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Comparative studies of three-dimensional analysis and measurement for establishing pulse electromagnet design

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Contents

- Introduction of the pulse electromagnet targeted for design called bump magnet.
- Flow of evaluating the establishment of a design method.
- Explanation of analysis method using the OPERA-2D and 3D.
- Explanation of magnetic field measurement method using various probes.
- Evaluation results
- Summary

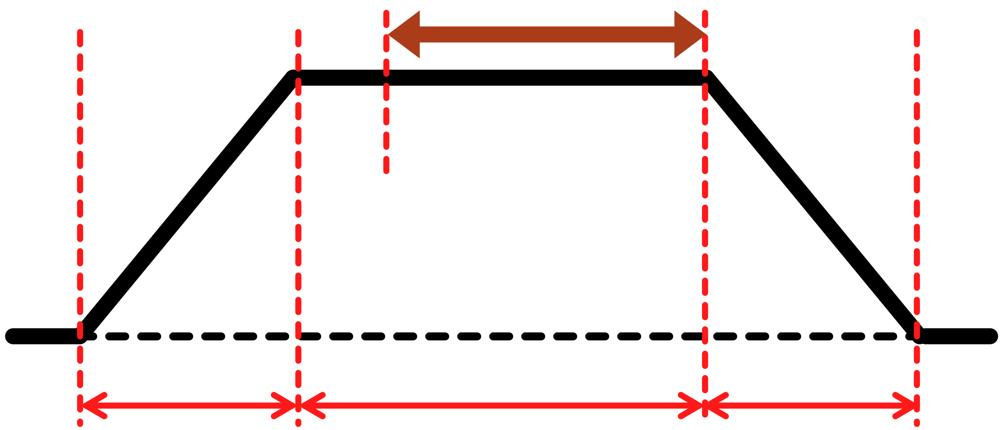
Today, I will introduce only the main part.
Please refer to my manuscript for details.

Parameters of Bump magnet

The bump magnet is an important pulse electromagnet that generates high-intensity beams in J-PARC.

Table 1: Main parameters of bump magnet

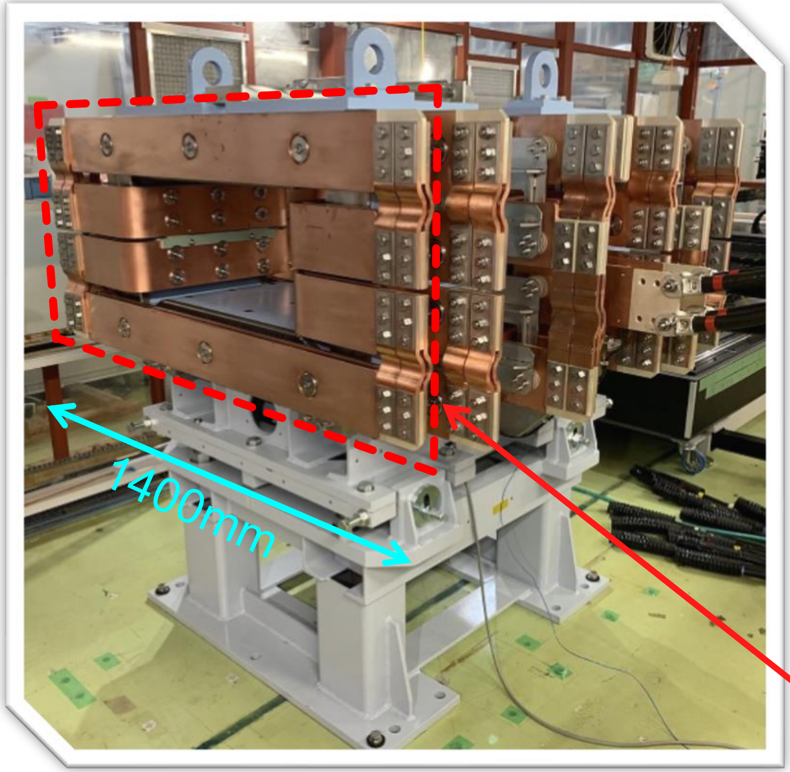
Item	Value
Waveform	Trapezoid(Pattern)
Excitation time	1.0～1.6ms(Controllable)
Maximum Output	16kA and 12kV
Repetition	25Hz
BL Field uniformity	±1.0%（Target value ±0.5%）



- High current, high voltage, fast repetition pulse excitation.
- Change the rise and fall times according to the required beam parameters.

Motivation

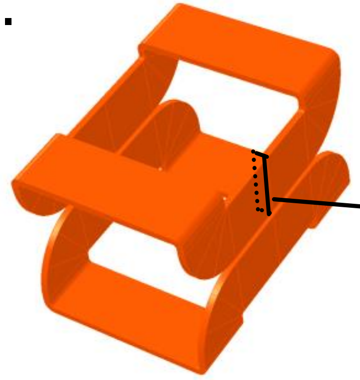
Establish a characteristic pulse magnet design method.

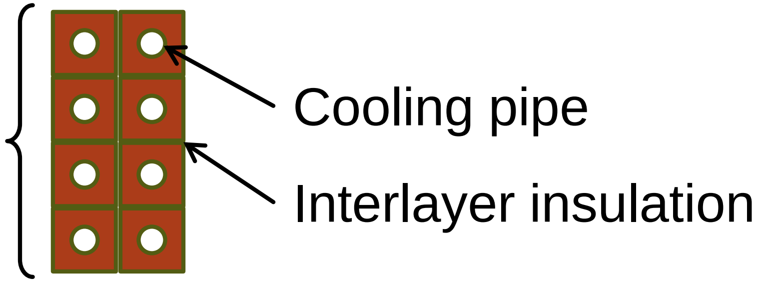


Fabricated bump magnet

Characteristic electromagnetic structure

- A general structure cannot be adopted for the bump magnet that excites a high-speed pulse with a large current.





✕ Saddle-type coil

✕ Hollow conductors (Multilayer structure)

- Reduce the number of turns to a low inductance.
- Use a bus bar with good heat dissipation.

Evaluation of pulse eddy current and skin effect according to the bump specifications is required.

Flow of evaluation and analysis

2D analysis
For basic design

- Use OPERA-2D.
- Change the current area of the coil cross section.
- Check the differences in the current pass.

Static magnetic field
- Virtual skin effect
- Virtual drift current

3D analysis
For final design

- Uses TOSCA and ELEKTRA of OPERA-3D.
- OPERA-3D has different coil conductor models.
- Check the differences in the models.

