RF CONTROL OF THE M9 SEPARATOR AT TRIUMF

by

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Abstract

High voltage RF systems are used to accelerate proton beams for nuclear physics experiments. The acceleration process shapes the proton beam into a train of narrow pulses with the same period as the RF. This bunched beam structure is used to separate and identify secondary particles that are produced when the proton beam is directed at a "target". An RF controller for a system that separates secondary particles was built.

Control of high power RF cavities that operate near resonance is discussed. The emphasis is on developing a control model for resonant systems and building a control system based on hardware and software modules that can be easily configured for different RF systems.
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Chapter 1

Introduction

1.1 RF Systems and Particle Accelerators

High power RF systems are used to control and accelerate particle beams in nuclear physics laboratories. In this process it is desirable that the RF system be as easy to operate as any power supply in an industrial environment. Before discussing the requirements for regulation and control, it is useful to introduce the basic function of RF systems in modern particle accelerators. Particle accelerators are machines that generate ion beams with sufficient kinetic energy to produce nuclear reactions. Usually the accelerated particles are electrons or protons and the kinetic energy of a particle is measured in electron volts (eV). An electron volt is the energy gained by an electron (or any particle with the same magnitude charge) in passing through a potential drop of one volt. Modern proton machines can produce particles with energies of many billion electron volts (GeV).

Charged particles are accelerated in vacuum by electric fields. The first high energy accelerators were DC machines using Cockcroft-Walton and Van de Graaff generators. These high voltage sources can produce particle beams with energies of a few million electron volts (MeV). The static fields encountered in DC machines limit the kinetic energy gained by the particle to the potential
energy of the system. The maximum energy of an electrostatic accelerator is determined by the voltage that can be maintained at the high voltage terminal. With careful design this can be as high as \(10^7\) volts.

Cyclic accelerators were developed to overcome the limits imposed by electrostatic fields. In these machines, particles are made to follow a path where they periodically encounter an accelerating voltage which is a small fraction of the final energy gained by the particle. The particle trajectory can be straight as in linear accelerators (Linacs), or the trajectory can be curved as in cyclotrons and synchrotrons. High kinetic energies are built up as the particle encounters the accelerating voltage a large number of times. This process develops a gradual acceleration which is not limited by the voltage drop in the machine.

![Diag](image.png)

**fig. 1** Drift-tube Linac structure.

Large energy gains are possible in cyclic accelerators because the electric fields in the machine change with time. Such systems are nonconservative in that it is possible to find a closed path along which the kinetic energy gained by the particle is not zero.
Figure 1 shows the structure of a drift tube Linac. It demonstrates that, with correct phasing of the accelerating voltage, one can inject charged particles at zero volts and later extract them into a zero volt region with a higher kinetic energy. Acceleration occurs in the gap between the drift tubes. While the particle is inside the drift tube, it is in an equipotential region and does not experience any change in energy. Cyclic accelerators use equipotential regions, such as the drift tube, to allow the voltage time to achieve the correct amplitude and phase as the particle approaches the next acceleration gap. In modern machines, the particle velocity quickly approaches the speed of light and, in order to keep the size of the machine small, it is advantageous to use high frequency voltages to accelerate charged particles. This minimizes the drift tube length and allows resonant RF structures to be used as the accelerating elements.

Most nuclear reactions of interest to researchers occur as relatively rare events. A great number of particles with a well defined kinetic energy are needed to study these events. Since there is an equivalence between mass and energy it is important to know the threshold energy needed to produce the exotic particles that make up the nucleus of the atom. To get meaningful statistics an experiment can run for a year at low event rates. The task of the accelerator designer is to produce a machine that delivers as much beam as possible at a very well defined energy. In cyclic accelerators a well defined energy occurs over a small range of RF phase and voltage. The result is that accelerators produce pulses or buckets of particles at a given energy. This is true for all
cyclic accelerators including the TRIUMF cyclotron (fig. 2).

![Graph showing typical time structure of the TRIUMF proton beam]

*fig. 2 Typical time structure of the TRIUMF proton beam.*

Cyclic accelerators produce beam pulses at the RF repetition rate with a typical pulse occupying approximately 30° of an RF cycle. Control of high intensity, high energy particle beams requires careful control of the RF phase and amplitude.

1.2 An RF Separator for Muon Studies

Particles extracted from the accelerator are collimated into a beam and are directed to a "target" where the desired nuclear reactions occur. Secondary particles produced in the reaction can be selected and used in further studies. One of the particles produced is the pion, an exchange particle that operates inside the nucleus. An atomic nucleus is made up of protons which have a positive charge and neutrons which have zero charge. The net charge of the nucleus is positive and since like charges repel, the nucleus should fly apart. The pion is an exchange particle that transmits a short range attractive force which allows stable nuclei to exist. This particle is one of a group of particles called mesons which are the object of much study at TRIUMF.
The name pion is a short form of $\pi$-meson. Outside the nucleus this particle has a high probability of quickly decaying to a $\mu$-meson (muon). After a longer time, the muon will decay into an electron. Pions are produced when a pulse of high energy protons (>100MeV) hits a Beryllium target in the beam line. The groups of pions leaving the target have the same time structure as the high energy protons from the TRIUMF cyclotron.

A cloud of muons will begin to form around the pions as they decay in flight from the production target. The particles have distinct and different energies such that the pions, muons and electrons form separate groups in flight. Pions and electrons can be suppressed to less than 1% of the beam by a static magnetic field and a perpendicular RF electric field. Particles are passed through the separator when the RF electric field cancels the $v\times B$ force of the horizontal magnetic field. By adjusting the phase of the RF voltage, physicists can let pions, electrons, or muons into the experiment.

![Diagram showing RF voltage and relative phase of π, μ, and e beam components.](image)

*fig. 3 Relative phase of $\pi$, $\mu$, and $e$ beam components.*
1.3 System Requirements

TRIUMF is similar to a utility company that delivers high energy protons to its customers and also provides technical services to the various experiments that use the proton beam. A device to separate decay products in flight from the pion production target is one of the pieces of equipment built for muon studies. The muon physics experiment is a large and complex installation of which the RF separator is only a small part. The separator cavity is driven at 23 MHz, the cyclotron operating frequency, and it is phase locked to the primary proton beam. It must be simple to operate; an on-off switch and a knob to select different particles, π, μ, or e. The RF requirements for the separator can be listed in three sections.

1. RF Generator, Cavity, and Deflection Plates
   • a frequency of 23MHz.
   • a power output of 120Kw
   • a peak plate-to-plate cavity voltage of 360Kv

2. RF Regulator
   • phase locked to the proton beam extracted from the cyclotron
   • phase stability better than 1°
   • amplitude stability better than 1 part in $10^3$

3. RF Controller
   • one button autostart
   • automatic cavity tuning
• automatic spark recovery and fault handling
• a self-excited, idle state when the cyclotron RF is off
• local display of the system state
• manual control of all loop parameters and system states

This report describes the analysis and design of the regulator, the controller, and the RF signal modules that were built and installed on the RF separator. A control model is developed for regulation and tuning RF systems operated near resonance.
The power amplifier, transmission line, and cavity were designed and commissioned by Bob Worsham and Vojta Pacak who are principal members of the TRIUMF RF group. Their work provides the basis for the lumped model which is used to develop a transfer function describing the system response to control modulations.

