ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

Some Theoretical Problems of Magnetic Diagnostics in Tokamaks and Stellarators

V.D. Pustovitov

(Received – Nov. 15, 1993)

NIFS-262 Dec. 1993

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

SOME THEORETICAL PROBLEMS OF MAGNETIC DIAGNOSTICS IN TOKAMAKS AND STELLARATORS

V.D.Pustovitov*

National Institute for Fusion Science, Nagoya 464-01, Japan

ABSTRACT

The main problem of magnetic diagnostics is discussed here: which plasma characteristics can be determined from magnetic measurements in tokamaks and stellarators. The reasons are elucidated why diamagnetic measurements are reliable and easily interpreted. We discuss also the capabilities of diagnostics based on the measurements of poloidal fields outside the plasma. This article is based on a lecture delivered at the Third International School on Plasma Physics and Controlled Fusion, held 15-22 June 1993 at St.Petersburg - Kizhi, Russia.

Article is submitted for publication to the journal "Plasma Physics Reports" ("Fizika Plazmy").

Keywords : tokamak, stellarator, magnetic measurements, plasma equilibrium

---

*Permanent address: Kurchatov Institute, Moscow, Russia

INTRODUCTION

Equilibrium of a plasma in systems with magnetic confinement is ensured due to the compensation of gas-kinetic expansion of a plasma by the Ampere force:

$$\nabla p = \mathbf{j} \times \mathbf{B} \quad . \tag{1}$$

Here p is the plasma pressure, **j** and **B** are the current density and magnetic field strength, correspondingly, which satisfy the equations

$$\mathrm{div}\mathbf{B} = 0 \,, \quad \mathbf{j} = \mathrm{rot}\mathbf{B}. \tag{2}$$

Currents flowing through the plasma produce a magnetic field which is called self-field of a plasma. This field, being a small but a noticeable part of a total field (self-field + external field) in tokamaks and stellarators, can be measured outside the plasma column by probes and coils. Theoretically, with results of these measurements this field can be reconstructed in a vacuum region up to the plasma boundary. Field measurements themselves and vacuum calculations are comparatively simple tasks. The main physical problem of magnetic diagnostics remains to be interpretation of the results obtained, determining plasma parameters by the known self magnetic field outside the plasma column or by its integral characteristics.

Magnetic measurements are an important part of plasma diagnostics in tokamaks and stellarators. Despite the principal difference, these systems have too much in common. Because of this we shall consider them together, in the frame of unified formalism. It helps to reveal universal regularities and to get the better physical insight of the related effects. For example, for the analysis of tokamaks it is useful, as a first step, to turn to the conventional current-free stellarator with planar circular axis. Because some details can be more easily studied in this system due to the absence of a longitudinal current.

By the measured magnetic field in tokamaks and stellarators the plasma energy content [1-11], Pfirsch-Schlüter current [3,5,6,8,9] plasma pressure and current profile [3-5,8,9,12], anisotropy degree [6,11], plasma column shape and position [13-17] are determined or estimated. Brevity of the presentation does not allow to survey the whole spectrum of relevant problems. Thus, we limit ourselves by those which are important for understanding the subject, insufficiently or not in the least described in literature, and discuss also some controversial items. Besides articles mentioned above, for more thorough study of the problem several review articles [18-23] can be recommended.

TO THE THEORY OF DIAMAGNETIC MEASUREMENTS

Let us start from diamagnetic measurements. The matter can be easily understood on the simplest example: straight plasma cylinder. Equilibrium equation for a cylinder is reduced to the equality

$$\nabla\left(p + \frac{\mathbf{B}^2}{2}\right) = (\mathbf{B}\cdot\nabla)\mathbf{B} = -\frac{B_u^2}{2}\mathbf{e}_\rho, \tag{3}$$

which, being multiplied by $\rho^2\mathbf{e}_\rho$ and integrated over ρ, leads to the well-known integral pressure-balance equation:

$$\bar{p} = \frac{B_0^2 - \overline{B_z^2}}{2} + \frac{B_J^2}{2}. \tag{4}$$

Here ρ, u are the polar coordinates related to the center of the plasma column cross-section, $B_J = J/(2\pi b)$ is the field of longitudinal current at the plasma surface, b is its minor radius, B_0 is the strength of a vacuum longitudinal field, $\bar{p}$ and $\overline{B_z^2}$ are the values obtained by averaging over plasma cross-section:

$$\bar{p} = \frac{1}{S_p}\int p dS_p = \frac{2}{b^2}\int_0^b p(\rho)\rho d\rho. \tag{5}$$

At small $\bar{\beta} = 2\bar{p}/B_0^2$ and strong toroidal field, $B_J/B_0 << 1$, Eq. (4) can be rewritten in the form

$$2\frac{\Delta\Phi}{\Phi_0} = \frac{B_J^2}{B_0^2} - \bar{\beta} \tag{6}$$

where $\Phi_0 = S_p B_0 = \pi b^2 B_0$,

$$\Delta\Phi \equiv \Phi_p - \Phi_V = \int_{S_\perp}(\mathbf{B} - \mathbf{B}_V)\cdot d\mathbf{S}_\perp, \tag{7}$$

Φ_p is the flux of the toroidal field through the transverse cross-section $S_\perp$ during the discharge, and Φ_V is the analogous flux of a vacuum field (it is supposed here that the external longitudinal field is not changed during the discharge).

The difference $\Delta\Phi$ can be measured during the discharge by the induced e.m.f. in a contour encircling the transversal area $S_\perp$, and current J can be measured by the Rogowski coil. Finally, with the help of Eq. (6) one can find $\bar{\beta}$.

The simple relationship (6) derived more than 35 years ago proved to be exceptionally useful in fusion studies. Though it was derived at, as it would seem, unjustifiedly strong limitations (axial symmetry, straight axis, circular plasma cross-section), in many cases its accuracy is quite acceptable for real tokamaks and stellarators.

To become convinced in that and to get an idea about possible change of the expression for $\Delta\Phi$ if it will be accurately calculated for real tokamaks and stellarators, it is sufficient to transform the right hand side of Eq. (7).

In stellarators

$$\mathbf{B} = \overline{\mathbf{B}} + \tilde{\mathbf{B}}, \tag{8}$$

where $\tilde{\mathbf{B}}$ is the component of the magnetic field oscillating over ζ, and $\overline{\mathbf{B}}$ is its axisymmetric component. Here and in the following r, ζ, z are the cylindrical coordinates with z-axis as the main axis of the device, Fig.1. For $\overline{\mathbf{B}}$ the next representation is valid:

$$\overline{\mathbf{B}} = \frac{1}{2\pi}\left[\nabla\left(\psi - \psi_V\right)\nabla\zeta\right] + \frac{F}{2\pi}\nabla\zeta, \tag{9}$$

where we are interested now by toroidal component only. In a tokamak $\tilde{\mathbf{B}} = 0$, $\psi_V = 0$, so tokamak can be considered as a particular case of a stellarator.

