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NEW CURRENT SEPTUM MAGNET USED FOR BEAM INJECTION AND EXTRACTION IN ULTRA-HIGH VACUUM SYSTEM

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Introduction

A pulse septum magnet for beam injection and extraction has usually an iron laminated core. It is set in a vacuum chamber, because the gap can be made small so long as the beam clears it vertically and also the septum conductor be made thin. But, a magnet of this type cannot be used in an ultra-high vacuum system like a storage ring because of much outgas from the laminated core.

In order to easily eliminate this defect, we may put the core in the atmosphere by inserting a duct for the bended beam in the core gap and attaching another duct for the circulating beam outside the septum as shown, for instance, in Fig.1. For this, however, the following technical problems should be solved. In order to reduce eddy currents, the inside duct might be made of non-conducting materials like ceramics, but it is fragile and expensive. Further the ceramic duct wall is thick and the beam aperture is decreased.[1] So, it is better to make the duct out of metals, but the wall thickness should be thin enough to reduce the eddy current loss to a minimum so long as the duct stands against the atmospheric pressure. To decrease the effective thickness of the septum, the inside and outside duct should be placed as closely to the septum conductor as possible. But some electrical insulation layers are necessary, which are strong against radiation damage and also abrasion due to the vibration of septum conductor. The outermost frame (Fig.1-9) should be insulated from the core, and also the inside duct be insulated from the outside duct, otherwise loop currents are induced which would produce leak fields outside the septum conductor.

In this paper, fabrication and measurements are given about a test magnet of this type which fulfill the above conditions. Good test results were obtained, and some of the septum magnets in KEK PS will be replaced by this new version.

Design Considerations

In the KEK Booster and PS, many septum magnets are used for injection and extraction of the beam. In design of the new type septum magnet, we took for the duct in the core gap the following parameters typical for those which are now in operation; the length $a = 3.0 \times 10^{-1}$ m, width $b = 8.6 \times 10^{-2}$ m, height $c = 3.8 \times 10^{-2}$ m.

The eddy current loss Q in the duct can be calculated[1] by

$$Q = \left(\frac{b}{3} + \frac{ac}{a+b}\right) \cdot \frac{ab^2 d\pi^2 B_m^2 f}{4rW} , \qquad (1)$$

where r is the resistivity of the duct material, d the thickness of the duct wall, and B_m, W, f are the peak, half sine width, duty cycle of the magnetic field applied to the duct, respectively (see Fig.2).

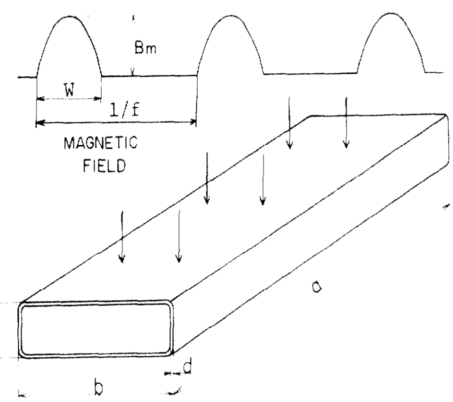

Fig.2 Inside duct of septum magnet and magnetic field applied to it.

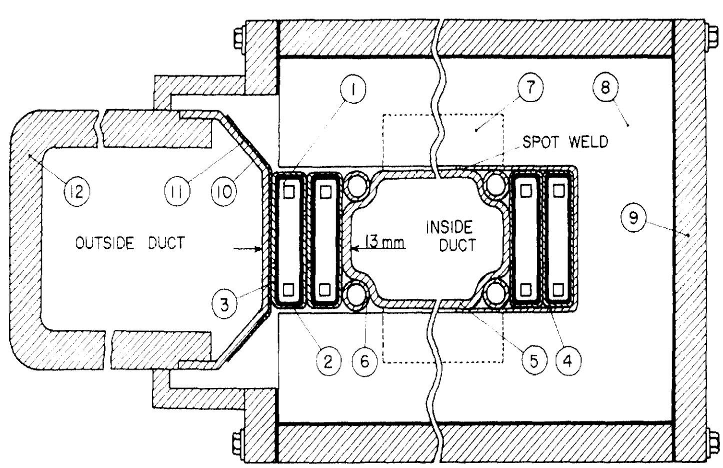

Fig.1 (arbitrary scale)

Cross section of test septum magnet.

