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New method of Helmholtz coil alignment

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A new alignment method for Helmholtz coils is proposed. This method is based on a probe, whose axis is the same as the alignment axis. This probe includes one magnetic sensor, whose position is slightly shifted from the probe axis, and which is set perpendicular to the axis. Using this probe, the tilt and shift of the magnetic centre of Helmholtz coils can be aligned to within an order of 0.1 mrad and 0.1 mm, respectively. Moreover, by this method, effects of terrestrial magnetism and tilt of the magnetic sensor can be removed from the measurement. This alignment method is presented along with an estimate of the alignment accuracy of the SPring-8 linac injector.

Keywords: Helmholtz coils; alignment; linacs; SPring-8.

1. Introduction

In a linac injector, Helmholtz coils have the important role of transporting low-energy beams against the divergent force of the space charge effect. Owing to the low energy, the electrons in the beam are very sensitive to the magnetic field of the Helmholtz coils. However, since the Helmholtz coil has no core, there is often an error in the field at the centre of the coil. Thus, precise alignment of the magnetic centre is needed.

In the SPring-8 linac injector, a rotatable magnetic probe was used for this alignment. This new technique is discussed below.

2. Principle

2.1. *Magnetic probe*

As shown in Fig. 1, a magnetic probe is set along the design alignment axis of a Helmholtz coil. This probe is able to move along the alignment axis and also to rotate around the axis. The probe has one magnetic sensor for measuring the radial component of the magnetic field.

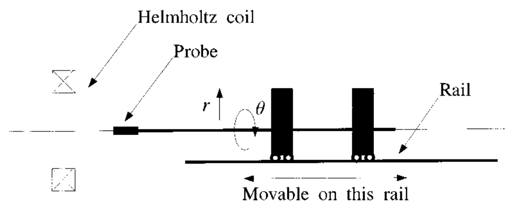

Figure 1
Scheme of the alignment of the Helmholtz coils.

Details of the probe are shown in Fig. 2. The sensor is set at a position which is offset by 1.8 mm from the rotating axis. The measurement device has a rail along the axis, and the probe moves along this rail. At first the probe is scanned along the alignment axis, keeping at a rotating angle θ, and thus a radial component of the magnetic field distribution curve is obtained. Next, the probe is rotated 180° around the axis, and another distribution curve is obtained. The former is named the θ distribution curve and the latter is the $\theta + \pi$ distribution curve. In these two cases the sensor directions are opposite to each other, and the sensor positions are separated by 3.2 mm. By comparing these two magnetic-field distribution curves, the alignment error of the Helmholtz coils can be estimated.

2.2. *Calculation of field distribution curves*

We have calculated the magnetic distribution curves for the SPring-8 linac Helmholtz coils under various conditions of misalignment. Fig. 3 shows the variations in the distribution curve caused by the tilt of the coil. This calculation is for one coil, of radius 210 mm and current 12 540 A turns. It is very clear that the phases of the two distribution curves (θ and $\theta + \pi$) are shifted when the tilt of the coil is large. When the tilt is smaller the shift becomes smaller, and finally the two distribution curves coincide

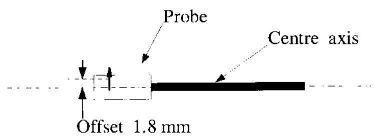

Figure 2
Details of the magnetic probe.

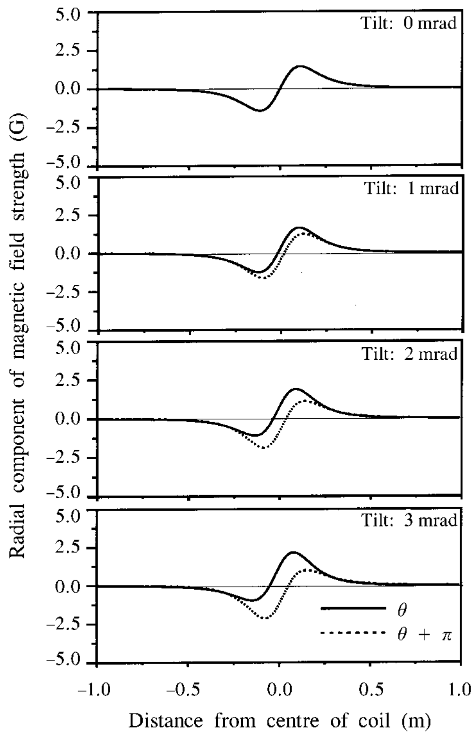

Figure 3
Calculated distribution curves for a single coil caused by the effect of tilt of the coil (1 G = 10^{-4} T).

when the coil is just aligned. Even if the tilt is 1 mrad, differences between the two curves are easily observed.

