RF SYSTEM DESIGN FOR THE SLAC STORAGE RING*

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Summary

In the proposed SLAC electron-positron storage ring, two one-ampere, 3-GeV beams will radiate energy at the rate of 1.13 megawatts with 880-kV peak voltage required for storage. This energy is restored through a six-cavity rf system operating at 50 MHz, the 36th harmonic of the rotation frequency. Of the total power over 90% will be delivered to the beams with the remaining part to the cavities and their associated networks. An experimental ultra-high vacuum cavity designed to operate at 200 kV peak across its accelerating gap and capable of dissipating 20 kilowatts in wall losses is described. The requirements of an automatic tuning and coupling system which will match continuously the cavity and the beam to the amplifier output are discussed.

Introduction

The SLAC storage ring is designed to have a bending radius of 12.7 meters and a magnetic field of 7.86 kilogauss. At 3 GeV, each charged particle will radiate 563 keV per revolution; thus, with one ampere each of electrons and positrons, the radiation demand will be 1.13 megawatts. Sufficiently high peak voltage is required to contain quantum excited phase oscillations with a lifetime of 10^6 seconds. The filling time at 3 GeV is one second, with longer times at lower energies and increased currents. An rf system is being designed to meet these requirements.

Choice of Frequency

The required peak voltage of the rf system is set by the excess voltage needed to contain the quantum excited phase oscillations. This excess voltage depends, among other factors, on the frequency of the rf system. Quantum lifetime calculations[1, 2] modified for a separated-function machine have been made. The rf voltage as a function of frequency to obtain a lifetime of 10^6 seconds, which is considered adequate, is given in Fig. 1. At a frequency of 50 MHz, a voltage about 50% higher than the voltage to make up for the radiation losses is necessary. For frequencies close to 500 MHz about three times as much rf voltage is required as at 50 MHz. However, higher shunt resistances are obtainable in cavities at the higher frequencies and thus the power dissipated in the cavity would be comparable at 500 MHz and 50 MHz. The stability of the beam-cavity system against growing coherent phase oscillations requires the cavities to be tuned below the driving frequency. The tolerances on tuning and matching are generally easier to achieve at lower frequencies where the required synchronous phase angle (which lies in the second quadrant) is smaller and the shunt resistance of the cavities is lower. Furthermore, the higher frequency systems are more costly mainly due to the higher cost of components. Thus mainly on economic grounds, it was decided to use a 50 MHz system with the exact choice of 50 MHz resulting from the required guide field configuration.

Power Requirements

It is necessary to supply 1.13 megawatts to the beam with a peak voltage per revolution from Fig. 1 of, at least, 850 kilovolts. It is convenient to develop this power in six independent output stages supplying resonant cavities in each of six available straight sections. Each cavity will develop a peak voltage of 145 kilovolts and each rf source will generate 190 kilowatts in addition to cavity and network losses of about 20 kilowatts. For the final amplifier it is planned to employ a tetrode tube rated at 250 kilowatts plate dissipation at 50 MHz. These tetrodes can be operated as linear AB amplifiers with 55% plate efficiency, yielding rf output powers of over 300 kilowatts which is well above the desired output power of 210 kilowatts for each rf source. Power amplifiers at these high continuous-wave operating power levels have been manufactured for broadcasting purposes. However, the problems of the design of a cavity at the required voltage and power dissipation levels are less understood and it is necessary to build an experimental model.

Cavity Design

Each straight section of the storage ring has an available free space of about 2 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 vacuum pumps, and simplifying the design of rf couplers and tuners. Several types of ceramics were investigated. The high dielectric losses due to the large voltages in the region where the windows must be situated, lead to large thermal stresses, and make this approach undesirable.

