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Helical Ferritic Steel Inserts for Resonant Magnetic Perturbation to Suppress ELMs in Tokamak DEMO Reactor

トカマクDEMO炉のELM抑制共鳴磁場擾乱用ヘリカル状フェライト鋼設置

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Edge localized mode (ELM) must be eliminated which enhances the erosion of divertor plates in the H-mode operation of tokamak reactors. Suppression of ELM has been experimentally achieved by the resonant magnetic perturbation (RMP) with multipartite coils. In a DEMO reactor with strong neutron flux, however, it is desired the coils near the first wall not to be put in. We propose an innovative concept of the RMP for tokamak DEMO reactors without installing coils but inserting ferritic steels of the helical configuration. Helically perturbed magnetic field is naturally formed in the axisymmetric toroidal magnetic field through the helical ferritic steel inserts (FSI).

1. Introduction

Edge localized modes (ELMs) in H-mode plasmas intermittently produce large heat load on the plasma facing components (PFC), especially on the divertor plate, and enhances erosion of the PFC materials [1,2]. To maintain long lifetime of divertor plates, ELM must be eliminated in the H-mode operation of tokamak reactors. Suppression of the ELM has been experimentally achieved by the resonant magnetic perturbation (RMP) with multipartite coils in DIII-D [3]. Figure 1 shows an RMP coil system placed on the low-field-side first wall in DIII-D. This coil system generates the perturbed field with the main toroidal mode number n = 3 and the broad spectra of poloidal mode number m. The maximum perturbation for an m/n mode is about 10 gauss. When the safety factor at the 95% poloidal flux surface is $q_{95} \sim 3.5$, the RMP is remarkable and magnetic filed lines behave stochastic near the plasma edge region. The pedestal plasma pressure is decreased by this RMP, and resultantly the ELM can be suppressed.

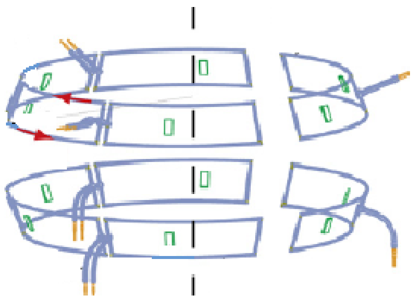

Fig.1. RMP coil system in DIII-D [3]

Based on this experimental demonstration, ITER is planning to install the RMP coil system to suppress ELM [4], while discussing about its additional cost.

In order to generate magnetic perturbation effectively, the coil system is better to put near the plasma surface. On the other hand, in the DEMO/ Commercial reactors with strong neutron flux, it is desired such coil systems near the first wall not to be put in. In this paper, we propose an innovative concept of the RMP for tokamak DEMO reactors without installing coils but inserting ferritic steels of the helical configuration. Helically perturbed magnetic field is naturally formed in the axisymmetric toroidal magnetic field through the helical ferritic steel inserts (FSI).

2. Helical magnetic field by helical FSI

Consider a cylindrical system (r, θ, z), where a longitudinal (toroidal) uniform magnetic field $\boldsymbol{H}_{\mathrm{ext}}$ is externally given in the z direction. A hollow ferritic tube is put at $a_F - d < r < a_F + d$. This ferritic steel inserts (FSI) creates the perturbed magnetic field $\boldsymbol{H}_1^{(v)}$ in the vacuum region. The perturbed field is expanded to the Fourier modes in θ and z directions. A single helical mode of the magnetic field $\boldsymbol{H}_1^{(v)} = \boldsymbol{H}_1^{(v)}(r) \exp i(m\theta - nz/R)$ is described by the solution to the set of equations,

$$\mathbf{rot}\, \boldsymbol{H}_1^{(v)} = 0 \quad \text{and} \quad \mathbf{div}\, \mu_0 \boldsymbol{H}_1^{(v)} = 0.$$

Note the relation to magnetic flux density $\boldsymbol{B}_1^{(v)} = \mu_0 \boldsymbol{H}_1^{(v)}$ (μ_0: permeability of vacuum). The solution is $H_{1z}^{(v)} \sim \mathrm{I_m}(nr/R)$ for the inner region $r < a_F - d$, and $H_{1z}^{(v)} \sim \mathrm{K_m}(nr/R)$ for the outer region $r > a_F + d$

(I_m, K_m: modified Bessel functions of the 1st kind and 2nd kind). For the high m mode, the equations are approximated as those in the Cartesian coordinates (x, y, z) with $x = r - a_F$. The solution of the form $\boldsymbol{H}_1^{(v)} = \boldsymbol{H}_1^{(v)}(x) \exp i(k_y y - k_z z)$ becomes simple as

$$H_{1z}^{(v)} \sim \exp(kx) \quad \text{for } x < 0 ,$$
$$H_{1z}^{(v)} \sim \exp(-kx) \quad \text{for } x > 0,$$

where $k_y = m/a_F$, $k_z = n/R$, and the inverse decay length is $k = (k_y^2 + k_z^2)^{1/2}$. When we choose the RMP mode, $n \sim 3$ and $m \sim 9$, the decay length is about 0.3 m for a DEMO device with $a_F \sim 3$ m. This length seems appropriate, not much decaying from the wall but decaying enough in the plasma core. The above inner and outer solutions are continued through the ferritic region, $a_F - d < r < a_F + d$.

