ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received - Feb. 15, 2000)

NIFS-633 Apr. 2000

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

Magnetic diagnostics: general principles and the problem of reconstruction of plasma current and pressure profiles in toroidal systems

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Abstract. The restrictions of the magnetic diagnostics are discussed. Being related to the integral nature of the measurable quantities, they follow from the fundamental laws of electromagnetism. A series of particular examples demonstrating the strength of these restrictions is given and analyzed. A general rule is emphasized that the information obtained from external magnetic measurements is obviously insufficient for the reliable evaluation of plasma current and pressure profiles in tokamaks or in stellarators. The underlying reason is that outside the plasma the own field of the equilibrium plasma currents is determined by the boundary conditions on the plasma surface only.

Keywords: Magnetic diagnostics, tokamaks, stellarators, plasma equilibrium, pressure profile, current distribution

1. Introduction

There is one problem in the theory of magnetic diagnostics with respect to which the completely opposite opinions are expressed. Its formulation is simple: whether it is possible to determine the plasma current distribution or/and plasma pressure profile from external magnetic measurements? The very statement of the question [1-5] shows the hope for the positive answer that determines till now the style of some publications [6-8], though "the conservative majority" has parted with this hope long time ago [9-12].

The confidence in impossibility to determine the profiles of the plasma current and pressure from external magnetic measurements alone, explicitly expressed in [1,2,9-12], certainly dominates in the tokamak community - the use of magnetic diagnostics has became long ago an obligatory element of the plasma position and shape control systems in tokamaks and remains a subject of serious discussion in ITER and other tokamak projects, but there are no discussions of more radical applications.

However, the unjustified optimism on the mentioned reconstruction of the profiles has not disappeared completely. Not being much excited by publications [3-5], from tokamaks it moved into the stellarator environment [13-15], where the attempts to gather arguments in favor of the positive answer still continue up to now [6-8]. Earlier such attempts have been made with a strong belief in the positive outcome, but recently - with reinsuring reserves (leaving, however, a freedom even for mutually exclusive conclusions), but always along the same scheme: prescribing some different profiles at first and demonstrating then that they correspond to different amplitudes of measurable magnetic quantities. The latter fact is proposed finally as the only proof of the alleged possibility of distinguishing different profiles. A simple idea that there is no and cannot be one-to-one correspondence is ignored by the "optimistic" authors. Sometimes the incorrectness of the problem is casually mentioned, but such true words are then lost without consequences behind the reiterated recurrences about the principal *possibility* of determining the plasma current and pressure profiles from the magnetic field measured outside the plasma.

In fact, this possibility has never been proved neither in [6-8] nor in the theory in general. But the style of the papers [6-8] is such as if their purpose is to inspire a reader the absolute confidence in the solvability of the problem. We mean not only the tone of the discussions - with a desire some statements from [6-8] might be attributed to free manipulations with a language. The very statement of the problem is tendentious, when "the magnetic probe system needed for the determination of both the plasma pressure profile and the current distribution" [8] is proclaimed a goal of the study and scrupulously analyzed in minor details.

The publication of several papers [6-8] on the same subject, the propaganda of their results at conferences [16] and in "Stellarator News" [17] is a more than sufficient invitation to their open discussion. But not only the originality of [6-8] induces us to this. First, the magnetic measurements were and remain one of the basic methods of diagnostics of the toroidal plasmas. Second, the formulations of the key questions of the theory of magnetic diagnostics are simple, concrete and clear to everybody (see, for example, the first paragraph of Introduction). Therefore, the interest to the problem is great. Some are attracted by the prospects of the desired practical applications, the others by the beauty and seeming simplicity of the statement of the related tasks. At the same time there is an obvious lack of definiteness in the evaluation of the upper limit of the useful information that, theoretically, could be extracted from external magnetic measurements alone.

The uncertainty and wide dispersion of opinions are engendered by the fact that the proofs offered to support the optimistic view are rather complicated, specific and related only to some particular cases. Such a situation is perceived as a natural because the magnetic diagnostics is traditionally considered as a subject of the plasma physics, where from the very beginning the equilibrium equation is put into the center of the problem. But the ultimate goal in the problem is, however, the calculation of the magnetic field *outside* the plasma. Therefore, in the problem of magnetic diagnostics it is necessary, first of all, to consider not the plasma, but the external domain.

With such an approach it becomes clear at once that in magnetic diagnostics those relations and restrictions are much more important which are dictated not by the equilibrium equation, but by the Maxwell's equations. Moreover, immediately those main universal regularities come to the light that convert the isolated facts into the elements of a general picture. We offer to make sure of this and to look at the problem from the viewpoint of the fundamental laws of electromagnetism.

