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Development of 3D ferromagnetic model of tokamak core with strong toroidal asymmetry

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Introduction

- Unsaturated ferromagnetic material affects magnetic field in its vicinity. In tokamaks – core, ferromagnetic inserts, etc.
- ELM mitigation experiments on JET using MP fields generated by EFCCs – effect of iron core on 3D field unknown.
- Model of arbitrary 3D-shaped ferromagnets in development presented here. Specifically:
  - Results of first benchmarking of 3D form of the code, using tokamak with strong iron core asymmetry.
  - Comparison of 3D model to 2D core axisymmetric equivalent (where possible)

Iron core model principle

Main idea – Represent the whole volume of the core by its surface (i.e. by boundary representing the μ_r discontinuity)

1. Homogeneously magnetized medium → **M** [Am^{-1}] magnetization vector → bound surface (screening) current:
$$\sigma(\mathbf{r}) = \mathbf{M}(\mathbf{r}) \times \mathbf{n}(\mathbf{r})$$
2. No free currents on ferromagnet - Ampére's law → continuity of tangential $\mathbf{H}_i$ on both sides of boundary:
$$\mathbf{n}(\mathbf{r}) \times (\mathbf{H_0}(\mathbf{r}) - \mathbf{H_1}(\mathbf{r})) = 0$$
3. Substitution of 2. into 1. :
$$\frac{\mu_0}{2}\sigma(\mathbf{r}) = \lambda(\mathbf{r})\mathbf{B}(\mathbf{r}) \times \mathbf{n}(\mathbf{r})$$

Sought quantity (calculated from σ)

$$\mathbf{B}(\mathbf{r}) = \mathbf{B_{ext}}(\mathbf{r}) + \mathbf{B_{core}}(\mathbf{r})$$

Therefore:
$$\sigma(\mathbf{r}) - \frac{\lambda(\mathbf{r})}{2\pi}\int_S \left(\sigma(\mathbf{r}') \times \frac{\mathbf{r}-\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|^3}\right) \mathrm{d}\mathbf{S}' \times \mathbf{n}(\mathbf{r}) = \frac{2\lambda(\mathbf{r})}{\mu_0}\mathbf{B_{ext}}(\mathbf{r}) \times \mathbf{n}(\mathbf{r}).$$

Left-hand side → relation for σ over the whole surface

Right-hand side → sources of magnetic field (coils+plasma)

If core boundary = set of N rectangular surfaces → Set of $2N$ non-linear equations:
$$\sigma_k^i + \lambda^i \sum_{j \neq i}^{N} \sum_{l}^{2} \left(A_l^{ij}\sigma_l^j\right) = \lambda^i C_k^i$$

Non-linearity:
$$\lambda(\mathbf{r}) = \frac{\mu_r(\mathbf{r})-1}{\mu_r(\mathbf{r})+1}$$
while:
$$\mu_r(\mathbf{r}) = f(\mathbf{B}(\mathbf{r}))$$

Summary

- We present model of ferromagnet, based on boundary integral method.
- Toroidal modulation of tokamak B_R field due to core presence observed experimentally. No significant effect on vertical B_Z component.
- 3D model predictively characterizes observed modulation:
  - Very good agreement for near-field configuration.
  - Satisfactory agreement for far-field configuration.
    → Non-linearity due to core saturation non-negligible?

Future work
- Implementation of non-linearity effects
- Modelling of iron core of tokamak JET

References

[1] T. Markovic, M. Gryaznevich et al., Evaluation of applicability of 2D iron core model for two-limb configuration of GOLEM tokamak, Fus. Eng. Des. 88 (2013).