Dynamic magnetic field
- Biot-Savart conductor
- Meshed conductor

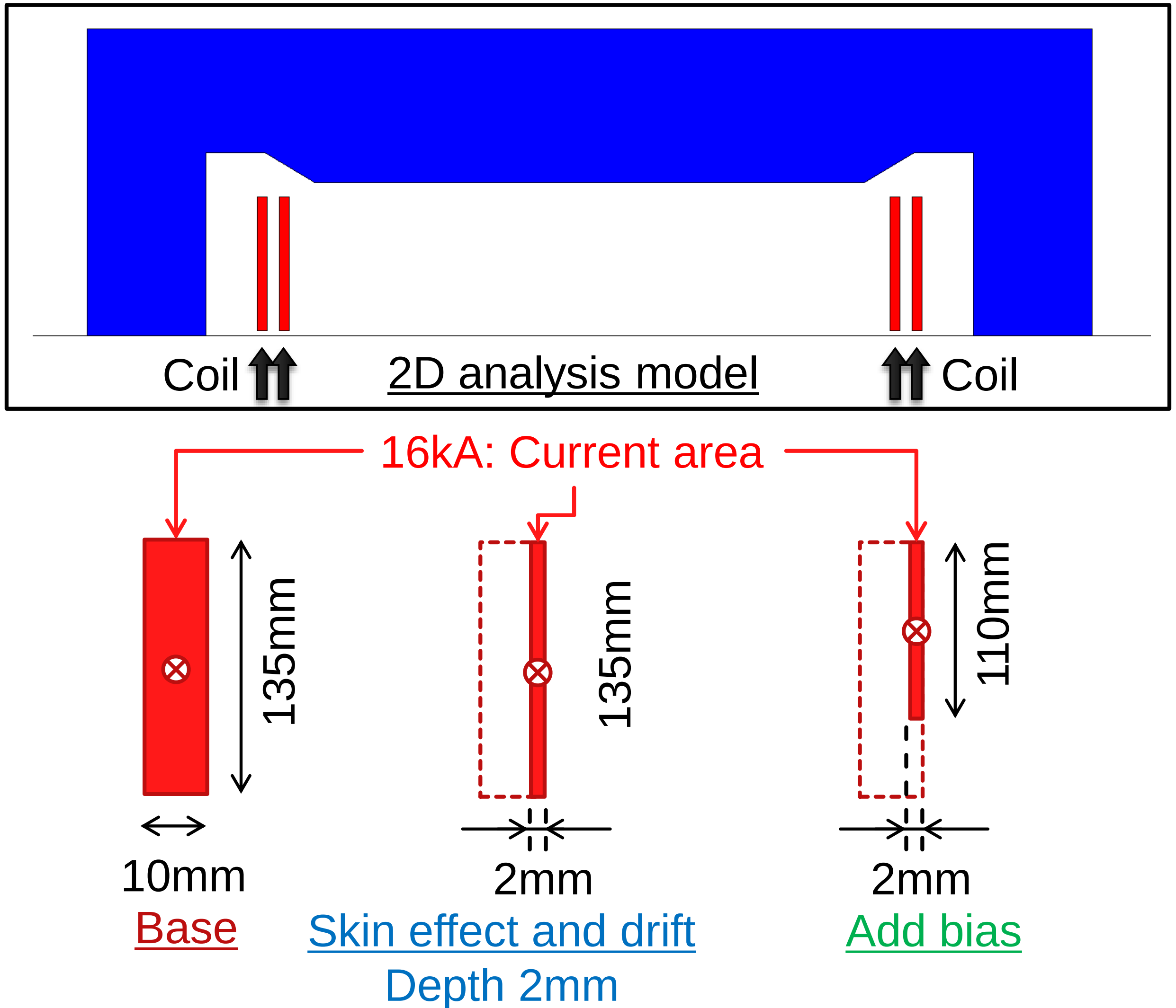
Final confirmation
Comparison with experimental results

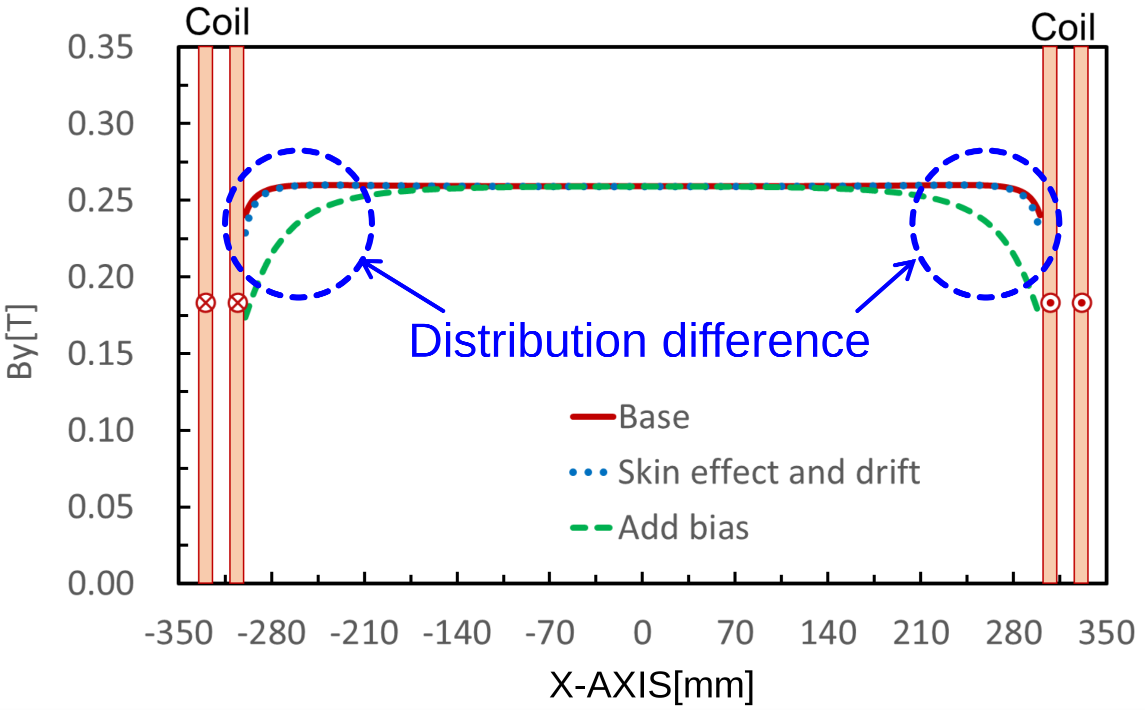
- High-precision measurement is required.
- Evaluate each instrument error.
- Check the differences in probe.

- Flux meter
- Hall prob
- Search coil

2D Analysis with OPERA-2D

Enter a virtual condition for pulse excitation because of the static magnetic field



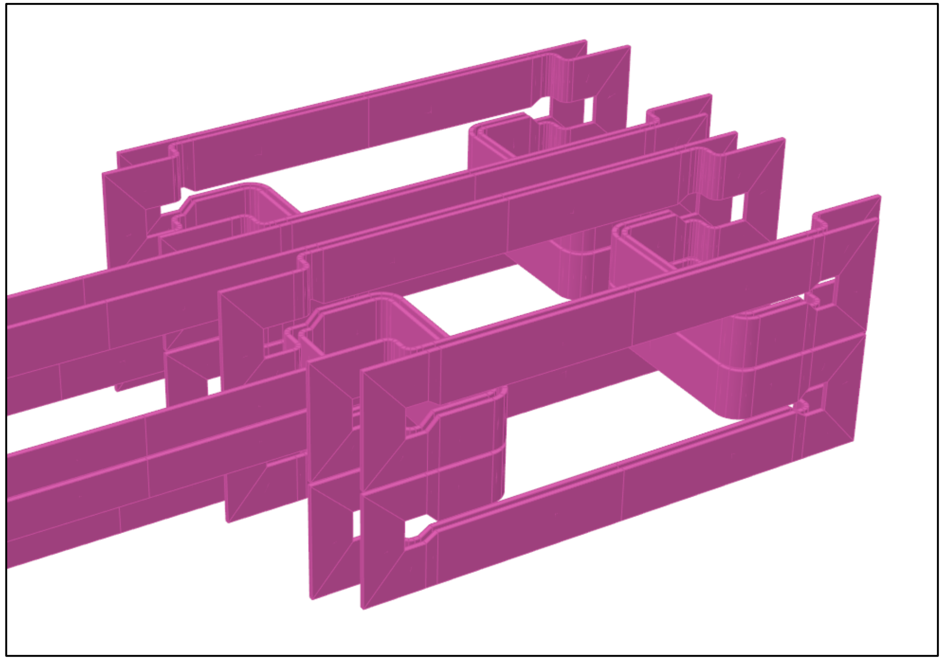


- The difference in the current pass of the coil cross section affects the magnetic field distribution.