If we disregard the difference between $\tilde{\mathbf{B}}$ and its vacuum value $\tilde{\mathbf{B}}_V$ (as it is usually done in the frame of the standard stellarator approximation), then after substitution of the expression (9) into (7) we shall get

$$\Delta\Phi = \frac{1}{2\pi}\int\limits_{S_\perp}\frac{F - F_b}{r}dS_\perp, \tag{10}$$

where F_b is the vacuum value of F characterizing the external longitudinal field. For a stellarator the expression (10) is approximate, but for a tokamak it is an exact one. A transition to the cylinder in (9) is accomplished by the replacement of $\nabla\zeta$ by $\mathbf{e}_\zeta / R$, where $R = \text{const}$, and, correspondingly, r by R in (10).

Toroidicity of a system reveals itself in (10) in two ways. First, by obvious presence of $r = R - \rho\cos u$ in the denominator. And, second, implicitly through the dependence $F(\psi)$. In toroidal systems magnetic surfaces $\psi = \text{const}$ are shifted outward, in the region of larger r, with β-rise, and $F(\psi)$ distribution becomes asymmetrical with respect to the geometrical axis r=R, Fig.2. With outward shift of the maximum of $\left|F - F_b\right|$ its contribution to the integral (10) is smaller than in a similar case for the cylinder (due to the division by the r>R). Thus, at the natural outward shift of the magnetic axis $\Delta\Phi$ should increase weaker with increasing β than one could expect from the expression (6). At the same time, as it is seen from (10), account of the toroidicity can lead to the appearance of the corrections of the order of the inverse aspect ratio b/R in the expression for $\Delta\Phi$. They can be noticeable only when there are strong relative shift of magnetic surfaces. Actually it means that in many cases the cylindrical approach should give quite reliable result for $\Delta\Phi$ for toroidal systems too.

This is confirmed by a lot of experiments, and, as we tried to show, this can be easily seen even in the general expression for $\Delta\Phi$. It is also confirmed by more strict analysis [24], where it is shown that in the current-free stellarator at any aspect ratio and arbitrary shape of magnetic surfaces

$$\Delta\Phi = -\frac{1}{F_b}\left(1 - \delta_S - \delta_h\right)\int_{V_p} p\,dV. \qquad (11)$$

Integration is performed here over the plasma volume V_p, δ_S is a quantity of the order of b/R, describing just discussed $\Delta\Phi$ dependence on the relative shift of magnetic surfaces, and δ_h is a small term related with helical fields (which are not taken into account in (10)). At outward shift of the magnetic axis $\delta_S>0$, at inward shift $\delta_S<0$. In stellarators axis shift of any sign can be produced at $\beta=0$, in vacuum configuration, with the help of an external vertical field. In such a case nonvanishing δ_S in a stellarator (in a helical system similar to CHS this value can be of the order of 0.1) should show its worth even at low β when Shafranov shift is yet small. First it was shown by Dr. H.Yamada (NIFS).

As it is seen from (11), the ratio $\Delta\Phi / \Phi_0$, Φ_0 being the flux of the vacuum field through the transverse plasma cross-section, practically should not depend on the plasma shape (let us remind that here we speak about current-free stellarator), so using the simple formula (6) will not lead to a large mistake even for a stellarator configuration with noticeably noncircular plasma shape.

One more substantial circumstance should be noted to the favor of diamagnetic measurements: the value of $\Delta\Phi$ as determined by (10) does not depend on the shape of the transversal area $S_\perp$ because only integration over the plasma cross-section gives nonvanishing contribution to (10). Thus, shape of the diamagnetic coil, generally speaking, is of a little importance. From practical viewpoint, it gives a lot of freedom. It is important, however, that this coil should lie in the plane perpendicular to the geometrical axis of the device. If this condition is not satisfied, then coil will react not only on the change of toroidal field, but on poloidal field also. In this case the value of measured signal will depend on both orientation and shape of the diamagnetic coil.

The value $\Delta\Phi$ is referred sometimes as the change of the longitudinal flux in the plasma. In some cases it is correct, but, generally speaking, such interpretation is wrong.

By definition, $\Delta\Phi$ is the change of the magnetic flux through the area encircling by the diamagnetic coil. Plasma boundary naturally divides this area $S_\perp$ into two parts: $S_\perp = S_{in} + S_{ext}$. Correspondingly, magnetic flux through $S_\perp$ consists of two parts: flux Φ_{in} through the transverse cross-section of a plasma S_{in} and flux Φ_{ext} of the external field through S_{ext}:

$$\Phi = \Phi_{in} + \Phi_{ext}. \tag{12}$$

During the discharge plasma column can move and change its shape. This can lead to the change of S_{ext}, and, correspondingly, of Φ_{ext}. These simple arguments, which are true for a system of arbitrary geometry, lead to the conclusion that some part of the signal measured by the diamagnetic coil can be attributed to the change of Φ_{ext}, which is a flux between coil and plasma boundary. This part can reach up to all 100% of a diamagnetic signal.

Indeed, hot plasma is a perfect conductor, and during fast processes magnetic fluxes should be frozen-in. Both longitudinal current and $\bar{\beta}$-value can change, but magnetic flux inside the plasma should remain unchanged. The state is realized which is called flux-conserving equilibrium. But value $\Delta\Phi$ should not be affected by that: it does not depend on the way of transition of the configuration to the final state, but it is determined by its equilibrium parameters only. And we calculated $\Delta\Phi$ as a difference of fluxes (7) one of which characterizes the final state, and another one the initial state (vacuum field). And, at that, to describe the final state, we used equilibrium equations (1), (2) only. Nonzero result for $\Delta\Phi^*$ does not contradict the condition that Φ_{in} is conserved: currents flowing in the plasma weakens (or magnifies) the longitudinal field inside the plasma, plasma expands (compresses), and due to this Φ_{in} remains unchanged, diamagnetic coil measures a signal related with pushing aside (pulling in) the external field. At vacuum toroidal field unchanged, the calculation of $\Delta\Phi$ is reduced to the calculation of the difference of fluxes through the transverse cross-section of a plasma, see (7) and (10). This difference shows how much the toroidal flux in a plasma differs from the flux of vacuum field through the same cross-section. Such interpretation is valid always, independently on the character of the discharge.

