IMPROVEMENTS IN THE ORIC RF SYSTEM*

S. W. Mosko and N. F. Ziegler
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Summary

The Oak Ridge Isochronous Cyclotron has been operating since January 1963. Initial experience with the rf system was enlivened by destructive sparking and general instability at the upper end of the rf tuning range. A network of protective devices developed during the past two years almost eliminates spark damage and improves the stability of the system. A multi-stage rf voltage regulator was also developed and installed.

Introduction

The Oak Ridge Isochronous Cyclotron is a fixed-frequency AVF machine with variable particle and energy capability. The MOPA rf system is continuously tunable from 7.3 to 22.1 Mc/s and has a power output in excess of 300 kW.

The block diagram in Fig. 1 shows the amplifier chain with some of the automatic tuning devices, the rf level regulator, and the transient control network. The master signal generator uses a phase-locked oscillator and supplies a 3-V, 120-mW signal with frequency stability of 1 pp 10^6 to the amplifier chain. The first three amplifier stages are combined in a single unit known as the intermediate amplifier. The IA has automatic tuning and its output is regulated at 300 V rf peak.

The 4CX5000A driver amplifier (DA) supplies the 2 to 4 kW drive signal required by the RCA 6949 power amplifier (PA). Both stages are grid driven amplifiers with automatic tuning. The PA is coupled to the resonator through a "drive capacitor" and a short transmission line (less than $\lambda/4$) called the "drive line."

The PA power output, and thus the dee voltage, is controlled by modulating the grid bias of the DA. The bias voltage developed across the DA grid resistor is controlled by any one of three 6CA7 tubes in series with the bias supply. V6104 (see Fig. 1) is the output stage of the rf regulator, V6401 is the transient control tube, and V6402 controls the bias when the rf regulator is off (manual operation). Normally, two of the control tubes are cut off.

History of Operation

The rf system was put in operation in January 1963, but the rf level regulator and the transient control circuitry were not added until September of 1963. Initially, there was heavy sparking on the drive line; the feedthrough bushing (vacuum seal) was broken on several occasions. The bushing is approximately half-way between the PA plate and the drive capacitor. The sparking probably resulted from high rf voltage developed in the PA plate circuit whenever transient conditions in the resonator caused sufficient detuning to unload the PA. An early version of the transient control network caused a momentary interruption of rf excitation whenever a loss of dee voltage was detected. The addition of several other fault detectors has improved the network considerably and allows the use of the rf regulator.

Incentive for installation of the rf level regulator came from expected improvement in accelerated beam quality and improvement of rf system stability. The latter was expected since the regulator would prevent sudden increases in dee voltage that could lead to sparking.

Transient Protection Circuitry

The transient protection system is a group of fault detectors and limiters which, when triggered, reduce the rf excitation level through a reduction of bias voltage on the transient control tube (V6401). A set of clamping circuits, triggered whenever V6401 grid bias is less negative than either V6402 or V6104 grid bias, locks the automatic tuning servos and holds the dee rf voltage regulators in an unsaturated condition.

There are seven limiters in the system; each is similar except in regard to the transient detector with which it is used. Each limiter is diode-coupled to the transient control tube grid circuit, (the transient control bus). Each of the coupling diodes is reverse-biased, except when the respective limiter drives the transient control bus more positive than its normal -18 V bias level. The limiter circuit demanding the greatest reduction of rf excitation at any given instant controls the excitation level.

The PA plate rf limiter prevents the plate rf voltage from exceeding the dc voltage whenever, typically, a loss of PA load results from detuning of the resonator. Without the limiter, the voltage on the unloaded PA plate circuit swings high enough to initiate drive-line sparking.

The PA plate rf level limiter circuit is shown in Fig. 2. The rf and dc voltage levels

*Research sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

are compared in differential amplifier Q31 and Q32. Normally Q32 is cut off. As long as the collector of Q is +12 V, Q34 is cut off and the output voltage of the limiter is -28 V. If the PA rf voltage becomes equal to or greater than the dc level, Q34 saturates and the transient control bus is grounded through the collector of Q34. The trigger circuit comprising Q35 and Q36 turns on indicator light I-31 whenever the collector of Q34 swings more positive than -8 V.

