

TRIUMF CYCLOTRON RF SYSTEM REFURBISHING

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Abstract

TRIUMF has operated its 500 MeV cyclotron facility for many years with an overall machine availability of 90-92%. The cyclotron rf system is one of the major downtime contributors with approximately 200 hours annually. The two different sources of problems are rf sparking in the cavity and hardware failures. Although the refurbishing program is not complete, the downtime due to rf sparking has already been reduced by a factor of 3, mainly due to an rf controls upgrade and an extensive program of resonator tuning with a new tuning control system. A considerable effort was devoted to improving equipment reliability and serviceability to the cyclotron resonators, RF amplifiers, and transmission lines.

INTRODUCTION

The TRIUMF cyclotron consumes about 1 MW of rf power at a frequency of 23.06 MHz. This power is provided by 8 EIMAC 4CW250000B tubes arranged in 4 power amplifiers (PA). The rf system layout is shown in Figure 1. The cyclotron main accelerating structure consists of 80 resonators electrically coupled together [1]. Most of the resonators, apart from 8 units in the center and 8 units at the ends, can be individually adjusted to the desired frequency by means of remotely controlled movable ground arm tips (GAT). There is another accelerating cavity operating at the 4th harmonic of the fundamental frequency that boosts the energy gain per turn at the outer radii.

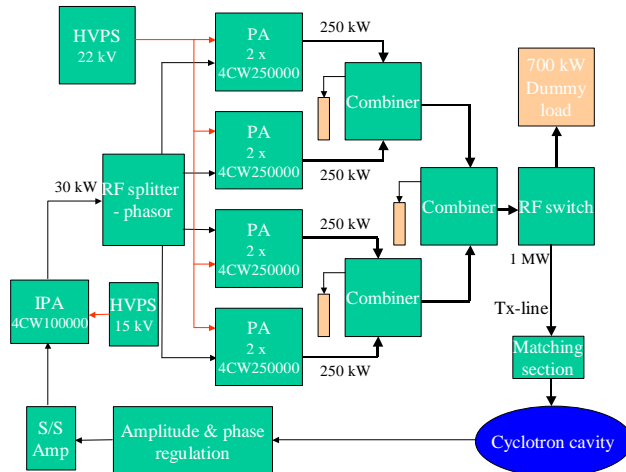


Figure 1. Cyclotron main rf system layout.

The rf refurbishing program at TRIUMF is driven by a goal of high intensity extracted beam, with reliable and stable operation dictated primarily by the ISAC isotope production targets vulnerability to beam interruptions. In the program we have set the following tasks:

- reduce the cyclotron sparking rate;
- reduce the duration of rf interruptions with improved restart procedures;
- redesign and replace troublesome components, employing a modular approach for fast and easy serviceability;
- develop and implement new fault diagnostics and equipment testing capabilities;
- use extensive data logging for preventive and postmortem troubleshooting.

DIMINISHING OF SPARKING IMPACT

Operational rf gradients in the cyclotron are moderate and therefore cannot be the primary cause of vacuum breakdowns. Theoretical studies and model measurements [2] showed, that in the cyclotron vacuum chamber there are parasitic resonant modes at frequencies relatively close to the operational mode. The TM_{310} and TM_{410} modes are the closest ones. An rf field propagation in the beam gap was found to be associated with these modes. The leakage field in the beam gap does not disturb beam dynamics, but it is just enough to create conditions for multipactor discharge. Multipactoring in the cyclotron was observed indirectly from resonator panel heating and vacuum deterioration, depending on the leakage field distribution. Also, evidence of secondary electron emission discharge can be seen as discoloration on the resonator panels, when the cyclotron lid is opened. Some areas in the cyclotron, where secondary electron streams could initiate an rf gap breakdown, are very vulnerable to multipactoring. Therefore a lot of effort has been put into leakage field measurement and adjustment. The leakage field amplitude is measured with 36 capacitive voltage probes, installed in the beam gap on the lower resonator panels. The leakage field level can be adjusted and minimized by varying the rf gap distance for individual resonators. The original remote control system for the GAT position adjustment, installed in the late 80s, became obsolete and very unreliable. In 2002 it was replaced with a new system with improved stability and reliable interface. Since then GAT tuning has been extensively used to reduce leakage fields.

It was also noticed that sparking downtime is largely determined by the time required to bring the system back to full operation. Spark and recovery processes were analyzed and a new restart procedure was developed and set up.