2. Basic restrictions of the magnetic diagnostics

To obtain as much as possible, this is the target determining the trend and style of all theoretical works on magnetic diagnostics. Such an approach is reasonable until it leads us beyond the bounds of reality. Otherwise, the mere coincidence can be mistakenly interpreted as a positive result.

To avoid such a situation and not pursue the apparently unreal mirages, it is necessary to know the inherent restrictions of the magnetic diagnostics. They never were a subject of a special discussion, though they always revealed themselves in tokamak simulations, which was clearly and definitely stated in [9]. The restrictions were rather strong, but they displayed themselves implicitly: it turned out that the information about plasma could be extracted from external magnetic measurements only up to some limit.

In theoretical works, the reasons for that (which we are going to discuss below) were mentioned allusively or casually and incompletely, whereas the complex models, bulky calculations and abundance of accompanying details always served to displace the accents to other subjects. So that till now the particular consequences are still discussed [7,8,18,19] instead of indication of their reasons, and till now the belief is maintained that for stellarators the problem of current and pressure profile restoration from external magnetic measurements might be, nevertheless, resolved, if a simulation model and accuracy of the measurements would be improved or the number of magnetic probes would be increased and their arrangement would be optimized [6-8,13,15].

This belief is based on unconvincing results that, with a desire, may be interpreted in any way. But this circumstance and the warnings from the tokamak theory [9-12] have not been taken into consideration. The very terminology "determination of the plasma pressure profile and current distribution" [7,8,13,15] implicitly thrusts an idea that the problem, being difficult, is, nevertheless, solvable. Such orientation with unproved dubious assumptions makes the discussion on profiles [6- 8,13,15] tendentious and unbalanced.

However, everything is put in the place by a simple question: what exactly can be measured by the magnetic probes and loops placed outside the plasma? The question should be understood literally and we must answer it directly and with strict definitions.

The diamagnetic coil, Rogowski coil and the magnetic probes and loops located outside the plasma allow measuring the diamagnetic signal

$$\Delta\Phi = \int_{S_d} (\mathbf{B} - \mathbf{B}_v) \cdot \mathrm{d}\mathbf{S}_d, \tag{1}$$

net plasma current

$$J = \int_{S_\perp} \mathbf{j} \cdot \mathrm{d}\mathbf{S}_\perp, \tag{2}$$

and (in an ideal case) the own field of the plasma

$$\mathbf{B}_{pl}(\mathbf{r}) = \frac{1}{4\pi} \int_{V_p} \frac{\mathbf{j}(\mathbf{r}_p) \times (\mathbf{r} - \mathbf{r}_p)}{|\mathbf{r} - \mathbf{r}_p|^3} \, \mathrm{d}^3\mathbf{r}_p, \tag{3}$$

created by the currents flowing through the plasma column. Here

$$\mathbf{B} = \mathbf{B}_{pl} + \mathbf{B}_{ext} \tag{4}$$

is the total magnetic field at the moment of measurement, $\mathbf{B}_{ext}$ is the field of the currents in external conductors, $\mathbf{B}_v$ is the vacuum magnetic field at the moment of initiation of the discharge, $\mathbf{j}$ is the current density. The integration is carried over the whole area S_d of the diamagnetic loop in (1), over the cross section $S_\perp$ of the plasma column in (2), over the plasma volume V_p in (3). We are interested in the characteristics of a static equilibrium, therefore, we shall not discuss the fluctuations of the magnetic field measured by the Mirnov probes.

The discussions about the possibility of reconstruction of the plasma current and pressure profiles from external magnetic measurements are always carried out far away from definitions (1) - (3). And the reason is not that (1) - (3) are trivial or known to everybody. The reason is much more serious - these relationships are extremely "inconvenient" because any optimistic conclusion is merely incompatible with them.

It is sufficient to write out (1) - (3) and to say directly that these quantities *only* can be found as a result of external magnetic measurements, and at once a specifics of the problem becomes visible: the measurements can give us the integral quantities, but the considered problem requires to find then the integrated functions.

The knowledge of $\Delta\Phi$ and current J is obviously insufficient for talking about the profiles, so all hopes should be related exclusively to the integral (3). Besides, there is the equation of equilibrium at our disposal,

$$\nabla p = \mathbf{j} \times \mathbf{B}, \tag{5}$$

where p is the plasma pressure, and two Maxwell's equations

$$\nabla \cdot \mathbf{B} = 0, \qquad \nabla \times \mathbf{B} = \mathbf{j}. \tag{6}$$

Without equation (5) we would have a purely magnetostatic task and no hope for determining the unknown distribution $\mathbf{j}(\mathbf{r})$ from the measured magnetic field $\mathbf{B}_{pl}$. Therefore, the sole "rescue" for the supporters of the optimistic answer could be equation (5) only or its consequences. It is not surprising that the analysis of the problem is always carried out on the basis of the solution of the equilibrium equation, with special emphasis of its importance, usefulness and necessity [1-9,13,15,19].

