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Validation of a high-gradient trapped field magnet with an open bore providing a quasi-microgravity space on Earth and its application to magnetic levitation

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I. Introduction

[1] K Takahashi, H Fujishiro and M D Ainslie, *Supercond. Sci. Technol.*, **34** 035001, 2021.

To provide a high magnetic field in a more cost-effective way, large-single grain bulk superconductors – such as the RE-Ba-Cu-O (RE: rare earth element or Y) family of materials – have shown promising potential for generating magnetic fields over several tesla as so-called trapped field magnets (TFMs). Compatibility between the magnetic performance and flexibility in operation is required to realize a practical TFM device that can provide such high magnetic fields in an open space outside the vacuum chamber. **The authors recently proposed a new concept of a high-gradient trapped field magnet (HG-TFM), which consists of slit ring bulks that can generate a downward-oriented magnetic field, are tightly stacked with conventional TFM cylinders [1].** It has been estimated numerically that **a magnetic field gradient product, $B_z \cdot dB_z/dz$, over 1500 T^2/m could be realized** by field-cooled magnetization (FCM) of such a device, even with a relatively small external field of 9 T at 40 K. This is comparable with the performance of conventional, large-scale hybrid magnets with 15 T.

◆ In this study, we report the conceptual design of an HG-TFM and the results of experimental validation: magnetic properties and magnetic levitation in an open bore space.

V. Conclusion

We have validated, experimentally, the HG-TFM with I.D. = 36 mm, which was magnetized by FCM at 21 K with B_{app} = 8.60 T, and have performed the demonstration of magnetic levitation inside a room-temperature bore with 25 mmφ of the HG-TFM. The important numerical results are summarized as below.

- It was shown that the present HG-TFM can be established during cooling process and magnetizing process, in which the trapped field, B_z = 8.57 T, and the field gradient product, $B_z \cdot dB_z/dz$ = -1930 T^2/m, was realized. Magnetic levitation of fundamental materials was successfully demonstrated exploiting an optical system for in-situ observation.
- Numerical results of magnetic profiles have shown the superiority of the HG-TFM with that superior magnetic performances. The levitation state along the horizontal direction can be explained based on the shape of the magnetic profile.

