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ABSTRACT

Flux conservation in Scyllac-type experiments shows up in two ways. First of all the poloidal flux between the outside edge of the plasma and the inside of the coil is conserved. This requires a net longitudinal current in the plasma, to cancel the poloidal flux caused by the helical stellarator fields. An expression for this net current is derived, and effects that could occur in sector experiments are discussed.

The flux conservation inside the conducting plasma leads to a conservation of the local rotational transform. Since the pinch itself is surrounded by a well-conducting low-density plasma, the rotational transform is conserved in a wide region. Depending on the time history of the applied fields, volume currents are induced in this region, as is shown for two examples. Although an additional capacitor bank can be used to cancel the net current, a cancellation of all the volume currents is extremely difficult.

The resulting equilibrium configurations differ considerably from the Scyllac equilibria without volume currents, which are used in stability calculations.

I. INTRODUCTION

In calculations on Scyllac, various assumptions are made to arrive at a model for the equilibrium configuration. One of these assumptions is about the pressure profile; sharp skin or diffuse models have been used. Other assumptions have to be made about the magnetic field configuration in and near the plasma, before the field profiles can be matched to their boundary values.

In an often used expansion, the zeroth order is a theta pinch and all first-order quantities are written as a product $f(r) \cos(\theta + hz)$ where h is equal to 2π divided by the length of one helical period. The integral $\oint B_\theta dl$ on any cylinder $r = \text{constant}$ is therefore zero, since both the zero order theta pinch and

the first order B_0 field do not contribute to the integral. This means that the total z current on any cylinder is zero. This represents a specific choice for a class of equilibria. Other choices are possible such as the one made by Weitzner,¹ who describes a calculation where a net z current flows on one surface, namely, the surface of the sharp skin plasma.

In the real experiment, processes during the formation phase determine what type of equilibrium the plasma will approach. This is obvious for the pressure profile, which is completely determined by the implosion process. The field profiles will likewise be determined by the plasma motion and the field diffusion which take place during the formation phase. Predictions about the resulting field profiles are difficult to make when the formation process is slow and when much turbulence is being excited as in Tokamaks and in turbulent heating experiments. When powerful implosion heating is being used, not much interdiffusion of field and plasma can occur. Plasma and field are then frozen together, which means that fluxes are conserved. If fluxes are conserved in a detailed sense, in other words, between adjacent magnetic surfaces, the rotational transform (or the q value) on any magnetic surface stays constant. This behavior has been observed in screw pinches for many years^{2,3} and is expected to become important in Tokamaks with powerful auxiliary heating (flux-conserving Tokamaks).⁴ In Scyllac, as in all powerful theta pinches, the implosion heating is certainly strong and fast enough to ensure the validity of this conservation model.

In this report we study the question whether the equilibria chosen in the theoretical papers are compatible with the model in which fluxes and rotational transforms are being conserved. This is an especially important question if the presence of a low-density plasma outside the central column is taken into account. This outside plasma has a low pressure and does not carry appreciable perpendicular currents, but it can carry large force-free currents. When the outside plasma is included the region in which flux conservation takes place is considerably widened.

Flux conservation should first of all be considered in a global sense, for the nonconducting region between the outer edge of the plasma and the external circuit, which can be the inside of the coils. Since the total flux enclosed should stay constant, the plasma carries a net current which cancels any changes in the enclosed flux (Sec. III). The difference with earlier studies by Sugisaki,⁵ Miller,⁶ and in Garcking⁷ is that the outer edge of the conducting

medium is now assumed to coincide with the quartz wall. This simplifies the calculation of the net current but does not answer the question where this current is flowing.

To find the current distribution, one should consider detailed flux conservation, or rather the conservation of rotational transform on each magnetic surface. A general description along those lines is difficult and we give therefore two simplified examples in Sec. IV. The first one describes what internal z currents one can expect when an $\ell = 1$ field is applied with the same time history as the main B_z field. The second example describes the internal current distribution which results when an $\ell = 2$ field is applied to an already formed theta pinch.

