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CHARACTERISTICS OF LARGE BEAM HOLE BIPERIODIC ACCELERATOR STRUCTURES

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Summary

Large beam hole biperiodic rf structures operating at $\pi/2$ mode with a/R of 0.31 and 0.51 have been studied. A larger beam hole reduces the amount of higher order mode excitations for modes with frequencies below the beam pipe cutoff frequency. Further reductions can be made by reducing the accelerating cell lengths. Endcell effects can be corrected by detuning the endcell; a residual field imbalance in the endcell remains because of the reduced coupling coefficient caused by field leakage into the beam pipe. The dependence of the coupling coefficient and cell frequency of a detuned cell has to be taken into account when a structure with a large tuning range is analyzed using a RLC equivalent circuit model. The reductions in the first neighbour coupling coefficient in the two structures with aperture radius 8 cm and 13 cm are respectively 0.023% and 0.056% per MHz increase in cell frequency. A comparison with a singly periodic structure operating in the π mode shows that:

1. The additional couplers in a biperiodic structure increase the energy loss slightly (9% in this case).

2. Although the field flatness of a π mode structure is worse than that of a $\pi/2$ mode structure close to the design frequency, a singly periodic structure, which has no lossy couplers, may be preferred if a large tuning range is required.

3. An 'idle' biperiodic structure can be detuned to reduce the Q and therefore cause less disturbance than a singly periodic structure.

Introduction

Rf structures with a large beam hole have been employed in accelerator rings to reduce the excitations of higher order modes and minimize beam instabilities. With a large beam hole, the number of resonant modes below the beam pipe cutoff frequency and the shunt impedances of all the higher order modes are reduced.

Because a large beam hole reduces the shunt impedance of the accelerating mode, the choice of the ratio a/R of the beam hole radius to the cavity outer radius is a compromise between considerations of efficiency and beam stability. Rf structures with a/R ratios of 0.30 are now used in storage rings like PEP[1] and PETRA[2]. These a/R values are about a factor of two higher than those usually found in an efficient structure. Recently, structures with a/R up to 0.48 have been proposed[3]. These structures are all singly periodic, designed to operate in the π mode of the TM_{010} passband. The effects of the size of beam aperture in these structures have been reviewed by Allan and Wilson[4].

A biperiodic structure operating in the $\pi/2$ mode with an a/R value of 0.29 was first proposed for the Canadian High Energy Electron Ring Study (CHEER)[5]. Recently, designs with a/R up to 0.51 have been proposed for the HERA proton ring[6]. The use of the $\pi/2$ operating mode in these structures would enhance field stability against tuning and assembly errors, frequency shifts due to temperature change, and beam disturbances. These proposed biperiodic structures have not been implemented. In the case of CHEER, the project has not been funded. In the case of HERA proton ring, the changed specifications removed the need for multi-cavity structures.

In this paper, the characteristics of large beam hole biperiodic structures of the type proposed for HERA[6] will be examined. These are shown schematically in Fig. 1. The designs, A and B, have beam hole radii of 8 cm and 13 cm for a/R values of 0.31 and 0.51 respectively. Each has seven accelerating cells and operates at 500 MHz. The higher order mode passband and energy loss parameters calculated using the code URMEL[7] will be presented. The influence of the large beam hole (and the resulting high cell to cell coupling) on tuning will be described. A comparison with a singly periodic structure operating in π mode is made.

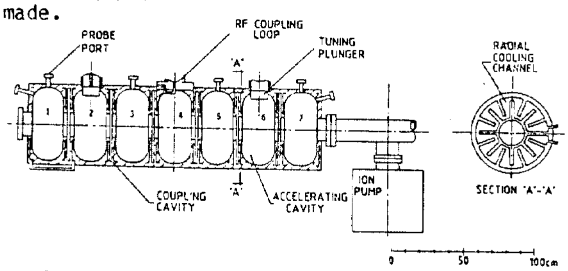

Fig. 1 Schematic of a biperiodic structure (with large beam hole radius) proposed for the HERA proton ring. Two structures, A and B, of beam hole radius 8 cm and 13 cm are proposed.

