Journal of Nuclear and Particle Physics 2013, 3(5): 145-148
DOI: 10.5923/j.jnpp.20130305.04

Plasma Thermal Energy Measurement based on the Plasma Diamagnetic Effect in the IR-T1 Tokamak

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Abstract Determinations of the poloidal beta and plasma energy are important in tokamak plasma experiments. In this paper we presented an experimental method especially based on a diamagnetic effect for measurement of these parameters in the IR-T1 tokamak. For this purposes a diamagnetic loop (toroidal flux loop) with its compensation coil constructed and installed on outer surface of the IR-T1, and the poloidal beta and then the plasma thermal energy measured.

Keywords Tokamak, Poloidal Beta, Plasma Thermal Energy, Diamagnetic Loop

1. Introduction

Determinations of the poloidal beta and plasma thermal energy are important in tokamak experiments. Some of the plasma important information can be deduced from these parameters, such as the energy confinement time, plasma pressure, plasma temperature, and magnetohydrodynamics (MHD) instabilities.

Magnetic diagnostics, in particular a diamagnetic loop (toroidal flux loop) are commonly used in tokamaks to measure the variation of toroidal flux induced by the plasma, and then the poloidal beta and the plasma thermal energy [1-67]. In this paper we presented an experimental method based on a diamagnetic effect for measurement of these parameters in IR-T1, which is a small, low beta and large aspect ratio tokamak with a circular cross section (see Table 1). Diamagnetic loop method for measurement of the poloidal beta and the plasma thermal energy will be presented in section 2. Details of design and construction of the diamagnetic loop will be presented in section 3. Experimental results will be discussed in section 4. Summary is also will be presented in section 5.

Table 1. Main Parameters of the IR-T1 Tokamak

Parameters	Value
Major Radius	45 cm
Minor Radius	12.5 cm
Toroidal Field	< 1.0 T
Plasma Current	< 40 kA
Discharge Duration	< 35 ms
Electron Density	0.7-1.5 × 10^{13} cm^{-3}

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Published online at http://journal.sapub.org/jnpp

2. Determinations of the Poloidal Beta and the Plasma Thermal Energy using the Diamagnetic Loop (Toroidal Flux Loop)

Diamagnetic loop measure the toroidal diamagnetic flux for the purposes of measurements of the plasma parameters e.g. poloidal beta and thermal energy of the plasma. The toroidal flux that produced by the plasma is related to the total perpendicular thermal energy of the plasma. This diamagnetic flux is usually measured with the diamagnetic loop. It is usually a single wire which circling the plasma column either inside or outside of the plasma vacuum chamber. Intrinsically this loop will also pickup the toroidal magnetic flux from the toroidal field coil and any current circulating in the poloidal plane, in particular toroidal field coil current, eddy currents in the conducting vacuum chamber induced during transient changes in the plasma energy and plasma current. In other words, the diamagnetic loop consist of a simple loop that links the plasma column, ideally located in a poloidal direction in order to minimize detecting the poloidal field. In cases of the ohmically heated tokamaks (low beta) where the plasma energy density is small compared to the energy density of the magnetic field, the change in the total toroidal magnetic flux is small. Therefore a reference signal equal to the vacuum toroidal magnetic flux is usually subtracted from it, giving a net toroidal flux equal to the diamagnetic flux $\Delta\Phi_D$ produced by the circular plasma. The relation between the diamagnetic flux and the poloidal beta derived from simplified equilibrium relation is [1-3]:

