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RF CAVITY FOR SLAC STORAGE RING

by

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I. INTRODUCTION

This report describes the design, construction and testing of a radiofrequency cavity for the proposed SLAC storage ring. In the absence of a completed ring it has, of course, been impossible to obtain cavity performance data under beam loaded conditions. However, much useful information has been obtained on vacuum capabilities, high voltage stand-off capabilities, and the design of tuning and coupling structures.

The proposed SLAC storage ring is designed with a bending radius of 12.7 meters and a magnetic field at 3 GeV of 7.86 kilogauss. At an energy of 3 GeV, a charged particle will radiate 563 keV of energy per revolution, and with a current of one ampere each of electrons and positrons the power demand to replace the energy lost by radiation will be 1.13 megawatts. This energy will be replaced at a radiofrequency of 50 MHz, corresponding to the 36th harmonic of the particles' revolution frequency. The required voltage of the rf system is set by the excess voltage which is needed to contain the quantum excited phase oscillations. At the frequency chosen, a voltage about fifty percent higher than the voltage to make up for the radiation losses is necessary. Thus it is necessary to supply the 1.13 megawatts to the beam at a peak voltage of at least 870 kilovolts. It is convenient to develop this power in six independent output stages supplying resonant cavities in each of six available straight sections of the storage ring. Each cavity is then required to develop a peak voltage of 145 kilovolts and each rf source must generate 190 kilowatts in addition to supplying cavity and coupling network losses of about 20 kilowatts. It is also planned to operate the storage ring at energies less than 3 GeV, where, since radiation losses decrease as the fourth power of energy, it will be possible to store much larger currents with the available rf power. At the lowest energies of interest, the magnitude of the current is limited only by stability or aperture requirements. The maximum current is 24 amperes per beam at 1.36 GeV. The cavity tuning and coupling systems must have sufficient range to accommodate this very heavy beam loading. The requirements for stable operation of a suitable cavity have been studied and a prototype cavity has been built and tested.

II. CAVITY DESIGN REQUIREMENTS

In order to maintain a match between the final rf amplifier and the cavity, and to insure the stability of the beam-cavity system, it is necessary to adjust for a particular beam current and energy, both the tuning in the cavity and the coupling between the amplifier and the cavity. In this section, expressions will be derived for the required tuning and coupling adjustments as a function of beam current.

The output stage of the rf system can be represented by the circuit of Fig. 1. V is the voltage across the cavity gap; G_g is the generator conductance; n is the turns ratio of the coupling network between the final amplifier and the cavity; I_B is the rf component of the beam current, and I_g is the generator current. For a match it is required that the current flow from the generator be in phase with the voltage across the gap, that is, the generator must deliver an in-phase current to the load, and equal powers must be dissipated in the generator internal impedance and the load. These conditions lead to the phasor diagram of Fig. 2. The angle θ is the synchronous phase angle: ϕ_c is the angle between the susceptance and the conductance in the cavity. The cavity admittance is given by the following equation:

$$\begin{aligned} Y_c &= G_c + jB_c \\ &= G_c (1 + j \tan \phi_c) \end{aligned} \tag{1}$$

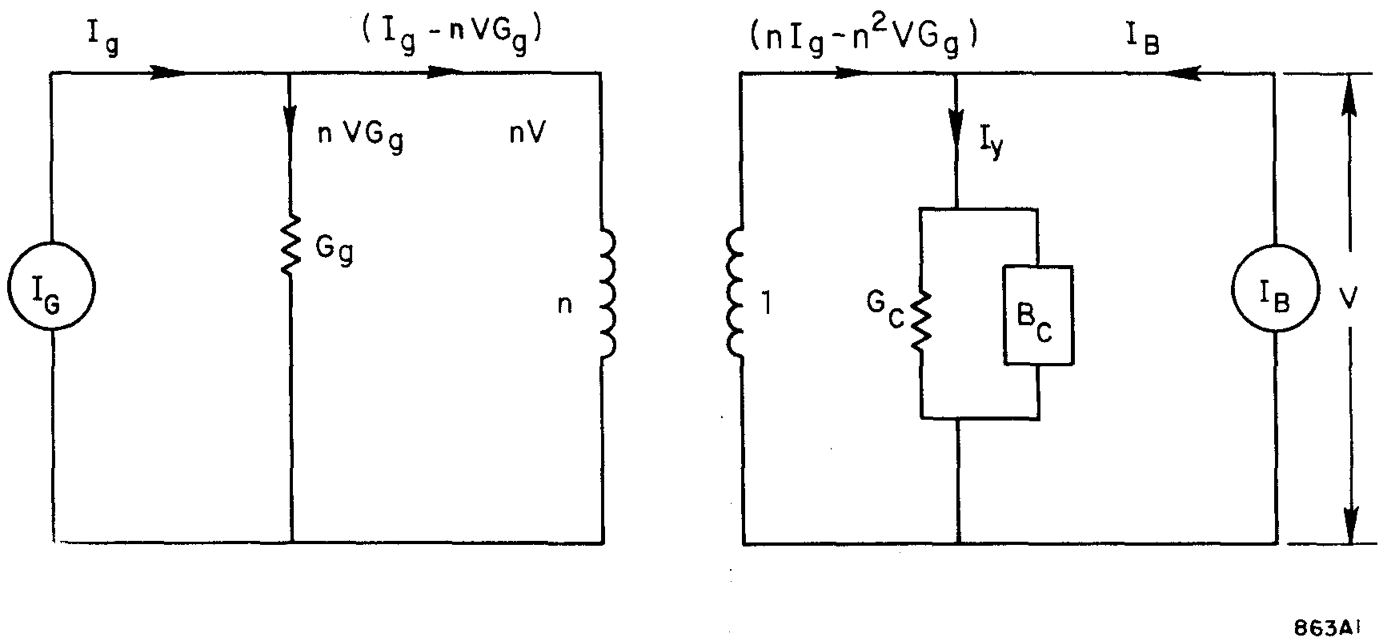

FIG. 1 — EQUIVALENT CIRCUIT OF rf OUTPUT STAGE.

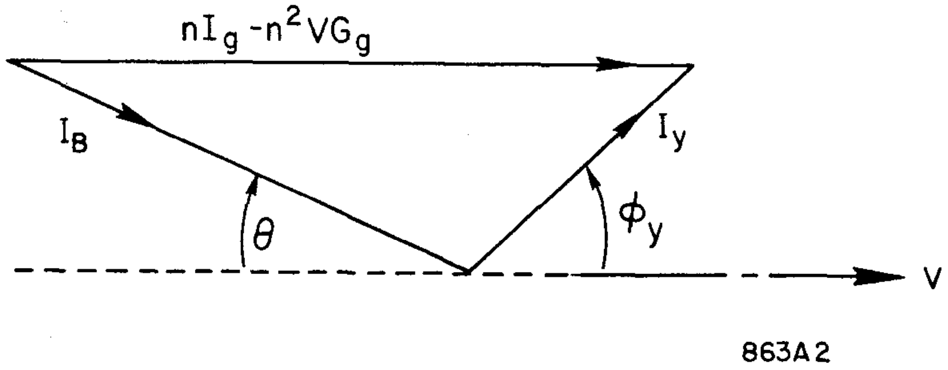

FIG. 2 — VECTOR DIAGRAM OF CURRENT FLOW IN rf OUTPUT SYSTEM.

The angle θ is fixed by the following requirement:

$$U/V = \cos\theta , \tag{2}$$

where U is the radiation demand of an electron or positron. From Fig. 1 the network equation is

$$\begin{aligned} nI_g - n^2VG_g &= V(G_c + jB_c) + I_B(\cos\theta - j\sin\theta) \\ &= VG_c + I_B\cos\theta + j\,(VB_c - I_B\sin\theta). \end{aligned} \tag{3}$$

The requirement of real current flow from the generator gives:

$$VB_c - I_B\sin\theta = 0 , \tag{4}$$

yielding the detuning requirement on the cavity:

$$\tan\phi_c = \frac{(I_B)\sin\theta}{VG_c} \tag{5}$$

The requirement that equal power must be dissipated in the generator internal impedance and in the load yields:

$$n^2V^2G_g = V^2G_c + VI_B\cos\theta , \tag{6}$$

which gives the requirement on the coupling network:

$$n^2 = \frac{G_c}{G_g} + \frac{I_B\cos\theta}{VG_g} \tag{7}$$

Assuming that a fixed coupler is included to transform the high cavity impedance with no beam present to the low tube impedance, the turns ratio n' required as the beam is introduced is given by:

$$(n')^2 = 1 + \frac{I_B\cos\theta}{VG_c} \tag{8}$$

Equations (5) and (8) can be rewritten as

$$\tan\phi_c = \frac{P_B}{P_c}\tan\theta , \tag{9}$$

$$(n')^2 = 1 + \frac{P_B}{P_c} , \tag{10}$$

where P_B is the power transferred to the beam and P_c is the power dissipated in the cavity. It is assumed that I_B equals twice the dc current.

For stored beams of one ampere each of electrons and positrons at 3 GeV, and with 7-1/2% of the power going to the cavity losses, n^2 is 13.2 and tan ϕ_c is 14.6. For stored beams of 24 amperes each of electrons and positrons at 1.36 GeV, n^2 is 61 and tan ϕ_c is 1010. This means that, during filling, the cavity must be tuned through seven unloaded bandwidths to fill to the design current at 3 GeV, and through 500 half-power bandwidths at the higher current. Figure 3 shows the required detuning as a function of beam current at 3 GeV. Figures 4 and 5 show the input standing-wave ratio and the forward and reverse power level in the input transmission lines to the cavity when the cavity gap voltage is held constant, the cavity is resistively matched at a beam current of 2 amperes, and the cavity tuning is always adjusted so that the reactive component of the load impedance is zero.