II. Experimental setup and Procedure

◆ Motivation and Concept

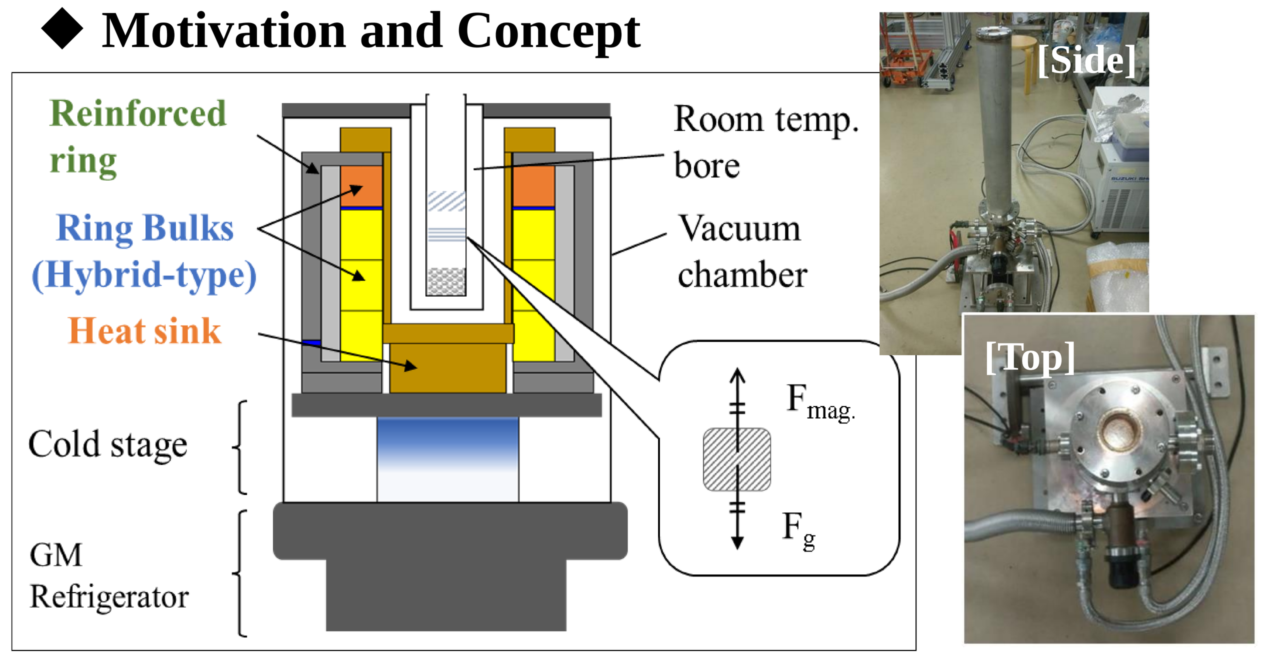
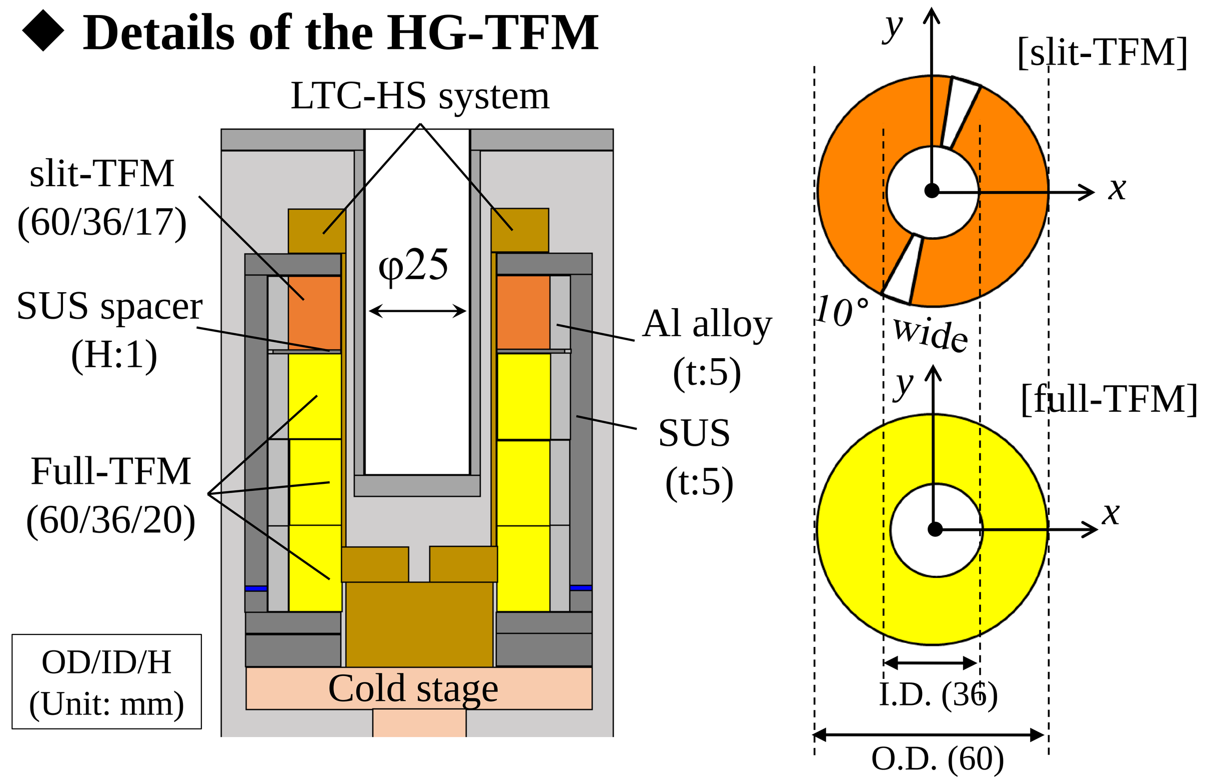
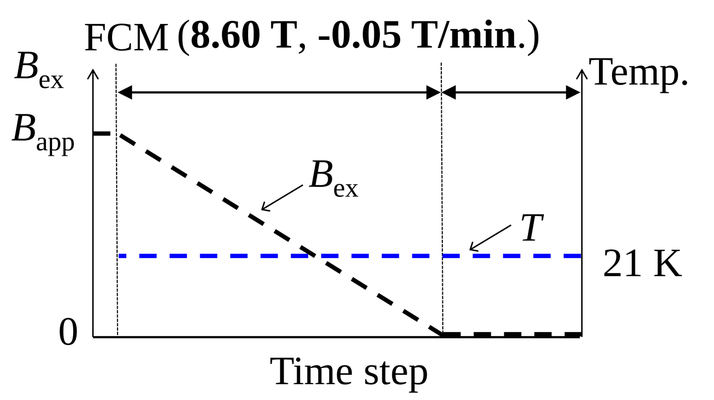