Acknowledgements

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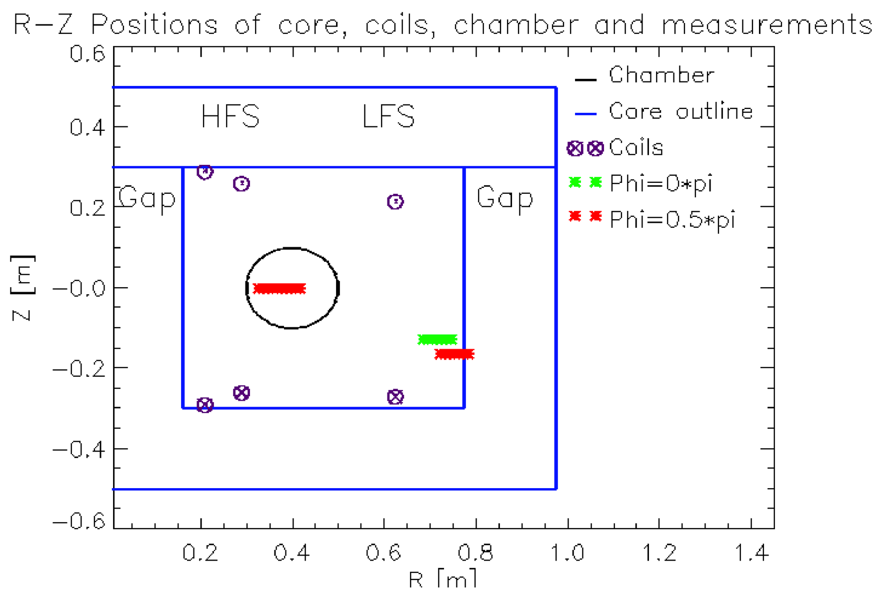
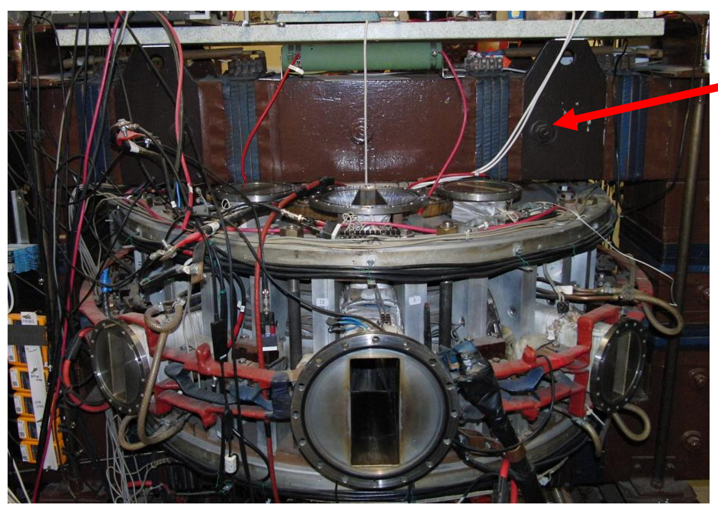
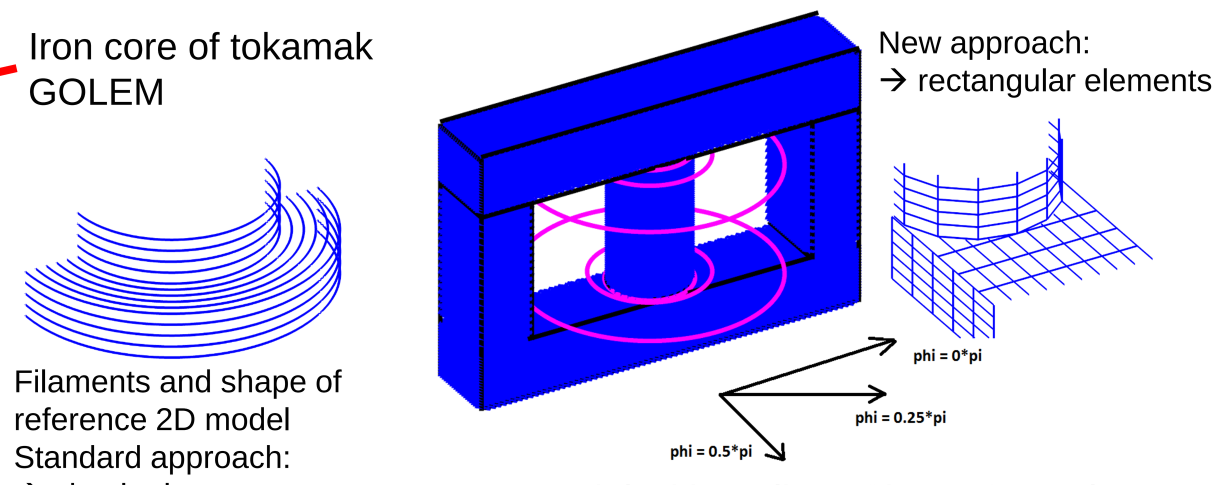
Experimental arrangement

- Benchmarking device – Tokamak GOLEM
  → Strongly asymmetric iron core.
- B_R generated by tokamak poloidal field coils
- 3D Hall probe placed in different toroidal and R-Z positions and used to measure B_R
- Measurements and axisymmetric model from [1] included in analysis as well.





