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PLASMA POSITION CONTROL BY ISO-FLUX METHOD IN TEXTOR

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Plasma Position Control by Iso-Flux Method in TEXTOR

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For measuring and controlling the plasma in the TEXTOR tokamak, the iso-flux method is to be applied. It is to be performed by one loop coil and one magnetic probe, so in this case an error of the flux at the plasma surface which is calculated by this method has been estimated. It is at most 7% of the total flux generated at zero displacement of the plasma from the equatorial plane, so it is no problem on practical application. A linearity between the flux near the plasma surface and the vertical displacement of the plasma has been also estimated, and it is verified to be very good. The practical electronic circuit of the iso-flux method has been discussed and a simple adjustement of the circuit has been done.

Keywords: TEXTOR, Tokamak, Plasma Position, Iso-flux Method, Error, Calculation, Linearity, Vertical Displacement, Electronic Circuit, Adjustment, Control

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On leave within the IEA-Implementing Agreement on TEXTOR.

TEXTORにおける等磁束法によるプラズマの位置測定・制御

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松　崎　　誼

（1982年7月1日受理）

等磁束法（iso－flux method）をTEXTORにおけるプラズマ垂直位置の測定・制御に適用した。真空容器の空間取合上，1本のループコイルと1個の磁気プローブでプラズマ表面の磁束を推定・計算する。それでこうした手段で評価されるプラズマ表面の磁束の，位置に対する誤差を評価した。誤差は赤道面上の磁束に対し最大で7％程度であり，実用上問題ない事が示された。プラズマ位置に対するプラズマ境界付近の磁束の線形性も評価し，磁束が位置に対し良い線形性をもつ事が示された。

次に実際の電子回路の構成について示し，TEXTORの場合について，実際の信号処理及び信号の校正方法について述べた。又この電子回路の調整を行った。

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1. Introduction

The TEXTOR tokamak[1] has been built for the purpose of studying the plasma-wall interaction. For this objective, it is very important to get a highly stable and reproducible plasma. One of the most important procedure for achieving this purpose is to measure and control the precise position of the plasma.

In order to measure and control the plasma position there are many methods, for example, a multi-channels μ-wave interferometer device[2] from which we can measure two spatial points of the electron density and control the plasma position, a PIN diode array[3] from which we can measure the soft X-ray intensity spatially and control the position of the plasma and a electromagnetic diagnostics. This has many kinds, for example, magnetic probes[4], sine-cosine coils[5], flux-loop coils, partial Rogowski coils and saddle coils, and they measure not a core plasma directly, but a poloidal magnetic filed outisde the plasma. Among these electromagnetic diagnostics the magnetic probes are most popular. However, the equation which decide the horizontal displacement by two magnetic probes' signals includes a poloidal beta β_p and an internal self-inductance ℓ_i. The value of β_p changes at every second in discharge and also changes largely at the time of additional NBI and/or RF heating. The value of the internal inductance changes also at every second. For determing the position of the plasma by this method we must assume a current distribution. The similar problems are in non-circular plasma, so in the ASDEX tokamak the other emthod — iso-flux method[6)7] — has been employed.

In TEXTOR the sine-cosine coils and the saddle coils are now employed[8]. These system has been worked very well since the beginning of its operation on September, 1981[9). There are, however, same defects in this method like the magnetic probes' method, so we are to employ the iso-flux method in TEXTOR.

In this paper we describe the principle of the iso-flux method and the result of calculations which are applied to a vertical displacement of the plasma from an equatorial plane in the TEXTOR tokamak, then sketch the practical electronic circuit of the method and a result of a function test on the practical electronic circuit applied in TEXTOR.

2. Principle and Calculation

2.1 Principle of the iso-flux method

The iso-flux method is that the flux just at the plasma surface is estimated by one loop coil and two magnetic probes, and also that the displacement of the plasma can be estmated horizontally and/or vertically from the signals between the outer and the inner and/or the upper and the lower signals respectively which are get by the loop coil and the magnetic probes. According to D.B. Albert[7) the flux just at the plasma surface ψ_p is written by a Taylor expansion around the measuring point m which is outside the plasma

$$\psi_p = \psi_m + d\,\frac{\partial\psi_m}{\partial r} + \frac{d^2}{2}\,\frac{\partial^2\psi_m}{\partial r^2} + \text{-----} \qquad (1)$$

where ψ_m, $\partial\psi_m/\partial r$, $\partial^2\psi_m/\partial r^2$ are the flux and its first, and second delivertieves at measuring point, d is the distance between the measuring point and plasma surface (see Fig.1). In order to get more practical equation, we introduce the loop flux and two magnetic fields at the measuring point as shown in Fig. 1. The above-mentioned beginning of its operation on September, 1981[9)]. There are, however, same defects in this method like the magnetic probes' method, so we are to employ the iso-flux method in TEXTOR.