Fig. 1. A concept of the HG-TFM device (W:35, D:35, H:100 cm) as a compact, high-field magnet, and magnetic levitation in an open bore space.

◆ Details of the HG-TFM





⇑ Fig. 2. Cross-sectional of the HG-TFM and the top views of bulk samples.

⇐ Fig. 3. Time step sequence of Field-cooled magnetization (FCM) for the HG-TFM.

III. Experimental Results and Demonstration

◆ Cooling test before magnetization

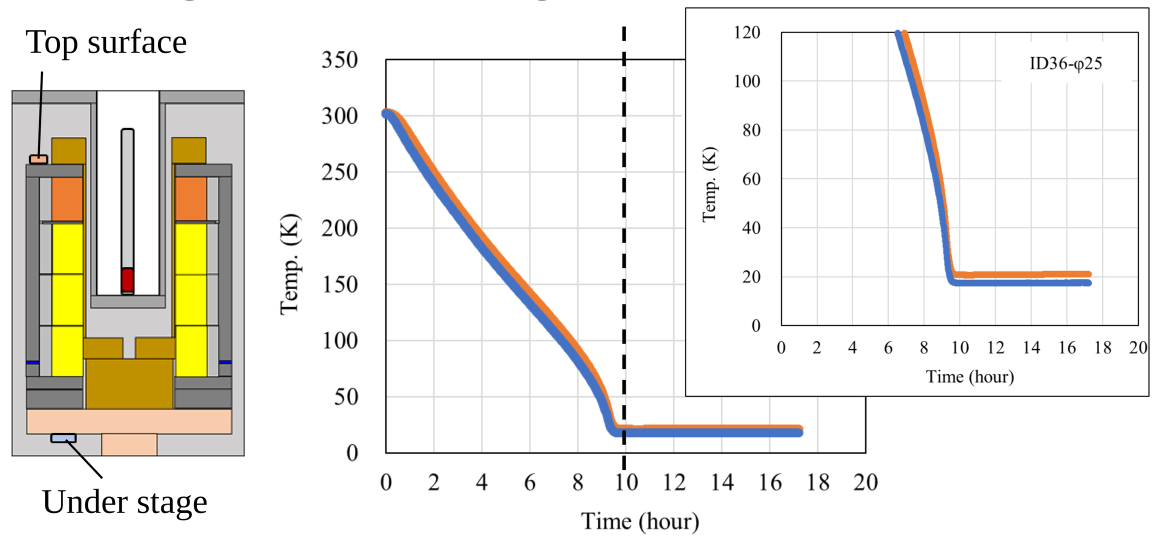
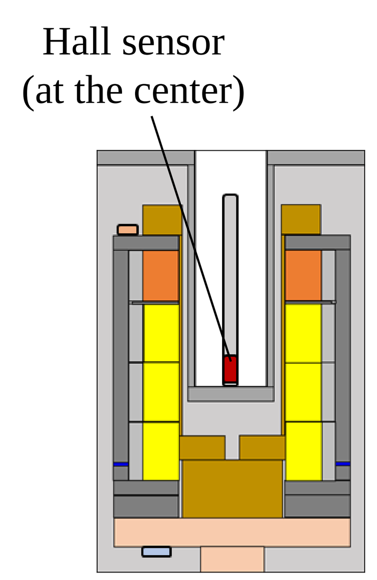


