SLAC-PUB-1142
(ACC)
October 1972

LINAC-TYPE RF STRUCTURES FOR HIGH ENERGY 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.(1) The energy loss per turn and the required rf voltage for the first few storage rings built was quite modest; for example, the storage ring ACO at Orsay required a peak rf voltage of about 20 kV. This voltage was supplied at a frequency of 27 MHz by an rf cavity formed around a ceramic gap in the vacuum chamber of the ring. Later rings required higher voltages. In the SPEAR ring at SLAC, a peak rf voltage of about 600 kV is required to operate at the present design energy of 2.8 GeV. Ceramic gaps are no longer feasible at these high voltages, and in SPEAR the rf voltage is provided by two vacuum cavities operating at 51 MHz. These cavities are about 2-1/2 meters long and provide a shunt impedance of about 2 megohms each, which is far from an optimum design. At these frequencies an optimum design would have required a cavity several meters in diameter, but with the straight section space available it was not necessary to produce a cavity design with the highest obtainable shunt impedance. An improvement program is now underway to increase the energy of the SPEAR ring to 4.5 GeV. 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 around 7 MeV is required. Thus, the rf system is similar to a continuously operating 7 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 an optimum shunt impedance per unit length so that the power dissipated in cavity wall losses will be held to a reasonable value. 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. Other electron storage ring proposals are being considered by the PEP(2) study group at SLAC and LBL, and the ISABELLE(3) group at Brookhaven. These rings would store electrons up to an energy of 15 GeV, and would require peak accelerating voltages of around 50 MV, with about 100 meters of straight section space available for accelerating structures.

Structure Design Considerations

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 the highest shunt impedance. Thus, many of the same considerations entering into the design of the LAMPF accelerating structure(4) also apply to structures for high energy storage rings, but there are in addition some special design problems. These problems include the large aperture required to accommodate the beam excursions at injection, the need for tuning to compensate for reactive loading and for thermal detuning effects, and the requirement to mask against intense synchrotron radiation. The peak voltage, $\hat{V}$, required to attain a sufficient quantum lifetime is a function of frequency; the higher the frequency, the higher the voltage required.(1) For an optimized cavity design the shunt impedance per unit length r_ℓ scales as $f^{1/2}$, where f is the frequency, assuming that the cavity geometry is held constant. The cavity wall losses for a specified peak voltage requirement can be obtained from the power-length product, defined as

$$P_cL = \frac{\hat{V}^2}{r_\ell}$$

Dividing P_cL by the active structure length L gives the total power dissipation. Using $r_\ell = 40$ MΩ/m at 800 MHz, as measured for the Los Alamos side coupled structure with a phase velocity equal to the velocity of light, and $\hat{V}$ calculated (as an example) using the parameters(5) for the 15 GeV PEP e^+e^- storage ring, the quantity P_cL can be calculated as a function of frequency as shown in Fig. 1. The power length product is shown for various values of the ring lattice focussing parameter, γ_t, where γ_t is the transition energy. The transition energy is inversely proportional to the length of one period in the lattice. A shorter period implies a larger number of magnets in the ring circumference, stronger focussing and a higher transition energy. A more weakly focussing lattice requires a higher peak voltage to contain quantum fluctuations, and hence a higher power dissipated in cavity losses. Ring designers prefer weak focussing because the natural beam cross sectional area is larger, resulting in larger attainable luminosities.(1) It is seen from Fig. 1 that, for moderately strong focussing, frequencies around 400 MHz require about 1 MW of rf power into wall losses for 100 m of active cavity length.

In a practical rf system design, the requirement of a large beam hole diameter must also be considered. In Fig. 2, the shunt impedance per unit length for a fixed beam hole diameter of 15 cm is shown for a side coupled structure of the Los Alamos design. At higher frequencies, where the size of the hole relative to the wavelength is large, r_ℓ is reduced considerably below its optimum value. Using the values from curve B in Fig. 2, the values of P_cL have been recalculated for the PEP 15 GeV ring and are given in Fig. 3. It is seen that lower frequencies are now more strongly favored with this design restriction taken into account, requiring about 1.5 MW of rf power dissipated in cavity losses at 400 MHz for the case of a lattice with moderately strong focussing. Some variations on the basic Los Alamos structure design, which give comparable values of shunt impedance for large beam apertures, are discussed in the concluding section.