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$$\psi_p = \psi_m + d2\pi R_m \frac{B_i + B_o}{2} + \frac{d^2}{2} 2\pi R_m \frac{B_i - B_o}{e} \tag{2}$$

where ψ_m is the loop flux measured by the loop coil, R_m is a radius of the loop, B_i, B_o are the magnetic fields measured by two magnetic probes and e is the distance between these two probes.

2.2 Estimation of error and linearity

In the TEXTOR tokamak we apply the iso-flux method for measuring and controlling the vertical displacement of the plasma. The loop coil and the magnetic probes are situated as shown in Fig. 2. For lack of a room to set one loop coil and two magnetic probes in the vacuum chamber, the loop coil is situated outside the chamber and only one magnetic probe is set inside the chamber. From these restrictions, the flux just at the plasma surface ψ_p in eq.(2) is written the following equation on the assumption that the outer field B_o is equal to the inner field B_i.

$$\psi_p = \psi_m + d\ 2\pi R_m\ B_i \equiv \psi_m + \psi_m' \tag{3}$$

We must estimate an error of the flux ψ_p expressed the above-mentioned equation. As a degree of the error we take a difference of the flux between the upper and the lower flux obtained by the equation (3) which correspond to the vertical displacement of the plasma. This means that when the difference of the flux $\Delta\psi_p$ between the flux of the top boundary ψ_p^u and the bottom boundary ψ_p^d on the plasma, $\Delta\psi_p = \psi_p^u - \psi_p^d$, is zero whatever the plasma shifts vertically, the error of the flux which is calculated by equation (3) is zero, and that the larger is $\Delta\psi_p$, the larger is the error.

The first term of the right-hand side in the equation (3) ψ_m is easy to caliculate by electromagnetic formula[10) on the assumption that the plasma is a current-carrying ring and that the loop coils and the ring have the same axis and are parallel to each other (see Fig. 3). The flux ψ_m generated by the current of a loop 1 is the followings

$$\psi_m = \mu_0 \sqrt{ab}\ [(\frac{2}{k} - k)\ K\ (k)\ - \frac{2}{k}\ E(k)]I_1 \qquad (4)$$

$$k^2 = \frac{4ab}{(a+b)^2+c^2}$$

where a, b are the radii of the loop 1, 2 respectively, c is the distance between the loop 1 and the loop 2, K (k), E (k) are the complete elliptic integrals of the first and second kinds respectively, μ_0 is a free space permeability $4\pi \times 10^{-7}$ H/m and I_1 A is the plasma current. The second term of the right-hand side in the equation (3) can also easily be calculated by Ampere's formula. The calculation was done in the case that the current of the ring is 500 kA.

The result is shown in Fig. 4 where ΔV cm is the vertical displacement of the ring from the equatorial plane, $\Delta\psi_p^0$ V.sec is the error which is estimated from calculating only ψ_m in the equation (3) and $\Delta\psi_p^1$ V.sec is the error of which calculations were included the second term ψ_m' in the equation (3). As shown in Fig. 4 the larger are the displacement, the larger are the degree of the error. It reachs to about 20% and 7% of the total flux at zero displacement ψ_{p0} which is generated by the current ring situated on the equatorial plane in case of $\Delta\psi_p^0$ and ψ_p^1 respectively, where the displacement is maximum. The result also indicates that when applying the iso-flux method to the TEXTOR tokamak by using one loop coil and only one magnetic probe it is practically no problem because that the error is 7% at maximum and in practice the displacement of the plasma from the the equatorial plane is small. Fig. 4 also shows that the error is linear to the displacement.

In practice it is difficult to change the distance d between the measuring point and the plasma surface during the dicharge. When we apply the method practically to measuring the displacement, we have to fix the value of the distance d before the discharge. As a result we measure the flux not just at the plasma surface, but near the plasma boundary. If the flux near the plasma boundary is linear to the displacement as shown in Fig. 5, it is convenient to decide the position of the plasma. For verifying this relation we calculate the upper and lower flux ψ_M^u, ψ_M^d respectively in case that the distance d is constant in eq.(3). From the calculation we get the following result that the flux ψ_M^u and ψ_M^d are linear to the vertical displacement ΔV of the plasma (see Fig. 6), and the difference between these flux $\Delta\psi_M = \psi_M^u - \psi_M^d$ is also linear to ΔV as shown in Fig. 7. This figure is also useful to decide the displacement from practically measured flux $\Delta\psi_M$ in case that d is constant.

