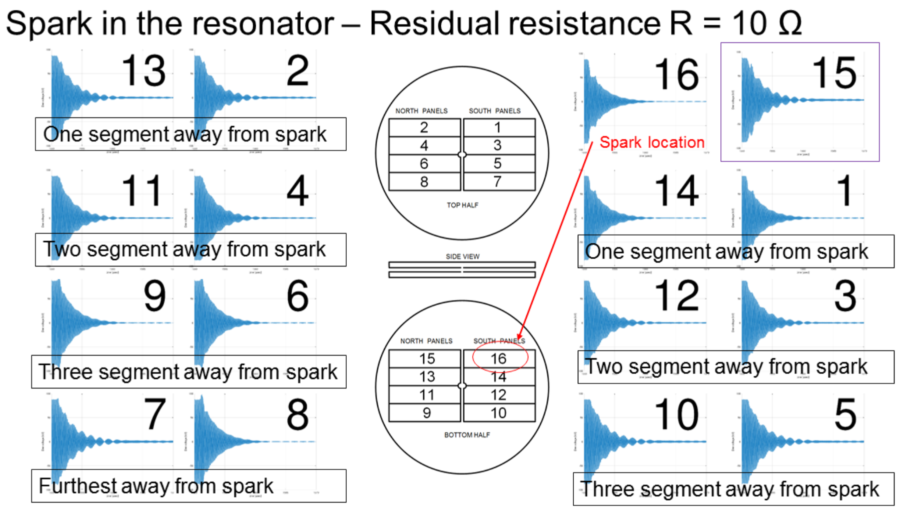

Figure 8: Simulation result of spark inside the resonator with voltage pickup at every segment.

ANALYSIS

In our P-Spice model, there are 16 resonator segments, split between top and bottom part of the schematic. The top corresponds to the north panels and bottom corresponds to the south panels. For our cyclotron, the lid of the cyclotron is connected to the base of the cyclotron with flux guides. This results in all the north panels connected together and all the south panels connected together.

A spark is introduced to segment 16 in the simulation, shown in Fig. 8 and the voltage was plotted in order to see how the spark propagates within the resonator. We observe that the waveform shape varies based on how far away from the origin of the spark. At the origin of the spark, the pickup voltage sharply decays. Ringing is very pronounced directly across from the location of the spark. If the spark occurs at the south panel, the north panel has some initial overshoot.

Unfortunately, the time resolution for the oscilloscope images captured in the database was only 50 µs/div and not small enough to capture spark events within the resonator in detail. In order to capture the events, a timescale of 5 µs/div will be required. We are in the process of obtaining these oscilloscope image captures during the start-up of the cyclotron after our annual maintenance shutdown.

Furthermore, there are 60 voltage probes located within the cyclotron that are used to provide an averaged DEE-voltage. Currently, these voltage probes are diode rectified with a low pass filter in order to provide a DC voltage. In the future, an event based oscilloscope can be used to capture events and correlate this data with our simulations.

From other parts of our simulation, we notice ringing occurs when the cyclotron is driven at an off frequency away from the resonant frequency. The DEE voltage decrease significantly as well, similar to Fig. 9.

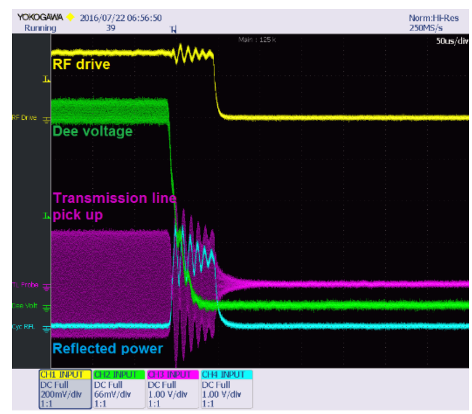

Figure 9: Image of spark event from oscilloscope.

CONCLUSION

A detailed P-Spice model for TRIUMF's cyclotron RF system has been developed to study sparks inside the resonator and along the transmission line. From both the simulation results and event oscilloscope waveform, we can clearly identify whether a spark occurs inside the resonator (due to the fast decay response) or in the transmission line system (due to the slower decay response). With this information, we can start analyzing the oscilloscope database to gain a better insight of the location of spark and common failure points in the RF system. This will enable us to properly predict failure points in the system and perform real time analysis in the future.

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