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A HIGH POWER COUPLER FOR THE SLAC STORAGE RING CAVITY

Introduction

The coupler for the storage ring cavity must meet the following requirements:

1. The coupler must be continuously variable during the filling of the ring.
2. The coupler must be capable of matching resistive loads over a range of 60 to 1, or as a compromise, 10 to 1.
3. The coupler must be capable of transferring 200 kilowatts cw power with as little loss as possible.
4. The coupler should not introduce reactance in the transmission line to the cavity.

Circuit

A coupler which meets several of these requirements and shows promise of meeting all of them has been designed. A circuit diagram of the coupler is given in Fig. 1.

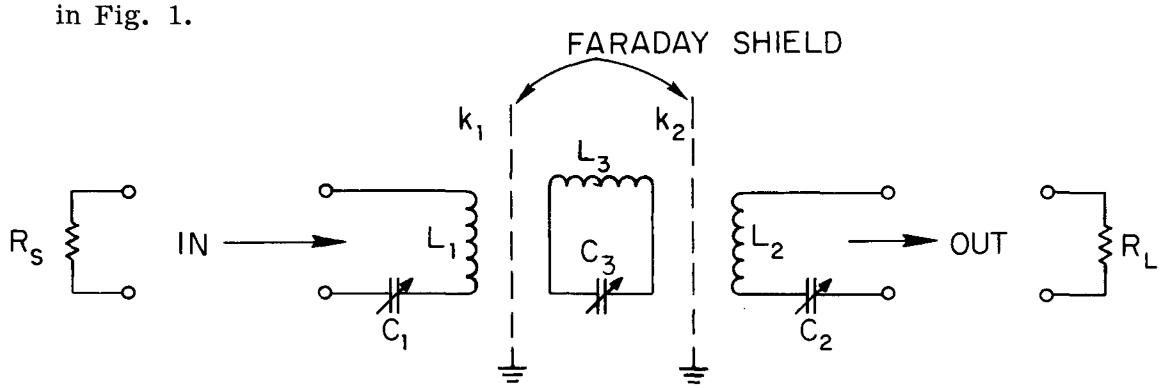

FIG. 1--High Power Coupler

Adjustment

The input circuit, L_1C_1, and the output circuit, L_2C_2, are resonated in the absence of the central circuit. Then, with $k_1 = k_2$, the central circuit is resonated. That is, L_3 plus mutual inductance coupled from L_1 and L_2 resonates with C_3. By adjusting coupling coefficients k_1 and k_2 through positioning of the central circuit, a load impedance R_L can be matched to a source impedance R_S. To a first approximation

$$\frac{k_1}{k_2} = \left(\frac{R_S}{R_L}\right)^{1/2} \quad . \tag{1}$$

Advantages

In the storage ring rf system, 200 kilowatts of power is transmitted in 50 ohm lines. The resulting peak voltage and average current are 4500 volts and 63 amperes. Simple couplers can be designed using rotating inductances or variable inductances and capacitances. However, sliding metallic contact surfaces are generally a part of such components, and at the high voltage and current levels, and with continuous duty cycles, it is not anticipated that the reliability of electrically conducting bearing surfaces would be satisfactory.

Furthermore, to simplify the requirements on automatic tuning and coupling systems, to maximize the stored energy in the cavity, and to minimize the stored energy in the input transmission line to the cavity, it is desirable to avoid reactive matching networks.

In the coupler described here, the central circuit is mechanically floating. All the electrical connections are made through magnetic field coupling between the inductors. All circuits are adjusted to and maintained at resonance. Thus sliding metallic surfaces are avoided, and the coupler is a nonreactive device. This coupler may be regarded as a transformer of variable turns ratio.