Beam Cavity Interaction

The main reason for having a large beam hole structure is to minimize beam energy loss and the excitation of higher order modes. Table 1 summarizes the monopole energy loss information for structures A and B calculated for a beam bunch with a parabolic shape and a 10 cm full width. k_{total} is the total energy loss parameter, k_0 is the energy loss parameter to the accelerating mode, and k_{par} is the sum of energy loss parameters to the parasitic modes with frequencies below the beam pipe cutoff frequency. The total energy loss is reduced by 40% by increasing the beam aperture radius from 8 cm to 13 cm. Inasmuch as both structures have to provide the same energy gain, it is more appropriate to compare the energy loss parameters after normalizing by the respective accelerating mode shunt impedance, or equivalently by k_0. The normalized total energy loss parameter does not show a significant difference but there is a 28% reduction in the normalized energy loss to the parasitic modes with frequencies below the beam pipe cutoff frequency for structure B. This is because more of the energy of the parasitic modes in structures with a larger beam aperture leaks out of the structure.

Figure 2 shows a monopole mode spectrum for structure A. The mode spectrum for structure B is similar. The beam pipe cutoff frequencies for 8 cm and 13 cm radius apertures are 1434 MHz and 883 MHz respectively. There are six monopole passbands below the cutoff frequency of the smaller aperture structure, but only two monopole passbands, i.e., TM_{010} and TM_{011} like, for the larger aperture structure, showing that the chance of resonant excitation of higher order modes is greatly reduced.

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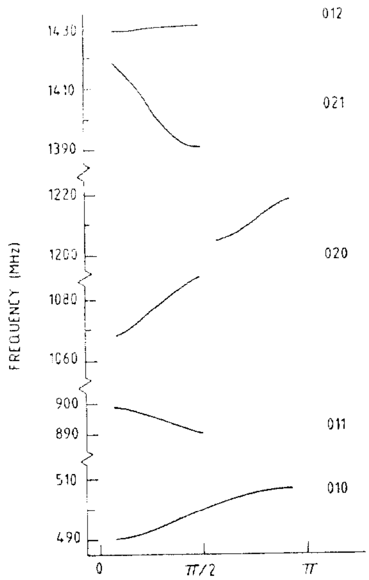

Fig. 2 Monopole mode spectrum of a biperiodic structure with a beam hole radius of 8 cm.

The frequency of the TM_{011}-like passband can be readily raised above the beam pipe cutoff frequency for structure B by decreasing the accelerating cell length. Figure 3 shows frequencies of some low lying modes of a single accelerating cell as a function of cell length. The frequencies of all the modes with axial mode number p greater than zero increase with decreasing cell length. Because the energy loss to a mode decreases with increasing mode frequency due to the effect of the bunch form factor, a shorter cell length can also result in decreased energy loss to p>0 modes. By reducing the cell length from 27 cm to 21 cm, the energy losses of a parabolic shaped beam bunch of 20 cm full width are reduced to 77% and 54% for the TM_{011} and TM_{012} modes respectively. A further reduction can be realized if the bunch is longer. The associated penalty in efficiency is small because the reduction of the accelerating mode shunt impedance for this reduced cell length is only 5%. This effect is also seen in the design of a 'Single Mode Cavity' proposed by Weiland[8] where the TM_{011}-like passband is above the beam pipe cutoff frequency because the elliptical cell profile has an effectively shorter cell length.

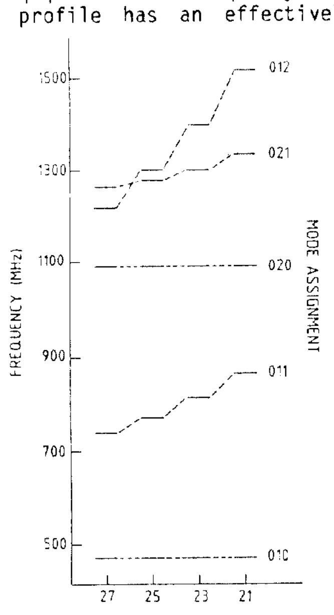

Fig. 3 Mode frequency in a single accelerating cell as a function of cell length.

