RF STRUCTURE STUDIES FOR THE HERA PROTON RING

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Summary

Approximately 20 MV must be provided to bunch the 0.2 A proton beam in the proton ring of HERA. This paper summarizes the parameter space that has been studied for rf cavity geometry selection. The properties of particular geometries at 500 MHz are presented in more detail. Power requirements, field stability, tolerances, beam-cavity interaction, frequency detuning and transients are discussed. The preferred system is an on-axis coupled structure operating in the π/2 mode.

Introduction

An rf system at 500 MHz is required to provide a 20 MV beam bunching voltage for intense proton bunches in the HERA[1] proton ring. The system must minimize beam-cavity effects and operate reliably over extended periods of time. The 500 MHz frequency was chosen on the basis of a number of factors investigated by the HERA group including longitudinal bunch length, circulating current, previous rf source experience and detailed beam dynamics.

This paper describes a π/2-mode system that could meet HERA requirements. Although most coupled cavity structures for rings operate in the π mode, a π/2 mode structure has advantages that make it a suitable candidate for further study. Some of the parameters discussed below apply to both π and π/2 mode structures. Two cavity geometries are presented that represent possible aperture bounds in system design. One bound consists of a geometry with a large enough beam aperture to permit the propagation of unwanted higher order modes out of the structure[2]. The other bound has a geometry that is more efficient in converting rf power to useful beam fields. The bore aperture for this bound was chosen to provide sufficient intercavity coupling without the need for web coupling slots.

Cavity Profile

General design curves for β=1 cavities were determined using the computer code SUPERFISH[3]. Figure 1 shows calculated effective shunt impedance, opt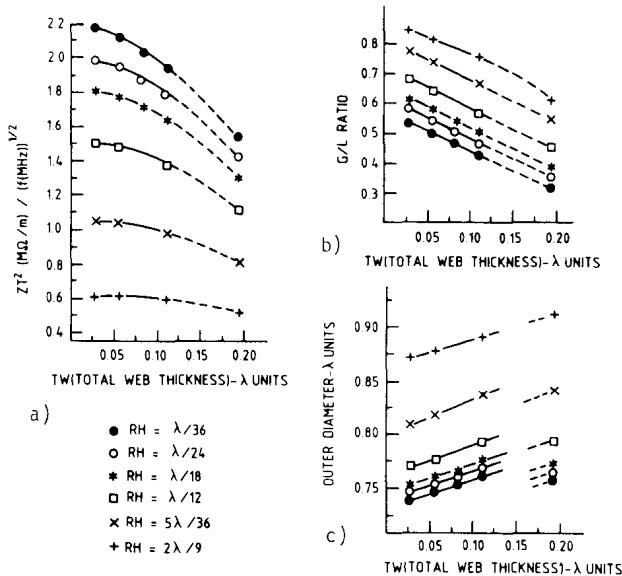imum g/L ratio and outer radius as a function of web thickness for bore apertures ranging from 0.028 λ to 0.22 λ. Other cavity dimensions were a 30° nose cone angle, 0.011 λ nose cone radius and a 0.189 λ outer cylinder-web matching radius (except for the thickest 0.19 λ web that required a 0.153 λ radius because of dimensional constraints). Figure 1(a) shows that there is very little incentive for decreasing web thickness to less than 0.05 λ. Improvements in ZT^2 of at most 5% are possible but at the expense of web mechanical strength and web cooling capabilities.

As expected, Fig. 1 shows that as a function of increasing web thickness, the outer diameter increases while the optimum g/L ratio decreases. Figure 2 provides examples of the bore geometry for different web thickness and bore aperture. Note the change in nose cone length for optimum ZT^2.
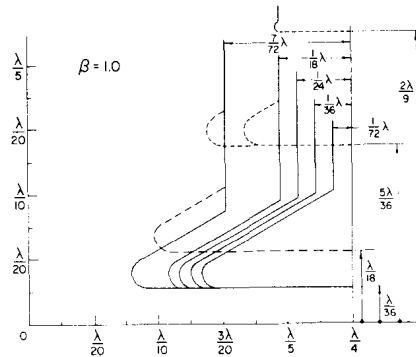

Fig. 2   Cavity shapes for optimized geometries.

