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THE MASER EXPERIMENT

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SUMMARY

A wideband low noise preamplifier system will be utilized for the ATS series of satellites at the Mojave Tracking Station. This particular preamplifier was developed by the Advanced Development Division of Goddard Space Flight Center, and involves a travelling wave maser and a closed cycle helium refrigerator. It operates over the 4.065-4.195 gigahertz (Hz) band, with an effective noise temperature of less than 10°K. The functional maser system consists of the amplifier, a low noise header assembly, and a superconducting magnet. The antenna mounted support equipment includes the microwave pump, pump modulator, pump monitor, transfer switches, tunnel diode amplifier, and a noise source, as well as the closed cycle helium refrigerator. The major system components and their layout are shown in Figure 1.

The scheme of operation is as follows: the signal from the antenna is passed through the header assembly to and from the maser by C-band waveguides, and to the post-amplifier by coaxial cable. In the maser, 27 db of amplification is achieved, and an additional 10 db is provided by the post amplifier.

The equipment for controlling and monitoring the system is located in the Operations Building. Here are located the power supplies for all the components, with the exception of the closed cycle refrigerator, which is supplied with its own 440 v, 3-phase 10 kva supply directly at the antenna. The maser system performance characteristics are listed in Table I.

PERFORMANCE CHARACTERISTICS

Signal Frequency	4.065 - 4.195 GHz
Bandwidth	130 MHz
Gain	27 db
Noise Temperature	10°K max.

THE COMPONENTS

The Maser System

The maser input structure (header assembly), the maser structure, and the superconducting magnet are located within the closed cycle refrigerator in the antenna cone and form the maser magnet assembly. Not located within the refrigerator, but still in the antenna cone are the microwave pump assembly, the pump monitoring system, the noise source and transfer switch, and tunnel diode assembly. The refrigerator's expansion engines are located on the closed cycle refrigerator (CCR) and the compressors are mounted on the antenna structure. These are shown schematically in Figure 2, and will be discussed in detail.

THE MASER

The name "maser" is an acronym describing the device's operating principle: Microwave Amplification by Stimulated Emission of Radiation. The mechanics of stimulated emission was predicted by Einstein¹ in 1917; and a publication by Weber² in 1953 proposed that the phenomenon could be utilized as a gain mechanism. Since the conception of a practical three-level solid-state maser by Bloembergen,³ maser technology has progressed rapidly. The impetus for this accelerated research arises mainly from two characteristics of the maser: it is the most sensitive low-noise microwave amplifier available today, and it is a reliable device which can be ruggedly constructed.

Stated very briefly, the maser principle is as follows: When a paramagnetic ion is placed in a magnetic field, its electron spin systems may assume only the discrete energy states allowed by the principles of quantum mechanics. Under equilibrium conditions more electron spins will be in the lower than in the higher energy states, and to obtain maser action, this situation must be reversed. This population inversion is accomplished by pumping - that is, providing radiated energy from an external source of the proper frequency to elevate the electron spin systems in the lower energy levels to higher energy states. Such an inverted population can be used as a gain mechanism, since electromagnetic waves of the proper frequency, interacting with these excited electrons, will stimulate them to return to the lower energy levels, emitting photons of the same frequency. The latter add to the energy of the incident wave, which is thus amplified.

The most complex problem which had to be solved in the development of masers was the retention of the excited energy states, since atoms tend to return to their lowest energy states through spontaneous emission of radiation. The mechanism utilized in the microwave maser is the thermal isolation of the paramagnetic ions. At very low temperatures (e.g., that of liquid helium 4.2°K) these ions are substantially free of thermal agitation. This effective isolation extends the time that an ion may remain in an excited state.

The heart of the amplification is an iron doped rutile ($T_1 O_2 \cdot Fe^{+++}$) crystal. Some important characteristics of this crystal are:

1. Large zero field splitting.
2. Large inversion ratio.
3. Large spin density.
4. Short Recovery time.

To achieve high gains, the period of interaction between the crystal and the input signal wave must be as long as possible, and so the maser structure is essentially a slow wave circuit along which the rutile is distributed. A large slowing factor is achieved by using a meander line with a 12:12 copper to air ratio. This is shown in Figure 3.