Iron core of tokamak GOLEM



Filaments and shape of reference 2D model
Standard approach:
→ circular loops

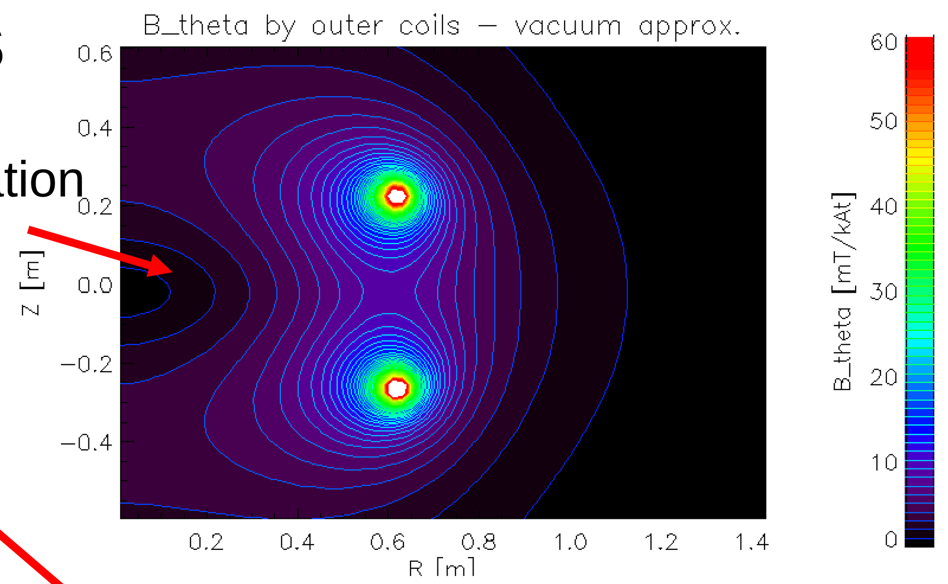
New approach:
→ rectangular elements

3D core model with outline of its surface elements

Model vs. Measurements

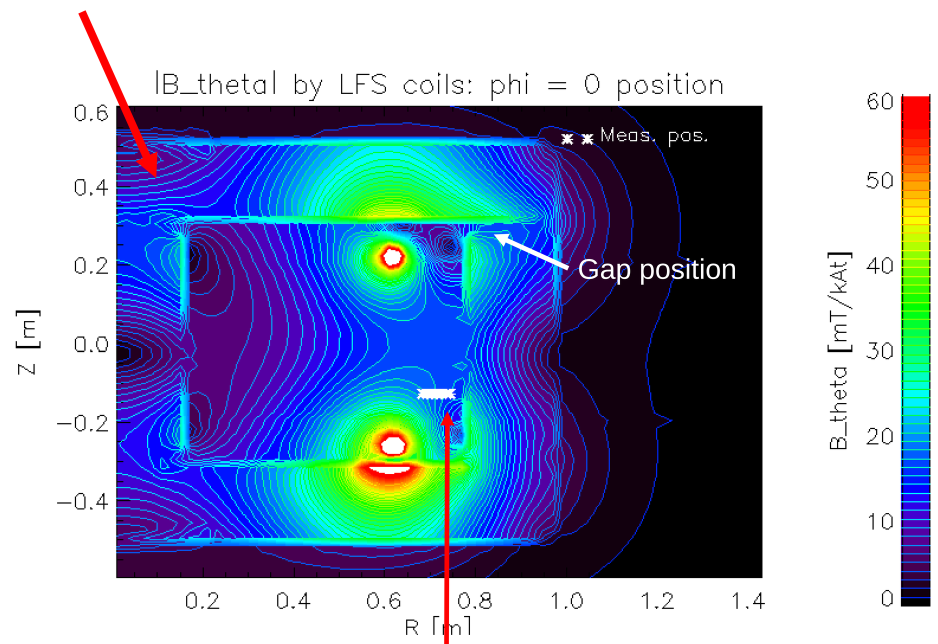
R-Z profiles of:
$$|\mathbf{B}_\theta| = \sqrt{B_R^2 + B_Z^2}$$
generated by LFS coils

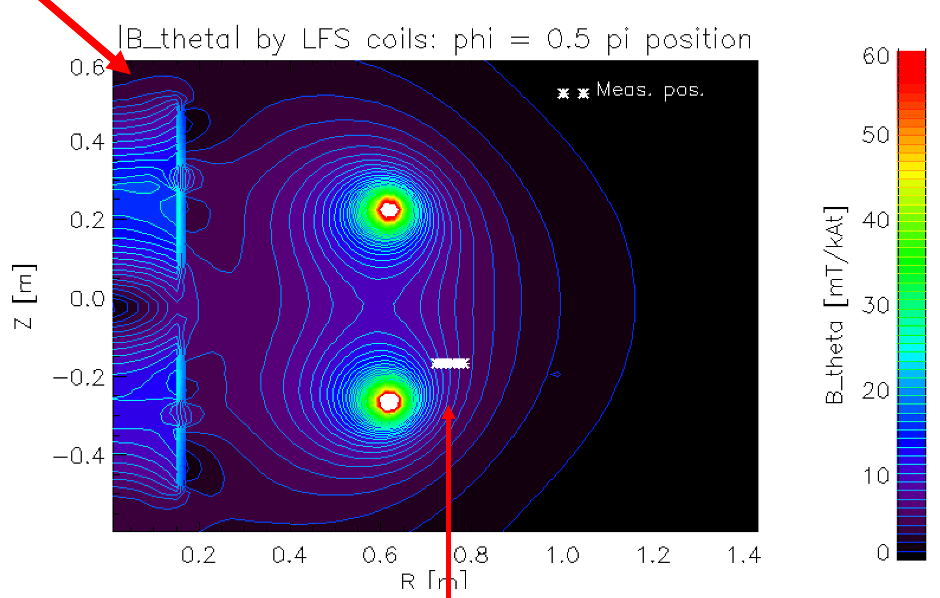
Vacuum approximation (without iron core)

