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RF SYSTEMS FOR HIGH-ENERGY e^-e^+ STORAGE RINGS*

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Introduction

Electron or positron beams in a storage ring radiate electromagnetic energy at a rate proportional to the fourth power of the recirculating energy, and this loss must be supplied by an rf system. Furthermore, a substantial overvoltage is required to contain the stored beam against losses due to quantum fluctuations in the emitted photons. As an example, an improvement program, SPEAR II, is now underway to increase the energy of the SPEAR ring to 4.5 GeV.[1] At this energy, the radiation loss per turn is 2.8 MeV, and to maintain a reasonable lifetime against quantum fluctuations, a peak voltage of 7.5 MeV is required. Thus, the SPEAR II rf system is similar to a continuously-operating 7.5-MeV linear accelerator. Furthermore, the available straight-section space in the ring which is suitable for containing the accelerating structures is limited, and this means that a cavity design must be sought with a high shunt impedance per unit length so that the power dissipated in cavity wall losses will be held to a reasonable level. In the case of SPEAR, about 9 meters of straight section space is available for accelerating cavities, requiring a gradient of close to 1 MV per meter. The PEP 15-GeV ring would require peak accelerating voltages of around 50 MV, with about 60 meters of straight-section space available for accelerating structures.[2]

Choice of Frequency

The rf systems of e^-e^+ storage rings constructed until recently have operated at frequencies below 100 MHz; the present SPEAR rf system, for example, operates at a frequency of 51 MHz.[3] Although operation at this low a frequency has some important advantages, the shunt impedance per unit length of the cavities is only on the order of 1 MΩ/m. Thus, in order to attain the high peak voltages required for SPEAR II and PEP using such cavities, the length of the rf structures would need to be on the order of 50 meters and 500 meters respectively. By using a higher frequency, the geometric shape of the cavities can be optimized and the shunt impedance per unit length can be increased dramatically. On the other hand, as the operating frequency is increased, the overvoltage ratio (peak voltage divided by the synchrotron radiation loss per turn) required to give a reasonable quantum lifetime also increases. Taking these two competing factors into account, it can be shown that there is a rather broad optimum in the range 100 to 400 MHz for the SPEAR II and PEP rf frequencies. Above 400 MHz, the size of the beam hole, which is determined by beam excursions during injection, becomes large relative to the wavelength with a resulting loss in shunt impedance.

Within this frequency region, economic and engineering considerations dominate the choice of rf frequency. The structure diameter, weight and cost become unreasonably large below about 200 MHz. The availability of suitable rf power sources must also be considered. A careful study of the comparative advantages of klystrons vs gridded tubes was made in connection with the design of the rf system for SPEAR II, and it was concluded that klystrons were superior to tetrodes with respect to initial and annual operating costs, reliability and expected life. Klystron size and cost are lowest at the upper end of the 100 to 400 MHz range. This factor, together with the decrease in structure costs with increasing frequency, led to a choice of 358 MHz for the SPEAR II rf system. Similar reasoning applies to the PEP rf system, for which the SPEAR II system may be considered as a prototype.

Structure Design

As discussed above, the requirement of CW operation at high energy gain, together with the limited space available in the straight sections of a storage ring, demands an rf structure with a high shunt impedance per unit length. A high shunt impedance can be achieved by using a chain of shaped cells with nose cones, similar in design to the LAMPF accelerating structure.[4] There are, however, additional design requirements for structures for high-energy storage rings. These include: a large aperture to accommodate orbit distortions and beam excursions at injection; the need for tuning to compensate for reactive beam loading and for thermal detuning effects; the requirement to mask against intense synchrotron radiation; and adequate bandwidth to maintain reasonable field stability in the presence of differential thermal detuning.

Some structures of potential interest for high-energy storage ring applications are shown in Fig. 1.