However, another is inexplicable: for some reason remains unnoticed or undervalued the almost obvious fact that, actually, the addition of the equation (5) to (3) does not give a desired radical narrowing of the class of the solutions to the integral equation (3) for unknown $\mathbf{j}(\mathbf{r}_p)$. This should be said with a complete certainty because this is a fact of a basic importance for evaluating possible applications of the magnetic diagnostics. In the next section we present a series of demonstrative concrete examples explaining the real meaning of our statements. Before proceeding to them let us directly specify the reason why the dependence of $\mathbf{B}_{pl}$ on the distributions $p(\mathbf{r})$ and $\mathbf{j}(\mathbf{r})$ appears to be rather weak.

The plasma-induced magnetic field outside the plasma column is a *vacuum* field, $\mathbf{B}_{pl} = \nabla\varphi_{pl}$, so that

$$\nabla^2\varphi_{pl} = 0. \tag{7}$$

Naturally, in a toroidal system the field $\mathbf{B}_{pl}$ must decrease at large distances as a dipole field or even faster and vanish at infinity, and on the plasma boundary S_p, as follows from (5), it should satisfy the condition

$$(\mathbf{B}_{pl} + \mathbf{B}_{ext}) \cdot \mathbf{n} = 0, \tag{8}$$

where $\mathbf{n}$ is the external normal to S_p. Therefore, the problem of finding $\mathbf{B}_{pl}$ in a vacuum can be formulated as a classical external Neumann problem.

This tells all for a specialist. In any good textbook on mathematical physics (see, for example, [20]) it is explained that the shape of the boundary S_p and the normal derivative of φ_{pl} on S_p uniquely determine the required regular solution φ_{pl} in the external domain.

Such a statement of the problem in the language of strict mathematics completely clarifies the situation releasing it from all extraneous. Only plasma boundary S_p remains in the problem, but it absolutely does not matter how the interior of plasma is arranged. What then a role of the equilibrium equation (5)? As we see, not at all dominating, contrary to the optimistic belief. The equation can manifest itself only in that measure in which it determines the plasma boundary and the magnetic field on this boundary.

This fact makes it clear that a strict approach must inevitably lead us to the question: whether it is possible, at least in some cases, to establish one-to-one correspondence between the plasma current distribution or pressure profile and the boundary of the plasma column? More than that, we must say that evasion of the discussion of this question makes senseless any speculations on definition of $\mathbf{j}(\mathbf{r})$ and $p(\mathbf{r})$ profiles from magnetic measurements.

We would like to describe the problem as clear as possible, therefore we must honestly confess here that theory does not give yet a precise and complete answer to this question. The absence of the firm "No" cannot be, certainly, a basis for an unlimited belief into the positive answer. But the reasoning about the possibility of determining the current and pressure profiles from magnetic measurements implicitly implicates "Yes". Implicitly because the key role of the boundary is ignored in such reasoning, but the emphasis is put on the direct solution of the equilibrium problem.

Actually, there is no any ground for the positive answer. To confirm this viewpoint, let us list a series of well established facts. They are simple and convincing and cover a wide area. Another advantage is that besides just "No" they show as far strong is this prohibition. Let us emphasize that in all examples given below the equilibrium equation (5) is 100% used, but it does not help to improve the situation.

3. Examples of integrally indiscernible configurations

There are not so much strict theorems in the theory of plasma equilibrium, as we would desire. Therefore, some regularities should be guessed by their separate manifestations. In this particular case we are going to discuss the statement that given plasma boundary and magnetic field on this boundary can be attributed to equilibria with different $p(\mathbf{r})$ and $\mathbf{j}(\mathbf{r})$. Keeping in mind the principle "$\mathbf{B}_{pl}$ is determined by the boundary", we can call such configurations "integrally indiscernible" or "integrally equivalent": being different inside, they seem completely identical from outside. In other words, they cannot be distinguished by measurements of $\mathbf{B}_{pl}$, if pairs of $\Delta\Phi$ and J are also identical.

3.1. Circular plasma cylinder

In this case any profile of the longitudinal current and plasma pressure is possible, provided that cylindrical symmetry is not broken. The plasma-induced magnetic field on the plasma boundary is determined by one quantity only, the net longitudinal current J in the plasma:

$$\mathbf{B}_{pl} = \frac{J}{2\pi b}\mathbf{e}_\zeta. \tag{9}$$

Here b is the radius of the plasma column, $\mathbf{e}_\zeta$ is the unit vector along the gradient of the athimuthal angle ζ. This equality does not give any information on the plasma profiles. The equilibrium equation does not influence the result. It is possible to find only two numbers from external magnetic measurements: J and diamagnetic signal $\Delta\Phi$.