The design of the coupler is dictated by the following requirements:

1. The coupler should be continuously variable during the filling of the ring.
2. The coupler must be capable of transferring 200 kilowatts cw power with as low a loss as possible.
3. The coupler is required to perform resistive impedance transformations only, with all reactive adjustments being accomplished by the cavity tuning control.

Since it is difficult to place a coupler with these requirements within the vacuum system, a preliminary design has been made in which a fixed coupling loop is

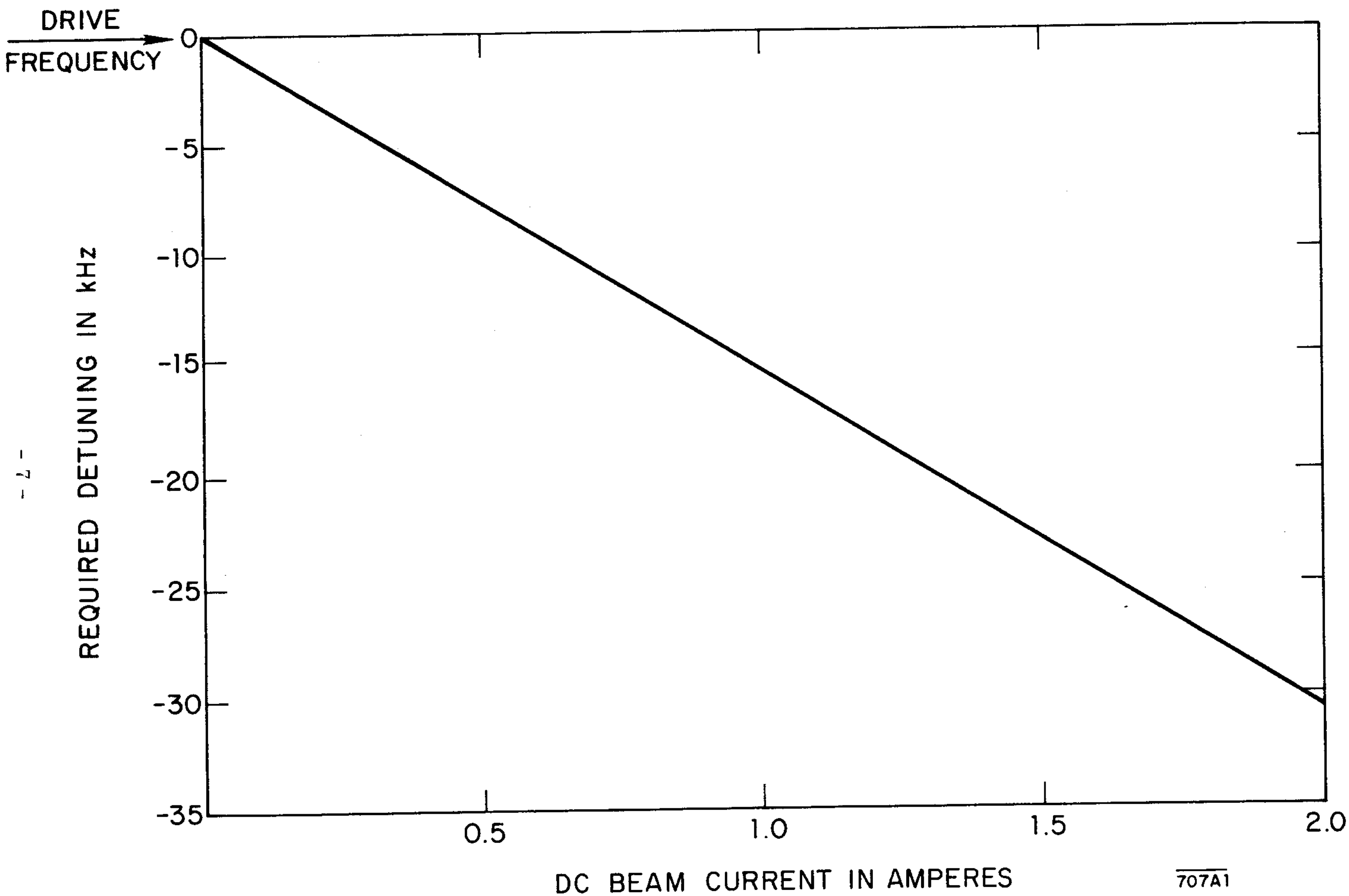

Fig. 3 – CAVITY DETUNING vs BEAM CURRENT

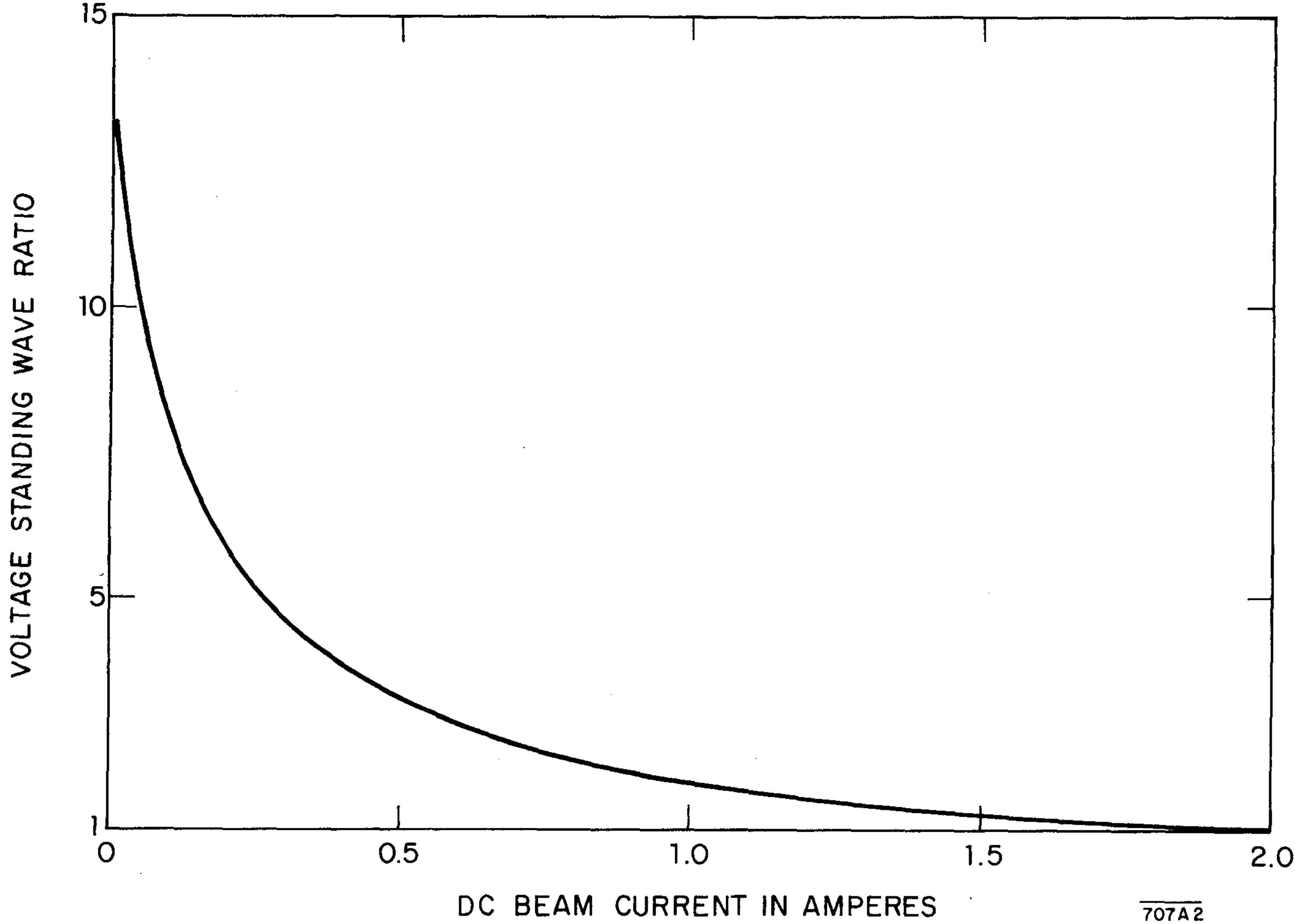

Fig.4- CAVITY INPUT STANDING WAVE RATIO vs BEAM CURRENT

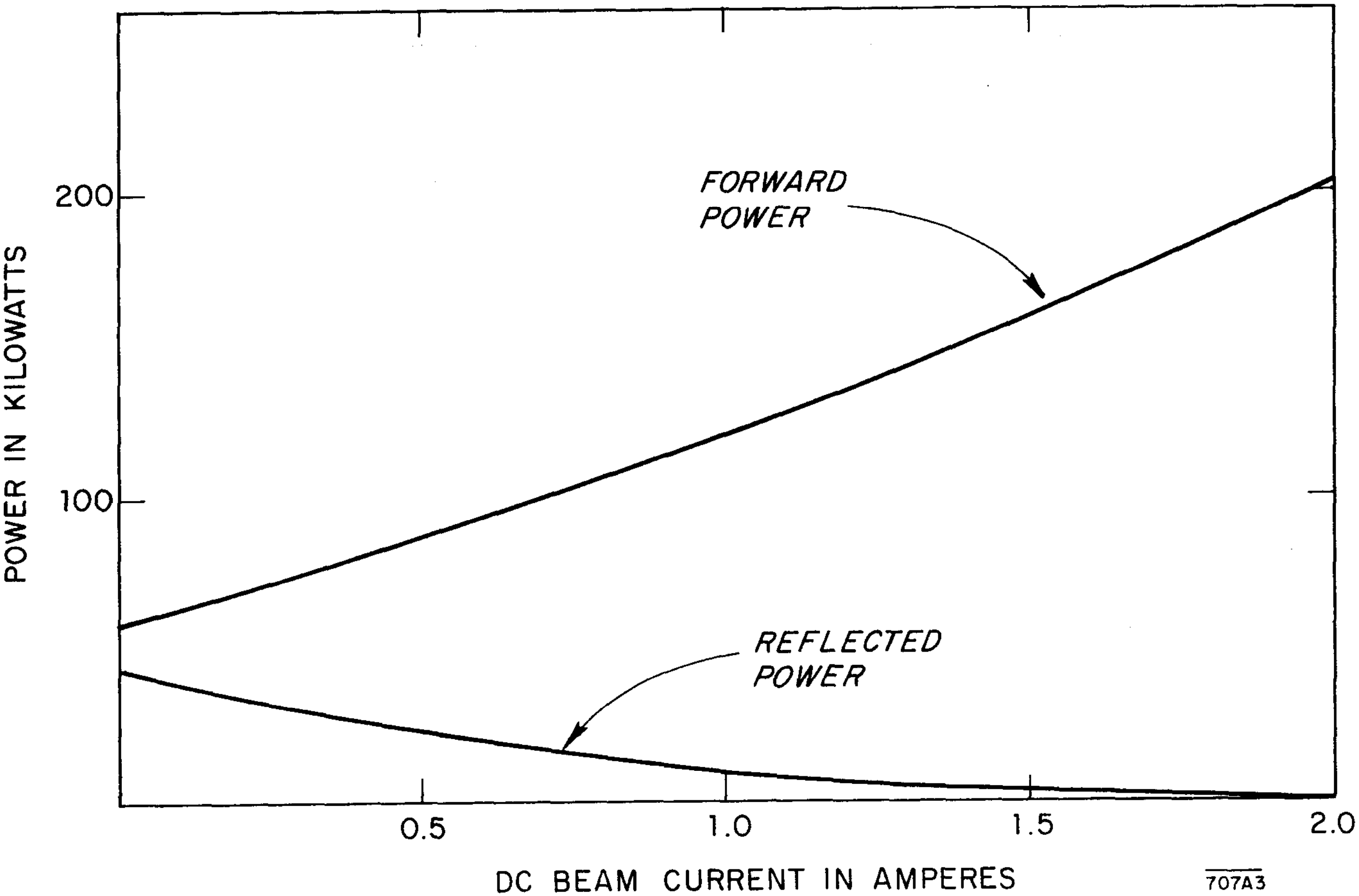

Fig.5 - FORWARD AND REVERSE POWER vs BEAM CURRENT

placed inside the cavity and the variable coupler is located immediately outside the cavity. Among the couplers under consideration are the L network and several variations of swinging links. The possibility of using a fixed coupler is also being considered. Since a time interval of the order of seconds is required to fill the storage ring to 2 amperes, high vswr's exist for time intervals of a few seconds, as can be seen from Fig. 4. When the storage ring is run at lower energies and higher currents the filling time is much longer because of limitation on the amount of positron current which can be supplied by the accelerator and other phase space considerations. However, even at high vswr's the reflected power is small relative to the dissipation capabilities of the rf sources and thus it may be possible to use a fixed coupler, ignoring the transient conditions of low beam currents.

Stability

The stability of heavily beam-loaded cavity systems has been investigated.[1] For stability against growing coherent phase oscillation it is necessary to tune the cavity below the driving frequency, which is consistent with the matching requirements discussed above. Thus, if the cavities are tuned in a way that the reactive currents of the generator and the induced beam current cancel, then the system is always stable. Also, if the coupler is always adjusted for matching at a larger beam current and the tuner compensates for the reactive beam current, then the system is stable for smaller currents,[1] allowing the method of filling with no coupler adjustment, as discussed above. At the higher current levels the region of stability becomes smaller, placing correspondingly tighter requirements on the tuner control system.