![Diagram showing the separator cavity structure](image)

*Fig. 4 Schematic of the separator cavity structure.*

The RF separator consists of two \( \lambda/4 \) short circuit coaxial transmission line cavities that are tightly coupled through the tip capacity at the high voltage electrodes. Two fundamental resonant modes result from the close coupling between the cavities. These are a push-pull resonance, which is the desired mode, and a push-push resonance which occurs at the frequency...
defined by the $\lambda/4$ cavities. At the push-push resonance, the cavity $Q$ and the shunt resistance measured at the high voltage gap are:

$$Q = 4800$$  \hspace{1cm} \textit{cavity parameters}

$$R_{sh} = 141k\Omega$$

A $2\lambda$ long, 50$\Omega$ transmission line connects the upper cavity to the high $Q$ plate circuit of a class "C" grounded grid power amplifier. This introduces an 87ns delay between the plate circuit and the cavity. The $Q$ and shunt resistance of the plate circuit are:

$$Q = 3000$$  \hspace{1cm} \textit{plate circuit parameters}

$$R_p = 1200\Omega$$

The response of the separator RF system is dominated by high $Q$ elements in the plate circuit of the power amplifier and by the cavity. A lumped model of this system also includes the transmission line and the power tube represented by an RF current source. Starting from the push-push model, one can arrive at a simple equivalent circuit for the dominant RF elements.

\[ fig.~5 \text{ Push-Push model of the cavity and plate circuit.} \]
The push-push resistance measured at the gap is the parallel combination of the shunt resistance from each cavity. The desired push-pull mode operates at a frequency below the parallel resonance defined by the push-push mode. At this frequency, each cavity appears inductive and resonance is formed by the gap capacitance in series with one side. A capacitive voltage probe at one side of the high voltage gap sees a lumped model similar to that in the figure below.

\[ \text{fig. 6} \quad \text{Push-Pull model of the cavity and plate circuit.} \]

The amplitude and phase of the gap voltage is regulated using the signal measured by a capacitive voltage probe on one side of the gap. To develop a transfer function for the system it is useful to transform the plate circuit to the high voltage gap. In the circuit below, \( Z_1 \) is the transformed plate impedance, \( Z_2 \) is the cavity impedance seen from the deflection plate, and \( e^{-sT} \) is the total delay in the transmission lines, from the plate circuit to the measurement point; a distance of \( 4\lambda \).
A control model for the RF cavity and the amplifier plate circuit is developed from the admittance of these elements. The relationship between the transformed plate current and the gap voltage is given by:

$$I(s) = V(s) \left( \frac{1}{Z_1} + \frac{1}{Z_2} \right) e^{sT} = V(s) Y(s)$$

When the plate circuit is matched to the cavity, the effective plate resistance seen by the cavity will be equal to the cavity shunt resistance, $R_{sh}$. The total shunt resistance seen by the RF current generator will be $1/2 R_{sh}$. 

\[ \text{fig. 7 Equivalent circuit of high Q elements.} \]
Chapter 3
Transfer Functions for RF Regulation

3.1 An RLC Model

To develop a transfer function for cavity regulation, it is useful to consider a simple lumped resonator driven by an RF current source.

\[ Y = \frac{1}{Z} = \frac{1}{R} + j\omega C + \frac{1}{\omega L} = \frac{1}{R} \left[ 1 + j \left( \frac{\omega R C}{\omega L} - \frac{R}{\omega L} \right) \right] \]

\[ = \frac{1}{R} \left[ 1 + jQ \left( \frac{\omega}{\omega_o} - \frac{\omega_o}{\omega} \right) \right] \]

where: \( \omega_o = \frac{1}{LC} \)

\[ Q = \frac{R}{\omega_o L} = \omega_o RC \]

let \( \omega = \omega_o + \Delta \omega \)

\[ \frac{1}{Z} = \frac{1}{R} \left[ 1 + jQ \left( \frac{\omega_o + \Delta \omega}{\omega_o} - \frac{\omega_o}{\omega_o + \Delta \omega} \right) \right] \]

\[ \approx \frac{1}{R} \left[ 1 + jQ \left( \frac{\omega_o + \Delta \omega - \omega_o - \Delta \omega}{\omega_o} \right) \right] \]

\[ \approx \frac{1}{R} \left[ 1 + j \frac{2Q}{\omega_o} \Delta \omega \right] \]

\[ Z \approx \frac{R}{1 + j \frac{2Q}{\omega_o} \Delta \omega} \]
This approximation, with less than 5% error for $\Delta \omega \leq \omega_0/10$, is very useful for calculations within the control bandwidth. It represents the cavity as a first order pole about the resonant frequency, $\omega_0$. The RLC circuit responds to control modulations like a simple RC low pass filter with a time constant:

$$\tau = \frac{2Q}{\omega_0} \quad \text{RF cavity time constant}$$

### 3.2 A Simple Transfer Function for the Separator

A similar transfer function for the separator cavity and power amplifier can be evaluated by expanding the equivalent admittance expression about resonance. For maximum power transfer, the shunt resistance of the transformed plate circuit is equal to the shunt resistance of the cavity so that the admittance of the separator power amplifier (PA), transmission line, and cavity becomes:

$$Y(s) = e^{sT} \left[ \frac{1}{Z_1} + \frac{1}{Z_2} \right]$$

$$= e^{sT} \left( \frac{1+s\tau_1}{R_{sh}} + \frac{1+s\tau_2}{R_{sh}} \right)$$

where: $\tau_2 = \frac{9600}{\omega_0} = 66\mu s$, $\tau_1 = \frac{6000}{\omega_0} = 42\mu s$

$$T = 200\text{ns} < \tau_1, \tau_2 \quad \Rightarrow \quad e^{sT} \approx 1+sT$$

Approximating the delay by a first order expansion gives:

$$Y(s) \approx \frac{2}{R_{sh}} \left[ 1 + \frac{s(\tau_1+\tau_2)}{2} \right] \left[ 1 + sT \right]$$

$$\approx \frac{2}{R_{sh}} \left[ 1 + \frac{s(\tau_1+\tau_2)}{2} \right] \quad \text{over practical control bandwidths}$$
The relatively small delay in the transmission line allows the two resonant structures to be modeled as a single RLC circuit. The transmission line adds a second pole at 1MHz.

\[ Z(s) = \frac{R}{1 + s\tau} \]

where: \[ R = \frac{R_{sh}}{2} \]
\[ \tau = \frac{\tau_1 + \tau_2}{2} \]

The calculated time constant of the model is 54μs, the average of the two time constants. Open loop pulsed power tests gave a measured value of 55μs for the time constant of the RF amplifiers and cavity.

*fig. 9 Pulsed power tests.*

The photo shows two falling edges of the detected cavity voltage captured on a digital oscilloscope. One trace shows the \( \approx 50\mu s \) time constant of the RF system. The other trace records a cavity spark which effectively short circuits the cavity and power.
amplifier. This avalanche condition remains in effect as long as the RF drive is present. The 20Hz, 5% pulse modulator turns off the drive and the short circuit mechanism is extinguished in the period between pulses.

Other tuned circuits in PA cathode circuit and the driver stage use discrete elements with Q's less than 100. This is considerably less than the Q's achieved with distributed resonant structures in the cavity and PA plate circuit. The effect of the energy stored in the discrete coupling circuits of the driver stage is to slightly increase the time constant of the system measured during pulsed power tests. These tests show that the delays and energy storage in the driver stages and transmission line can be described as a transconductance of the form:

\[
\frac{G_a}{\prod (1+s\tau_i)} \propto \frac{G_a}{1+s\sum \tau_i} \propto \frac{G_a}{1+s\tau_a}
\]

\[
\begin{align*}
V_{in} &\rightarrow \frac{G_a}{1+s\tau_a} &\rightarrow R \frac{1}{1+s\tau} &\rightarrow V_{out} \\
\tau_a &\approx 2\mu s &\tau &\approx 54\mu s
\end{align*}
\]

*fig. 10 One dimensional transfer function for the RF system.*

Open loop pulsed power measurements indicate that a second order model is sufficient to describe the dominant response of the RF system. The approximate pole locations determine adjustment ranges in the regulator compensation networks. An estimate of $G_a$ is not needed if the RF regulator design allows some gain adjustment.
This is discussed later in chapter 5.

