IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

RF ACCELERATING VOLTAGE CONTROL AND STABILIZATION IN THE TRIUMF CYCLOTRON

R.H.M. Gummer
TRIUMF
Vancouver, Canada

Introduction

The basic RF system of the TRIUMF cyclotron consists of a resonant accelerating electrode structure powered at 23.05 MHz by a 1.8 MW transmitter.[1] The prime objective of the RF control system described in this paper is to ensure an accelerating voltage of stable amplitude and frequency. Through the extensive use of feedback loops and fixed-program logic circuits the problems of multipactoring, resonator detuning, RF voltage breakdown, and RF voltage disturbances are dealt with. The system is almost completely automatic, so that straightforward operation of the RF system, via a CAMAC link, from the main cyclotron control desk is achieved.

Resonator Characteristics

Some of the most challenging problems encountered in the design and implementation of the RF control system arose from the characteristics of the resonator. The important electrical parameters of the resonator are listed below:

Nominal resonant frequency	23.05 MHz
Cyclotron RF frequency	23.05 MHz
Resonator voltage	100 kV peak
Power dissipated at 100 kV	1.2 MW
Q	6000
Bandwidth between -3 dB points	4 kHz
Tuning range	±4 kHz
Resonant frequency range during warm-up at 100 kV	23.09 to 23.05 MHz

Frequency Drifts During Start-up

The resonator can develop voltage efficiently only when the driving frequency corresponds with the resonator bandwidth. Thermal expansion of the dees causes the resonant frequency to change by as much as 40 kHz during the first ten to twenty minutes of operation. This variation is many times the resonant bandwidth, and exceeds by a factor of 5 the resonator's tuning range. This means that until the thermal conditions stabilize, the system cannot be driven at a constant frequency. Manual tuning of the frequency source to track the varying resonant frequency is not practicable. Therefore, during the initial warm-up period, the RF system is run in the self-excited mode. First there is a brief excitation period when the transmitter is driven from the frequency synthesizer. Once the resonator has developed a few kilovolts, the transmitter input is switched over to a signal derived from a probe in the resonator. By keeping the phase around the oscillatory loop correct, the system will free-wheel at the instantaneous resonator frequency. Amplitude-limiting circuits placed in the signal path prevent a runaway condition, and the resonator voltage regulating loop operates normally.

Thus the self-excited mode allows the resonator to be brought up to full power regardless of the initial frequency excursions which occur (see Fig. 1). Once the self-excited frequency has drifted within the range of the tuning system, the driven mode may be restored, with the frequency synthesizer determining the operating frequency. The resonator tuning plungers handle small drifts and allow a narrow range of tuning for optimizing the cyclotron.

Resonator RF Probes

The first requirement for fine regulation of the resonator voltage is a reliable voltage measurement. The measurement stability limits the accuracy with which the voltage can be regulated. Both of the usual methods of obtaining an RF signal from the resonator have been tested: capacitive pickup at the high-voltage tip and inductive pickup near the short-circuit end using a loop. The first should give a more direct reading of the voltage, but changes in capacitance caused by movement of the resonator hot arm alter the probe's sensitivity. In practice, sparking at the tip has made these probes unreliable, and they have been abandoned in favour of the inductive loop. Here stability problems arise from thermal expansion of the loop and from hot arm vibrations which vary the characteristic impedance of the resonator and change the relationship between the magnetic flux and the tip voltage. As the movement of the 80 hot arms is somewhat random, there is probably significant cancellation of the latter effect. Nevertheless, stable voltage measurement remains a problem, and the extracted beam itself will have to be used as the final sensor when the critical stability of ±2.5 parts in 10^5 is needed for single-turn extraction.

