OPTIMAL TIMING FOR SPARK RECOVERY IN THE TRIUMF CYCLOTRON

K. Fong, M. Laverty and Q. Zheng, TRIUMF, Vancouver, Canada.

Abstract

In the TRIUMF cyclotron when a spark occurs it is necessary to shut off the RF drive and to initiate an RF restart procedure. It is also desirable to restore the full operational dee voltage as soon as possible in order to prevent thermal detuning of the resonant cavity. However, when the RF drive is shut off, the disappearance of Lorentz force on the resonator hot-arms causes the hot-arms to vibrate at their mechanical resonant frequency. When the RF field is being restored, the electromagnetic resonance is coupled to the mechanical resonance through the Lorentz force, and the amplitudes of the both the mechanical vibration and the RF field depend on when RF drive is re-applied. Computer simulations and experimental results will be presented to demonstrate that an optimum exists for the RF restart timing. With this optimal timing, the Lorentz force is used to suppress the mechanical vibration of the hot-arms. The reduction in hot-arm vibrations increases the probability of successful restarts as well as reduces the stress on the RF components.

INTRODUCTION

When sparking occurs inside the TRIUMF cyclotron resonator, the RF power is cut off in order to extinguish the spark[1]. If it takes more than a few seconds before voltage comes back to its nominal value, then the cyclotron thermal balance is lost. This is due to the substantial amount of heat removed from the structure by efficient cooling which is not being replenished by the RF power. Temperature variations affect the cyclotron resonant frequency. In the operational mode, automatic control of the resonant frequency is performed by varying the cooling water pressure which gives a limited tuning range of about 3 kHz. Thermal imbalance due to recovery time causes a resonant frequency shift of about 10 kHz. It requires about 3 minutes for the system to come back to the operational frequency, when it can be switched to generator driven mode. Beam injection restart requires some 10-20 seconds more. Recovering from a spark can cause 4-5 minutes of total machine downtime. In order to prevent this lengthy downtime, the restart procedure is initiated as soon as possible. Spark detection is based on cyclotron voltage drop analysis. When the voltage drop differential exceeds 10 kV/µs, the event is recognized as a spark. At this point the RF drive turns off for 60 ms to let the spark products diffuse away from the arc channel. Then the RF drive instantly comes back to generator driven mode. In the past, we have observed that more than half of these fast recovery attempts were unsuccessful. Also, in every attempt, measurements have shown that there were large fluctuations in field voltage and reflected power during the restart attempts.

THEORY

Suppose a resonator is operating in a steady state condition with field voltage V_0. This produces a Lorentz force and causes the resonant cavity to be detuned by $\Delta\omega_0$. At time interval $0 < t < t_R$, the field voltage is removed and the cavity will start a mechanical oscillation with frequency Ω_μ and damping time constant τ_μ. Neglecting Coulomb friction, the mechanical equation for this detuning is

$$\frac{d}{dt}\begin{pmatrix}\Delta\omega \\ \dot{\Delta\omega}\end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\Omega_\mu^2 & -\frac{2}{\tau_\mu}\end{pmatrix}\begin{pmatrix}\Delta\omega \\ \dot{\Delta\omega}\end{pmatrix} + \begin{pmatrix} 0 \\ -\Omega_\mu^2 k_\mu\end{pmatrix} V^2 \qquad (1a)$$

The initial conditions are

$$\begin{pmatrix}\Delta\omega_0 \\ \dot{\Delta\omega_0}\end{pmatrix} = \begin{pmatrix} -k_\mu V_0^2 \\ 0\end{pmatrix}, \qquad (1b)$$

and

$$V = 0 \text{ for } 0 < t < t_R \qquad (1c)$$

For $t \geq t_R$, a constant RF drive is re-applied. Since the detuning is changing due to mechanical vibration, the field voltage is given by the approximation

$$V^2 \approx \frac{\alpha^2}{1 + \left(2\frac{\Delta\omega - \Delta\omega_0}{\omega_{BW}}\right)^2} V_o^2 \qquad (2)$$

With $\Delta\omega << \omega$, ω_{BW} is the electrical bandwidth of the resonator, and α is the recovery reduction factor. The field voltage in turn generates a Lorentz force which modifies the mechanical vibration through the inhomogeneous term in Eq. 1a. Despite its appearance, Eq. 1's are nonlinear due to the nonlinear nature of Eq. 2.