Since the vacuum chamber of the rest of the ring will be constructed out of aluminum, and the problem of transition from aluminum to stainless steel has been solved, it is feasible to use an all-vacuum cavity constructed from aluminum. The prototype cavity design is shown in Fig. 2. This cavity has a design Q of 12000, a shunt resistance of 700 kilohms and consists of two quarter-wave capacitively-loaded coaxial cavities with a common high-voltage gap. The overall length is 57-1/2", the outer and inner conductor diameters are 37" and 10" respectively and the gap spacing is 6". A one-quarter scale model at 200 MHz was constructed from copper with soldered joints, and measurements confirmed the design Q and shunt impedance. Also, all high-order modes with field in the beam region were mapped up to a frequency whose wavelength is comparable to the bunch length at 3 GeV (28 cm). None of these higher order modes were close to a harmonic of the fundamental frequency. The material of the prototype cavity is 6061-T6 aluminum and all joints are fusion welded with an inert-gas-shielded tungsten arc (TIG) process. The welds are of ultra-high vacuum

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quality with careful precautions taken to eliminate voids and sub-surface defects. The cavity is designed to withstand vacuum bakeouts of 250° C. The outer wall thickness is one-half inch and the reinforced end plates are 5/8-inch thick. The counter-flow heat exchanger on the center conductor is designed conservatively to handle 15 kilowatts dissipated power. All connections to the outside are by means of aluminum-to-stainless steel ultra-high vacuum flanges employing aluminum foil gaskets. A coaxial input vacuum window, originally designed for a high-powered klystron, is used. The necessary frequency tuning 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. Two glass viewports are incorporated for observation of the cavity interior during high voltage testing. The surfaces in the region of high voltage all have extremely smooth finishes. Figures 3 and 4 are two views of the cavity during construction.

Cavity Tuning and Matching

A simplified schematic equivalent circuit of the output stage is given in Fig. 5. The fixed coupler matches the cavity to the tube in the absence of the beam and the variable coupler provides for matching as the beam current increases. It is required that the current from the generator be in phase with the voltage across the gap and that there is maximum power transfer to the beam. These requirements give

$$n^2 = 1 + \frac{P_b}{P_c} \qquad \text{and} \quad \tan\theta_c = \frac{P_b{}'}{P_c}\,\mathrm{ctn}\,\phi$$

where P_b is the power transferred to the beam, P_c is the power dissipated in the cavity, θ_c is the phase angle of the cavity admittance and ϕ is the synchronous phase angle. For stored beams of one ampere each of electrons and positrons at 3 GeV and with 7.5% of the power going to the cavity losses, n^2 is 13.2 and tan ϕ_c is 14.6. This means that during filling the cavity must be tuned through about seven unloaded band-widths to fill to the design current at 3 GeV. Figure 6 shows the required detuning as a function of beam current. Figures 7 and 8 show the input standing-wave ratio and the forward and reverse power level in the cavity input transmission lines under the following conditions:

(a) The cavity gap-voltage is held constant.
(b) The cavity is resistively matched at a beam current of 2 amperes.
(c) The cavity tuning is always adjusted so that the reactive part of the load impedance is zero.

It is seen that both tuning and coupling should be continuously varied during filling of the ring in order to maintain a favorable load-impedance for the rf source.

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

(a) The tuner must provide a range sufficient to accommodate the beam loading effects shown in Fig. 6.
(b) The tuner must be able to compensate for thermal effects.
(c) The tuner should have negligible effect on the unloaded Q of the cavity.

A prototype tuner has been designed and is under test. The tuner is an inductive paddle inserted through a slot in the cavity wall as shown in Fig. 2. Preliminary results indicate that it is quite easy to obtain an 80 kHz change in frequency with only a 5% change in Q.

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

(a) The coupler must be continuously variable during the filling of the ring.
(b) The coupler must be capable of matching impedances over a range of 13 to 1.
(c) The coupler must be capable of transferring 200 kilowatts cw power with as little loss as possible.
(d) The coupler is required to perform resistive impedance transformations only, with all reactive adjustments being accomplished by the cavity tuning control.

The difficulties of placing a coupler with these requirements within the vacuum system have led to a preliminary design in which a fixed coupling loop is placed inside the cavity, with a variable coupler located immediately outside. Among the couplers under consideration are the L network, and several versions of swinging links.

The possibility of using a fixed coupler is also being considered. Since only 1 second is required to fill the storage ring to two amperes, high VSWR's exist for time intervals less than 1 second, as can be seen from Fig. 7. When the storage ring is run at lower energies (1 GeV) and higher currents the filling time is much longer because of limitation on the positron current supplied by the accelerator. However, the period of time for which the high VSWR's exist can be substantially reduced by filling with electrons first. Furthermore, even at high VSWR's the reflected power is small relative to the dissipation capabilities of the rf sources, so that it may be possible to use a fixed coupler and ignore the transient conditions at low beam currents.