Multipactoring

In a vacuum pressure of 10^{-7} Torr the resonator voltage must rise initially at a rate exceeding 400 V/µsec to avoid the occurrence of multipactoring.[2] If the rate of increase is too slow, as in Fig. 2, the voltage reaches a maximum of 2 kV in about 10 µsec. Multipactoring then produces heavy loading at the resonator tips, clamping the voltage near zero despite continued RF drive. Under these conditions the resonator presents a mismatched load to the transmitter. The problems of multipactoring and the resulting mismatch are solved by pulsing the RF power at low duty factor (2%) with steadily increasing amplitude until the voltage rises

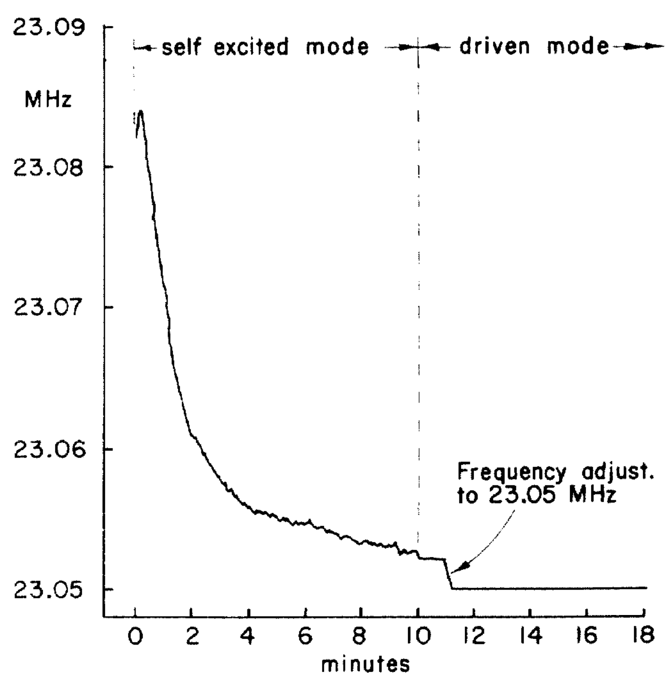


Fig. 1. RF system frequency vs time after turn-on at 52 kV.

rapidly enough to exceed the multipactoring range before the secondary-emission electron current can build up. Fig. 3 shows the leading edge of the pulse just overcoming multipactoring with an initial rise of 440 V/µsec, while at 500 V/µsec no sign of multipactoring is seen (Fig. 4). As the resonator time constant is 80 µsec, the pulse power level must be sufficient to produce a peak voltage of 80 µsec × 0.4 kV/µsec = 32 kV. Fig. 5 shows the complete 1 msec pulse reaching 40 kV with a power input of 180 kW. Note the effect of multipactoring on the last few kilovolts of the trailing edge. When the driving frequency is detuned from the resonator frequency the initial voltage rise remains the same, although the maximum voltage during the pulse is lower (Fig. 6). In fact it is possible to pulse through multipactoring with the driving frequency set as much as 30 kHz away from the resonator frequency, owing to the rich spectrum of sidebands produced when the RF is pulsed.

Control System

The RF control system embodies all the circuitry needed for the following primary functions:

1. Pulsing through multipactoring, with automatic switching to CW
2. Resonator voltage regulation by either
   a) transmitter input drive control, or
   b) screen modulation of a transmitter stage
3. Self-excited mode operation with automatic tuning of the operating frequency
4. Driven mode operation with automatic resonator tuning

For convenience, the circuitry is divided between a number of modules as indicated in the block diagram of Fig. 7. Their functions are described below.

Logic Unit

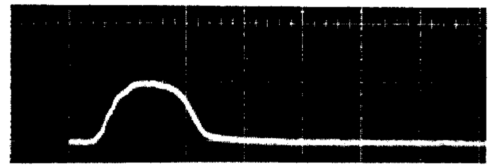
At the heart of the control system is a Logic Unit, through which the operator may start and stop RF operation and select the operating mode. The Logic Unit receives data from the other modules and activates their various functions. It also provides interfacing with the CAMAC link to the main cyclotron control console.