In the past we distinguished 3 levels of spark: small, medium, and large determined with a voltage fall speed analysis. With a large spark, which could potentially damage rf components, the system immediately shut off

the rf drive and in a couple of seconds initiated a regular start up procedure [3]. It commences with pulse ramping of the dee voltage up to 80% of the nominal in self-excited mode, then switches to cw, ramps to full voltage, and starts amplitude and phase automatic regulation. Then, the cyclotron operator has to adjust a frequency synthesizer to the live cavity frequency within the tuner regulation bandwidth of 500 Hz and switch to a driven mode. When a medium or small spark was detected the system maintained the drive power to the cyclotron with the expectation of a prompt voltage restoration. In many cases this led to an instant rf recovery, transparent to the beam acceleration. If the voltage remained below 10 kV for more than 10 μ s, the rf drive was shut off and a restart procedure commenced, similar to the large spark recovery. Overall time required for rf recovery in this scenario was from 2 to 5 minutes (See Figure 2 a).

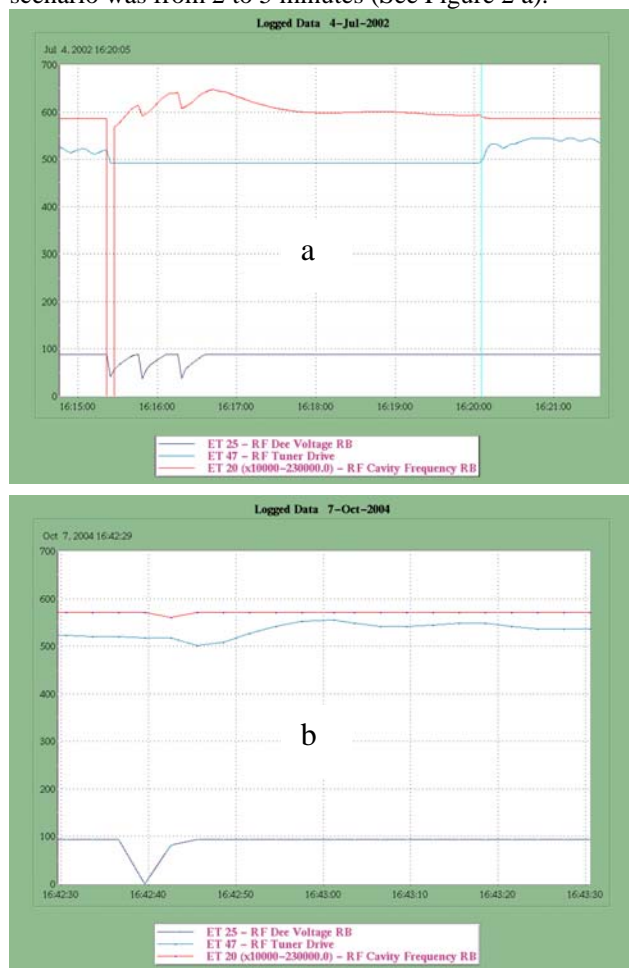


Figure 2. Dee voltage, rf tuner drive, and frequency during after spark recovery in a) 2002, and b) 2004. Time division scale: a) 1 minute; b) 10 seconds

Most of this recovery time was due to frequency detuning which occurred during voltage ramping when the cyclotron thermal balance was disrupted because of efficient cooling. Regulation of the resonator cooling water pressure provides automatic frequency control due to resonator panel deformation. This type of tuner is quite efficient, but has a limited tuning range of about 3 kHz.

Thermal imbalance during ~15 seconds of voltage recovery caused a cyclotron frequency shift well above the tuner operational range. Usually, in order to preserve a machine tune, operators waited until this offset dropped below 500 Hz to switch to the driven mode. The situation was aggravated because with rf restart the tuner was automatically set to the center of its tuning range, and that produced additional frequency offset from the operational value.

All these deficiencies were taken into account in the new recovery procedure. Now with every spark the rf drive instantly turns off for ~300 ms. Then a short (~1 second) voltage ramping starts: first pulse, then cw. Amplitude and phase stabilization after closing the regulation loops takes another ~2 seconds. The tuner stays in the position it was in before the spark. The system can then be easily switched to driven mode, which is now done automatically. Frequency offset due to resonator temperature change in this case is negligible because of the short running time without rf (~1 second). A typical present day spark recovery graph is shown in Figure 2 b) with a data sampling rate of 1 in 3 seconds. We will continue improving of the spark recovery procedure aiming to keep beam on during rf micro-sparks.

HARDWARE SERVICING AND UPGRADE

The continuous operation of the TRIUMF cyclotron does not leave much time for detailed test, troubleshooting, and upgrade of the RF system. Basically, the system is available for service for about 2 months a year: in January/February and in September.