It is interesting to note that if resistive matching is performed for a beam current of 1 ampere, the VSWR, r, at that point is reduced from r = 1.86 to r = 1. Every point on the VSWR curve in Fig. 7 is altered by this same factor, so that at zero beam current we obtain r = 7.09, and at 2 amps we obtain r = 1.86. A fixed coupler involving this sort of compromise may be an acceptable solution to the coupling problem.

With six cavities to be adjusted in tuning and coupling in a time of 1 second, it is apparent that the adjustments must be automated. Since the cavities are to be connected to their rf sources by a short length of 50 ohm transmission line, it is possible to derive information from the standing-wave pattern on the line which can be used to control tuning and coupling. Four diode detectors sample the line current at 1/8 wavelength intervals from the reference plane of the cavity. The difference signal from the detectors located at the $\lambda/8$ and $3\lambda/8$ positions yields a discriminator type of curve which can be used to control the cavity tuning. The difference signal from the detectors located at the $\lambda/4$ and $\lambda/2$ positions yields a function which can be used to control the coupling. The dc difference signals are chopped, amplified, and used to control 2-phase 30-cycle motors which drive the tuning and coupling mechanisms. The circuitry to convert the dc signal to ac has been taken almost in its entirety from circuits developed for the automatic phasing system of the Stanford two-mile accelerator.[3]

An alternative tuning control function can be derived by comparing the phase of the cavity current with that of the input line current. In this case an arc-tangent function is obtained which is superior to the discriminator function in its ability to retune the cavity in response to gross changes in beam current. The automatic tuning system on each cavity also ensures the stability of the beam-cavity system against coherent synchrotron oscillations by tuning the cavity to a frequency below that of the external generator.

Acknowledgements

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References

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2. M. Sands, "Observation of Quantum Effects in an Electron Synchrotron," International Conference on High Energy Accelerators and Instrumentations, CERN 1959, pp.298-302.
3. C. B. Williams et al., "The Automatic Phasing System for the Stanford Two-Mile Linear Electron Accelerator," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-13, No. 6 (November 1965).

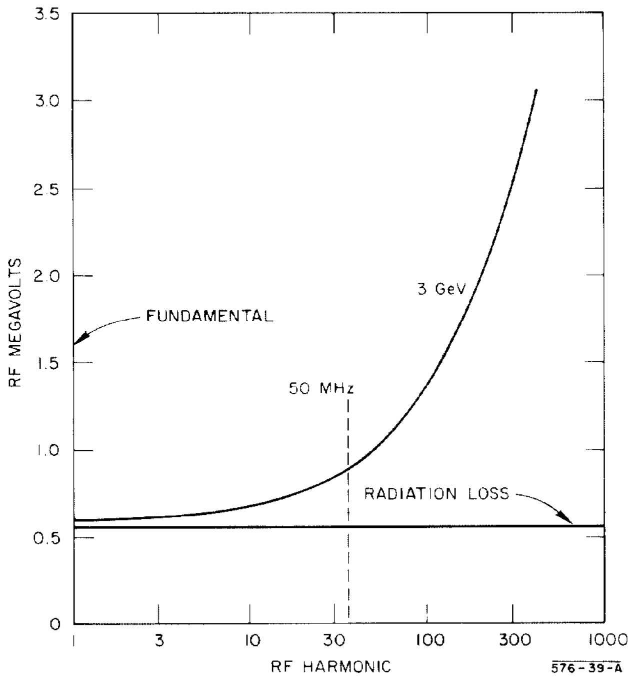


Fig. 1. RF voltage required as a function of frequency for quantum lifetime of 10^6 seconds.