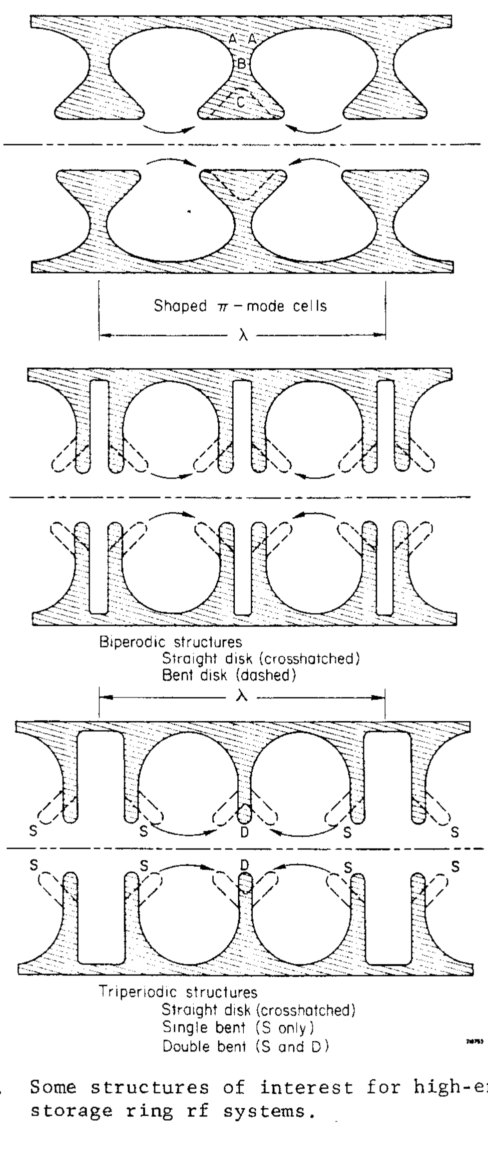

Fig. 1. Some structures of interest for high-energy storage ring rf systems.

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The top structure, Fig. 1a, is a chain of uncoupled cells spaced one-half wavelength apart. By optimizing the length and shape of the re-entrant nose cones to give the highest shunt impedance, and by adjusting the elliptical outer cavity boundary to hold the resonant frequency constant for different beam apertures, the top curve in Fig. 2, giving the shunt impedance per unit length (including transit time factor) as a function of beam aperture, is obtained. There is negligible coupling between neighboring cells in the structure as shown because the beam drift tubes are well below cutoff. A practical accelerating structure consists of a number of such cells, coupled together by one of several methods, fed from a single rf feedpoint. For example, by cutting a slot in the cavity wall at B, magnetic-field coupling makes possible operation in the π mode. By cutting slots at A-A, side-mounted cavities can be added to achieve resonant coupling and $\pi/2$ mode operation. A structure coupled in this way has a greater stability against perturbations in the tuning of individual cells, but entails a considerable increase in mechanical complexity. In either case, the addition of coupling slots increases the loss by perturbing the rf current flow, and the shunt impedance is reduced by perhaps 15% to that shown by the dashed curve in Fig. 2.

Several structures that have shunt impedances comparable to that of the side-coupled structure, but which make use of on-axis electric-field coupling, are also shown in Fig. 1. On-axis coupling offers several advantages: first, cylindrical symmetry and mechanical simplicity makes construction easier; second, the maximum overall diameter is smaller than that of the side-coupled structure, an advantage at very low frequencies; and third, the loss associated with coupling slots is avoided. Nonresonant electric-field coupling can be achieved in the shaped-cavity structure of Fig. 1a by opening up the drift tube dimensions as indicated by the dashed line at C. Resonant on-axis coupling is achieved in the biperiodic and triperiodic structures shown in Fig. 1b and 1c. The corresponding shunt impedances at 2856 MHz are given in Fig. 2. In each of these structures, the disk width is 5 mm, and unless otherwise indicated, the length of the unexcited cells in both biperiodic and triperiodic structures is also 5 mm. For comparison, shunt impedances are also given for two cases in which the ratio of large-to-small cell lengths is 2:1. Finally, from the lowest curve in Fig. 2, it is seen that the structures shown in Fig. 1 give shunt impedances which are considerably higher than that, for example, of a simple $2\pi/3$ mode structure consisting of straight disks and an elliptical outer boundary (as viewed in a longitudinal cross-section).