This is a case of the complete degeneracy (in the sense of the relation "profile - the measured field"). Of course, this case is trivial, but we must mention it for the reason that the reduction of the degeneracy, when we pass from the cylinder to real systems, turns out to be very weak. So weak that their comparison with a cylindrical plasma appears to be not only reasonable and useful, but necessary as well. Every time when the problem of determining the internal parameters of the plasma from magnetic measurements is touched, it is necessary to ask a question: what other physical quantities can be measured besides J and $\Delta\Phi$? Trying to answer directly and honestly we ascertain that actually there may be just several, say two or three such quantities. In the next example - only one.

3.2. "Circular" tokamak

In tokamaks, which are the toroidal systems with axial symmetry,

$$\mathbf{B} = \frac{1}{2\pi}\nabla\psi \times \nabla\zeta + \frac{F}{2\pi}\nabla\zeta, \tag{10}$$

where ψ and F are the external poloidal flux and current, respectively, ζ is the toroidal angle. If the magnetic surfaces near the plasma boundary are shifted toroids of circular cross section,

$$(r - R - \Delta)^2 + z^2 = a^2, \tag{11}$$

than on the plasma boundary

$$\mathbf{B} = \frac{\psi'}{2\pi r}\frac{\mathbf{n}\times\mathbf{e}_\zeta}{1-\Delta'\cos\theta} + \frac{F_b}{2\pi}\nabla\zeta. \qquad (12)$$

Here $\mathbf{n}$ is the unit external normal to the plasma boundary, F_b is the constant describing the vacuum toroidal field, θ is the poloidal angle, the prime means the derivative with respect to a.

In this case the solution to the equation (7) with boundary condition (8) will depend on two constants only, ψ' and Δ'. But given ψ' and Δ' represent a large family of equilibrium configurations with different profiles $\mathbf{j}(\mathbf{r})$ and $p(\mathbf{r})$.

The existence of such configurations in "circular" tokamaks is a well-known fact. It is enough to recall the classical result of the direct solution of the equilibrium problem [21]

$$\Delta'(b) = -\frac{b}{R}\left(\beta_J + \frac{l_i}{2}\right), \qquad (13)$$

which gives an explicit relation of Δ' with physical parameters (the notation is standard [1,2,9,18,21])

$$\beta_J = \frac{2\bar{p}}{B_J^2}, \qquad l_i = 2\int_0^b \frac{B_J^2(a)}{B_J^2}\frac{a}{b^2}\,\mathrm{d}a, \qquad (14)$$

the bar means the averaging over plasma cross section, $B_J \equiv B_J(b)$ is the field on the plasma boundary.

Configurations with identical values of $\beta_J + l_i/2$ are only a part of the class of equivalence with given $\Delta'(b)$ (in a general case the condition $b/R \ll 1$ and the fulfillment of (11) everywhere in the plasma are not needed). But even within this part the fixed set of three measured quantities J, $\Delta\Phi$ and $\beta_J + l_i/2$ can correspond to very different equilibria.

Using this example, let us also explain why simple logic "more probes - more information" is not absolutely correct. Certainly, with larger number of probes it would be possible to better measure the field distribution outside the plasma and to find more harmonics of $\mathbf{B}_{pl}$. But there are only two free parameters in (12), ψ' and Δ', therefore, all higher harmonics of the field (12), starting from the second one, are expressed through zero and first harmonics. In other words, in the infinite set of harmonics only two are independent, and the measurement of the others cannot give any additional information.

3.3. "Noncircular" tokamak

It is well known that in the case of noncircular boundary of the plasma column the magnetic measurements should give more information about the plasma [1,9-12,21-24]. But here we would like to specially emphasize another side of the problem: when we turn from the cylinder to the circular and then to the noncircular tokamak, the amount of useful information increases very weakly. Among ample evidences, one of the best for our purpose, exactly hitting the mark, is an example from [24]. In this paper the authors gave the results of calculations of four equilibrium configurations with almost identical D-shape plasma boundary and with identical poloidal magnetic field on this boundary, but with strongly different current profiles. The rule "$\mathbf{B}_{pl}$ is determined by the boundary" allows to consider these results [24] as the direct proof of the existence of integrally indiscernible configurations in "noncircular" tokamaks.

It is important to note that the difference of the current profiles in these four configurations is rather strong [24]. It shows that the plasma boundary and, accordingly, the own external field $\mathbf{B}_{pl}$ weakly react to variations of the current and pressure profiles. It is possible even to say - very weakly, recalling that the external fields $\mathbf{B}_{pl}$ of the precisely calculated equilibrium configurations may be modeled with the help of several current rings [9,23-26]. In [26], for example, it was asserted that "the approximation of two equivalent currents yields the external magnetic field within an error of 1 % all the way out to the plasma boundary".

