Abstract. Aiming to develop the compact nuclear magnetic resonance devices, the authors have been developing the uniform magnetic fields in the space between the face-to-face magnetic poles which contain HTS bulk magnets. The authors deformed the original convex shape of the magnetic field distribution to concave by attaching a ferromagnetic iron plate of 20 mm and 100 mm in diameter on one of the pole surfaces. The magnetic field distribution precisely measured along x-axis changed from concave to convex with increasing distance from the magnetic pole surface, which suggested the presence of magnetically flat region. From the results of mapping on the field uniformity data, we have succeeded in obtaining the field uniformity under 500ppm in the space of 4 x 4 x 0.8 mm$^3$ when the magnetic poles emitting concave and convex field distributions were settled face-to-face with various gaps 30-70 mm. This performance exceeded the target value of 1,500ppm which is necessary to detect the NMR signals.

1. Introduction
In general, since nuclear magnetic resonance (NMR) magnets require us extremely-high uniform magnetic field spaces, it has been suspected to be impossible to form such homogeneous field distributions with use of the high temperature bulk magnets (abbreviated as bulk magnets) which originally exhibit the conical-shaped magnetic field with steep field gradient [1]. Only as for the magnetic field intensity, the bulk magnets would be feasible candidates as intense field generators for NMR/MRI (Magnetic Resonance Imaging) devises when we would refer to the performances reported as 16 T, 17.24 T, and 17.6 T in the past papers [2-4].

According to the reports [5, 6], the field uniformity less than 1,500ppm should be required to detect the NMR signals. Then, we changed the shape of magnetic field distribution from convex to concave by attaching an iron plate on one of the pole surfaces. As shown in Figure 1, the magnetic field distribution exhibits convex shape up to 1.47 T. It was deformed to be concave, exhibiting 0.80 T at the center. The magnetic poles were activated by the pulsed field magnetizing (PFM) technique beforehand by feeding the current to a pulse coil.

As shown in Figure 2, the magnetic poles were settled face-to-face with various gap spaces, and the magnetic-field uniformity was estimated there. When we combined the concave and convex field distributions to compensate the uneven field distributions, the best uniformity reached 358ppm in the 30 mm gap, which exceeded the target value of 1,500ppm [7]. In addition, the numerical simulation
showed us the best uniformity of 30ppm at 1.1 T, which also suggested us the feasibility of novel compact NMR device [8]. In the study, the authors investigated the magnetic field distribution more precisely than ever by evaluating the uniformity on x-y plane to estimate the deformation by iron plates.

2. Experimental procedure

2.1. Magnetic pole structures and arrangements
We employed the single and the face-to-face bulk magnet systems, which were kept at 31 K by GM-cryocooler in the series of experiments. The actual instances of system configuration are shown elsewhere [8-10]. Figure 1 shows how to change the magnetic field distribution from the original convex to concave shapes by attaching an iron plate of 100 mm in diameter. The top view along z-axis indicates the measuring area by scanning Hall probe, the location of bulk magnet in the magnetic pole chamber, and an iron plate on the pole surface. In the experiment, a couple of iron plates of 20 mm and 100 mm in diameter and 2.26 mm in thickness were attached on one magnetic pole in turn.

Figure 2 shows a schematic structure of the face-to-face arranged magnetic poles with and without an iron plate. The magnetic fields of convex and concave shapes were combined with various gaps of 30-70 mm. In the figure, the scale indicates the position of the x-y plane on which the field intensity data were measured. Note that the distance from the bulk magnet surface to the iron plate surface is 5.9 mm, which is defined as the null point.

The bulk magnet was activated by the pulsed field magnetizing method beforehand, emitting magnetic flux density of 1.47 T on the left-hand side pole and 1.8 T on the other side pole.