Data from Fig. 1 were used to determine the cavity profile for the two extremes of geometry studied for the HERA proton ring. The two geometries studied are shown in Fig. 3. In both cases, a geometry without a nose cone was used. For the 8 cm radius aperture a possible 4% gain in rf efficiency (by adding a 1.6 cm nose cone) was more than offset by a loss in coupling constant, increased mechanical complexity and increased beam-cavity interaction effects. RF efficiency for the 13 cm radius bore aperture could be increased 13% by employing a curved shape for the outer part of the accelerating cavity profile, but at the expense of a 2 cm increase in outer radius.

Fig. 1   Cavity parameters versus web thickness. RH is the beam aperture radius and g/L is the gap to length ratio.

RH = λ/36
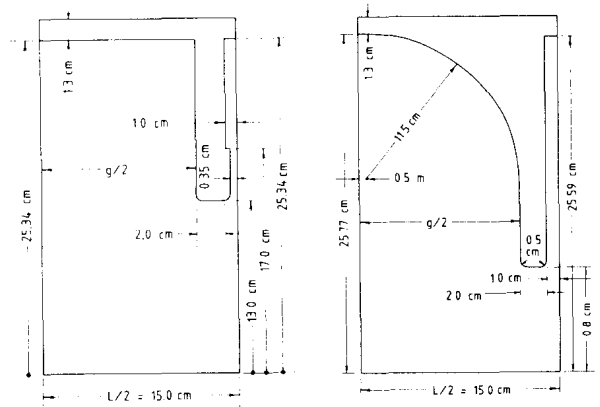RH = λ/24
RH = λ/18
RH = λ/12
RH = 5λ/36
RH = 2λ/9

Fig. 3   Large and small bore hole geometry.

Coupling slots on the webs between cavities were not required because the bore hole provided ample rf coupling between adjacent cavities (see Table 1). Tables 1 and 2 give characteristics of the two geometries and overall properties of the tanks. SUPERFISH calculations included losses in the coupling cavities, therefore experimental values should be close to theoretical. To account for additional losses from tuners and various ports in the structure, only 75% of theoretical ZT^2 was assumed for the rf power requirements of Table 2. Seven accelerating cavities per tank were selected for reasons of rf power transmission through the rf ceramic window (< 150 kW), tank weight (< 3 t), brazing furnace dimensions (< 2.5 m) and $\pi/2$ mode characteristics. Tanks must be separated by at least 60 cm to prevent intertank coupling via the large diameter interconnecting beam pipe.

Table 1

500 MHz Structure Characteristics

	Small Bore	Large Bore
Bore Hole Radius	8 cm	13 cm
Accelerating Cavity Radius	25.77 cm	25.34 cm
End Accelerating Cavity Radius	25.71 cm	24.96 cm
Outer Wall Curved Section Radius	11.5 cm	0 cm
Accelerating Cavity Half Width	11.99 cm	11.99 cm
Coupling Cavity Radius	25.59 cm	25.34 cm
Coupling Cavity Half Width	1.0 cm	1.0 cm
Coupling Cavity Nose Gap	2.0 cm	0.7 cm
Web Thickness	2.0 cm	2.0 cm
Full Cavity Stored Energy (1 MV/m)	0.119 J	0.203 J
Full Cavity Power Dissipation (1 MV/m)	8.0 kW	15.0 kW
Transit Time Factor, T	0.76	0.78
Quality Factor, Q	46,560	42,440
Effective Shunt Impedance, ZT^2	21.94 MΩ/m	12.09 MΩ/m
Peak Electric Field on Surface (1 MV/m)	2.6 MV/m	3.6 MV/m
Peak Electric Field on Axis (1 MV/m)	1.4 MV/m	1.5 MV/m
First Neighbour Coupling Constant	0.0353	0.108
Second Neighbour Coupling Constant	0.0046	0.058
Practical ZT^2 (75% of Theoretical)	16.4 MΩ/m	9.1 MΩ/m