The change of the minor radius of circular plasma column can be easily estimated with the help of Eq. (6). The frozenness of the toroidal flux into the plasma means that during transition from one state to another the next value must be unchanged:

$$\Phi(b) = \Phi_0(b) + \Delta\Phi = \Phi_0(b)\left[1 - \frac{\bar{\beta}}{2} + \frac{1}{2}\frac{B_J^2}{B_0^2}\right], \qquad (13)$$

where $\Phi_0(b) = \int B_0 dS_\perp$ is the magnetic flux of a vacuum toroidal field through the transverse plasma cross-section. In tokamaks and stellarators $\bar{\beta} << 1$, $B_J^2 / B_0^2 << 1$, so variation of b should be small. For example, at fast changing of $\bar{\beta}$ the condition that Φ is frozen is reduced to the equality $b^2(1 - \bar{\beta}/2) = \text{const}$. It follows from here that the change of the minor plasma radius is proportional to $\delta\bar{\beta}$:

$$\delta b / b = \delta\bar{\beta} / 4. \qquad (14)$$

With $\bar{\beta}$-rise plasma is expanding slightly. The area between the plasma boundary and diamagnetic coil is decreasing on $\delta S_\perp = -\pi b^2 \delta\bar{\beta} / 2$ at that. As a result the total flux through this coil decreases on the value $\delta\Phi = B_0 \delta S_\perp = -\Phi_0 \delta\bar{\beta} / 2$. Just this value, which is equal to $\Delta\Phi$, will be measured. On this illustrative example we have seen once more that diamagnetic signal $\Delta\Phi$ does not depend on whether magnetic flux is frozen into the plasma or not.

But possible frozenness of the flux into the external conductors, which can display itself through the small change of a vacuum toroidal field during the discharge, should be taken into account at diamagnetic measurements without fail [2]. It should be kept in mind that $\Delta\Phi$ is the "plasma contribution" into the variation of the magnetic flux. Besides, external sources of the toroidal field can affect the results of the measurements.

SELF-FIELD OF PLASMA CURRENTS OUTSIDE THE PLASMA COLUMN

Diamagnetic coil embraces the plasma column, thus it records the change of the field inside the plasma. But equilibrium currents in a plasma create self magnetic field outside plasma also. The task of the theory is to connect the changes of the magnetic field outside the plasma with its parameters.

Self magnetic field of a plasma, $\mathbf{B}_{pl}$, can be calculated "directly", if currents flowing through the plasma are known. On the other hand, calculation of the self magnetic field $\mathbf{B}_{pl}$ outside the plasma is the classical external boundary problem of the magnetostatics, which is reduced to the solution of the Maxwell equation for a vacuum field with natural conditions of its boundness and decreasing at the infinity. "Matching" of its solution to the equilibrium configuration is carried out by prescribing boundary conditions at the plasma boundary Γ_p, which divides the space into two parts: internal and external. In such statement of the problem the behavior of both current and field inside the Γ_p does not play any role, though they actually determine the shape of Γ_p and magnetic field $\mathbf{B}_\Gamma$ at Γ_p.

Independence of the external solution on the internal one at given boundary conditions means that two configurations, the real one and another one, with the same Γ_p and magnetic field $\mathbf{B}_\Gamma$ at Γ_p, but with $\mathbf{B}_{in}$=0, Fig.3, must have the same magnetic field $\mathbf{B}_{vac}$ in the external region. In the last case, Fig.3b, to provide a jump of a magnetic field at plasma boundary ($\mathbf{B}_\Gamma$ outside and $\mathbf{B}_{in}$=0 inside), the surface current should flow over Γ_p:

$$\mathbf{i}_\Gamma = -\mathbf{B}_\Gamma \times \mathbf{n}, \qquad (15)$$

$\mathbf{n}$ being the unit external normal to Γ_p. In the configuration with the surface current (15) in the external region

$$\mathbf{B}_i + \mathbf{B}_{ext} = \mathbf{B}_{vac}, \qquad (16)$$

and in the inner region

$$\mathbf{B}_i + \mathbf{B}_{ext} = 0, \qquad (17)$$

where $\mathbf{B}_i$ is the field of the surface current (15) and $\mathbf{B}_{ext}$ is the field produced by the currents flowing in the external conductors (they are not shown on the Fig.3). But, by definition,

$$\mathbf{B}_{vac} = \mathbf{B}_{pl} + \mathbf{B}_{ext}. \qquad (18)$$

Thus,

$$\mathbf{B}_i = \begin{cases} \mathbf{B}_{pl} & \text{outside } \Gamma_p \\ -\mathbf{B}_{ext} & \text{inside } \Gamma_p \end{cases}. \qquad (19)$$

The last relationship shows how with known magnetic field at the plasma boundary two problems can be solved: self magnetic field $\mathbf{B}_{pl}$ outside the plasma can be found, and external magnetic field $\mathbf{B}_{ext}$ which is needed for sustaining the given configuration in equilibrium can be calculated. In plasma physics this method of calculating $\mathbf{B}_{pl}$ and $\mathbf{B}_{ext}$ is often called virtual casing principle [19].

The result (19) itself is well known. We dwell upon it to stress the fact that plasma self field $\mathbf{B}_{pl}$ in the vacuum is determined only by the plasma boundary surface and by total (equilibrium) field $\mathbf{B}_\Gamma$ on this boundary. Thus, by measuring vacuum field $\mathbf{B}_{pl}$ outside the plasma one can get only that information about plasma parameters which is "hidden" in Γ_p and $\mathbf{B}_\Gamma$. Is it much or not? Is it possible (and is it worth), for example, to try to determine plasma current and pressure profiles as it was done in [12] for a tokamak and in [9] for a stellarator?

There are no clear unambiguous answer to this question until now, and optimism of some publications should not be perceived as a prove of the opposite. Actually, it is the main yet unresolved problem of the magnetic diagnostics, which, due to the simplicity of its statement, due to the necessity of its resolving and high potential importance of the final answer, is an interesting and actual subject for the discussion.

It is easy to see that the problem discussed is characterized by a high degree of degeneracy. Indeed, self magnetic field of a plasma cylinder with a circular cross-section depends only on the value of total longitudinal current J flowing through the plasma: $\mathbf{B}_{pl} = \mathbf{e}_\varphi J/(2\pi\rho)$. That is why in this case one can determine only J value by the measured poloidal field, and nothing more.