3. Practical Application to the TEXTOR tokamak

3.1 Schematic diagram of control circuit

We apply the above-mentioned iso-flux method to TEXTOR for measuring and controlling the vertical displacement of the plasma. (see Fig. 8) We need two pairs of one-turn loop coil and magnetic probe which are located upside and downside on the vacuum chamber as shown in Fig. 2. From the one-turn loop coil we get a loop voltage V_ℓ, and it is modified as follows.

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$$V_\ell = R_p I_p + L_p \frac{dI_p}{dt} = M_{ph} \frac{dI_h}{dt} + L_p \frac{dI_p}{dt} = \frac{d\phi_h}{dt} + \frac{d\phi_p}{dt} \qquad (5)$$

where R_p, L_p, I_p and ϕ_p are the resistance, inductance, current and flux of the plasma respectively, and I_h and ϕ_h are the current and flux of the primary winding respectively and M_{ph} is a mutral inductance between the plasma and the primary winding. From this equation an integrated signal of the difference signal between the upper and lower one-turn loop coils become the difference of the flux between the upper and lower flux generated by the plasma $\Delta\psi_m$, that is, $\int(V_\ell^u - V_\ell^d)dt = \phi_h^u + \phi_p^u - (\phi_h^d + \phi_p^d) = \phi_p^u - \phi_p^d = \psi_m^u - \psi_m^d = \Delta\psi_m$ where ψ_m is the first term in eq.(3). As the consequence two loop coils are connected as shown in Fig. 7 and the resultant signal is integrated by an integrator I2, and then the output signal of the integrator become the above-metioned flux $\psi_m^u - \psi_m^d = \Delta\psi_m$.

From the magnetic probes we get the derivative signals of the magnetic fields. According to integrating these signals by two in-egrators I1, I3 we get the magnetic field B_m^u, B_m^d V.sec/m^2. Then multiplied these by $F_u = 2\pi R_m d_u$ and $F_d = 2\pi R_m d_d$ respectively, and the products are $\psi_m'^u$ and $\psi_m'^d$ in eq.(3) where R_m is the distance between magnetic probes and the central axis of the tokamak, d_u and d_d are the distance between magnetic probes and upper and lower plasma surface respectively.

By summing up these signals $\Delta\psi_m$, $\psi_m'^u$ and $-\psi_m'^d$, we get the differnce of the flux $\Delta\psi_M$ V.sec between upper and lower plasma boundary. Through dividing $\Delta\psi_M$ by a plasma current I_p, the vertical displacement ΔV cm is obtained.

3.2 An adjustment of electronic circuit

We describe here practically the processing and calibrating of the signals in TEXTOR. An output signal of the integrator S_I is presented as follows;

$$S_I = \frac{1}{RC}\int v(t)dt \qquad (6)$$

where v(t) is an input signal, 1/RC is a sensitivity. The sensitivity of the integrator used in TEXTOR can be changed freely. Now we apply it to the loop coils' signal treatment as shown in Fig. 7. Through integrating this signal $V_\ell^u - V_\ell^d$ V by the integrator I2, we get the flux $\psi_m^u - \psi_m^d$ V.sec. And so in case that the sensitivity 1/RC is 100, 1 V of the output signal in I2 corresponds to 0.01 V.sec of the flux. In regard to the signal treatment of the magnetic probe used in TEXTOR (see Fig. 9), it has been already calibrated that the magnetic field 1 kG corresponds to 4.91 V output voltage of the integrator in case the sensitivity is 100[11]. And so in case that the sensitivity is 204, 1 V output voltage corresponds to 0.01 V.sec/m^2. If a magnitude of the multipling factor F_u and F_d are fixed that 1 m^2 is factor 1, 1V output voltage of the multiplier corresponds to 1 V.sec of the flux which are $\psi_m'^u$ and $\psi_m'^d$. As a result of above-mentioned processing of three signals, 1 V input signals of a summing circuit corresponds to 0.01 V.sec of the flux. Then summing up these signals, 1 V output signal corresponds to 0.01 V.sec of the flux which is $\Delta\psi_M = \psi_m^u - \psi_m^d + \psi_m'^u - \psi_m'^d$ in eq.(3). And further by dividing $\Delta\psi_M$ by the plasma current I_p as following equation, we get the vertical displacement of the plasma ΔV cm.

$$\Delta V\ (\mathrm{cm}) = K \times \Delta\psi_M(\mathrm{V.sec}) \times 1/\frac{I_p(\mathrm{kA})}{500\ (\mathrm{kA})} \qquad (7)$$

where K cm/V.sec is a ratio of the displacement to the flux as shown in Fig. 7.

