The Second Life of Ferrite Dominated Cavities

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Abstract

This paper presents the results on the experimental study of compensating the inductance impedance for a ferrite-dominated cavity. The method consists in introducing additional short circuit loops in the RF magnetic field of the cavity. The correlation between the parameters of the cavity and loops is described. The method allows one to make a new insight into the feasibility to optimize the parameters of RF ferrite-dominated cavities. The idea has been implemented to the IHEP PS cavity.

1 INTRODUCTION

The U-70 RF system was worked out to operate with the injector - linac at 100 GeV energy. The wide RF range was 2.6-6.1 MHz. For the U-70 new injector booster the wide RF range decreased and now it is 5.5-6.1 MHz. This fact and our the mounting needs to increase the value of the cavity gap capacitance resulted in elaboration of a method of operating change of parameters ferrite dominated cavity. For example, the method may be used to modernizing cavity for the second harmonic accelerating voltage in the IHEP U-70 synchrotron. The method is the simplest and very inexpensive.

2 METHODS OF OPERATING PARAMETERS IN FERRITE DOMINATED CAVITIES

Modern cavities have magnetic coils to change the ferrite magnetic permeability. It is the main method of changing the cavity frequency in a wide range. Figure 1 shows the typical elements of a cavity, for example, CERN PS Booster cavity [1].

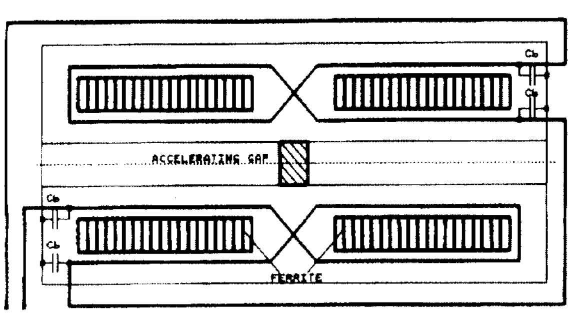

Fig.1 CERN PS Booster cavity

In the IHEP U-70 cavity the two windings consisting of ten turns are crossed in the figure-of-eight mode in each half of the cavity. In this type of cavity, Fig. 2, a virtual RF ground exists in the middle of the accelerating gap and the voltages on the resonators are in anti-phase. The special windings are arranged as a figure of eight to produce balanced RF voltages on each winding [2]. The RF amplifier can have a single ended or differential output as there is a strong coupling between the two cavities via the special windings.

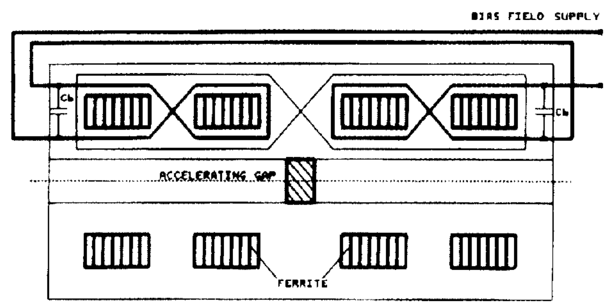

Fig.2 IHEP U-70 cavity

There are problems such as:

- creation of a cavity for the second harmonic accelerating voltage;
- increase of the gap capacitance of the cavity to accelerate short bunches of high intensity (transient beam loading effect).

They can be solved in old cavities if the inductance of the cavity be decreased by a large value.

The methods of reducing the cavity inductance are known. One of them is to reduce the ferrite magnetic permeability. Another way out is to change the design of the cavity. It is very expensive steps.

Figure 3 shows the equivalent circuit of the cavity. The cavity is represented as a simple parallel L, C_g resonator with R_d losses. The beam I_b and the RF amplifier I_g are modeled as ideal current generators. C_g is transformed to the cavity gap capacitance. Inductors formed with ferrite as a core material will exhibit an increase in inductance value compared with an air-cored version and will also have increased losses due to hysteresis and eddy current loss in the core. This loss can be represented by assigning a complex value to the magnetic permeability such that

{Terminology is used by I.S.K. Gardner [2]}:

$$\mu = \mu' - j\mu''. \tag{1}$$

The real part μ' measures the increase in inductance. The imaginary part is a measure of the core loss. Thus the impedance of the inductance is:

$$\begin{aligned} Z &= j\omega\mu L_0 \\ &= j\omega L_0(\mu' - j\mu'') \\ &= j\omega\mu' L_0 + \mu''\omega L_0 \\ &= j\omega L + R_d , \end{aligned} \tag{2}$$

where L_0 is the value of the air-cored inductance, $\omega = 2\pi f$, $L = \mu' L_0$, $R_d = \mu''\omega L_0$.

