# OPERATION OF THE SPEAR RF SYSTEM*

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## Introduction

The SPEAR RF system has previously been described in these Transactions.[1,2] Therefore, only a brief description of the system is given here including a few additions and modifications, and most of the remainder of the paper is devoted to a discussion of the operation of the RF system with stored beams. A concluding section describes the improved RF system which is under design and construction, and which will permit operation of SPEAR at 4.5 GeV.

## Description of System

The RF system replaces the energy lost by synchrotron radiation during storage of beams. This energy loss ranges from 35 keV per turn at 1.5 GeV (the injection energy) to 370 keV per turn at 2.7 GeV. Over-voltages of about 1.5 times the radiation loss are required to give the phase stability necessary to maintain a long lifetime in the presence of quantum fluctuations.

## RF Cavities

Two accelerating cavities are installed in adjacent straight sections of the ring and are phased, using the stored beam, so that the gap voltages of the two cavities are additive. An outline drawing of the cavity is shown in Fig. 1. It consists of two quarter-wave capacitively loaded coaxial cavities with a common gap. The structure is made of welded aluminum (AL6061) and is completely evacuated. The cavity Q is 13,500, and the shunt impedance is 1 megohm. Tuning to compensate for thermal effects and reactive beam loading is accomplished by a water-cooled copper saddle-shaped tuner which operates on the fringing fields of the loading plates and is coupled mechanically to an external actuator through a stainless steel bellows.

RF power is carried to the cavity by a 6-1/8 inch diameter coaxial line, and coupled through a ceramic window and water-cooled loop situated close to one end of the cavity. The coupling to the cavity is fixed, though it can be changed by unbolting a vacuum flange and rotating the loop.

## Amplifiers

RF power is supplied by eight Collins linear amplifiers (four per cavity) operating at 51.22 MHz and each rated at 20 kilowatts continuous output. The output of each of four amplifiers is combined in four-port coaxial hybrid combiners.

## Phasing

For proper combination the phase of each amplifier must be adjusted. This is accomplished by a low-power phase shifter at the input to each amplifier. The phase stability of the amplifiers and combiners is such that only infrequent adjustment of the phasing is required.

## Oscillator

The RF oscillator for the system operates at 1.28 MHz, which is the rotation frequency of the stored particles in the ring. Originally the oscillator was a commercially manufactured voltage controlled crystal oscillator. This unit proved to have spurious outputs which caused coherent motion of the stored beam, so it was subsequently replaced by a vacuum tube LC oscillator. Later tests have shown that the stability of the beam is very critically dependent on the spectral purity of the RF oscillator and drive system. One of these tests involved substituting a very expensive commercial frequency synthesizer for the LC oscillator with disastrous results for stability. At this time the 1.28 MHz signal is being multiplied by a factor of 40 in a vacuum-tube frequency multiplier to generate the 51.22 MHz drive signal. Soon we hope to bring into service a SLAC-designed frequency synthesizer which will produce the 40th, 78th, 120th, 121st, and 122nd harmonics of the 1.28 MHz fundamental. The 40th harmonic, as stated above, is used for the main RF system, the 78th harmonic is used for a beam position feedback control system and several other timing functions; the 120th, 121st and 122nd harmonics are to be used in a VHF cavity whose function is described in a later section.

## Automatic Tuning

Tuning of the cavity is controlled by a feedback system. A phase comparison is made between the signal incident upon the cavity, and a small sample of the signal transmitted through the cavity. Any departure from a zero phase condition results in a control signal of the proper polarity which is applied to a stepping motor which in turn drives the cavity mechanical tuner. In this manner, compensation for reactive beam loading is automatically attained.

## Gap Voltage Control

An automatic gap voltage control system controls the cavity gap voltage to within about 0.3%. The same transmitted signal sample used in the tuning control system is compared to a dc reference, and the difference signal is used to control a low-level PIN diode attenuator which controls the RF drive level to the high power amplifiers. This attenuator exhibits quite low phase shift over a wide range of attenuation, a necessary feature in order to maintain proper phasing between the two cavities.

## Block Diagrams

Block diagrams of the power distribution system, the gap voltage control system and the tuning control system are shown in Figs. 2, 3, and 4.