THE SUPPORT EQUIPMENT

The maser receiver has input signals through two input waveguides, one from the receiving antenna, and one from the microwave pump assembly (Figure 2), supplying pump power at 55 GHz. This latter signal provides the energy for the population inversion in the rutile. The incoming received signal causes stimulated emission from inverted spin system, and thereby amplification is achieved. Gadolinium doped Yttrium Iron Garnet (YIG: Gd) is employed as a reverse isolator, to provide non-reciprocal forward gain and nonreciprocal reverse isolation. The reverse isolation must be great enough that the system will be unconditionally stable against any combination of input and output mismatch.

The transition between spin energy levels is strongly stimulated when the incident electromagnetic field is approximately circularly polarized. The propagating circuit is such that this field will have the circular polarization orthogonal to the direction of propagation. These waves exhibit an opposite sense of polarization above and below the circuit plane. Therefore, if an absorbing material of the proper polarization (a ferrite slab) is appropriately placed in this field, the backward wave is attenuated. In addition, the ferrite must be of such composition and dimensions that it will "track" (that is, when the magnetic field, and hence the operating frequency, is changed, the ferrite must provide absorption of the backward wave at the new field and frequency).

The Header Assembly

The primary function of the header assembly is to provide RF and electrical access to the maser and superconducting magnet. It is the input structure to the maser. It consists of two C-band waveguides for the input and output signals to and from the maser, and a third, V-band, waveguide to supply the pump power to the maser. The header assembly also provides the internal structural support to the refrigerator.

The Superconducting Magnet

The magnet is composed of seven segments, each segment being wound with a main coil of 1600 turns. In addition, each segment has a trim coil of 300 turns each. The main coils are connected in series, so that one current produces the same magnetic field throughout, this being the main magnetic field. The trim coils are used to vary the gain-bandwidth curve, in the following manner:

The magnetic field provided by the superconducting magnet is ± 50 gauss from the main 1.5 Kilogauss required for operation at 4 GHz. This is applied to the paramagnetic crystal distributed along the slow wave circuit. The magnet-maser configuration is shown in Figure 4. Once the center of the band is established, the current is manipulated to the individual trim coils, and the required gain and bandwidth is obtained. The maser can therefore be continuously tuned, by varying the current in the trim coils, thus varying the magnetic field and also by making necessary changes in the pump frequency.

The Pump Package

The pump provides the microwave power for pumping the maser, and so is the source of the power used in the amplification. It consists of a backward wave oscillator (powered by two B.W.O. power supplies), a modulator, a motor driven attenuator, directional coupler, and a detector, together with support equipment. The latter consists of an FC-75 fluoro chemical oil bath, used to maintain a constant temperature environment, blower to cool the oil, and a temperature sensor, which will activate a signal on the pump control chassis in the event of a temperature rise above a safe operating value.

In operation, four input voltages are applied to the B.W.O. elements, providing an output signal of 55 GHz. The output signal is fed through a motor driven attenuator and a directional coupler to the maser. The power fed to the maser may be adjusted from the pump control panel. The directional coupler contains a detector which samples the RF power; the detected signal is the relative pump power. It is amplified by the pump monitor, and displayed on the pump control chassis in terms of 0-100%.

A solid state unit provides 800 volts of modulation voltage on the B.W.O. reflector; the output of the modulator can be adjusted by adjusting the dc voltage to the unit. A multivibrator oscillator provides the 300 kc signal which passes through the first RF amplifier. This signal is amplified and sent to the driver, which is transformer coupled to the push-pull output amplifier.

Transfer Switch and Tunnel Diode Assembly

This assembly consists of three transfer switches, two tunnel diode amplifiers, and a detector. It provides post amplification for either the 4.2 GHz maser signal or for a test signal. In the operational mode the incoming maser signal may be switched to either of the two tunnel diodes, as determined by selection made of the Control Panel. The tunnel diode provides an additional 10 db of gain.

