HIGH-DUTY LONG-DURATION REPETITIVE TOKAMAK DISCHARGE WITH STATIC OR ROTATING HELICAL MAGNETIC FIELD AT THE EDGE

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1. Introduction
A rotating magnetic perturbation (RMP) at tokamak edge has been anticipated to be one of promising configurations for heat and particle control [1,2]. Dynamic aspect of this magnetic configuration are intensively investigated recently to have a better confinement owing to a possible plasma flow and its shear induced by dynamic torque [3].

We have succeeded in obtaining high-duty (up to 0.5) and long-duration (up to 60 seconds) repetitive tokamak discharges with an invertor power supply for Ohmic and vertical field circuits [4,5]. Modifications of hydrogen recycling associated with edge stochastic magnetic perturbation are identified in such a long duration discharge by the detailed observation of time evolutions of gas pressure [6].

In the present paper, the first preliminary results on the RMP are reported, especially spectral analysis of rotating stochastic magnetic field, penetration of ac magnetic field through the thin metal wall and the plasma, the effect on the tokamak edge plasma, and the heat load on the wall.

2. Experimental Device
We employed a high-duty long-duration repetitive tokamak discharge relevant to the particle behavior in long pulse tokamak reactor. Two sets of local helical coils (LHC's, Fig. 1) installed on the outside surface of vacuum chamber at eight different toroidal sections make a poloidally as well as toroidally rotating magnetic field with a rather clean mode structure m/n=6/1 associated with some sidebands. Each LHC surrounds the whole poloidal circumference of the vacuum chamber.

A new invertor circuit supplying two ac currents with the phase difference of 90 degrees has been installed to give a good characteristics for generating such a RMP with variable frequency.

Table 1. Specification of invertor power supply for local helical coils.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Nominal voltage</td>
<td>±600Vp</td>
</tr>
<tr>
<td>Nominal current</td>
<td>±150Ap</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>10kHz</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1k~30kHz</td>
</tr>
<tr>
<td>Phase control</td>
<td>0°, 90°, 180° (±10µs with 0.1µs resolution)</td>
</tr>
<tr>
<td>Load impedance</td>
<td>0.5Ω, 40µH</td>
</tr>
<tr>
<td>Mode</td>
<td>7ms continuous</td>
</tr>
<tr>
<td>Duty factor</td>
<td>less than 0.5</td>
</tr>
</tbody>
</table>
The specifications is shown on Table I. The power supply provides a train of rectangular ac voltage to the resistive and inductive load of LHC so that the coil current contains not only fundamental frequency but also higher harmonics which eventually attenuate when passing through the stainless steel wall of vacuum chamber with the thickness of 2 mm.

3. Spectrum Analysis on Poloidally Rotating Magnetic Field

The wall of vacuum chamber works as a low-pass filter for the penetrating magnetic field. The transfer function for a plane wave would be $\exp\{- (1 + j) \delta / \delta_0 \}$, where $\delta$ is the thickness of the wall and $\delta_0$ is the so called skin depth inversely proportional to the square root of frequency. However, it is not the case. Rather, it is given empirically by

$$G(f) = \left\{1 + (f/f_{c1})^2\right\}^{-1/2} \exp\{-j(f/f_{c2})^{2/3}\}$$ (1)

so that we may obtain the effective waveform of coil current which is now applicable for RMP inside the vacuum chamber without considering the presence of the metal wall.

We decompose the poloidal magnetic field into Fourier series of poloidal mode number $m$ and frequency harmonic number $k$ by fixing the radius. Figure 2 shows the examples of spectrum for 5 and 10 kHz, indicating a good quality of spectra with the main contribution $m = \pm 6$ and $k = \pm 1$.

4. Penetration of Strong Perturbed Field and the Effects on Tokamak Plasma

LHC is energized by $\pm 100$ Ap with the frequency of 5 kHz and the phase shift of 90 degrees

![Fig. 1. Schematic of local helical coil](image)
as shown in Fig.3. We can see the sinusoidal magnetic field although the current waveform is something like triangular. The distribution in vacuum is plotted by broken line in Fig.4, which is compared with that numerically obtained and shown by thin line in the same figure. The solid line shows the penetration in the plasma with the plasma current of 1.1 kA. The field becomes weak at the edge relative to the value in vacuum, and the attenuation seems to become strong around \( r \sim 8 \) cm. But the perturbation penetrates deep inside the tokamak plasma where the attenuation seems to be very weak. The resonance of the main mode with the helicity due to plasma current is estimated to be around \( r \sim 7 \) cm. But we note that the resonance layer for higher sidebands are located outside.

We have observed a slight steady increase in the loop voltage similarly to the case of quasi-static magnetic perturbation. Microscopically, some modulations have been detected with a triple probe installed at the edge. Figure 5 shows an example of temporal variation of the electron temperature at \( r = 8 \) cm. A periodic variation synchronized with externally applied RMP superimposed by a steady increase is clearly observed. Such a general increase in \( T_e \) has been observed also in a quasi-static perturbation.

Concerning to the heat load on the wall, an inhomogeneity due to static perturbed field has been observed [6]. One of the concept of RMP is spreading of plasma heat load on the whole surface of the first wall. This is clearly demonstrated here as shown in Fig.6 where the time evolutions of the wall temperature distribution observed with IR camera are shown in a long duration tokamak discharge without any perturbation field, with static perturbation and
with RMP. Some dips in temperature distributions corresponds to the windings of LHC. The overheating at X point in the case of static perturbation($\theta \approx -18$) is smeared out when RMP is applied although some uniform increase in the wall temperature is observed probably due to the slight increase in Ohmic heating power and possible dissipated power induced by time-varying magnetic field in the plasma.

5. Summary
The first experimental and analytical results on the dynamic behavior of tokamak discharge due to RMP are presented. The construction of good hardware for the fundamental research is described for tokamak device, LHC and its power supply. A comprehensive analysis on the penetration of RMP through the metal wall and the mode structure is given to show the clean mode spectrum owing to a series of complete LHC. The preliminary results on the penetration of ac magnetic field through the tokamak plasma and the modulations of plasma parameters are given.

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References