Bandwidth Requirements

In high energy storage ring applications, the sum of the rf power dissipated in the structure per unit length and the rf power transferred to the beam per unit length is typically high (~50 kW/m). The length of structure supplied by each power source is, as a consequence, limited. For frequencies in the range 250-500 MHz, and for rf sources with an output power ~200 kW, the length of structure supplied by each rf feed will be 5 to 10 half-wavelengths (5-10 π-mode cells, or 10-20 π/2-mode cells). The number of cells is sufficiently small so that operation in the π-mode can be considered.

*Supported by the U. S. Atomic Energy Commission.

(Presented at Conference on Proton Linear Accelerators, Los Alamos, New Mexico, October 10-13, 1972)

In the case of π-mode operation, a phase shift from cell to cell away from an exact π phase shift is necessary to transmit power along the structure to make up for losses, both to the beam and to the structure walls. Assuming a center-fed structure, the phase shift between the end cells and the center cell is[6]

$$\Delta\theta = \left(\frac{N-1}{2}\right)^2 \frac{1}{kQ_{eff}}$$

where N is the total number of cells, k is the relative bandwidth, $k = [\omega(\pi) - \omega(0)] / \omega(\pi/2)$, and Q_{eff} is an effective Q which takes into account both beam and wall losses. If $\Delta\theta$ is to be limited to, say, 0.2 radians, and if $Q_{eff} \sim 10^4$, then for $N \sim 5 - 10$ a bandwidth $k \sim 0.2 - 1.0\%$ is required. In the case of the $\pi/2$ mode, the first order effect due to losses is the introduction of fields in the nominally unexcited cells. The field in the unexcited cell next to center cell coupled to the rf source is, relative to the field in an excited cell

$$\frac{\Delta E}{E} = \left(\frac{N-3}{2}\right) \frac{1}{kQ_{eff}}$$

If $\Delta E/E$ is limited to 0.1, and if $N \sim 10\text{-}20$ and $Q_{eff} \sim 10^4$, then a bandwidth in the range $k \sim 0.1\text{-}0.4\%$ is required. The bandwidth requirement is less than for the π-mode case, but not by very much for the short structure lengths considered here.

The field profile is also affected if one of the cells is mistuned. This could happen if, for example, a tuner placed in one cell is used to pull the frequency of the entire structure, or if there is a tracking error between ganged tuners located in each cell. If $\delta\omega/\omega$ is the relative frequency error for a tuner located in the center cell, then in the case of the π mode the principal effect is to cause a droop in the field profile between the center and end of the structure given by[6]

$$\left(\frac{\Delta E}{E}\right)_\pi = \frac{(N-1)^2}{2k} \left(\frac{\delta\omega}{\omega}\right)$$

In the case of a $\pi/2$-mode structure, such a tuning perturbation produces a field level in the nieghboring, nominally unexcited, cell given by

$$\left(\frac{\Delta E}{E}\right)_{\pi/2} = \frac{(N-3)}{k} \left(\frac{\delta\omega}{\omega}\right)$$

The tuning range will be satisfactory if the cavity frequency can be tuned several bandwidths on either side of resonance, or if $\delta\omega/\omega \sim \pm 3 \times 10^{-4}$. If we again limit $\Delta E/E$ to ~ 0.1, and if $N \sim 5\text{-}10$ for the πmode and $\sim 10\text{-}20$ for the $\pi/2$ mode, then the bandwidth requirements for the two cases are $k(\pi) \sim 2\text{-}1/2 - 12\%$ and $k(\pi/2) \sim 2\text{-}5\%$. For a structure 5 half-wavelengths long a single tuner might be practical for either case, while for a longer structure several ganged tuners will probably be required.

Structure Design Examples

Several specific rf structure designs will be considered here, taking into account the requirements discissed in the preceding sections. The structure parameters have been calculated using the Los Alamos LALA program.[7] Although the calculations have been made at 2856 MHz, the shunt impedances are easily scaled to other frequencies.

