A NEW TYPE OF BROADBAND, HIGHER ORDER MODE COUPLER USING PARALLEL RIDGED WAVEGUIDE IN COMPARISON WITH A COAXIAL FILTER VERSION

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Summary

For possible use in the 200 MHz SPS- single cell cavities a broadband, higher order mode coupler has been developed for damping both zero-pole (longitudinal) and dipole (transverse) cavity modes. The device consists of a coupling head acting independently on E_r- and H_φ-field components, a ridged wave guide section as a high pass filter and a lossy ferrite load at the end of the waveguide. This lay-out permits damping of zero-and dipole modes with a single HOM coupler unit of this type on each cavity.

A loop-coupled coaxial filter version has been developed in parallel. Calculations, low level measurements and technical details are discussed for both coupler versions. High power tests on the coaxial version are described. A comparison between the two versions is made and the final choice of the coaxial filter is explained.

Introduction

The 200 MHz SPS single cell cavity system consists of 32 cavities, each one powered up to 60 kW and delivering an accelerating voltage of about 1 MV [1, 2]. For the SPS working as LEP-injector 6.5 x 10^{10} electrons or positrons will be accelerated whereas during high intensity SPS operation about 3.5 x 10^{13} protons are circulating through the cavities. The system is only activated during LEP-filling. During high intensity operation the cavities will be strongly damped for the fundamental frequency with a so-called main damping loop [2]. However, this loop does not damp sufficiently most of the higher order cavity modes and is completely decoupled when the accelerating system is activated. Therefore additional higher order mode suppressors (HOMS) are required to obtain stable beams.

Only two coupling holes positioned at 90° are provided in each cavity for higher order mode suppression. Selective coupling to individual modes is therefore excluded and broadband solutions must be applied. Two possibilities have been investigated, namely, a coupler using a parallel ridged waveguide and a coupler using a coaxial filter.

Parallel ridged waveguide coupler

A waveguide with a cut-off frequency higher than the fundamental cavity frequency is inserted between a coupling head and a terminating load. The waveguide operates as a high pass filter. Higher order modes are coupled to the load whereas the fundamental frequency is rejected. The complete coupler is shown in Fig. 1. Its total length is 640 mm and its cross section at the flanges 220 mm x 140 mm . Its different components are described briefly in the following.

Parallel ridged waveguide

A cross section of the waveguide can be seen in Fig. 2. Two parallel ridges are located in a WR-650 rectangular waveguide at the E-field maxima of the unperturbed H_{20}- mode. The gap between the ridges and the waveguide top wall is filled with alumina ceramic in order to increase the electrical length and to obtain the required low cut-off frequencies for the mechanical dimensions limited to the WR-650 waveguide due to the available space. The cut-off frequencies have been calculated for the H_{10}- and H_{20}- modes using the computer program LWK [3]. An air gap of 0.5 mm between ceramic and waveguide has been considered for the calculations in order to take into account the mechanical tolerances of ceramic bars and waveguide. The calculated cut-off frequencies are 260 MHz for the H_{10}- and 350 MHz for the H_{20}-mode.

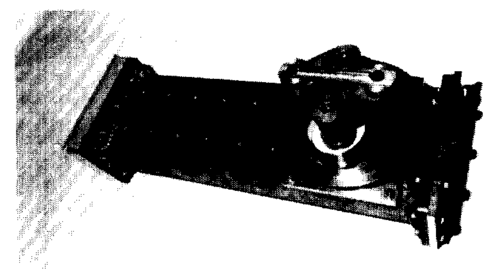

Fig. 1 Parallel ridged waveguide coupler

If a coupling loop is connected between the two ridges, magnetic coupling (H_φ cavity field) excites the waveguide in the H_{20}-mode and electrical coupling (E_r cavity field) in the H_{10} -mode. The fundamental cavity mode is coupled magnetically, i.e. its frequency of 200 MHz is well below the cut-off frequency of 350 MHz. The frequencies of the first higher order cavity modes at 306 MHz for the H_{10}- and at 395 MHz for the H_{20}-waves are well above the cut-off frequencies.

Two waveguide sections have been built and equipped with coaxial connectors, mounted between the ridges and the top wall of the guide at one end of each section. By screwing the two sections together transmission coefficients for the H_{10}- and H_{20}-modes could be measured. Their cut-off frequencies are close to the calculated values and a good decoupling > 70 dB is reached for the 200 MHz fundamental frequency for the two sections.

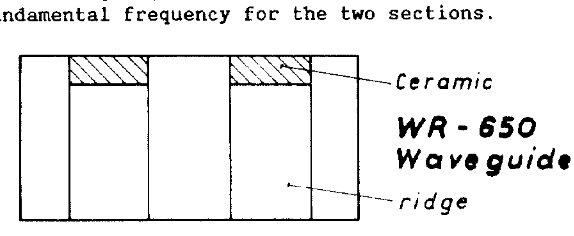

Fig. 2 Cross section of the parallel ridged waveguide

Coupling head

The coupling head consists of a loop, whose two ends are connected via two coaxial ceramic windows to the two ridges of the waveguide. The loop has a particular form (Fig. 1). Due to limited space the

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waveguide coupler must be orientated parallel to the beam axis. A simple loop would then be in a position of small coupling to the H_φ cavity field. With the specially shaped loop however, efficient coupling to this field component is possible.