II. ROTATIONAL TRANSFORM AND POLOIDAL FLUXES

The rotational transform generated inside a Scyllac coil results from the $\ell = 1$ and $\ell = 2$ fields. The combination of a helical field and the main B_z field distorts the field lines into spirals with one gyration per period of the coil and a much slower rotation around the axis of the coil. This slow rotation can be expressed in terms of a rotational transform which, for the full torus and for a vacuum field is given by⁸

$$\text{for } \ell = 1 \quad i = \frac{\pi h R A_1^2}{B_z^2} \left\{ 1 + O(h^2 r^2) \right\} \quad (1)$$

and

$$\text{for } \ell = 2 \quad i = \frac{2\pi R A_2^2}{4B_z^2} \left\{ 1 + O(h^2 r^2) \right\} \quad (2)$$

where h equals 2π divided by the length of one helical period, R is the major radius of the torus, and A_1 and A_2 are coefficients characterizing the amplitudes of the helical field. In the limit of small hr , A_1 equals the absolute value of the $\ell = 1$ field whereas A_2 equals the absolute value of the $\ell = 2$ field at a given radius, divided by that radius. The number of helical periods on the circumference of the torus is hR .

The presence of the rotational transform implies that a poloidal flux ϕ_ℓ is generated. The equation relating the toroidal flux and the poloidal flux is⁹

$$i = 2\pi d\phi_{\ell} / d\phi_{\text{tor}} . \quad (3)$$

Outside the dense central plasma $d\phi_{\text{tor}}$ can be written as $2\pi r B_z dr$, so that the poloidal flux follows from

$$\phi_{\ell} = \int i_{\ell} B_z r dr , \quad (4)$$

where the flux is that between the two radii used as the limits for the integration at the right hand side.

III. NET TOROIDAL CURRENT

A. Simple Case

The flux between the inside radius b_c of the coil and the outer edge of the conducting plasma at $r = b_p$ can be calculated from Eq. (4).

$$\phi_{\ell} = 1/2 B_z (b_c^2 - b_p^2) i_{\ell} , \quad (5)$$

where the terms of order $h^2 r^2$ in Eqs. (1) and (2) have been neglected. Also neglected is the influence of the shape of the plasma surface on the fields. This is reasonable when the radius of the dense plasma a is much less than the outer radius of the low-density plasma b_p [compare Eq. (12)].

The toroidal plasma encloses the flux ϕ_{ℓ} which rises with B_z . This induces a toroidal plasma current I_z , whose flux ϕ_c should be equal and opposite to ϕ_{ℓ} . In case the coil is continuous along the torus the ratio of ϕ_c to I_z is given by the inductance for a coaxial cylinder of length $2\pi R$, $\mu_0 R \ln b_c/b_p$. The current I_z is then

$$I_z = \frac{B_z (b_c^2 - b_p^2)}{2\mu_0 R \ln(b_c/b_p)} i_{\ell} . \quad (6)$$

The flux ϕ_c depends on the net current within the radius b_p . Equation (6) therefore gives this net current, but no information at all on how this current is distributed within the plasma.

B. Numerical Examples

In the Scyllac full torus experiments of summer 1974¹⁰ with $\ell = 1$ coils, the toroidal current calculated from the Eqs. (1) and (6) for the parameters $R = 4$ m, $b_c = 7.1$ cm, $b_p = 4.4$ cm, $B_z = 4$ T, $h = 15$ m⁻¹, and $B_{\ell=1}/B_z = 0.064$ turns out to be 1.99 kA, which is of the same order as the currents that were actually measured.

The $\ell = 2$ field of the coils that were used in 1977 would induce a current, in a full torus, which calculated from Eqs. (2) and (6) turns out to be 15.4 kA, for the parameters $R = 4$ m, $b_c = 10.6$ cm, $b_p = 4.4$ cm, $B_z = 2$ T, $h = 6$ m⁻¹, and $A_2 = 2.64$ T/m. The rotational transform caused by the $\ell = 1$ field, which in this case equals 0.265 T, is smaller than that caused by the weaker $\ell = 2$ field and consequently the current, which the $\ell = 1$ field would induce in the torus, is only 2.8 kA.

C. Special Cases, End Effects

For the calculation of the net plasma current in Sec. II.A the theta-pinch coils were assumed to be continuous in the toroidal direction. When the various sections are connected with some additional inductance between the sections, the flux ϕ_c which has to cancel ϕ_ℓ will be

$$\phi_c = I_z \left\{ \mu_0 R \ln(b_c/b_p) + L_e \right\}, \quad (7)$$

where the total additional inductance is given by L_e . The Eqs. (5) and (7) will give an I_z current smaller than that given by Eq. (6).