Design of the Cavity

Each straight section of the storage ring has an available free space of about two meters and within this space limitation it is necessary to design a 50-MHz cavity with a peak voltage capability of 200 kilovolts. Initially, a cavity design was considered in which vacuum windows separated various regions of the cavity. The use of windows allows most of the cavity to be outside the main vacuum system thus easing the load on the ultra-high vacuum pumps and simplifying the design of rf couplers and tuners. Several types of ceramics were investigated but the high dielectric losses due to the large voltages in the region where the windows must be situated make this approach undesirable.

The present design of the storage ring is for aluminum construction, and ultra-high vacuum flanges have been designed which will mate aluminum flanges to stainless steel flanges. Thus it is feasible to use an all vacuum cavity constructed from aluminum. A large cavity with good structural strength can be constructed relatively inexpensively from aluminum with welded joints. A prototype cavity design is shown in Fig. 6. This cavity has a design Q (unloaded) of 12,000 and a shunt resistance of about 1 megohm and consists of two quarter-wave capacitively-loaded coaxial cavities with a common high voltage gap. The overall length is 57-1/2 inches and the outer and inner conductor diameters are 37 inches and 10 inches, respectively, with a gap spacing of 6 inches. All connections to the outside are by means of aluminum-to-stainless steel ultra-high vacuum flanges employing aluminum foil gaskets. A coaxial input window originally designed for a high-powered klystron is used and the coupling loop is water cooled. The necessary frequency tuning for the 3 GeV, 2-ampere case is achieved by means of a water-cooled paddle which may be moved into or out of the cavity by a lateral motion of a vacuum bellows. The large amount of cavity detuning necessary for the high current case is provided by means of a "capacitive" tuner

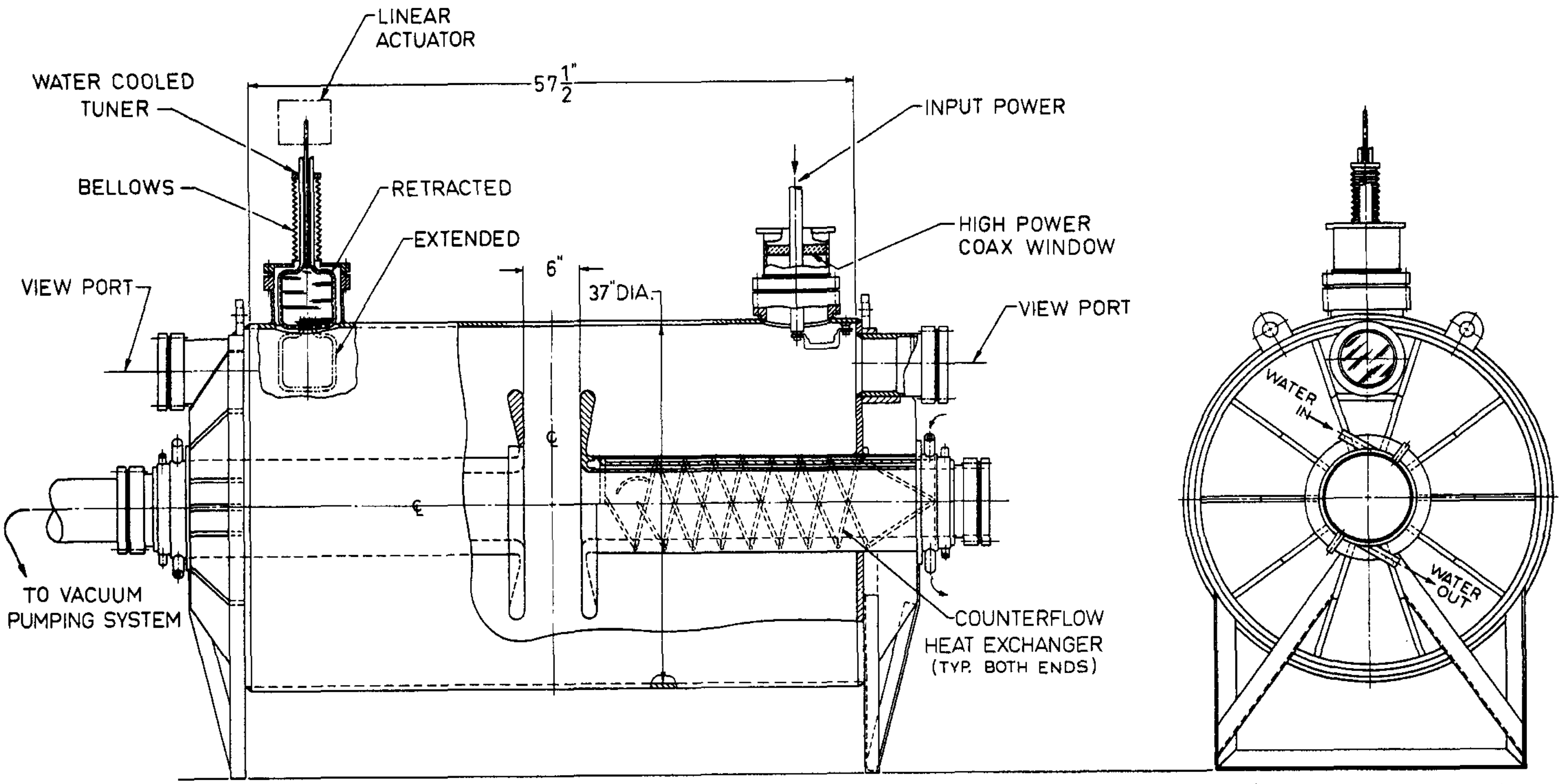

FIG. 6 — EXPERIMENTAL RF VACUUM CAVITY

moved in the region of high electric field as shown in Fig. 7. Since approximately half the lumped capacitance in the cavity is in the fringing fields of the capacitive plates, this tuner is capable of causing large tune shifts.