Cylinder, certainly, is an excessively rough model of a real system. Let us turn to a tokamak. In a tokamak

$$\mathbf{B}_\Gamma = B_p \mathbf{e}_p + B_\zeta \mathbf{e}_\zeta, \tag{20}$$

where B_p is the strength of a poloidal field, $\mathbf{e}_p = \mathbf{e}_\zeta \times \mathbf{n}$, $\mathbf{n}$ is the normal to Γ_p (in our case $\mathbf{n} \cdot \mathbf{e}_\zeta = 0$). For $\mathbf{i}_\Gamma$ we have now

$$\mathbf{i}_\Gamma = B_p \mathbf{e}_\zeta - B_\zeta \mathbf{e}_p. \tag{21}$$

Plasma self magnetic field is "created" by the first term in (21). If magnetic surfaces are shifted torii with circular cross-sections,

$$(r - R - \Delta)^2 + z^2 = a^2, \tag{22}$$

then

$$B_p \cong B_J \left[1 + \left(\frac{b}{R} + \Delta' \right) \cos\vartheta \right], \tag{23}$$

where ϑ is a poloidal angle, and Δ' is the Δ derivative over a. Besides B_J, only one other parameter characterizing plasma entered here: Δ'. Thus, maximum which can be expected to get from results of measuring magnetic field outside the plasma is determining the total plasma current J (which is measured by the Rogowski coil) and the value Δ' at plasma boundary. For the completeness we should mention also the possibility of measuring plasma position (major radius). It is not seen in (23) because this relationship is written in coordinates with the origin at the center of Γ_p.

Let us suppose that with the help of the Rogowski and diamagnetic coils the current J and $\bar{\beta}$-value had been measured, and, finally, measurements of the poloidal field resulted in finding $\Delta'(b)$. For this value in a tokamak the next expression is known:

$$\Delta'(b) = -\frac{b}{R}\left[\beta_J + \frac{l_i}{2}\right], \qquad (24)$$

where

$$\beta_J = \frac{2\bar{p}}{B_J^2}, \qquad l_i = \frac{\overline{B_J^2}}{B_J^2} = 2\int_0^b \frac{B_J^2(a)}{B_J^2(b)}\frac{a}{b^2}da. \qquad (25)$$

With its help at known, as we agreed, $\bar{\beta}$ and J, only integral characteristics $\bar{p}$ and $\overline{B_J^2} / B_J^2$ can be determined by obtained value of $\Delta'(b)$.

We made sure that also in a tokamak magnetic measurements give not too much information to make a conclusion about current and pressure profiles: by the value of the integral below some curve it is difficult to judge about this curve. In the example considered account of a toroidicity has resulted in the appearance of only one additional parameter which can be "measured", $\Delta'(b)$, in the expression for the B_p. It should be mentioned, of course, that we used approximate relationships, and, in addition, we supposed that magnetic surfaces are circular. But the absence of a desired effect in the main approximation is yet a rather serious result. And more correct expressions should also depend only on $\Delta'(b)$ in this model. Thus, an additional information about current and pressure profiles cannot be obtained from them.

As to noncircular cross-section, it is enough to mention here the results of calculations [25]. In [25] four concrete examples of configurations were given with approximately the same shape of a plasma cross-section and the same poloidal field at its boundary, but with strongly different current profiles. According to (15) and (19), at the same Γ_p and $\mathbf{B}_\Gamma$ all four configurations must have the same self plasma field $\mathbf{B}_{pl}$ outside the plasma column. Hence, in this case it is also impossible to determine the current (and pressure) profiles by measured $\mathbf{B}_{pl}$.

All arguments given cannot, of course, substitute the full strict proof of this statement in a general case. However, they rather definitely indicate the limitedness of the magnetic diagnostics capabilities. All examples considered show a weak dependence of the external field $\mathbf{B}_{pl}$ of equilibrium currents on their distribution. It is also seen in that self plasma field $\mathbf{B}_{pl}$ outside the plasma column can be modelled with a good accuracy as a field of several circular currents inside Γ_p [25].

All said above about tokamaks remains qualitatively right for stellarators also. For stellarators with circular in "average" plasma cross-section the relationship (23) must be replaced by

$$\overline{B}_p \cong B_J + \frac{b}{R}\left\{B_J + B_0\left[\mu\Delta' + \frac{\Delta_b}{b}(\mu_h a)'\right]\right\}\cos\vartheta, \qquad (26)$$

where $\mu = \mu_h + \mu_J$ is the total rotational transform, $\mu_J = RB_J/(bB_0)$ is its part produced by a current, and μ_h is that due to the helical field, Δ_b is the plasma column shift with respect to the stellarator geometrical axis. At B_J=0 (current-free plasma) for plasma-current-produced vertical field at the plasma column boundary we get:

$$B_\beta = \frac{b}{2R}B_0\left[\mu\Delta' + 2(\mu_b - \mu_0)\frac{\Delta_b}{b}\right] \cong \int_0^b \frac{a^2}{b^2}\frac{p'(a)}{\mu(a)B_0}da. \qquad (27)$$

And in this case also one can determine only one parameter from the measurements of the poloidal field. Let us note that according to (27) in a shearless stellarator (μ=const) B_β is proportional to the same value $\bar{\beta}$ which is measured by a diamagnetic coil, and in l=3 stellarator ($\mu = \mu_b a^2/b^2$) B_β depends on β_0 only (the value of β at the axis of plasma column).

Which is said above touches only one, important, but not the main aspect of the problem of magnetic diagnostics based on the measurements of a poloidal field. From practical point of view the main thing, certainly, is the possibility of determining the plasma column shape and position with the help of magnetic measurements. It is a vitally important element in the circuit of the feedback control of plasma equilibrium in tokamaks (equilibrium in tokamaks is impossible without external vertical field reacting on the changes of discharge parameters). For stellarators the necessity of plasma column position control will become inevitable when experiments in these devices will succeed in approaching the region of high β's. The opportunity to determine plasma position in tokamaks and stellarators from magnetic measurements is related to the "asymmetry" of a poloidal field, see (23) and (26), and does not require knowledge of current and pressure profiles. We do not dwell on the discussion of this problem because in tokamaks such measurements became a routine long ago, and theoretical problems are described in details in a literature, see reviews [19,23].

CONCLUSION

Magnetic measurements are, by their nature, the integral measurements: probes and coils located outside the plasma column react on a total field of plasma currents, or on fluxes of this field. Due to this the results of measurements give, from one hand, very precise and reliable information about integral plasma parameters (such as total current J, $\bar{\beta}$, plasma column shift), but, at the same time, absolutely insufficient one to determine plasma pressure and current profiles.