Values of Q, shunt impedance per unit length and bandwidth for the various structures that have been disdussed are listed in Table I for a beam aperture radius of 1.0 cm at 2856 MHz.

An additional parameter of importance in structure design is the relative bandwidth, k, defined as the frequency difference between the zero and π modes divided by the frequency of the $\pi/2$ mode. Expressions relating the stability of a structure against perturbations in tuning to the bandwidth have been given previously.[5] Bandwidths for the various structures under discussion here are also listed in Table I.

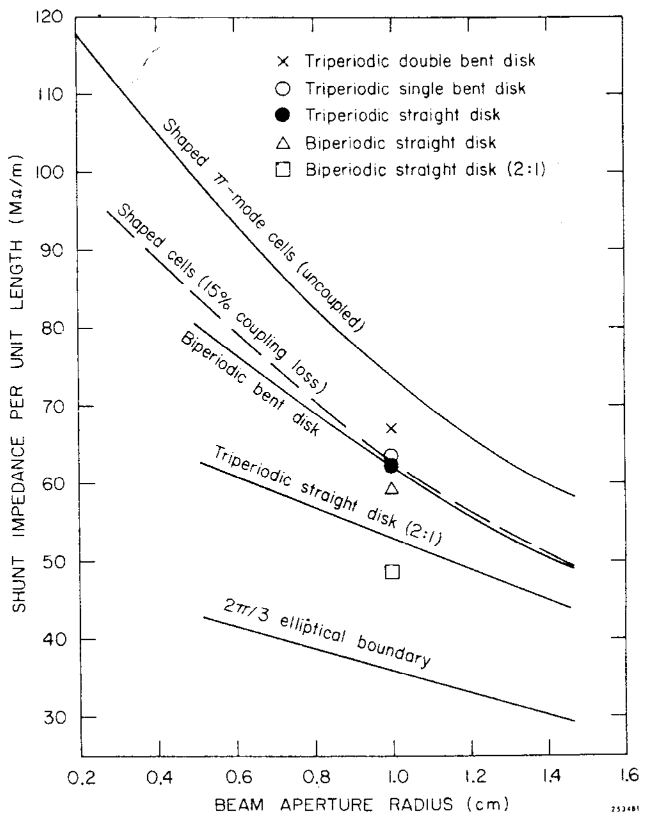

Fig. 2. Shunt impedance per unit length at 2856 MHz as a function of beam aperture radius for various rf structures.

Table I.

Shunt Impedance per Unit Length, Q and Bandwidth for Various Structures at 2856 MHz for a Beam Aperture Radius of 1.0 cm

Structure	r (MΩ/m)	Q	k(%)
Shaped $\lambda/2$ Cells (uncoupled)	74.4	1.78×10^4	0
Triperiodic Double Bent Disk	66.9	1.84×10^4	0.35
Triperiodic Single Bent Disk	63.4	1.91×10^4	0.72
Shaped $\lambda/2$ Cells (15% coupling loss)	63.3	1.51×10^4	1 - 2
Biperiodic Bent Disk	62.5	1.73×10^4	0.74
Triperiodic Straight Disk	62.2	1.96×10^4	0.73
Biperiodic Straight Disk	59.3	1.81×10^4	1.00
Triperiodic (2:1) Straight Disk	53.1	1.79×10^4	0.83
Biperiodic (2:1) Straight Disk	48.4	1.56×10^4	1.23
$2\pi/3$ Shaped (elliptical) Boundary	36.6	1.57×10^4	0.89
$2\pi/3$ Straight (cylindrical) Boundary	32.6	1.40×10^4	0.90
$\pi/2$ Shaped Boundary	31.1	1.23×10^4	1.30