Requires 3D dynamic magnetic field analysis

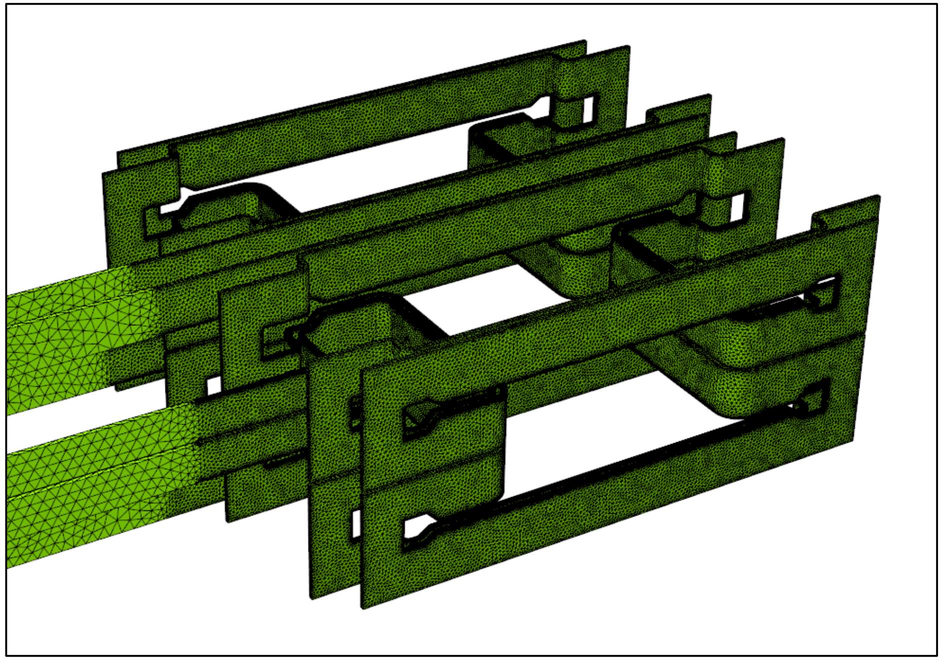
Two coil conductor models of OPERA-3D

- TOSCA is a static magnetic field analysis. Use Biot-Savart conductor. Only DC analysis.
- ELEKTRA is a dynamic magnetic field analysis. Use either Biot-Savart or meshed conductor.



Biot-Savart conductor

- Expands Biot-Savart integration and calculates magnetic field from the conductor coil.
- Conductors independent of mesh and used for magnetic field analysis by DC and AC currents.

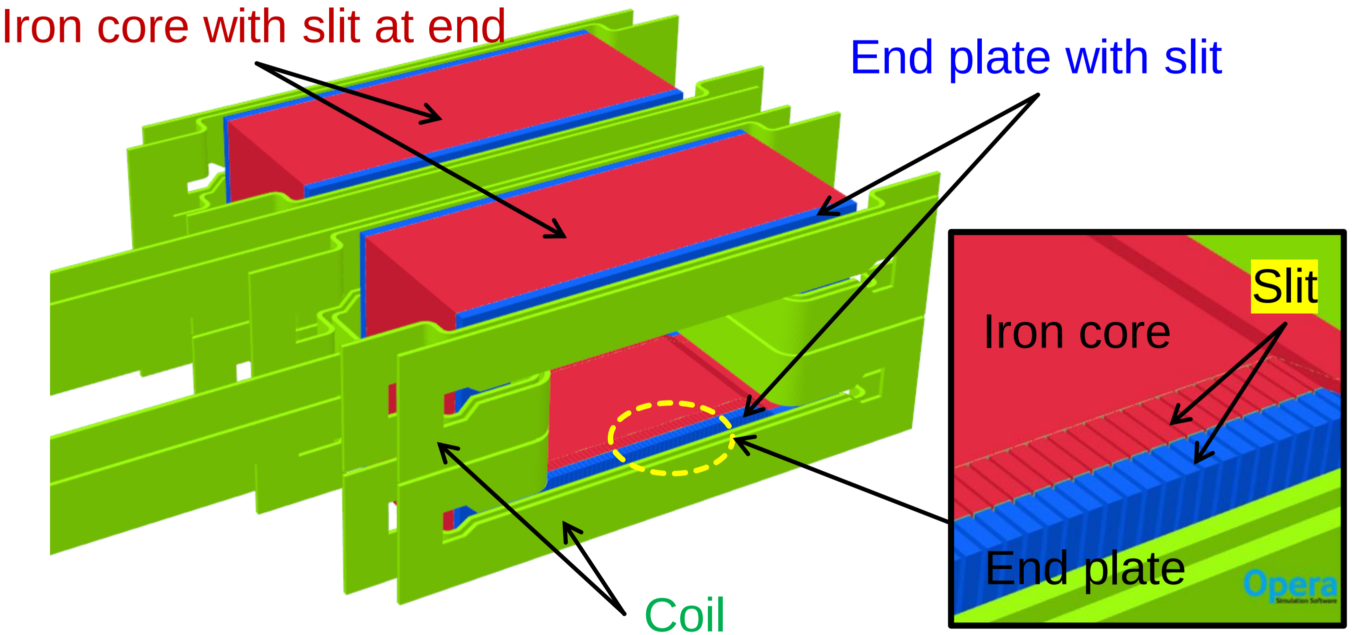


Meshed conductor

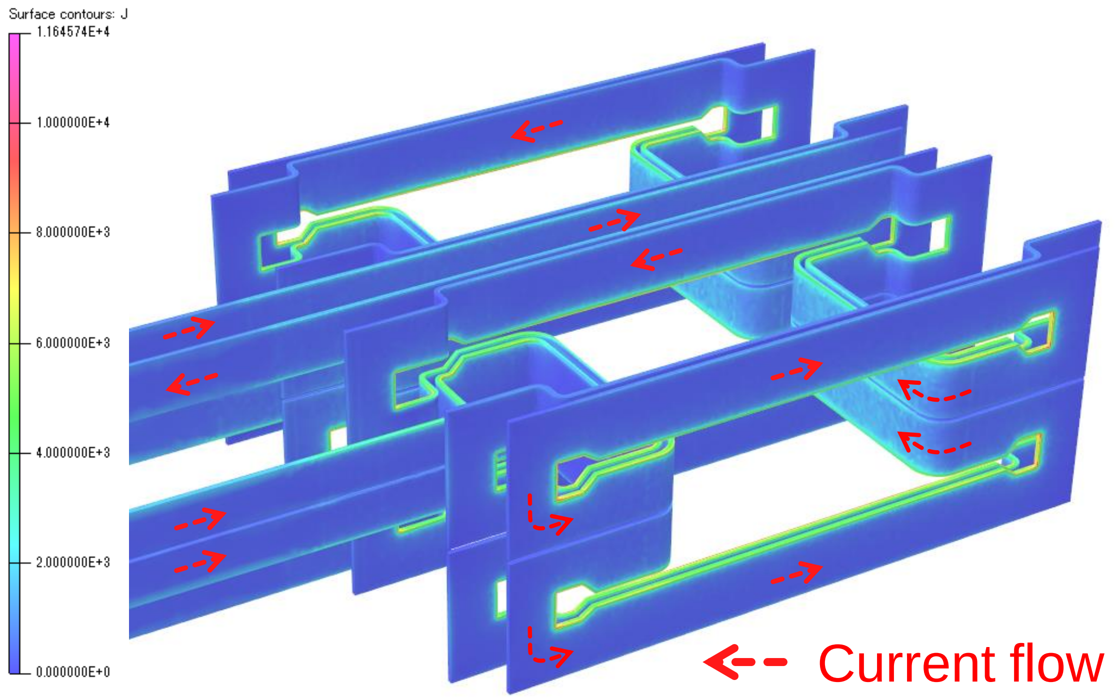
- The inside of the conductor coil is meshed and formed of cells.
- Conductors can be driven for high-speed pulse excitation, which is transient electromagnetic.