3.3 Matrix Transfer Functions for Amplitude and Phase Regulation

Regulation of both amplitude and phase of the separator gap voltage is a two dimensional problem in which a current vector from the power tube is used to control the output voltage vector. The current vector can be described by a steady state term and a small time varying, modulation term.

\[ I + dI(t) = Ie^{j\theta_1} + Ie^{j\theta_1} \left( \frac{dI(t)}{I} + j\theta(t) \right) \]

The gap voltage is the product of the generator current and the load impedance. The impedance can be written in polar form as \( Z\phi \) where:

\[
|Z| = \frac{R}{\sqrt{1 + (\tau\Delta\omega)^2}} \quad \tan\phi = -\tau\Delta\omega
\]

At resonance, \( \Delta\omega = 0 \) and the tube works into a resistive load. Vibration and other sudden changes can move the resonant frequency and cause large impedance changes in high Q systems driven at a fixed frequency. When the gap voltage is adjusted by small modulations of the cavity current, the effect of the detuned cavity is to cross couple the variations in the phase and amplitude.

To calculate this effect in high Q systems, it is desirable to express the detuned circuit impedance at the modulation sidebands. Starting from the previous impedance approximation, the admittance can be written in terms of a displacement from the carrier
frequency rather than a displacement from the resonant frequency.

let:

\[ \Delta \omega = \text{total frequency displacement from resonance} \]
\[ \omega_{rf} = \text{displacement of the carrier frequency from resonance} \]
\[ w = \text{modulation sideband frequencies} \]

\[ Y(w) = \frac{1 + j\tau \Delta \omega}{R} \approx \frac{1 + j\tau \omega_{rf}}{R} + j\frac{\tau w}{R} \approx \frac{1}{Z_{rf}} + j\frac{\tau w}{R} \]

where: \[ \Delta \omega = \omega_{rf} + w \]
\[ Z_{rf} = \text{circuit impedance at the carrier frequency} \]

The control modulations will appear as RF sidebands. The Laplace variable for the RF control is defined as \[ s = j\omega, \text{ where } \omega = \Delta \omega - \omega_{rf}. \]

The admittance of the circuit at these control frequencies is:

\[ Y(s) = \frac{1}{Z_{rf}} + \frac{s \tau}{R} \approx \frac{1}{Z_{rf}} \left( 1 + s \tau \frac{Z_{rf}}{R} \right) \]

\[ \approx \frac{1}{Z_{rf}} \left( 1 + \frac{s \tau}{1 - j\tan \theta_z} \right) \approx \frac{1}{Z_{rf}} \left[ \frac{(1 + s \tau) - j\tan \theta_z}{1 - j\tan \theta_z} \right] \]

where: \[ \tan \theta_z = -\omega_{rf} \]
\[ \omega_{rf} = \text{constant} \]

The impedance at the modulation sidebands for a cavity detuned to an arbitrary angle, \( \theta_z \), from resonance is:

\[ Z(s) = Z_{rf} \left[ \frac{1 - j\tan \theta_z}{(1 + s \tau) - j\tan \theta_z} \right] \]

\[ \approx \frac{Z_{rf}}{(1 + s \tau)^2 + \tan^2 \theta_z} \left[ (1 + s \tau + \tan^2 \theta_z) - j s \tau \tan \theta_z \right] \]

This expression describes the impedance of an "off center" Q
curve. If there are no control modulations then \( s = 0 \) and the circuit impedance is \( Z(0) = Z_{rf} \). The steady state and modulation terms in the gap voltage are given simply by Ohm's law; the product of the current vector and the circuit impedance.

\[
V + dV(t) = Ve^{j\theta_v} + Ve^{j\theta_v}\left(\frac{dV(t)}{V} + j\theta_v(t)\right)
\]

where \( Ve^{j\theta_v} = Z_{rf} Ie^{j\theta_i} \)

In the Laplace domain (\( s=jw \)), the variation in the gap voltage can be expressed in terms of the current modulation. The expressions are simplified if the amplitude variations of the current and voltage vectors are expressed as fractional changes.

\[
\mathcal{L}\left[\frac{dV(t)}{V} + j\theta_v(t)\right] = v(s) + j\theta_v(s)
\]

\[
= \frac{1}{(1+s\tau)^2 + \tan^2 \theta_z} \begin{bmatrix} s\tau + (1+\tan^2 \theta_z) - js\tau \tan \theta_z \end{bmatrix} \begin{bmatrix} 1(s) + j\theta_i(s) \end{bmatrix}
\]

Separating the real and imaginary parts, this expression can be rewritten in matrix form to show the transmission of phase modulations and fractional amplitude modulations through the high Q section.

\[
\begin{bmatrix} v(s) \\ \theta_v(s) \end{bmatrix} = \frac{1}{(1+s\tau)^2 + \tan^2 \theta_z} \begin{bmatrix} s\tau + (1+\tan^2 \theta_z) & s\tau \tan \theta_z \\ -s\tau \tan \theta_z & s\tau + (1+\tan^2 \theta_z) \end{bmatrix} \begin{bmatrix} 1(s) \\ \theta_i(s) \end{bmatrix}
\]

*Cross Coupling Matrix for Amplitude and Phase Modulations*
Driving the circuit off resonance causes the cross terms in the matrix to increase by a factor \( \tan \theta z \). This detuning can come from several sources:

- random vibrations and dimensional changes in the plate and cavity circuits.
- changes in the cyclotron operating frequency.
- The separator is locked to the beam phase which changes due to a 5 Hz mechanical vibration in the cyclotron resonators.

The effective impedance of the separator RF system is the parallel combination of the plate circuit and the cavity structure. No means is presently available to automatically tune the plate circuit. The cavity, which exhibits considerable frequency drift, is independently adjusted by an automatic tuning loop that is described later.

It is likely that the plate circuit and the cavity will become tuned to different frequencies. In this case, the effective admittance of the high Q circuit can be rewritten as:

\[
Y(s) = \frac{1}{Z_{rf}} \left( 1 + \frac{s(\tau_1+\tau_2)}{2-j(tan \theta_1+tan \theta_2)} \right)
\]

where \( \frac{1}{Z_{rf}} = \frac{1}{Z_1} + \frac{1}{Z_2} \)

Independent tuning effects of the plate circuit and the cavity are easily described by adjusting the terms in the coupling matrix.

\[ \tan \theta z \rightarrow \frac{1}{2} (\tan \theta_1 + \tan \theta_2) \quad \text{and} \quad \tau \rightarrow \frac{1}{2} (\tau_1 + \tau_2) \]
When automatic tuning is restricted to the cavity, the regulator must be able to handle A.C. disturbances in both the plate circuit tune, \( \theta_1 \), and the cavity tune, \( \theta_2 \), and D.C. errors in the plate circuit tune, \( \theta_1 \). The cyclotron usually operates between 23.05 MHz and 23.07 MHz, a 20 KHz range. With a plate circuit Q of 3000 and a cavity tuner that works perfectly, the plate circuit can be detuned as much as \( |\theta_1| \leq 70^\circ \) which translates to a system detuning angle of \( |\theta_z| \leq 54^\circ \).

Before the separator is run for an extended period of time, the plate circuit is tuned to match the existing cyclotron frequency. If the cyclotron magnet is stable and does not suffer any power bumps, the cyclotron frequency can usually be held within 5KHz of the initial tune which limits the possible separator detuning range to \( |\theta_z|\leq 34^\circ \) when the cavity tuning loop is active.

After the separator system has been manually adjusted, the expected detuning angle, \( \theta_z \) will be zero. If the impedance matrix is expanded about \( \tan^2 \theta_z = 0 \) and terms of \( \tan^3 \theta_z \) and greater are neglected then the transfer function matrix can be simplified to:

\[
\begin{bmatrix}
    v(s) \\
    \theta_v(s)
\end{bmatrix}
\approx
\begin{bmatrix}
    1 + \frac{\tan^2 \theta_z}{1 + \tau^2} & \frac{\tan^2 \theta_z}{1 + \tau^2} \\
    -\frac{\tan \theta_z}{1 + \tau} & \frac{\tan \theta_z}{1 + \tau} \\
\end{bmatrix}
\begin{bmatrix}
    1(s) \\
    \theta_1(s)
\end{bmatrix}
\]

This gives a convenient form to study the tuning loop as a perturbation of the resonant system.
3.4 Particle Beam Loading as a System Disturbance

The separator uses the RF electric field to select a given periodic group of charged particles and reject others. As particles enter the high voltage gap they distort the electric field and so load the RF system. By superposition, one can determine the voltage disturbance induced on the deflection plates by a periodic group of charges travelling between them.