In test mode, transfer switch three is operated under two conditions. It may be used to switch an incoming test signal through either tunnel diode amplifier. It may also be used to test the maser system by switching a signal through the noise source, directional coupler, and maser and onto the tunnel diode amplifier. This signal is accessible at the patch panel in the control console.

Pump Monitor

The RF pump monitor consists of three dc amplifiers and a power supply, and provides amplification of test signals or detected pump power from the B.W.O. Two types of signals arrive at the monitor: (1) an incoming test signal goes through the tunnel diode assembly and is then amplified by the pump monitor; (2) in testing of the maser system, an incoming signal goes through the noise

tube, directional coupler, maser, and detector, and is then amplified by the pump monitor. Signals amplified by the pump monitor are available at the patch panel.

The pump monitor may also be used to amplify detected signals from the pump package. Detected pump power from the B.W.O. is amplified by one of the dc amplifiers and is then transmitted to the pump control chassis and indicated as relative pump power.

Noise Source

The noise source is a three-unit system, the noise tube, power supply, and remote keyer. When the maser noise temperature is being measured, the neon noise tube is energized, and the output noise fed through a cross guide 26 db coupler into the maser and to a tunnel diode amplifier. From the tunnel diode amplifier the signal is sent to a communications receiver which provides a 70 MHz IF output, and which is sent to the signal monitor receiver. The noise source provides relative day-to-day checks of the system noise temperature.

Refrigerator Equipment

A temperature of approximately 4.2°K is required for the maser and for the superconducting magnet. Refrigeration is achieved by a closed cycle refrigerator, composed of redundant expansion engines and dry-lubricated compressors which pressurize and circulate the helium.