3D Analysis model with OPERA-3D

Perform analysis under five conditions using 3D model of core and coil of the same shape.



Waveform	Coil type	Pattern condition
DC	Biot-Savart	2.4kA(Effective value of pattern 16kA)
Sine	Biot-Savart	2.4kA, 1kHz(Effective frequency)
Pattern I	Mesh	4kA, Rise time is 400us
Pattern II	Mesh	8kA, Rise time is 850us
Pattern III	Mesh	16kA, Rise time is 400us

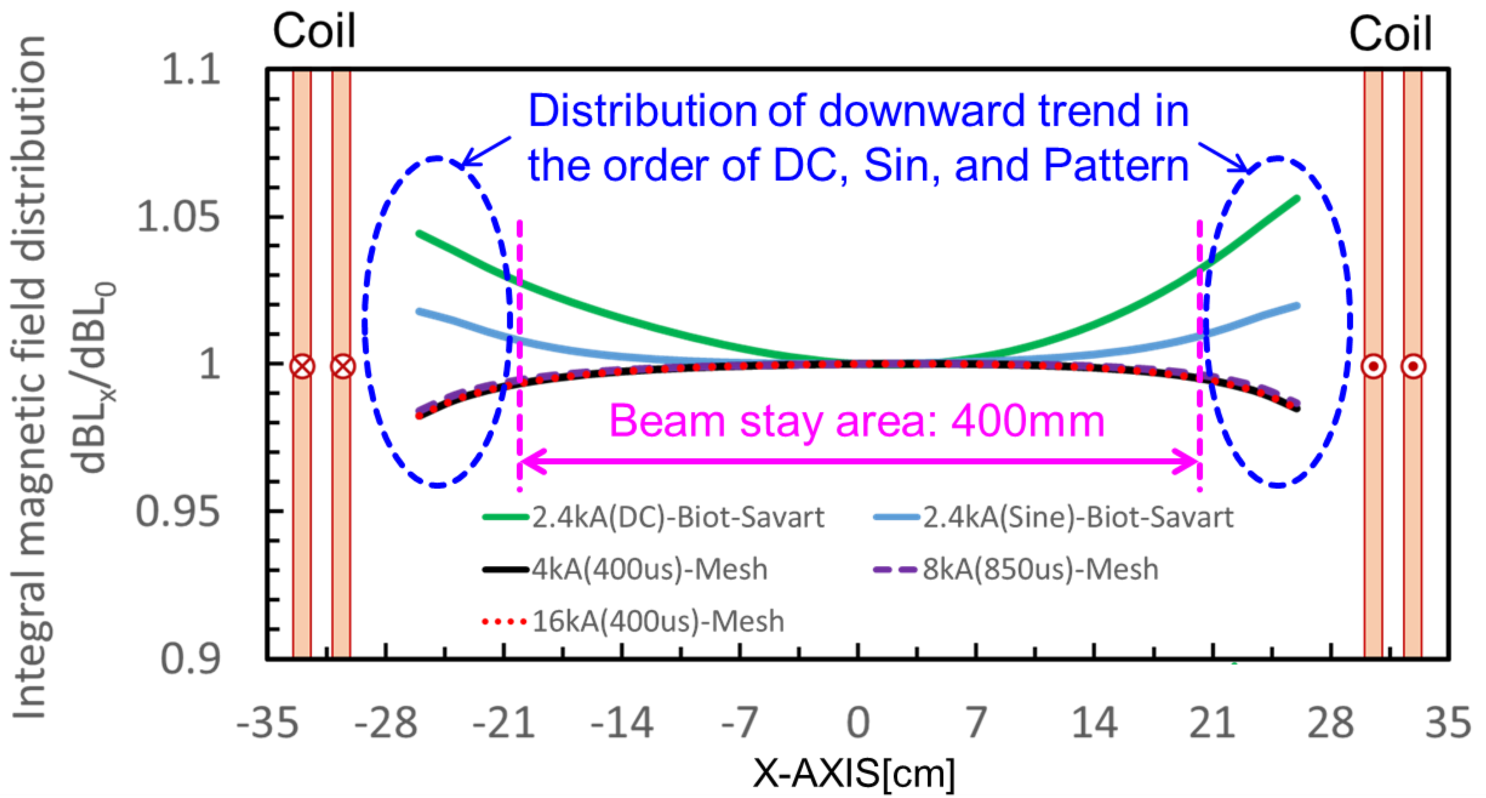


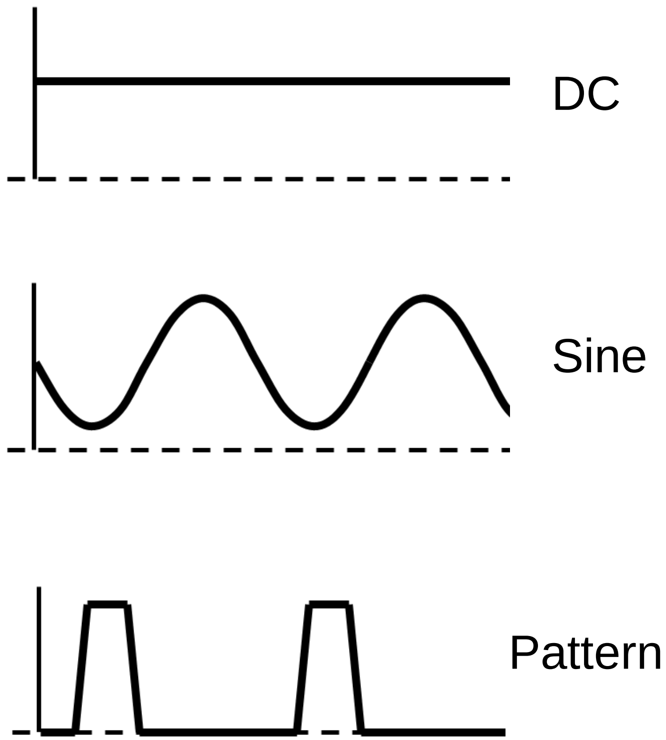
Current density distribution analyzed with Pattern III.

- Yellow is a high density region.
- Most of the current drifts through the shortest route.