SPEAR II Rf System

To run SPEAR at energies up to 2.5 GeV, a peak rf voltage of about 7.5 MV is required. Four normal straight sections are available for the rf cavities. With allowance for position monitors, bellows, etc., the nominal three meters of length in each straight section is reduced to about 2.1 meters, giving a total of 8.4 meters of space available for cavities. Based on considerations discussed in previous sections, a frequency of 358 MHz was chosen (280th harmonic); 5 half-wave-length cavities at this frequency can fit into each of the straight sections. An accelerating structure consisting of five cavities of the high shunt impedance, shaped-cell design shown in Fig. 1a has been designed and built for the SPEAR II rf system. The cavities are coupled together with azimuthal slots in the common wall, and the structure is designed to run in the π mode. Rf power is fed into the structure by means of a loop in the center cavity. For ease of construction, the cavities were fabricated out of 6061 aluminum alloy. A schematic drawing of the cavities is shown in Fig. 3 and a picture of the cavities in Fig. 4. Tuners with a tuning range of over 1 MHz are provided in each cavity. In normal operation all five tuners are ganged together, but provision is made to allow the individual tuners to be adjusted independently. Each cavity has been provided with a pickup loop for sampling the field level. The unloaded Q of the cavities was measured to be 25,000. Using standard perturbation techniques, the shunt impedance was measured to be 7.0 MΩ per cavity (corrected for transit time effects). Adequate water cooling is important because of the high average power dissipation. Cooling is provided to the inner cavity surfaces by means of radial cooling channels in the common walls between cavities as shown in Fig. 3.