Analysis of Operation

Consider the following circuit of a simple rf transformer:

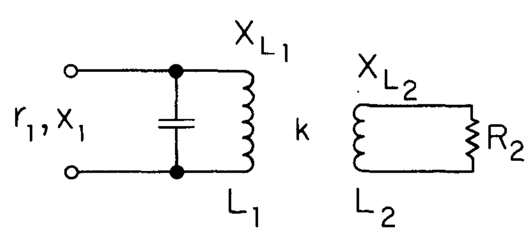

FIG. 2--Simple RF Transformer

The resistance coupled into the primary is given by[1]:

$$r_1 = \frac{(\omega M)^2 R_2}{R_2^2 + X_{L_2}^2} \quad . \tag{2}$$

The reactance coupled into the primary is:

$$X_1 = \frac{(\omega M)^2 X_{L2}}{R_2^2 + X_{L_2}^2} \quad . \tag{3}$$

In (2) and (3),

$$(\omega M)^2 = k^2 X_{L_1} X_{L2} \quad . \tag{4}$$

From (4) we find

$$k = \frac{M}{(L_1 L_2)^{1/2}} \quad . \tag{5}$$

Consider now the circuit of Fig. 1. For an impedance match, the source and load resistances must both transform into equal resistances r_1 and r_2 in the central circuit.

$$r_1 = \frac{(\omega M_1)^2 R_S}{R_S^2 + X_1^2} \quad . \tag{6}$$

$$r_2 = \frac{(\omega M_2)^2 R_L}{R_L^2 + X_2^2} \quad . \tag{7}$$

If, using C_1 and C_2, we can make the reactances in circuits L_1C_1 and L_2C_2 equal to zero, the reactance coupled into the central circuit is:

$$X = \frac{(\omega M_1)^2}{R_S^2 + X_1^2} X_1 + \frac{(\omega M_2)^2}{R_L^2 + X_2^2} X_2 \quad , \tag{8}$$

but $X_1 = X_2 = 0$, so that $X = 0$.

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1. Radio Engineering Handbook, Henney, 5th Ed., Chapt. 18, Sec. 14.

Equating (6) and (7),

$$\frac{(\omega M_1)^2 R_S}{R_S^2 + X_1^2} = \frac{(\omega M_2) R_L}{R_L^2 + X_2^2} \quad . \qquad (9)$$

Since X_1 and X_2 are zero, (9) simplifies to

$$\frac{(\omega M_1)^2}{R_S} = \frac{(\omega M_2)^2}{R_L} \qquad (10)$$

or

$$\frac{R_S}{R_L} = \left(\frac{M_1}{M_2}\right)^2 \quad . \qquad (11)$$

Using (4) we find

$$\frac{R_S}{R_L} = \frac{k_1^2 L_1 L_3}{k_2^2 L_2 L_3} \quad . \qquad (12)$$

By making L_1 and L_2 equal,

$$\frac{R_S}{R_L} = \left(\frac{k_1}{k_2}\right)^2 \quad . \qquad (13)$$

Accordingly, the load and source can be matched by adjustment of the coupling coefficients k_1 and k_2. For example, suppose the storage ring cavity is beam loaded with two 24 ampere beams and matched to 50 ohms. In the absence of beam, the impedance will rise to 3060 ohms. From (13)

$$\frac{R_S}{R_L} = \frac{50}{3060} = \left(\frac{k_1}{k_2}\right)^2$$

$$\frac{k_1}{k_2} = \left(\frac{50}{3060}\right)^{1/2} = \frac{1}{7.84} \quad .$$

If $k_2 = 0.35$ (the maximum obtainable with end coupled solenoidal inductors), then $k_1 = 0.045$.

Implicit in the above analysis is the assumption that as k_1 and k_2 are varied, the mutual inductance coupled into the central circuit remains constant. Stated in another way,

$$k_1 + k_2 = \text{a constant} = k \quad . \tag{14}$$

From (13) and (14) we find

$$k_1 = \frac{2k}{\left(\frac{R_L}{R_S}\right)^{1/2} + 1} \quad . \tag{15}$$

$$k_2 = \frac{2k}{\left(\frac{R_S}{R_L}\right)^{1/2} + 1} \quad . \tag{16}$$

If k_1 and k_2 are made to vary in accordance with (15) and (16) we find that the conditions imposed by (13) and (14) are both met.