3D Analysis results

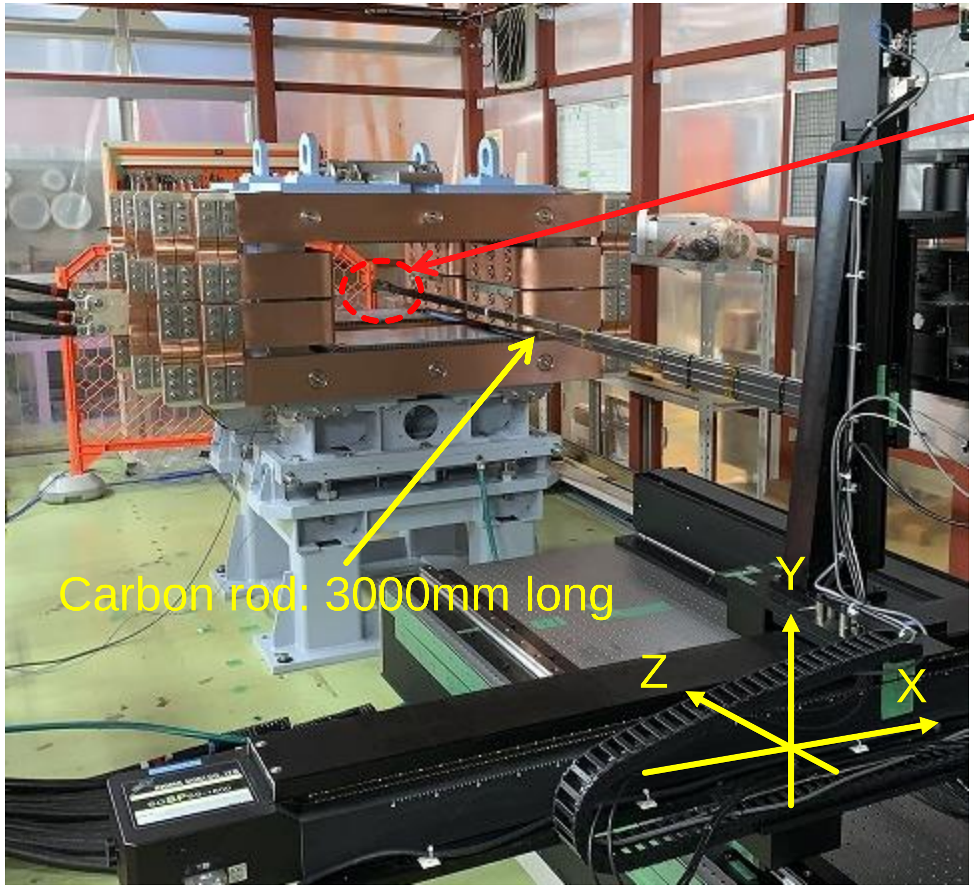
Comparison results of integrated magnetic field distribution under five conditions



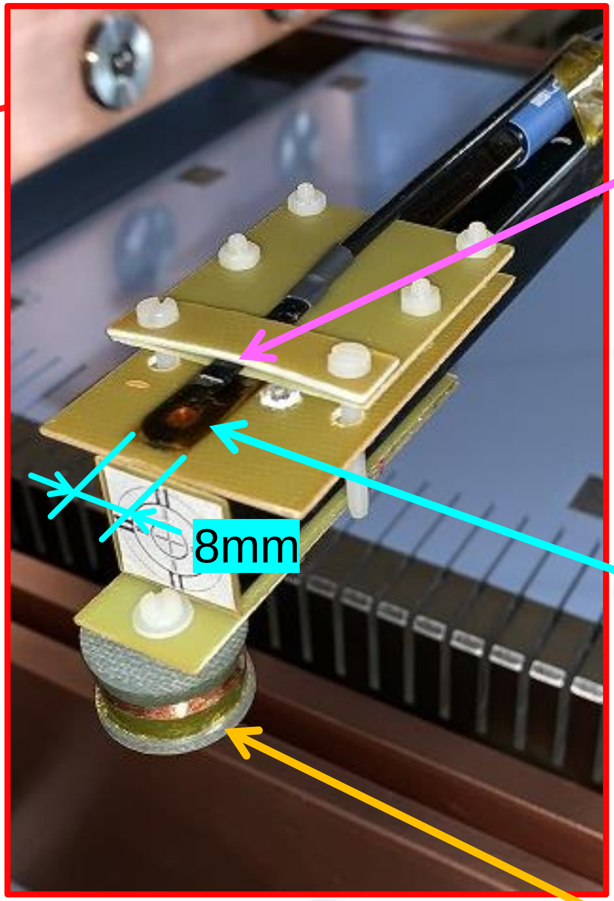


- Different distributions are shown for DC, Sine, and Pattern, and the effect of using a mesh coil by 3D analysis can be confirmed.
- Under three pattern conditions, there was no significant difference in distribution due to the difference between the rise time and current of the pattern waveform.

Measurement using three types of probes



Magnetic field measurement scene



The tip of the carbon rod

Transverse Hall probe

- Made by Lake Shore
- HMFT-4F15-VR-HF-10
- DSP Gaussmeter Model 475
- The width of the tip is about 4mm.
- Peak frequency range is 50kHz.

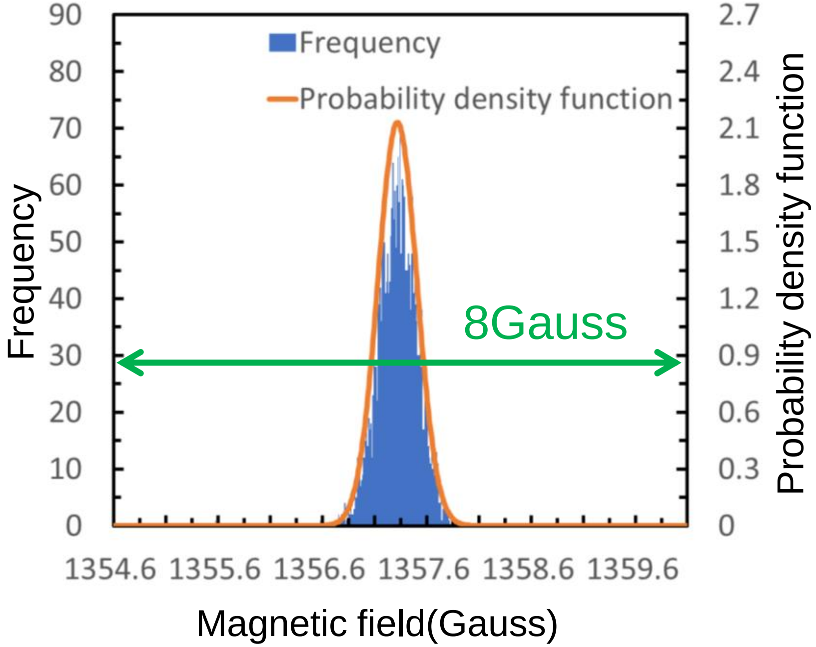
Fluxmeter field probe

- Made by Lake Shore
- FNT-5P04-30
- Model 480 Fluxmeter
- The width of the tip is about 8mm.
- Area-turns is 30 cm^2
- AC frequency response to 50kH.