Table 2

Tanks with Seven Accelerating Cavities

	Small Bore	Large Bore
Number of Tanks	12	16
Length of Structures	25.2 m	33.6 m
Number of Tuners per Tank	2	1
Total RF Power to Tanks	1.7 MW	2.1 MW
RF Power per Tank	145 kW	128 kW
Average On-axis Field	0.79 MeV/m	0.60 MeV/m

Mode Selection

A $\pi/2$ mode structure was selected for study on the basis of advantages that include field stability cavity-to-cavity as a function of temperature change, frequency shift, beam loading and transients. Tuning and assembly of a structure operating in the $\pi/2$ mode is easier because such a structure is more tolerant of machining errors and surface finish than one operating in any other mode. A $\pi/2$ mode structure has a much higher group velocity than a π mode structure. Thus, energy propagation through the $\pi/2$ mode structure is faster and reactions to beam disturbances (such as injection beam loading) will be reduced. Furthermore, other modes of the operating mode passband will be excited less for this energy propagation.

The $\pi/2$ mode structure has more webs than an equivalent π mode structure, leading to an estimated 5% higher structure fabrication cost - easily offset by savings related to fewer tuners required for the $\pi/2$ mode structure. A π mode structure would require a larger tank radius - about 0.3 (0.2) cm for an equivalent small (large) bore geometry. The equivalence was based on about the same temperature increase from the cooled outer cylinder to the inner corner of the web with the π mode being slightly higher. The $\pi/2$ mode

Table 3

500 MHz Five Accelerating Cavity Structure

Coupling Constants $\pi/2$ mode - 3.5%, π mode - 1.7%

Tuning Plunger Cavity Number	Structure Frequency Shift (MHz	$\pi/2$ Mode Plunger Cavity Frequency Shift (MHz)	$\pi/2$ Mode Field Ratio R*	π Mode Plunger Cavity Frequency Shift (MHz)	π Mode Field Ratio R*
3	+ 0.4	+ 2	1.005	+ 1.3	0.5
3	- 0.4	- 2	1.05	- 4.1	2.4
2 and 4	+ 0.4	+ 1, + 1	1.008	+ 0.9, + 0.9	0.8
2 and 4	- 0.4	- 1, - 1	1.03	- 1.2, - 1.2	1.2

* R - ratio of on-axis field between end cavity and tuning plunger cavity.

geometries studied had two adjacent webs each 2 cm thick separated by 2 cm for a total of 6 cm, while the π mode geometries had one 3 cm thick web.

Table 3 compares $\pi/2$ and π mode calculations using SUPERFISH for the small bore geometry and tanks with only five accelerating cavities (a local SUPERFISH limitation). End cavities were tuned for each mode to produce equal on-axis fields in each of the central accelerating cavities of an unperturbed tank. Relative field distributions for the $\pi/2$ mode are much less sensitive to frequency perturbations of cavities with tuning plungers. As expected from analytic calculations, the field ratio changes in the same manner for the $\pi/2$ mode, independent of the sign of the perturbed cavity frequency shift.

Similar relative results were obtained with the large bore geometry which had coupling constants of 10.8% for the $\pi/2$ mode and 8.3% for the π mode. In general, our calculations have shown that a $\pi/2$ mode system, with the same coupling as an equivalent π mode system, could have one quarter the number of tuners and one half the number of rf drives for the same relative cavity-to-cavity field characteristics.