In the case of a complete break in the coil the inductance L_e increases to the z inductance of the toroidal coil which is

$$L_z = \mu_0 R \left[\ln(8R/b) - 2 \right] \quad (8)$$

where b is the outside radius of the coils and R the major radius. With $R = 4$ m and $b = 0.15$ m, $L_z = 16.9$ μ H. This inductance has to be compared to the coaxial inductance $\mu_0 R \ln(b_c/b_p)$ to see by what factor the I_z found from Eq. (6) is reduced by a break.

The net z current can be reduced if the coil has a break, or can be canceled by means of an auxiliary capacitor bank. Neither of those methods ensures however, that the z currents will be zero throughout the plasma (Sec. IV).

Many Scyllac experiments have been carried out in sectors. Since in those machines all magnetic field lines intersect the insulating wall at the ends, conservation of poloidal flux and conservation of rotational transform would seem not to occur, so that the conclusions of this report would not be relevant. There are, however, two effects¹¹ that can cause conservation of poloidal flux as in the full torus.

1. A change in rotational transform in a sector experiment leads to angular velocities of the field lines and the low-density plasma near the ends. In a long machine this rotation can correspond to an appreciable kinetic energy, even for fairly low outside densities. A polarization current, flowing across the field lines is needed whenever the angular velocity is changing. Since this polarization current continues as a z current on the axis and at the outer edge of the outside plasma, it tends to screen off the change of the rotational transform. This mechanism leads to a complete screening off, as in a full torus, for fast changes of the applied rotational transform and to easy penetration for slow changes. To be in the slow category the frequency ω , with which the applied rotational transform changes, must satisfy^{11,12}

$$\omega^2 \ll 2 V_A^2 / L^2 = 2 B^2 / \mu_0 \rho L^2 , \quad (9)$$

where Alfvén velocity V_A and the mass density ρ have to be taken for the outside plasma and where L is the length of the sector. For $B = 4$ T, $L = 8$ m, and for an outside deuterium plasma of density 10^{14} cm⁻³, the limiting ω turns out to be 1.1×10^6 s⁻¹.

2. A change of rotational transform in a sector is accompanied by a change of poloidal flux. This change of flux causes radial E fields. Because all field lines leave the machine at the ends, a shorting of the E fields along the inner surface of the insulating discharge tube may occur. A perfect shorting would lead to a conservation of rotational transform, as in a full torus.

Both effects mentioned here make it difficult to predict what role the outside plasma will play in a sector, and make the extrapolation from a sector to a full torus problematic.

IV. INTERNAL CURRENT DISTRIBUTION

The precise distribution of the z currents in the plasma is more important than the net z current itself, because even when the net current is canceled, remaining opposing z currents in the plasma may still have their influence on equilibrium and stability.

A general description of the internal current distribution is not easily given, because too many factors play a role. The time history of the external fields, B_z , B_ℓ , and B_θ , the inward motion of fields and plasma during the formation, and the time dependence of the distortions of the central plasma all influence the z currents.

To illustrate the problem we give two examples; in the first one an $\ell = 1$ helical field and the main field are applied with the same time history, as by a shaped coil, whereas in the second example, an $\ell = 2$ helical field is applied late in time as by a feedback or a trimming field coil.

A. Helical $\ell = 1$ Field Rising With Main Field

In this first example both $B_{\ell=1}$ and B_z rise with the same time history, as in the case when they are both produced by a shaped coil. All field lines come in from the outside and move inwards into the plasma, which extends to the radius b_p . When the field lines are at the position b_p two effects contribute to their rotational transform; the helical field produces an ι_ℓ given by Eq. (1) and the longitudinal plasma current produces a rotational transform ι_c , which is related to the current by

$$\iota_c = \frac{\mu_0 R I_z(r)}{r^2 B_z} . \quad (10)$$

For a continuous toroidal coil, or for perfect shorting at the ends of a sector, Eq. (6) gives the current. Substitution of this current and of $r = b_p$ into Eq. (10) yields ι_c , which turns out to be opposite to and larger than ι_ℓ . The resulting rotational transform is then

$$\iota_{res} = \frac{2 \ln(b_c/b_p) - b_c^2/b_p^2 + 1}{2 \ln(b_c/b_p)} \iota_\ell , \quad (11)$$

where the coefficient of ψ_ℓ is negative and its absolute value exceeds 1 for $b_c/b_p > 1.87$.