We have practically made sure of the above-mentioned signal processing on electronic control circuit including three integrators and one 4-terminal summing amplifier[12] by using three function generators.

The integrator has functioned well as shown in eq.(6), and also the 4-terminal amplifier has functioned well as multiplying two signals by the set values and as summig up three signals.

4. Conclusion

The iso-flux method is applied to the TEXTOR tokamak for measuring and controlling the vertical displacement of the plasma. As a detector one loop coil and one magnetic probe which are located upside and downside respectively are used, so an error was estimated in determining the vertical position of the plasma. In calculation we assume that the plasma is a wire ring carrying a current. The maximum error is about 7% of the total flux generated at zero displacement of the plasma, which occur in the maximum displacement of the plasma, so it may be no problem for practical use. A linearity of the flux to the displacement near the plasma boundary is also checked for the convenicence of determining the displacement, and it is verified as shown in Fig. 6.

We consider a practical control circuit for applying the iso-flux method as shown in Fig. 8. From the difference of the loop voltage between upside and downside loop coils we get the flux $\psi_m^u - \psi_m^d$ in eq.(3) by integrating where u and d denote upside and downside respectively. From the magnetic probes we get the flux $\psi_m'^u$ and $\psi_m'^d$ in eq.(3) through the integrating and multiplying a set value. In order to sum up these signals, a voltage of each signal has to be the same to the same flux by setting the adequate values of the integrators and multiplying factors as shown in section 3.2. Through dividing the signal summed by a plasma current we get the vertical displacement of the plasma by using eq.(7). Finally the electronic circuit composed of three integrators and one 4-terminal

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Acknowledgement

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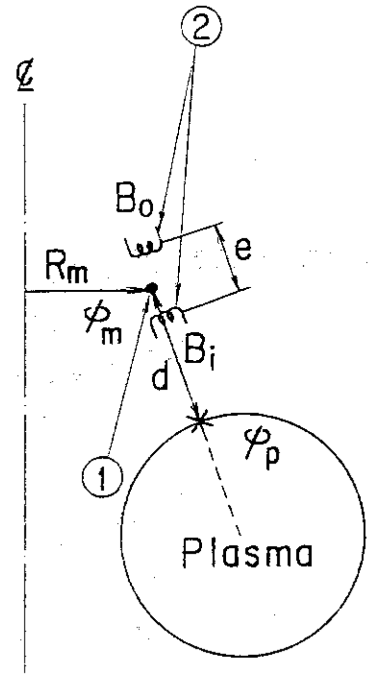

Fig. 1 A schematic diagram of the principle of the iso-flux method.: one turn loop coil--①, magnetic probes--②

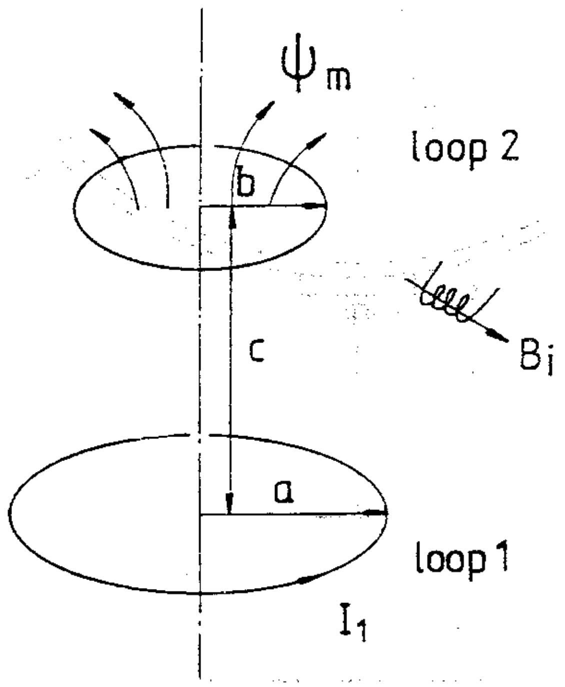

Fig. 3 An illustration diagram of the calculation in eq.(3) and (4)