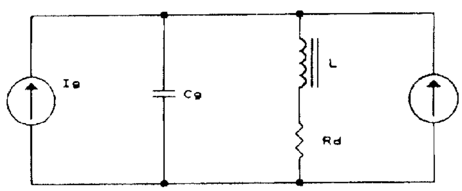

Fig.3 Equivalent circuit

From (2) we can see, when we want to decrease L then we must reduce μ' or L_0. But there is another method.

3 THE SYSTEM WITH INDUCTION COUPLING

If the inductance of the cavity is represented as a inductor of the transformer primary circuit which has induction coupling with the low resistivity metallic mass of the secondary circuit, then effect of the secondary circuit on the primary circuit will consist in a series switching of the real and imaginary parts of the impedance secondary circuit in the equivalent primary circuit. The system with an induction coupling principle is shown in Fig.4.

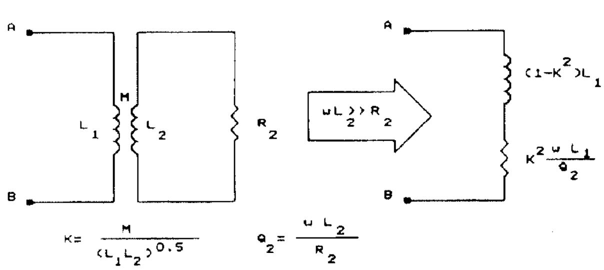

Fig.4 System with an induction coupling principle

Thus:

$$\text{the real part } = \frac{(\omega M)^2}{R^2 + X^2} R_2 , \tag{3}$$

$$\text{the imaginary part } = -j\frac{(\omega M)^2}{R_2^2 + X_2^2} X_2 \tag{4}$$

will be included in the impedance of the primary circuit from secondary circuit. Here R_2 and X_2 are the real and imaginary parts of the impedance secondary circuit, M is the inductance between the inductance L_1 of the primary circuit and the inductance L_2 of the secondary circuit. For the case of low losses in the secondary circuit ($\omega L_2 \gg R_2$) terms (3), (4) will be:

$$\text{the real part } = K^2\frac{\omega L_1}{Q_2} , \text{ where } Q_2 = \frac{\omega L_2}{R_2} , \tag{5}$$

$$\text{the imaginary part } = -j\omega K^2 L_1 , \tag{6}$$

where K is the coupling coefficient. Then the inductance value (L_1) of the primary circuit will be reduced, and it is:

$$L_1' = (1 - K^2)L_1 . \tag{7}$$

The realization of this idea in the cavity consists in switching on closed loops as in Fig.4 where the loops are put in the U-70 cavity bottom.

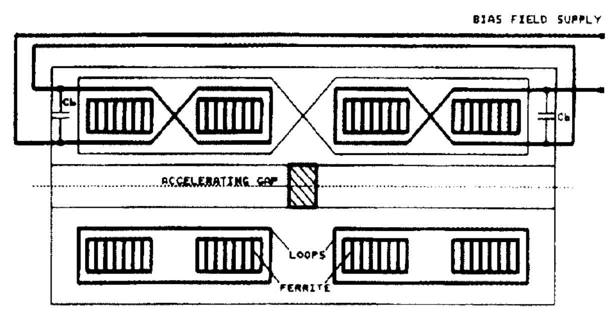

Fig.5 U-70 cavity with loops

The inductance of the cavity with loops is:

$$L' = \mu'(1 - K^2)L_0 , \tag{8}$$

and the resistance losses

$$R_d' = (\mu''\omega + \frac{K^2 R_2}{L_2})L_0 , \tag{9}$$

where R_2 and L_2 are the resistance and inductance of the loops. RF electric and magnetic fields topography in the cavity does not change. The power dissipation in the cavity uses the whole amounty ferrite.