The above analysis neglects the fact that there is an interaction between k_1 and k_2. That is, if k_2 is changed, k_1 also changes even though no change has been made in the geometry of the coupling defined by k_1. A coupling coefficient K can be derived for the circuit shown in Fig. 3.[2]

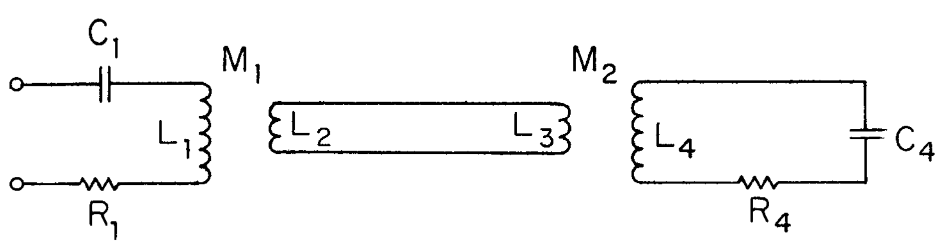

Fig. 3--Link Coupled Circuit

[2] Radio Engineering Handbook, Henney, 5th Ed., Chapt. 5, Sec. 24.

The coupling coefficient for this circuit is

$$K = \frac{M_1 M_2}{L_m \left[\left(L_1 - \frac{M_1^2}{L_m}\right)\left(L_4 - \frac{M_2^2}{L_m}\right)\right]^{1/2}} \tag{17}$$

where $L_m = L_2 + L_3$.

Relabeling and redrawing the circuit of Fig. 3, we can obtain the circuit of Fig. 4 by combining L_m into a single inductor, and incorporating some of the capacitive reactance of the input and output circuits into a capacitive reactance in the central circuit of Fig. 4.

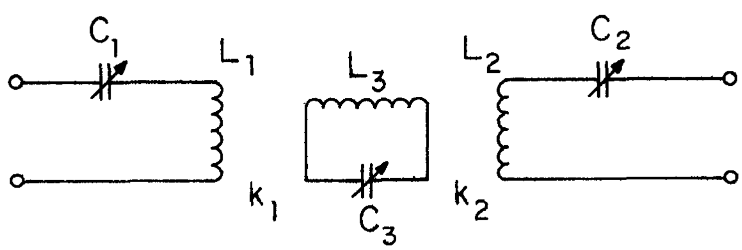

Fig. 4--A Redrawing of Fig. 3.

It can be seen that Fig. 4 is the same as Fig. 1. Then

$$K = k_1' k_2' = \frac{M_1 M_2}{\left[L_3\left(L_1 - \frac{M_1^2}{L_3}\right)\right]^{1/2}\left[L_3\left(L_2 - \frac{M_2^2}{L_3}\right)\right]^{1/2}} \tag{18}$$

with

$$M_1 = k_1 \sqrt{L_1 L_3}$$

$$M_2 = k_2 \sqrt{L_2 L_3}$$

and $L_1 = L_2$ by design ,

we find

$$k_1' k_2' = \frac{k_1 k_2}{\left(1 - k_1^2\right)^{1/2}\left(1 - k_2^2\right)^{1/2}} , \tag{19}$$

or

$$k_1' = \frac{k_1}{\left(1 - k_2^2\right)^{1/2}} . \tag{20}$$

$$k_2' = \frac{k_2}{\left(1 - k_1^2\right)^{1/2}} . \tag{21}$$

Repeating the steps of (14), (15), and (16), we find

$$k_1' = \frac{2k}{1 + \left(\frac{R_L}{R_S}\right)^{1/2}} . \tag{22}$$

$$k_2' = \frac{2k}{1 + \left(\frac{R_S}{R_L}\right)^{1/2}} . \tag{23}$$

Using (20), (21), (22), and (23), we find

$$k_1 = \frac{2k\left(1 - k_2^2\right)^{1/2}}{1 + \left(\frac{R_L}{R_S}\right)^{1/2}} . \tag{24}$$

$$k_2 = \frac{2k\left(1 - k_1^2\right)^{1/2}}{1 + \left(\frac{R_S}{R_L}\right)^{1/2}} . \tag{25}$$

Another arrangement of (24) and (25) results in:

$$\frac{k_1^2 - k_1^4}{k_2^2 - k_2^4} = \frac{R_S}{R_L} . \tag{26}$$

Since k_1 and k_2 never exceed 0.35, the approximate expression (13) is sufficient for most purposes.