## Operation of the System

### Results

Perhaps the best measure of the success of the SPEAR RF system is that luminosities of $1 \times 10^{31}$ cm$^{-2}$ sec$^{-1}$, at energies of 2.6 GeV have been attained. We have also successfully stored a single beam at 2.75 GeV. Stable beam currents of over 100 mA in a single bunch have been achieved. Operation at these energies and currents implies gap voltages for each cavity of 275 kV, power into cavity wall losses of 38 kW per cavity, and power into the beam of up to 30 kW.

### Problems

From the viewpoint of the machine physicist, we believe that the operation of the RF system has been smooth and dependable. This opinion, and the successes reported above do not, however, obscure from the RF system engineers the fact that there have been difficulties of various kinds, and it is probably of some interest to briefly describe these problems.

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Both RF cavities have exhibited an instability at gap voltages of 175 to 210 kV. This instability manifests itself in the form of sudden gap voltage changes (in the absence of gap voltage control) and a change in input coupling coefficient as the input power is increased.

We suspect that a multipactor discharge is taking place between the end of the input coupling loop and an adjacent section of the cavity center conductor. The only effect of the instability is a reduction in the apparent shunt impedance of the cavity.

Both cavities have also displayed limitations upon the maximum average power that can be applied to them, for two reasons. The tuner is required to compensate for dimensional changes resulting from RF heating, and in so doing runs into its mechanical limits of travel at about 275 kV or 38 kW. This problem was temporarily solved by removing some cooling from the cavity outer shell, thus improving the self-compensating characteristics of the cavity. Unfortunately, the removal of cooling led to rather high temperatures on the tuner and window flanges and on the outer shell itself (on the order of 160° C), and although from the standpoint of tuner travel it became possible to operate at 300 kV (45 kW), a second problem manifested itself.

After operation for about 45 minutes at 300 kV (45 kW), one of the cavities developed a small leak between the evacuated region and an air passageway near the periphery of the loading plates. Fortunately, it was possible to place a vacuum pump on this air passageway, and aside from losing a measure of security from a possible water to vacuum leak in this area, the cavity remains entirely operational. The same type of failure, apparently due to excessive heating on the edges of the loading plates, was also encountered in the other cavity during its initial tests over a year ago.

It should be mentioned in passing that these cavities emit very strong x-ray radiation (on the order of 6 R per hour), and for this reason no entry to the ring housing is permitted during high power operation of the cavities, even when no beam is being stored.

Another problem which has been with us for as long as we have been working with this type of cavity is that of multipactor, or secondary electron resonance, which presumably takes place between the loading plates. This has been a particularly troublesome problem with new, freshly assembled cavities. The loading effect of the multipactor discharge is so severe as to limit the amount of power which can be forced into the cavity, because of impedance mismatching. The effect generally occurs between about 200 mW and 40 W of applied power, or between about 600 and 9000 volts across the gap. We have uniformly found it impossible to turn on a cavity until the internal pressure reaches the $10^{-7}$ Torr range, and this range in turn can only be reached by exercising the utmost care in keeping the cavity clean during assembly, and by RF processing after assembly with pulsed RF. We have found empirically that pulses of about 150 $\mu$s at 100 pulses per second and at about 10 kW peak are most effective in processing the cavities.

It has also been necessary to develop techniques for turning the cavity on in routine operation, even after the initial processing, and for ease of operation it has been necessary to automate the entire turn-on process. Briefly, the cavity is first turned on at about 100 mW, and the automatic tuning system is given several seconds' time to tune up the cavity. RF power is then completely removed for a few milliseconds, long enough for the fields within to completely die away, and then the RF power is again applied at high level, 20 kW or so. Solid-state gating circuits are used in this operation, since it was found that relays, with contact bounce, did not permit field buildup to occur rapidly enough to overcome the multipactor effect.

## Vacuum Performance

The vacuum performance of the cavities has been excellent. One cavity was baked at 160°C. The other has not been baked. Both have received the same RF processing, with some areas reaching 160° C from RF heating. Both cavities display a nonoperating pressure of about $3 \times 10^{-9}$ Torr, and operating pressures typically in the region of $1 \times 10^{-8}$ Torr or better.

## Calibration of Gap Voltage

Measurements of the cavity Q and R/Q have resulted in a calculated shunt impedance of over 1 megohm. The power applied to the cavity (corrected for reflections from deliberately introduced over-coupling) was measured using carefully calibrated directional couplers, and the gap voltage was then calculated. This calculation was verified by making measurements of stored beam lifetime as a function of gap voltage, in comparison to theoretical values, and it was found that the two methods confirm each other to better than 10%. We now feel that use of the beam lifetime is the most accurate method we have for calibrating the gap voltage.

