APPLICATION OF MAGNETIC DIAGNOSTICS TO DETERMINE BASIC ENERGY CHARACTERISTICS OF PLASMA

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Method of determination of plasma parameters and magnetic configuration of toroidal magnetic traps according to measurement results of magnetic fields of plasma currents out of volume of plasma confinement is implied now by magnetic diagnostics [1-3]. Rokosovskiy coil, diamagnetic loop and saddle coil are now used most often to determine macroscopic plasma parameters; they allow to determine longitudinal current magnitude and energy content of plasma in the confinement volume. The most important characteristics of plasma are energy confinement time of plasma τ_E and power W injected into plasma. Possibility to determine τ_E, W and Z (average charge value) values using sensors of magnetic diagnostics in stellarators is discussed.

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THE OBTAINED RESULTS

Longitudinal unidirectional plasma current

$$I = 2\pi \int_0^a j_0 r dr \qquad (1)$$

is measured by Rogovski coil. Here, α – average small radius of plasma column, j_0 – density of longitudinal current and r – current radius. Longitudinal current is usually generated by ohmic discharge or is a consequence of "neoclassical effects" (bootstrap-current) [4]. Longitudinal current can also be a result of heating process (drag current) at heating using neutral injection, RF or HF waves.

Diamagnetic flow $\Delta\Phi$ is bounded in magnetic traps with plasma parameters and magnetic configuration with the following ratio [5]

$$\Delta\Phi = \frac{8\pi^2}{B_0}\int_0^a \Pr dr + \frac{4\pi I^2}{c^2 B_0} + \frac{4\pi^2}{cR}\int_0^a j_0 \frac{\partial}{\partial r}\left[r^2 \int_0^a x\iota_{st} dx\right] dr. \qquad (2)$$

Here, B_0 – magnetic field value on the axis of facility, P – gas-kinetic plasma pressure and ι_{st} – angle of rotational transformation generated by stellarator field.

As it is clear from the expression (2), diamagnetic flow consists of two terms that are general for tokamaks and stellarators (the first and the second component) and stellarator additive. This additive can turn out rather essential in a number of cases.

Magnetic field flow generated by Pfirsch-Schlüter currents

$$j = -\frac{2cP'}{B_0 \iota}\cos\vartheta \qquad (3)$$

is measured by saddle coil and is described by the expression [5]

$$\frac{\Delta\Psi}{s} = \frac{I}{cR}\left[\ln\frac{8R}{b} - 1\right] - \frac{2\pi}{c}\int_0^a \left(\frac{2cP'}{B_0 \iota}\left[1 + \Delta\frac{N\iota_{st}}{R}\right] + \Delta j_0' + \frac{r}{R} j_0\right)\frac{r^2}{b^2} dr, \qquad (4)$$

where $\iota = \iota_c + \iota_{st}$ – is a total angle of rotational transformation, ι_c – current angle of rotational transformation, ϑ - poloidal angle, S – area of saddle coil, b – radius where the coil is located, Δ – drift of magnetic surfaces, N – number of stellarator field periods and ()' – dash means radius derivative.

As it is seen from expressions (1), (2) and (4), using magnetic sensors one can determine value of plasma energy content Γ, knowing basic characteristics of magnetic system and plasma current

$$\Gamma = 2\pi^2 R a^2 \overline{P}, \ \overline{P} = \frac{2}{a^2}\int_0^a \Pr dr. \qquad (5)$$

Plasma energy balance is described by the known expression

$$\frac{3}{2}\frac{\partial}{\partial t}\Gamma + \frac{3}{2}\frac{\Gamma}{\tau_E} = W, \qquad (6)$$

In statical situation, as it is known, expression (6) is simplified to the following form:

$$W = \frac{3}{2}\frac{\Gamma}{\tau_E}. \qquad (7)$$

Study of transient process while measuring power injected into plasma is of a certain interest. If the discharge process passes a step-like increase of power on a value of $\delta W << W$ for the time $t << \tau_E$, then, according to the expression (6), temporal modification of energy-content of plasma can be described in the following way:

$$\delta\Gamma(t) = \delta\Gamma_0(1 - e^{-t/\tau_E}). \qquad (8)$$

Here, $\delta\Gamma_0$ - value on which energy content increases for the time $t >> \tau_E$. From the expression (8) it is clear, that at a step-like increase of power the energy-content of plasma will change with typical time $t \cong \tau_E$. Value of energy life time can be determined by the expression

$$\tau_E = \frac{\delta\Gamma_0}{\left.\frac{\partial}{\partial t}\Gamma\right|_{t\to 0}}. \qquad (9)$$

At emergency shut-down of power for the time $t << \tau_E$ changes of energy-content of plasma are determined according to (6) by the following expression:

$$\delta\Gamma = \delta\Gamma_0 e^{-t/\tau_E}. \qquad (10)$$

i.e. after shut-down of heating source the energy-content of plasma decreases exponentially with typical time $t \cong \tau_E$. Energy time τ_E According to (10) is determined by the expression:

$$\tau_E = -\frac{\delta\Gamma_0}{\left.\frac{\partial\Gamma}{\partial t}\right|_{t\to 0}}. \qquad (11)$$

It is clear from the given expressions (9) and (11) that step-like change of power injected into plasma allows to determine value τ_E. While according to expression (7), knowing value τ_E allows to determine the power injected into plasma.