Two coaxial ceramic windows with an external diameter of 73 mm are used. These are easier to build than one big ceramic window with two feedthroughs. The inner conductors are mounted to the loop on one side and to the ridge on the other side. This construction eases the water cooling of the coupling head which is required due to eddy current losses on surfaces exposed to the magnetic field of the cavity.

The loop acts independently on E_r- and H_φ- field components. A single coupler is therefore sufficient to damp zero (longitudinal) and dipole (transverse) modes.

Terminating waveguide load

The load has a length of only 30 mm and a cross-section similar to that of the waveguide. However, the non-metallic part is filled with ferrite tiles (Emmerson & Cumming, type ZN). The ferrite has a comparable value for both dielectric constant and permeability, i.e. the characteristic impedance corresponds approximately to that of air. Since the waveguide of the coupler uses ceramic between the ridges and the top wall, the air gap at the ridges of the load must be smaller to compensate for the capacitive loading.

Water cooling for the load is not required, since the power at fundamental frequency is small.

Coaxial filter coupler

In principle this coupler consists of a coupling loop connected to a matched 50 Ω coaxial line. However to avoid excessively strong coupling at the fundamental frequency a coaxial filter is connected in series with the matched line. This filter should present a high impedance at the fundamental frequency and a low impedance at all other frequencies.

Coaxial filter

The design of this filter is mainly determined by the available space. The axial length of the filter body, measured from the cavity flange is limited to 120 mm and its external diameter to 215 mm. A detailed cross-section of the filter is represented in [2] and will not be duplicated here. A series of transmission line sections with different characteristic impedances and lengths transform a short-circuit at the end of the structure into an open-circuit at the plane of the coupling loop for the fundamental frequency (200.4 MHz). To reduce the total axial length, the lines are folded back along the axis. The filter is optimized by varying transmission line lengths and characteristic impedances in order to get the second open-circuit transformation at as high a frequency as possible and to keep electrical field strength and power losses within the filter at acceptable values.

Model measurements have shown that the second open-circuit transformation appears at about 980 MHz. Between 310 and 840 MHz the insertion loss is less than 0.5 dB. At the fundamental frequency of 200.4 MHz the insertion loss is 58.5 dB and within a bandwidth of ± 400 kHz it is still higher than 40 dB. Since these measurements have been made with an aluminium model, the final characteristics for a copper filter will be slightly better. Nevertheless, at 60 kW cavity power, losses in the order of 300 W can be expected in the filter. In addition there will be losses on those surfaces which are exposed to the magnetic field of the cavity resulting in total power losses of at least 700 W. Since due to the vacuum environment the heat of the inner filter parts is practically only transferred by thermal conduction, the filter body should be kept at low temperature. Water cooling of the body is therefore unavoidable.

Power and temperature distribution on the different filter sections have been calculated approximately to ensure that no part of the filter is overheated.

Coupling loop

Low level measurements have shown that a loop cross-section of about 20 cm² is a good compromise for effective damping of modes in the range from 300 to 1000 MHz. The loop current is small and of no importance for the layout of the loop. Care must however be taken when resonance of the loop is near the fundamental frequency since then loop current and filter losses rise drastically.

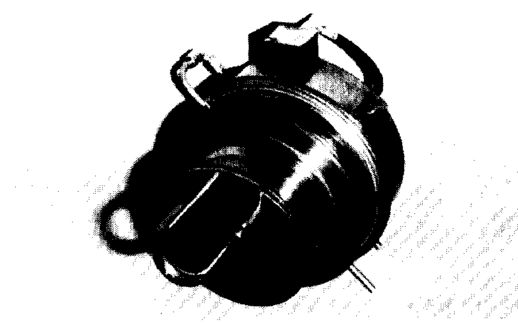

Fig. 3 Coaxial filter coupler

Eddy currents which are induced by the magnetic field of the cavity on the loop surface are of more concern. The power losses per unit length of a cylindrical wire with the radius r are [4]:

$$P = 2\pi\ r\ R_S\ H_0^2$$

where R_S is the surface resistance and H_0 the magnitude of the unperturbed magnetic field. Relating the above formula to unit area of the wire surface yields $R_S\ H_0^2$, which is twice the surface loss $\frac{1}{2} R_S\ H_0^2$ at the cavity wall.

With a wire diameter of 15 mm and a wire length of 165 mm the losses reach about 200 W. To keep the loop temperature at an acceptable value water cooling is required.

Assembly with coaxial window and terminating load

Coupling loop, filter and 50 Ω coaxial line are directly mounted to the cavity coupling hole and are therefore under vacuum. A small coaxial ceramic window (external diameter of the ceramic 16 mm) built into the 50 Ω line is sufficient, since under no circumstances will the power passing through this window exceed 100 W. The output of the window is connected via a flexible coaxial cable to a 100 W terminating load.