In the past we experienced a few failures due to water leaks in different locations, for example, in the transmission line matching section containing high power capacitors, causing rf sparking and severe damage to the equipment. In some cases the problem was traced to behavior of the low conductivity water with respect to copper. Solutions were applied: gold plating of rf contacts exposed to water in the dummy loads, the introduction of sacrificial (zinc) dummy electrodes in the PA inductors, and improving water connections in many critical junctions. Thus we have changed the design for all 3 capacitor stations in the transmission line matching section. The new modular approach incorporates reliable water connections, and allows fast and easy access to the capacitors for a visual inspection and high voltage test.

Another major activity in the rf refurbishing program was related to the redesign of 3 high power (up to 1 MW) combiners. The original units required a substantial effort to suppress parasitic oscillations, and were difficult to maintain and adjust. Three new combiners feature easy adjustment and fast access for inspection and service (see Figure 3).

A substantial effort was dedicated to develop a high power resistive load. It is an essential tool in testing, tuning, and troubleshooting of PA's and combiners. The load was commissioned in 2002 at 500 kW. Recently we tested it up to 700 kW and plan to bring it up to 1 MW

with a new heat exchanger for a soda solution. Next shutdown this dummy load will be installed together with a motorized rf switch at the output of the final combiner (see Figure 1). The four port, 9" coaxial line rf switch, built by Dielectric Inc., was originally rated for 700 kW. We have upgraded it to 1 MW with additional water and air cooling.



Figure 3. New rf combiner

In the past we manually measured rf power transmission through the amplifier stages, in the rf splitter and combiner branches. A new automatic data acquisition system based on 32-channel rf multiplexer and 2 vector voltmeters was developed in 2003. It provides rf power monitoring in amplitude and phase, and is very helpful in PA's and rf splitter tuning.

Another important data acquisition and logging system is being commissioned now. It will cover all DC voltage and current measurements (~ 100 signals) in PA's and high voltage power supplies (HVPS). An early 80's attempt to accomplish this was abandoned due to high rf interference impact on the currents measurements. We have chosen electrically shielded current transducers to solve this problem.

To improve troubleshooting efficiency, we have also built a first spark event detector system [4]. It receives the rf signals from as many as 24 voltage pickups and resolves which one drops first in the case of sparking. This allows us to localize a hardware failure in the rf chain from the frequency synthesizer to the cyclotron cavity, and to log it for a postmortem analysis. The system resolution between 2 subsequent signals is 0.1 μ s.

Last year we lost one high power rf tube due to malfunctioning of the anode HVPS crowbar firing circuitry. It could have also happened in the past without being noticed. A new firing circuit features a more reliable design, full chain test capability, crowbar stage firing sequence analysis, and improved serviceability.

In the September 2004 mini-shutdown a new rf controls system similar to a recently developed system in the ISAC rf controls [5] was commissioned for the rf booster. It is based on custom made modules installed in a VXI mainframe. Amplitude, phase, and tuning control is accomplished through I/Q loop.

Many other improvements have been carried out on various rf components like the filament power supplies, HVPS choke protective circuitry, HVPS water cooled resistors, transmission line cooling, resonator cooling system regulating valve controllers, transmission line high VSWR protection, and others. These cannot be described in detail in this paper, but altogether they played an important role in improving machine reliability and serviceability.

The next major step in the RF refurbishing program will be the replacement of an outdated IPA with 4 independent 20 kW amplifiers, each of which would drive one of the 4 final PA's. This will eliminate a troublesome rf splitter-phasor, and allow all the amplitude and phase adjustments for balancing of the combiners' inputs to be done at low signal levels. It will also simplify individual PA troubleshooting and tuning into the dummy load.

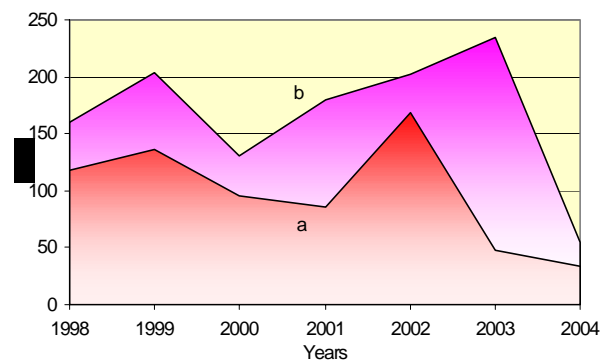


Figure 4. RF annual downtime: a) due to sparking; b) total

CONCLUSION

The extensive rf refurbishing program, together with detailed studies and thorough adjustments, reduced the rf downtime due to sparking and component failures (see Figure 4, numbers for 2004 are up to October only). Also, we have introduced a few new tools for system performance monitoring and troubleshooting. In many critical places the system's reliability and serviceability were dramatically improved. All these measures have greatly contributed towards our goal of reliable and stable high intensity beam extracted from the cyclotron.

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