$$\beta_p = 1 - \frac{8\pi\, B_{\phi 0}}{\mu_0^2 I_p^2}\Delta\Phi_D, \quad (1)$$

where $\Delta\Phi_D = \Phi_{Total} - \Phi_{vacuum}$, and $\Phi_{vacuum} = \Phi_T + \Phi_O + \Phi_V + \Phi_E$, and where $B_{\phi 0}$ is the toroidal magnetic field in the absence of the plasma which can be obtained by the magnetic probe, I_p is the plasma current which can be obtained by the rogowski coil, Φ_T is the toroidal flux because of toroidal field coils, Φ_O and Φ_V are the passing flux through loop due to possible misalignment between ohmic field and vertical field and the diamagnetic loop and Φ_E is the toroidal field due to eddy current on the vacuum chamber. These fluxes can be compensated either with compensation coil or dry runs technique (fields discharge only shots i.e. no plasma shots). It must be noted that compensating coil for diamagnetic loop is wrapped out of the plasma current, and only the toroidal flux (which is induced by the change of toroidal field coil current when plasma discharges) can be received. As seen in Eq. (1) the diamagnetic loop signal contains two parts, plasma diamagnetic flux and the vacuum toroidal flux. So the diamagnetic flux $\Delta\Phi_D$ caused by plasma current can be measured from the diamagnetic loop and compensating coil using subtraction.

If we want to have a determination of the volume averaged plasma kinetic pressure $\langle p \rangle$, it is can be measured directly from the definition of the poloidal beta:

$$\langle p \rangle = \beta_p \frac{B_\theta^2(a)}{2\mu_0} = \frac{\mu_0 I_p^2 \beta_p}{8\pi^2 a^2}, \tag{2}$$

where a is the plasma minor radius.

For measurement of the plasma thermal energy we start from the plasma state equation:

$$\langle p \rangle = \sum_i n_i T_i = \frac{2}{3}\sum_i E_i = \frac{2}{3}E, \tag{3}$$

where subscript i indicate the plasma species i, and E indicate the plasma thermal energy density, therefore the plasma thermal energy U, is obtained:

$$U = \frac{3}{2}\left(\sum_\alpha n_\alpha T_\alpha\right)V = \frac{3}{2}\langle p \rangle V, \tag{4}$$

where V is the plasma volume.

Therefore according to above discussion we can find the poloidal beta and the plasma thermal energy by the diamagnetic loop. Experimental results for determinations of these parameters will be presented in the next section.

3. Design and Construction of the Diamagnetic Loop

In general the magnetic sensors works based on Faraday's law and measures component(s) of the local magnetic fields or magnetic fluxes for use in plasma control, equilibrium reconstruction and detection of the plasma energy, poloidal beta and MHD instabilities.

Diamagnetic loop design characteristics presented in Table 2.

Table 2. Design Parameters of the Diamagnetic Loop

Diamagnetic Loop Parameters	Value
R (Resistivity)	100 Ω
L (Inductance)	20mH
n (Turns)	170
S (Sensitivity)	0.5V/G
f (Frequency Response)	5kHz
Effective nA	16 m^2
d (Wire Diameter)	0.2mm
r_m (Coil Average Radius)	175mm

4. Experimental Results

Table 3. Plasma Parameters at t=15ms in Target Shot

Plasma Parameters	Values
Total Discharge Duration	$35(ms)$
Plasma Current	$30500(A)$
Input Heating Power	$109.34\ (kW)$
Plasma Density	$1.2\times 10^{19}\ m^{-3}$
Toroidal Field	$0.82\ (T)$
Loop Voltage	$3.585\ (V)$
Shafranov Parameter Λ	0.4700

We constructed and installed a diamagnetic loop with its compensation coil on outer surface of the IR-T1 tokamak. Then the poloidal beta and the plasma thermal energy were measured from them, as shown in the Figures (1d) and (2b), respectively. In the Figures (1a) and (2a) plasma current plotted which measured by the Rogowski coil. In the Figures (1b) and (1c) the toroidal field and the diamagnetic flux plotted which measured by the magnetic probe and diamagnetic loop, respectively. Also in the Figures (2c) and (2d) the plasma energy confinement time and the plasma particle temperature plotted which obtained from the poloidal beta and plasma thermal energy, respectively. Some of the values of plasma parameters in the target shot at t=15ms presented in the Tables 3 and 4 which determined from combination of the diamagnetic loop and other diagnostics such as the magnetic probe, Langmuir probe, and the poloidal flux loop.