1. Copper hollow conductor (4 mm^t),
2. Ceramic coating (0.3 mm^t),
3. Aluminum oxidized sleeve (0.3 mm^t),
4. return-coil holder (0.5 mm^t stainless steel),
5. inside duct (1 mm^t s.s.),
6. cooling water pipe (4 mmϕ s.s.),
7. iron fin (0.5 mm^t),
8. iron laminated core (300 mm long),
9. frame insulated from core by ceramic coating (10 mm^t s.s.),
10. silicon steel plate (0.35 mm^t),
11,12. outside duct (1 mm^t and 5 mm^t s.s.).

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To decrease Q, the thickness d should be small and also the resistivity r be high. Taking account of easiness of welding, we choose the 18-8 stainless steel plate, resistivity r of which is 7.2×10^{-7} Ω•m. To avoid deformation after welding, it is desirable that the thickness d is at least 1 mm. By inserting the values a, b, c given above into eq.(1) and also taking $d = 1 \times 10^{-3}$ m, $B_m = 3.5 \times 10^{-1}$ teslas, $W = 2.5 \times 10^{-3}$ sec, f = 10 Hz, we obtain $Q = 2.2 \times 10^2$ watts. When each corner of the duct is cooled by water and held at a fixed temperature T_0 as shown in Fig.3, the temperature T at the duct center due to this eddy current loss is given[1] by

$$T = \frac{Q_p b}{8ad\rho} + T_0 , \tag{2}$$

where ρ is the heat conductivity and Q_p is the eddy current loss at the top or bottom surface of the duct, which is just half of the first term of eq.(1)

$$Q_p = \frac{b}{6} \cdot \frac{ab^2 d\pi^2 B_m^2 f}{4rW} . \tag{3}$$

By using $\rho = 1.6 \times 10$ watts/m•deg for the 18-8 stainless steel, we obtain $T - T_0 = 1.2 \times 10^2$ °C. This value is, however, much overestimated, because the duct wall is in contact with the core in some parts and the heat would be dissipated also into the core. Even if all the heat flows into the core, the core would not be damaged at this heat level. As we will mention later, the temperature rise of the duct is not severe problem. This eddy current loss, however, means an increase of the total loss of 18 %, because the power lost by the pure resistance of the septum coil is about 1.2×10^3 watts. If we use a duct wall 2 mm in thickness, the eddy current loss increases doubly, and it is beyond the capacity of the power supply. Therefore, in the present design we choose for the duct wall the 1 mm thick stainless steel plate.

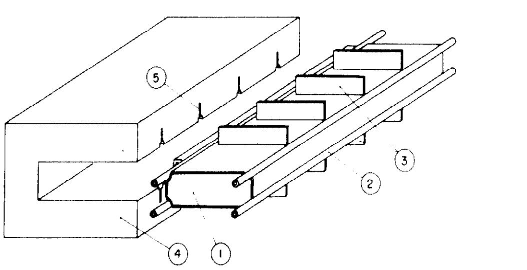

Fig.3 Inside duct and core of test septum magnet. 1. inside duct, 2. cooling water pipe, 3. iron fin, 4. core, 5. slit for inserting fin.