## Beam - RF System Instabilities

In two papers some years ago,[3,4] K. W. Robinson described beam-RF system instabilities related to the tuning and coupling conditions of the RF cavity. In brief, Robinson derives two differential equations describing the RF system and two differential equations describing beam motion. These four equations are coupled by their coefficients. This system of four coupled equations is tested for stability, and a stability condition is derived:

$$0 < \sin 2\phi_y < 2 \frac{V_S}{V_B} \cos \phi_{BS} \qquad (1)$$

in which

$\phi_y$ = phase angle of the cavity admittance

$V_S$ = cavity gap voltage due to RF source

$V_B$ = beam induced gap voltage

$\phi_{BS}$ = synchronous phase angle

Figure 5 illustrates this stability condition. At very small beam currents $V_B$ is small, and the line $2(V_S/V_B) \cos \phi_{BS}$ does not intersect the plot of $\sin 2\phi_y$ vs. $\phi_y$. Hence, the system is stable for all values of $\phi_y$ between 0 and $\pi/2$. At heavy beam loading, two stability regions exist. Normally, only the one near $\pi/2$ is used, since it is in this region that $\phi_y$ must be placed so as to cancel the reactive component of beam loading.

If the cavity is tuned so as to compensate for reactive beam loading, but is not matched to the RF source, then the stability condition can be written as:

$$\sin 2 \tan^{-1}\left[\frac{(P_B/P_D) \cot \phi_{BS}}{2 + (P_{BM}/P_D)}\right] < \frac{P_D}{P_B}\left[2 + \frac{P_{BM}}{P_D}\right] \sin 2\phi_{BS} \qquad (2)$$

in which

$P_B$ = power delivered to the beam

$P_D$ = power dissipated in cavity wall losses

$P_{BM}$ = power delivered to the beam which will cause the cavity to be matched

$\phi_{BS}$ = synchronous phase angle

If the conditions of Eqs. (1) or (2) are violated, the results are phase oscillations of the beam.

In SPEAR we have been able to verify that at least one of these instabilities occurs as predicted. At very low beam loading a deliberate detuning of the cavity above the driving frequency induces phase oscillations. In the normal operation of SPEAR, the heavily loaded condition of Fig. 5 is not reached. In fact, attempts to reach this condition by filling eight of the forty available buckets have consistently resulted in loss of substantial beam current at levels slightly below the desired beam loading. We conclude that there is an as yet undiagnosed instability associated with very heavy beam loading which may be controllable by the application of phase feedback as described below.

## Control Systems

Two types of systems are employed to damp the growth of possible longitudinal instabilities. The first is phase feedback[5] on the main RF system and the second is the use of a cavity at a high harmonic number[6] to modify the characteristic of the RF buckets.

### Phase Feedback

The phase feedback system is shown in Fig. 6. A pickup electrode which is responsive to the radial position of the beam provides the input to an electronic phase shifter placed at the input of a group of four amplifiers which drive one cavity. Since the radial position of the beam is related to small changes in beam energy, $\Delta E/E$, and $\Delta E/E$ in turn contains the beam phase information, the output signal from the radial position monitor electrode is precisely the signal required for input to the phase shifter. Amplitude and phase adjustment is provided for this signal (which typically is in the range of 5 to 10 kHz) before it is applied to the phase shifter input. We have been able to deliberately induce phase oscillations with the feedback turned off, and then completely damp these oscillations by the application of feedback. However, by compensating for reactive beam loading the beam has always been stable up to 100 mA of single bunch current and 200 mA of multibunch current and thus the phase feedback system is not normally used. At heavier beam loading we might encounter instabilities which the feedback system will, hopefully, suppress.

### High-Harmonic Cavity

In one of the straight sections of SPEAR a ceramic gap has been installed. This gap separates two electrodes in the vacuum system across which a longitudinal field may be applied. A resonant cavity has been built around the gap outside the vacuum system and the cavity can be energized at frequencies corresponding to harmonic numbers h = 120, 121, and 122 — the main RF system is at h = 40. Manual coarse tuning allows operation at these three harmonic numbers and automatic fine tuning can adjust the frequency of the cavity to allow for beam loading. The cavity has been run at up to 10 kV in testing without a stored beam, but has not yet been run with beam. At h = 120 (the 3rd harmonic of the RF frequency) its purpose will be to modify the potential well of the RF system to increase the Landau damping for longitudinal oscillation. At h = 122 a difference of synchrotron oscillation frequency between the $e^+$ bunch and the $e^-$ bunch can be obtained without shifting the collision point. This might stabilize a non-barycentric mode of oscillation involving both bunches if it occurs.