Fig. 4 shows the effects of the offset of the coil. In these cases the difference between the two distribution curves is in their amplitudes. As before, these two distribution curves coincide when the coil is just aligned. From Fig. 4, the θ distribution curve is clearly distinguishable from the $\theta + \pi$ curve, even if the offset is 1 mm.

The sensor is small and may be slightly tilted in the probe, so it does not always point to only the radial direction. Fig. 5 shows this case when alignment is completed. The distribution curve amplitudes are different on the right- and left-hand sides. This effect is different from the effect of misalignment of the coil. Even though the sensor is tilted, the two curves coincide when alignment is just achieved, as in Fig. 5. Therefore, the effect of tilt of the sensor can be neglected from the alignment measurement.

Fig. 6 shows the effect of an external (terrestrial) magnetic field. This effect can be easily seen in that the two distribution curves are separated constantly in all regions along the axis. Therefore, this effect is also able to distinguish another effect of misalignment. The magnitude of this separation is twice the magnitude of the external magnetic field. If this external field is the terrestrial field, it is about 0.6 G at the SPring-8 site.

In the SPring-8 linac, the injection part is composed of six Helmholtz coils. Fig. 7(a) shows the magnetic distribution curves for six coils when alignment is just achieved; the sensor has no tilt and there is no external field. Fig. 7(b) shows the curves if the sensor is tilted, and Fig. 7(c) shows the curves if there is an external magnetic field.

3. Actual alignment

The Helmholtz coils are aligned using this technique in the SPring-8 linac. At first, the tilt and shift of each single coil is adjusted. Next, the whole Helmholtz coil system is aligned. Fig. 8 shows data at the SPring-8 linac when alignment is achieved.

The reason why the graphs are divided into two parts in both Figs. 8(a) and 8(b) is as follows. The probe length is shorter than

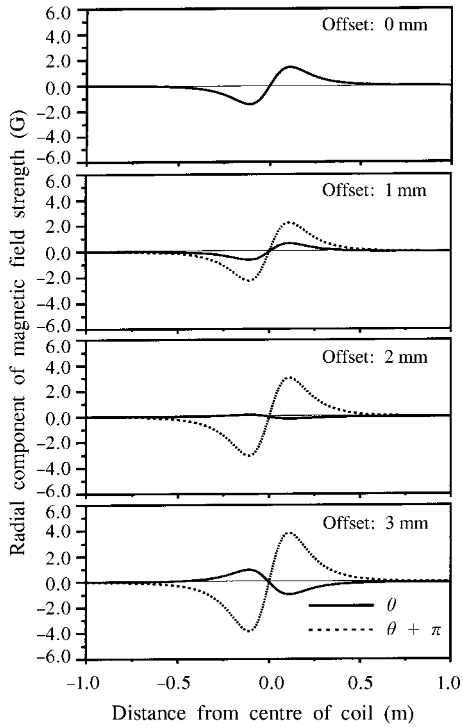

Figure 4
Calculated distribution curves for a single coil caused by the effect of offset of the coil (1 G = 10^{-4} T).

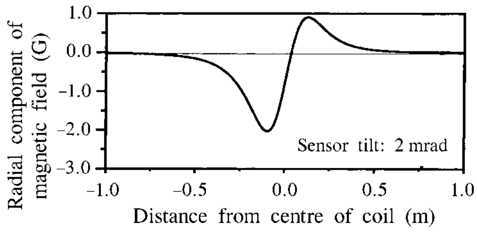

Figure 5
Calculated distribution curve for a single coil caused by the tilt of the sensor in the magnetic probe (1 G = 10^{-4} T).

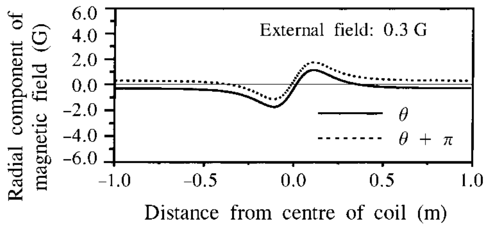

Figure 6
Calculated distribution curve for a single coil caused by an external field (1 G = 10^{-4} T).