III. MECHANICAL DESIGN AND FABRICATION

In Sections II and IV the electrical design and performance of the prototype cavity are described. In this section the mechanical design and fabrication are described.

Material

Type 6061 T-6 aluminum was chosen for its electrical, vacuum, and mechanical properties. Its conductivity is adequate; it is appropriate for use in ultra-high vacuum systems, and it is sufficiently strong to enable the cavity to withstand external atmospheric pressure when the cavity is baked at 250°C.

Fabrication

The most critical aspects of fabricating the shell were welding, ultra-high vacuum cleanliness, dimensional control of the capacitance loading plates, and surface finish.

A welder qualification program was initiated which, in essence, required the welder to complete several successive, typical weld joint samples, which were subsequently sectioned and checked for flaws.

Type 4043HQ chemically etched rods were used with a helium-shielded arc. Where etching the weld joint was not possible and where delays occurred after etching, the weld joint was hand scraped or routed out with a motor-driven carbide tool.

Type 6061 T6 aluminum tooling plate was rolled to the shell diameter to within 3/8-inch roundness. Contact paper was used to protect the surface finish of the aluminum from the rolling operation. Further protection was provided by

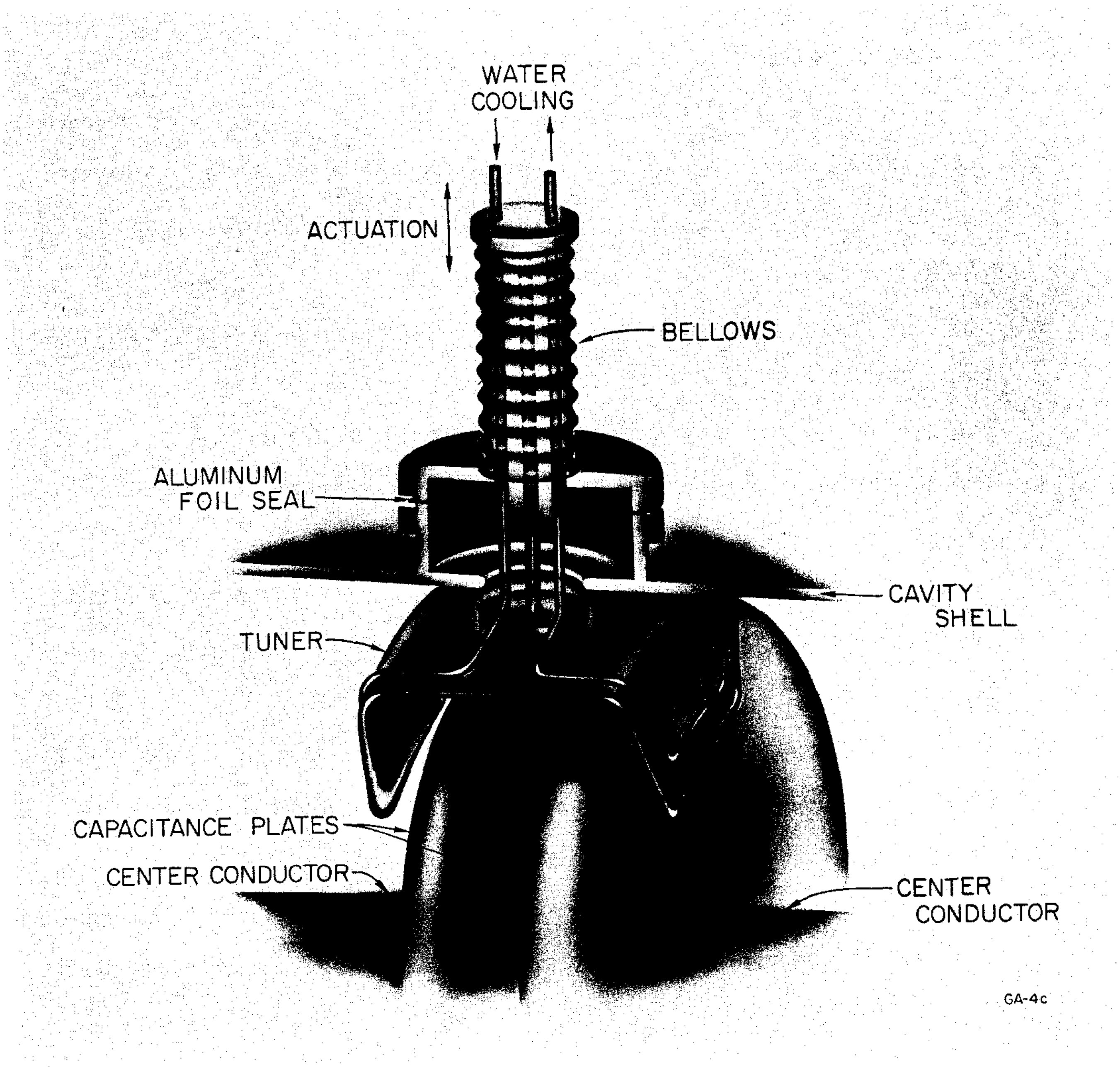

FIG. 7-SADDLE-TYPE TUNER

wrapping the rolls with template paper. Excess material was allowed on the circumference to allow trimming off the flat ends of the plate resulting from the rolling operation.

A weld V-groove was then machined on the inside of the longitudinal shell joint previously trimmed. After chemically cleaning and etching, the joint was helium TIG welded. A copper back-up strip was used to channel argon gas to the back side of the joint. The weld inside the shell was machined flush with a hand-held carbide tool and the outside weld flush removed by grinding. After completion of the longitudinal weld, the shell was then re-rolled to the required roundness.

X-ray inspection was used to check penetration, porosity and foreign inclusions in the longitudinal shell weld joint. All weld joints were checked with dye penetrant for cracks, pinholes and flaws. All surface defects indicated by the dye penetrant check were repaired. After machining the weld joints were rechecked with penetrant.

All detail components were chemically etched. Where possible, assembly was done in a special room to reduce air- and traffic-borne contaminants. The completed weldment was flushed out with methyl alcohol. If chemical cleaning was not possible or practical, methyl alcohol was used to wipe or rinse contaminated parts. Where possible, lint-free gloves and paper were used to handle all vacuum parts.

The internal dimensions of the cavity were dictated by the electrical design. The tolerances are typical of weldments of this size except for the requirement for precise spacing of the capacitive loading plates.

The internal surfaces of the cavity were required to be extremely smooth (8-microinch finish) in areas of high-voltage gradient, such as the faces and edges of the capacitance loading plates, and the central area of the inner surface of the outer conductor.

Stress Relief

The end assembly weldments (including the capacitance plates, heat exchanger and shell ends, but excluding the foil seal flanges) were stress relieved in an oven. After stress relief the end assemblies were machined to final tolerances.

The circumferential weld joints between the end assemblies and the shell were stress relieved with an acetylene flame. Temperature-indicating crayons were used to check the temperature.

Final Assembly

A special centering fixture shown in Fig. 8 was constructed to measure the gap spacing, and to maintain correct alignment of the center conductor bore while the cavity and assemblies were welded to the shell. Total weld shrinkage for both ends was measured to be 0.20 inch. This same shrinkage allowance will be used to determine the required excess shell length for subsequent cavities. After welding one end to the shell, the weld shrinkage is measured and an appropriate allowance made for the weld shrinkage of the other end. With this technique, the capacitance gap and resulting resonant frequency of the cavity can be accurately established within the range of mechanical tuning.