Fig. 4. Time dependence of the temperature measured using Cernox™ thermometers at the top surface and under a cold stage during cooling process from 300 K.

After 10 hours, it reached to T_{Stage} = 17.5 K, T_{Top} = 21.0 K

◆ Magnetizing process (FCM at 21 K)



No flux creep.

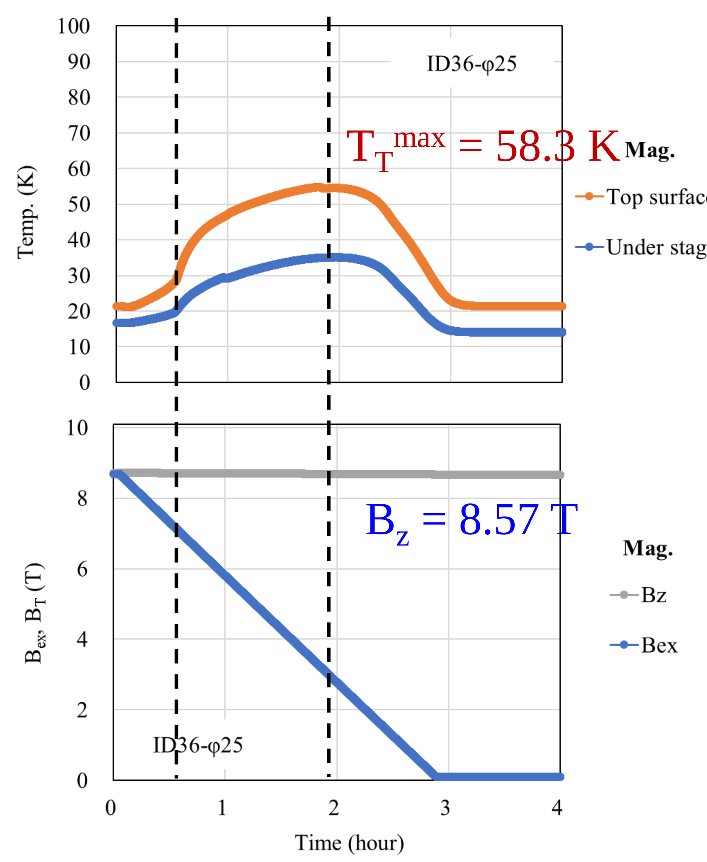
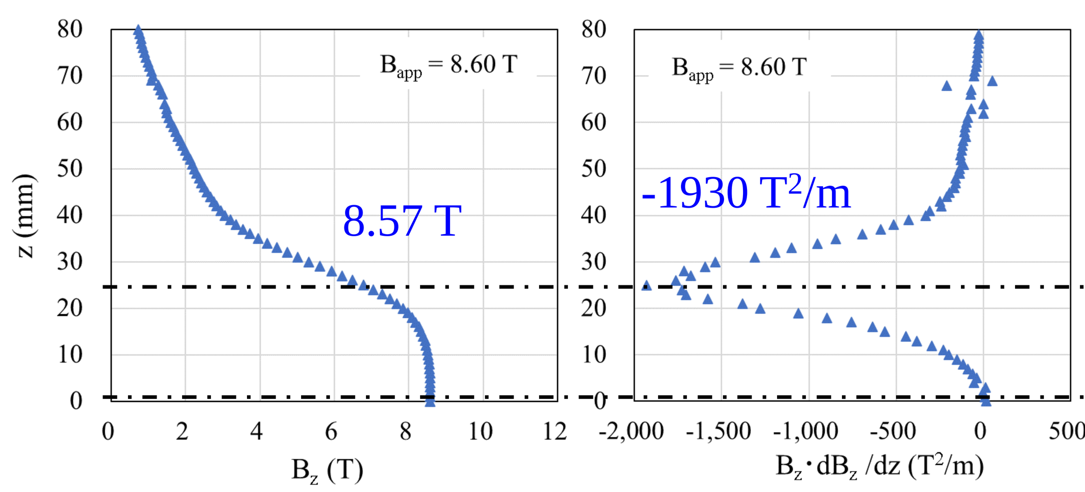