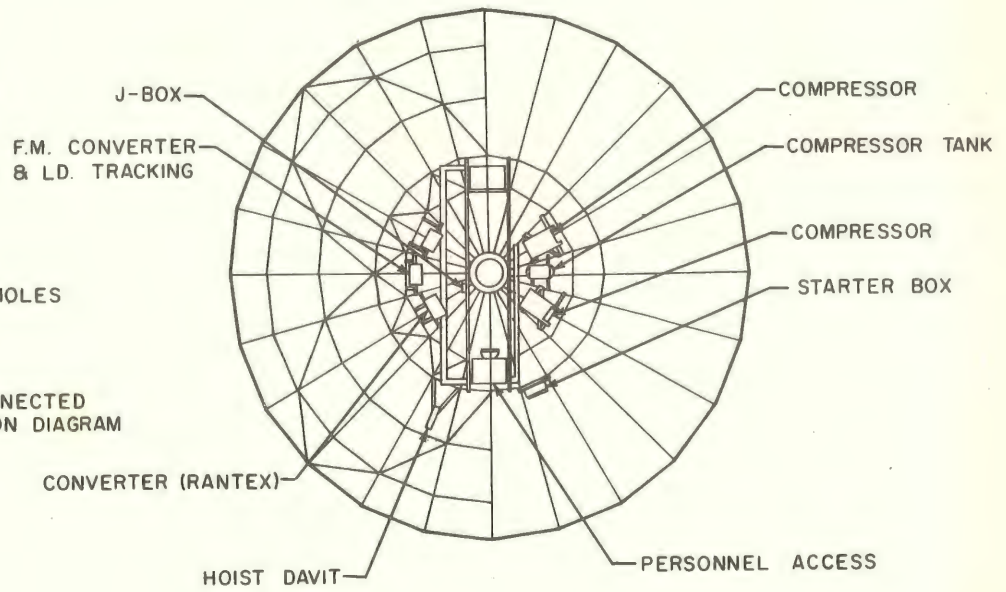
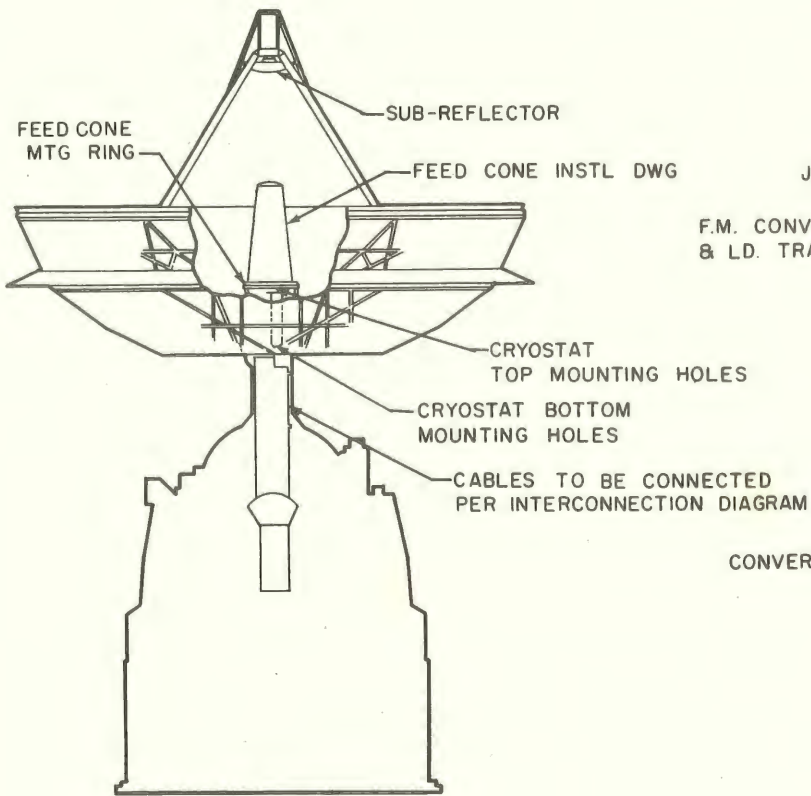
The capacity at the cooling station is 1 watt at 4°K. The refrigerator, manufactured by Air Products & Chemicals, Inc., Advanced Products Department, Defense and Space Division, Allentown, Pa., requires a high vacuum (better than 10^{-17} mm Hg). This is achieved by the use of a vacuum pump. A roughing stage, achieving 10^{-4} mm Hg, is provided by a mechanical pump, the further reduction in pressure to 10^{-7} mm Hg being achieved by the vacuum pump.

The Control Console

The control console houses all the power supplied for the entire system and is shown in Figure 5. In addition it provides for control and monitoring of the system.

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3. Bloembergen, N., "Proposal for a New Type Solid-State Travelling Wave Maser," Phys. Rev. 109:324, October 1956.