Defining the dimensionless quantity

$$\varepsilon \equiv \frac{\Delta\omega}{k_\mu V_o^2} \text{ and } v \equiv \frac{V}{V_o}, \qquad (3)$$

where ε is the mechanical detuning normalized by the initial Lorentz force detuning, and v is the ratio of the cavity voltage to the initial voltage. The normalized equation of motion is

$$\frac{d}{dt}\begin{pmatrix}\varepsilon \\ \dot{\varepsilon}\end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\Omega_\mu^2 & -\frac{2}{\tau_\mu}\end{pmatrix}\begin{pmatrix}\varepsilon \\ \dot{\varepsilon}\end{pmatrix} + \begin{pmatrix} 0 \\ -\Omega_\mu^2\end{pmatrix} v^2 \qquad (4a)$$

$$\begin{pmatrix}\varepsilon_0 \\ \dot{\varepsilon}_0\end{pmatrix} = \begin{pmatrix} -1 \\ 0\end{pmatrix} \qquad (4b)$$

$$v^2 = \frac{\alpha^2}{1 + \left(2\frac{\varepsilon + 1}{\varepsilon_{BW}}\right)^2} \qquad (4c)$$

When $\varepsilon_{BW} >> 1$, i.e. the detuning is small compared to the bandwidth, Eq. 4c becomes independent of ε and Equation 4a becomes a second order ordinary differential equation and can be solved analytically.

For $0 < t < t_R$,

$$\varepsilon(t) \cong e^{-\frac{t}{\tau_\mu}} \cos \Omega_\mu t \qquad (5)$$

The phase trajectory is a stable spiral focused at (0, 0).

For $t \geq t_R$,

$$\varepsilon(t) + \alpha^2 \cong A e^{-\frac{t}{\tau_\mu}} \cos(\Omega_\mu t + \phi) \qquad (6)$$

with A and ϕ dependent on t_R. The phase trajectory is a stable spiral focused at ($-\alpha^2$, 0). The results for different t_R's are plotted in Figure 1.

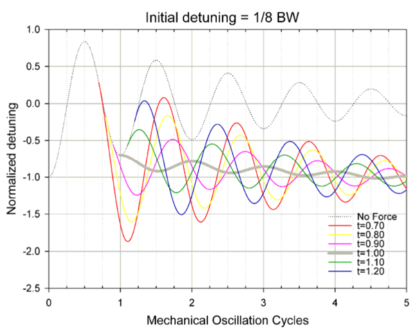

Figure 1: Dependency of mechanical oscillation on recovery timing

The phase portrait for a system with damping, different t_R's and $\alpha = 1$ is shown in Figure 2. At $t < 0$, the system is at rest at (-1, 0) in the normalized phase plane. For $0 < t < t_R$, with no Lorentz force present, the trajectory follows a stable spiral depicted in a gray line focused at (0, 0). When the RF field re-establishes for $t > t_R$, the focus moves back to (-1, 0). By observation it follows that in order to obtain the smallest spiral focused at (-1, 0), the switching should occur at when the phase trajectory is at the negative real axis at the end of the first oscillation cycle. We will call this time as $t_{2\pi}$. Furthermore, due to mechanical damping, the amplitude of vibration decreases exponentially, and does not reach (-1, 0) but instead at $(-e^{-\frac{2\pi}{\tau_\mu \Omega_\mu}}, \ 0)$. To stop the vibration using Lorentz force, we can synchronize α with damping such that $\alpha = e^{-\frac{\pi}{\tau_\mu \Omega_\mu}}$. After the mechanical vibration is stopped, we can ramp the voltage back to its original amplitude as shown in Figure 3. For resonators with Coulomb friction, the foci's are shifted to the left for trajectories on the upper half phase plane and shifted to the right for trajectories on the lower half phase plane. This has the effect of decreasing the radii of the trajectories but does not affect the optimal recovery time.