Undoubted virtue of magnetic diagnostics is that with its help plasma position and $\bar{\beta}$-value are determined with good accuracy without any information about plasma pressure and current profiles. More than that, relationships connecting measurable magnetic values with plasma parameters are simple, which makes simple the interpretation of results. And in the case of diamagnetic measurements, as it was shown, $\Delta\Phi$ weakly depends on plasma toroidicity, and $\Delta\Phi/\Phi$ in a current-free stellarator almost does not depend on a plasma shape, see (11). Due to this errors in determining geometrical characteristics of a plasma column inevitable in experiment should not affect the accuracy of determining $\bar{\beta}$ from the measured diamagnetic signal.

When evaluating capabilities of magnetic diagnostics one should keep in mind that self plasma field $\mathbf{B}_{pl}$ in a vacuum region is determined by the geometry of the plasma boundary and by magnetic field on the surface only.

REFERENCES

1. V.D. Shafranov, Atomnaya Energiya **19**, 175 (1965) [in Russian].
2. K.A. Razumova, Atomnaya Energiya **20**, 20 (1966) [in Russian].
3. A.G. Dikij, S.S. Kalinichenko, Yu.K. Kuznetsov, P.I. Kurilko, A.I. Lysojvan, V.K. Pashnev, V.F. Tarasenko, V.A. Suprunenko, V.T. Tolok and O.M. Shvets, Plasma Physics and Controlled Nuclear Fusion Research 1976 (IAEA, Vienna, 1977), Vol. **2**, 129.
4. E.D. Andryukhina and O.I. Fedyanin, Sov. J. Plasma Phys. **3**, 447 (1977).
5. V.V. Bakaev, S.P. Bondarenko, V.V. Bronnikov, V.S. Vojtsenya, M.P. Vasil'ev, A.Yu. Voloshko, Yu.V. Gutarev, A.G. Dikij, I.A. Dikij, Yu.K. Kuznetsov, A.E. Kulaga, M.S. Kulak, V.B. Korovin, B.V. Kravchin, S.S. Kalinichenko, E.M. Lats'ko, A.P. Litvinov, A.I. Lysojvan, Yu.K. Mironov, N.I. Nazarov, G.P. Opaleva, O.S. Pavlichenko, V.K. Pashnev, V.V. Plyusnin, N.F. Perepelkin, N.P. Ponomarenko, A.S. Slavnyj, A.I. Skibenko, S.I. Solodovchenko, K.N. Stepanov, V.S. Taran, V.T. Tolok, V.M. Tonkopryad, I.P. Fomin, O.M. Shvets and A.F. Shtan', Plasma Physics and Controlled Nuclear Fusion Research 1984 (IAEA, Vienna, 1985), Vol. **2**, 397.
6. E.D. Andryukhina, I.S. Danilkin, K.S. Dyabilin and O.I. Fedyanin, in Proc. 12th Europ. Conf. on Contr. Fus. and Plasma Phys., Budapest, 1985, Vol. 9A, Pt. 1, 481.
7. S. Besshou, C.E. Thomas, T. Ohba, A. Iiyoshi and K. Uo, Nuclear Fusion **26**, 1339 (1986).
8. Yu.V. Gutarev, Yu.K. Kuznetsov V.K. Pashnev and N.P. Ponomarenko, Sov. J. Plasma Phys. **14**, 164 (1988).
9. S. Morimoto, N. Yanagi, M. Nakasuga, T. Obiki, A. Iiyoshi and K. Uo, Nuclear Fusion **28**, 1491 (1988).
10. M. Murakami, S.C. Aceto, E. Anabitarte, D.T. Anderson, F.S.B. Anderson, D.B. Batchelor, B. Brañas, L.R. Baylor, G.L. Bell, J.D. Bell, T.S. Bigelow, B.A. Carreras, R.J. Colchin, N.A. Croker, E.C. Crume, Jr, N. Dominguez, R.A. Dory, J.L. Dunlap, G.R. Dyer, A.C. England, R.H. Fowler, R.F. Gandy, J.C. Glowienka, R.C. Goldfinger, R.H. Goulding, G.R. Hanson, J.H. Harris, C. Hidalgo, D.L. Hillis, S. Hiroe, S.P. Hirshman, L.D. Horton, H.C. Howe, D.P. Hutchinson, R.C. Isler, T.C. Jernigan, H. Kaneko, M. Kwon, R.A. Langley, J.N. Leboeuf, D.K. Lee, D.H.C. Lo, V.E. Lynch, J.F. Lyon, C.H. Ma, M.M. Menon, P.K. Mioduszewski, S. Morita, R.N. Morris, G.H. Neilson, M.A. Ochando, S. Okamura, S. Paul, A.L. Qualls, D.A. Rasmussen, R.K. Richards, Ch.P. Ritz,

J.A. Rome, J. Sanchez, J.G. Schwelberger, K.C. Shaing, T.D. Shepard, J.E. Simpkins, C.E. Thomas, J.S. Tolliver, T. Uckan, K.L. Vander Sluis, M.R. Wade, J.B. Wilgen, W.R. Wing, H. Yamada and J.J. Zielinski, Phys. Fluids B **3**, 2261 (1991).
11. H. Yamada, K. Ida, H. Iguchi, S. Morita, O. Kaneko, H. Arimoto, M. Hosokawa, H. Idei, S. Kubo, K. Matsuoka, K. Nishimura, S. Okamura, Y. Takeiri, Y. Takita, C. Takahashi, K. Hanatani, H.C. Howe, S.P. Hirshman and D.K. Lee, Nuclear Fusion **32**, 25 (1992).
12. Yu.K. Kuznetsov, V.N. Pyatov and I.V. Yasin, Sov. J. Plasma Phys. **13**, 75 (1987).
13. D.W. Swain and G.H. Neilson, Nuclear Fusion **22**, 1015 (1982).
14. Yu.K. Kuznetsov, M.I. Mikhailov, V.K. Pashnev and V.M. Tonkopryad, Nuclear Fusion **23**, 15 (1983).
15. G.N. Deshko, T.G. Kilovataya, Yu.K. Kuznetsov, V.N. Pyatov and I.V. Yasin, Nuclear Fusion **23**, 1309 (1983).
16. S.P. Bondarenko, V.E. Golant, M.P. Gryaznevich, Yu.K. Kuznetsov, V.N. Pyatov, V.S. Taran, K.G. Shakhovets and I.V. Yasin, Sov. J. Plasma Phys. **10**, 520 (1984).
17. P.N. Vabishchevich and I.V. Zotov, Sov. J. Plasma Phys. **13**, 373 (1987).
18. V.S. Mukhovatov and V.D. Shafranov, Nuclear Fusion **11**, 605 (1971).
19. L.E. Zakharov and V.D. Shafranov, Reviews of Plasma Physics (M.A. Leontovich ed.), Consulants Bureau, New York, 1986, Vol. **11**, p. 153.
20. S.V. Mirnov, Physical processes in a tokamak plasma, Energoizdat, Moscow, 1983 [in Russian].
21. D.J. Braams, The Interpretation of Tokamak Magnetic Diagnostics: Status and Prospects, Rep. IPP 5/2, Garching, 1985.
22. D.V. Orlinskij and G. Magjar, Nuclear Fusion **28**, 611 (1988).
23. V.D. Pustovitov, Itogi Nauki i Tekhniki (V.D. Shafranov ed.), VINITI, Moscow, 1993, Vol. **13**, p. 3 [in Russian].
24. V.D. Pustovitov, Journal of Plasma and Fusion Research **69**, 34 (1993).
25. L.L. Lao, H.St. John, R.D. Stambaugh and W. Pfeifer, Nuclear Fusion **25**, 1421 (1985).