RF Unit

The RF Unit handles the input drive signal to the transmitter. The drive is turned on and off in response to a signal from the Logic Unit, and the drive amplitude is varied according to a drive control signal developed by the RF Drive Controller module. The RF Unit selects either of two input sources to feed to the transmitter, the frequency synthesizer or the resonator RF sample, for the driven and self-excited modes, respectively. Again, the Logic Unit controls the signal selection. Phase shifters in the two input signal paths are modulated by control voltages from the Tuning Controller module. The phase of the resonator RF sample is varied to adjust the self-excited mode operating frequency; and in the driven mode the frequency synthesizer phase compensates for phase disturbances in the resonator voltage. Smooth transitions between modes are ensured by inhibiting the change-over unless a phase-frequency detector monitoring the two input signals at the selection point indicates to the Logic Unit that switching may occur.

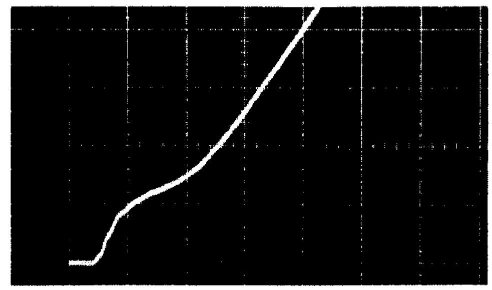
Resonator Voltage Detector (RVD)

The RVD converts a resonator probe RF signal to a dc level proportional to the peak resonator voltage. The circuit supplies a temperature-compensating forward bias to the hot-carrier rectifying diode, also improving



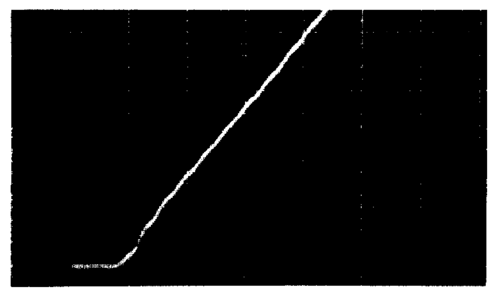
vert: 2 kV/div peak RF hor: 10 µsec/div

Fig. 2. Resonator voltage rise inhibited by multipactoring.



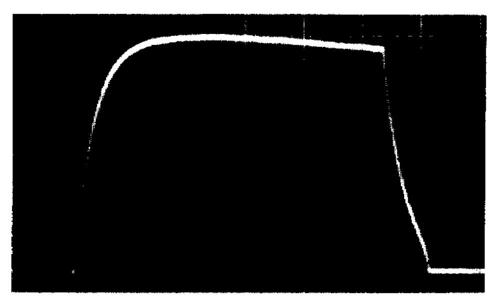
vert: 2 kV/div peak RF hor: 10 µsec/div

Fig. 3. Resonator voltage rise just overcoming multipactoring.



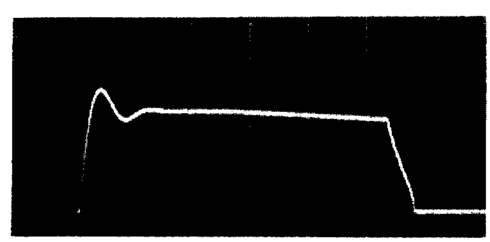
vert: 2 kV/div peak RF hor: 5 µsec/div

Fig. 4. Resonator voltage rise without multipactoring.



vert: 10 kV/div peak RF hor: 0.2 msec/div

Fig. 5. Resonator voltage pulse when driving at resonator frequency.



vert: 10 kV/div peak RF hor: 0.2 msec/div

Fig. 6. Resonator voltage pulse when driving 5 kHz off resonator frequency; transmitter input as in Fig. 5.