Once the field lines have entered the conducting plasma, they conserve the rotational transform ψ_{res} . Figure 1a shows the resulting distribution of the rotational transforms, ψ_ℓ , ψ_c , and ψ_{res} , and the B_θ field caused by the volume currents, for the hypothetical case of a low-beta central plasma. The current density j_z is homogeneous for this case and is equal to the net current divided by the plasma area πb_p^2 .

For the more realistic case of a high-beta central plasma an additional rotational transform ψ_d is produced by the diamagnetic currents in the skin of the helically distorted plasma column. This rotational transform is, for a sharp skin plasma with radius a and for the full torus,¹³

$$\psi_d = \frac{4\pi\beta^2 hR}{(2 - \beta)^2} \left\{ \frac{B_{\ell=1}}{B_z} \right\}^2 \frac{1}{(ha)^2} \left| \frac{a}{r} \right|^6. \quad (12)$$

This ψ_d can be two orders of magnitude larger than the ψ_ℓ given by Eq. (1) but it falls off sharply with r . This means that ψ_d usually does not contribute to the poloidal flux between the outer edge of the plasma and the coil [Eq. (5)]; only when a helically shaped quartz tube is used ψ_d contributes to that flux early in time when the dense plasma is still close to the wall. In that case the net current rises initially faster than given by Eq. (6). When a smooth-bore quartz tube is used, the distortions of the dense plasma and the peak in ψ_d develop after the implosion of the dense plasma has taken place.

The large peak in ψ_d produces in the conducting plasma just outside the main column an equal and opposite ψ_c peak to keep the total transform equal to ψ_{res} (see Fig. 1b). To find the local current densities we differentiate Eq. (10)

$$\mu_0 R 2\pi r j_z = \frac{\partial}{\partial r} \left(\psi_c r^2 B_z \right). \quad (13)$$

Since the derivative of $\psi_c r^2 B_z$ has opposite signs on either side of the peak, oppositely directed j_z currents have to be flowing to generate the ψ_c peak.

A $\beta = 1$ plasma with $a = 1$ cm confined in the $\ell_{0,1}$ torus of the first example in Sec. III.B has an ψ_d peak of 137 rad and a z current on either side of the peak of 10.9 kA.

It is likely that a diffuse skin will lead to a lowering of the i_d peak and the thereby induced z currents. The above example shows nevertheless how much the configuration in the experiment can differ from the "standard" configurations where the net z current on any surface is assumed to be zero.

The large localized j_z currents are not easily detected in the experiment, because they will not affect the net z current. Even oscillations of $\delta_1 a$ (see Ref. 6) should not show up in the net current because all corresponding local oscillations in j_z are screened off by the surrounding low-density plasma region.

Note that the description given here uses as its only assumption the presence of a highly conducting, low-density plasma outside the dense central column. Especially close to the column where most of the effects occur, the presence of this plasma is hardly debatable.

B. Helical $\ell = 2$ Field Applied Late in Time

In this second example we apply a relatively weak $\ell = 2$ field to an already formed pure theta pinch. Neglecting diamagnetic effects of the central plasma we consider the initial state as a low-density, highly conducting plasma in a strong B_z field, somehow confined in a torus.

We then apply from the outside an $\ell = 2$ field which in the empty tube would have field components

$$\begin{aligned} B_r &= A_2 r \cos(2\theta - \omega t) \\ \text{and} \quad B_\theta &= A_2 r \sin(2\theta - \omega t). \end{aligned} \tag{14}$$

Image currents in the outer edge of the plasma, at $r = b_p$, try to prevent the penetration of these poloidal fields. The combination of image currents and poloidal fields pushes the low-density plasma in until its outer surface is distorted in the same manner as the magnetic surfaces generated outside the plasma. As a result of the distortion of the plasma surface, $\ell = 2$ fields are produced inside the plasma, as components of appropriately distorted longitudinal field lines. An important difference with the vacuum field of Eq. (14) is however, that the rotational transform of the field lines in the plasma must remain zero. Therefore, a z current in the plasma has to cancel the rotational transform of the $\ell = 2$ field. The i_ℓ from Eq. (2) generates an equal and opposite i_c which is approximately uniform in space as i_ℓ is. This leads to a uniform current density [from Eq. (10)]

$$j_z = 2 A_2^2 / \mu_0 h B_z, \quad (15)$$

and a corresponding B_θ field, $B_{\theta c}$,

$$B_{\theta c} = 1/2 \mu_0 j_z r = r A_2^2 / h B_z, \quad (16)$$

which turns out to be a factor A_2/hB_z times the maximum value $A_2 r$ of the B_θ component of the $\ell = 2$ field. Although this factor does not seem to be large in most cases, the component $B_{\theta c}$ obviously destroys the magnetic surfaces, since a rotational transform is necessary to generate the surface in many revolutions around the torus.