2.2. Evaluation of magnetic field uniformity
Figure 3a shows an evaluation method for magnetic field uniformity. A facet of 4 mm x 4 mm area is derived from the magnetic field distribution map, and the uniformity is calculated by the formula (1) by 21 data points except those from four corners of the region. As shown in Figure 3b, the uniformity

![Figure 1. Change of magnetic field distribution by attaching an iron plate (a), and the top view (b).](image1)

![Figure 2. Schematic structure of face-to-face arranged magnetic poles.](image2)

![Figure 3. Evaluation for magnetic field uniformity.](image3)

![Figure 4. Magnetic field distribution on the single pole surface deformed by attaching a 20-mm iron plate.](image4)
data were also derived from the averaged 5-point data in the 4-mm span of x- or y-axes cross section as in the manner in the past papers [8-10], where $B_{z\text{Max}}$ and $B_{z\text{Min}}$ mean the highest and lowest $B_z$ values in the area, respectively.

$$U = \frac{B_{z\text{Max}} - B_{z\text{Min}}}{B_{z\text{Max}} \times 10^6} \ [\text{ppm}] \quad (1)$$

3. Results and Discussion
An iron plate was attached on the left pole of face-to-face system. In Figure 4, the magnetic field distribution gives us a concave shape on the iron plate surface due to its shielding effect. The iron plate was composed of Fe-C (<0.25%) with the dimensions of 20 mm in diameter and 2.26 mm in thickness. The original intensity 1.47 T changed to 1.26 T at the center of the bulk surface. As for the single pole, the uniformity was evaluated as 3,619 ppm (parts per million) at the center point.

Figure 5 shows the unidirectional magnetic flux distribution measured along x-axis as a function of distance from the iron surface. The negative values mean S pole. The distribution changed from convex shape to concave with increasing distance. The magnetic field intensity changed from 1.26 T at 8.3 mm to 0.90 T at 14.3 mm. One may expect the magnetically-flat region at around 11.3 mm from the null point. When we replaced the 20-mm iron plate to 100-mm in diameter, the magnetic field intensity degraded due to enhanced shielding effect in comparison with that of 20 mm in diameter.

When we refer to the face-to-face system with a gap of 70 mm between the poles, as shown in Figure 6b, the magnetic field intensity measured at 8.3 mm increased to 1.32 T at the center point. As shown in Figure 6b, the intensity degraded to 0.92 T at 8.3 mm when the iron plate size was changed from 20 mm to 100 mm.
which were calculated by averaging surrounding 21-point uniformity data. The centered position of pink region corresponds to the area less than 1,500 ppm. The best uniformity reached 463 ppm at the maximum field of 1.25 T. Figure 8 shows the mapping of magnetic field data measured in 1 mm pitch on x-y plane. The sheets show the uniformity along z-axis of 0.5-2.5 mm from the pole surfaces. As for the region which exhibited the uniformity less than 1,500 ppm, we obtained the uniform area in the range of 0.5-1.3 mm along z-axis from the surface. Then, we have succeeded in obtaining the uniform field area less than 1,500 ppm in the space of 4 mm x 4 mm x 0.8 mm.

Figure 9a shows the position dependence of uniformity data vs position along z-axis, which were obtained in x-y planes, in the cross section of x-axis, and y-axis, respectively. We obtained the best uniformity data 878 ppm at z=10.9 mm in the plane, 706 ppm in x-axis, and 788 ppm in y-axis directions. As shown in Figure 9b, we attempted to evaluate the reproducibility of the measurement. One sees slight deviation in the repeatedly-measured data, which clearly exhibited however the presence of uniform region less than 1,500 ppm in the range of 0.8 mm, from 0.5 mm to 1.3 mm of z-axis from the pole surface. As this uniformity is sufficient to detect NMR signals.

Figure 8. Thickness of uniform area along z-axis.

Figure 9. Position dependence of uniformity measured along z-axis, obtained in the x-y plane, x- and y-axis cross sections, and uniformity along x- and y-axes cross sectional distribution measured in the gap of magnetic poles (a), while (b) shows the reproducibility of magnetic field measurement.
4. Conclusion
We discussed about our recent attempts to develop the uniform magnetic field space for NMR applications. Attaching iron plate to one magnetic pole was found to be sufficiently effective in forming magnetically uniform field space, and we have succeeded in obtaining the field space with the best uniformity less than 500ppm at 0.5 mm position, and less than 1,500ppm in the range 0.5-1.3 mm. This implies that the application to the novel compact NMR/MRI devices must be feasible with use of HTS bulk magnets and PFM activation.

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