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GYROTRON ANODE MODULATION OF THE ELECTRON CYCLOTRON RESONANT HEATING (ECRH) FROM dc TO 50 kHz ON THE TANDEM MIRROR EXPERIMENT-UPGRADE (TMX-U)

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Abstract

This paper describes control of gyrotron microwave energy output by modulation of gyrotron anode voltage. At present, Electron Cyclotron Resonant Heating (ECRH) uses five gyrotrons on the Tandem Mirror Experiment-Upgrade (TMX-U) for plasma heating. One is in the 10 kG region of each end plug, one at the 5 kG region of each end plug, and one is used for central-cell heating. Also described are the design and operation of the anode modulation system. The operating advantages of gyrotron anode modulation include power balance, independent control of each gyrotron, an ability to modulate microwave output power up to 50 kHz, and gyrotron tuning. The performance results of anode modulation will be discussed.

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Introduction

The TMX-U uses five 28 GHz, 200 kW, Varian VGA-8050 gyrotrons for plasma heating. These gyrotrons are powered by two 80 kV modulated power supplies built by Universal Voltronics Corporation. The two gyrotrons for heating in the outer 10 kG regions are connected to the first modulator. The two gyrotrons for heating the 5 kG regions and the one for heating the inner 10 kG region are connected to the other modulator. Figure 1 is a block diagram of the system configuration.

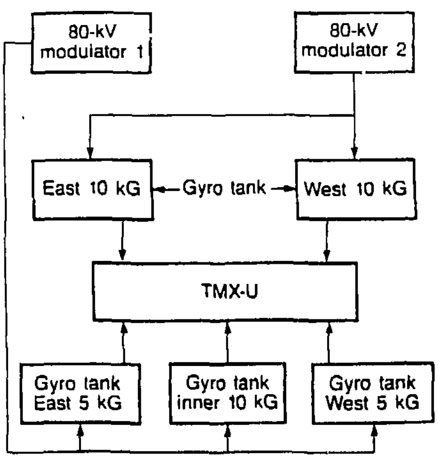

Figure 1. ECRH System Block Diagram.

In the original system configuration, control of the gyrotrons was through the 80 kV modulators. All of the safety interrupts protecting the gyrotrons from faults were made through the high-voltage modulator. The anode voltage level was set by a tap changer and a resistor network. Figure 2 is a block diagram showing how the system was first configured.

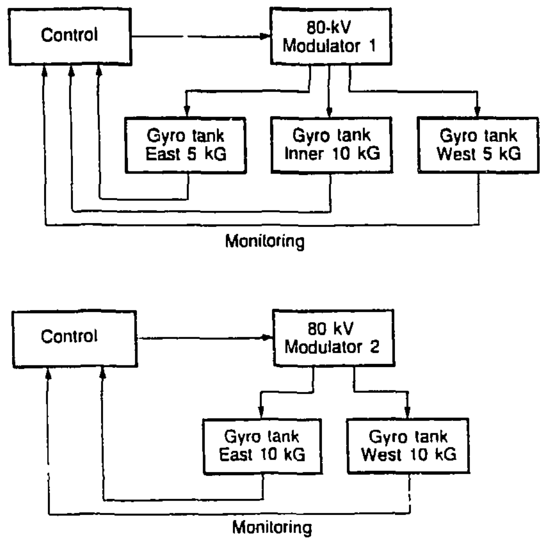

Figure 2. Fixed Anode Voltage System Configuration.

The disadvantages of operating the system in this configuration are as follows:

The failure of one gyrotron during a shot, and the associated rolling back of the modulator, terminates the operation of all of the other gyrotrons on that modulator.

Power balance between gyrotrons is difficult to achieve. This is because the same high voltage supplied to all gyrotrons may be optimum for one but not for the others. Consequently, some of the gyrotrons operate on the edge of mod shifting, resulting in erratic performance.

Output power control is difficult, due to the high voltage limitation mentioned above. Six gyrotron magnet power supplies and the filament current for each gyrotron must be adjusted to control power output.