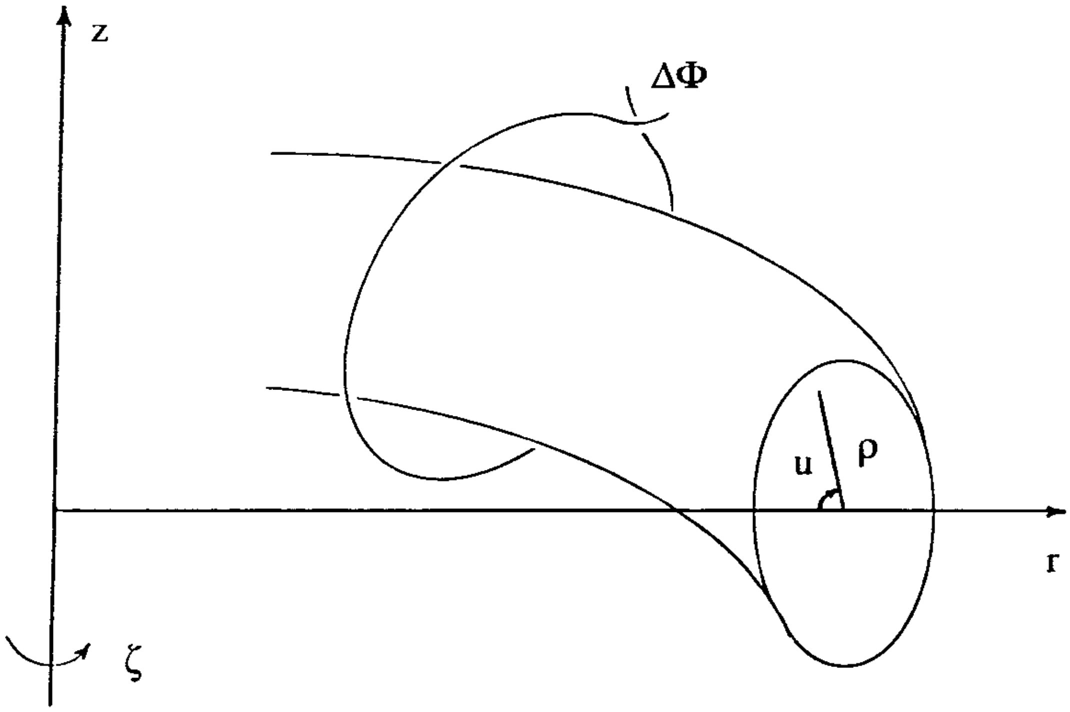

Fig.1. Scheme of diamagnetic measurements and coordinates used

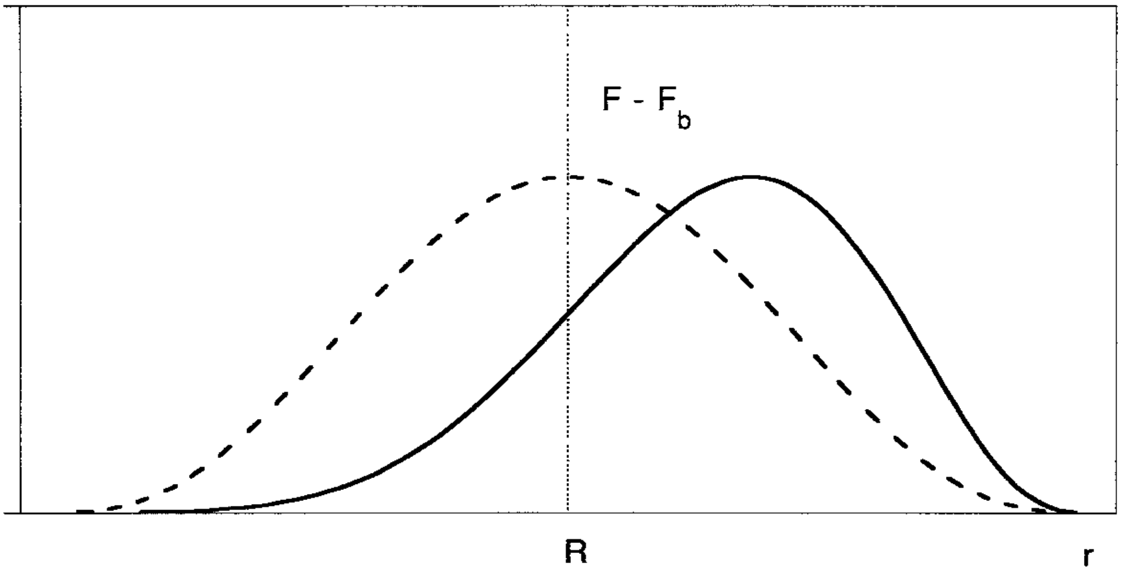

Fig.2. Qualitative difference between $F - F_b$ in a cylindrical plasma column (dashed line) and in a toroidal one (solid line)