## Improvement Program

An improvement program is under way to increase the maximum energy of SPEAR to 4.5 GeV. The magnets in the ring are capable of operating at fields corresponding to this energy, but with the addition of new power supplies. At 4.5 GeV the radiation loss per turn is 2.8 MeV and, thus, peak voltages of several million volts are required to store the beam. The present RF system is inadequate to provide this voltage. Furthermore, the present RF cavities are far from an optimum design which at the present RF frequency would have required a cavity of several meters in diameter. Since the straight section space available for the cavities is strictly limited, a cavity design which geometrically optimizes the shunt impedance per unit length is required and, hence, to have mechanically acceptable designs of cavities an RF system of a much higher frequency is required. The lower limit of frequency for a reasonable size cavity is about 200 MHz. As the frequency goes up the over-voltage demand to contain quantum fluctuation increases, but also, the available shunt impedance per unit length increases, thereby compensating for the necessary over-voltage. However, a large beam aperture is required to accommodate the beam excursions at injection and as the frequency goes up this degrades the available shunt impedance obtainable. An assessment of available tubes for this requirement resulted in a decision to use klystrons, and to accommodate klystrons as high a frequency as possible was chosen and this frequency is the 280th harmonic corresponding to a frequency of 359 MHz. Four straight sections are available for RF cavities and cavities are being designed based on the Los Alamos design. Each straight section will accommodate five cavities of this design. They will be coupled together by two circumferential slots in each of their common walls and operate in the $\pi$-mode. Computer studies and preliminary cold tests indicate that 100 megohms will be obtained from the 20 cavities. The cavities are being designed to dissipate a total of 300 kW of RF power in wall losses. Each group of five cavities will be energized by a single 125 kW CW klystron. The accelerating cavities and the klystrons are presently under design at SLAC and it is planned to have the new RF system operational in the autumn of 1974. A conceptual drawing of the cavities is shown in Fig. 7.

## Acknowledgements

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## References

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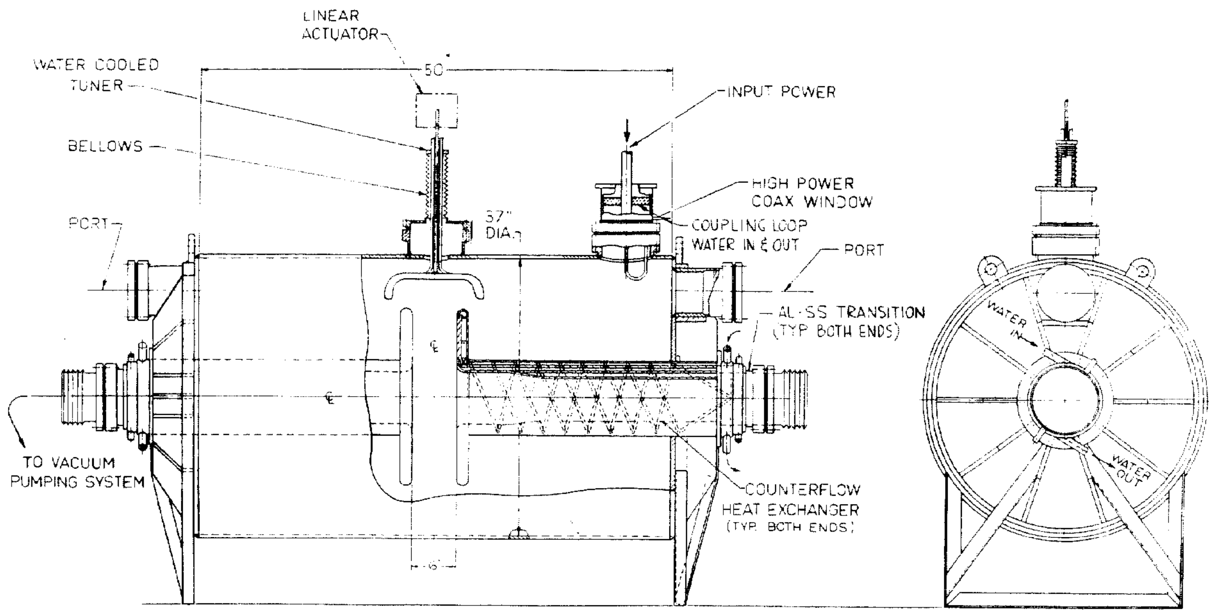


FIG. 1--RF cavity.

