DESIGN AND OPERATION OF THE SPEAR II RF SYSTEM*

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Introduction

The SPEAR storage ring was initially designed to operate at an energy of 2.5 GeV but with a capability built into the magnets for operation above 4.0 GeV. To operate at these high energies, a completely new RF system was necessary. Four straight sections were available to provide the over 7 megavolts of RF necessary. A frequency of 358 MHz was chosen with a decision made to use klystron amplifiers for the power tubes. Design considerations have been given in earlier papers.[1,2]

Cavities

The RF accelerating voltage is provided by 4 accelerator sections in each of the 4 straight sections of the storage ring. Each accelerator section consists of 5 coupled cavities operating in the π mode at the 280th harmonic of the ring frequency, 358.5 MHz. A schematic of an accelerator section is shown in Fig. 1. The shunt impedance is approximately 18 megohms ($V^2/2P$). The cavity is constructed from 6061 aluminum alloy. The end walls of the cavities are machined from forgings. Coupling is provided by azimuthal slots in the common-end walls and cooling is provided by means of radial cooling channels bored in these forgings close to the nose cones. Each section is designed to dissipate over 75 kW of RF power. The outer shells were rolled from aluminum sheets and their cooling is provided by channels welded externally. Each cavity is provided with a water-cooled tuner with a tuning range of 1.2 MHz. All 5 tuners are ganged together and driven by a single motor. Coupling of RF power is by means of a water-cooled loop in the center cavity. Power is fed to the coax loop from WR 2100 waveguide through a coax to waveguide transition which consists of a cylindrical ceramic window as shown in Fig. 1. This window was developed for the high power klystron.[3] During initial testing of the accelerator section, severe multipactoring problems were encountered. The cavity was then coated with titanium nitride. A layer between 100 and 1000 Å was applied by evaporating a source of titanium in each cavity in a partial pressure of 2×10^{-5} Torr nitrogen.[2] This completely cured the multipactoring problem. Two 400 liter per second pumps are provided at the pumping ports located above the coupling loop. A photograph of one of the four accelerating structures is shown in Fig. 2. Close to the mode there are four other possible modes of operation shown in Fig. 3. None of these modes lies close to harmonics of the ring frequency so none is expected to interact with the beam during operation. A single resonant cavity similar to a single cell of an accelerator section is fabricated from an aluminum forging. It operates at 476 MHz and acts as a synchrotron frequency splitter to stabilize a nonbarycentric mode of oscillation of two bunches if it should occur. The cavity is designed to dissipate over 30 kW of RF power. Coupling is by means of an RF loop similar to that of the main section. The cavity is fed by 6" air-filled coax line with the same coaxial input window as used in SPEAR I.[1] A photograph of the cavity installed in the ring is shown in Figure 4.

Klystron and Power Supply

Each accelerator section is powered by a CW 130 kW klystron which was developed at SLAC. The klystron is fully described elsewhere in the Proceedings[3] and its operating parameters are given in Table I. The klystrons, as shown

in Figure 5, are housed in structures adjacent to the ring housing. The power is delivered to the structures by means of WR 2100 waveguide which penetrates the housing.

TABLE I
KLYSTRON CHARACTERISTICS

Frequency	358.54	MHz
Instantaneous Bandwidth (1 dB Points)	0.5	%
Beam Voltage	41	kV
Beam Current	6	A
RF Output Power	125	kW
Duty Factor		CW
Gain	50	dB
Efficiency	50	%
Load VSWR	Up to 2:1 at any phase angle	

Each klystron is run with its own separate power supply. The power supply furnishes 47 kV and 8 amps with regulations provided by a 100 kW tetrode (4 CW 100,000 E) as a series pass tube.

Instrumentation and Control

Drive Signals

The drive signal for the RF system is derived from a master oscillator which provides 1.28 MHz, 358.5 MHz, and 476.3 MHz signals corresponding to the 1st, 280th, and 372nd harmonics of the ring frequency. The 358.5 MHz signal is split four ways for transmission to the klystrons via phase-stable foam-dielectric coaxial lines.

Phasing

Phase adjustments among the four klystrons are made by an electronic phase shifter employing varactor diodes in shunt across a strip transmission line. The phase shifter is capable of providing 180° shift at the 100 MW level. This phase shifter and all other low level RF components are located in an "RF chassis" in the klystron hut. The phase shifter is controlled from the main operating position. Electrically, the phase shifter is located just after the division of the drive signal into its four paths, and just before a number of other phase shifters, attenuators, modulators, and amplifiers in the low-level RF path. This phase shifter will subsequently be referred to as the "branch" phase shifter.