The magnetization of the ferritic steel is saturated for the strong magnetic flux density $B > B_{sat} \sim 1.5$ T. The permeability of the ferritic steel can be approximated as $\mu_F/\mu_0 \approx (B_{sat} + B_{ext})/B_{ext} = 1.1\sim1.3$ in the tokamak DEMO reactor condition $B_{ext} = 5\sim10$ T. Now we insert ferritic steels ideally so that the permeability distribution become helical,

$$\mu = \langle\mu\rangle + \mu_1 \exp i(k_y y - k_z z)$$

in the region $-d < x < d$. Here the average $\langle\mu\rangle = (\mu_F + \mu_0)/2$ and the amplitude $\mu_1 = (\mu_F - \mu_0)/2$. Figure 2 is a sample of the FSI configuration with a single helical mode $m/n = 9/3$.

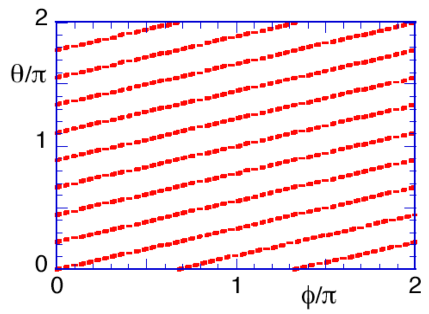

Fig.2. Helical FSI configuration with $m/n = 9/3$. FSs are placed on the wall at $r = a_F$ (ϕ: toroidal angle and θ: poloidal angle)

The set of equations in ferritic region, $\mathbf{rot}\,\boldsymbol{H} = 0$ and $\mathbf{div}\,\mu\boldsymbol{H} = 0$, is solved by assuming the smallness of helical permeability amplitude; $\mu_1/\langle\mu\rangle << 1$. The first order equation becomes

$$\partial^2 H_{z1}^{(F)}/\partial x^2 - k^2 H_{z1}^{(F)} + \langle\mu\rangle^{-1} (\partial^2\mu/\partial z^2) H_{ext} = 0,$$

and its solution is

$$H_{z1}^{(F)} + (k_z^2/k^2)(\mu_1/\langle\mu\rangle) H_{ext} = C\{\exp(kx) + \exp(-kx)\} ,$$

$$H_{x1}^{(F)} = (i/k_z)\, \partial H_{z1}^{(F)}/\partial x .$$

At the ferritic steel boundary, $x = \pm d$, the tangential component of the magnetic field $\boldsymbol{H}_{//}$ is continuous, while the normal component of the magnetic flux density $\boldsymbol{B}_\perp$ is continuous;

$$H_{z1}^{(v)} = H_{z1}^{(F)} \quad \text{and} \quad \mu_0 H_{x1}^{(v)} = \mu H_{x1}^{(F)} .$$

We obtain the magnitude of the perturbation

$$H_{x1}^{(v)} = (k_z/k)(\mu_1/\langle\mu\rangle) H_{ext} / (1 + \mu_0/f\langle\mu\rangle)$$

where f is a function on the ferritic thickness $2d$,

$$f = \{\exp(kd) - \exp(-kd)\}/\{\exp(kd) + \exp(-kd)\}.$$

It is confirmed that the helically perturbed magnetic field is naturally formed in the axisymmetric toroidal magnetic field through the helical FSI. We estimate the helical magnetic perturbation on the ferritic boundary, for the typical parameter of DEMO condition, $k_z/k \approx na_F/mR \sim 0.2$ ($n/m \sim 1/3$, $a_F/R \sim 1/2$) and $\mu_1/\langle\mu\rangle \sim 0.1$ ($\mu_F/\mu_0 \sim 1.2$):

$$H_1/H_{ext} \approx 0.02 f/(1+f) .$$

The f value is easily designed in the range $f = 0\sim0.7$ with $2d = 0\sim0.6$ m ($kd = 0\sim1$), and consequently the maximum perturbation is up to ~1% of the toroidal field strength. This amplitude can be more than enough for the RMP to suppress ELM.

3. Summary and discussion

The RMP is a promising method to suppress ELM in H-mode plasmas. In DEMO/Commercial reactors with strong neutron flux, it is desired the RMP coil system near the first wall not to be put in. We propose an innovative concept of the RMP for tokamak DEMO reactors without installing coils but inserting ferritic steels of the helical configuration. Helically perturbed magnetic field is naturally formed in the axisymmetric toroidal magnetic field through the FSI. The perturbation amplitude can easily be set ~1% of the toroidal field strength.

Ferritic steels will be employed for the blanket structural materials in a DEMO reactor. The helical FS configuration, therefore, can also be attained by the helical arrangement of blanket modules.

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