A gyrotron anode modulation system was designed and built to overcome these disadvantages. The system provides other operating advantages, including:

1. Rf power modulation from dc to 50 kHz. ECRH energy drives the plasma potential, and it is believed that the modulation of ECRH power may cause a drift-pump action for the low energy ions trapped in the thermal barrier.

2. Each gyrotron can be operated independently of the other gyrotrons.

3. Rf power can be ramped up or down during shots. There has been some indication that high ECRH power in the 10 kG region of the machine causes the plasma density to drop during long shorts. An ability to ramp the ECRH power will help in determining if this is the case.

In the new configuration, which uses anode modulation, all gyrotrons are controlled independently from the console rather than by the high-voltage modulator. In the event of faults, all safety interrupts for the gyrotrons are generated by their own monitoring circuits as a first line of defense. This prevents the output of the other gyrotrons connected to a common high-voltage modulator from terminating in the event of a fault in one gyrotron. If interrupt circuits of a gyrotron fail to terminate its operation during a fault condition, the main control console halts the operation of the high-voltage modulator. Figure 3 is a block diagram of this system.

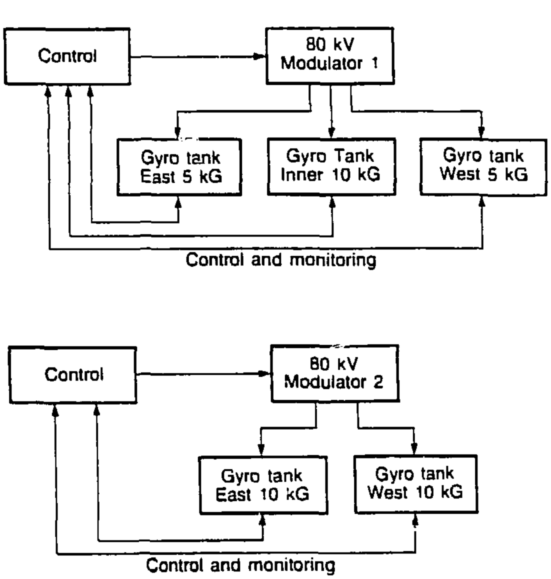

Figure 3. Modulated Anode Voltage System Configuration.

Gyrotron Anode-Modulation System

The introduction briefly described the workings of the old and new systems. Here we examine the system design. Specifications are give in Table 1.

Table 1. Anode Modulation Design Specifications

Gyrotron Frequency	28 gHz
Cathode Voltage	80 kV max.
Anode Voltage	30 kV max.
Cathode Current	8 A max.
Anode Voltage Modulation	±2.5 kV
Rf power modulation	75% @ 200 kW
Rf Modulation Rate	dc -50 kHz

Originally, the gyrotron anode voltage was set by a resistive string. Figure 4(a) represents this type of system. Changing anode voltage settings required opening the gyrotron tank and resetting the tap changer to a new voltage level. Then the system had to be made up and operated to check the new voltage level. The cathode voltage was measured and recorded while the system was running. Next, the Anode voltage was measured and subtracted from the cathode voltage. (For example, a cathode voltage of 80 kV to return, minus an anode voltage of 55 kV to return, equaled the anode voltage of 25 kV.) As one can see, the gyrotrons anode voltage is a function of the cathode voltage and will vary as the cathode voltage changes and to adjust it was time consuming and difficult. As shown in Fig. 4(b), the anode modulation system replaces the tap changer and its resistors with a Thompson CSF TH 5186 tetrode vacuum tube. The tetrode and resistors R1, R2 now form a resistive divider with the TH 5186 tube as an active element. The current flow through the tube controls the voltage drop across R1 (250 kΩ ± 1%). A feedback signal representing the voltage drop across R1 can be fed back to a control circuit to maintain the voltage drop across R1, regardless of changes in the cathode voltage.