The impossibility to distinguish different current profiles even in noncircular tokamaks was clearly realized at the first serious attempts of the practical solution of the problem by methods of the magnetic diagnostics [1,23]. This was even shown by one example in [1]: three different distributions of a current giving an identical result.

3.4. Conventional stellarators, standard configurations

There are more similarity than distinctions between tokamaks and stellarators in the theory of plasma equilibrium [27]. It can be said with assurance that all said above about tokamaks is essentially true for conventional stellarators as well. For example, in many cases the plasma in stellarators can be considered as "circular in average". Then using the same methods [21] that lead to (13) we can obtain for the own poloidal field on the plasma boundary [13,14,27-29]

$$B_\beta \approx \int_0^b \frac{p'(a)}{\mu(a)B_0}\frac{a^2}{b^2}\,\mathrm{d}a, \qquad (15)$$

where μ is the rotational transform, B_0 is the toroidal magnetic field at the axis of the system. If there are no longitudinal current, $J = 0$, then

$$\frac{\Delta\Phi}{\Phi_0} = -\frac{\beta}{2} \equiv -\frac{\bar{p}}{B_0^2} = -\int_0^b \frac{2p}{B_0^2}\frac{a}{b^2}\,da. \qquad (16)$$

It is clear that two values B_β and $\Delta\Phi$, which can be measured, are not sufficient for determining the profile $p(\mathbf{r})$. For example, Fig. 1 shows two profiles $p(\mathbf{r})$ giving the identical pair $(\Delta\Phi, B_\beta)$ in a stellarator with parameters of CHS. The general algorithm for constructing such profiles is described in [30].

In addition to this it is possible to find other interesting facts in the family of stellarator devices.

3.5. Conventional stellarators, configurations independent from the pressure

In 1961 Greene J.M. and Johnson J.L. have demonstrated on a particular example [31] that in an $\ell = 3$ stellarator it would be possible to obtain an equilibrium configuration independent of the pressure. Later [32] a similar equilibrium was found in calculations for a stellarator with $\ell = 2$, and recently it was studied analytically [33,34] and was observed in experiments in Heliotron E [35,36].

In configurations locally or integrally independent from the pressure, the plasma boundary does not react to variations of internal parameters [31-36]. This is sufficient for speaking about their integral indiscernibility at different $p(\mathbf{r})$. The result is explained by the fact that the Pfirsch- Schlüter current (the dipole equilibrium current along the torus) in such configurations is small or even absent. No current means no plasma-induced magnetic field. The degeneracy can well be compared with a cylindrical one.

For conventional stellarators the configurations with a strongly reduced Pfirsch-Schlüter current are not typical. But the knowledge about them is useful, at least, because they can serve as a geometrically much more similar standard for comparison than a cylinder. From the viewpoint of magnetic diagnostics the typical or standard configurations in conventional stellarators are not so far from those ideal integrally independent from the pressure. It is proved out, in particular, by the direct calculations for real systems showing that the plasma shape and the measured magnetic signals weakly respond to variations of the pressure profile [37-39]. The same, in fact, can be seen in [6-8]: dependence of the calculated magnetic quantities on the profiles of the plasma pressure is very weak. However, in spite of this the results were interpreted there as a proof of possibility to identify the profiles.

3.6. Quasi-symmetrical stellarators

They are three-dimensional systems with a hidden symmetry [40-45]. These systems are attractive in many respects, but here we would like to mention one their property only: in such systems the Pfirsch-Schlüter current is much smaller than in similar conventional stellarators. In other words, the sensitivity of quasi-symmetrical configurations to plasma pressure is weak. In [42], for example, the numerical results were presented for a configuration that practically did not vary with plasma pressure increasing up to $\beta = 50\%$, the value that by far surpasses the level of present-day aspirations. The insensitivity to the pressure in general means as well the insensitivity to its profile in particular.

We should also note that in quasi-symmetrical systems, irrespective of the way of their particular realization, the spectrum of the magnetic field contains only several harmonics [46-54], and amplitudes of only two or three of them are changed appreciably with growing β. Hence, in this case too the information that could be potentially extracted from the magnetic measurements would be rather scarce.

All the examples listed above show that in many cases the statement about the fundamental *impossibility* of determining the profiles $\mathbf{j}(\mathbf{r})$ and $p(\mathbf{r})$ from magnetic measurements can be supported by convincing proofs, including those based on the solution of the equilibrium problem. The complex geometry and account of the equation (5) do not remove the strong degeneracy related to the integral character of the magnetic measurements.

It is true that the evidential force of separate facts is limited. But we cannot disregard them. Assembled together they turn into the strong arguments against the positive answer.