The deformation δ at the duct center by the atmospheric pressure is given[1] by

$$\delta = \frac{2.8 \times 10^{-2}\, b^4}{(1+1.06n^5)Ed^3} , \tag{4}$$

where E is the modulas of longitudinal elasticity and n = b/a. Putting 2.0×10^6 kg/cm^2 typical for the 18-8 stainless steel into E, we get $\delta = 7.7 \times 10^{-4}$ m. This is a rather great deformation. To decrease δ, the thickness d of the duct should be larger, but it makes Q increase as shown in eq.(1). To make both of them small, thin iron fins are welded perpendicularly to the duct as shown in Fig.3. The maximum deformation δ_f in this case[1] is

$$\delta_f = \frac{3.9 \times 10^{-2} b^4}{E_i g h^3 N} , \tag{5}$$

where E_i is the modulas of the longitudinal elasticity of iron, N is the number of fins per unit length of the duct, and g, h are the thickness, height of the fin, respectively. By inserting the values $E_i = 2.1 \times 10^6$ kg/cm^2, $g = 5.0 \times 10^{-4}$ m, $h = 1.5 \times 10^{-2}$ m and $N = 1.3 \times 10$/m into eq.(5), we obtain $\delta_f = 4.6 \times 10^{-5}$ m, which is an acceptable value.

Fabrication and Measurements

The model septum magnet which we made is shown in Fig.1, the conductor of which is a two-turn coil. The conductor is made of OFHC copper, and has copper water pipes brazed at its upper and lower end. It is coated by a 0.3 mm thick ceramic layer, and then enclosed with an oxidized aluminum sleeve 0.3 mm in thickness. The return coil is further enclosed tightly with 0.5 mm thick stainless steel plate which is spot-welded to the side wall of the inside duct. Then the duct is inserted into the core gap together with the septum coil, and the outside duct is pressed to the septum coil. Thus the septum coil is sustained rigidly between the inside and outside duct. The leakage magnetic field outside the core is induced by the following two causes. First, it is due to a small gap between the septum conductor and core, and is decreased by a silicon steel plate of 0.35 mm thickness as shown in Fig.1-10. Further it is originated from an electrical loop between the inner core and the outer surface of the core. As shown in Fig.1, the loop would be due to mainly two causes. One is the loop between the inside duct, laminated core and outer frame. The other is the loop between the inside duct and the outside duct, because they are connected together at the end flanges. So, it is very important to cut off the loops by some insulators.

The temperature rise $T - T_0$ is measured at the duct center as a function of the peak field B_m. It is shown in Fig.4. This temperature rise is not dangerous for the magnet.

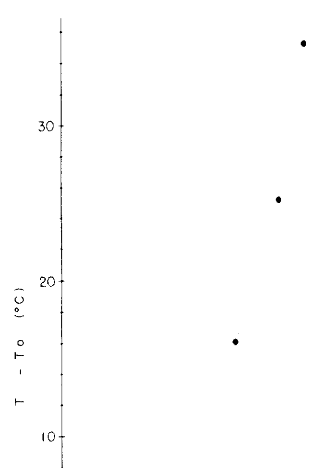

Fig.4

Temperature rise measured at duct center due to pulsed field with $W = 2.5 \times 10^{-3}$ sec, f = 10 Hz.

The measured maximum deformation of the duct $\delta_{f\,mea}$ is about 5×10^{-4} m. It is much larger than the calculated value $\delta_{f\,cal} = 4.6 \times 10^{-5}$ m. This difference comes from the deformation of the duct side wall and also twist of the fin. But, the decrease of the gap height due to this deformation can also be neglected.

The results of magnetic field measurement inside and outside the core are as follows. At first, the leakage field outside the septum was larger than 25 % of the gap field, when there were closed electric loops as described above. This leakage can not be shielded by the thin silicon steel plate because of its low saturation field. In preliminary experiments, one of the loops was cut off by a ceramic coating on the surface of the frame outside the core, and the other was also cut by taking away the flanges. Then the leakage due to the above loops was perfectly eliminated. The only remaining field is due to the small gap between the septum and core, and is 0.3 % of the gap field as shown in Fig.5. This would be about six times greater, if there is no silicon shield plate. In the neighbourhood of the slits cut in the core for fins, the leakage field increases by 50 % compared with the other part, but it is still practically negligible. The gap field inside the septum were measured. As shown in Fig.5, the field variation is about 5 %. It is still not small enough, because we might have a change of the beam emittance shape in the gap of the septum magnet. Unfortunately, this field irregularity has not yet been reduced.