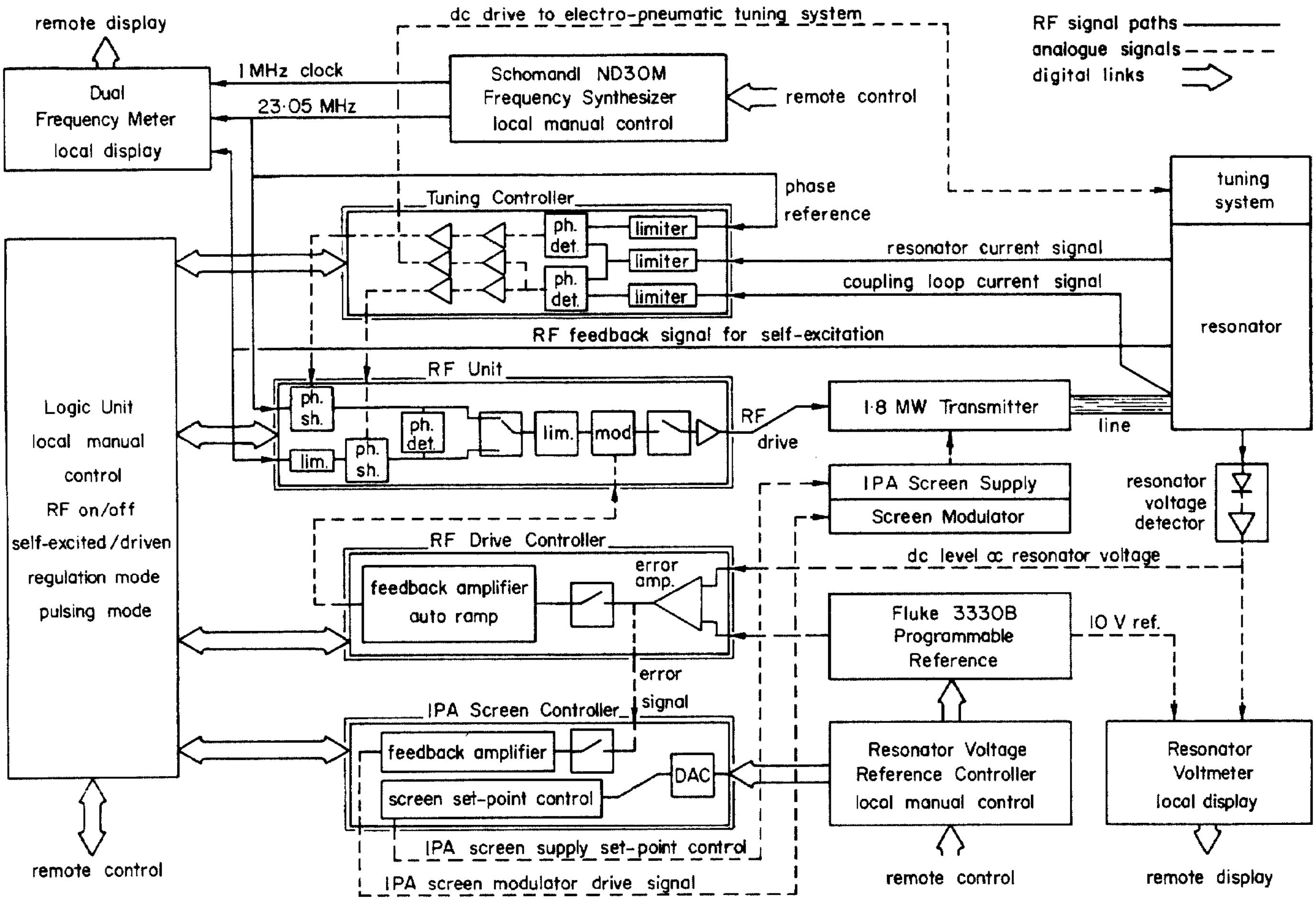


Fig. 7. Simplified block diagram of the RF control system.

its linearity at low RF levels. A buffer amplifier sets the RVD calibration and drives 200 ft of shielded cable with a 1 MHz bandwidth and a slew rate of 10 V/µsec. The overall stability of the RVD is better than ±5 V referred to the resonator tip (5 parts in 10^5).

RF Drive Controller

This module generates the drive control signal fed to the RF Unit. With the resonator voltage regulating loop closed, the drive control signal is developed by a feedback amplifier chain from an error signal produced by comparing the RVD output with a stable reference voltage. The response characteristics of the feedback amplifier are shaped to ensure that the loop is stable and yet has high gain at frequencies where the troublesome disturbances occur. Lead-lag compensation is used, the lead compensating the break at 2 kHz introduced by the resonator time constant, and the lag giving increasing gain at low frequencies. A further lead-lag introduced between 600 Hz and 6 kHz increases the low frequency gain by another 20 dB while leaving the loop unconditionally stable for a gain crossover (0 dB loop gain) below 50 kHz. Phase shift caused by delay in the RF chain imposes a limit of about 50 kHz on the loop bandwidth which can be attained.