A voltage-tuned audio oscillator and loud speaker is connected to the transient control bus. The speaker, located in the control room, emits a rather unpleasant screech when a fault occurs. The cyclotron operator is thus "encouraged" to correct the fault.

The "air drive line spark detector" is a trigger circuit which completely cuts off the rf excitation when drive line sparking occurs. A pair of strategically placed photoelectric detectors are used to sense visible light resulting from rf sparking on the air side of the drive line feed-through bushing. The spark detector minimizes drive line damage when sparking does occur.

The "vacuum drive line spark detector," also a trigger circuit, senses sparking conditions on the vacuum side of the drive line bushing. The detector is a high voltage electrode located in the vacuum system near the feedthrough bushing. Leakage current to ground through the ionized residual gas, resulting from sparking, triggers the limiter. The vacuum drive line spark detector also serves as a means to prevent operation of the rf system under poor vacuum conditions.

The PA high voltage interlock is a trigger circuit which prevents operation of the rf system in the absence of PA plate dc voltage. The circuit is used mainly for protection of the PA tube. The trigger cuts the rf drive off whenever the crowbar fires, and it helps prevent excessive PA grid dissipation, which might occur if the PA plate voltage was accidentally lost.

The PA plate current limiter holds back the rf excitation sufficiently to keep the PA plate current below the maximum allowable level. This prevents unnecessary firing of the crowbar and operation of the HV circuit breakers.

The PA grid current limiter holds the grid current below the maximum rated value for the tube.

Both the PA plate and the PA grid current limiters help protect the PA tube from damage which could occur if the PA plate circuit were inadvertently detuned. These limiters are also particularly useful in their ability to prevent the rf regulator from overdriving the PA.

The DA grid bias limiter compares the DA grid bias level to the peak rf drive voltage. The limiter prevents the DA from drawing grid current and thereby developing self bias. This limitation is essential for stable operation of the rf regulator.

The Regulator

The rf regulator consists of a three-loop feedback system as shown in Fig. 1. The feedback signals are proportional to DA plate rf voltage, the PA plate rf voltage, and the dee rf voltage. Errors are amplified and applied to the grid of the DA through the regulator control tube V6104.

Design of the regulator was complicated by the fact that part of the loop is a carrier system (the rf amplifiers) employing high Q tuned circuits, and by large non-linearities such as sparking in the dee system. The design is thus compromised by the requirement that the system remain stable over a wide range of operating conditions.

The response of a tuned circuit operating at resonance, to a modulating signal of frequency ν is $1/(1 + j\nu/\nu_c)$, where $\nu_c = f_c/2Q_c$, and f_c is the carrier or resonant frequency. Since the operating frequency of the cyclotron is variable over the range of 7.3 to 22.1 Mc/s, the transfer functions of the rf amplifiers for modulating signals also vary over wide ranges. As an example, it is estimated that ν_c for the resonator varies over a ten-to-one range. The transfer functions of the regulator amplifiers have been restricted to provide stability over the complete frequency range.

Circuit diagrams of the regulator amplifiers are shown in Fig. 3. The approximate transfer functions with the modulating frequency ν in kc/s are:

$$G_1 \approx 75 \frac{(1 + j\nu/0.06)(1 + j\nu/0.75)}{(1 + j\nu/0.01)^2(1 + j\nu/500)}$$

$$G_2 \approx 75 \frac{(1 + j\nu/6)}{(1 + j\nu/0.08)(1 + j\nu/500)}$$

$$G_3 \approx \frac{-200}{(1 + j\nu/0.2)(1 + j\nu/300)}$$

A circuit diagram of a typical rf detector, or de-modulator, is shown in Fig. 4. The detectors are located in the cyclotron vault while the regulator amplifiers are remotely located some 100 feet away. This particular detector circuit has a fairly low output impedance so that the regulator response is not seriously affected by the long signal cables. The detectors normally operate with a dc grid bias such that the tube conducts only on the positive rf peaks.