Flanges

The aluminum cavity must be joined and vacuum sealed to stainless components and must maintain this seal through bakeout thermal cycling to 250°C. For this purpose, aluminum foil sealed flanges were developed and used throughout. A typical flange, originally developed by Batzer[2] is shown in Fig. 9. With this system, a pair of flanges, one 6061 T6 aluminum and one 309 stainless steel, are used with a 0.005-inch thick soft aluminum foil gasket between them. The stainless

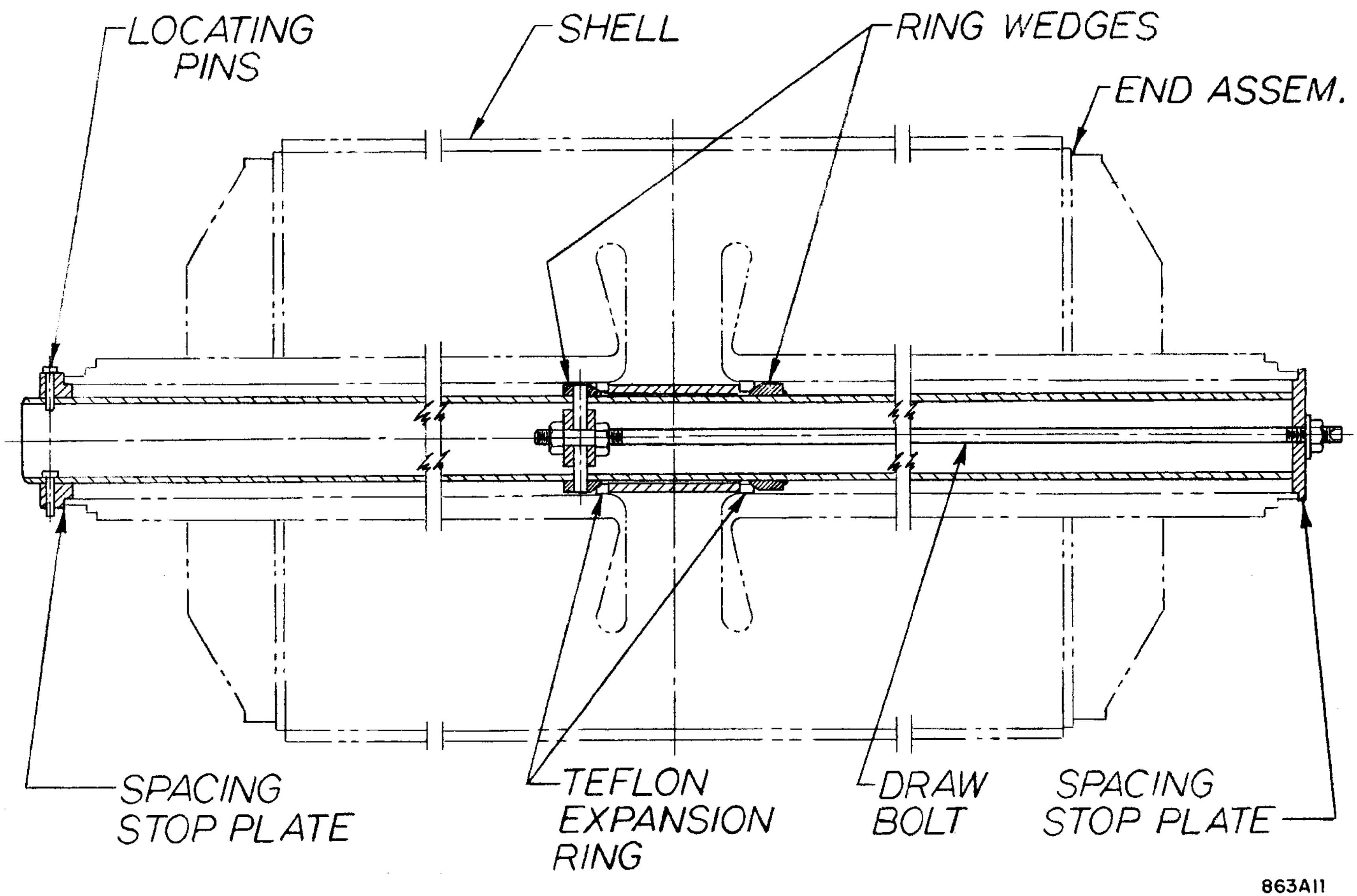

FIG. 8 — CENTERING FIXTURE

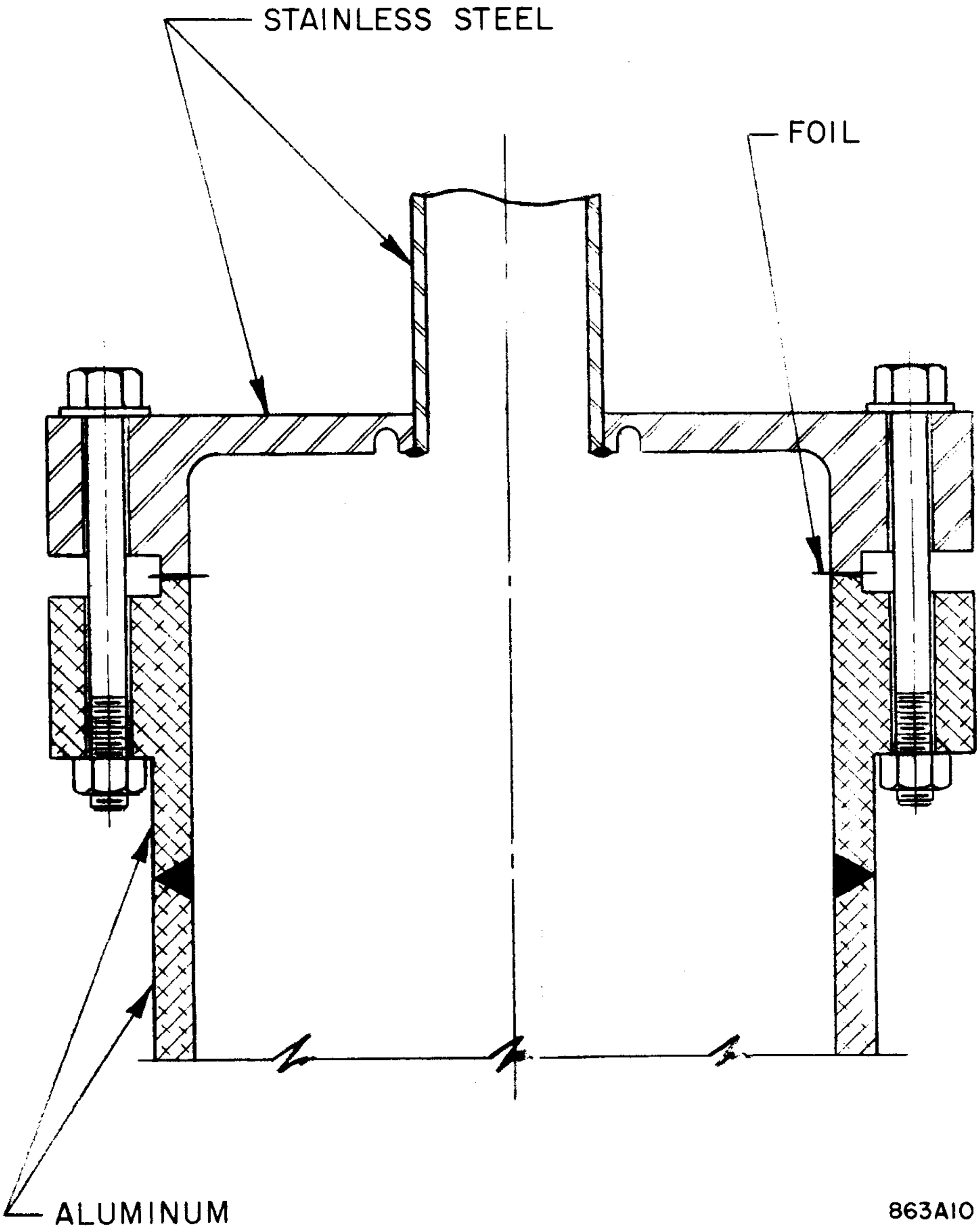

FIG. 9 - ULTRA-HIGH VACUUM FLANGE ASSEMBLY

steel flange has a 2°, 1/8-inch wide conical sealing face while the mating aluminum flange has a flat face of the same width. The flanges and bolts provide sufficient elasticity to maintain a seal through bakeout temperature excursions. Flatness and dimensional tolerances are important and no radial scratches are permitted on the sealing faces. A special resurfacing tool was devised for the flat aluminum surfaces. This tool consists of a pivoted ground plate to which emery paper is attached. The emery paper is applied to the seal face in a rotary motion which prevents radial scratches. Small scratches are removed from the stainless flanges with a small hand-held hone. Two flanges, one at each end of the cavity, are fitted with flush-mounted Corning 7056 distortion-free glass windows for observation and access purposes. The glass is sealed directly to Kovar seal rings for matched thermal expansion rates. The Kovar is then TIG welded to the 304 stainless steel aluminum foil seal flange. The view ports are capable of repeated bakeouts at the specified $250^{\circ}C$.

Vacuum System

A 500-liter/sec ion pump was used to pump down the 1000-liter cavity. Rough pumping was accomplished with a mechanical pump with a molecular sieve trap for protection against back streaming of oil into the cavity. The ion pump is supported by three 200-lb spring scales which provide a stress-free vacuum joint without bellows between the ion pump and the cavity. This arrangement is shown in Fig. 10.