4. What gives a hope for excessive expectations?

It is useful to understand why appeared and was maintained the illusion that positive answer was possible. The basic reason is, of course, an obvious neglect of the fundamental principles of the theory of electromagnetism and of the warning results of the tokamak theory [9,21]. Then, the shift of the discussion into minor details, fixing and masking the breaking with the first principles. Finally, it is necessary to say about the substitution of notions, without which the discussion would have died away long ago.

How it happens? It is stated that some components (harmonics) of $\mathbf{B}_{pl}$ strongly depend on the distribution of $\mathbf{j}$ and/or plasma pressure [6-8,15]. This sounds plausible, besides it is always possible to pick up results of some calculations confirming the statement, therefore, it is impossible to classify the statement as erroneous. But just here the first basic substitution is done. Actually, it is possible to assert only that the components of $\mathbf{B}_{pl}$ are uniquely determined by the geometry of the boundary surface and by the distribution of the magnetic field on this surface. The difference between these two statements is that the latter is always correct, being mathematically faultless. But the validity of the former statement is limited. Strictly speaking, it should be classified as the uncertain statement: it can be true for some profiles, but can be false for others.

In [6-8,15] to prove the validity of this uncertain statement the Bio-Savart law (3) was actually used. Indeed, with a glance at (3) the dependence of $\mathbf{B}_{pl}$ on the distribution of $\mathbf{j}$ seems to be beyond doubts. But whether the different profiles $\mathbf{j}(\mathbf{r})$ will always give different $\mathbf{B}_{pl}$? The incompleteness of the discussions [6-8,15] was, at least, that this question was not even mentioned.

This can be easily understood. First, the question is "unpleasant" because it shifts immediately the evaluation criteria for the presented results and completely changes the character of the problem. Second, even without this question the analysis by the scheme proposed in [6-8,15] is related to complicated and bulky calculations: it is necessary to solve the equilibrium problem for each profile $p(\mathbf{r})$, then to calculate integral (3), and finally to compare small values for their even smaller differences.

With such an immersion into details it is not easy to see general regularities. At once they are not seen in (3) as well. But the arguments about $\mathbf{B}_{pl}$ as a vacuum field, leading to (7), prompt that for clear statement of the problem one should reduce (3) to a surface integral. This can be easily done. Let us multiply the Maxwell's equation $\mathbf{j} = \nabla \times \mathbf{B}$ by

$$\mathbf{q} \equiv \nabla f \times \mathbf{a}, \tag{17}$$

where $\mathbf{a}$ is some constant vector, and f is the harmonic function ($\nabla^2 f = 0$). Under these conditions $\nabla \times \mathbf{q} = \nabla(\mathbf{a} \cdot \nabla f)$ and

$$\int_V (\mathbf{q} \cdot \mathbf{j})\, \mathrm{d}^3\mathbf{r} = \int_S \{\mathbf{B} \times \mathbf{q} + (\mathbf{a} \cdot \nabla f)\mathbf{B}\} \cdot \mathrm{d}\mathbf{S}, \tag{18}$$

where S is the boundary of the volume V. If the surface of the plasma column S_p is taken for S, the last term on the right side of (18) disappears (on the plasma boundary $\mathbf{B} \cdot \mathrm{d}\mathbf{S} = 0$), and (18) reduces to

$$\int_{V_p} (\mathbf{j} \times \nabla f)\, \mathrm{d}^3\mathbf{r} = \int_{S_p} (\mathbf{n} \times \mathbf{B} \times \nabla f)\, \mathrm{d}S_p \tag{19}$$

For our purposes an appropriate harmonic function is $f = |\mathbf{r} - \mathbf{r}_p|^{-1}$. Its substitution into (19) with account of the definition (3) gives us

$$4\pi\mathbf{B}_{pl}(\mathbf{r}) = \int_{V_p} \mathbf{j}(\mathbf{r}_p) \times \frac{\mathbf{r} - \mathbf{r}_p}{|\mathbf{r} - \mathbf{r}_p|^3}\, \mathrm{d}^3\mathbf{r}_p = \int_{S_p} \mathbf{n} \times \mathbf{B} \times \frac{\mathbf{r} - \mathbf{r}_p}{|\mathbf{r} - \mathbf{r}_p|^3}\, \mathrm{d}S_p. \tag{20}$$

A similar method of the reduction of volume integrals to surface integrals was proposed for a general case in [55], and for tokamaks (axial symmetry and other functions f) was used in [21]. The equality (20) shows that the own field of plasma currents coincides with the field of the surface current

$$\mathbf{i} = \mathbf{n} \times \mathbf{B} \tag{21}$$

"flowing" on the surface S_p separating the plasma and vacuum regions. The result (20) is valid for *any* current profiles (not even necessarily satisfying equation (5)), if $\mathbf{B} \cdot \mathbf{n} = 0$ on S_p.