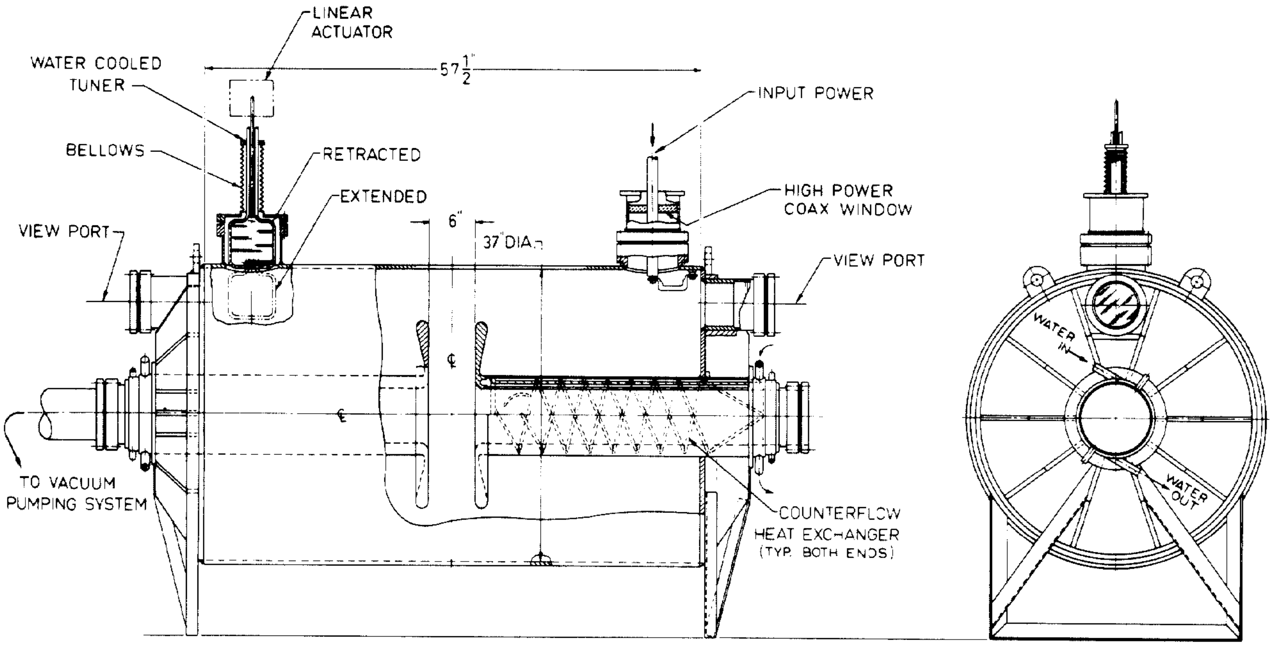


Fig. 2. Experimental rf vacuum cavity.

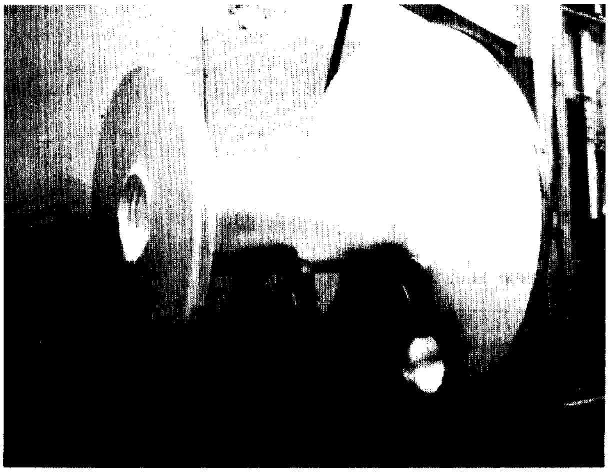


Fig. 3. Vacuum-cavity capacitor baffle and inner-conductor subassembly.