In Fig. 4, the top structure shows a series of shaped π-mode cavities. By optimizing the length and shape of the re-entrant nose cones, and by adjusting the elliptical outer cavity boundary to hold the resonant frequency constant for different beam apertures, the theoretical curve for shunt impedance shown in Fig. 5 is obtained. There is negligible coupling between neighboring cells as they are shown in Fig. 4, because the beam drift tube is well below cut-off. 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, at the expense of a considerable increase in mechanical complexity. In either case, the addition of the coupling slots increases the loss by perturbing the rf current flow, and reduces the shunt impedance by 15-20% to the values shown by the dashed curves in Fig. 5. It is seen that the shunt impedance for a slot coupled or a side coupled structure falls off rather rapidly at larger beam apertures.

Several structures using on-axis electric field coupling, that might compete with the side coupled structure at larger beam apertures, were investigated. On-axis coupling offers several advantages. First, cylindrical symmetry and mechanical simplicity makes construction easier. Second, the maximum overall diameter is smaller, an advantage at very low frequencies. Third, the loss associated with magnetic field coupling slots is avoided. Fourth, the coupling constant k is set by the beam aperture. This dimension can be controlled with greater precision than is possible for the dimensions of a slot cut in the curved outer cavity wall. Nonresonant electric field coupling can be achieved in the shaped cavity structure by opening up the drift tube dimensions as indicated by the dashed line at C in Fig. 4. Calculations have not yet been made which will indicate whether sufficient coupling can be obtained in this way. An interesting $\pi/2$-mode structure, using resonant on-axis coupling cells, is the "bent disk" structure shown in Fig. 4. This structure is obtained by deforming the disk-loaded biperiodic structure by bending the disks inward into the excited cells to form nose cones. In this way the transit angle is reduced and the shunt impedance increased. Note that, for a beam aperture of 1.0 cm radius at 2856 MHz, the bent disk structure has a shunt impedance comparable to that of the side-coupled structure after coupling loss has been taken into account.

Another structure of interest for large beam apertures is the triperiodic structure, shown at the bottom of Fig. 4. The calculations for this structure have been made for the case of a 2 to 1 ratio between the lengths of the excited and unexcited cells. The disks have bulges which form, in effect, short nose cones. As is seen in Fig. 5, for very large beam openings this structure also becomes competitive with the side-coupled structure. For comparison, the shunt impedances of several other structures are also plotted in Fig. 5 for a beam aperture radius of 1.0 cm.

As discussed in the previous section, the bandwidth is an important structure parameter. For a beam aperture radius of 1.0 cm at a frequency of 2856 MHz, the bandwidths of the bent disk, triperiodic bulgy disk, and biperiodic bulgy disk structures are respectively 0.4%, 0.6% and 1.0%. The bandwidth increases rapidly for larger beam openings, approximately as the fourth power of the diameter. These bandwidth figures can be compared with the requirements outline previously. For example, a 20 cell $\pi/2$-mode structure requires a bandwidth of 5% if tuning is to be accomplished by a single tuner located in the center cell. A bent disk or triperiodic structure with a 15 cm diameter beam opening, operating at 400 MHz, would have a bandwidth about one-tenth of this value, and more than one tuner must therefore be used. If ganged tuners are located in each excited cell of such a structure, they must track with a relative accuracy on the order of 0.1.

Acknowledgements

The authors wish to thank K. L. F. Bane for his assistance in making the LALA calculations which provided the data for Fig. 5, and J. R. Rees for the computer program used for the calculations for Figs. 1 and 3.

References

1. M. Sands, "The physics of electron storage rings, an introduction," Report no. SLAC-121, Stanford Linear Accelerator Center (November 1970).

2. C. Pellegrini et al., "A high energy proton-electron-positron colliding beam system," Proceedings of the VIIIth International Conference on High Energy Accelerators, CERN, September 1971; p. 153.

3. "200 GeV Intersecting Storage Accelerators — ISABELLE," BNL-16716, Brookhaven National Laboratory (May 1972).

4. E. A. Knapp, B. C. Knapp, and J. M. Potter, Rev. Sci. Instr. 39, 979 (1968).

5. J. Rees, "15 GeV electron-positron storage ring-II, Radio frequency acceleration," SPEAR-118, Stanford Linear Accelerator Center (June 1971).