Phase Lock

Since many of the components in the RF system are subject to phase shift because of thermal effects or as a result of the control signals applied to them it was found necessary to lock the phase between the klystron output and an early point in the RF drive path. Immediately following the branch phase shifter, a reference signal is obtained from a 3 dB power splitter. This signal is sent to a Hewlett-Packard 8405A Vector Voltmeter. A second signal is sent to the Vector Voltmeter from a directional coupler located very near the RF cavity, and the Vector Voltmeter continuously performs a phase measurement of the two signals. A dc

control voltage proportional to phase is derived from the Vector Voltmeter, and after amplification and offset is sent to two phase shifters in cascade which are identical in design to the branch phase shifter described above. These two phase shifters provide ± 180° shift and, when the system is locked, maintain phase lock to within ± 4°. Remote readout of phase lock is provided in the control room. In passing, it should be mentioned that the klystron rotates through thousands of degrees of phase shift as its collector voltage is increased from the tuneup value of 20 kV to the operating value of 40 kV, and, to ensure phase stabilization of this component alone, some kind of phase lock circuit is necessary.

Phase Modulation Capabilities

The RF drive system is capable of being phase-modulated at up to several hundred kilohertz via another electronic phase shifter of the same design as the branch phase shifter. In this case the phase shifter is permanently biased at a favorable operating point, and an ac coupled input to its controlling amplifier is used to produce phase modulation. It was intended that this capability would be used to control longitudinal beam instabilities, as was done with success in SPEAR I.

Gap Voltage Control

A gap voltage feedback control system has been incorporated to stabilize the cavity gap voltage against beam loading effects and against changes in klystron output power. After filtering through a 400 MHz cutoff low pass filter, a diode detector rectifies a small RF sample signal from the cavity, and produces a dc voltage proportional to the gap voltage. This sample is compared to a reference signal in a comparator, and the difference signal is used to control an electronic attenuator in the low level RF drive path. This attenuator provides about 18 dB of attenuation with about 30° of phase shift, the phase shift of course being compensated by the phase lock circuit.

Cavity Tuning Control

The same tuning system which was used in SPEAR I has been applied to SPEAR II.[1] This system compensates for changes in driving frequency, thermal effects, and beam loading.

Synchrotron Splitting System

The synchrotron splitting system is used to impart different synchrotron frequencies to each beam, and thus stabilize against π-mode longitudinal oscillations of the beams.[4] This system operates on the 372nd harmonic of the ring frequency, or 476.3 MHz. Five kilowatts in the cavity provides 20% splitting.

Tuner Position Readout

A very simple electromechanical readout system has been devised to give an indication of cavity tuner position. A linear potentiometer with a travel of nine inches is mounted on the cavity. The arm of the potentiometer is attached to the tuner mechanism. A regulated power supply provides nine volts dc across the potentiometer, and a digital voltmeter then reads the voltage from arm to low end. The readout is accurate to about .001 inch, and has been most helpful for setting unused cavities off resonance at specified repeatable positions, and for spotting difficulties in the tuner system.

Operational Experience

Klystrons

Initially, problems were encountered with instabilities in the klystrons when the tubes were operated at less than drive saturation. Careful adjustment of focusing and tuning in the klystron has brought about the elimination of most instabilities. The klystron performance is critically dependent upon load impedance.

Cavity Performance

With several violently manifested exceptions, cavity performance in the main RF system has been good. In one instance several tuners were destroyed by melting. This was the result of poor mechanical connections between several tuners and their heat sinks. Subsequently, all tuners were modified in design and brazed to their heat sinks. In another incident one of the cylindrical ceramic windows which couple the waveguide to the cavity cracked, letting the entire ring up to substantially atmospheric pressure. The cause is thought to be a deposit of carbon on the window, which caused excessive localized heating and resulting thermal stress.

Another problem in the cavities has been field tilt. An unbalanced condition occurs and grows, sometimes in a runaway fashion, in which more and more power appears at one end of the cavity, with less and less at the opposite end. Careful balancing of levels at high power by adjustment of individual tuners has alleviated this condition.

Vacuum performance of the cavities has been excellent. New cavities turn on with about 10^{-6} Torr pressure. After conditioning in the ring with beam several cavities now operate in the 5×10^{-9} Torr range.

Gap Voltage Control

The gap voltage control system has resulted in regulation of the gap voltage to within about 0.4%. Although the electronic attenuator has a range of 18 dB, the system has a range of only 10 dB, due to gradual saturation of the klystron, with a resulting gap voltage range of only about 3:1. Because rather low gap voltages are necessary for injection, while high voltages are required for high energy conditions, this limited range of control will have to be improved. In addition, the gap voltage control system and the residual instabilities in the klystrons seem to work hand-in-hand to produce RF system instabilities, particularly at the low and high extremes of the control range. This problem is not entirely understood as yet.