Each regulator is equipped with a clamp triode on its input circuit. These clamps, as previously mentioned, hold the regulator amplifiers in a condition corresponding to minimum dee rf voltage. The clamp signals decay slowly so that the regulator regains control without producing serious overshoot in rf excitation. Another function of the clamp circuits is to hold the regulator amplifiers in a condition corresponding to maximum dee voltage when the rf excitation is manually controlled (unregulated). This protects the detectors from being overdriven and keeps the regulator loop unsaturated so that it is possible to switch from regulated to unregulated operation, or vice versa, without interrupting the rf excitation.

The regulator reduces rapid variations in dee voltage to about 0.3% and holds the average value to about 0.1% over short periods (several minutes). Control of slow variations is limited primarily by drift in the dee-tip voltage divider and detector. When the rf excitation is operated unregulated, the dee rf voltage is modulated some 20% to 30% by mechanical vibration in the resonator and by the ripple in the PA plate dc power supply.

Conclusion

Following the installation of the regulator and the transient protection network, the ORIC rf system has proved to be quite reliable. Damage to equipment by rf sparking is now quite rare. The regulator, originally considered a useful accessory, is now considered essential to cyclotron operation. In fact, it is very difficult to produce an external ion beam without the help of the rf regulator.

An example of the effect of the regulator on beam quality is shown in Fig. 5. The curves show beam attenuation in the last few orbits before deflection and after the beam is deflected. The lower curve was made without the regulator while the upper curve was made with the regulator. Orbit bunching due to radial oscillation of the beam is observable only when the rf regulator is in operation.

References

1. R. J. Jones, et al, Nucl. Instr. and Meth. 18, 19 (1962).

2. S. W. Mosko, et al, International Conference on Sector-Focused Cyclotrons, CERN 63-19 (1963).

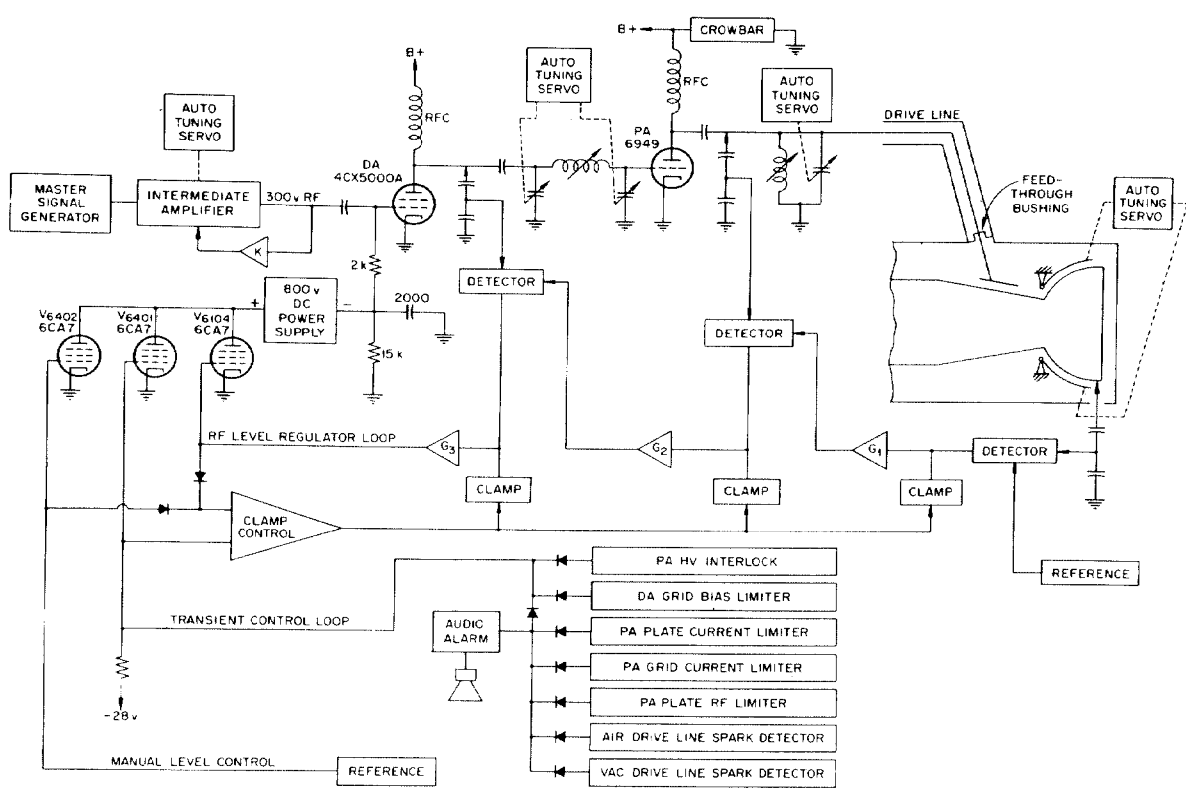

Fig. 1. Block diagram of ORIC rf system.