6. P. B. Wilson, IEEE Trans. Nucl. Sci. NS-16, no. 3, 1092 (1969).

7. H. C. Hoyt, D. D. Simmons and W. F. Rich, Rev. Sci. Instr. 37, 755 (1966). The LALA program was adapted to run on the IBM 360/91 at SLAC by W. Herrmannsfeldt.

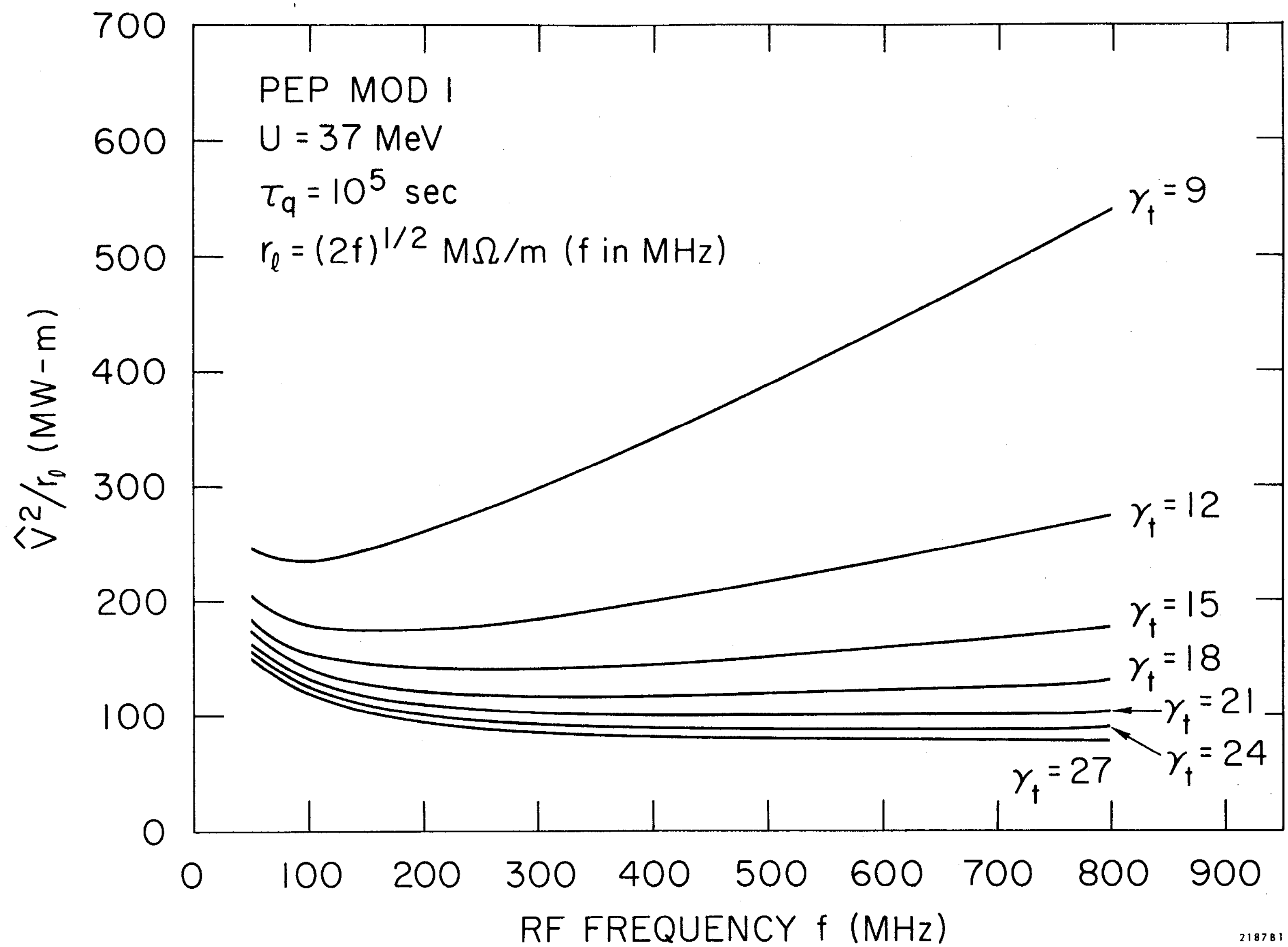

FIG. 1--Total wall loss times structure length for a proposed PEP rf system, using a side-coupled structure of the Los Alamos type, for various values of the transition energy.