To start RF operation, the RF Drive Controller ramps up the RF drive to find the correct operating level. At first the drive is pulsed by the RF Unit to pulse through multipactoring. Once the resonator voltage builds up to a few kilovolts, the pulsing is stopped. CW drive continues to increase until the resonator voltage comes within 1 kV of the set reference level. Then the ramp is stopped and the feedback loop closed. This ramp-up feature has proved quite indispensable in limiting pulsed operation to the minimum power level required to overcome multipactoring, and in producing a smooth rise in resonator voltage up to the set reference level with no overshoot. If resonator voltage is lost because of a spark, the Logic Unit puts the system back into pulsed operation, while the drive is clamped at a lower level and ramped up again as before. Using this technique, overdriving and tripping of the transmitter are avoided.

Intermediate Power Amplifier (IPA) Screen Controller

During normal regulated drive operation, the IPA Screen Controller automatically sets the voltage applied to the screen grid of the transmitter's IPA stage as a function of the resonator voltage reference level. Thus the transmitter gain is adjusted according to the power level required, keeping the input drive signal and also the voltage regulating loop gain essentially constant over the full 10 kV to 100 kV resonator voltage range.

The IPA Screen Controller also provides an alternative method of closing the resonator voltage regulating loop. The transmitter input stages are driven into saturation so that their noise contribution is virtually eliminated; the IPA Screen Controller then drives a wideband modulator in the IPA screen circuit in response to the resonator voltage error signal. The screen control mode is used when amplitude modulation noise on the resonator voltage must be minimized for separated turn extraction of the beam. Once again, the Logic Unit programs the change-over between control modes.

Tuning Controller

The purpose of this module is to ensure that the resonator is powered at its resonant frequency. A tuning error signal is developed by measuring the phase between the current flowing in the resonator and the coupling loop current. This phase is exactly 90 deg when the driving and resonator frequencies are equal, and varies with tuning error at the rate of 3 deg/100 Hz. The tuning error signal is used during self-excited operation to drive a phase shifter in the RF Unit and so control the system frequency. In the driven mode the resonator tuning system[3] is actuated to minimize the tuning error signal. The Tuning Controller also closes the resonator voltage phase stabilizing loop which comes into operation in the driven mode, using the frequency synthesizer as phase reference. The Logic Unit controls the activation of the three tuning feedback loops.

Instrumentation

In addition to the functional modules described above, the RF control console contains a digital voltmeter to display the resonator voltage and a dual digital frequency meter to indicate the synthesizer and resonator frequencies. Both these devices provide digital outputs to the CAMAC link for displaying the parameters on the cyclotron console. The CAMAC system also gives the cyclotron operator control over the synthesizer frequency and the resonator voltage reference. The only other RF control functions required at the cyclotron console are RF on/off and driven/self-excited mode selection.

Transmission Line Scanner. Although the three adjustable capacitors on the standing-wave line may be set in many ways to match the coupling loop to the 50 Ω flat line, as indicated by minimum reflected power at the RF amplifier output, only one tuning condition gives the correct standing-wave pattern. The standing-wave ratio should be high enough so that this section of line acts as a buffer between resonator and transmitter, but not so high as to cause excessive power dissipation in the line or to exceed the capacitor voltage ratings. In order to monitor the standing-wave, 40 RF probes are installed at 1 ft intervals along the line. A multiplexer scans the rectified probe voltages and generates the histogram display of Fig. 8.