Two expressions (20) for $\mathbf{B}_{pl}$ represent and relate two possible views on $\mathbf{B}_{pl}$ outside the plasma column. When we look "from inside", $\mathbf{B}_{pl}$ is a field produced by the current $\mathbf{j}$ flowing inside S_p. Looking "from outside", it is a vacuum field disappearing at infinity and determined by the boundary conditions on the plasma surface S_p only. As shown by (20), these two interpretations are completely equivalent.

The equality (20) closes a chain of all discussions around $\mathbf{B}_{pl}$. It is a *direct* proof of the fact that for any way of calculating $\mathbf{B}_{pl}$ the result will be determined by the plasma boundary *only* (geometry + magnetic field). As we have seen, the comprehension of a simple idea "$\mathbf{B}_{pl}$ is determined by the boundary" allows to relate the problem to those facts that have not seemed to be related to magnetic diagnostics, but unexpectedly appeared to be extremely useful in application just to this area. The essential extension of the "database" allows applications of stricter criteria for evaluation of any particular result or proposal in magnetic diagnostics. The amount of these data is sufficient, for example, to evaluate the resolution (if any) of the proposed methods [6-8,15] of identification of the profiles $p(\mathbf{r})$ and/or $\mathbf{j}(\mathbf{r})$ as rather poor.

It may seem strange, but one can find the confirmations to this even in the results of [6-8]. The opposite statements in [6-8] are based on the proposal to make a choice of the profiles from a rather narrow family. Why? There are no explanations in [6-8], therefore we should fill this vacuum: the reason is that external magnetic measurements can give only several independent quantities, see Section 3. It is impossible to propose an algorithm "several quantities $\longrightarrow$ a profile". Really in this case one have to draw a curve through two-three points, and this is only possible with a simple initial parameterization of $p(\mathbf{r})$. In [7,8] ($x = a/b$ is the dimensionless radius)

$$p = p_0 \left(1 - x^2\right)^n , \qquad (22)$$

which "allows" to relate a certain profile to two measurable quantities. But it is sufficient to take function $p(\mathbf{r})$ from another family, and all this logic immediately fails, see Fig. 1. Perhaps, for the first time this has been noticed by Luxon and Brown [1]. They have shown numerically for tokamaks that adding an extra free parameter in a similar situation gives at once the whole family of configurations which are integrally indiscernible.

5. Conclusion

A key to understanding of the possibilities and restrictions of the magnetic diagnostics is the statement that the own field of the plasma $\mathbf{B}_{pl}$ outside the column is completely determined by the surface "plasma - vacuum" S_p and by the magnetic field on this surface. This is a well-known fact which, for example, was formulated in [55] on page 257 as a brief theorem for a vacuum magnetic field: "The vector $\mathbf{B}$ is uniquely determined within any domain by the values of its tangential component $\mathbf{n}\times\mathbf{B}$ over the boundary". How to find S_p and $\mathbf{B}$ on the boundary - this is a separate question. For our discussion the fact is important that the field $\mathbf{B}_{pl}$ measured outside the plasma carries the information about its boundary and nothing more.

Just due to this fact the problems of determining the position and shape of the plasma from externally measured magnetic signals are successfully solved either for tokamaks [56-60] or for stellarators [35,36,61]. Very good accuracy is achieved in a practice, and the knowledge of $p(\mathbf{r})$ and $\mathbf{j}(\mathbf{r})$ is not required for that.

At the same time it is necessary to admit that the plasma pressure profile and/or current distribution cannot be determined from external magnetic measurements. This is impossible because the finding of $\mathbf{j} = \mathbf{\nabla} \times \mathbf{B}_{pl}$ requires the knowledge of $\mathbf{B}_{pl}$ in all internal domain, but the measurements can serve to find $\mathbf{B}_{pl}$ on its boundary only. In order to continue $\mathbf{B}_{pl}$ inside, one has to solve the equilibrium equation. But the prescription of only S_p and magnetic field on S_p is, apparently, insufficient for this purpose because inside S_p the problem is not already vacuum one.

Actually, we repeat the copybook maxims. But they have not been mentioned neither in the beginning nor during the debates [6-8,13,15] on magnetic diagnostics that came already up to serious discussions of "a more suitable method of determining the current distribution" [6], "mathematical basis for plasma profile identification" [7], and already mentioned "the magnetic probe system needed for the determination of both the plasma pressure profile and the current distribution" [8]. The very statement of this problem is a challenge. The binding of the discussion to the real installation LHD makes the work [8] even more offensive and leads a tampering with notions, promising a large result for a small price, to a limit where the response is plainly required and does not need any additional motivation.