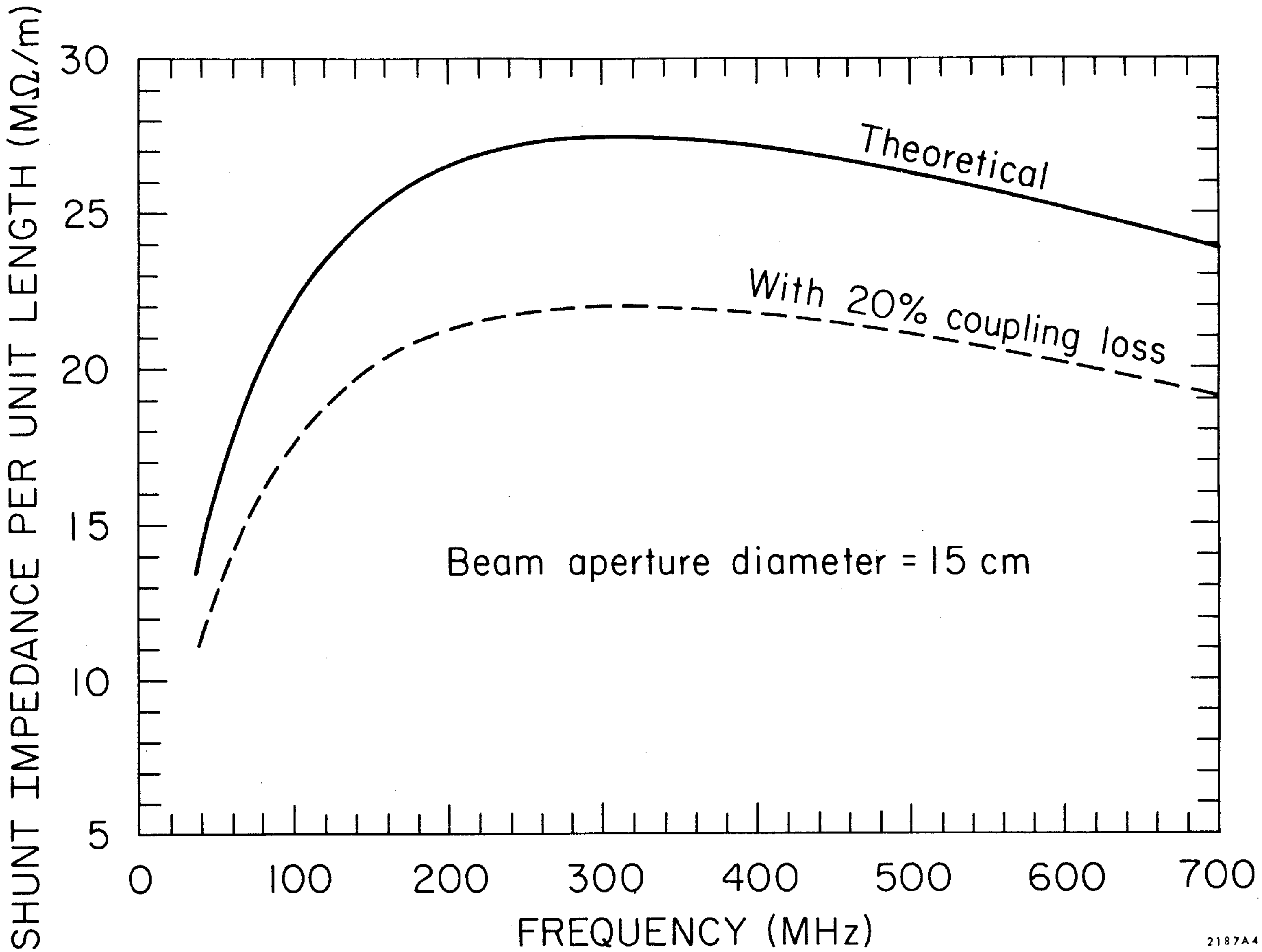

FIG. 2--Shunt impedance per unit length as a function of frequency for an optimized side-coupled structure with fixed beam aperture.