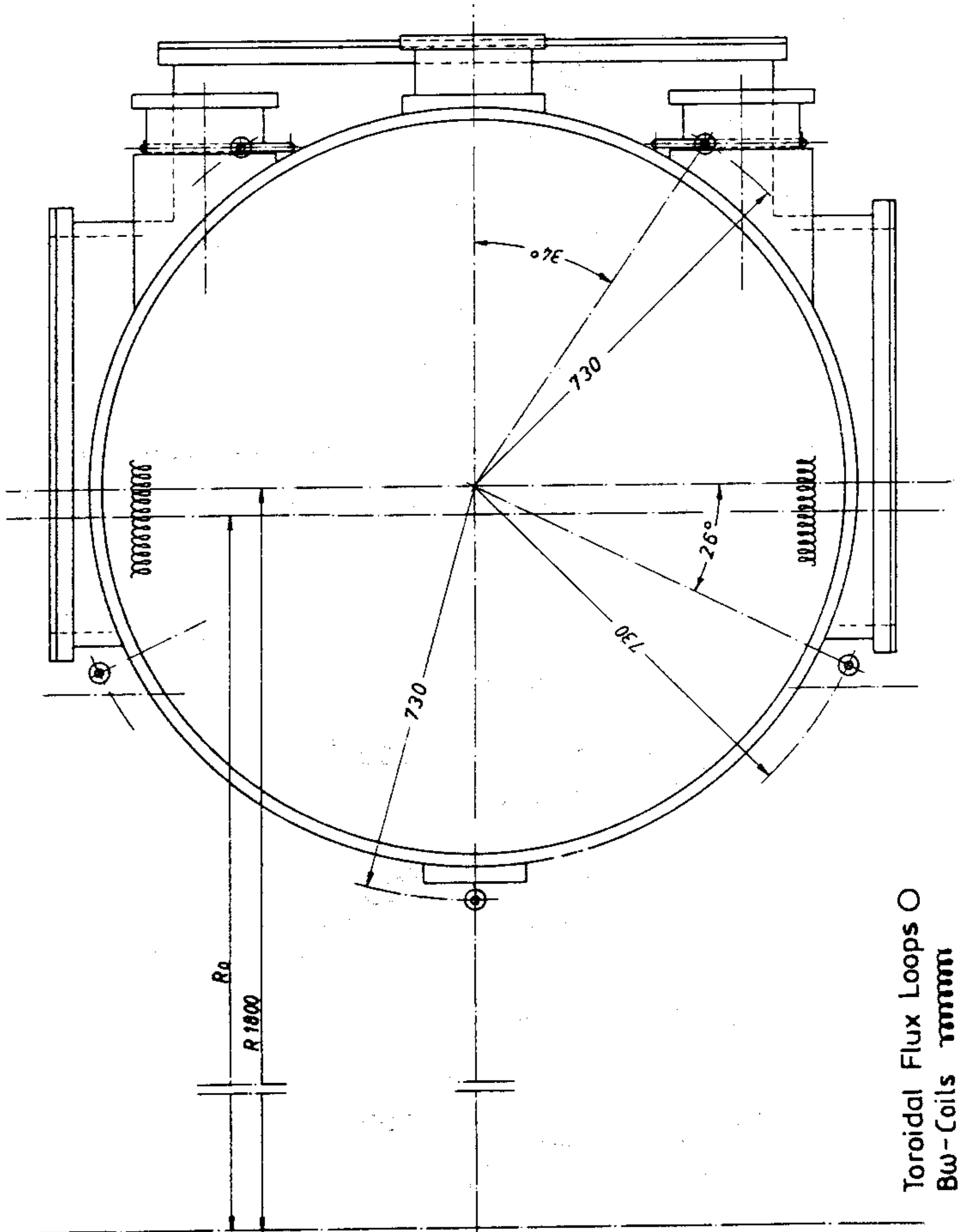

Fig. 2 A configuration of the loop coils ① and magnetic probes ② in the TEXTOR tokamak