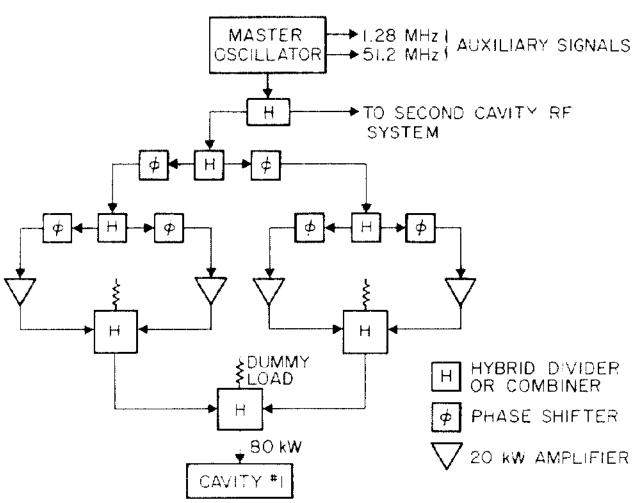


FIG. 2--RF power distribution system.

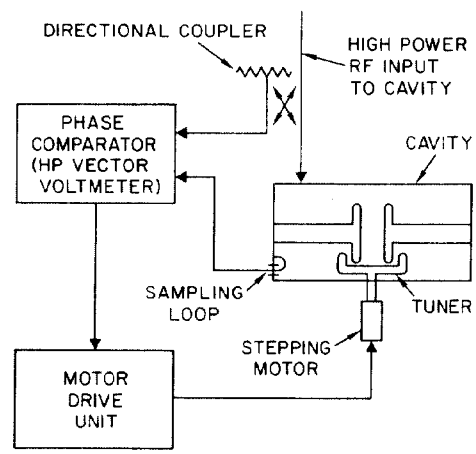


FIG. 3--Cavity tuning control system.

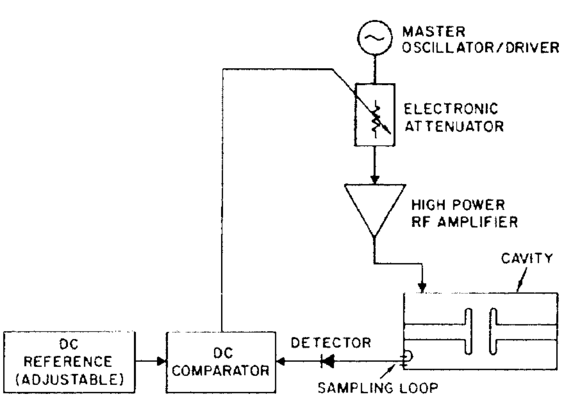


FIG. 4--Gap voltage control system.

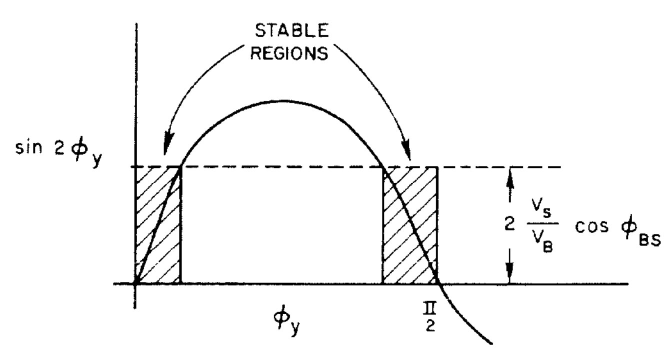


FIG. 5--Stability condition for heavy beam loading.

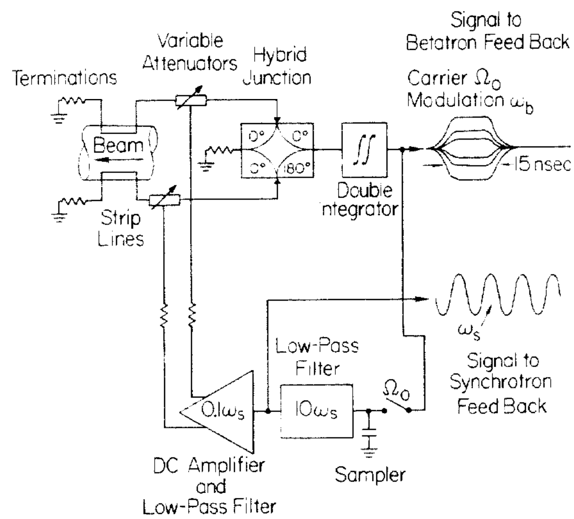


FIG. 6--Phase feedback system.