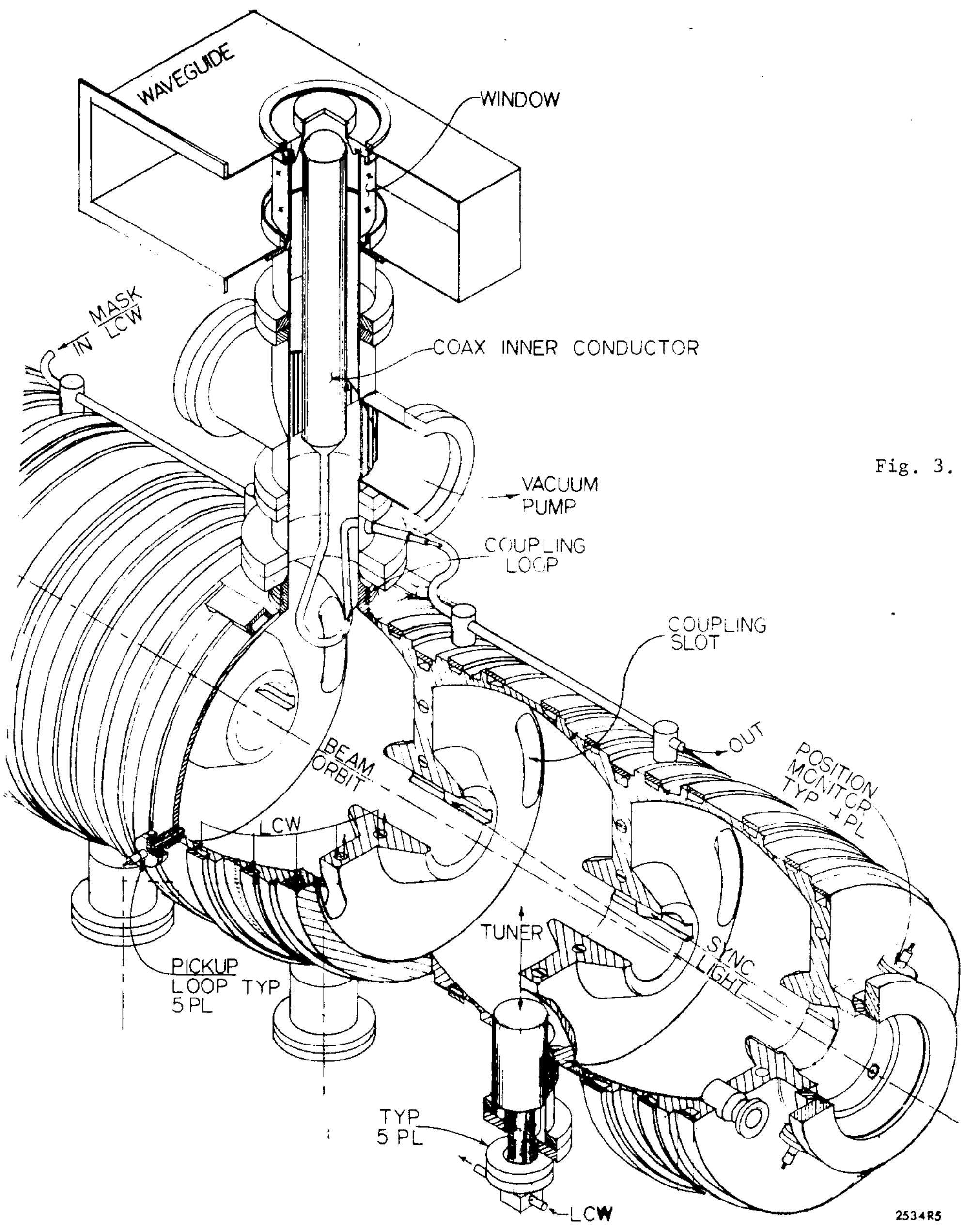

Fig. 3. Cut-away drawing of the SPEAR II accelerating structure.

The cavities have been tested up to 15 kW per cavity (75 kW for a structure of five coupled cavities) with very little thermal detuning (less than 100 kHz). Severe multipactor problems were encountered on initial testing, but these were overcome by coating the entire surface of the cavities (except for the synchrotron light masks) with titanium nitride. A layer between 100 and 1000 Å thick was applied by evaporating titanium from a source inside each cavity in a partial

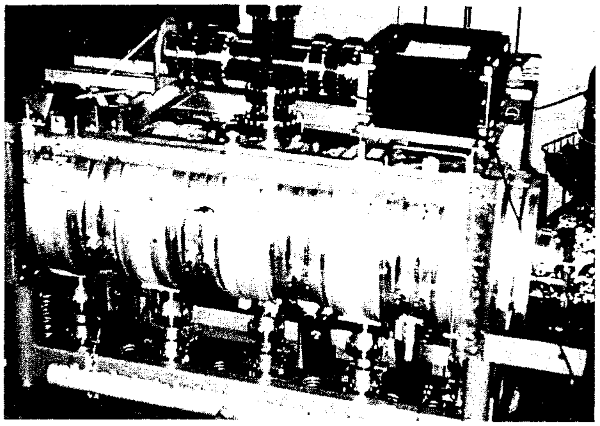

Fig. 4. Photograph of one of the four SPEAR II Accelerating structures.

pressure of about 2 x 10^{-5} Torr of nitrogen. The loop assembly and the tuners were similarly coated. Multipactoring ceased to be a problem after the coating was applied.

Figure 5 gives the frequencies of the five modes

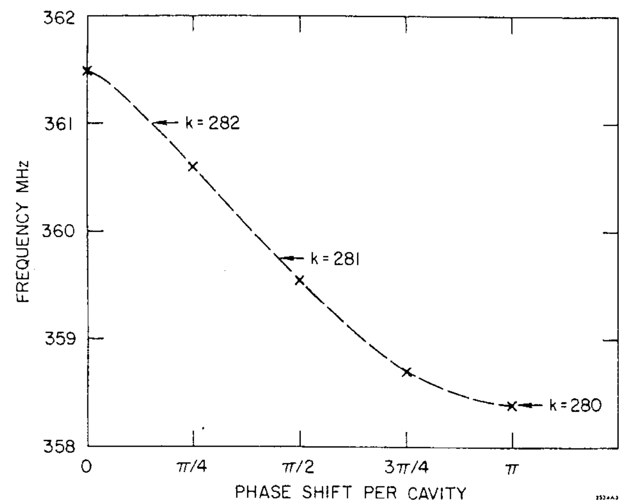

Fig. 5. Dispersion diagram showing the five resonances in the pass-band of the SPEAR II structure.

in the pass-band of the five-cell SPEAR II accelerating structure. Since these modes do not lie close to harmonics of the going-around frequency, they will not interact significantly with the beam during operation.

Each five-cavity structure is driven by a 130-kW CW klystron developed by the Klystron Group at SLAC. The klystrons have a measured efficiency greater than 50%. The present schedule calls for installation and operation of all four of the new 358-MHz structures in SPEAR by September, 1974.