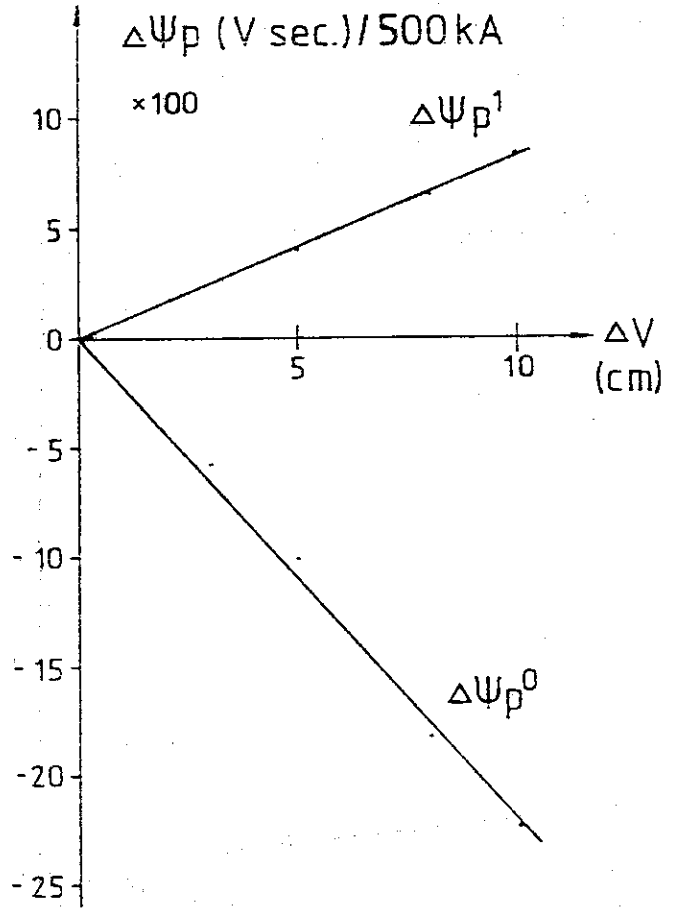

Fig. 4 The error in Taylor expansion of the flux at the measuring point. $\Delta\psi_p^0$ is the error on occasion that the calculation is done only zero-order term in Taylor expasion and $\Delta\psi_p^1$ is the error of which calculation is done first-order term in Taylor expnsion.

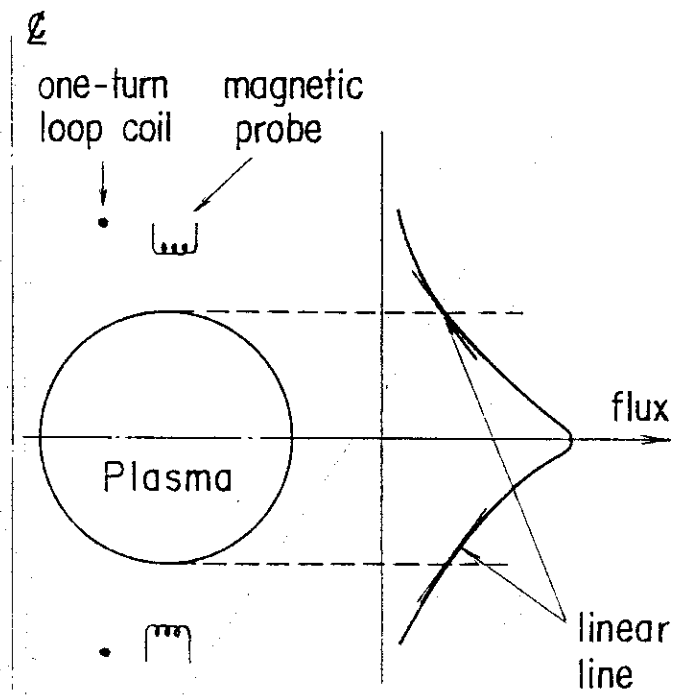

Fig. 5 An illustration diagram of measuring the position of plasma by using the iso-flux method.