The Proposed HERA Structure

A layout of the seven accelerating cavity tank for the small bore geometry is shown in Fig. 4. The large bore geometry layout is similar but would employ only one tuner of 16 cm diameter in cavity 3. The two 12 cm diameter tuning plungers for the small bore geometry can provide the ± 0.4 MHz tuning range by a stroke of about ± 3 cm. Calculations for this arrangement show that the maximum excursion of fields in the accelerating cavity (for the full tuner penetration) is less than 3%, while fields in coupling cavities remain at less than 8% of the accelerating cavity fields. Similar calculations for the large bore geometry show less than 1% shifts in accelerating cavity fields with coupling cavity fields less than 4% of the accelerating cavity fields.
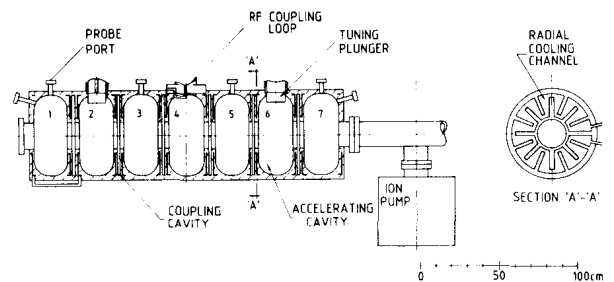

Fig. 4   Schematic of seven cavity tank for small bore geometry.

In the following discussion, parameters for the small bore geometry will be followed by those for the large bore geometry in brackets. Manufacturing tolerances of 0.012 cm lead to an acceptable system that

should require minimal tuning. The coupling constant k increases by the 0.59 (0.33) power as a function of a web thickness decrease and by the 2.5 (2.4) power as a function of a bore hole radius increase. For the above tolerances, the maximum change in k would be ± 0.7% (± 0.5%). Effects on the accelerating and coupling cavity frequencies as a function of outer radius, web thickness and bore hole radius lead to maximum frequency shifts of ± 0.4 (± 0.4) MHz and ± 0.7 (± 0.9) MHz respectively for the above tolerance. Changes in quality factor for each cavity of ± 10% were used to account for dimensional changes, surface finish and brazing alloy on the surface. All of these tolerance effects have been included in calculations of rf fields for different combinations of random errors within the above bounds. The results show that the resultant resonant frequency would be within 0.2 MHz of the design value, the relative accelerating cavity fields would be within 94 (98)% of a perfectly tuned system, accelerating cavity phases would be within 0.1° and coupling cavity fields would increase by a factor of ten from values for a perfectly tuned system (but still a factor of 50 smaller than that in the accelerating cavity).

To maintain 20 MV at a gradient of 0.8 (0.6) MV/m, 1.0 (1.4) MW of rf power is required. During beam coasting a 3.7 (3.5) MV voltage is required to make up for inductive wall loss, resistive wall loss, and parasitic mode beam-cavity interaction losses. The beam power for 0.2 A at this voltage is 0.73 (0.70) MW yielding a total rf requirement of 1.7 (2.1) MW. Assuming a waveguide line loss of about 10%, the total requirement is less than 2.5 MW for either geometry. Each tank has a beam loading of 42 (34)% and requires 145 (128) kW. Thermal calculations assuming a 35°C outer wall cooling surface have predicted a 24°C increase at the hottest point on the web (near the bore hole) for the 20 MV operating conditions. Associated with this temperature increase is a calculated 4.9% increase in rf loss from the 20°C values listed in Table 1. Adding radial cooling within the web would reduce the maximum temperature increase to 6°C and the rf loss increase to 3.5%.

Beam Cavity Interaction

Because of the high average proton current, beam cavity interactions are important both in terms of excitation of parasitic modes leading to longitudinal and transverse instabilities and in terms of beam loading of the fundamental mode.

Parasitic modes (from URMEL calculations using the small bore half-cavity geometry) below the beam pipe cutoff frequency are summarized in Table 4. Figure 5 shows for both geometries, as a function of the rms beam bunch length (σ_{rms}), the calculated total longitudinal energy loss parameter (k_T) and the energy loss parameter for the parasitic longitudinal modes (k_{par}).

Because both geometries have relatively large bore holes [8 (13) cm radius] many of the higher order modes will have frequencies above the beam pipe cutoff frequency. Under such conditions, the energy of the higher order modes will readily propagate out of the cavity, thereby minimizing beam induced instabilities via higher order modes. Results show that only nine (three) dipole modes are lower than the beam pipe dipole cutoff frequency of 1098 (676) MHz. The dominant mode has a frequency of 991 (637) MHz and a dipole $ZT^2/2Q$ of 0.53 (0.19) $\Omega \cdot cm^{-2}$.