The mode energy loss parameter is proportional to ZT^2/Q of the mode. Table 2 summarizes ZT^2/Q for the monopole and dipole modes of structures A and B. The ZT^2/Q for a dipole mode is calculated for a beam displaced from the axis by a distance of k^{-1}, where k is the mode wave number. $(ZT^2/Q)_0$ is for the accelerating mode, and $\sum p$ is a summation over all the parasitic modes below the beam pipe cutoff frequency. These again show a general reduction in higher order mode shunt impedance when the beam hole radius is increased from 8 cm to 13 cm. The shunt impedances of the dipole modes are reduced more than the monopole modes. There is a substantial reduction even when normalized by $(ZT^2/Q)_0$.

Table 1

Monopole Energy Loss Parameters

	π/2 Mode Structures A	π/2 Mode Structures B	π Mode Structure
a (cm)	8	13	8
a/R Ratio	0.31	0.51	0.31
k_{total} (V/pC)	1.65	0.98	1.52
k_{total}/k_0	2.22	2.17	2.22
k_{par}/k_0	0.95	0.68	0.98

Table 2

ZT^2/Q of Monopole and Dipole Modes

	π/2 Mode Structures A	π/2 Mode Structures B	π Mode Structure
a (cm)	8	13	8
a/R	0.31	0.51	0.31
$(ZT^2/Q)_0$ (ohm)	998	610	926
Monopole:			
$\sum_p (ZT^2/Q)$ (ohm)	629	319	568
Max. (ZT^2/Q) (ohm)	195	106	194
$\sum_p (ZT^2/Q)/(ZT^2/Q)_0$	0.63	0.52	0.61
Dipole:			
$\sum_p (ZT^2/Q)$ (ohm)	584	170	455
Max. (ZT^2/Q) (ohm)	156	87	149
$\sum_p (ZT^2/Q)/(ZT^2/Q)_0$	0.58	0.28	0.49

Tuning of Large Beam Hole Biperiodic Structure

Large beam hole radii allow the electric field to leak out of the accelerating cells resulting in high intercell coupling and large endcell effects. No coupling slots are required in these structures. The first neighbour coupling coefficients via the beam hole for structure A and B are 3.5% and 10.8% respectively.

The structure endcells require some frequency detuning to achieve field flatness. The endcell correction is more important in a π mode structure because it is more susceptible to tuning errors[9]. For a biperiodic structure, the frequency correction is proportional to the coupling coefficient, k_2, between accelerating cells which is usually small. The correction becomes important for structures with large bore holes because of the larger coupling coefficient. In structure B, SUPERFISH[10] calculations show that the frequency of the endcell must be raised by 7.6 MHz when k_2 is 5.99%. With this endcell detuning, the fields in the coupling cells are minimized and the structure frequency is equal to the frequency of the π/2 accelerating mode obtained with SUPERFISH calculations for an infinitely long structure. This amount of endcell tuning is also predicted by an RLC equivalent circuit model[11]. With the endcell corrected, a flat field profile is obtained for all of the inside accelerating cells but the field in the endcells is approximately 1.07 times that of the other cells. This is caused by the shift of field distribution in the endcell toward the beam tube which reduces the coupling between the endcell and its neighbouring coupling cell.

In using the equivalent RLC circuit calculation for the design of these structures, the dependence of coupling coefficients on cell frequency has to be taken into account. Figure 4 shows the ratio of on-axis fields of the midcell to that in an endcell when the midcell of structure B is detuned. The required changes in first neighbour coupling coefficients to reproduce SUPERFISH results for structures A and B are -0.023% and -0.056% per MHz change in cell frequency respectively. The second neighbour coupling coefficients are changed proportionally. This dependence of coupling coefficients is the same for cells other than the midcell.