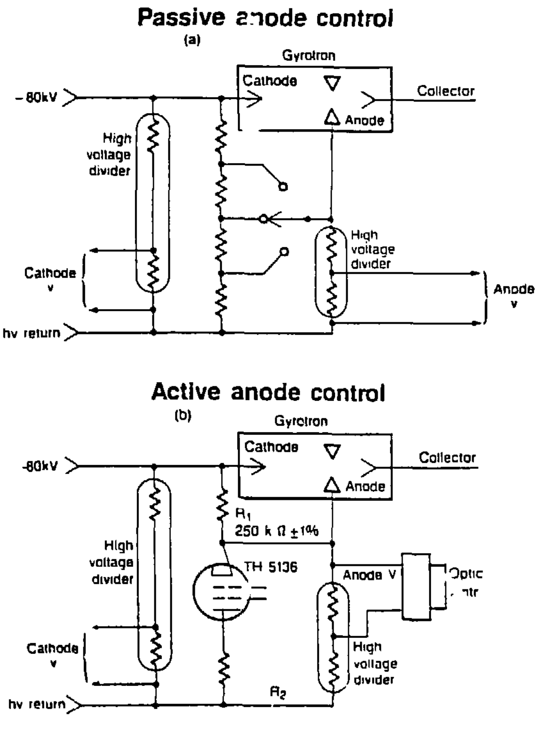

Figure 4. Types of Anode Control Circuits.

Gyrotron Anode Modulation Control

The gyrotron anode modulation control is shown in Fig. 5. The anode voltage level set signal is received by the F/O transmitter/receiver board and converted to a 0 to 5 V dc reference signal, which is applied to the reference amplifier on the anode modulator control board. A 2.5 V reference is equivalent to 25 kV anode to cathode of the gyrotron. The output of the reference amplifier and the feedback amplifier is fed to a differential amplifier that amplifies the difference between them. The output of the differential amplifier is maximum at turn on because the feedback signal is zero. The output of the differential amplifier is maximum b ause the feedback signal is zero. The differential amplifier's output connects to one side of a solid-state analog switch. When the switch is open, the gyrotron is off and the cathode-to-anode voltage is zero. When the switch is turned on by a TTL level voltage from the F/O receiver-transmitter board, the analog voltage is transferred from its input to its output terminal. The F/O transmitter/receiver board experiences a light pulse for the duration of the requested pulse and converts it to a TTL level pulse. The output of the switch connects to the input of the control grid driver's buffer.

The control grid driver is composed of two pnp, high voltage transistors connected in a modified cascode arrangement. The grid driver regulates the -700 V control grid bias. Driving the grid in a positive direction turns on the tetrode, causing current to flow in R1, R2, and the tube circuit. Current flowing in this circuit produces a voltage drop across R1. One side of R1 connects to the cathode of the gyrotron; the other side connects to the cathode of the tetrode tube and the anode of the gyrotron. Therefore, the voltage drop across R1 equals that across the anode and cathode of the gyrotron. The anode voltage sense resistor monitors the anode voltage level and returns a voltage proportional to its amplitude, to the feedback amplifier on the anode modulator control board. As the anode voltage feedback rises, the output from the differential amplifier falls until the feedback signal equals the reference voltage. This maintains the anode voltage at the requested level. Rf modulation is achieved by amplitude modulating the TH 5186 control grid voltage.

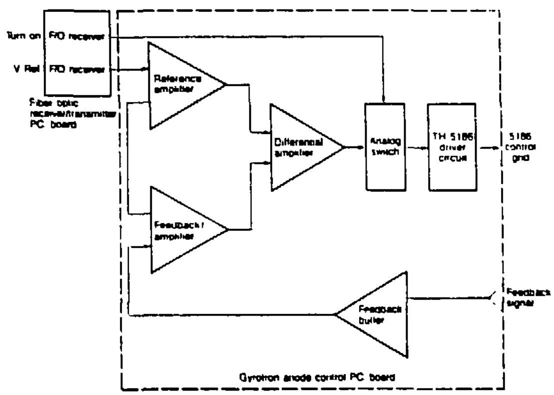

Figure 5. Gyrotron Anode Modulation Control Block Diagram.