A test charge located near a grounded metal surface will induce an image charge on the metal surface. Similarly, a beam bunch travelling across the gap electrode will induce an image current on the electrode. The fundamental component of this bunched beam induces an alternating current on the deflection plates which, in turn, creates a disturbance voltage on the high impedance resonant cavity. Ideally, the cavity presents a low impedance to other frequency components of the bunched beam and, as a result, these
components generate negligible disturbance voltage. The maximum induced current that can disturb the RF system is equal to the fundamental component of the beam current in the gap. Evaluating the spectrum of a periodic series of narrow pulses shows that the fundamental component of beam current is approximately twice the average value of beam current.

![Diagram](image)

*fig. 12 Beam loading seen by a single voltage probe.*

Approximately equal currents are induced on each electrode which produces a common mode disturbance voltage on the deflector plates. To a single voltage probe, the beam disturbance appears as an asymmetrical current source. A differential voltage measurement would be needed to cancel the common mode interference.

In a system with only one measurement probe, both the beam and the generator currents affect the measured voltage but only the generator amplitude and phase are available as control variables. If the beam loading current is large then the control loops can become further cross coupled due to the steady state vector geometry seen by the single probe. Writing down the steady state
current that determines the measured voltage:

\[ I = \sqrt{(I_g \cos \phi_g + I_{bl} \cos \phi_{bl})^2 + (I_{bl} \sin \phi_{bl} + I_g \sin \phi_g)^2} \]

\[ \theta_i = \arctan \left( \frac{I_{bl} \sin \phi_{bl} + I_g \sin \phi_g}{I_g \cos \phi_g + I_{bl} \cos \phi_{bl}} \right) \]

The RF generator current provides the control input for the system. As with the previous matrix, the beam loading effects are simplified if the variations in amplitude are expressed as fractional changes.

\[
\begin{bmatrix}
\frac{dI}{I} \\
\frac{d\theta_i}{I}
\end{bmatrix} = \frac{I_g}{I} \begin{bmatrix}
\cos(\theta_i-\phi_g) & \sin(\theta_i-\phi_g) \\
-\sin(\theta_i-\phi_g) & \cos(\theta_i-\phi_g)
\end{bmatrix} \begin{bmatrix}
\frac{dI_g}{I_g} \\
\frac{d\phi_g}{I_g}
\end{bmatrix}
\]

Beam loading effects are easily demonstrated with \( \phi_g = 0^\circ \) and \( \phi_{bl} = -90^\circ \). For this worst case, the control of cavity current by the RF generator vector can be written as:

\[
\begin{bmatrix}
\frac{dI}{I} \\
\frac{d\theta_i}{I}
\end{bmatrix} = \frac{I_g}{I_g^2 + I_{bl}^2} \begin{bmatrix}
I_g & -I_{bl} \\
I_{bl} & I_g
\end{bmatrix} \begin{bmatrix}
\frac{dI_g}{I_g} \\
\frac{d\phi_g}{I_g}
\end{bmatrix}
\]

where: \( I_g = \) amplitude of the generator current

\( I_{bl} = \) amplitude of the beam loading current

It is apparent that the cross terms in the matrices increase as the beam loading current increases while the overall control gain decreases. When the beam loading current is greater than the generator current, the phase and amplitude controls become reversed.
In the separator, the loading current has three components due to electrons, pions, and muons as indicated in figure 3. If all three particle groups were in phase, the total beam loading current is still less than 1μA. To produce a cavity voltage of 130KV into a resistive load of 75KΩ (Rsh/2), the RF generator must supply about 1.7A of current; more than 10⁶ times the beam loading current. In this environment, the single voltage probe voltage produces virtually no distortion of the gap voltage measurement.

The only significant cross coupling terms are introduced by high Q elements in the RF amplifier and cavity.
4.1 Phase and Amplitude Loops

The control vector for the separator RF system becomes rotated as the resonance of the output circuit drifts with respect to the driving frequency. This is described by a perturbation matrix, $A$.

\[
\begin{bmatrix}
v(s) \\
\phi_v(s)
\end{bmatrix} = \frac{K_a}{(1+s\tau a)(1+s\tau)} A \begin{bmatrix} ac(s) \\
\phi_c(s)
\end{bmatrix}
\]

where:

\[
A = \begin{bmatrix}
\tan^2 \theta_z & s\tau \tan \theta_z \\
-\frac{s\tau \tan \theta_z}{1+s\tau} & 1+s\tau
\end{bmatrix}
\]

Orthogonal phase and amplitude controls, $ac(s)$ and $\phi_c(s)$, can be built to operate over a wide range when the inverse transfer matrix is known.

\[
\begin{bmatrix}
v(s) \\
\phi_v(s)
\end{bmatrix} = \frac{K_a}{(1+s\tau a)(1+s\tau)} A A^{-1} \begin{bmatrix} ac(s) \\
\phi_c(s)
\end{bmatrix}
\]

Very little cross coupling is introduced in the low Q RF driver stages. The transfer function for these relatively wide band sections can be approximated by the product of one dimensional expressions similar to the system in figure 10. An inverse matrix,
A^{-1} provides the control decoupling at low signal levels so that the RF phase and amplitude can be regulated by two independent control loops.

It is not convenient to implement a solution in this form because the A matrix requires an updated estimate of tanθz. The system becomes further complicated if one must estimate cross terms in the RF driver stages. If all the cross coupling terms are treated as system disturbances, then the transfer function of the RF system can be described by a simple second order expression like that shown in figure 10. Even without the decoupling matrix it is still possible to build a controller for this system around two independent second order regulators if the cross terms are treated as system disturbances.

For control purposes, it is convenient to represent the entire RF system as a 2x2 matrix that maps the control input vector into the output space. Measurement and control functions are also represented by 2x2 matrices while the system signals are described by two dimensional vectors.

\[ \text{fig. 13 Block diagram of the RF regulator loop.} \]
The gap voltage vector, $V_{out}$, can be written in terms of the set point vector, $V_{ref}$ as:

$$V_{out} = [1 + PGcM]^{-1} PGc V_{ref}$$

$$= [M + (PGc)^{-1}]^{-1} V_{ref}$$

If the system is controlled by two independent regulators then $Gc$ becomes a diagonal matrix. The control loop contains an amplitude detector and a phase detector, both of which can be constructed to provide independent measurements thus eliminating cross terms in the measurement matrix. Only the RF matrix, $P$, contains cross terms.

$$Gc = \begin{bmatrix} g_{11} & 0 \\ 0 & g_{22} \end{bmatrix} \quad M = \begin{bmatrix} m_{11} & 0 \\ 0 & m_{22} \end{bmatrix} \quad P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$$

where: $p_{11}=p_{22}$ and $p_{12}=-p_{21}$

The plant matrix, $P$ describes the rotation of orthogonal phase and amplitude modulation vectors. At low modulation frequencies ($s\tau<1$), the rotation is given by $\tan \phi = s\tau \tan \theta_2$ and at higher frequencies ($s\tau>1$) the rotation approaches $\phi = \theta_2$.

fig. 14

RF Control Space
Phase and amplitude changes in the gap voltage are shown along the vertical and horizontal axis. The matrix coefficient $p_{11}$ is the projection of the amplitude control vector, $v_1$, on the amplitude axis and $p_{22}$ is the projection of the phase control, $v_2$ on the phase axis. The determinant of the $P$ matrix, $p_{11}p_{22}-p_{12}p_{21}$ is the area of the parallelogram defined by the input vectors.