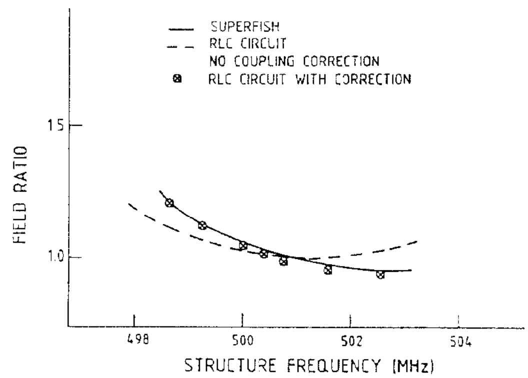

Fig. 4 Field ratio of midcell to endcell on axis fields calculated using SUPERFISH and RLC equivalent circuit.

The above endcell corrections and the dependence of coupling coefficients on cell frequency are also applicable to structures with three and five accelerating cells.

Comparison with a Singly Periodic Structure

Currently only singly periodic structures operating in π mode are employed in accelerator rings, even though the field stability and flatness of a biperiodic $\pi/2$ mode structure has been well demonstrated[5,6]. In this section, a comparison is made between structure A and a π mode structure with an 8 cm beam hole radius.

Energy loss parameters to the monopole modes are compared in Table 1. With structures of similar shunt impedance, the total energy loss of a beam to a π mode and a $\pi/2$ mode structure are very much the same. A $\pi/2$ mode structure has slightly more energy loss because of its coupling cells. The additional energy loss, approximately proportional to the ratio of the lengths of the coupling cells to the accelerating cells, is less than 10%. The additional coupling cells double the number of eigenmodes in the structure and consequently increase the chance of resonantly exciting one of the parasitic modes. Table 2 summarizes ZT^2/Q for the monopole and dipole modes for these structures; there are no significant differences.

Calculations with URMEL have been used to study the field changes in these structures when they are detuned by tuning plungers. Close to the tuned frequency of the structure and over a range of ± 0.5 MHz, a $\pi/2$ mode structure maintains a field flatness of better than 10% in the accelerating cells, while a π mode structure has large field amplitude differences between the detuned cells and the other cells and the maximum electric field is increased by a factor of two in some cases. When the structure frequency change is increased to ± 1 MHz, the field imbalance of a $\pi/2$ mode structure approaches that of the π mode structure.

Figure 5 shows the change of structure Q values of the accelerating mode as a function of structure frequency. When detuned ± 0.5 MHz from the resonant frequency the Q value of a $\pi/2$ mode structure is significantly reduced because of the increased fields in the couplers, while that of a π mode structure remains constant. This implies that a $\pi/2$ mode structure, if detuned during acceleration, will suffer significantly in overall power efficiency. Therefore, although a biperiodic structure has favorable properties close to the design frequency, a singly periodic structure may be preferred if a large tuning range is required. On the other hand, it shows that one can minimize the perturbation to the beam from an 'idle' $\pi/2$ mode structure by detuning, the beam induced voltage being attenuated by the high loss couplers.

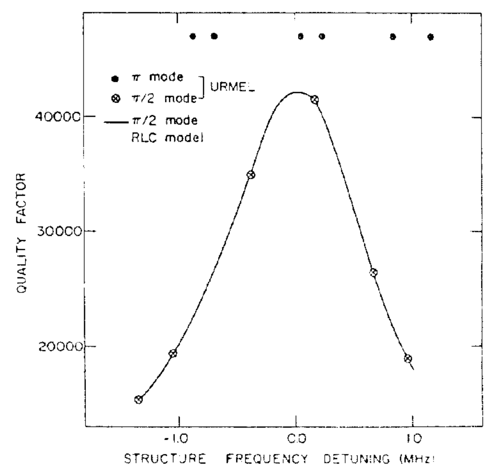

Fig. 5 Changes of structure Q values in a large hole structure detuned by a tuning plunger.

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