The cavity must be capable of maintaining a pressure of 10^{-9} torr with 20 kilowatts of rf heating of the cavity walls. In order to achieve this ultra-high vacuum, a $250^{\circ}C$ vacuum bake was specified. This temperature is substantially higher than any surface temperatures reached during normal operation. Fiberglas-insulated heating tapes were wrapped around the cavity. A layer of aluminum foil

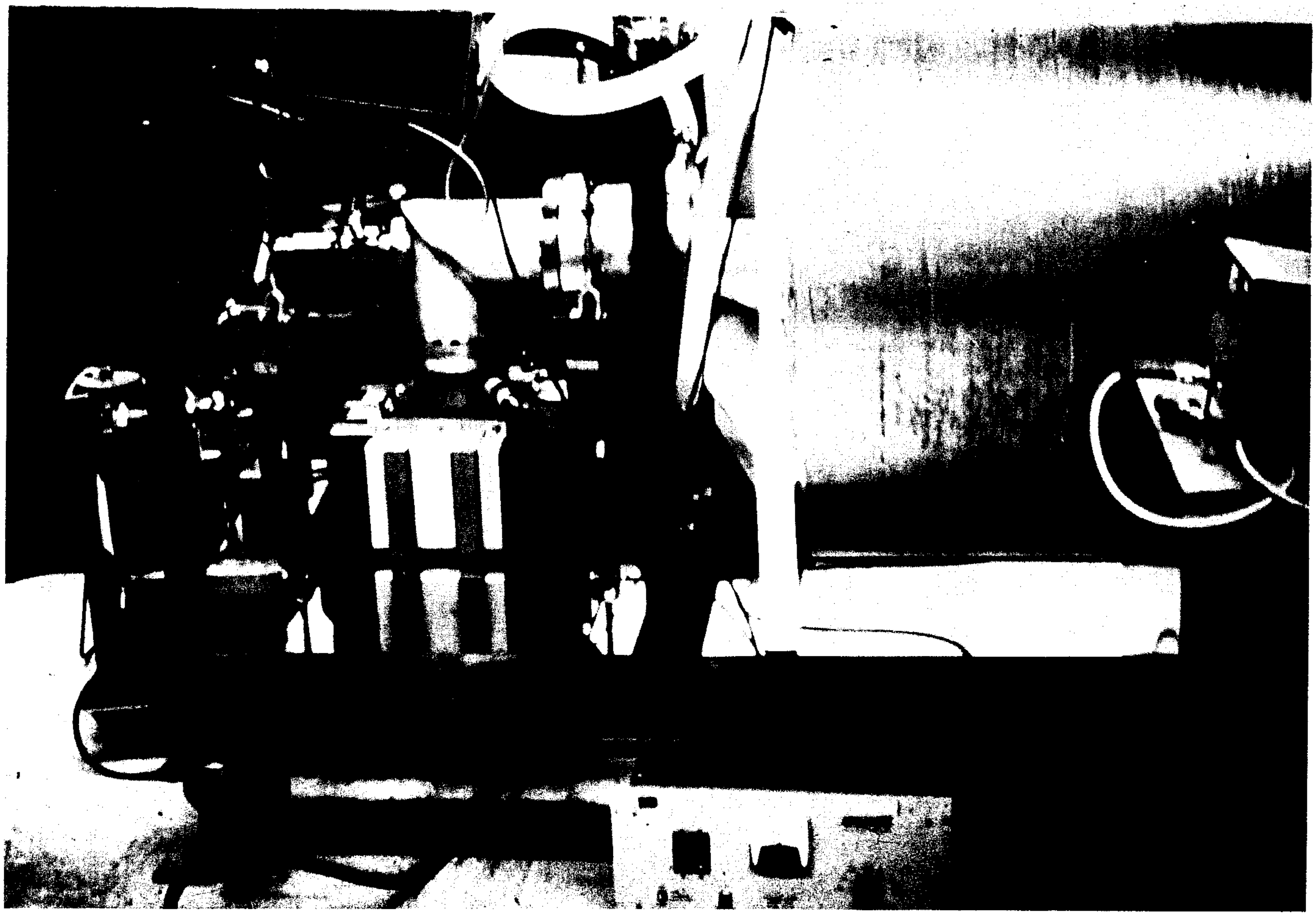

FIG. 10 - ION PUMP SUSPENSION SYSTEM

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was then placed over the tapes for insulation. Approximately 7800 watts was applied to the cavity to achieve $250^{\circ}C$.

Tuning

Two tuners have been designed and are shown in Figs. 6 and 7. Both the paddle and wide-range tuners were required to have linear actuation and water cooling with no water-to-vacuum joints.

The paddle tuner was installed in the cavity during initial assembly and was used in the first series of rf tests. After these tests the paddle tuner was removed and the saddle tuner installed. This tuner was designed in a manner which allowed its insertion into the cavity through the existing 6-inch diameter coupling-loop port. The water-cooling pipes and mechanical supports were introduced through a 1-inch diameter hole cut in the cavity wall at the center plane.

Cooling

In normal operation twenty kilowatts is dissipated in the cavity losses. In order to cool the cavity, a cooling jacket has been incorporated in the center conductor. This cooling jacket has counterflow (double helix) water passages which can vent to atmosphere if a leak develops. As with other parts of the cavity, there are no direct water-to-vacuum welds. This system is shown in Fig. 11. During the testing of the cavity it was decided to cool the outer conductor as well. Copper tubing was wrapped around the outer conductor, and a heat-transfer cement (Zeston) was used to produce a mechanical and thermal bond between the tubing and the cavity shell. The completed cavity is shown in Fig. 12.

IV. PERFORMANCE

In Sections II and III the electrical and mechanical design features of the prototype cavity were presented. In this section the electrical performance of the cavity is described. Table I summarizes some of the important characteristics of the cavity.