The load consists of an RF power chip resistor, mounted on a copper block heat sink. The heat sink is bonded onto the water cooled filter body to ensure a good heat transfer.

Fig. 3 shows a photograph of the complete HOMS. Two couplers, shifted by 90°, are mounted on the cavity to allow damping of both dipole mode polarizations.

Power tests

Before starting the power test, the filter must be tuned in such a way as to ensure best decoupling at the fundamental frequency, when mounted in the cavity. This tuning is slightly different from the one found by the filter measurements, since the effects of the loop (loop capacitance, non-coaxial feeding) must be compensated. The adjustment of the tuning is simply obtained by mechanically deforming the filter.

During the power test some light-emitting effects could be observed and traces of multipactoring were found at the brazing between copper parts. Since the copper surfaces themselves were not attacked we attempted to cure the problem by copper-plating the brazings. After this treatment no more multipactoring traces were found.

At 60 kW CW cavity power and with the filter tuning not yet optimized, an output power of 8 W and total losses of 850 W (calorimetric measurement) have been measured.

Comparison between waveguide and coaxial version

TABLE I

Zero and dipole modes of the 200 MHz cavity

Frequency MHz	Mode	Undamped cavity			1 waveguide +1 coax HOMS† + amplifier	2 coax. HOMS	Main damping loop	2 coax. HOMS + main damp. + amplifier
		* R/Q meas. Ω	* R/Q calc. Ω	Q meas.	Q meas.	Q meas.	Q meas.	Q meas.
200	E_{010}	186	175	49,900	33,800	46,800		
306	E_{011}	16	12	41,400	1,500	4,000	28,100	4,400
395	E_{110}	18	35	71,600	1,800	1,900	40,500	1,800
446	E_{020}	8	7	44,400	2,600	1,400	8,700	1,200
511	E_{120}	3	8	56,600	3,100	2,600	54,700	2,500
522	E_{111}	6	5	56,600	2,200	1,900	49,700	2,100
540	E_{021}	7	4	1,900	170	540	1,800	690
577	E_{121}	2	5	52,400	2,300	890	9,900	820
599	E_{012}	14	13	107,900	19,900	7,200	6,600	1,500
677	E_{130}		3	77,000	43,300	3,600	65,300	12,400
681	E_{131}		13	51,500	2,300	1,400	43,700	2,000
707	E_{122}		1	82,900	9,300	5,100	65,800	3,100
752	E_{022}		1	1,800	520	-	740	760
759	E_{132}		1	12,900	3,600	1,100	4,300	780
799	E_{023}	13	13	77,900	1,800	1,100	2,500	1,000
848	E_{030}		1	79,300	32,300	4,700	39,900	1,000
984	E_{032}	6	3	71,500	4,100	26,200	72,300	9,900

* equivalent circuit definition † intermediate version

Extensive calculations and measurements of the undamped cavity have been made [5] to identify the different modes in the range between 200 and 1000 MHz and to find their resonant frequency f_0, their quality factor Q and their impedance R/Q. A computer controlled measurement set-up was used for these measurements. The first five columns in Table I represent a summary of the results for zero and dipole modes. The next columns indicate Q-factors reached with different HOMS. Care has been taken for the measurement of the dipole modes to find the two polarizations which have a slightly different resonance frequency and are not necessarily oriented horizontally and vertically but may have any orientation due to asymmetries of the cavity. Table I always indicates the polarization with the higher Q.

The waveguide coupler has a better performance for low frequencies around 300 MHz and at 984 MHz, where the coaxial filter has its second open-circuit resonance. At some other frequencies however, the coaxial version is superior, especially at 677 and 848 MHz. Both couplers are not very efficient for damping the E_{012} mode which is dangerous due to its high Q and R/Q. Fortunately the main damping loop, which is not very effective for most of the modes, helps at this frequency. The power amplifier (switched off) assists in damping the mode at 984 MHz.

The Q-values which can be reached for high intensity operation with two coaxial HOMS, the main damping loop and the power amplifier are indicated in the last column of Table I. A computer calculation has shown that these values are probably low enough to ensure beam stability [6], even though the E_{011} mode at 306 MHz and the E_{130}-mode at 677 MHz are critical. If necessary, these modes could be damped selectively by replacing the 50 Ω terminating load by a specially tuned load providing better damping at 306 MHz, or by adjusting the tuner position, which strongly affects the 677 MHz resonance.

The waveguide coupler is mechanically more complicated and has, at least with its present (non-optimized) coupling loop, higher losses at the fundamental frequency.

Conclusion

Even though the waveguide coupler has a better performance than the coaxial coupler at low frequencies it has been decided to use the coaxial coupler, since it is easier to manufacture and its performance, especially in conjunction with the main damping loop, seems to be adequate for the SPS operation.

Acknowledgements

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