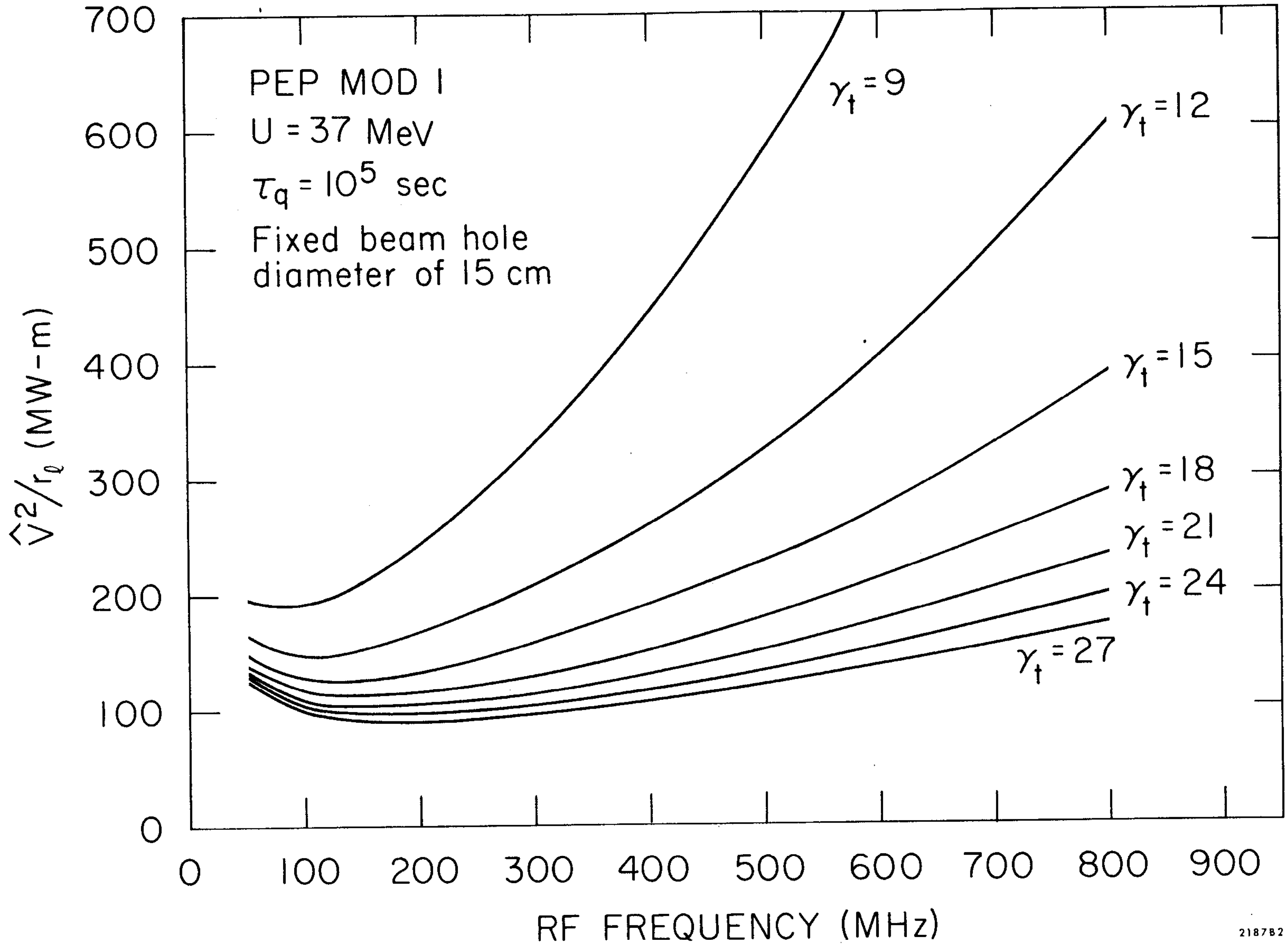

FIG. 3--Total wall loss times structure length for a proposed PEP rf system, using a side-coupled structure with a fixed beam aperture of 15 cm, for various values of the transition energy.