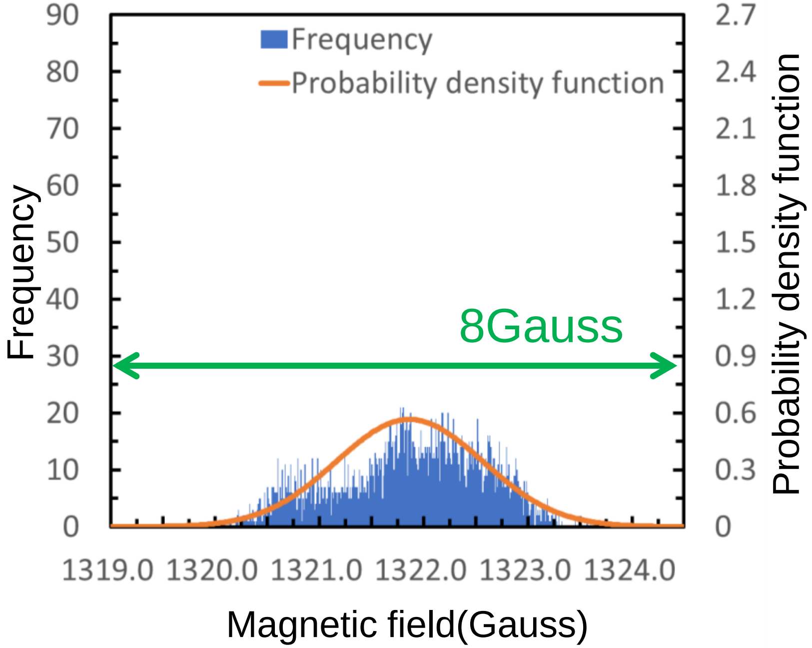
Search coil

- Φ20mm, 20 turns,
- Wire diameter 0.1mm
- Handmade

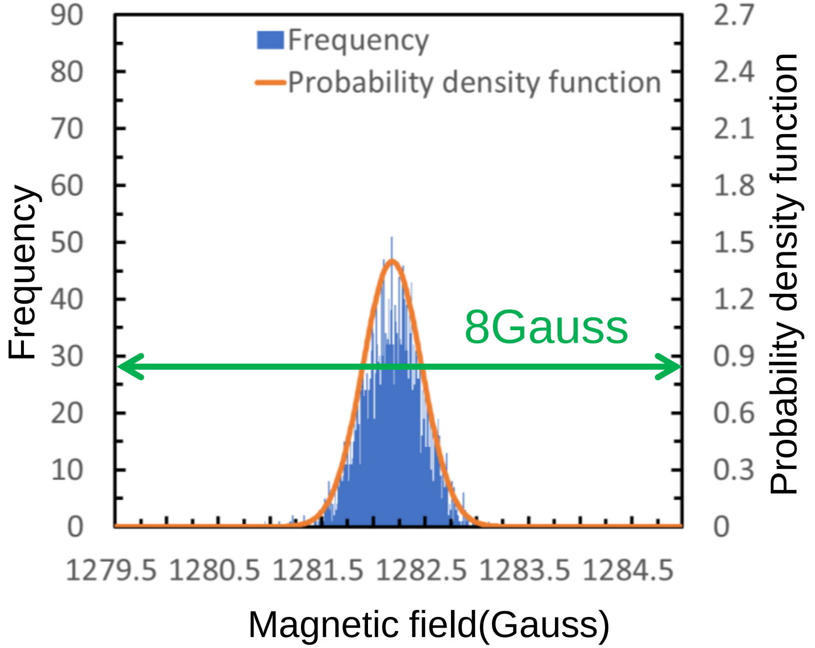
Differences due to measurement probes



Fluxmeter field probe



Search coil



Transverse Hall probe

Measurement conditions

- Comparison using Pattern II Peak is 8kA, Rise time is 850us
- Each probe fixed to the center of the core. (X=Y=0, Z=330mm)
- Total frequency is 2668 shots. The data for each probe is saved at the same time.
- The fluctuation of the current value for each shot was normalized at 8kA. The standard deviation after correction indicates the measurement error of each probe.

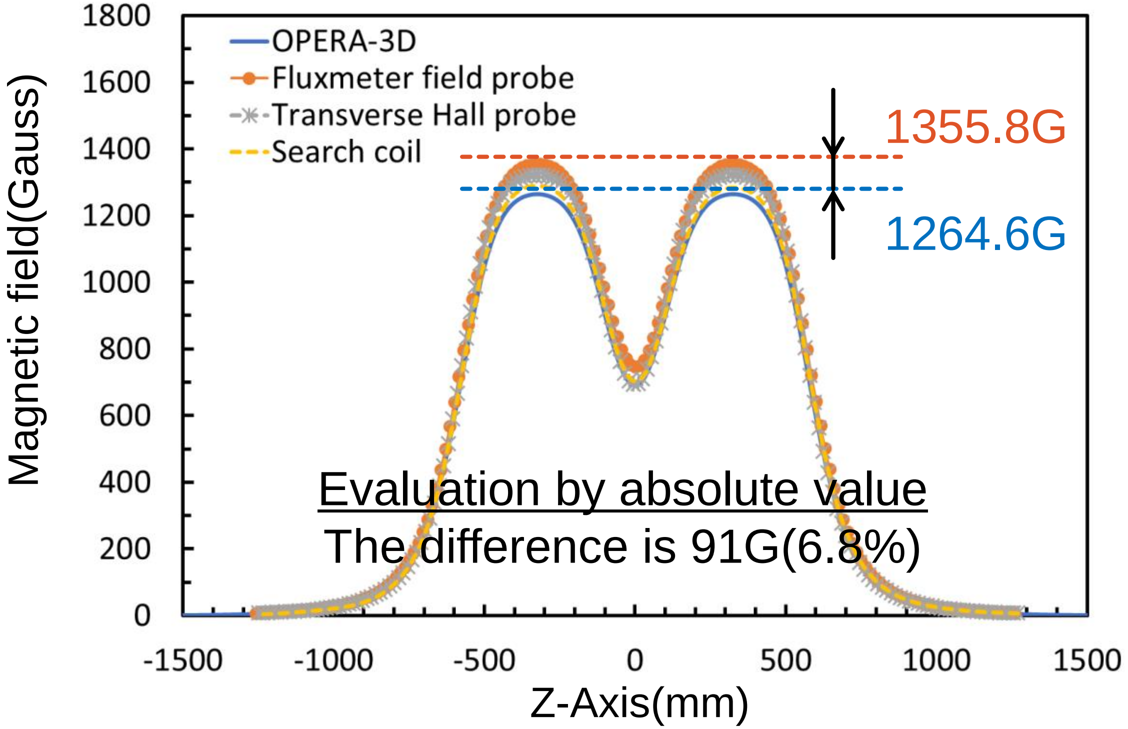
※The histogram classification is fixed at 8 Gauss.

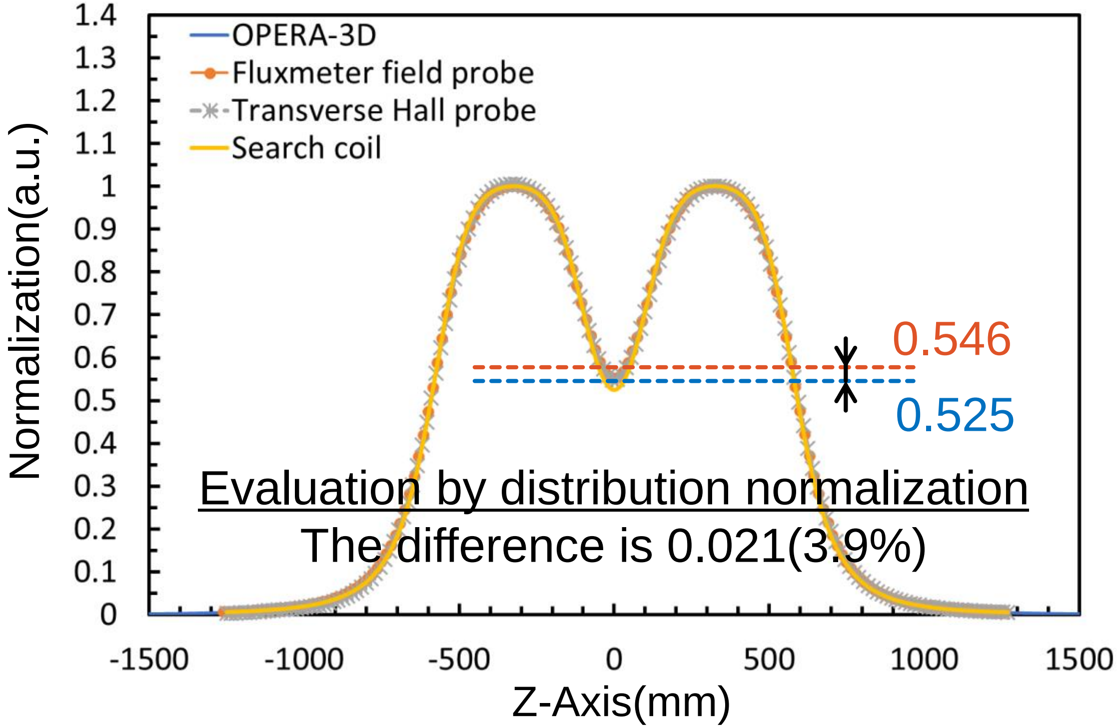
Item	Fluxmeter	Search coil	Hall probe
Average	1357	1322	1282
Standard deviation	0.187	0.705	0.290

The minimum standard deviation was fluxmeter.