Performance of Models

A low power model of the coupler was constructed. At power levels of 5 watts the coupler had an insertion loss of 0.4 db. With a 50 ohm load the coupler could be adjusted to provide unity coupling. With a 500 ohm load the coupler reduced the mismatch from 10:1 to 1.2 : 1. Failure to achieve unity coupling in both cases was probably the result of capacitive coupling between the inductors.

A high power motor-driven model of the coupler has been constructed and tested. The coupler successfully withstood 35 kw cw power at 50 MHz. The insertion loss was less than 0.1 db. When terminated in a 50 ohm load the coupler provided unity coupling. When terminated in a 150 ohm load the coupler reduced the 3:1 mismatch to 1.2:1. The coupler was not capable of matching larger than 3:1 impedance ranges because of limited travel of the central circuit. Figure 5 is a photograph of the high power model.

Improvements in Next Model

It is proposed to construct the next model using flat spiral inductors rather than the present solenoidal configuration. Flat spirals will increase the distance of travel permitted to the central circuit. The spiral configuration may also permit coupling coefficients higher than 0.35 to be attained. Increasing the distance of travel and increasing the maximum value of coupling coefficient will increase the range of impedances that can be matched. A further advantage of the spiral inductor is that it should be possible to make the central circuit self-resonant, thus eliminating the mechanically awkward shunt capacitor. The spiral inductor can be adjusted to self-resonance using a shorting bar or by trimming the length. Naturally it is also possible to make a solenoidal inductor self-resonant; however, the spiral inductor lends itself to a more stable mechanical arrangement.

Faraday screens will be added in the next model to reduce capacitive coupling between the inductors. This should permit improved impedance matching when the coupler is at other than the symmetrical position, matching 50 ohms to 50 ohms.

The present high power coupler is water cooled. In order to improve the mechanical design and reduce losses caused by the water connections, the next coupler will be submerged in a low loss oil for cooling. Immersion in oil should improve the high voltage breakdown characteristics as well.

Conclusion

The coupler described here partially meets the four requirements outlined in the introduction. It can be continuously varied during the filling of the ring. It has been tested at 35 kw without difficulty, and so, with improvements, should be capable of handling 200 kw. The insertion loss is acceptably low. The coupler introduces some reactance as a result of capacitive coupling between inductors. The main effect of this is to slightly detune the central circuit, and consequently the coupler cannot produce a perfect match except at the 1:1 impedance condition. Faraday screens should alleviate this problem.

The goal of matching over a range of 60 to 1 in impedance has not been reached. However, the use of spiral inductors should permit a great improvement in this area. The low power model is capable of reducing a 10:1 mismatch to 1.2:1. If comparable performance could be obtained in the high power model, such range of matching might be acceptable if the 60:1 range proves impossible to attain.

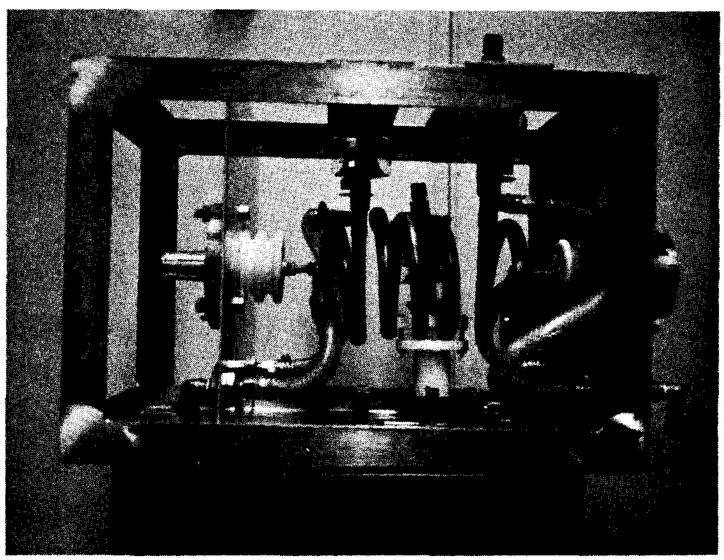

FIG. 5