PEP Rf System

As mentioned previously, the SPEAR II rf system is a prototype for the rf system proposed for PEP. The operating frequency is the same, and the rf structure for PEP is expected to be similar to the SPEAR II design. Before PEP is constructed, operational experience with the SPEAR II rf system will have served as a test of many aspects of the 358-MHz design. For PEP, however, the power output per klystron will be increased from 130 kW to 300 kW, and the klystron will be redesigned to achieve an efficiency of 70%. This high efficiency will be attained by the use of harmonic cavities, which produce sharper bunching and a higher rf current component.

It is expected that the accelerating structure for the PEP rf system will be fabricated from aluminum, following the SPEAR II design. A shunt impedance per unit length of 16.5 MΩ/m has been measured for a SPEAR II prototype cavity. Improvements in design and fabrication techniques are expected to bring the shunt impedance to about 19 MΩ/m for the PEP structure. The unloaded Q of the structure will be about 29,000. At the maximum operating energy, when the maximum beam current of about 200 mA (both beams) will be stored, the beams will extract more power from the rf source than is dissipated in the cavity walls. For optimum power transfer to the beam, and for zero reflected power, the cavities must therefore be overcoupled with a coupling coefficient of about 3.5. A cavity tuning angle* of -37° is required to achieve zero net reflected power for this value of coupling coefficient. The loaded Q for the structure is about 6,500, and the corresponding cavity filling time is about 6 μsec.

The parameters as presently proposed for the PEP rf system are summarized in Table II. The numbers

Table II.

PEP Rf System Parameters at 15 GeV[1]

Frequency	358.6	MHz
Harmonic Number	2592	
Synchrotron Radiation Loss per Turn	26	MeV
Peak Rf Cavity Voltage[2]	44	MV
Particles per Beam	4.4×10^{12}	
Circulating Current per Beam	100	mA
Synchrotron Radiation Power (both beams)	5.2	MW
Total Length of Accelerating Structure	60	m
Active Structure Length	50	m
Total Shunt Impedance[3]	950	MΩ
Unloaded Cavity Q	29,000	
Total Cavity Power Dissipation	2.0	MW
Number of 300 kW Klystrons	24	
Total Rf Power	7.2	MW
Total Power Input to Rf Power Supplies[4]	11	MW

[1] These parameters are calculated without taking into account radiation loss into higher-order cavity modes.

[2] For a quantum lifetime of 12 hours.

[3] The shunt impedance used here is defined by $R = V_C^2/P_C$, when V_C is the peak cavity voltage and P_C the power dissipated in the cavity walls.

[4] Based on a klystron efficiency of 70% and a power supply efficiency of 95%.

shown should be considered an initial estimate. As will be discussed next, the final rf system design may need to be enlarged to provide power for additional loss mechanisms not taken into account by the usual beam loading expressions. These expressions are valid for the case of a small-diameter storage ring. More accurately, they are valid when the passage time between bunches is small compared to the cavity filling time. For a ring such as PEP which is large in diameter and has only a few circulating bunches, it is possible for the fields in the cavity to change substantially between successive bunch passages. When this transient

*The tuning angle is defined as $\tan^{-1}[2Q_L(\omega_0 - \omega)/\omega_0]$, where Q_L is the loaded Q, ω is the rf frequency and ω_0 is the cavity resonant frequency.

behavior is properly taken into account, it is found that additional power is required from the rf source beyond that calculated using the usual beam-loading relations.[6] For PEP, this additional power requirement is not large; at 15 GeV and 200 mA of circulating current, the increase in power is only 3%, or 0.2 MW. The cavity coupling coefficient for optimum coupling is decreased slightly to 3.4.