Fiber Optic Control/Data Links

The analog control link is composed of a Burr-Brown FOR-110 receiver and a FOT-110 transmitter. These optical devices have analog input/output capabilities with peak-to-peak amplitude modulation (AM) of 1.1 V over frequencies up to 1 mHz. [See Fig. 6(a).]

Resistor R1 sets the bias voltage at the AM input terminal to 1.3 V. This sets the output signal of the fiber optic transmitter to zero with 2.0 volts input at D1. Biasing the transmitter's input results in a linear output. For a 3 V input, with a digital voltmeter connected to the output of the receiver, R2 is adjusted for -1 volt on the meter. The buffer amplifier inverts this voltage and produces a gain of five. The reference voltage output is 0 to 5 V dc, with 1 V = 10 kV anode voltage. Input to the F/O transmitter is sent from a LeCroy 8601 function-generator module. The function generator is capable of giving a dc offset voltage with an amplitude-modulated signal riding on it.

Figure 6(b) shows the turn-on, F/O control link. The transmitter's TTL data-input terminal is driven high for the duration of a shot. This signal keeps the turn-on receiver's output high until the shot ends.

The data-transmitter F/O link is sketched in Fig. 6(c). The TTL input of the transmitter is controlled by a 0 to 1 mHz voltage-to-frequency converter. The transmitter's output proceeds to the control console over fiber optic cables. A fiber optic receiver in the control console receives the frequency signal.

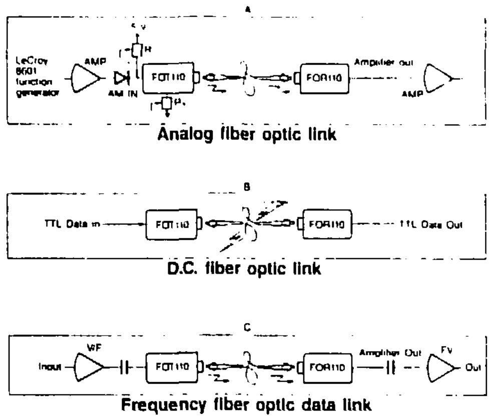

Figure 6. Types of Data Links Used in System.

Regulation Feedback Circuit

An instrumentation amplifier was chosen for its high gain, high common mod rejection, and wide-bandwidth characteristics. The reference, feedback, and differential amplifiers make up the instrumentation amplifier, which has a gain of 100 and a bandwidth of 2 mHz. The wide bandwidth is needed to reduce the phase shift between the input reference signal and the feedback signal during the amplitude-modulated operation. The differential amplifier, the dominant pole in the control circuit, has its roll-off frequency set at 75 kHz to prevent the circuit from hunting during modulated operation. The feedback buffer provides impedance matching between the anode voltage sensor and the feedback amplifier. The voltage follower drives the voltage-to-frequency circuit that transmits the anode voltage level to the control console over a F/O data link. The analog switch transfers the output from the differential amplifier to the output-driver circuit for the duration of a pulse. The block diagram in Fig. 7 shows the regulation feedback circuit.

Output Driver

Figure 8 is a schematic of the output driver and its related circuitry. U9 is an inverting buffer amplifier used to drive the grid driver amplifier. The latter is composed of two pnp transistors connected in a modified cascode configuration. The cascode amplifier allows the cathode of the TH 5186 to

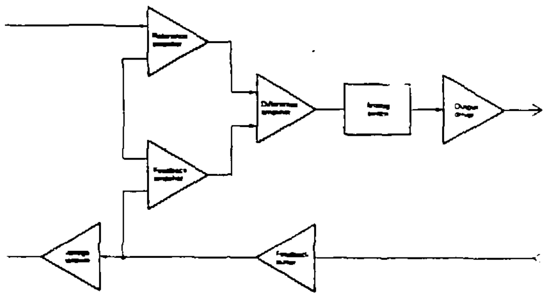

Figure 7. Regulation Feedback Circuit Block Diagram.

be referenced to the dc common of the anode modulator control chassis.