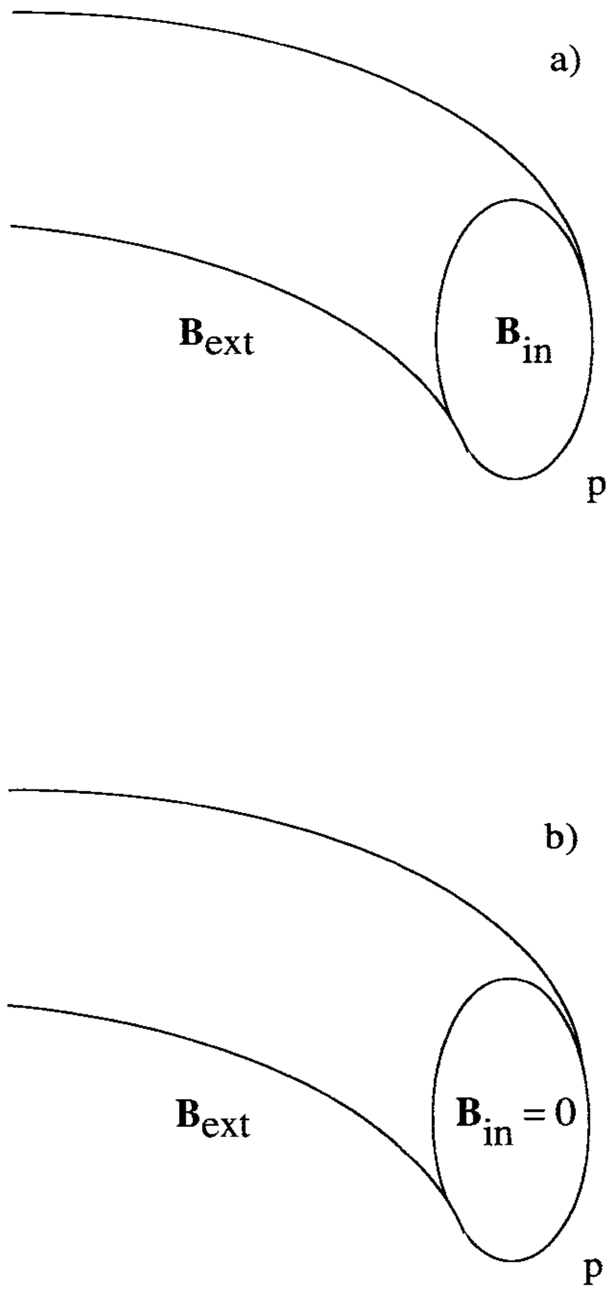

Fig.3. Equilibrium plasma configuration (a) and equivalent model (b) with the same external field

Recent Issues of NIFS Series

NIFS-212 Y. Kondoh, Y. Hosaka and J.-L. Liang, *Demonstration for Novel Self-organization Theory by Three-Dimensional Magnetohydrodynamic Simulation*; Mar. 1993

NIFS-213 K. Itoh, H. Sanuki and S.-I. Itoh, *Thermal and Electric Oscillation Driven by Orbit Loss in Helical Systems*; Mar. 1993

NIFS-214 T. Yamagishi, *Effect of Continuous Eigenvalue Spectrum on Plasma Transport in Toroidal Systems*; Mar. 1993

NIFS-215 K. Ida, K. Itoh, S.-I.Itoh, Y. Miura, JFT-2M Group and A. Fukuyama, *Thickness of the Layer of Strong Radial Electric Field in JFT-2M H-mode Plasmas*; Apr. 1993

NIFS-216 M. Yagi, K. Itoh, S.-I. Itoh, A. Fukuyama and M. Azumi, *Analysis of Current Diffusive Ballooning Mode*; Apr. 1993

NIFS-217 J. Guasp, K. Yamazaki and O. Motojima, *Particle Orbit Analysis for LHD Helical Axis Configurations* ; Apr. 1993

NIFS-218 T. Yabe, T. Ito and M. Okazaki, *Holography Machine HORN-1 for Computer-aided Retrieve of Virtual Three-dimensional Image* ; Apr. 1993

NIFS-219 K. Itoh, S.-I. Itoh, A. Fukuyama, M. Yagi and M. Azumi, *Self-sustained Turbulence and L-Mode Confinement in Toroidal Plasmas* ; Apr. 1993

NIFS-220 T. Watari, R. Kumazawa, T. Mutoh, T. Seki, K. Nishimura and F. Shimpo, *Applications of Non-resonant RF Forces to Improvement of Tokamak Reactor Performances Part I: Application of Ponderomotive Force* ; May 1993

NIFS-221 S.-I. Itoh, K. Itoh, and A. Fukuyama, *ELMy-H mode as Limit Cycle and Transient Responses of H-modes in Tokamaks* ; May 1993

NIFS-222 H. Hojo, M. Inutake, M. Ichimura, R. Katsumata and T. Watanabe, *Interchange Stability Criteria for Anisotropic Central-Cell Plasmas in the Tandem Mirror GAMMA 10 ;* May 1993

NIFS-223 K. Itoh, S.-I. Itoh, M. Yagi, A. Fukuyama and M. Azumi, *Theory of Pseudo-Classical Confinement and Transmutation to L-Mode;* May 1993

NIFS-224 M. Tanaka, *HIDENEK: An Implicit Particle Simulation of Kinetic-MHD Phenomena in Three-Dimensional Plasmas;* May 1993

NIFS-225 H. Hojo and T. Hatori, *Bounce Resonance Heating and Transport in a Magnetic Mirror;* May 1993

NIFS-226 S.-I. Iton, K. Itoh, A. Fukuyama, M. Yagi, *Theory of Anomalous Transport in H-Mode Plasmas;* May 1993

NIFS-227 T. Yamagishi, *Anomalous Cross Field Flux in CHS ;* May 1993

NIFS-228 Y. Ohkouchi, S. Sasaki, S. Takamura, T. Kato, *Effective Emission and Ionization Rate Coefficients of Atomic Carbons in Plasmas;* June 1993

NIFS-229 K. Itoh, M. Yagi, A. Fukuyama, S.-I. Itoh and M. Azumi, *Comment on 'A Mean Field Ohm's Law for Collisionless Plasmas;* June 1993

NIFS-230 H. Idei, K. Ida, H. Sanuki, H. Yamada, H. Iguchi, S. Kubo, R. Akiyama, H. Arimoto, M. Fujiwara, M. Hosokawa, K. Matsuoka, S. Morita, K. Nishimura, K. Ohkubo, S. Okamura, S. Sakakibara, C. Takahashi, Y. Takita, K. Tsumori and I. Yamada, *Transition of Radial Electric Field by Electron Cyclotron Heating in Stellarator Plasmas;* June 1993

NIFS-231 H.J. Gardner and K. Ichiguchi, *Free-Boundary Equilibrium Studies for the Large Helical Device,* June 1993