After some algebra, one can write the closed loop transfer function for the 2x2 system.

$$\left[M+(PGc)^{-1}\right]^{-1} = \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \end{bmatrix} + \begin{bmatrix} 0 & b_{12} \\ b_{21} & 0 \end{bmatrix}$$

The forward transfer functions are:

$$b_{11} = \frac{1}{m_{11} + \frac{1}{g_{11} p_{11}(k_{22}p_{22}+1)-k_{22}p_{12}p_{21}}} \approx \frac{1}{m_{11} + \frac{1}{g_{11} p_{11}p_{22}-p_{21}p_{12}}}$$

where $k_{22} = g_{22}m_{22}$ and $k_{22}p_{22} \gg 1$

$$b_{22} = \frac{1}{m_{22} + \frac{1}{g_{22} p_{22}(k_{11}p_{11}+1)-k_{11}p_{12}p_{21}}} \approx \frac{1}{m_{22} + \frac{1}{g_{22} p_{22}p_{11}-p_{21}p_{12}}}$$

where $k_{11} = g_{11}m_{11}$ and $k_{11}p_{11} \gg 1$

These forward transfer functions are of the usual form:

$$H_{ii} = \frac{G_{ii}}{1 + m_{ii}G_{ii}} \quad \text{where} \quad G_{ii} = g_{ii} \frac{|P|}{P_{jj}}, \quad k_{jj}p_{jj} \gg 1$$

$$= g_{ii}p_{11}, \quad k_{jj}p_{jj} \ll 1$$

When an amplitude change is made in the reference vector the regulators will attempt to hold the gap phase constant. At
frequencies where the regulator gain is large, the projection on the y axis, $p_{22}$ can be held constant and the effective amplitude gain in the plant becomes the projection on the x axis. This projected amplitude gain is given by the area of the control vector parallelogram, $|P|$, divided by $p_{22}$. (fig. 14)

Within the regulator bandwidth, the cross coupling is reduced by the loop gain and a factor equal to the area spanned by the control vectors.

$$b_{12} = \frac{g_{22}p_{12}}{(k_{11}p_{11}+1)(k_{22}p_{22}+1)-k_{11}k_{22}p_{12}p_{21}} \approx \frac{p_{12}}{k_{11}m_{22}(p_{11}p_{22}-p_{12}p_{21})}$$

$$b_{21} = \frac{g_{11}p_{21}}{(k_{11}p_{11}+1)(k_{22}p_{22}+1)-k_{11}k_{22}p_{12}p_{21}} \approx \frac{p_{21}}{k_{22}m_{11}(p_{11}p_{22}-p_{12}p_{21})}$$

Two independent PID regulators are used to cancel the dominant poles in the phase and amplitude control loops. Figure 15 shows a simulation of the small signal step response for a detuned RF system with $\theta_z = \pm 27^\circ$. When the loops are closed, cross coupling between phase and amplitude control is practically eliminated. Simulations show that two independent regulators for phase and amplitude can reject cross coupling terms introduced by an RF system operated near resonance ($|\theta_z| \leq 50^\circ$).

A cavity tuning loop is included in the separator system. While the tuner does reduce cross coupling between the phase and amplitude control signals, its chief task is to match the cavity
impedance to the transmission line and minimize reflected power seen by the tube.

\[ \tan \theta_z = \frac{1}{2} (\tan \theta_1 + \tan \theta_2) \]

where: \( \tan \theta_1 = \) plate circuit detuning
\( \tan \theta_2 = \) cavity detuning

A tuning loop is used to control the cavity drift and force a steady state value of \( \tan \theta_2 = 0 \). The tuner mechanism produces
small mechanical deformations of the cavity which in turn produces a shift in the cavity resonance. A linearized transfer function for the tuner mechanism and the tuning loop is of the form:

\[
\frac{K_M}{s(1 + sT_M)} \cdot d \rightarrow K_2 \rightarrow \Delta \omega_2 \rightarrow \tau \rightarrow \tan \theta_2 = \tau \Delta \omega_2
\]

**fig. 16 Cavity tuning mechanism.**

\[K_M \approx 2 \text{mm/s/V}, \quad K_2 \approx 5 \text{KHz/mm} = 10^4 \pi \text{s/mm}, \quad \tau \approx 70 \mu\text{s}, \quad \tau_M \approx 0.1 \text{s}\]

Cavity tune is measured by a phase detector which compares the phase of the transmission line voltage injected into the cavity and the gap voltage. At resonance, these two voltages are in phase. A 90° phase shift is introduced between the signals so that the phase detector will register zero when the cavity is driven at its resonant frequency. Operating near resonance (\(|\tan \theta_2| \leq 0.5\)), such that \(\tan \theta_2 = \theta_2\), the output of the phase detector will give a good estimate of the cavity tune. The tuning loop, shown below, is designed to operate with the reference, \(R = 0\).

**fig. 17 Cavity tuning loop.**
Output from the phase detector is a linear function of the phase difference between the RF injected into the cavity and the gap voltage. The detector responds much faster (1μs) than the mechanical tuning system (100ms) with the result that when a simple proportional controller is used, the loop transfer function is dominated by the motor. Disturbance inputs such as static tuning errors and long term drifts are reduced by the closed loop.

\[
\tan \theta_2 = \frac{D}{1 + H} \quad \quad H = \frac{K_t}{s(1+STM)}
\]

The ratio of reflected power to forward power seen by the cavity transmission line is:

\[
\Gamma^2 = \frac{|Z-R_0|^2}{|Z+R_0|^2} = \frac{(R_L-R_0)^2 + X^2}{(R_L+R_0)^2 + X^2}
\]

where 
\[
Z = \frac{R_0}{1+j\tan \theta_2} = R_L + jX \quad \text{transformed cavity impedance seen by the transmission line}
\]

\[
\Gamma^2 = \frac{\tan^4 \theta_2 + \tan^2 \theta_2}{(2+\tan^2 \theta_2)^2 + \tan^2 \theta_2} \approx \frac{\tan^2 \theta_2}{4} \quad \text{for } \Gamma^2 \leq 0.1
\]

To keep the power reflected from the cavity to less than 1%, the tuning loop must keep $|\theta_2| \leq 10^\circ$. This easily achieved over the control bandwidth however, the tuner must transmit mechanical motion through a vacuum seal and there is reason to reduce the bandwidth of this movement. Depending on the disturbance spectrum, the reflected power can show significant fluctuations while the average value is regulated to less than 1%.
The cavity time constant of about 70μs produces a lag between a phase change injected into the cavity and the appearance of the change at the cavity gap. Phase differences measured across the cavity are the result of tuning disturbances, D, and the propagation delay of phase modulations through the cavity. The tuning loop treats the output of the phase detector as system disturbances and attenuates both signals by a factor \((1 + H)\).

In operation, the loop keeps the cavity tuned near resonance such that terms of \(\tan^2\theta_2\) can be neglected and the phase signals in the cavity can be represented as:

\[
\phi(s) = \frac{\text{st2tan}\theta_2}{1+\text{st2}} \text{ cross term} + \frac{1}{1+\text{st2}} \text{ D disturbance}
\]

\[
\phi(s) = \frac{\text{st2tan}\theta_2}{1+\text{st2}} \text{ cross term} + \frac{1}{1+\text{st2}} \text{ D disturbance}
\]

\[
\theta_2 = D + \frac{1}{1+\text{st2}} [\phi(s) + v(s) \frac{\text{st2tan}\theta_2}{1+\text{st2}}] - \phi(s)
\]

\[
\theta_2 = D + \frac{\text{st2}}{1+\text{st2}} [v(s) \frac{\text{st2tan}\theta_2}{1+\text{st2}} - \phi(s)]
\]

Both the cross modulation terms and tuning disturbances, D are attenuated by the tuning loop. Phase modulations are treated differently. The cavity output phase is \(\phi_{out} = \theta_2 + \phi(s)\). Setting D and v(s) to zero such that only the phase control modulations interact with the tuning loop, one can write \(\phi_{out}\) in terms of the \(\phi(s)\) and the closed loop disturbance of the tuning system, \(\frac{\theta_2}{1+H}\).
\[
\phi_{out} = \left( 1 - \frac{st_2}{1 + st_2} \frac{1}{1 + H} \right) \phi(s)
\]
\[
= \frac{1}{1 + st_2} \left( 1 + \frac{H}{1 + H} st_2 \right) \phi(s)
\]

Over the range where \(|H| \gg 1\), the tuning loop effectively flattens the cavity response to phase modulations such that \(\phi_{out} = \phi(s)\). The bandwidth of the motor driven tuning loop is of the order of a few hertz, much less than the cavity bandwidth of \(\approx 2.5\text{KHz}\) and much less than the regulator bandwidth. As a result, the separator tuning loop is not strongly coupled with the amplitude and phase regulation. Since cross coupling introduced by a detuned RF system is treated as a disturbance by the regulator system, the tuning loop acts like a slow moving, feedforward term that is well within the bandwidth of the regulators.