Comparison of measurement and analysis

Comparison using Pattern II : 8kA, Rise time is 850us.
Distribution in the Z-axis direction at the center of electromagnet (X=Y=0). Plot the average of 5 shots.

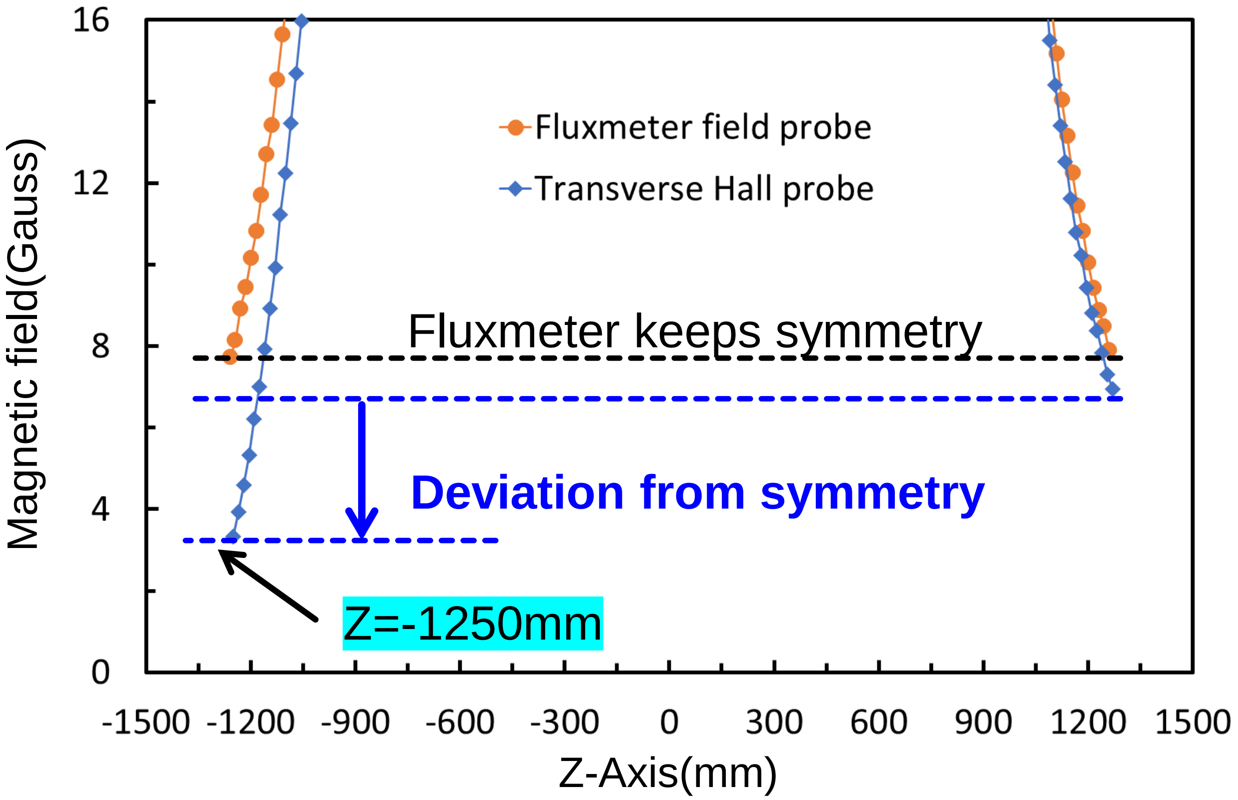


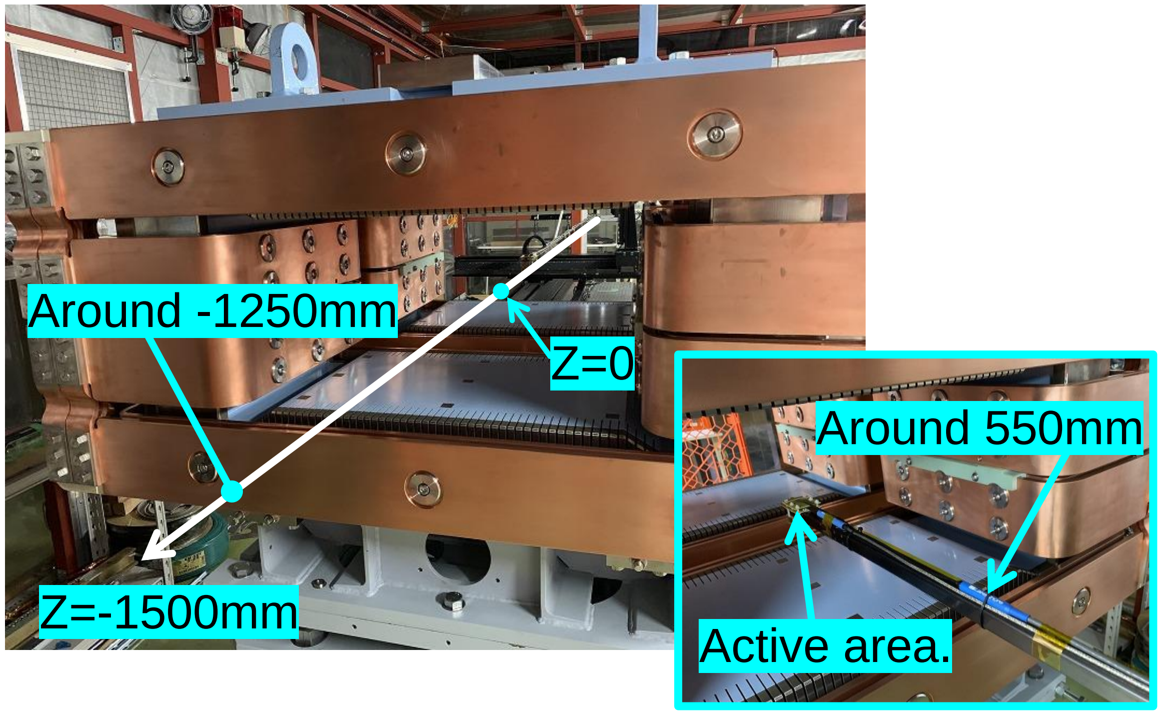


- The Fluxmeter was the maximum value under the same conditions.
- The normalized distribution shape is almost the same except for the search coil.

- The cause of the difference between absolute value and measurement accuracy will be investigated in the future.