NIFS-232 K. Itoh, S.-I. Itoh, A. Fukuyama, H. Sanuki and M. Yagi, *Confinement Improvement in H-Mode-Like Plasmas in Helical Systems,* June 1993

NIFS-233 R. Horiuchi and T. Sato, *Collisionless Driven Magnetic Reconnection,* June 1993

NIFS-234 K. Itoh, S.-I. Itoh, A. Fukuyama, M. Yagi and M. *Azumi, Prandtl Number of Toroidal Plasmas;* June 1993

NIFS-235 S. Kawata, S. Kato and S. Kiyokawa , *Screening Constants for Plasma;* June 1993

NIFS-236 A. Fujisawa and Y. Hamada, *Theoretical Study of Cylindrical Energy Analyzers for MeV Range Heavy Ion Beam Probes;* July 1993

NIFS-237 N. Ohyabu, A. Sagara, T. Ono, T. Kawamura and O. Motojima, *Carbon Sheet Pumping;* July 1993

NIFS-238 K. Watanabe, T. Sato and Y. Nakayama, *Q-profile Flattening due to Nonlinear Development of Resistive Kink Mode and Ensuing Fast Crash in Sawtooth Oscillations;* July 1993

NIFS-239 N. Ohyabu, T. Watanabe, Hantao Ji, H. Akao, T. Ono, T. Kawamura, K. Yamazaki, K. Akaishi, N. Inoue, A. Komori, Y. Kubota, N. Noda, A. Sagara, H. Suzuki, O. Motojima, M. Fujiwara, A. Iiyoshi, *LHD Helical Divertor;* July 1993

NIFS-240 Y. Miura, F. Okano, N. Suzuki, M. Mori, K. Hoshino, H. Maeda, T. Takizuka, JFT-2M Group, K. Itoh and S.-I. Itoh, *Ion Heat Pulse after Sawtooth Crash in the JFT-2M Tokamak;* Aug. 1993

NIFS-241 K. Ida, Y.Miura, T. Matsuda, K. Itoh and JFT-2M Group, *Observation of non Diffusive Term of Toroidal Momentum Transport in the JFT-2M Tokamak;* Aug. 1993

NIFS-242 O.J.W.F. Kardaun, S.-I. Itoh, K. Itoh and J.W.P.F. Kardaun, *Discriminant Analysis to Predict the Occurrence of ELMS in H-Mode Discharges;* Aug. 1993

NIFS-243 K. Itoh, S.-I. Itoh, A. Fukuyama, *Modelling of Transport Phenomena;* Sep. 1993

NIFS-244 J. Todoroki, *Averaged Resistive MHD Equations;* Sep. 1993

NIFS-245 M. Tanaka, *The Origin of Collisionless Dissipation in Magnetic Reconnection;* Sep. 1993

NIFS-246 M. Yagi, K. Itoh, S.-I. Itoh, A. Fukuyama and M. Azumi, *Current Diffusive Ballooning Mode in Seecond Stability Region of Tokamaks;* Sep. 1993

NIFS-247 T. Yamagishi, *Trapped Electron Instabilities due to Electron Temperature Gradient and Anomalous Transport;* Oct. 1993

NIFS-248 Y. Kondoh, *Attractors of Dissipative Structure in Three Disspative Fluids;* Oct. 1993

NIFS-249 S. Murakami, M. Okamoto, N. Nakajima, M. Ohnishi, H. Okada, *Monte Carlo Simulation Study of the ICRF Minority Heating in the Large Helical Device;* Oct. 1993

NIFS-250 A. Iiyoshi, H. Momota, O. Motojima, M. Okamoto, S. Sudo, Y. Tomita, S. Yamaguchi, M. Ohnishi, M. Onozuka, C. Uenosono, *Innovative Energy Production in Fusion Reactors*; Oct. 1993

NIFS-251 H. Momota, O. Motojima, M. Okamoto, S. Sudo, Y. Tomita, S. Yamaguchi, A. Iiyoshi, M. Onozuka, M. Ohnishi, C. Uenosono,

Characteristics of D-^{3}He Fueled FRC Reactor: ARTEMIS-L,
Nov. 1993

NIFS-252 Y. Tomita, L.Y. Shu, H. Momota,
Direct Energy Conversion System for D-^{3}He Fusion, Nov. 1993

NIFS-253 S. Sudo, Y. Tomita, S. Yamaguchi, A. Iiyoshi, H. Momota, O. Motojima, M. Okamoto, M. Ohnishi, M. Onozuka, C. Uenosono,
Hydrogen Production in Fusion Reactors, Nov. 1993

NIFS-254 S. Yamaguchi, A. Iiyoshi, O. Motojima, M. Okamoto, S. Sudo, M. Ohnishi, M. Onozuka, C. Uenosono,
Direct Energy Conversion of Radiation Energy in Fusion Reactor,
Nov. 1993

NIFS-255 S. Sudo, M. Kanno, H. Kaneko, S. Saka, T. Shirai, T. Baba,
Proposed High Speed Pellet Injection System "HIPEL" for Large Helical Device
Nov. 1993

NIFS-256 S. Yamada, H. Chikaraishi, S. Tanahashi, T. Mito, K. Takahata, N. Yanagi, M. Sakamoto, A. Nishimura, O. Motojima, J. Yamamoto, Y. Yonenaga, R. Watanabe,
Improvement of a High Current DC Power Supply System for Testing the Large Scaled Superconducting Cables and Magnets; Nov. 1993

NIFS-257 S. Sasaki, Y. Uesugi, S. Takamura, H. Sanuki, K. Kadota,
Temporal Behavior of the Electron Density Profile During Limiter Biasing in the HYBTOK-II Tokamak; Nov. 1993

NIFS-258 K. Yamazaki, H. Kaneko, S. Yamaguchi, K.Y. Watanabe, Y.Taniguchi, O.Motojima, LHD Group,
Design of Central Control System for Large Helical Device (LHD);
Nov. 1993

NIFS-259 K. Yamazaki, H. Kaneko, S. Yamaguchi, K.Y. Watanabe, Y.Taniguchi, O.Motojima, LHD Group,
Design of Central Control System for Large Helical Device (LHD);
Nov. 1993

NIFS-260 B.V.Kuteev,
Pellet Ablation in Large Helical Device; Nov. 1993

NIFS-261 K. Yamazaki,
Proposal of "MODULAR HELIOTRON': Advanced Modular Helical System Compatible with Closed Helical Divertor; Nov. 1993