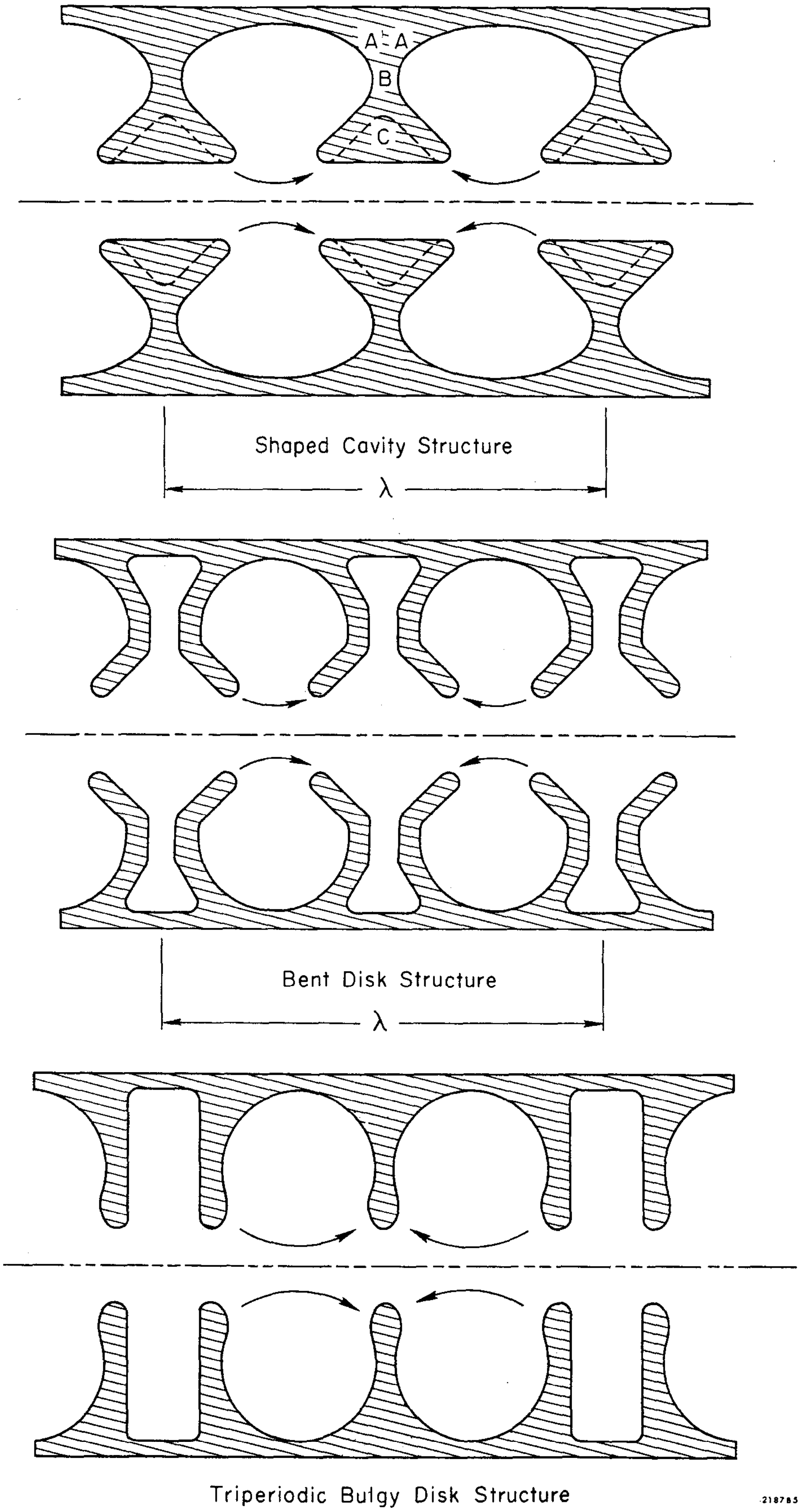

FIG. 4--Some possible structures for high energy storage ring rf systems