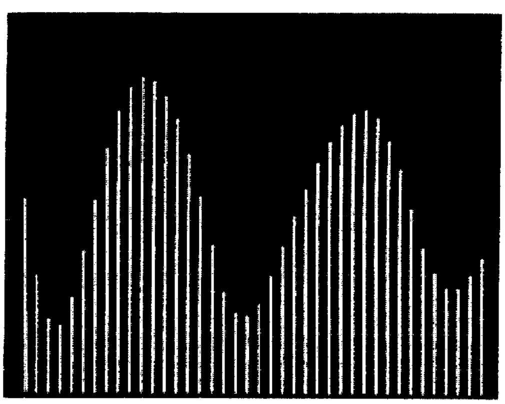


Fig. 8. Voltage distribution on the standing-wave line.

RF Control System Performance

During the first two months of operation at TRIUMF there have been no beam instabilities which could be attributed to accelerating voltage disturbances. When eventually single-turn extraction is attempted, voltage and frequency stabilities of ±2.5 parts in 10^5 and ±7.5 parts in 10^8, respectively, will be required. The latter is already available from the Schomandl ND30M frequency synthesizer. With regard to voltage stability, preliminary beam measurements have been of limited resolution and show merely that variations do not exceed 2 parts in 10^3. Variations in the resonator's characteristic impedance caused by vibration of the hot arms at their mechanical resonant frequency (5 Hz) produce estimated voltage fluctuations of ±6 parts in 10^5. If necessary the long-term stability could be improved with an auxiliary regulating loop, using the extracted beam to detect its own energy fluctuations.

The amplitude modulation noise, for modulating frequencies above 20 Hz where probe sensitivity fluctuations do not occur, is measured by observing the error signal. Up to 2 kHz the noise tolerance allows amplitude disturbances at -92 dB with respect to the resonator voltage level. Above 2 kHz the tolerance is relaxed linearly with frequency. After passing through an appropriate weighting filter, the error signal shows a noise level of -82 dB in the RF drive control mode, and -90 dB when screen control is used. Further improvements in the gain-bandwidth of the feedback loop are expected to give the desired figure of -92 dB or better.

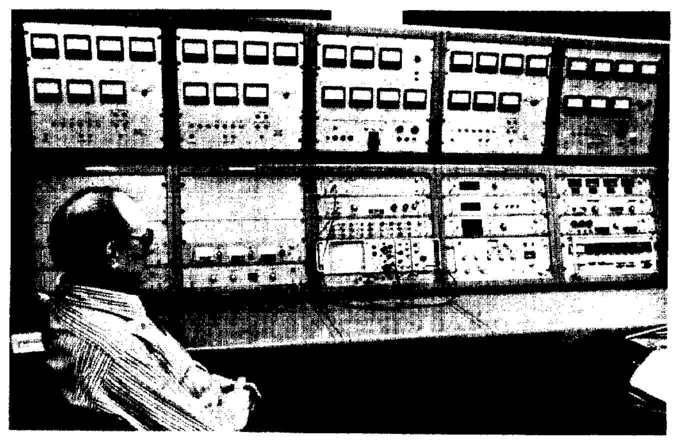


Fig. 9. The RF system control console. The top row of panels contains metering for the transmitter; the control modules are below.

Conclusion

The basic concept and design of the RF control system described above arose from experience gained with the central region cyclotron.[4] During nearly three years of subsequent development the equipment has demonstrated considerable flexibility in facilitating resonator tests both in air and under vacuum, and at power levels ranging from 0.5 W up to the full capacity of the RF system.

More recently, the RF controls have been refined to the point where the RF system runs unattended after the initial twenty minute period required to reach the driven mode, thus greatly simplifying cyclotron operation.

References

1. R.L. Poirier and M. Zach, 'TRIUMF RF System', IEEE Trans. Nucl. Sci., submitted to this Conference.
2. J.R. Richardson, 'Sector Focusing Cyclotrons', Progr. Nucl. Tech. & Instr., 1, 57 (1965).
3. K.H. Brackhaus, 'The Generation and Control of 1.5 MW of RF Power for the TRIUMF Cyclotron', Ph.D. thesis submitted to Univ. of British Columbia 1975.
4. E.W. Blackmore et al., 'TRIUMF Central Region Cyclotron Progress Report', Proc. 6th Int. Cyclotron Conf., AIP Conf. Proc. #9 (AIP, New York, 1972) 95.