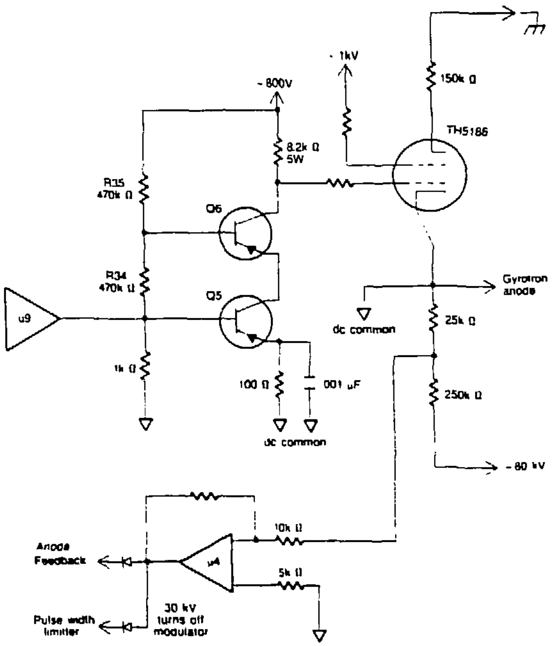

Figure 8. TH5186 Grid Driver CKT.

Description of System Operation

The high voltage output request is sent to the modulated power supply 1 millisecond before turning on the anode modulator. This charges the 150 ft of RF-22D coax cable before the gyrotron is turned on.

Upon powering up the system, the gyrotron tank sends an anode modulator-ready signal to the control console indicating that it is ready for operation. When the control console receives this ready signal, it enables the anode voltage request reference signal transmitter, sending a constant anode voltage request signal over a fiber optic link to the anode voltage request receiver in the gyrotron tank. The anode voltage request reference signal is left on during operation to insure it stabilizes.

When the gyrotron is to be turned on, an anode turn-on signal is sent to the fiber optic receiver/transmitter board. This signal is in the form of a light pulse that lasts for the duration of the requested shot.

The anode voltage and current levels are measured and processed by the anode modulator control board and the fiber optic receiver/transmitter board. They are then sent to the control console over fiber optic cables.

A block diagram of system operation appears in Fig. 9.

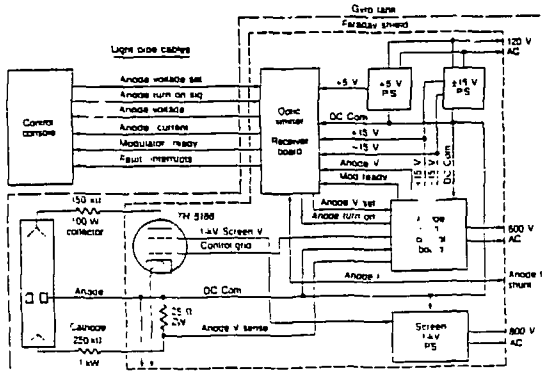

Figure 9. Gyro Anode Modulator Block Diagram.

Conclusions

To date, two of the gyrotron tanks have been modified to incorporate anode modulation, and one has been replaced by a new, smaller tank. These tanks, tested intensively, were found to perform as designed. We are now having an additional five of the new, smaller, self-contained gyrotron tanks built to replace the larger, old ones. The new, shorter tanks leave a greater distance between the gyrotron tank top and the bottom of the TMX-U vessel. This additional space will permit the installation of longer pulse tubes with their larger collectors.

The new tanks will have the electronic capability to control gyrotron filament voltage as well as monitor the current and voltage of the filament and cathode.

Mounting the anode modulation electronics inside the gyrotron tank avoids having to drive a long cable and its related capacitances with an alternating current.

It is expected that the gyrotron anode modulation system will improve reliability, flexibility, and gyrotron control. Many operating conditions that might not otherwise be achieved, such as independent output power levels, modulated Rf power, and staggered gyrotron operation, are now possible using the improved system flexibility.