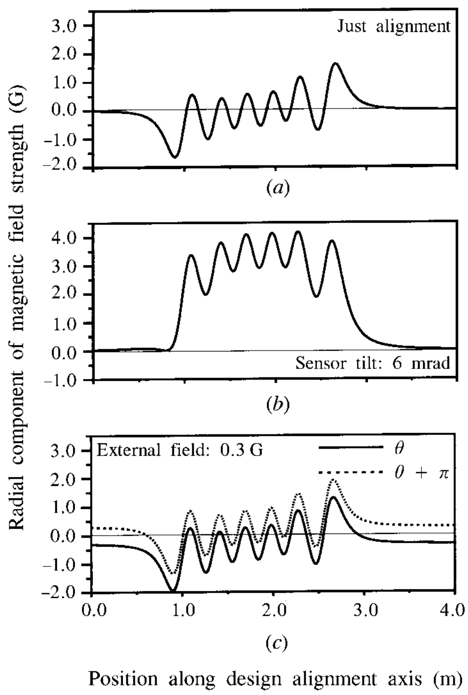

Figure 7
Calculated distribution curves for six coils when they are just aligned (1 G = 10^{-4} T): (a) alignment just achieved, (b) when the sensor in the probe has a tilt of 6 mrad, (c) with an external magnetic field.

the total length of the six coils; it could not be measured immediately so at first the coils in the upper stream side are aligned. Next, the measurement device is moved downstream and the remaining coils are measured. In the former measurement, coils 1–5 are driven, and in the latter measurement, all coils are driven. The five peaks in the upper graphs of (*a*) and (*b*) correspond to coils 1–5. The four peaks in the lower graphs correspond to coils 3–6. 90 and 270° corresponds to the vertical direction, 0 and 180° to the horizontal direction. The left-hand side of the upper graph corresponds to a magnetic shield made of iron, and so the distribution curves quickly fall to zero. The separation of the two distribution curves becomes larger on the right-hand side of the curve. This indicates that the external magnetic field becomes larger here. It is considered to be the effect of magnetization of the rail (which is made of iron) of the measurement device (see Fig. 1).

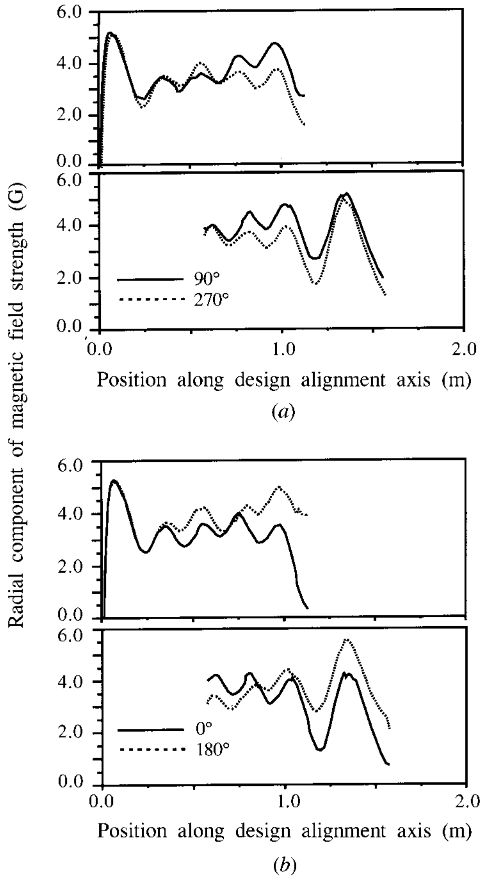

Figure 8
Distribution curve data of the SPring-8 linac injector (*a*) in the vertical direction and (*b*) in the horizontal direction when alignment of the Helmholtz coils is completed (1 G = 10^{-4} T).

In Fig. 8 the distribution curves are separated by about 3.5 G from the zero Gauss line. This indicates that the sensor is slightly tilted. The magnitude of this tilt is about 6 mrad by comparison with Fig. 7(*b*). The two distribution curves do not coincide perfectly, but the phase and amplitude of the curves are almost coincident. The amplitudes of the curves in the middle of the graphs are about 1.5 G, which is almost the same as in Fig. 7(*b*). Thus, we can recognize that alignment is completed. As compared with Figs. 3 and 4, on the left-hand part of the curves (magnetization of the rail is not effective in this part) the tilt and shift are aligned to less than 1 mrad and 1 mm, respectively, and they may be within an order of 0.1 mrad and 0.1 mm, respectively.

There are several problems. How should the magnetic shield effects be considered. Why is terrestrial magnetism (about 0.6 G separation) not observed on the left-hand side of Fig. 8(*a*)? Why do the two distribution curves cross when alignment is achieved? Are they effects of magnetization of other parts or of inside the coil? In any case, it is clear that alignment is completed in Fig. 8.

4. Summary

A new alignment method for Helmholtz coils is proposed. We applied this method to the SPring-8 linac injector and aligned the magnetic centre of the Helmholtz coils. The accuracy of the alignment is of the order of 0.1 mrad in tilt and 0.1 mm in shift.