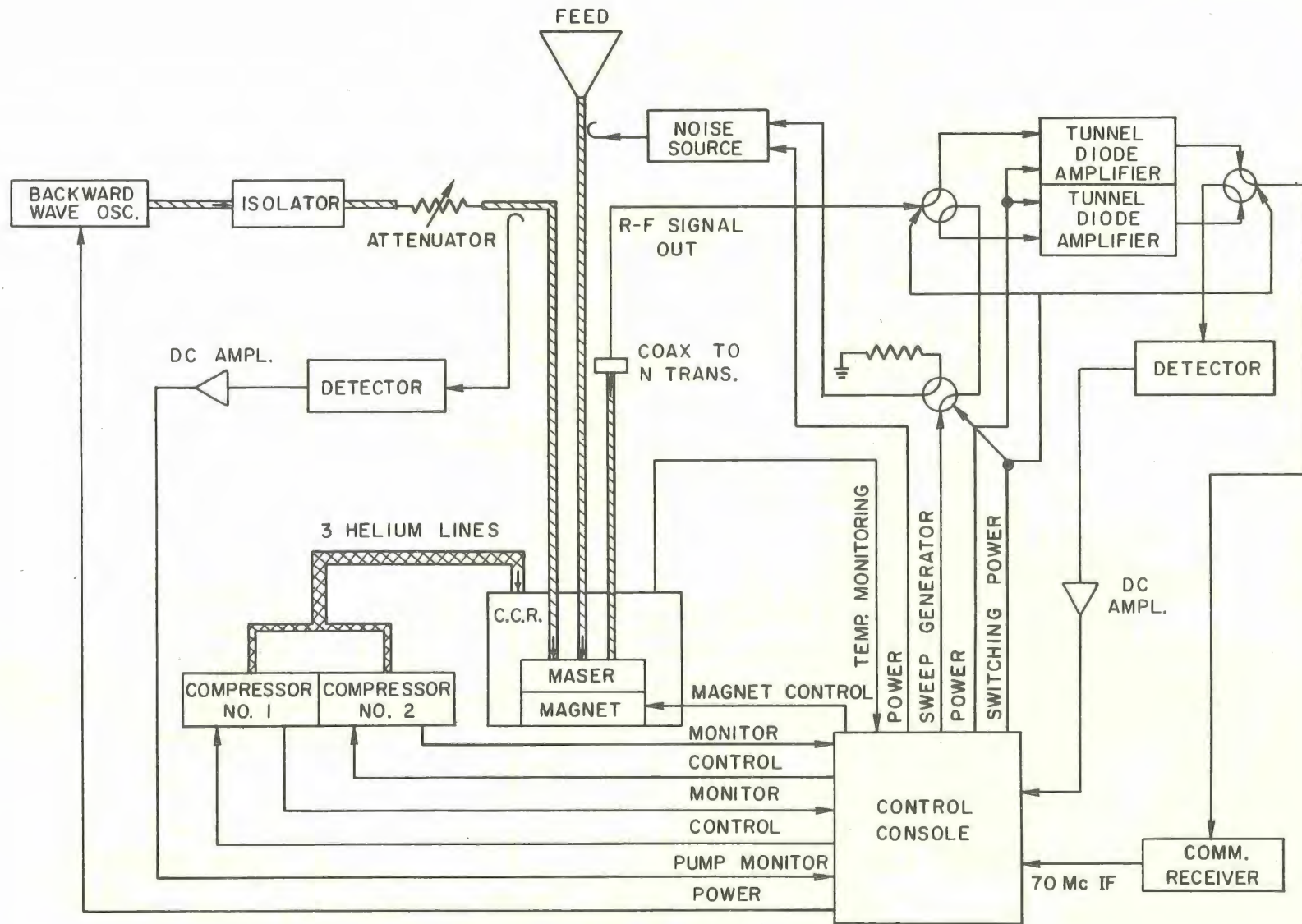
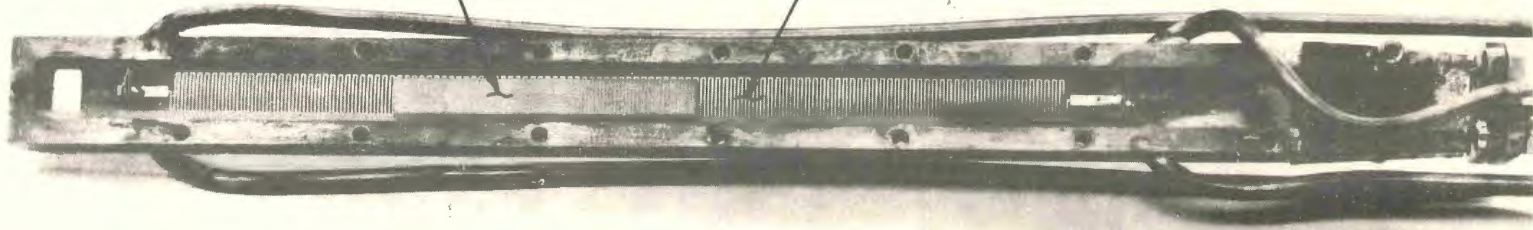


Figure 2. System Block Diagram.