Recently the gap voltage control system was placed on computer control. This has enabled us to hold the synchrotron frequency constant while ramping in energy, and thus avoid various synchrobetratron resonances.

Synchrotron Feedback System

The capability of phase modulation feedback was mentioned above. In SPEAR I we had a highly successful phase feedback system which worked from the moment the loop was closed. Unfortunately, such has not been the case in SPEAR II. When phase modulation is applied to the SPEAR klystron, there results an accompanying amplitude modulation, apparently due to an interaction between the klystron, which delivers significantly more power into lower than normal load

impedances, and the cavity impedance characteristic on and off resonance. For very small beams and low amounts of phase feedback, the system behaves normally. For larger values of feedback, the amplitude modulation excites the stored beam. A simple but very expensive solution would be an isolator between klystron and cavity. Before going to that solution we are looking at amplitude modulation feedback circuits which would cancel the undesired AM, and at phase feedback applied to the synchrotron splitting system, which has an isolator.

References

1. M. A. Allen and R. A. McConnell, "Operation of the SPEAR RF System," IEEE Trans. Nucl. Sci. NS-20, No. 3, 373-377 (June 1973).

2. M. A. Allen and P. B. Wilson, "RF Systems for High Energy e⁻e⁺ Storage Rings," Proc. IXth Int. Conf. on High Energy Accelerators, Stanford Linear Accelerator Center, Stanford, Calif., May 2-7, 1974 (CONF-740522, available NTIS), p. 92.

3. G. T. Konrad, "High Efficiency, CW, High Power Klystrons for Storage Ring Applications," this proceedings.

4. M. A. Allen, M. J. Lee, and P. L. Morton, "Synchrotron Frequency Splitting in the SLAC Storage Ring," IEEE Trans. Nucl. Sci. NS-18, No. 3, 1084-1085 (June 1971).
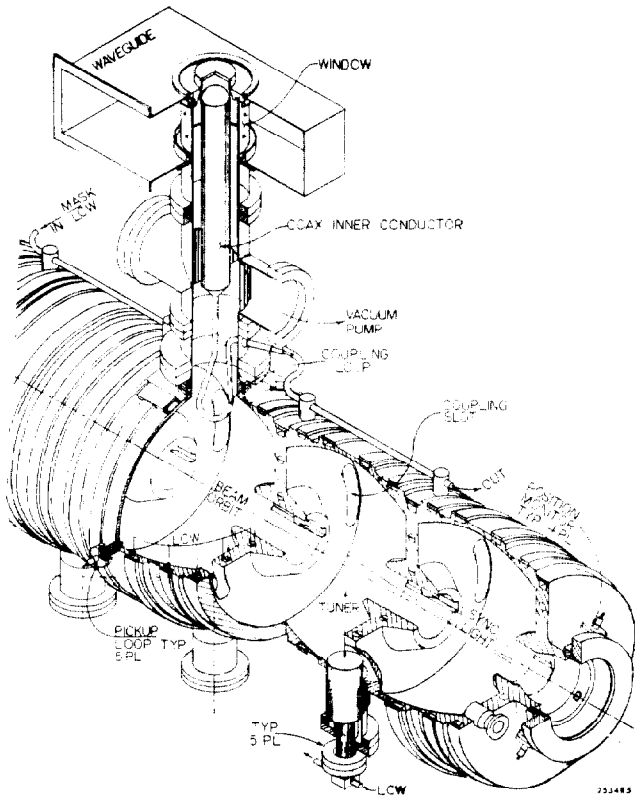
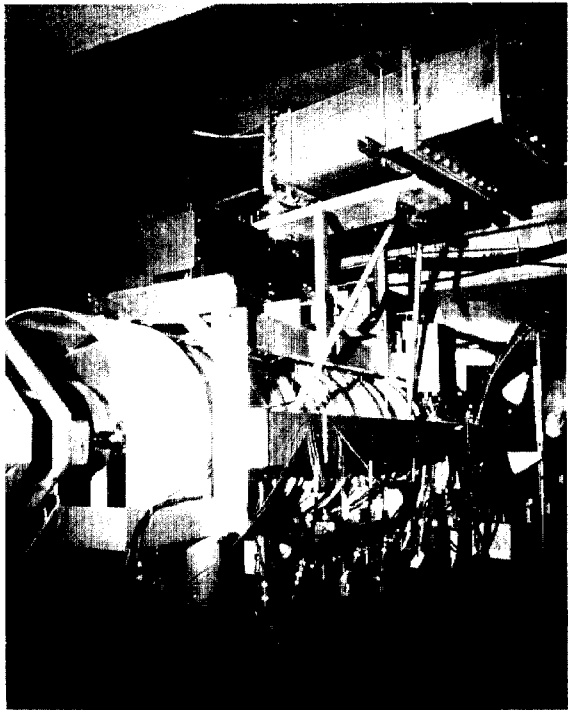FIG. 1--Cutaway drawing of accelerating section.