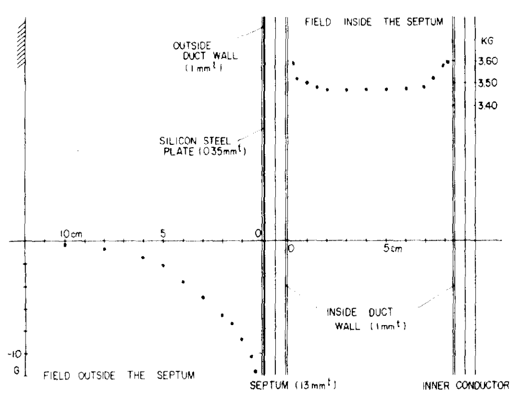

Fig.5 Measured magnetic field inside and outside septum.

Conclusions and Improvements

As stated above, we have obtained satisfactory results with regard to the test septum magnet having a metal inside duct, except for the flatness of the gap field. It will be used in UHV systems, and is also more compact and stronger than the usual one. We are now making a magnet of this new type which will be actually used for the fast extraction of the 12 GeV beam of the KEK PS. In this case, the change of the emittance shape due to the irregularity of the gap field causes no problems for the extracted beam.

In order to insulate the electrical loops discussed in the previous section, the supporting frame of this magnet is also coated by ceramic just as the test magnet. The insulation between the inside and outside duct is obtained by a new flange, part of which is made of ceramics as shown in Fig.6.

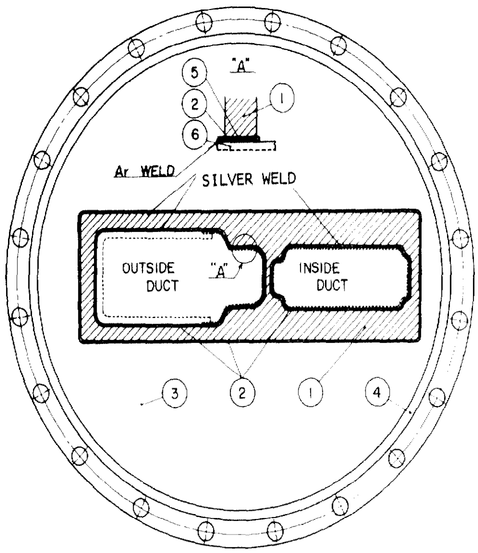

Fig.6 Flange for new extraction septum magnet. 1. ceramics, 2. kovar frame, 3. stainless steel flange, 4. groove for gasket, 5. metalized ceramics, 6. metal duct of magnet.

In this magnet we have another improvement. As shown in eqs.(1) and (2), the eddy current loss Q is mainly proportional to the cube of the width b of the duct, and the temperature rise $T - T_0$ is proportional to b^4. To decrease b makes also the deformation δ_f small as shown in eq.(5). It is very important to make the width as small as possible. Therefore we are making a curved core for the present septum magnet, and the curvature is the same as the beam orbit inside the gap. Then the width would be narrower because we need not take sagitta into account. The sizes of the inside duct of this magnet are;

$$a = 1.4 \text{ m},\quad b = 6.1 \times 10^{-2} \text{ m},\quad c = 3.0 \times 10^{-2} \text{ m},$$
$$d = 1.0 \times 10^{-3} \text{ m},\quad g = 5.0 \times 10^{-4} \text{ m},$$
$$h = 2.0 \times 10^{-2} \text{ m, and } N = 7.1 \text{ /m}.$$

When the following magnetic field is applied; $B_m = 1.1$ teslas, $W = 1.0 \times 10^{-2}$ sec, $f = 1$ Hz, we obtain the values by eqs.(1)∿(5); $Q = 1.1 \times 10^2$ watts, $T - T_0 = 7$°C, $\delta_f = 9.1 \times 10^{-6}$ m. These are reasonable values for practical use.

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Reference

1) T. Kawakubo, to be published in KEK report.