ACTIVE CRYSTAL

MEANDER LINE



16-36

Figure 3. The Slow Wave Meander Line and Maser Crystal.

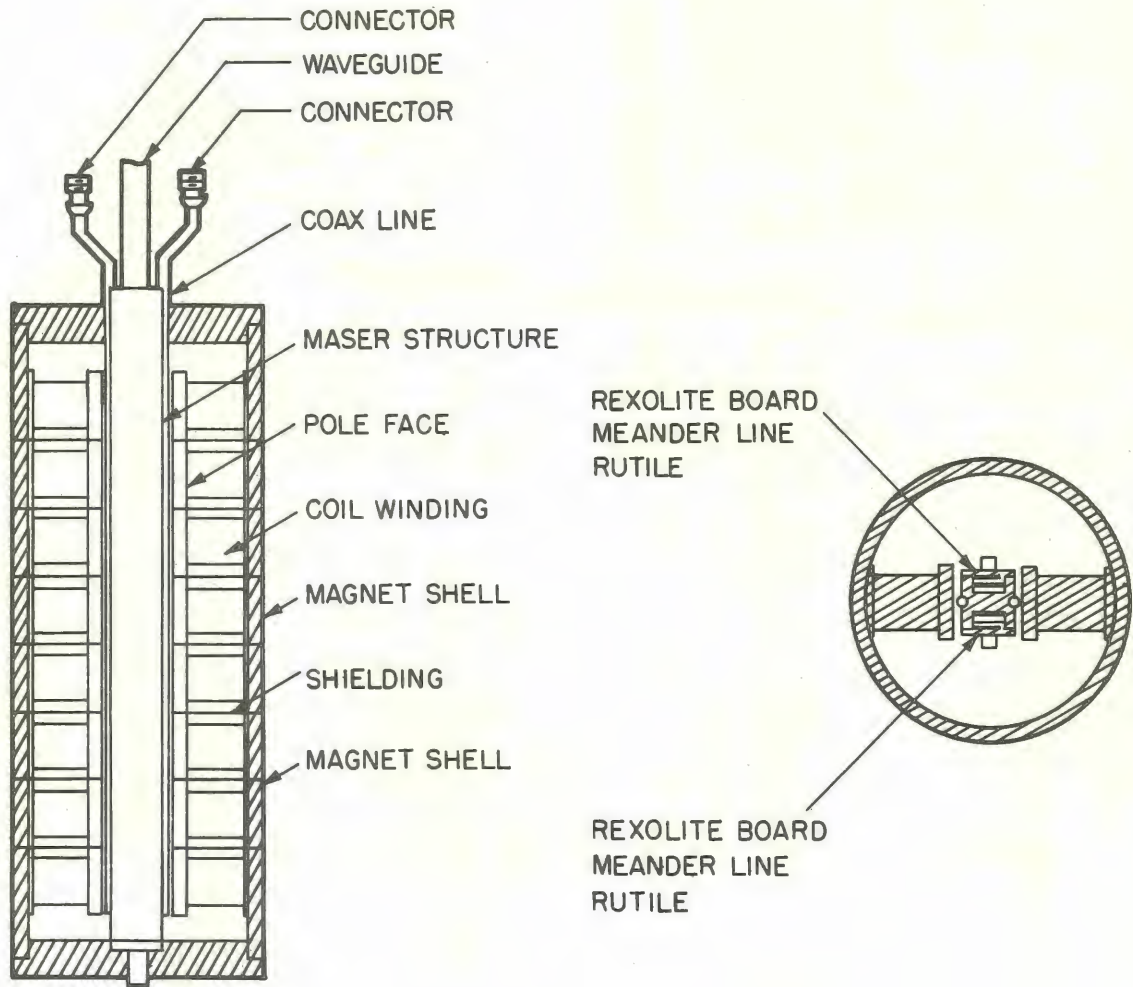


Figure 4. Cross Section of Maser in Magnet.