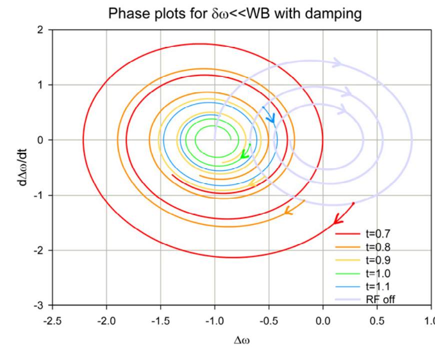

Figure 2: Phase portrait of recovery timing

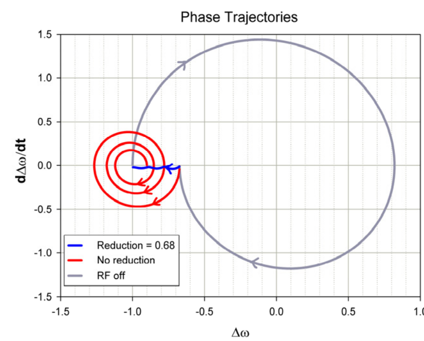

Figure 3: Phase Trajectories for optimal recovery timing for damped oscillation

RESULTS

The mechanical resonances of the TRIUMF cyclotron Dee's consist of a sharp resonance peak at 5 Hz due to the fundamental mode of the strongback of the individual segment in the Dee[2,3]. Fig. 4 shows the recovery that occurred at 60 ms after a spark. The top yellow trace

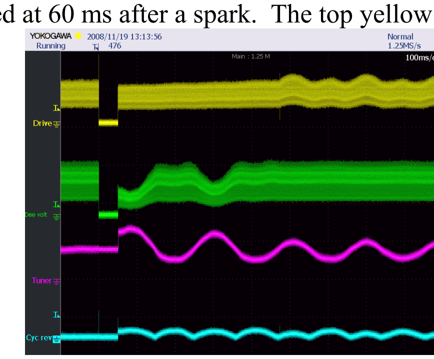

Figure 4: 60 ms delay spark recovery

indicates the RF drive amplitude; the second green trace measures the Dee voltage amplitude. The third pink trace is the tuner drive signal, which gives a good indication of the Dee tip position. The last cyan trace is the measured reflected power. As can been seen in the third (pink) curve, the resonator is almost at the peak of its deflection at the time when the RF is reapplied. As a result of this there are large fluctuations in RF forward and reflected power which lasted for several seconds until the oscillation decayed.

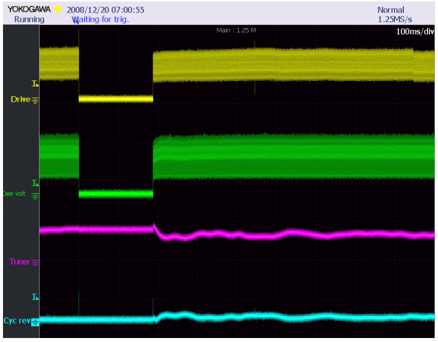

Figure 5: 200 ms delay recover

In contrast Figure 5 shows the same RF parameters when the recovery is timed at $t_{2\pi}$ of 200 ms after the initial spark. At this time the RF is switched back on, and the equilibrium position coincides with the instantaneous position of the resonator. As a result very little residual resonator movement is observed.

NARROW BANDWIDTH CAVITIES

When the Lorentz detuning becomes comparable to the resonator bandwidth, i.e., $\Delta\omega \cong \omega_{BW}$, the phase trajectories are no longer simple spirals but take on shapes like dumb-bells. The critical points are located where

$$\begin{pmatrix} 0 & 1 \\ -\Omega_\mu^2 & -\frac{2}{\tau_\mu} \end{pmatrix}\begin{pmatrix} \varepsilon \\ \dot{\varepsilon} \end{pmatrix} + \begin{pmatrix} 0 \\ -\Omega_\mu^2 \end{pmatrix} \frac{\alpha^2}{1+\left(2\frac{\varepsilon+1}{\varepsilon_{BW}}\right)^2} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{7}$$

or

$$\varepsilon^3 + 2\varepsilon^2 + \varepsilon\left(1+\frac{\varepsilon_{BW}^2}{4}\right) + \alpha^2\frac{\varepsilon_{BW}^2}{4} = 0\,. \tag{8}$$