From the control point of view, the cavity should be tuned to be the complex conjugate of the transformed plate circuit impedance to give \(\theta_1 = -\theta_2\) and \(\tan \theta_2 = 1/2(\tan \theta_1 + \tan \theta_2) = 0\). In its present form, the tuning loop eliminates phase and amplitude cross coupling due to cavity drifts but it has little influence on effects introduced by a detuned plate circuit. It is not difficult to change the existing resonance tuner to a conjugate tuning configuration but this may change the power amplifier design.
Chapter 5

Hardware Implementation of the Controller

5.1 Overview
The RF controller handles routine system faults, provides automatic start up, and keeps the cavity tuned to the cyclotron frequency. It also regulates the phase and amplitude of the gap voltage, providing wideband control of the particle flux delivered to the experiment. The system is built around analog control loops which were designed to have unity gain bandwidths greater than 100KHz. These loops are supervised by a computer which controls the setpoints and the regulator parameters.

![Diagram of basic controller concept.](image)

*fig. 19 Basic controller concept.*

5.2 System Description
The RF controller was developed as a modular system. Individual system functions were identified and then hardware modules were
built to perform that single function. Such modules can be easily changed or upgraded and complex systems can be pieced together from these basic elements in much the same way that they are assembled on paper using block diagrams.

![Control modules diagram](image)

*Fig. 20 Control modules.*

A dedicated computer provides access to the controller variables. It also handles graphic display of the system information and sequencing for automatic start-up and spark recovery. The computer permits the modular design to be extended to the user interface, sequencing operations, and upgrading to provide new system states. The regulator I/O lines connect to the same backplane as the computer but are optically isolated from the bus.

The software for automatic sequencing and system I/O was developed
on an MS DOS computer using compiled BASIC. This system had all of
the graphics and timer support needed to produce the bar graphs,
system pictorials, and sequencing operations. The controller was
built using a 7MHz PC on STD bus with Prolog's System 2 operating
system. This configuration worked well and could easily handle the
necessary tasks using a simple polling loop.

A gas plasma display is used as the front panel display. It is
compatible with IBM's EGA graphics but unlike a CRT it is not
sensitive to magnetic fields or phosphor burn. The amplitude and
phase control can operate in open loop or closed loop with the
state of each loop shown graphically on the front panel display.
Set point and readback values are displayed numerically and with
horizontal bar graphs. The modulator drive signals and an
adjustable drive limit value are displayed in a vertical bar
graph. System status is shown in the right side of the display.

Fig. 21 Front panel display.
During start up, the RF voltage is pulsed to overcome multipactoring in the cavity. A peripheral card for the STD bus was built to handle this operation. The computer writes the pulser frequency and pulse width to this card. When the system is operated in pulsed mode, the pulse width can be adjusted by a front panel knob from 0% to 100%. In CW operation, the RF is turned On or Off by writing a pulse width of 100% or 0%.

Push buttons on the front panel are used to toggle the system states such as RF On/Off, RF Pulsed/CW, etc. Continuous parameters can be adjusted using five optical shaft encoders on the front panel. Each loop has one shaft encoder that can be assigned to adjust either the regulator gain, the two transfer function zeros, or the drive limit for the loop. The remaining three shaft encoders are not assignable but remain dedicated to the amplitude and phase set points and the RF pulser duty cycle. The assignable knobs are used mainly during setup and commissioning while the dedicated knobs are used during manual operation of the RF system. Keeping multiple assignments to a minimum reduces the complexity of the front panel controls.

5.3 Self-Excited Operation

To start the RF system, the cavity and power amplifier usually need to be tuned before full power is applied. Experience with the cyclotron cavity has shown that it is best started in self-excited mode where the signal from the cavity pickup is fed back to the low level RF driver amplifier. The self-excited frequency is
determined by the cavity resonance and the phase shift around the loop.

**fig. 22 Self-excited configuration.**

Self-excited operation provides an idle mode where the RF system operates independent of a reference phase or frequency and can be tuned by a phase shifter in the feedback loop instead of the usual mechanical tuning loop. This arrangement has proved to be useful for commissioning and debugging the various RF systems on site and has become a standard requirement for TRIUMF RF systems.

**fig. 23 Principal system states.**

If beam production is interrupted, the separator loses its RF reference signal and the system waits at full power in self-excited mode until beam is again delivered to the experiment. Similarly, from a cold start, the system waits at full power in self-excited mode until the cavity frequency is matched to the reference frequency.
Limiters and a bandpass filter are included in the self-excited signal path. The limiters keep the signal amplitude the same as it would be in the driven mode while the bandpass filter ensures that the cavity is self-excited by the desired push-pull mode.

The self-excited system behaves like a classical oscillator in which the total phase shift around the loop is $2\pi$. When the loop is initially closed, system noise generates a current in the power tube which excites the high Q plate circuit and cavity. If the delay around the loop at the cavity resonant frequency, $\omega_0$, is $2\pi-\phi$ then a steady state frequency is reached when the cavity is excited at a frequency above resonance, $\omega=\omega_0+\delta\omega$ where the cavity provides the extra phase lag to make the loop delay equal to $2\pi$. The impedance of the cavity at this frequency is:

$$Z = \frac{R}{1+j\frac{2Q}{\omega_0} \delta\omega} = |Z|e^{-\phi}$$

At steady state, $\phi = \tan^{-1}\left(\frac{2Q}{\omega_0} \delta\omega\right)$ and the self-excited frequency is given by:

$$\omega = \omega_0 + \delta\omega = \omega_0 \left(1 + \frac{\tan \phi}{2Q}\right)$$

5.4 Self-Excited and Driven Tuning Systems
Drift in the cavity resonance or in the phase delay around the loop will cause the system to operate off resonance. In terms of reflected power and load matching, the self-excited mode, like the driven system, needs an automatic tuning loop. When in driven
mode, the mechanical tuning loop keeps the cavity tuned to resonance and minimizes reflected power. In self-excited operation, the tuning mechanism drives the cavity to the cyclotron frequency while the phase regulation loop minimizes reflected power.

![Diagram of self-excited tuning loop.](image)

**fig. 24 Self-excited tuning loop.**

In the self-excited mode the frequency comparator allows the tuner to adjust the cavity resonance to within 1 KHz of the cyclotron RF. This module produces a signal that is positive if the self-excited frequency is greater than the cyclotron frequency, negative if the frequency is less than the reference and zero if the self-excited frequency is within 1 KHz of the cyclotron frequency.

The phase regulator maintains a delay of $2\pi t$ around the self-excited loop. The bandwidth of the phase regulator is very much greater than the mechanical tuning system and no reflected power fluctuations are detected when the self-excited tuning loop
is functioning. Under automatic control, the system can be taken into the driven state when (\(\Delta F_{\text{Ok}} \text{ AND Drive\_Present} \)) is true.