But this is more an excuse than the reason for writing the present paper. The main reason is that with growing interest to magnetic diagnostics in stellarators [35-39,61-65] and with excessive orientation of the modern theory to numerical simulation there arises a natural necessity for a general evaluation of the problem and for stating the physically clear general criteria of estimation of any particular result. We would like to emphasize a simple idea that the measured magnetic signals are integral by their nature, and interpreting the experimental results we by no means must reckon with this. Besides, actually one can speak about only several independent scalar quantities that can be extracted from external magnetic measurements.

It is necessary to add that the measured magnetic quantities, as a rule, weakly depend on the plasma current distribution and pressure profile. But this is an advantage, not a shortcoming: due to this the monitoring and control of integral equilibrium characteristics of the plasma column and, first of all, its geometry becomes feasible.

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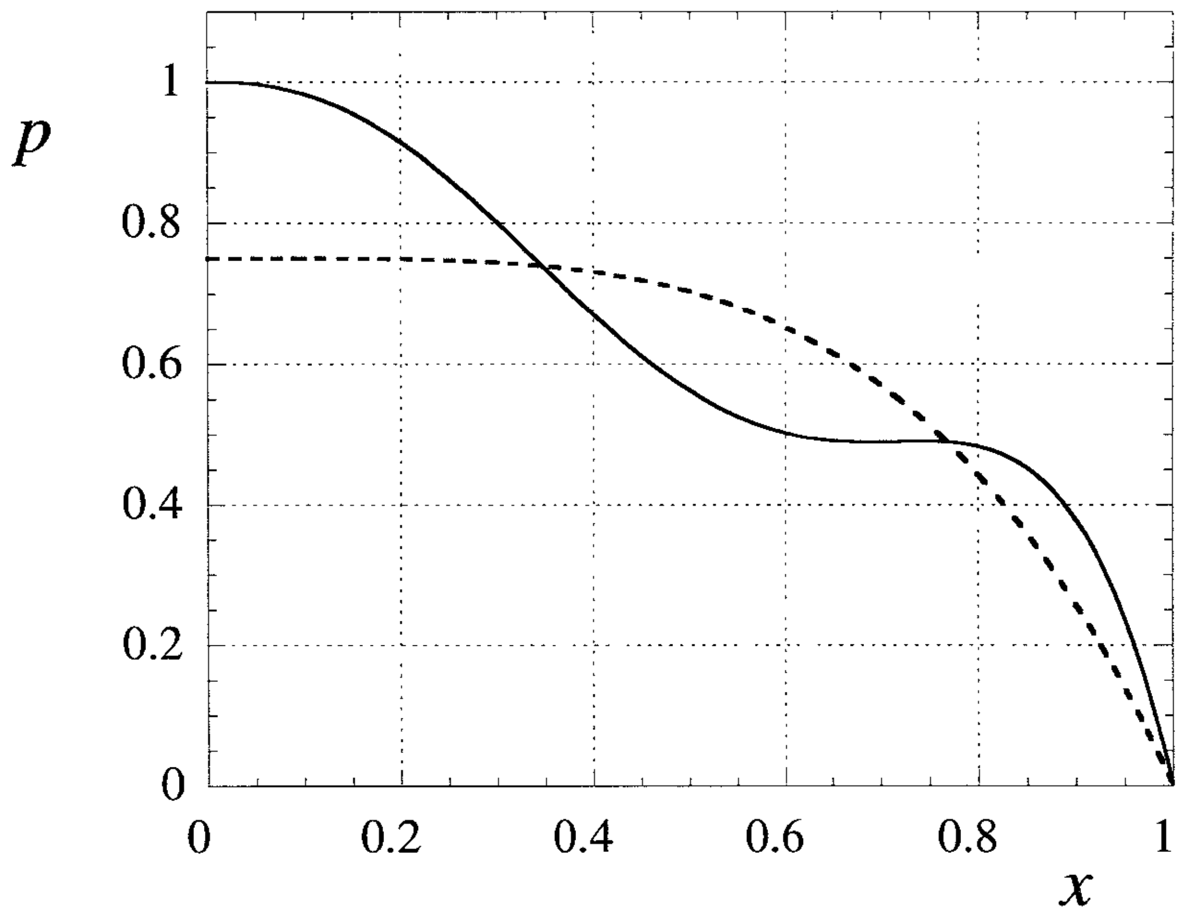
Figure Caption

Fig. 1. Two pressure profiles giving an identical pair of measurable values $(\Delta\Phi, B_\beta)$ in a stellarator with $\mu(0)/\mu(b) = 1/3$ (CHS or LHD type).
Dashed line: $p = 0.75\,(1 - x^4)$;
solid line: $p = 1 - x^2 - 2x^3(1 - x)(5 - 7x)$.

Figure 1



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