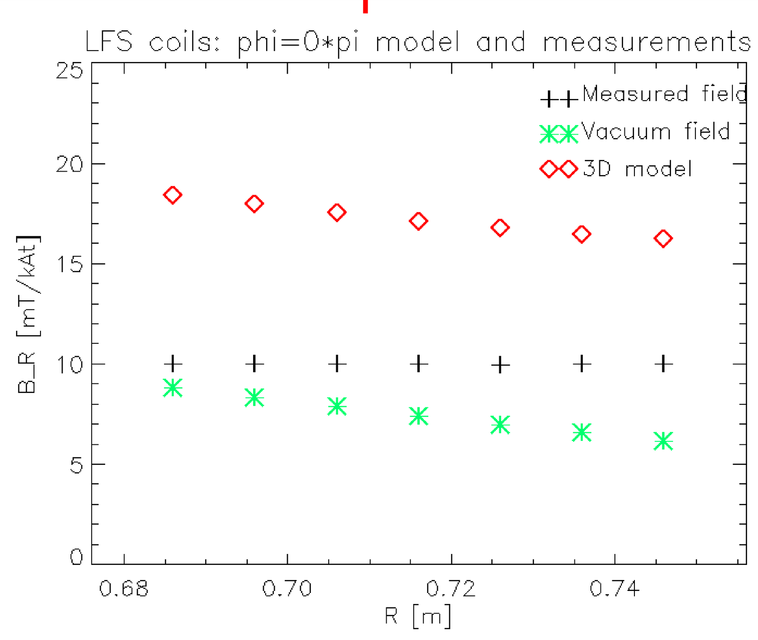


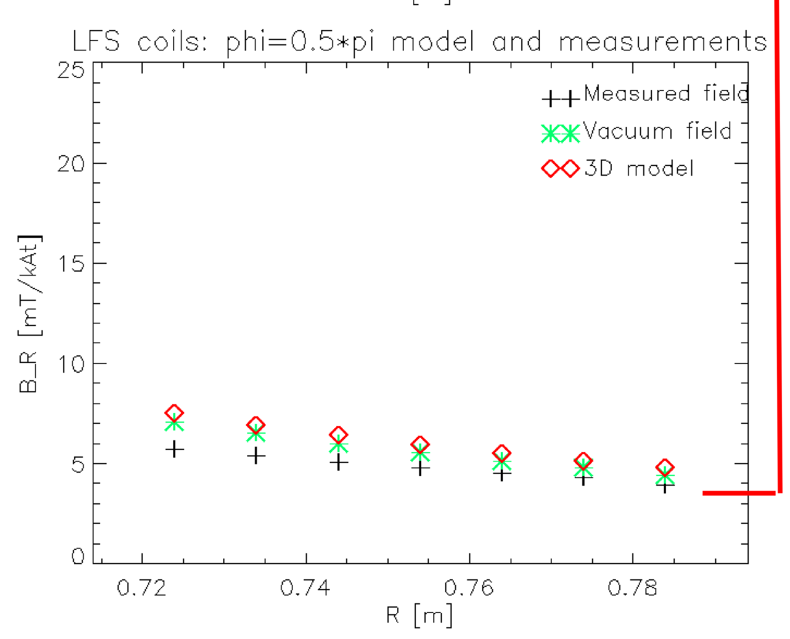
Under and inside of core limbs

Perpendicular to core limbs









Measurements outside chamber

- Field generated by LFS coils only
  → Far-field configuration
- Close to limbs – field amplification
- Perpendicular to limbs – vacuum field
- Measured magnitude lower than modelled – partial saturation?

Measurements inside chamber

- Field generated by HFS coils only
  → Near-field configuration
- Position – close to central column
  → Both 2D and 3D model applicable