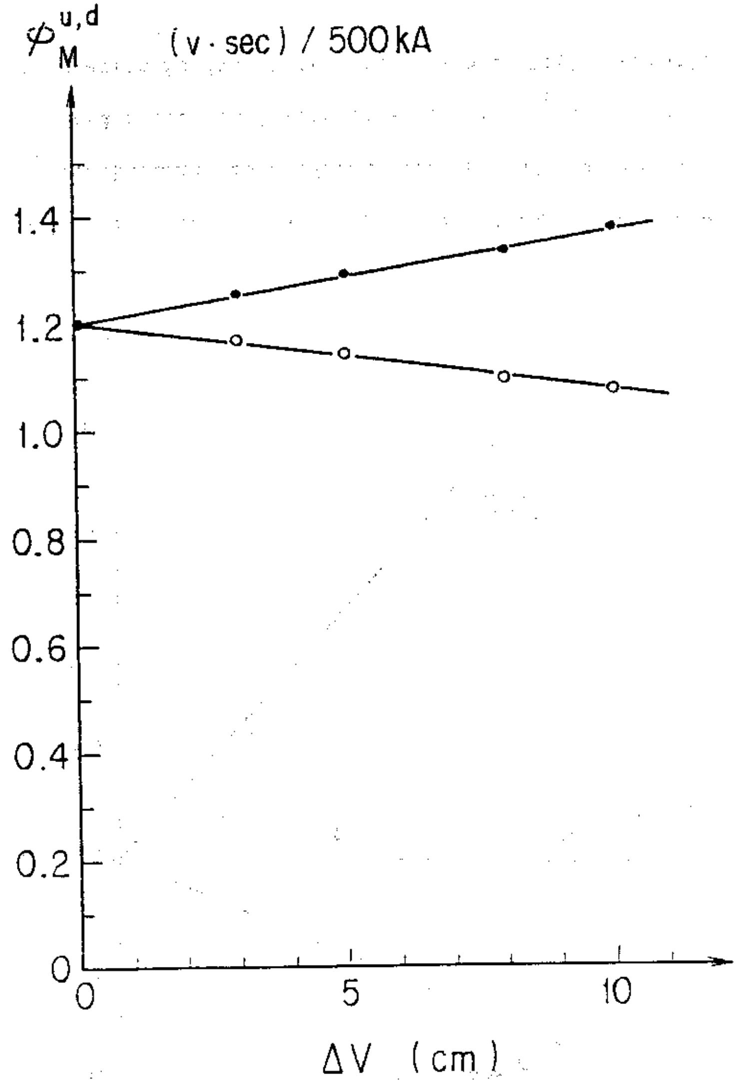

Fig. 6 The relation between the flux ψ_M^u, ψ_M^d which are calculated in case that d is constant in eq.(3) and the vertical displacement of the plasma ΔV, where u and d denote upside and downside respectively.

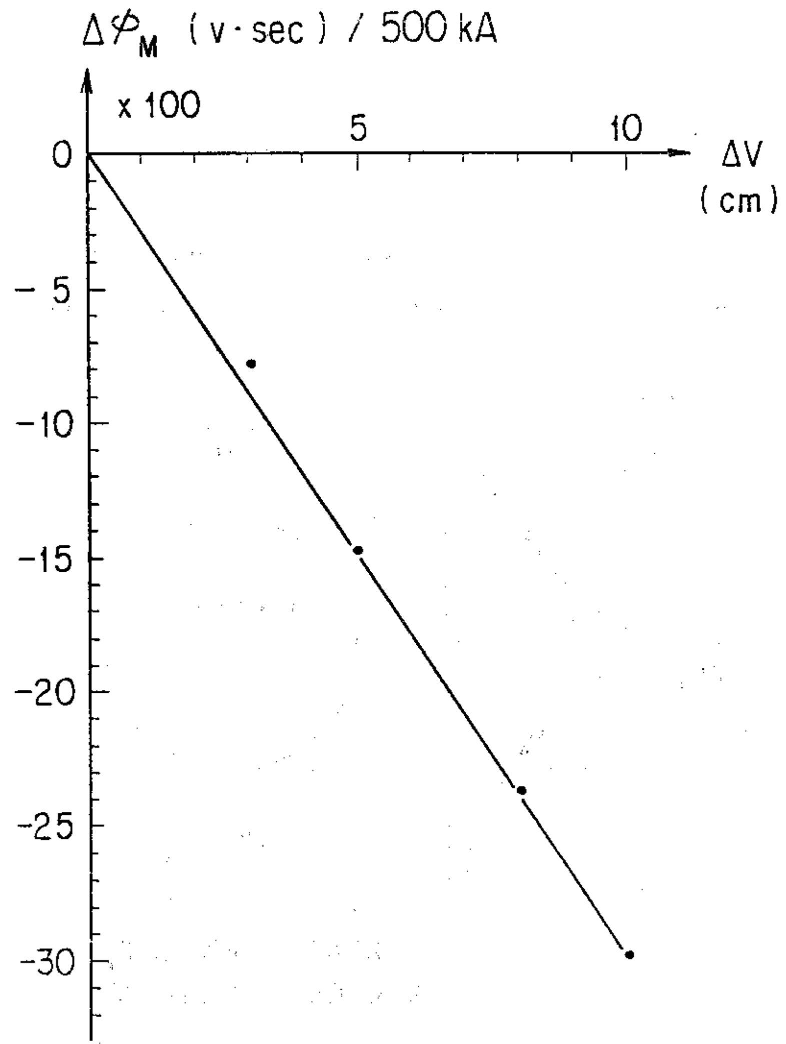

Fig. 7 The relation betwen the displacement of the plasma ΔV and the difference of the upside and downside flux $\Delta\psi_M$.