4 CHANGING PARAMETERS IN THE CAVITY WITH LOOPS

4.1 *Coupling coefficient*

The K value can be written as:

$$K = \frac{\int B_{nl} dS_l}{\int B_{nc} dS_c} , \tag{10}$$

where S_l, S_c are the section longitudinal squares of loops and the cavity, B_{nl}, B_{nc} are normal components of RF magnetic fields in the loops and cavity. Experimental values of K of the U-70 cavity for the maximum and minimum of magnetic bias fields are $0,75 \div 0,98$ and can be found:

$$K = \sqrt{1 - f_0^2/f_0'^2}\,, \tag{11}$$

where f_0 is the cavity resonance frequency without loops and f_0' is the cavity resonance frequency with loops at the same bias fields.

4.2 Influence L_2 onto K

If p_l is the section transverse perimeter of the loop and s_l is the length of the loop then:

$$K \propto \frac{1}{\sqrt{L_2}} = \frac{1}{\sqrt{\alpha_1 s_l(\alpha_2 lg\frac{\alpha_3 s_l}{p_l} - \theta)}}\,, \tag{12}$$

where $\alpha_1, \alpha_2, \alpha_3, \theta$ are the coefficients from [3].

4.3 Range of frequency

The range of frequency over which the system can be tuned is given by the change in μ_e value. In the cavity without loops this range is:

$$\eta = \sqrt{\frac{\mu_{e\ max}}{\mu_{e\ min}}}, \tag{13}$$

where $\mu_{e\ max}$ is the maximum value of the effective permeability of the air and ferrite at the minimum bias field, and $\mu_{e\ min}$ is the minimum value of the effective permeability at the maximum bias field.

In the cavity with loops the range is:

$$\eta' = \sqrt{\frac{(1 - K^2_{\mu_e\ max})\mu_{e\ max}}{(1 - K^2_{\mu_e\ min})\mu_{e\ min}}}\,, \tag{14}$$

where $K_{\mu_e\ max}$ is the maximum value of the coupling coefficient at the minimum bias field, and $K_{\mu_e\ min}$ is the minimum value of the coupling coefficient at the maximum bias field.

4.4 Cavity shunt impedance

In the cavity without loops the shunt impedance is:

$$R_s = \frac{(\omega_0 L)^2}{R_d} = Q_0\omega_0 L = R_d Q_0^2 = \frac{L}{R_d C_g} = \frac{\mu_e}{C_g \mu''\omega_0}\,, \tag{15}$$

where $Q_0 = \omega_0 L/R_d$ is the cavity quality at the frequency $\omega_0 = 1/\sqrt{LC_g}$.

In the cavity with loops the shunt impedance is:

$$R_s' = \frac{\mu_e(1 - K^2)}{C_g(\mu''\omega_0' + \frac{K^2 R_2}{L_2})}\,, \tag{16}$$

where $\omega_0' = 1/\sqrt{L'C_g}$. $R_s' <\simeq R_s$ at the $\omega_0' = \omega_0$ (C_g will be a new value of the capacitance at the same frequency).

4.5 Cavity quality

For the cavity with loops the quality can be written as:

$$Q_0' = \frac{\omega_0' L'}{R_d'} = \omega_0' C_g R_s'. \tag{17}$$

The comparison of Q_0 with Q_0' at the same frequency ($\omega_0' = \omega_0$) gives an increase of Q_0 by about a factor C_g increase.

4.6 Power dissipation

They are added from the dissipation in the ferrite $P_{ferrite}$ and loops P_{loops} then the power dissipation in the cavity is:

$$P' = P_{ferrite} + P_{loops}\,. \tag{18}$$

Or

$$P' = \frac{V_g^2}{2R_s'} = \frac{V_g^2}{2Q_0'\omega_0' L'}\,, \tag{19}$$

where V_g is the peak RF voltage across the gap and Q_0' will vary with voltage and frequency.

5 CONCLUSIONS

The proposed alternative method of changing parameters in the cavities opens up new possibilities for designing ferrite dominated cavities:

- for available constructions of the cavity one can improve some parameters at low expenses;
- for new constructions of the cavity one can widen possibilities of the using the cavity numerous purposes and decrease prepaid expenses.

6 REFERENCES

[1] I.S.K. Gardner, "Ferrite dominated cavities", CERN 92-03, 11 June 1992, Vol.II,p.349-374.

[2] A.M. Gudkov, I.I. Sulygin, B.K. Shembel, "The investigation of RF cavities for IHEP accelerator", Preprint IHEP, 80-135, Serpukhov 1980.

[3] H.B. Dwight, and F.W. Grover, "Some series formulas for mutual inductance of solenoids", EIE, Vol.56, p.347, March 1937.