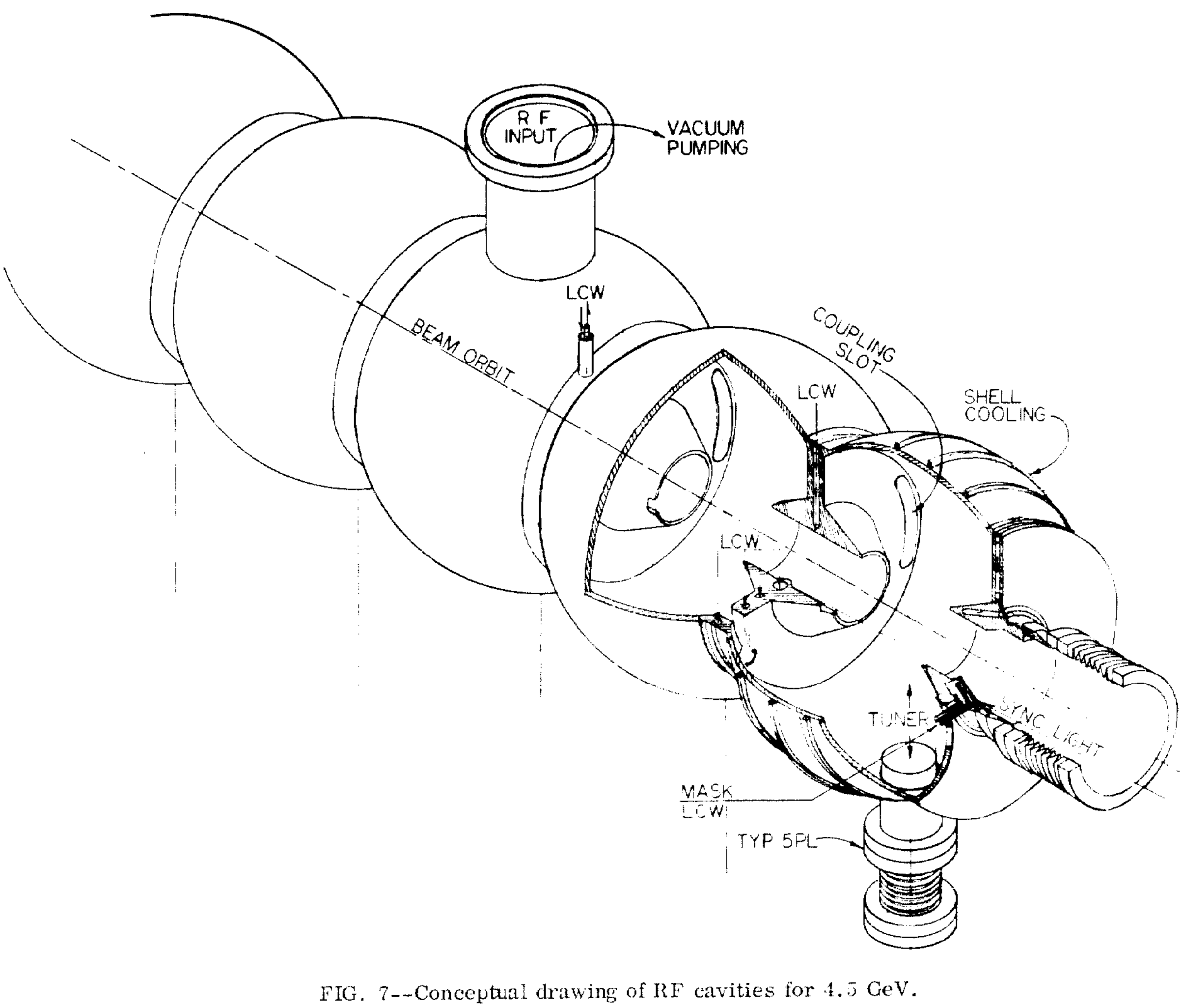


FIG. 7--Conceptual drawing of RF cavities for 4.5 GeV.