Fig. 5. Time dependence of the temperature and the magnetic fields of the HG-TFM measured using a hall sensor at the central position during FCM at 21 K, exploiting an applied field, B_{app} = 8.60 T.

◆ Magnetic field profile along the height (z) direction



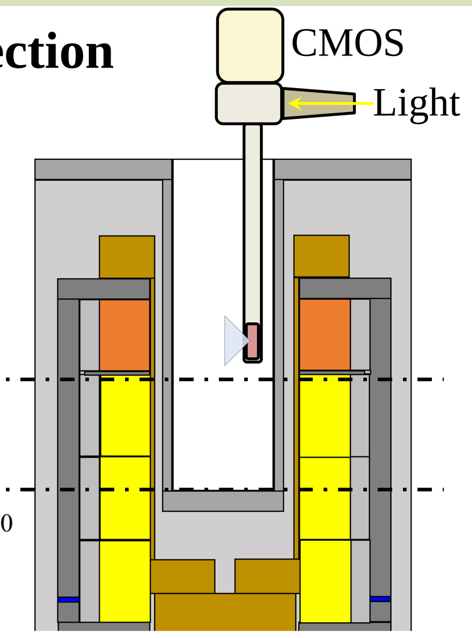
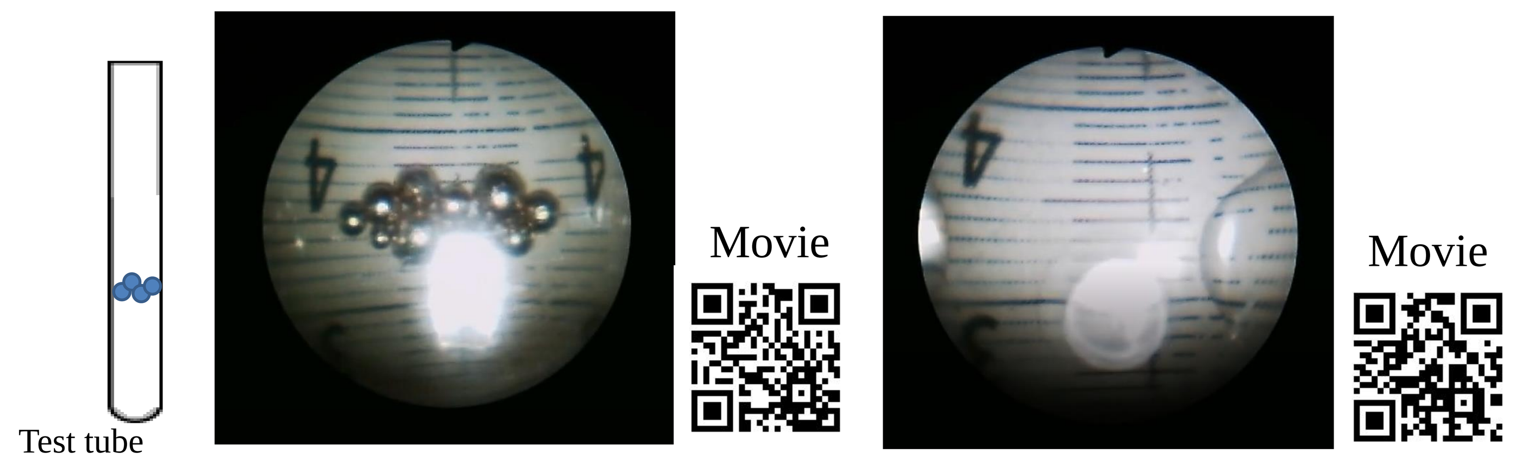


Fig. 6. The magnetic field, B_z, and the calculated field gradient product, $B_z \cdot dB_z/dz$, profile along the z-axis in a room temperature bore after magnetization. Image also present an optical system for in-situ observation of magnetically levitated targets.