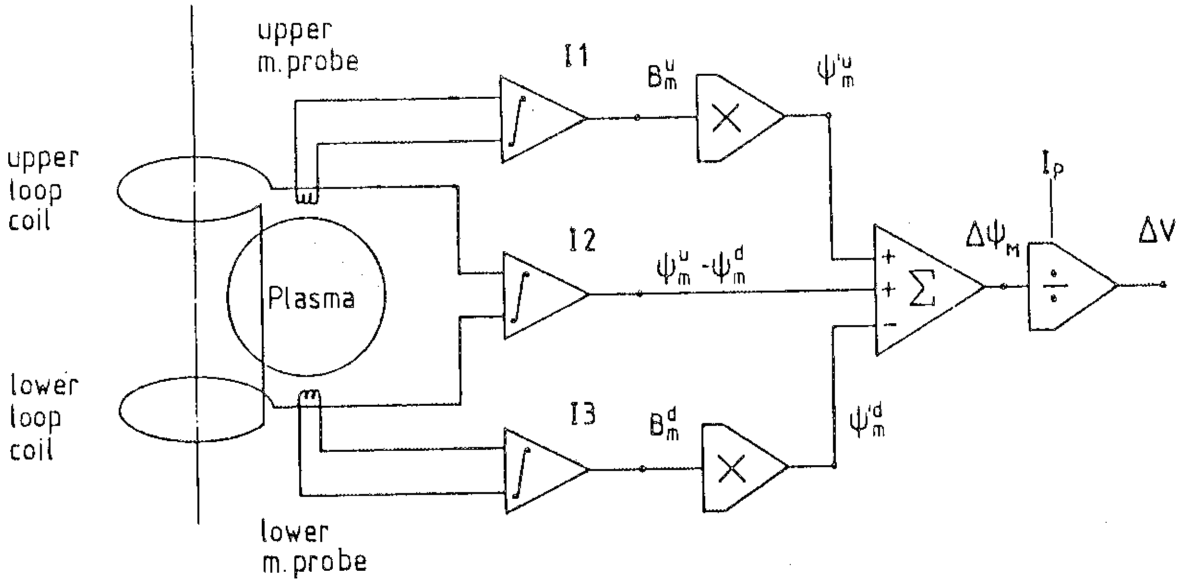

Fig. 8 An electronic circuit for measuring the displacement of the plasma.

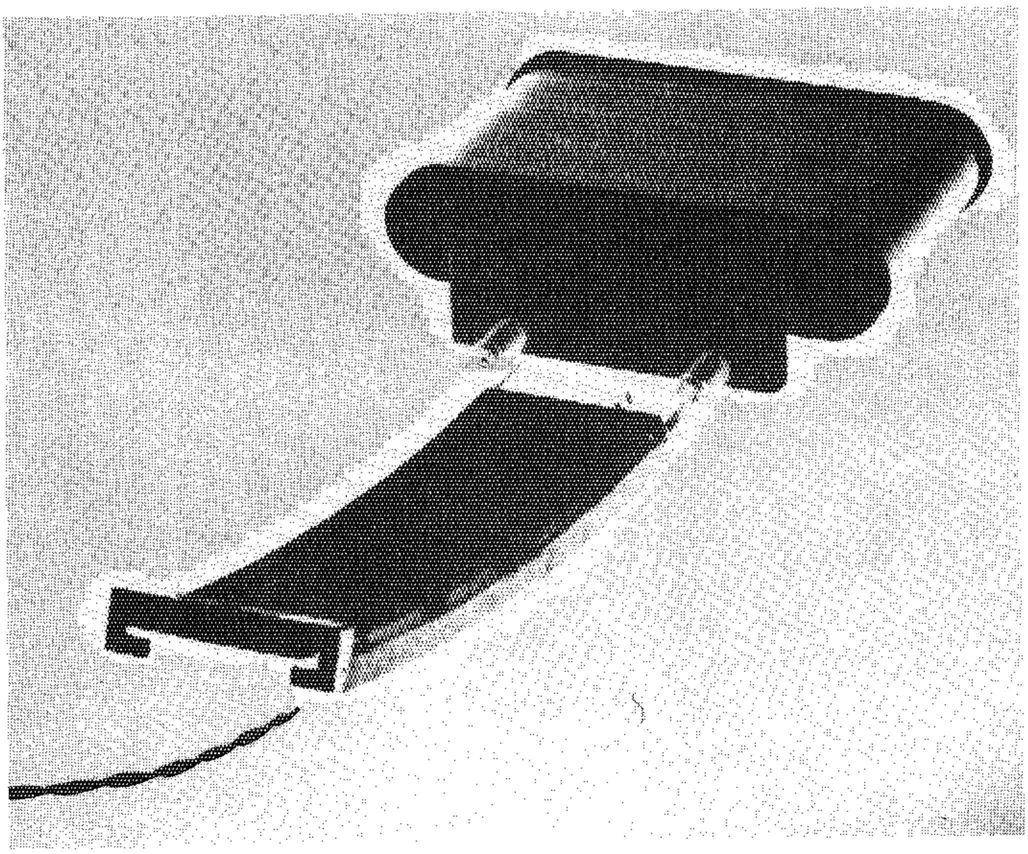

Fig. 9 A picture of the magnetic probe which is applied to the TEXTOR tokamak.