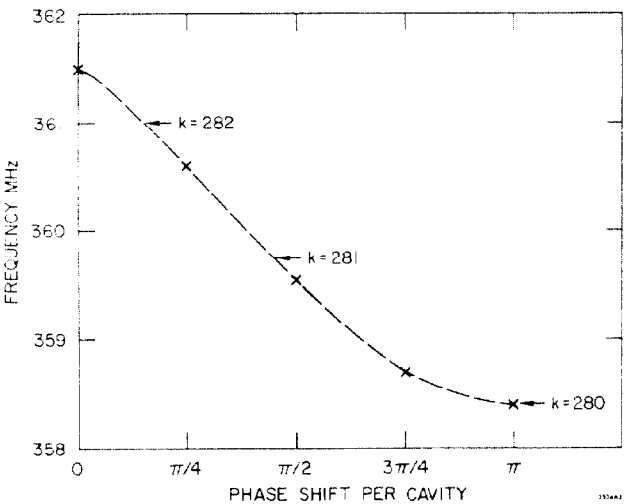FIG. 2--Photograph of accelerating section as installed.

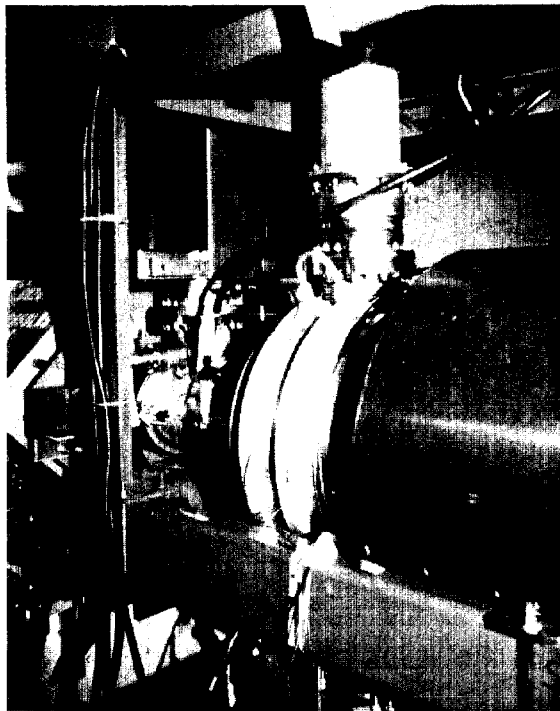FIG. 3--Diagram showing five main resonances of accelerating structure.
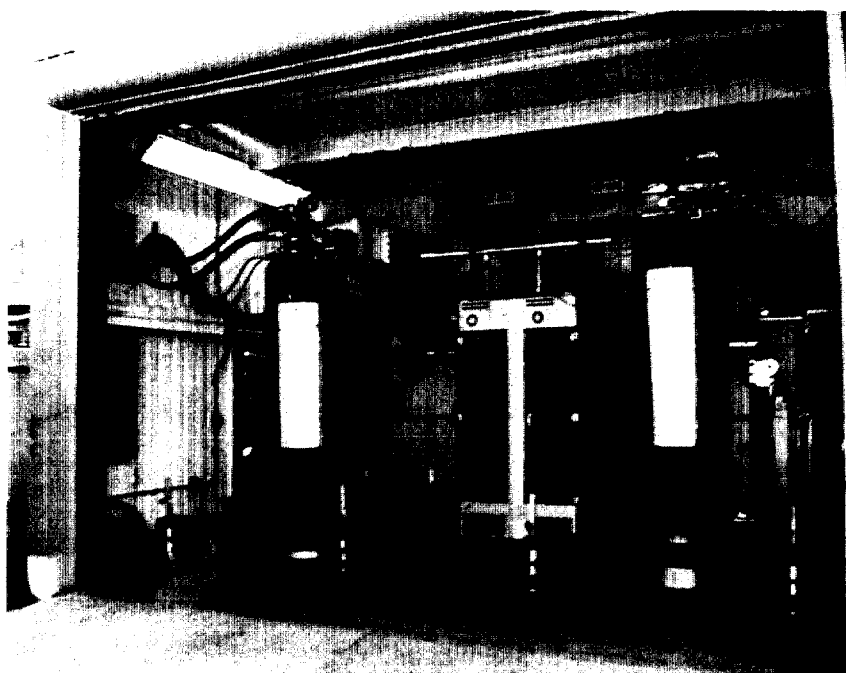
FIG. 4--Photograph of synchrotron-splitting cavity
as installed.

FIG. 5--Two klystrons installed in a klystron hut.