◆ Demonstration of magnetic levitation in air



Bi particles (Solid) Pure water (Liquid)

Table I: Properties of levitated materials and calculated $B_z \cdot dB_z/dz$ values

Targets	Density (g/cm^3)	Susceptibility (-, SI)	Calculated $B_z \cdot dB_z/dz$ (T^2/m)	Levitated position (mm)
Bismuth*	3.54	-4.93E-5	-879	**+35**
Pure water	0.995	-8.54E-6	-1376	**+30**

*Density and Susceptibility are effective values measured by magnetic balance, MSB-MkI

$$B_z \frac{dB_z}{dz} = \frac{\rho_1 - \rho_{air}}{\chi_1 - \chi_{air}} \mu_0 g.$$

Bi particles (z=35±1): -695～-950 T^2/m
Pure water (z=30±1): -1308～-1595 T^2/m

levitated positions are reasonable against the estimated values.

IV. Numerical results and Discussion

◆ Comparison with numerical results

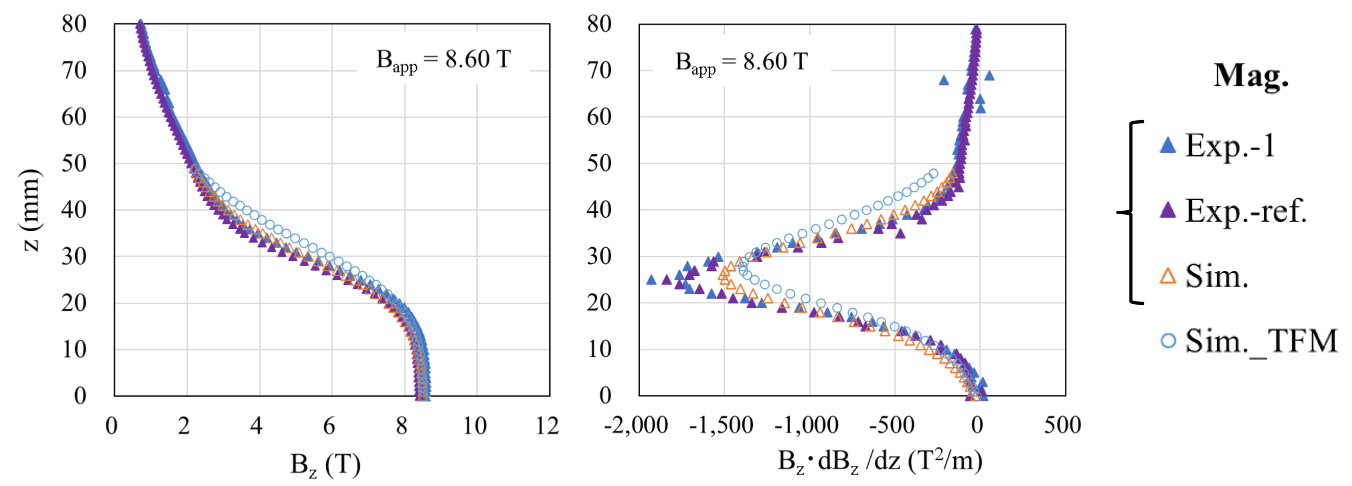


Fig. 7. Numerical results of the magnetic field, B_z, and the calculated field gradient product, $B_z \cdot dB_z/dz$, profile along the z-axis after magnetization. The other experimental results are also included as Exp._ref. for comparison.