Assuming that longitudinal current in plasma is generated by "increasing" effect. Then, in case of step-like increase of heating power the change of current δI will be described by the expression

$$L\frac{\partial}{\partial t}\delta I + R\delta I = \delta U \qquad (12)$$

Here, δU - change of electromotive force related to the change of heating power value. Solution to this equation at $\delta U = const$ will be

$$\delta I = \delta I_0(1 - e^{-t/\tau}), \qquad (13)$$

where δI_0 - increase of current value for the time $t >> \tau = L/R$. According to the expression (13), value τ can be determined by the following way

$$\tau = \frac{\delta I_0}{\left.\frac{\partial}{\partial t}\delta I\right|_{t\to 0}}. \qquad (14)$$

If longitudinal current is determined by neoclassical effects (bootstrap-current), then, in case of step-like change of the injected power of the expression (12) it is changed to the following format

$$L\frac{\partial}{\partial t}\delta I + R\delta I = \delta U_0(1 - e^{-t/\tau_E}). \qquad (15)$$

Here, δU_0 - electromotive force change related to influence of neoclassical effects. As a result of solution of this equation we will obtain

$$\delta I = \delta I_0\left[1 - \frac{\tau_E}{\tau_E - \tau}e^{-t/\tau_E} + \frac{\tau}{\tau_E - \tau}e^{-t/\tau}\right], \qquad (16)$$

and

$$\left.\frac{\partial}{\partial t}\delta I\right|_{t\to 0} = 0. \qquad (17)$$

Then, expression (7) can be rewritten in the format

$$\tau = \frac{\delta I_0}{\left.\tau_E\frac{\partial^2 I}{\partial t^2}\right|_{t\to 0}}. \qquad (18)$$

Comparison of expressions (14) and (18) shows that different mechanisms of current excitation give different speed of current changes at sharp change of plasma heating power. By the known value $\tau = \frac{L}{R}$ and the known profile $T_e(r)$ - electron temperature one can determine an average plasma charge Z. Ties between average plasma charge and value $\tau = \frac{L}{R}$ can be easily obtained from ratio

$$\overline{Z} = \frac{1.14*10^{-4}}{\tau}\left[\ln\frac{8R}{a} - 1.5\right]\int_0^a T_e^{3/2}rdr. \qquad (19)$$

CONCLUSIONS

Possibilities to use sensors of magnetic diagnostics (Rogovski coil, diamagnetic loop and saddle coil) to determine basic energy characteristics of plasma are discussed in this work.

It is shown that at sharp changes of plasma heating power $t << \tau_E$, $\tau = \frac{L}{R}$ using the enumerated above sensors of magnetic diagnostics one can determine the following: τ_E - energy life time of plasma, *W* is absorbed power injected into plasma, Z is average charge of plasma and there is a possibility to find out mechanisms of current excitation. The most important advantage of the discussed methodology is absence of necessity to conduct absolute measurements of plasma parameters to determine τ_E.

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ПРИМЕНЕНИЕ МАГНИТНОЙ ДИАГНОСТИКИ ДЛЯ ОПРЕДЕЛЕНИЯ ОСНОВНЫХ ЭНЕРГЕТИЧЕСКИХ ХАРАКТЕРИСТИК ПЛАЗМЫ

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Показано, что при скачкообразном изменении мощности нагрева плазмы с помощью датчиков магнитной диагностики может быть определена величина энергетического времени жизни плазмы τ_E, вводимая в плазму мощность *W*, средний заряд плазмы Z, а также появляется возможность выяснения механизмов возбуждения тока в плазме.

ЗАСТОСУВАННЯ МАГНІТНОЇ ДІАГНОСТИКИ ДЛЯ ВИЗНАЧЕННЯ ОСНОВНИХ ЕНЕРГЕТИЧНИХ ХАРАКТЕРИСТИК ПЛАЗМИ

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Показано, що при стрибкоподібній зміні потужності нагріву плазми за допомогою датчиків магнітною діагностики може бути визначена величина енергетичного часу життя плазми, потужність, що вводиться в плазму, средний заряд плазми, а також з'являється можливість з'ясування механізмів збудження струму в плазмі.