A far more serious problem arises as a result of the large time between bunch passages for PEP. For the PEP parameters, it is shown that substantial additional power may be lost due to the excitation of higher-order modes in the rf structure.[6] The power that must be transferred to the beam to make up for this loss is equivalent to an additional synchrotron radiation loss; consequently, in order to contain quantum fluctuations, a higher peak cavity voltage is necessary. Altogether, the additional power that must be furnished by the klystrons might be on the order of 50% of the design power of 7.2 MW. This result assumes that the energy loss to higher-order mode excitation is 42 i_0 MeV, where i_0 is the circulating current. If the circulating current is decreased to 132 mA (both beams), the power transferred to the beam and the peak cavity voltage requirement are both decreased, and the total rf power is reduced to the 7.2 MW design level. Alternatively, this same total power would be adequate for a circulating current of about 180 mA at 14 GeV. Considering the uncertainty in the estimate of the additional cavity losses due to the excitation of higher-order modes, it is not possible at present to specify exactly some of the parameters of the PEP rf system, such as cavity coupling coefficient and loaded Q. Theoretical and experimental work between now and the time that construction might begin on PEP will define more precisely the extent of the loss to higher-order modes for the proposed PEP structure. By making suitable modifications in the structure and by the addition of special tuners to perturb the frequencies of the higher modes, it may be possible to effect a substantial reduction in this loss. There is in addition the alternative of increasing the power capability of the rf system.

Control of Longitudinal and Transverse Instabilities

The N circulating bunches in a storage ring such as PEP can be considered as coupled harmonic oscillators with N normal modes. The in-phase (zero-mode) oscillations of the bunches can be controlled by a feedback loop coupling an amplified signal picked up from the beam to varactor diodes which phase-modulate the input drive to one or more of the klystrons. In order to damp the other (N - 1) possible modes, an additional rf cavity operating on a different harmonic of the revolution frequency is required. If such a cavity is installed in the proper location in the ring, the time derivative of the voltage seen by each of the bunches is different, leading to different synchrotron oscillation frequencies. If this "splitting" of the synchrotron frequencies is sufficiently large, the bunches are effectively decoupled against longitudinal phase oscillations, as has been demonstrated in other storage rings.

Single-beam instabilities have also been observed due to the interaction of the beam with transverse cavity modes.[7] The threshold for these transverse instabilities depends on average current, and the problem is therefore not as severe in a machine such as PEP which has only a few circulating bunches. In any case, the troublesome transverse deflecting modes may be selectively loaded, as has been demonstrated in connection with the elimination of beam breakup in a superconducting accelerator.[8]

Conclusions

Both theory and experimental observations have shown that there are two significant ways in which a bunched beam can interact with higher modes in the rf cavities of high-energy storage rings. First, the bunches can radiate power into higher cavity modes, leading to enhanced beam loading and a higher peak voltage design requirement. Second, higher cavity modes can lead to both transverse and longitudinal bunch oscillations. In addition, the bunch length is short in a storage ring with a high-frequency rf system. Shorter bunches imply that modes up to a higher limiting frequency (such that the mode wavelength is comparable to the bunch length) can be excited by the beam in vacuum chamber components around the ring.

Because of the large number of cavities employed in the rf system of a high-energy storage ring (e.g., 20 individual cavities for SPEAR II and 120 for PEP Stage I), the beam can interact strongly with any higher mode with a frequency close to a harmonic of the revolution frequency. It may be advisable to give each individual cavity in a five-cavity structure a somewhat different shape, while maintaining the same fundamental mode frequency. Each cavity would then have a different spectrum of higher modes, and the possibility would be avoided of a strong interaction between the beam and all 20 or 120 cavities at any higher-mode frequency. This result can be achieved to a limited extent by staggering the individual tuners on the cavities in a five-cavity structure, but at some cost in shunt impedance at the fundamental frequency. An additional tuner could also be added to each cavity; by appropriate adjustment of the two tuners in a given cavity, the spectrum of higher-order modes can be perturbed while maintaining the frequency of the fundamental mode.

The "rigid-bunch" beam-loading enhancement due to power radiated into higher-order cavity modes, and potential transverse and longitudinal instabilities arising from the interaction of the beam with these modes, pose the greatest problems in the design of the rf system for a high-energy storage ring. In addition to the various techniques discussed above for perturbing the higher-mode frequencies, active feedback can be employed for damping bunch oscillations.

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