For the proposed rf system with 12 (16) tanks and a 1 cm σ_{rms}, the loss to the parasitic modes is 60 (56) kW. Compensation for this loss requires an additional beam acceleration of 0.3 (0.28) MV. Included in this loss is 30 (56) kW that goes to modes that propagate into the beam pipe. Without a higher order mode trap, this power could prove harmful to

Table 4

Parasitic Longitudinal Modes - Small Bore Geometry

Mode Frequency (MHz)	Mode Designation in URMEL	Cavity ZT^2/Q (Ω)	Q
488.1	TM0-EE-1	149.700	13898
499.9	TM0-ME-1	19.117	6196
506.4	TM0-EE-2	35.624	8901
884.9	TM0-ME-2	75.648	41749
895.3	TM0-MM-1	34.310	42601
1066.6	TM0-EE-3	0.754	48855
1090.3	TM0-EM-2	8.924	65036
1204.5	TM0-ME-3	8.366	11207
1222.4	TM0-EE-4	24.804	10880
1383.7	TM0-ME-4	13.902	35020
1411.0	TM0-MM-2	27.090	56593
1426.8	TM0-EE-5	1.706	56606
1427.5	TM0-EM-3	8.618	56478

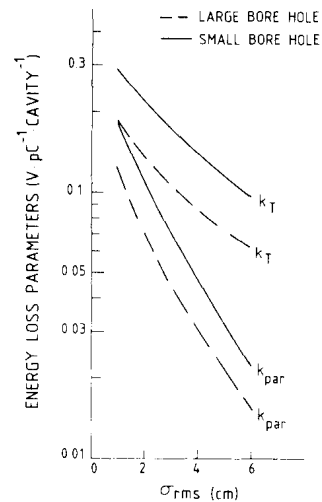TM Beam Pipe Cutoff = 1435 MHz

Fig. 5 Energy loss parameters versus beam bunch length (σ_{rms}).

operation of the cooled vacuum beam pipes in other parts of the HERA proton ring. The rest, 30 (< 1) kW, remains in the rf structure with high Q and could adversely affect following beam bunches. To avoid possible instability buildup, these modes would be loaded by loop and antennae probes that would not affect the fundamental mode.

Beam energy loss calculations without rf drive for a single bunch at the fundamental mode showed a beam induced voltage of 0.37 (0.4) MV. Assuming an rf coupling coefficient of 2, the equilibrium induced voltage (without compensation) from the total accumulated circulating bunches would be 34.8 (27.1) cos ψ (MV), where tan ψ = 5.86 * 10^{-5} * (drive frequency-structure resonant frequency). Such a beam induced voltage could affect structure operation significantly during steady state and during injection if the cavities were not excited under proper rf drive conditions. Particularly during injection, the transient induced voltage should be compensated by programming the phase and output power of the klystron to ensure that the same voltage is seen by every bunch. One possible means for completely compensating the fundamental mode beam induced voltage would be to provide an rf overdrive of 2.9 (3.7) MW with a 52° phase shift from the 1.0 (1.4) MW rf drive conditions without beam.

Discussion

Calculations have confirmed that a $\pi/2$ mode structure is a good choice for the rf structure of the HERA proton ring. Since a $\pi/2$ mode structure has not been employed in a ring before, testing such a structure at high power in the PETRA ring is being considered.

It is expected that a cavity profile geometry will be chosen between the two aperture bounds presented in this paper. The choice will be influenced by costs, rf efficiency and beam loading effects. The small bore geometry is a more efficient design but requires a significant amount of higher order mode damping in the structures. The large bore geometry is not as efficient but allows propagation of most of the energy associated with high order modes out of the structures. Further work is required on trapping higher order modes in the beam pipes separating tanks and on rf klystron control to compensate for the beam induced effects.

References

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