In driven mode, the phase regulator locks the cavity signal to the RF reference signal. When \text{Drive\_Present} \text{ is False, the controller will return to the RF Off state. Under automatic control, it will bring the system back to the self-excited state and wait for the RF drive.}

To change from self-excited to driven, the RF source is switched from the cavity to the reference signal. A DPDT switch box configures the control signals for the tuner and for the phase regulator.
5.5 The Frequency Comparator

The automatic controller must be able to tune the self-excited cavity to the reference frequency before the system is driven. Necessary information for this task is provided by the frequency comparator which uses 2 mixers, a 0° power splitter and a 90° power splitter to derive two signals, \( \sin(\omega_1 - \omega_2)t \) and \( \cos(\omega_1 - \omega_2)t \).

With respect to the cosine term, the sine term is inverted when \( \omega_2 > \omega_1 \).

\[
\cos(\omega_1 - \omega_2)t = \cos(\omega_2 - \omega_1)t \\
\sin(\omega_1 - \omega_2)t = -\sin(\omega_2 - \omega_1)t
\]

The quadrature signals are converted to digital waveforms and decoded by simple logic circuits. Experience has shown that when the two frequencies are matched to within 1 KHz, the system can be driven. A retriggerable one shot and a latch detects this condition. The time constant of the one shot determines how closely the frequencies are matched.
5.6 Spark Detection

Sparks in the RF cavity effectively short circuit the cavity and power amplifier. The avalanche condition, which the spark initiates, is extinguished when the RF drive is removed. To prevent damage to the RF system, the drive is turned off for a minimum of 1 second when a spark is detected. A photograph of the different waveforms for normal RF Off and a spark are shown in figure 9. The spark detector responds to amplitude signals that fall 70% in less than 5μs. Normal RF Off signals decay to this level in about 50μs and do not trigger the circuit.

**fig. 28** Spark Detector
5.7 System Hardware Configuration

Long cable runs (60m) between the cavity and the controller can introduce ground loop noise into the system. The connection diagram for hardware modules includes DC blocks and optical couplers that isolate the controller from 60Hz ground loops. The DC blocks are coupling capacitors that pass only the RF signals on the cable shield and center conductor. Connections to the tuning motor and to the computer I/O bus are optically isolated.

Phase detectors operate over a restricted range, usually ±90°. The controller contains 4 manual phase shifters which are adjusted when the system is installed. One of the phase shifters adjusts the phase delay in the self-excited loop. The other three set the operating range of the phase detectors.

Bandpass filters are included on the reference input and the cavity feedback. They have a pass band of ±1 MHz about the 23 MHz center frequency and introduce less than ±1° phase error over the separator's 10 KHz operating range. The filter in the cavity feedback path attenuates out of band noise before the signal is presented to the phase and amplitude detectors. A filter on the reference input is needed to condition the various signals that can provide the reference frequency.
fig. 29
Separator RF Control Modules
5.8 Regulator Electronics

A simplified diagram of the regulator loop and its connection to the RF system is shown in figure 30. It is a PID configuration in which 8 bit multiplying DACs are used to change the loop gain and the regulator zeros. A 12 bit DAC is used to control the set point and an 8 bit ADC is multiplexed to monitor the drive level and the detector output.

Wide band phase and amplitude modulators and detectors add high frequency poles to the RF system. These effects and the high order poles in the regulator are not included in the simplified diagram because the circuit is designed to reach unity gain before these high order terms affect the loop stability.

Control signals to the RF modulators are generated by operational amplifiers and vary between ±10V. Signals from the amplitude and phase detectors are processed by similar devices and are also in this ±10V range. Within an order of magnitude, one can write the product of the plant gain and the measurement gain as $K_aK_m \approx 1$. If the regulator design cancels the two dominant poles in the second order plant and is unity gain stable then the regulator gain can be adjusted to be closed loop stable in all TRIUMF RF systems where $K_aK_m \approx 1$. An 8 bit multiplying DAC is used as a variable resistor to adjust the controller gain, $K_c$, over 2 decades (48db) between $10^5$ to $2.5 \times 10^7$. $\Delta$ is adjustable from 0 to 330μs in 255 steps. This range is able to compensate for $Q$'s usually attained in copper cavities.
When the RF system is operated in open loop, the PI term is strapped for unity gain and follows the set point. This prevents the integrator from drifting and permits a nearly bumpless transfer between open loop and closed loop control. Ideally, τr should be equal to τf and, at the cost of increased complexity, it is possible to make τr adjustable so that it tracks τf. A simpler circuit configuration with a fixed value of τf was used to make the regulator unity gain stable under all settings of Kc and τf.

The derivative term is restricted to the feedback path. This configuration provides less DAC noise on the output as the set point changes. It is adjustable from 0 to 100μs in 255 steps. For most systems, the dominant pole can be canceled in either path.
The simplified schematic of the regulator shows an op-amp lead circuit in the feedback path. This circuit does not perform well at high frequencies. A better differentiator can be built from discrete components as shown in figure 32. It is a capacitor in series with a common base stage with emitter followers on the input and output. The current in the common base stage is 4.5mA which gives an input resistance of 5.5Ω. The output resistance of the emitter follower feeding the capacitor is about 2.5Ω. These values (8Ω and 0.01μF) indicate that the differentiator phase should fall to 45° around 2MHz. This agrees with the simulation.

fig. 31 Simplified Regulator Schematic

fig. 32 Discrete Component Differentiator
Several companies now provide operational amplifiers with bandwidths in excess of 20 MHz. Most of these devices are transimpedance amplifiers which have a high impedance positive input and a low impedance negative input. The negative input is typically a common base stage which maintains a low input impedance over a wide frequency range. Bench tests show that a useful differentiator can be built using one of these devices.

The transimpedance op-amp is also well suited to the multiplying DAC circuits in the PID regulator. The DACs have a large output capacitance (120 pf) which can reduce the stability of voltage op-amp circuits unless the high frequency gain is reduced. Bench tests indicate that the bandwidth and gain of the regulator can be considerably improved if current input op-amps are used with the multiplying DACs.
6.1 The Main Program Loop

A program was written to monitor system operation and supervise transition of the system from one state to another. It also provides an operator interface and graphic display of the controller variables. Manual or automatic control can be selected from the front panel. The software permits more flexibility under manual control. In automatic mode the system is constrained to follow rigid rules.

The controller follows a polling loop of the form:

Do While Control=True

Scan_Knobs
Scan.Buttons
Read_Inputs
Fault_Control
Control_Devices
Display_Data

{ \textit{state transition requests} \\
\{ \textit{apply fault rules} \\
\{ \textit{apply control rules} \\
\{ \textit{update display} \\

End While

To achieve a new state, the machine needs to consider two input vectors; the present state and external input. The present state
is available in the machine memory while external input can come from the operator or from the RF system as a detected spark or loss of drive, etc. External input acts as a request to change the resident image of the system state and the appropriate hardware. Safe operation of the RF system does not permit arbitrary transition from a given state to any other state. In manual mode and in automatic mode, the requests for state change are filtered by control rules. As experience is gained with the system, the control rules are changed to accommodate new functions.

6.2 Task Communication

System information is stored in global variables, available to all tasks. Flags are used to communicate between tasks. The two principal tasks are display and control and the flags associated with these tasks are:

- Amplitude_Display_Mail
- Phase_Display_Mail
- System_Display_Mail
- Pulser_Display_Mail
- Amplitude_Control_Mail
- Phase_Control_Mail
- System_Control_Mail
- Pulser_Control_Mail

Each mail flag is two bytes long and has an internal structure indicating the individual requests. If the flag is zero, the task is not invoked. If the flag is non-zero, bits are reset in the flag as each request is processed.
6.3 Control Tasks

A task such as Control_Devices is of the form:

SUB Control_Devices

    Check_Control_Rules
    IF System_Control_Mail THEN System_Control
    IF Amplitude_Control_Mail THEN Amplitude_Control
    IF Phase_Control_Mail THEN Phase_Control
    IF Pulser_Control_Mail THEN Pulser_Control

END SUB

Check_Control_Rules filters the requests in individual control flags to make them compatible with the present system state. Changes are made to the system if the validated control flag is non-zero.