Hall probe weaknesses

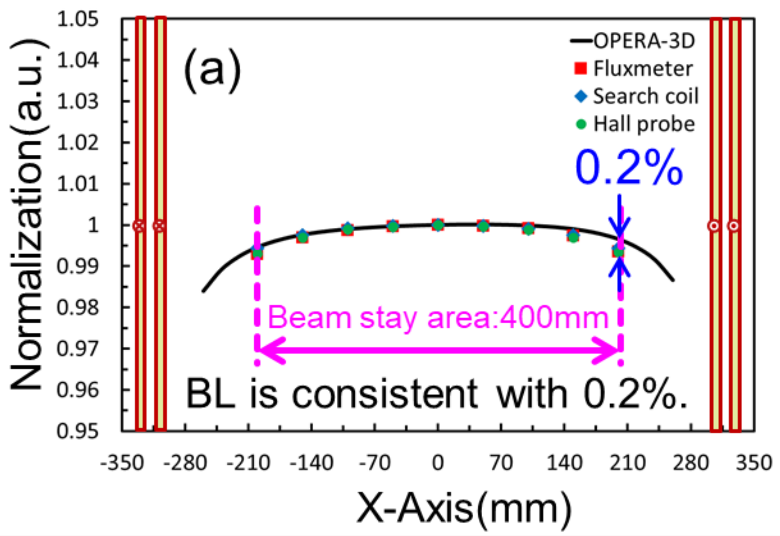


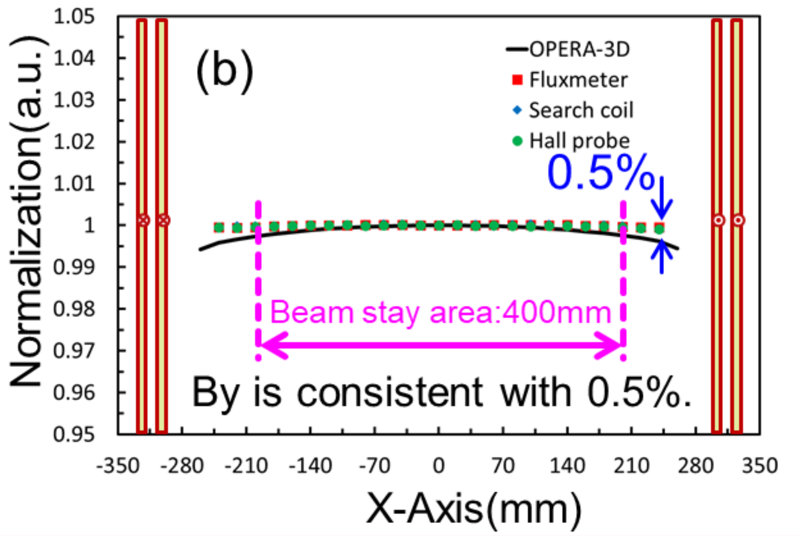


Transverse Hole probe

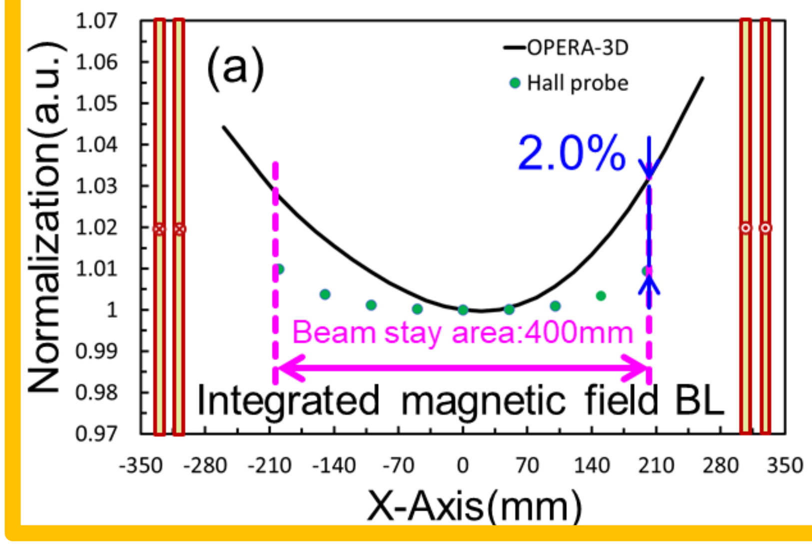
- Deviations from symmetry at the bottom of the magnetic field distribution were confirmed only for the Hall probe.
  - Since the Hall probe is a temperature compensation probe, the decrease in magnetic sensitivity due to the heat of the electromagnet is compensated.
  - Therefore, the pulse magnetic field affected the sensor as noise, which may have reduced the measurement accuracy.

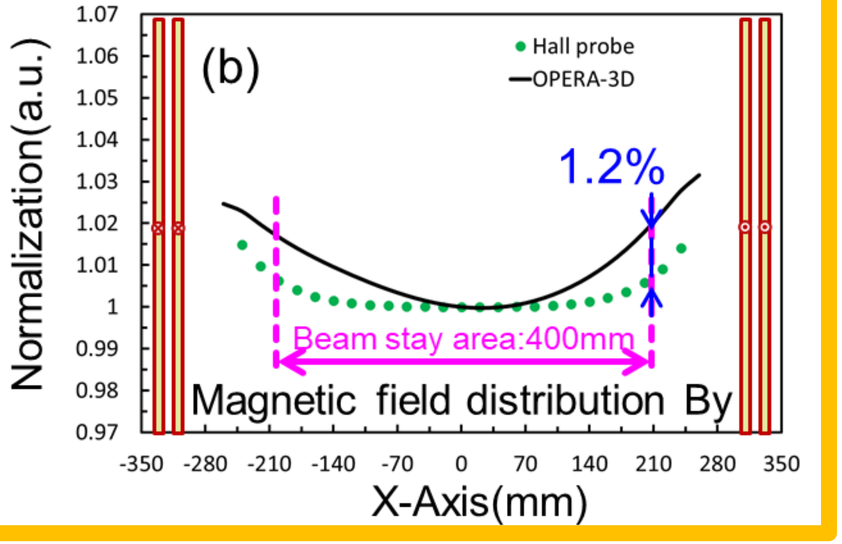
Comparison of analysis and measurement





- Comparison between ELEKTRA with mesh conductor and pattern II excitation
- The analysis and measurement results are in good agreement.
- Measurement probe differences are not noticeable in a few percent comparison.





- Comparison between TOSCA and DC excitation.
- Measurement was performed by exciting 600A DC current to the bump magnet with pulse design.
- There is a few percent difference between BL and By.
- By peak of 600A is about 95G, and it is considered that there was an influence of several gauss of residual magnetic field.

Summary

- A characteristic pulsed electromagnet with high current, high voltage and fast repetitive pulse excitation was designed and fabricated.
- In this design, it was found that high-precision **magnetic field analysis including eddy current and skin effect** is possible by combining the dynamic magnetic field analysis of **OPERA-3D** and **the mesh conductor coil model**.
- The result of the 3D analysis were compared to measurements with pattern excitation using three magnetic field measurement probes.

  There was a slight difference between absolute and relative results, respectively. However, the comparison between **the relative values and the analysis was very good**. In particular, **the fluxmeter was an excellent tool**.
- The difference between DC magnetic field analysis and measurement seems to be influenced by the residual magnetic field.

  I would like to try a test that cancels the residual magnetic field, or a test that reduces the effect of the residual magnetic field by preparing a high-current DC power supply.

Acknowledgments

Thank you for the teaching and the cooperation of Mr. Tanaka in Kyokuto Boeki Kaisha, Ltd.