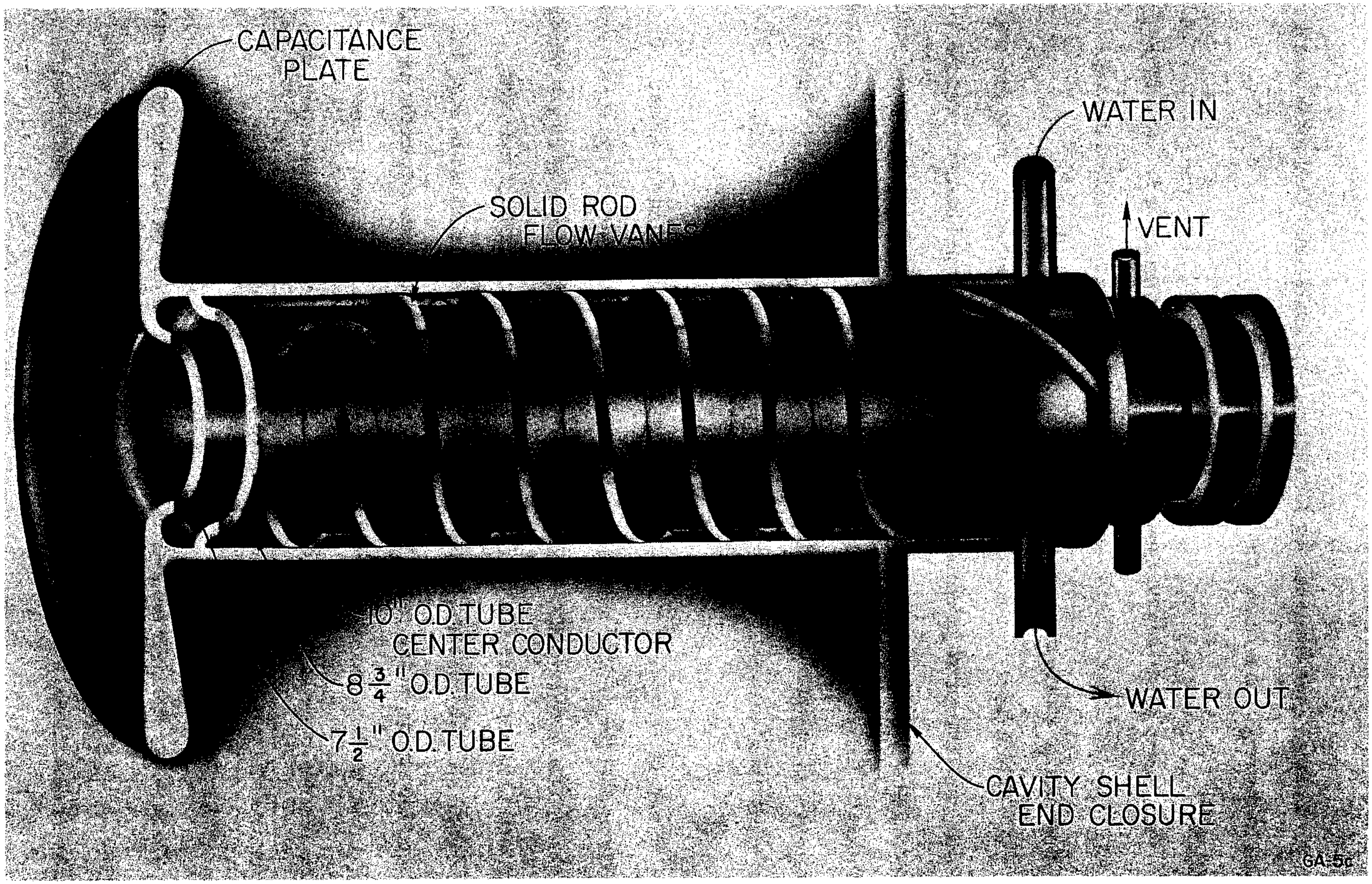

FIG. 11 -- CENTER CONDUCTOR HEAT EXCHANGER

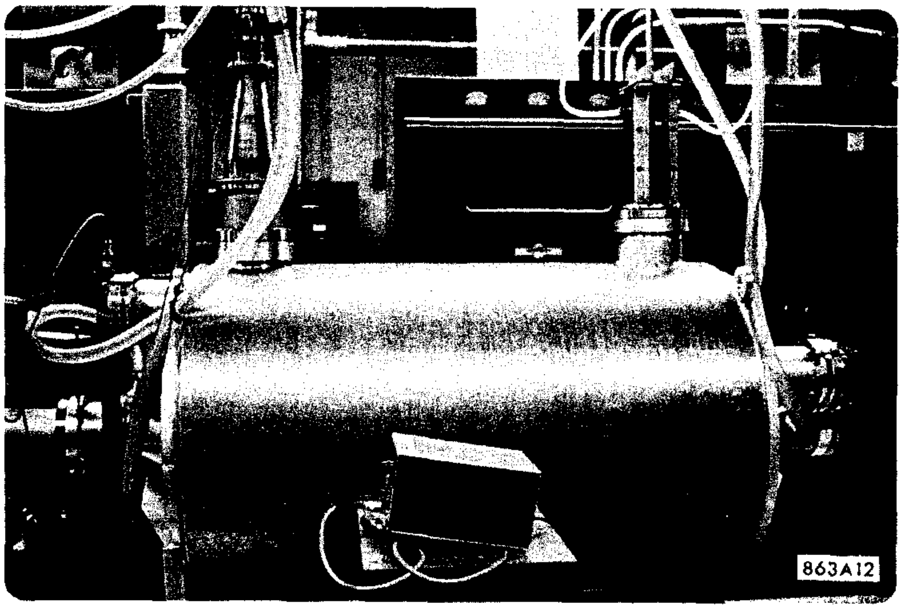

FIG.12 — PHOTOGRAPH OF ASSEMBLED CAVITY

TABLE I

Prototype Cavity Characteristics

Frequency	47.140 MHz
Unloaded Q	13,400
R_0/Q_0	89.5
R_0	$\approx 1.2 \times 10^6\ \Omega$
Tunability	± 15 kHz
Frequency Shift with Evacuation	− 15 kHz
Frequency Shift with Temperature	− 210 kHz for 70° F rise
Vacuum	5×10^{-9} torr
Lower Multipactor Power Level	180 mW
Upper Multipactor Power Level	40 W

Frequency

An error in transmitting dimensions from design through drafting to the machine shop resulted in the capacitive loading plates being larger than intended, and as a result the cavity frequency is 3 MHz lower than intended. This frequency error should not significantly affect any other measurements.

Measurement of Q_0

The unloaded Q was measured by two different methods. Initially a very lightly coupled signal generator was used to excite the cavity, and a lightly coupled pickup probe was used to determine the half power points of the cavity. By this method the Q_0 was determined to be in the range of 13,000 to 14,000.

A method for determining the Q_0 of an unmatched single port resonator is described in Ref. 3. First, the standing wave ratio at resonance is measured, and then it is determined whether the cavity is over-or under-coupled by using the nodal shift method.[4] Finally, Q_0 is found by use of the following equations:

$$Q_L = \alpha \frac{f_0}{\Delta f} \quad , \tag{11}$$

$$Q_0 = (1 + \beta) Q_L \; , \tag{12}$$

$$\alpha = \left[\frac{|\rho|^2 - |\rho_0|^2}{|\rho_1|^2 - |\rho|^2} \right]^{1/2} \quad . \tag{13}$$

where

Q_L = loaded Q,

Q_0 = unloaded Q,

β = coupling coefficient,

ρ_0 = reflection coefficient at resonance,

ρ_1 = reflection coefficient far from resonance,

ρ = reflection coefficient corresponding to Δf

Δf = an arbitrary departure in frequency from resonance.

Assuming a lossless input circuit, ρ_1 can be taken as unity. As will be seen later, this is a valid assumption.

Measurements on the prototype cavity yielded the following results:

ρ_0 = 0.17

$\rho_1 \approx$ 1.00

ρ = 0.707 (at 3 dB points)

Δf = 8.26 kHz

f_0 = 47.141 MHz

β = 1.41 .

α was computed to be 0.971, and the resulting calculation of Q_0 from Eqs. (11) and (12) gave a value of 13,400.

Measurement of R_0/Q_0

The ratio R_0/Q_0 was found by measuring the charge in cavity resonance-frequency when a dielectric rod is placed in the cavity gap. Using the known dielectric constant of the rod and the volume of rod and gap, the change in gap capacitance can be computed, assuming the gap to be a parallel-plate capacitor. The change in cavity frequency is measured, and R_0/Q_0 can be computed, using the following equation:[4]

$$\frac{R_0}{Q_0} = -\frac{2}{\omega_0^2}\frac{d\omega}{dC} . \tag{14}$$

The quantity R_0/Q_0 was found to be 89.5 ohms, and from the previous measurement of Q_0, R_0 was found to be 1.24×10^6 ohms at the edge of the gap. At the center of the gap R_0 was found to be 1.12×10^6 ohms.

The measurements were first made with a 0.100-inch diameter sapphire rod, and were repeated with identical results with a 0.25-inch diameter lucite rod.

Direct Measurement of Shunt Resistance, R_0

A direct measurement of R_0 was made by placing a small metal sphere in the gap. By measuring the amplitude of signals transmitted through the cavity as a function of the position of the perturbing sphere, R_0 can be obtained directly.[5] Using this method, R_0 was found to be 1.04×10^6 ohms at the center of the gap. The sphere was a 3/4-inch diameter brass ball which was moved across the gap in 1-inch increments.

Tunability

The inductive paddle tuner provides a total frequency change of 30.5 kHz which is sufficient for a 2 amp, 3-GeV beam. The tuner has no significant effect upon the Q of the cavity. A calorimetric measurement of tuner losses indicated that with 20 kW input to the cavity, approximately 150 W were lost in the tuner.

Subsequent to the assembly of the cavity it was decided to design a tuner which would also accommodate the beam loading effects of the highest design current (24 ampere, 1.36 GeV), and compensate for manufacturing tolerances and the effects of temperature and pressure variations. A wide-range capacitive tuner, small enough to be installed through the input coupling port, was designed. This tuner is located in the gap of the cavity and operates upon the gap fringing fields. The tuning range is 2.4 MHz. As with the other tuner, the effect upon Q is negligible, and at 18 kW input to the cavity, the power dissipated in the tuner is 318 W. The resulting heat is carried away by water cooling. The tuner has proved capable of operating at gap voltages of 300 kV.

Since the installation of the wide-range tuner involved a significant change in the gap capacitance, R_0 will decrease. The R_0/Q_0 and Q_0 were measured with the tuner in its extreme positions. The shunt resistance was found to vary from 969 kilohms (tuner fully inserted) to 1.14 Megohms (tuner fully withdrawn).

<u>Frequency Shift with Evacuation</u>

As the result of changing the dielectric constant in pumping the cavity down from air to vacuum, it can be expected that the cavity frequency will increase, if no dimensional changes occur from external atmospheric pressure. Measurements of the cavity frequency (defined as the frequency of minimum reflection) showed that the cavity frequency decreased by 15 kHz after pumping. It can be shown[6,7] that the frequency shift resulting from change in dielectric constant alone is given by:

$$\Delta f = 105 \frac{P}{T} \times 10^{-6} f_0 , \qquad (15)$$

where P is the pressure in mm Hg and T is the temperature in $^{\circ}$K. For 760 mm Hg, 293°K and $f_0 = 47$ MHz, this calculation yields + 12.7 kHz.

It is evident that dimensional changes resulting from external atmospheric pressure are about twice as effective in lowering the cavity frequency as the change in dielectric constant is in raising the frequency.

Frequency Changes in Temperature

The frequency-temperature characteristics in a cavity of this geometry are complex. With increasing temperature, the overall length increases, tending to lower the frequency. But since the capacitive loading plates are ultimately attached to the cavity ends, they tend to move apart, raising the frequency. On the other hand, the plates themselves and the center conductors expand, which increases the gap capacitance and decreases the frequency. Initially only the center conductors were cooled. The frequency shift was about - 210 kHz at 32 kW input with an accompanying rise of 70°F in the temperature of the outer conductor. Subsequently, the outer conductor was also cooled, and the frequency shift was then found to be about - 300 kHz for the 32-kW input power.

With both outer and inner conductors cooled, only the capacitance plates are free to change dimensions significantly. Consequently, most of the frequency shift can be attributed to an expansion of the plates, with a corresponding increase in gap capacitance. The temperature of the plates was measured using an infrared thermometer, and found to be 105°C $\pm$ 10°. A significant stabilization of the frequency would be obtained by direct cooling of the capacitance plates.

Higher-Order Modes

All higher-order modes with field in the beam region were investigated up to a frequency whose wavelength is comparable to the bunch length at 3 GeV (28 cm). None of these higher-order modes was close to a harmonic of the fundamental frequency.

Multipactor

Multipactor occurs in the prototype cavity at an input power level of 180 mW, corresponding to about 600 volts across the gap. When the cavity is operating at high power and the input power is reduced, multipactor again occurs at about 40 W, or about 9,000 volts across the gap. It is probable that multipactor occurs in the gap at the low-level input. Whether the phenomenon occurs in the gap or elsewhere in the high level case is not known. It has not been possible so far to get good correlation between measurements and multipactor theory. However, multipactor is easily avoided by switching on the rf power rapidly in order to pass through the multipactor power range before the discharge builds up to significant proportions. Thus the phenomenon presents no obstacle in operation of the cavity.