The homogeneous j_z of Eq. (15) takes care of the flux conservation inside the plasma. In addition to this current a net current is needed to compensate for the flux ϕ_p between the coil and the outer edge of the plasma. The difference between the net current [Eqs. (2) and (6)] and the volume current [from Eq. (15)] must flow as a surface current I_s at $r = b_p$.

$$I_s = \frac{\pi A_2^2}{\mu_0 h B_z} \left\{ \frac{b_c^2 - b_p^2}{\ln b_c/b_p} - 2 b_p^2 \right\}. \quad (17)$$

Figure 1c shows the jumps in i_c , i_{res} , and in $B_{\theta c}$ that correspond to this surface current. As one can see from Eq. (17), I_s only disappears when the conducting wall moves in, so that b_c approaches b_p . If one cancels the net current by means of an auxiliary bank, the surface current would change direction but the volume current Eq. (15) would be unaffected. To cancel the volume current also, one could build in a volume current during the formation of the theta pinch so that the volume current would disappear again upon the application of the $\ell = 2$ field. In addition to that the net current would have to be canceled. Whereas such a procedure might still be practical when just one auxiliary field is used, it would be impossible to cancel all currents when two or more auxiliary fields are used.

The treatment given in this section resembles the one given by Furth,¹⁴ but differs in the description of the global flux conservation between the plasma and the coil.

Fig. 1

Radial distribution of the rotational transforms caused by the helical fields, i_l , caused by the longitudinal current, i_c , and the resulting rotational transform, i_{res} . Also plotted is the field $B_{\theta c}$ caused by the longitudinal current. The outside edge of the conducting plasma is at b_p , the inside of the coil is at b_c . a) Situation for a low- β Scyllac where the $B_{\theta c}$ field and the $\ell = 1$ field are applied simultaneously. Since the flux between b_p and b_c is kept zero by the plasma, the incoming rotational transform is changed and a homogeneous j_z results in the plasma. b) Situation as in a) but with a high- β plasma core with radius a . The helical deformations of the central plasma cause a strong peak in i_l just outside the core. This causes an equal and opposite peak in i_c , so that i_{res} can stay constant. The i_c peak corresponds to strong opposing j_z currents that do not change the net current. c) An $\ell = 2$ field applied to an already formed pure theta pinch. The $\ell = 2$ fields distort the central region so that a plasma current has to flow to avoid a change of i_{res} . A skin current keeps the flux between b_p and b_c zero. The curves near the axis will be changed somewhat if a high-beta core is present.

V. CONCLUSIONS

- The helical fields in a Scyllac configuration generate a poloidal flux between the outside edge of the plasma and the inside of the coil. The change of this flux during the risetime of the fields induces a net current in the plasma [Eq. (6)]. The magnitude of this current is larger for higher ℓ fields.

- The net plasma current depends on whether and where a longitudinal return current can flow in the theta coils. No net current will flow in a sector experiment, in a torus one can cancel the net current with an additional bank.

- Volume currents inside the plasma are induced whenever the local rotational transform tends to change. These volume currents conserve the fluxes between the magnetic surfaces and hence conserve the rotational transform. This conservation takes place in a wide region, since the low-density plasma between the quartz wall and the central plasma is well conducting on the time scales considered.

- When the helical and the longitudinal field are applied with the same time history, the volume currents are related to the above-mentioned net current and to the helical displacement of the diamagnetic central plasma.

- When the helical field is applied after the main field, both surface and volume currents are needed to conserve the outside and the inside fluxes.

- Volume currents may flow in a sector experiment, when wall shorting takes place at the ends, or when changes in the rotational transform produce rapid changes in the angular velocities of the plasma.

- Complete cancellation of net current and volume currents in a torus is extremely difficult, especially when more auxiliary fields are used.

- The plasma currents resulting from the flux conservation lead to equilibria which differ from those commonly considered for Scyllac stability calculations.

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