We will restrict the analysis to the case where $\alpha = 1$ because the strong dependency of $\Delta\omega$ on α makes it impractical to be otherwise. The roots of this cubic equation then have rather simple forms

$$-1,\ -\frac{1}{2}\left(1 \pm \sqrt{1-\varepsilon_{BW}^2}\right) \tag{9}$$

When $\varepsilon_{BW} > 1$, there is only one critical point at (-1, 0). The result is similar to the previous cases where $\Delta\omega << \omega_{BW}$. For $\varepsilon_{BW} < 1$, there are three critical points: (-1, 0) and $\left(-\frac{1}{2}\left(1-\sqrt{1-\varepsilon_{BW}^2}\right),\ 0\right)$ which are either centres (no damping) or stable foci (with damping). In between of the above two points is a saddle point at $\left(-\frac{1}{2}\left(1+\sqrt{1-\varepsilon_{BW}^2}\right),\ 0\right)$. Since the success of the recovery process means that the trajectory converges to (-1, 0), the separation of (-1, 0) and the saddle point becomes very important. Due to the appearance of the extra focus and saddle point for narrow-band devices, the success of a recovery depends on the timing of the restart and is no longer arbitrary. A phase portrait of $\varepsilon_{BW} = 0.9$ with damping is shown in Figure 6. The trajectories have

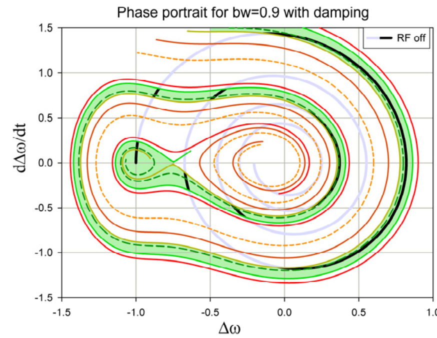

Figure 6: Phase portrait for high distortion cavity

2 boundaries separating a region indicated by its green colour. The trajectories are bifurcated into 2 families, with the green region representing the family of trajectories that converge to the singular point (-1, 0), where the RF field can be restored successfully. The other converges to (-0.28, 0) where the RF field is at a much lower value, due to the fact that at $\varepsilon_{BW} < 1$ there exist a strong dependency of amplitude on detuning. The success of the recovery depends on the mechanical damping of the resonator as well as the location of the saddle point. For resonators with little mechanical damping, the free oscillation trajectory passes on the left-hand side of the saddle point, making $t_{2\pi}$ the optimum recovery time. If the trajectory passes the saddle point on the right-hand side due to higher damping, then the successful recovery time is less than $t_{2\pi}$. With decreasing ε_{BW}, as the saddle point moves toward the focus at (-1, 0), the separation between the 2 regions becomes smaller, making successful recovery more difficult.

CONCLUSION

As shown by the computer simulation described, the recovery is quite sensitive to the timing when the RF field is re-established. Re-applying the RF drive as soon as possible does not lead to a faster recovery to a stable operating point. For a wide bandwidth cavity, the optimal time is when the mechanical oscillation has completed one oscillation. For a narrow bandwidth cavity, this timing may be required to be earlier, depending on the mechanic damping of the resonator.

REFERENCES

[1] I. Bylinskii et al., "TRIUMF cyclotron RF system refurbishing", Cyclotrons-2004, Tokyo, Japan, 18-22 October 2004.

[2] D. Dohan et al., "Requirements for a new resonator structure at TRIUMF", Proc. 10th Intl. Conf. Cyclotron, p. 357. (1984)

[3] G. Stanford et al., "A New and Improved RF Resonator Segment for the TRIUMF Cyclotron", IEEE Tran. Nucl. Sci, Vol. NS-32, No. 5, Oct 1985, p. 2942.