Vacuum Performance

Initially the cavity was operated without a high-temperature bakeout. The lowest pressure achieved in the absence of rf input was 4×10^{-9} torr. With 20 kW applied, the pressure was 1.5×10^{-6} torr. Subsequently, about 7800 watts of heat was applied externally by means of heating tape wrapped around the outer conductor, and the temperature of the cavity was raised to 250°F over large areas of the surface. The pressure then obtained in the absence of rf input power was about 1.5×10^{-9} torr, and with 20 kW of input power, 5×10^{-9} torr. Thus a modest bakeout improved the vacuum by almost three orders of magnitude with full operating power applied. It had been anticipated that the aluminum foil flanges might develop leaks, or that the flange bolts would require tightening after the bakeout, but neither of these events occurred.

Input Coupling Circuit

Earlier work on a non-vacuum cavity had led to the use of a single-turn loop terminating the 50-ohm coaxial input line, and located near the end of the cavity.

Initially, in the prototype cavity, an uncooled loop consisting of a simple copper strap enclosing an area in the cavity of about 4 square inches was used. From previous experience with the non-vacuum cavity it was thought undesirable to operate an uncooled loop at input powers greater than 5 kW. Accordingly, a water-cooled loop was designed to permit operation of the cavity at 20 kW, and to make possible a calorimetric determination of input coupling circuit losses. The water-cooled loop causes an input standing wave ratio of 1.4:1, and the cavity is under-coupled. A larger loop would be required for unity coupling.

The loop is a coaxial structure for water flow, a 1/4-inch copper tube being placed inside a 1/2-inch tube. With a flow rate of 5 feet per second, the resulting power handling capability is 1.42 kW for a 10^{o}C temperature rise in the cooling water.

At 20 kW input to the cavity, the losses in the loop are only 30 watts. Thus the earlier assumption of a (nearly) lossless input circuit is validated, and it seems that a similar coupling structure can be easily cooled even at the 200-kW power levels required in the operation of the storage ring.

Details of the loop are shown in Fig. 13. The input window is a modified high-power klystron window.

Cavity Power and Voltage Capabilities

The prototype cavity has been operated at 46 kW average power input for a few minutes at a time, at 32 kW for several hours at a time, and at 20 kW for as much as eight hours continuously. With both the inner and outer conductors water cooled, the cavity can be safely touched at 20-kW input. Without water cooling of the outer conductor, and at 32-kW input, the outer conductor reaches a temperature of 144^{o}F.

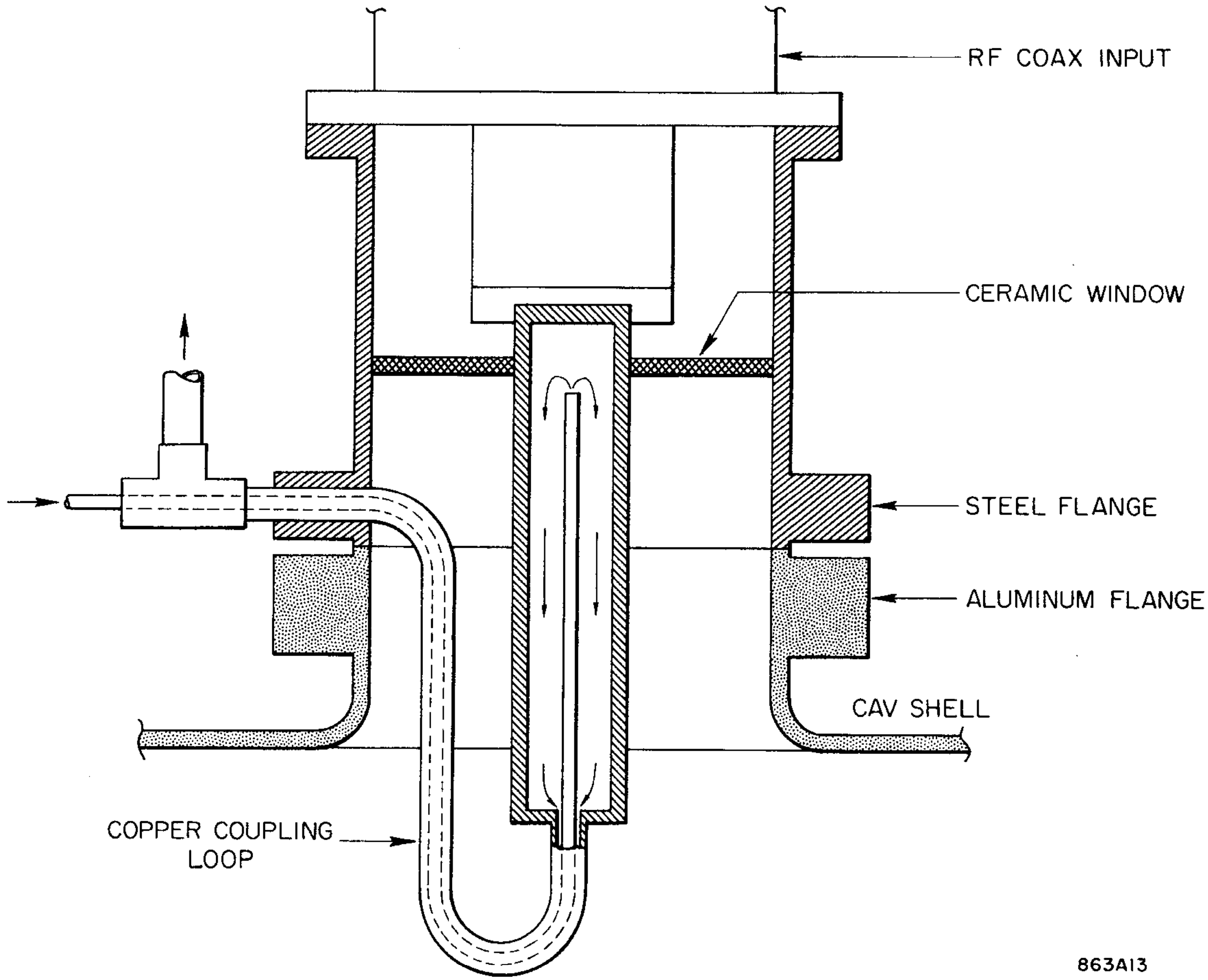

FIG. 13 — COUPLING LOOP

The peak gap voltage is given by

$$V_p = \sqrt{2PR_0} \tag{16}$$

where P is the input power to the cavity and R_0 is the shunt impedance, previously determined to be approximately 1×10^6 ohms. At 46 kW, the gap voltage is 303 kV. This is more than double the voltage required to store a 2-amp, 3-GeV beam.

Radiation

Significant amounts of soft x-rays are produced by this cavity when more than 10 kW of input power is applied. Two areas of particularly intense radiation are present, one at a spot on the edge of the capacitive baffle nearest the input end of the cavity, and the other on the opposite end plate, about one-half radius from the cavity center. It is thought that field emission may be responsible for the effect. Measurements are in progress to determine if this is the case.

The amount of radiation is a critical function of power, and at the maximum available power of 46 kW, as much as 6r/hr has been detected close to the cavity. Radiation is accompanied by an increase in gas pressure of several orders of magnitude. With removal of rf power, the pressure quickly returns to a low value. (The cavity is continuously pumped with a 500 ℓ/s ion pump.) Lead shielding has been added to the cavity in order to reduce the radiation level.

High Power Test System

A maximum of 46 kW at 47 MHz is available for high power testing of the cavity. Two Collins 205G transmitters are operated in parallel through a coaxial line hybrid ring structure. Although each transmitter is rated at 20 CW, it is possible to obtain 46 kW at 47 MHz.

Coaxial relays make possible a number of different modes of operation. Either or both transmitters can be switched in, either the cavity or a 50 kW load can be used as the load for the transmitter, and the cavity can be switched from the high-power source to a signal generator if it is desired to perform low power tests. Power measurements can be made to 2% accuracy with a calorimeter load.

Automatic Frequency Control System

Since the cavity resonant frequency changes rapidly when high power is applied, it is necessary to automatically retune the cavity. The system which has been devised to do this is of interest, since it will probably be used in the operation of the storage ring to compensate for beam loading effects.

Two directional couplers are placed at arbitrary positions in the input transmission line to the cavity. One coupler samples forward power, and the other reverse power. A phase measurement between the two couplers yields the angle of the reflection coefficient (plus an arbitrary constant, depending on coupler location). When the cavity is over-coupled, the phase is zero at resonance, and goes to $\pm 180^{\circ}$ on either side of resonance. A phase to voltage conversion results in a signal appropriate for control of the cavity tuner. The system has the disadvantage that when the cavity is under-coupled, the phase of the reflection coefficient at resonance is 180°. Therefore it is impossible to utilize this system as the cavity is changed from an over-coupled to an under-coupled condition. Also, at large separations between the driving frequency and the cavity resonant frequency, the phase of the reflection coefficient again becomes 180°, leading to ambiguities in the operation of the system.

The above limitations can be avoided if the phase measurement is made between a forward power coupler on the input line and an output port of the cavity. In this case, the angle which is measured is that of the vector representing the difference between the input signal and the reflection coefficient. This angle is zero at resonance and goes to $\pm 90^{\circ}$ off resonance, whether the cavity is over-coupled or under-coupled. Thus all ambiguities are avoided.

The phase measurement and conversion to voltage are readily performed by the Hewlett-Packard 8405A Vector Voltmeter. The phase recorder output terminal on the rear of the instrument provides a voltage proportional to phase. This voltage is used to drive the tuner motor which then holds the cavity to resonance at the applied frequency despite temperature changes within the cavity.

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