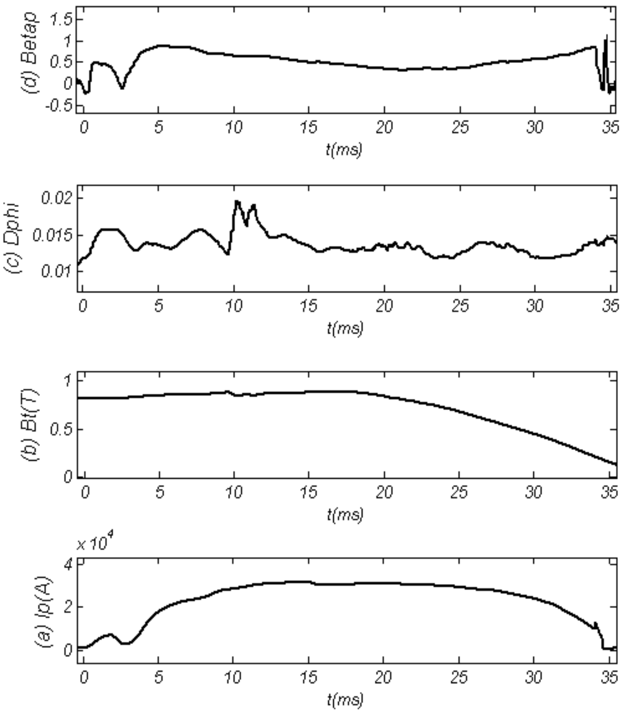

Figure (1). Diamagnetic Loop Method for Measurement of Poloidal Beta: (a) Plasma Current, (b) Toroidal Magnetic Field, (c) Plasma Diamagnetic Flux, and (d) Poloidal Beta along the Plasma Current

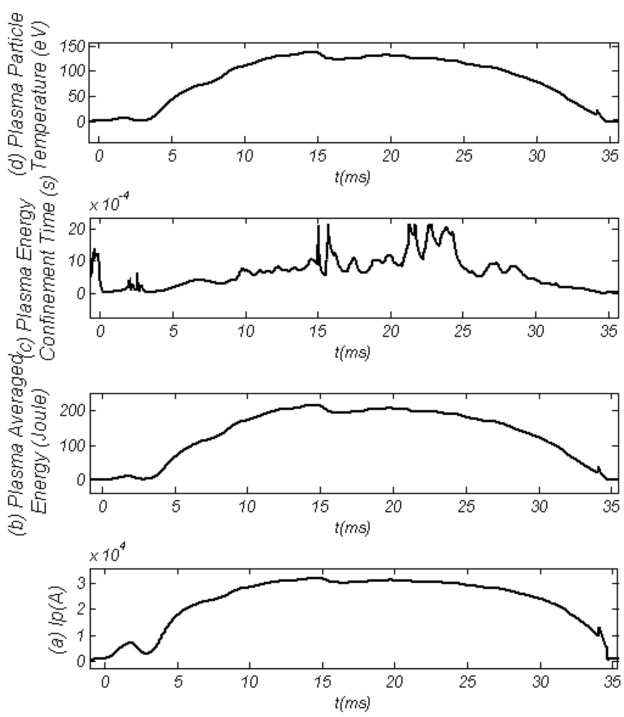

Figure (2). Diamagnetic Loop Measurement Results: (a) Plasma Current, (b) Plasma Averaged Thermal Energy, (c) Plasma Energy Confinement Time, (d) Plasma Particles Averaged Temperature

5. Summary

In this paper we presented an experimental method especially based on a diamagnetic effect for measurement of the poloidal beta and the plasma thermal energy in the IR-T1 tokamak. For this purposes a diamagnetic loop (toroidal flux loop) with its compensation coil constructed and installed on outer surface of the IR-T1, and the diamagnetic flux and then the poloidal beta and the plasma thermal energy measured.

Table 4. Plasma Parameters at t=15ms in Target Shot which Determined based on the Diamagnetic Effect

Plasma Parameters	Value
Poloidal Beta	0.550
Internal Inductance	0.840 (H)
Plasma Averaged Pressure	970.800 $(Pascal)$
Plasma Averaged Energy	197.1271 $(Joule)$
Plasma Particles Temperature	136.8323 (eV)
Plasma Ohmic Resistance	0.11754 $(m\Omega)$
Effective Atomic number	3.6505
Plasma Energy confinement Time	1.8 (ms)

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