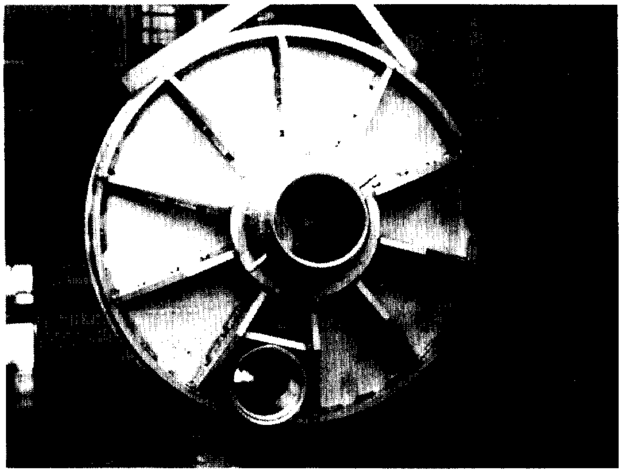
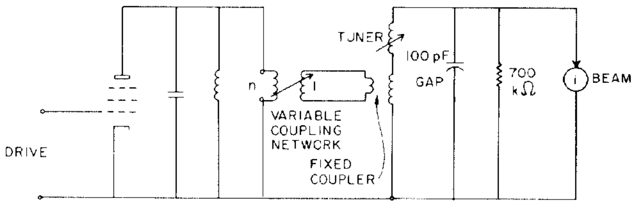
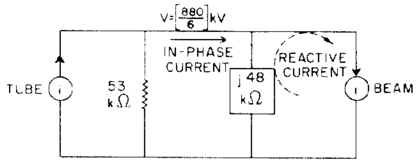


Fig. 4. End view of cavity.



(a) SIMPLIFIED SCHEMATIC CIRCUIT OF OUTPUT STAGE



(b) SIMPLIFIED SMALL-SIGNAL EQUIVALENT CIRCUIT FOR 3-GeV OPERATION

Fig. 5. Equivalent circuit of the rf output stage (parameters are given for typical operation at 3 GeV).

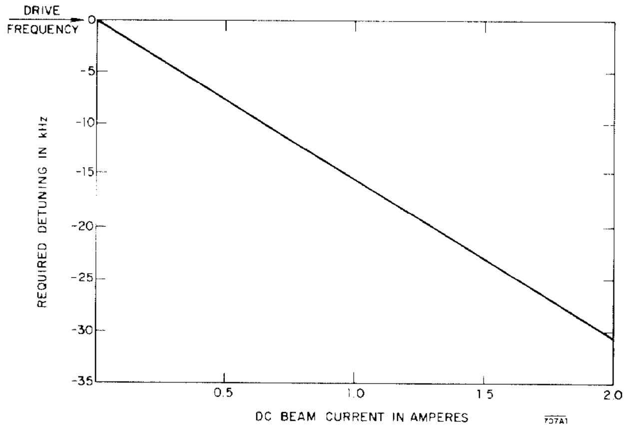


Fig. 6. Cavity detuning vs beam current.

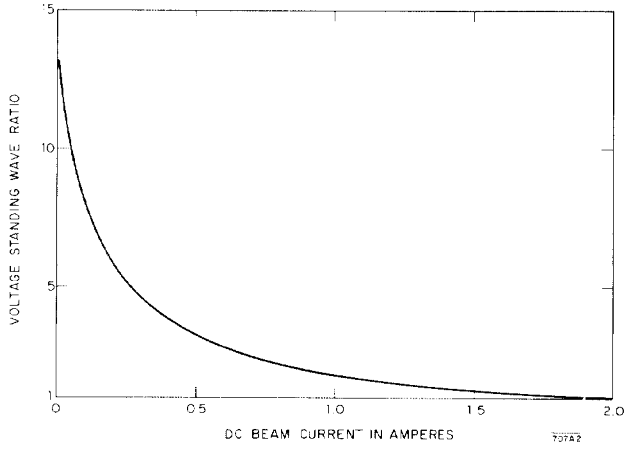


Fig. 7. Cavity input standing wave ratio vs beam current.

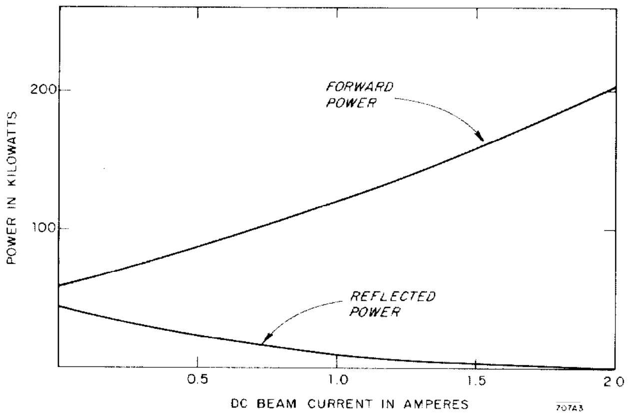


Fig. 8. Forward and reverse power vs beam current.