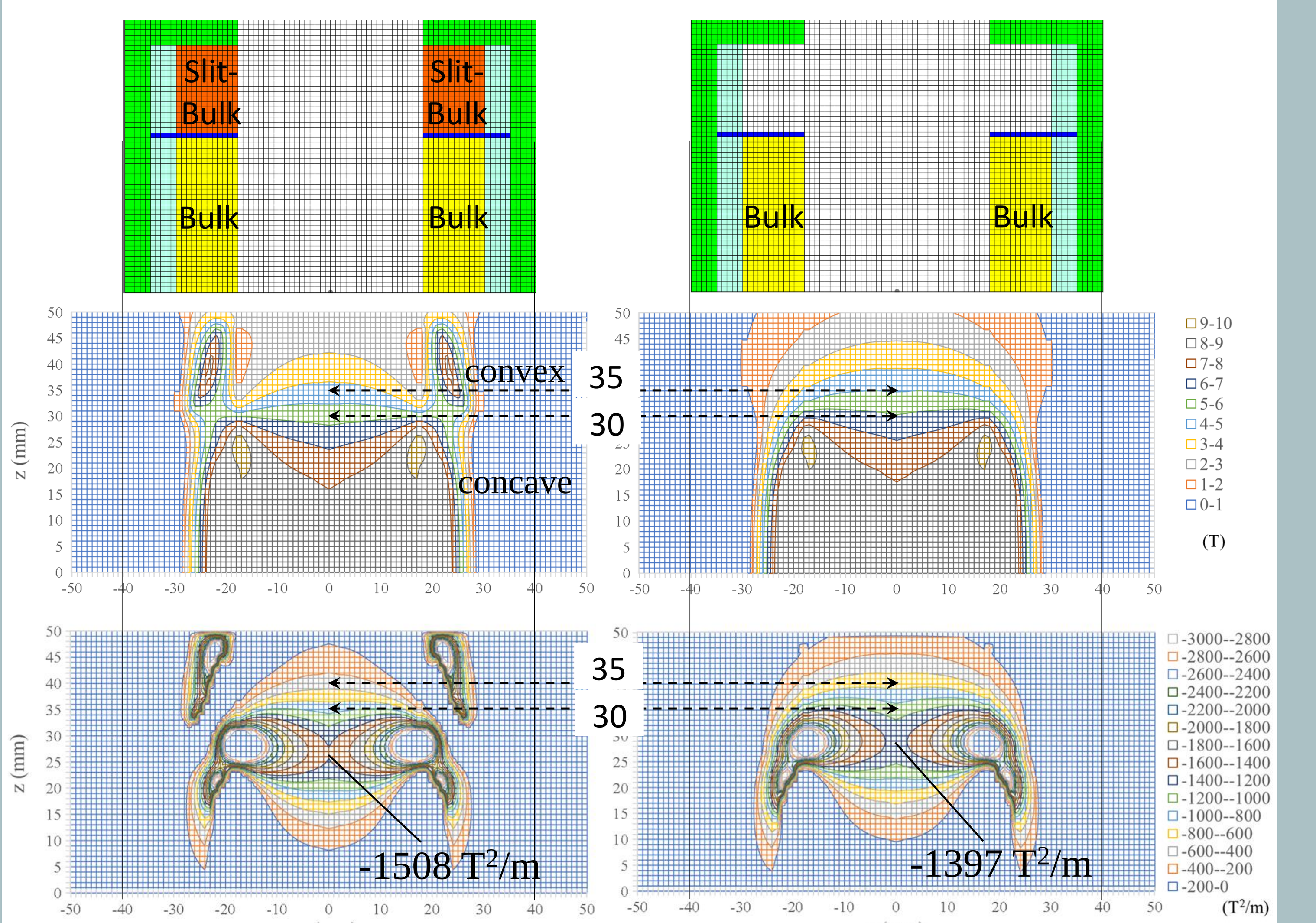


Fig. 8. Numerical results of the magnetic field, B_z, and the calculated field gradient product, $B_z \cdot dB_z/dz$, profile inside after magnetization, comparing with "the HG-TFM" and "only TFM".

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