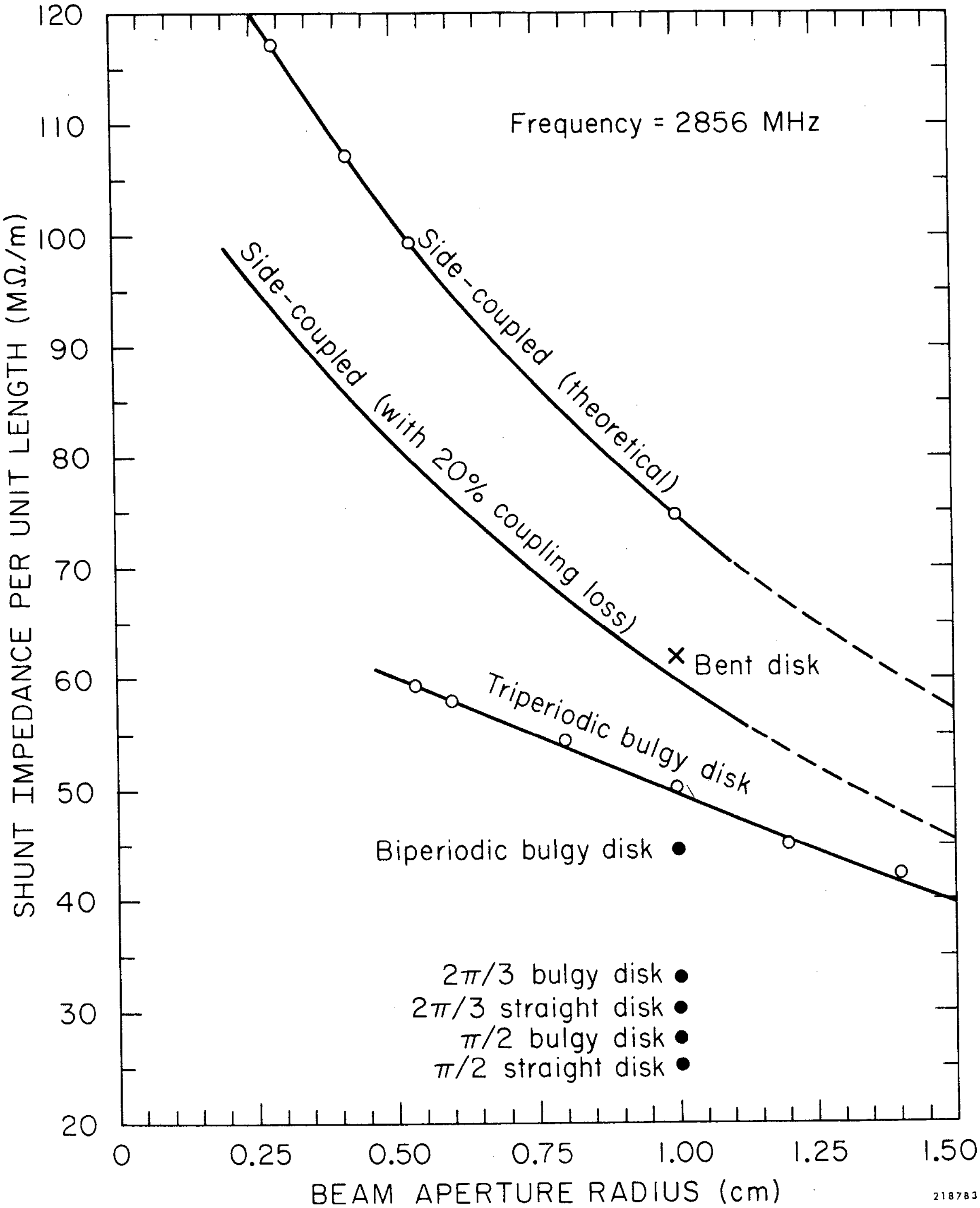

FIG. 5--Shunt impedance per unit length as a function of beam aperture radius for various rf structures.