Program constants have been declared as integer masks that test individual bits in the appropriate display and control flags. If an individual bit tests TRUE then that specific action is taken and then the bit is reset. This process will clear all the bits in the control flag. Amplitude_Control is typical of the control modules.

Sub Amplitude_Control

    IF Amplitude_Control_Mail AND Setpoint_Flag THEN

        OUT Amplitude_Setpoint_Port, Amplitude_Setpoint

        Amplitude_Control_Mail = Amplitude_Control_Mail XOR Setpoint_Flag

    END IF
IF Amplitude_Control_Mail AND Tau_D_Flag THEN

    OUT Amplitude_Tau_D__Port, Amplitude_Tau_D

    Amplitude_Control_Mail = Amplitude_Control_Mail XOR Tau_D_Flag

END IF

END SUB

Phase_Control and Amplitude_Control write new values to the phase and amplitude regulators. The loop variables that are changed by these routines are:

- Setpoint
- Limit — hardware limit for the modulator drive
- Gain — loop gain
- Tau_I — regulator zero
- Tau_D — regulator zero

6.4 Front Panel Input

A peripheral card was built to latch the front panel knobs and push buttons. When a button is pushed or a knob turned, the event sets a single bit in one of two 8 bit registers. These two registers are read during the polling loop and ANDed with masks that enable inputs compatible with the present machine state. Action is taken only if the result is non-zero. The hardware automatically clears the registers at the end of the read cycle, minimizing latency in scanning the front panel.
Push buttons are assigned to toggle boolean system variables. Both the display and control flags are set by front panel input that is enabled by the appropriate masks. No problems have occurred with this procedure, however, it is probably better to set the display flag when the actual control is accomplished.

SUB Scan_Buttons

    Push.Buttons = INPUT(Push_Button_Port) AND Button_Mask

    IF Push.Buttons THEN

        IF Push.Buttons AND On_Off_Flag THEN

            System_Display_Mail = System_Display_Mail OR On_Off_Flag

            System_Control_Mail = System_Control_Mail OR On_Off_Flag

        END IF

    END IF

END SUB

Input from the front panel shaft encoders is more complicated than the boolean information received from the push buttons. If the Knob_Register is non-zero then the Direction_Register is read. If a bit is set in the Knob_Register then the Direction_Register bit is tested to see if the associated variable should be incremented or decremented. The changed variable is validated to ensure that
(0 ≤ value ≤ max_value) and then the appropriate bits are set in the control and display flags. The system only responds to a person turning one knob at a time.

SUB Scan_Knobs

Knob_Register = INPUT(Knob_Port) AND Knob_Mask

IF Knob_Register THEN

Direction = INPUT(Direction_Port)

............. increment setpoint step size (initial value = 0) ............

IF Setpoint_Step < Max_Step THEN Setpoint_Step = Setpoint_Step + 1

1) IF Knob_Register AND Amplitude_Setpoint_Knob THEN

IF Direction AND Amplitude_Setpoint_Knob

THEN Amplitude_Setpoint = Amplitude_Setpoint + Setpoint_Step

ELSE

Amplitude_Setpoint = Amplitude_Setpoint - Setpoint_Step

END IF

* validate 0 ≤ setpoint ≤ max_setpoint

* set control, display flags

2) ELSE IF Phase setpoint

3) ELSE IF

o amplitude loop parameters

4) ELSE IF

o phase loop parameters

5) ELSE IF

o pulse width

END IF

............. no knob turned, relax setpoint step size ............

IF Setpoint_Step > 0 THEN Setpoint_Step = Setpoint_Step - 1

END SUB
One advantage of scanning the front panel knobs in this fashion is that it produces no large step functions outside the response time of the control and display tasks in the polling loop. The loop can be slow (>10ms) and ramping the voltage with a 12 or 16 bit DAC becomes a tedious job with a system that loses shaft encoder counts. The apparent response is changed by incrementing the setpoint by an amount that depends on how fast the front panel knob is turned.

If the program detects that each time through the polling loop, the setpoint is always flagged, then the setpoint knob is being turned faster than the system can respond. The size of the setpoint step is increased until it reaches a maximum value or until the program detects that the setpoint is not flagged and then the setpoint step is decreased. In this way the "feel" of the system is tailored to suit manual operation.

6.5 Auto Start

The initial start-up condition is:

RF Off

Phase and Amplitude loops open

Amplitude setpoint = 0

mode = self-excited

When a spark is detected, hardware immediately turns off the RF drive and sets an I/O bit that is scanned by the computer each
time through the polling loop. The computer will restart the system if it is in automatic mode.

IF Spark_Detected THEN
  Spark_Count = Spark_Count + 1
  IF Spark_Count = 1 THEN Auto_End_Amplitude = Amplitude_Setpoint
  Initialize
  Display_Message("SPARK: waiting for vacuum")
  Pause(8) wait 8 seconds
  System_Control_Mail = Auto_Start_Flag
  Fault = True
END IF

Sparks can occur during the auto start process. If sparking occurs too many times the system will abandon its attempts to start and wait for an operator. Auto_Start can be halted by a system fault or operator intervention. A simplified auto start sequence is of the form:

- Initialize
- Max_Sparks? ⇒ Exit
- set Button_Mask
- enable RF
  Fault or button pushed? ⇒ Exit
- Pulse at 5%
- set amplitude to 60% of target
- RF not detected? ⇒ Exit
- wait 2 seconds
Fault? => Exit

• go CW

Fault? => Exit

• wait 1 second

Fault or button pushed? => Exit

• Close Amplitude Loop

Fault? => Exit

• wait 1 second

• Close Phase Loop

• ramp to target voltage

Fault or button pushed? => Exit

• wait for beam

Fault or button pushed? => Exit

• match cavity freq.

Fault or button pushed? => Exit

• go driven

Fault or button pushed? => Exit

• set Button_Mask

• Spark_Count =0

Exit

The auto start routine provides:

- a means for the operator to turn on the RF system without special knowledge of the system.

- a means to automatically recover from known faults and to re-establish operation of the separator.

The present auto start routine performs satisfactorily but it is
not well structured. During the wait sequences, the computer scans for faults and can initialize the system if a fault is detected. The code associated with this routine needs work.

In general, the perceived performance of the RF controller rests with the software and the operator interface it provides. For example, if there is low voltage from the screen grid power supply, it is reported as a controller fault; the system does not come up to voltage when the on button is pushed. A successful operator interface requires more diagnostics and as much development as the does the regulator hardware.

The TRIUMF Controls Group is working to develop workstations for supervising site processes. Such a system is used at Los Alamos to supervise RF regulator loops and provide the user interface. This configuration will improve the RF controller.
Conclusions

A control system for the TRIUMF M9 Separator has been modeled, designed, and built. Experience with this and other RF systems indicates that a second order model is sufficient to control most, if not all, of the TRIUMF RF systems. It is not necessary to know the exact pole locations or the system gain. The regulator zeros can be adjusted over a range sufficient to cancel system poles introduced by the RF amplifiers and by copper cavities. Within an order of magnitude, the product of the plant gain and the measurement gain is $\approx 1$ for the installations at TRIUMF. The regulator design is unity gain stable and the plant loop can be made stable given the 48db of gain adjustment in the regulator.

Significant cross coupling between the open loop phase and amplitude controls is introduced when the plate circuit in the power amplifier is detuned. This can be almost eliminated if the cavity is tuned to the complex conjugate of the plate circuit. In systems where the transmission line is an integral number of wavelengths, a conjugate tuning scheme should present a resistive load to the tube. The present tuning system keeps the average cavity tuning within $5^\circ$ of resonance. The disturbance spectrum can sometimes exceed the bandwidth of this loop, causing fluctuations in reflected power greater than 1% of the forward power.
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