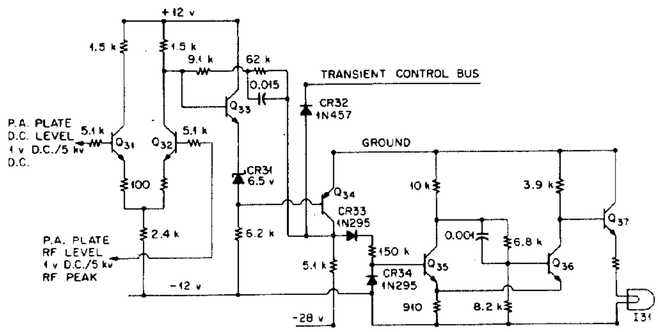

Fig. 2. PA Plate rf level limiter.

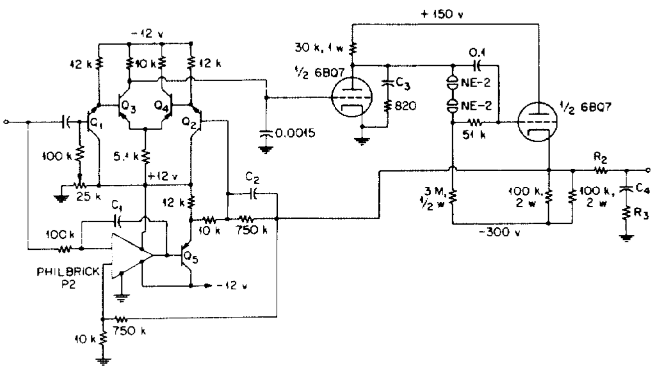

Fig. 3. (a) Amplifier G_1 and G_2.

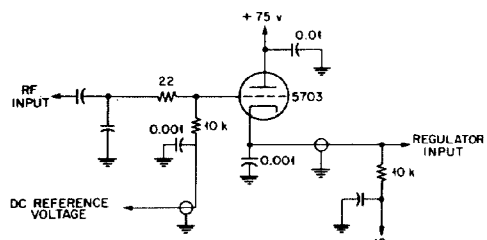

Fig. 4. Typical rf detector.

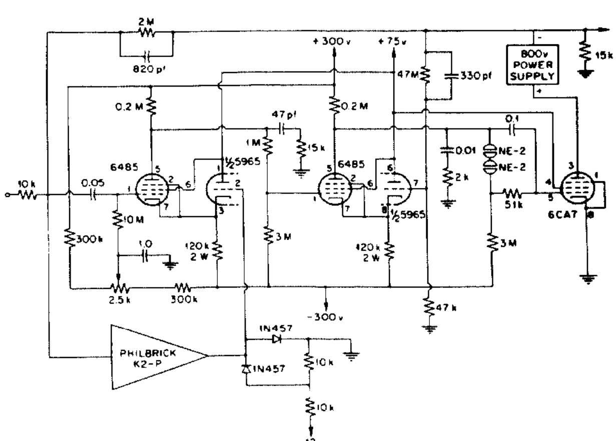

Fig. 3. (b) Amplifier G_3.

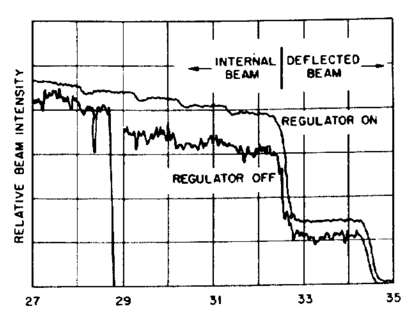

Fig. 5. Effect of regulator on beam quality.