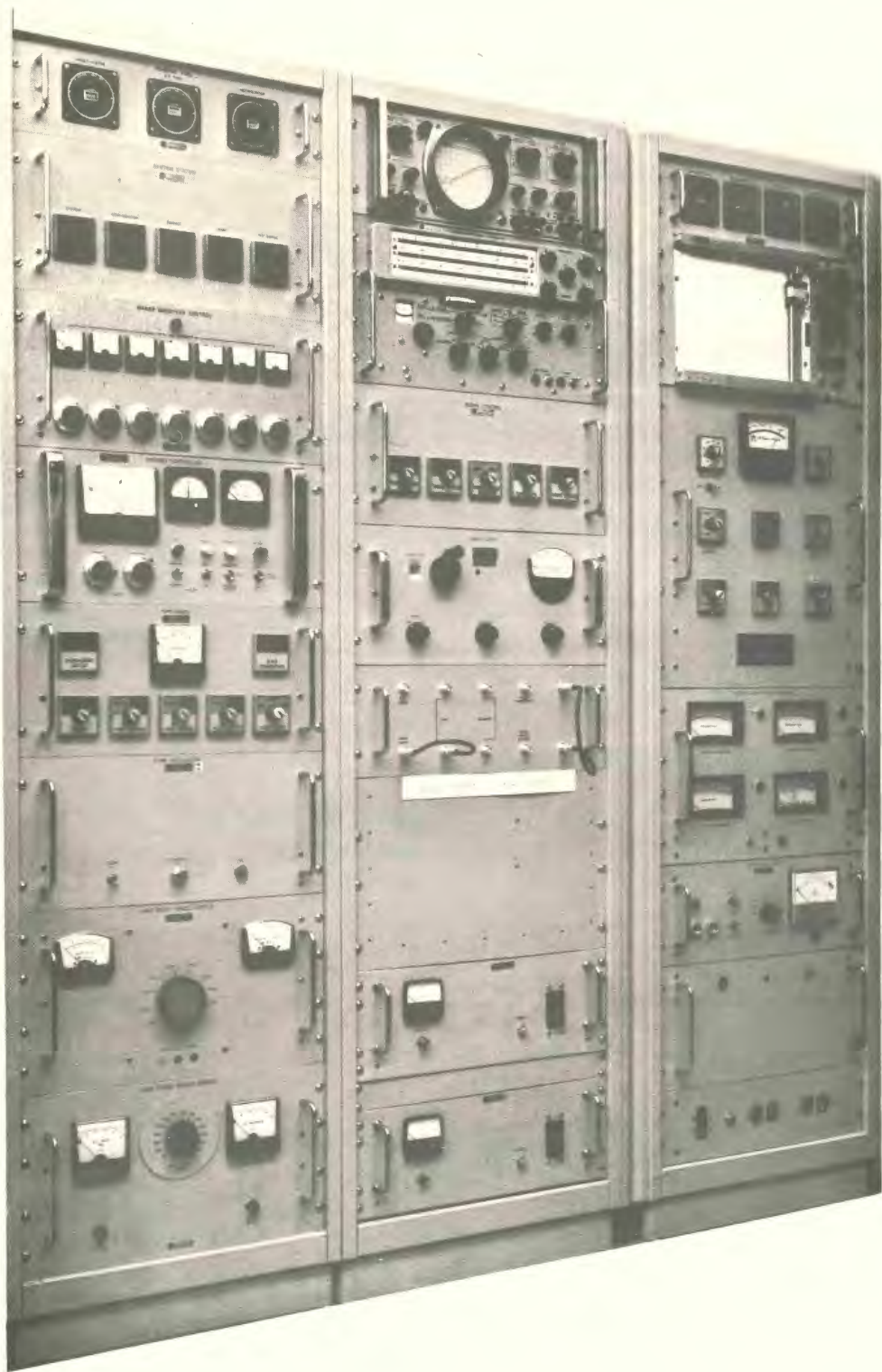


Figure 5. Control Console.